U.S. DEPARTMENT OF THE INTERIOR

U.S. GEOLOGICAL SURVEY

Cruise Report for a Seismic Investigation of Gas Hydrates in the Mississippi Canyon Region, Northern Gulf of Mexico -- Cruise M1-98-GM

By

Alan Cooper[1], Patrick Hart[1], Ingo Pecher[2]

[1]U.S. Geological Survey
Menlo Park, CA 94025

[2]Woods Hole Oceanographic Institute
Woods Hole, MA

Open-File Report 98-506

This report is preliminary and has not been reviewed for conformity with U.S. Geological Survey editorial standards (or with the North American Stratigraphic Code). Any use of trade, product, or firm names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

1998

Introduction

During June 1998, the U.S. Geological Survey (USGS) and the University of Mississippi Marine Minerals Technology Center (MMTC) conducted a 12-day cruise in the Mississippi Canyon region of the Gulf of Mexico (Fig. 1). The R/V Tommy Munro, owned by the Marine Research Institute of the University of Southern Mississippi, was chartered for the cruise. The general objective was to acquire very high resolution seismic-reflection data across of the upper and middle continental slope (200-1200-m water depths) to study the acoustic character, distribution and potential effects of gas hydrates within the shallow subsurface, extending from the sea floor down to the base of the gas-hydrate stability zone.

The Gulf of Mexico is well known for hydrocarbon resources that include petroleum and related gases. Areas of the Gulf that lie in waters deeper than about 250 m potentially have conditions (e.g., pressure, temperature, near-surface gas content, etc.) that are right for the shallow-subsurface formation of the ice-like substance (gas and water) known as gas hydrate (Kvenvolden, 1993). Gas hydrates have previously been sampled in sea-floor cores and observed as massive mounds in several parts of the northern Gulf, including the Mississippi Canyon region (e.g., Anderson et al., 1992). Extensive seismic data have been recorded in the Gulf, in support of commercial drilling efforts, but few very high resolution data exist in the public domain to aid in gas-hydrate studies. Studies of long-term interest include those on the resource potential of gas hydrates, the geologic hazards associated with dissociation and formation of hydrates, and the impact, if any, of gas-hydrate dissociation on atmospheric warming (i.e., via release of methane, a "greenhouse" gas).

Several very high resolution seismic systems (surface-towed, deep-towed, and sea-floor) were used during the cruise to test the feasibility of using such data for detailed structural (geometric) and stratigraphic (physical property) analyses based on the acoustic data. The cruise was conducted in two regions, on opposite flanks of the Mississippi Canyon, where gas hydrates are known and suspected from prior coring and seismic operations (e.g., Neurauter and Bryant, 1989). The regions are also characterized by thick surficial, relatively young (Pleistocene and younger) sediments. Swath-bathymetry data (Fig. 2) show extensive sea-floor faults, piercement features, and slumps -- features whose development could potentially be related to gas hydrates. The specific objectives of the cruise were (a) to image the gas-hydrate stability zone across the continental margin to document bottom-simulating reflections (BSRs) and changes in geometry of the hydrate stability zone; (b) to image known hydrate features (with several seismic systems) to estimate physical properties for hydrate and non-hydrate areas; (c) to outline the shallow structures of the hydrate stability zone to ascertain their potential effects on the formation/distribution of hydrates and on stability of the sea floor; and (d) to estimate, if possible, the amounts of hydrates present in the shallow sub surface.

During the cruise about 850 km of multichannel and single-channel seismic data were recorded. Seismic measurements at nine ocean-bottom seismometer (OBS) stations were recorded for several of the multichannel tracklines (Fig. 3). The following report describes the field operations and equipment systems employed, gives two examples of ship-board seismic records, and outlines a few preliminary results.

Personnel

The following personnel participated in the cruise:

Science staff		
Alan Cooper	Co-chief scientist, geophysicist	USGS
Tom McGee	Co-chief scientist, geophysicist	MMTC
Mike Belliveau	Huntec deep-tow technician	GC
Cathy Grace	Geology Research Associate	MMTC
Patrick Hart	Geophysicist	USGS
Bob Iuliucci	OBS technician	BCR
Larry Kooker	Electronics Technician	USGS
Walt Olsen	Mechanical Technician	USGS
Fred Payne	Electronics Technician	USGS
Ingo Pecher	OBS geophysicist	WHOI
Jim Petermann	Electronics Technician	MMTC
Hal Williams	Mechanical Technician	USGS

Ship's crew	***R/V Tommy Munro***	
Paul Beaugez	Captain	GCRL
Greg Skrmetti	First mate / engineer	GCRL
Kat Fletcher	Cook	GCRL
Buddy Ezell	Deck hand	GCRL
Chuck Block	Deck hand	GCRL
Van Overstreet	Deck hand	GCRL
Mike Kulivan	Deck hand	GCRL

Affiliations:
BCR: Bear Cove Resources (under contract to WHOI)
GC: Geoforce Consultants (under contract to USGS)
GCRL: Gulf Coast Research Laboratory, University of Southern Mississippi, Biloxi, MI
MMTC: Marine Minerals Technology Center, University of Mississippi, University, MI
USGS: U. S. Geological Survey, Menlo Park, CA
WHOI: Woods Hole Oceanographic Institute, Woods Hole, MA

Equipment Systems

The equipment systems used during the cruise are listed in Table 1. Most equipment was provided by USGS, with exception of the SeaScope recording system and 15 in^3 water gun, which were furnished by MMTC. Technical specification for the Ocean Bottom Seismometer (OBS) experiment are given in Table 2, and an operations log showing the amounts of data recorded with these systems is outlined in Table 3. Appendix A gives a detailed list of trackline data collected, and Appendix B gives a detailed list of OBS operations. Survey speeds ranged from 2.5 to 4 knots. Seismic systems were fired at different energy levels and rates, as noted. The seismic data were sampled at fast rates (4 kHz to 200 kHz) at or near the capacity of the recording systems, to attain the greatest possible resolution of waveforms for later data analysis. With the fast rates, nearly 50 gigabytes of data were recorded during the 8 days of data collection.

Seas were generally calm, and mostly less than 4-6 feet, above which operations were halted. Data quality is generally good, but is affected in various places by noise from several sources: electronic noise generated by corrosion (discovered at the end of the cruise) in the deck connector of the MCS streamer's lead-in cable; ship-derived mechanical noise, seismic-shooting ships, and nearby drilling operations. Seismic tracklines have continuous large oscillations due to the slow-seeking (20-yr-old) auto-gyro control system that directed the ship's rudder.

Additional information about the data recorded on the cruise, and its public availability can be obtained at the website: http://walrus.wr.usgs.gov/docs/infobank/tiger/m/m198gm/html/m-1-98-gm.html

Table 1: Equipment systems used on cruise M1-98-GM

System	*Components*	*Comments*
Navigation	USGS real-time YONAV system was used for lab/bridge display of positions and data recording. Inputs were from a KVH Heading Indicator and a SATPAK DGPS receiver.	Raster images of NOAA swath bathymetry were displayed for real-time positioning of tracks, to cross sea-floor features of interest.
Multi-channel seismic	MCS data were recorded using: 24-channel ITI streamer with 10 m groups and 3 phones per group -- streamer was towed at an estimated 1-3 m depths (no depth sensors on the streamer), and farthest offset channel was about 270 m behind the source; Geometrics STRATAVIEW digital recording system with marine controller; and 2/4 gbyte DAT tape drive.	MCS data were sampled at 4 kHz rate; and, one trace displayed aboard ship with a Printrex thermal plotter, via the STRATAVIEW marine controller.
Single channel seismic	SCS data were recorded using different configurations: Config. 1: SeaScope system (owned by MMTC): receiver to preamplifier to a "SeaScope" laptop PC recording system with data stored on hard drive and 1 gbyte Jaz drive, and transferred to CD-ROM. Config. 2: MudSeis system (developed by USGS): receiver to preamplifier to a 2-channel PC recording system with data stored on magneto-optical disk. Receivers used at different times: MMTC: 10-element ITI, 1 channel of ITI-MCS; Huntec external streamer; 3-element Benthos streamer. USGS: ITI-MCS streamer; Huntec internal phone and external streamer.	"SeaScope" sampled data at rates from 9-200 kHz. MudSeis sampled data at 33 kHz per channel. Data recorded via the Huntec streamer (i.e., Huntec and watergun) were displayed onboard using an EPC graphic recorder. Lead-in cable for SCS streamers too short to permit their use.
GI gun	Two GI gun sizes (35/35 and 105/105 in^{3}) were used in "Harmonic mode" (i.e., one chamber delayed relative to the other, by a SureShot gun-timing system. The navigation system provided gun-shot-triggers on a constant-time basis. A 50 scfm Bauer Compressor provided air at a pressure of about 3000 psi.	Gun fire rates were: 14 sec. for 35/35 in^3 and 42 sec. for the 105/105 in^3 gun (used for only 1 OBS line). Gun tow depth was about 1 m below surface and 25-30 m behind the GPS navigation antenna.
Water gun	A 15 in^3 water gun was used in the same way as the GI guns, but fired at a pressure of about 2000 psi.	Gun fired at 5 sec. intervals, and towed about 1m depth.
Huntec	A Huntec system owned by USGS was used, with its boomer source fired at variable power settings of 500-1000 joules. The systems two receivers were used (a hydrophone inside of the tow fish and a 1-m-long, 3-element streamer towed behind the fish).	A heavy duty generator was brought from Menlo Park to provide power for the Huntec winch. The boomer was fired at rates of

	Fish tow depth was about 200 m at a ship speed of 3.5 kt. Seismic signals from the fish were fed through shipboard amplifier/filters (set to OUT) and then to the MudSeis recording systems and EPC graphic recorder.	0.75 -1.25 sec. depending on water depth. Data were recorded at 33 kHz sampling rate.
Ocean Bottom Seismometers(OBS)	Six OBS were leased from Delhousie University for the experiment. The parameters for the OBS are listed in Table 3.	All OBS were recovered and generally operated well, with minor problems as noted.
Calibration phone	A USN-calibrated hydrophone was taken for acquiring signatures of the different seismic sources.	Strong ship noise and insufficient lead-in wire precluded calibrations.
Other	A 1000 joule 2-tip minispark system was taken as a backup to the Huntec system, but was not used.	Prior sparker data in the area showed good penetration (250 msec) with a 400-1000 joule multi-tip system.

Table 2: OBS-experiment specifications for OBSs and seismic sources

Deployment 1: OBS Lines 1-5 (MCS Lines 11-15):	
Geophone resonance frequency	4.5 Hz
Sampling frequency	698 Hz
Corner frequency of anti-aliasing filter	200 Hz
Digitizing depth	16 bit
GI-gun: Generator chamber	35 in^3
GI-gun Injector chamber	35 in^3
Source fire rate	14 sec
Air pressure	~2400-2800 psi
Deployment 1: OBS Line 6 (MCS Line 50):	
OBS: Same as above	
GI-gun: Generator chamber	105 in^3
GI-gun Injector chamber	105 in^3
Source fire rate	42 sec
Air pressure	~2400-2800 psi
Deployment 2:	
Geophone resonance frequency	100 Hz
Sampling frequency	5000 Hz
Corner frequency of anti-aliasing filter	1000 Hz
Digitizing depth	12 bit
Watergun chamber	15 in^3
Firing rate	5 sec
Air pressure	~2300 psi

Table 3: Operations log for cruise M1-98-GM

Operation	*Time Spent*	*Data Collected*	*Comment*
Multichannel seismic: GI gun	~40 hours	10 seismic lines	35/35 in^3 GI gun
Multichannel seismic: water gun	~45 hours	21 seismic lines	15 in^3 water gun
Single channel seismic: water gun	~24 hours	13 seismic lines	15 in^3 water gun, deep-tow streamer
Huntec deep-tow seismic system	~39 hours	24 seismic lines	Boomer source
Ocean Bottom Seismometer study	~37 hours	9 OBS stations and 8 MCS lines	2 deployments, 3 seismic sources: 2 @ GI gun and 1 water gun
Transit	~29 hours	none	To/from operational area
Equipment downtime	~15 hours	none	Startup and repairs
Lost time	~20 hours	none	Cruise reschedule and delays
Weather delay	~39 hours	none	Transit and 23-hour layover
TOTAL	288 hours		12 days

Seismic Studies

Several seismic studies were undertaken on the cruise using the equipment systems noted above -- the objectives are summarized in Table 4. The studies were conducted in two general regions, on the east flank and west flank of the Missississippi Canyon in water depths of 250 to 1200 m. The studies fall into two general categories: 1) those relating to the description and analysis of the geologic environment and processes of the gas-hydrate stability zone, and 2) those relating to the acquisition and analysis of highly-sampled (i.e., very high resolution) seismic data, to determine properties of the data that can be used for inferring physical characteristics of the hydrate system (e.g., inversion of seismic data, physical properties, impedances, AVO, P- to S-wave conversion, etc.) The USGS-seismic data sets are directed principally to the first objective, and the MMTC-seismic and USGS-OBS data sets are focused largely to the second.

Table 4: Seismic studies undertaken on cruise M1-98-GM

Study	*Area*	*Comments*
Stratigraphy and structure of the uppermost sedimentary section (i.e., to a sub-surface depth of about 2 times the estimated thickness of the hydrate stability field)	Upper- to middle-continental slope on both sides of the canyon where sea-floor hydrates are known or inferred, and P-T conditions are correct for hydrate formation.	Seek to establish criteria for identifying gas hydrates, BSRs, and underlying trapped gases -- to aid in determining extent and concentration of gas hydrates.
Geometry and extent of the gas-hydrate stability zone (GHSZ).	Upper- to middle-continental slope from shallowest known hydrate occurrence in the Gulf (225 m) to about 1200 m water depth.	Seek to identify local and regional thickness variations on transects of the continental slope, based on changes in acoustic character, BSRs, structures, etc.
Possible links between sea-floor failures, shallow faulting, intrusive structures and gas hydrates of the uppermost sedimentary section.	Areas of apparent sea-floor scarps and slumps on the continental slope, based on regional 100-m-gridded swath bathymetry data.	Seek to determine the role, if any, of hydrates in surface and sub-surface failures.
Special processing of seismic data for estimating acoustic parameters of the	Representative areas of the continental slope where hydrates are known or	Fast sampling rates (9-80 kHz) were used for accurate amplitude

hydrate stability zone.	suspected.	measurements of subsurface and multiple reflections.
Large-offset seismic-waveform-response of the hydrate stability zone to high-frequency seismic energy.	Areas of known hydrate deposits (and inferred underlying free gas) on the continental slope.	Use ocean bottom seismometers to seek P- to S-wave conversions, high-resolution velocities and other large-offset seismic attributes.

The following sections briefly describe the field experiments outlined in Table 4, and give some initial field observations.

Stratigraphy and structure

The field experiments build on the extensive studies reported previously on the structure and stratigraphy of the Northern Gulf of Mexico and Mississippi Canyon regions (e.g., Goodwin and Prior (1989), Weimer et al. (1998)). Several long seismic lines were recorded down the slope and across the canyon to establish the regional character and variability of the upper part of the Pleistocene and younger sedimentary section that drapes the continental slope. The locations of the lines were chosen, based on the NOAA swath bathymetry maps, to cross relatively undeformed sections of the continental slope and canyon floor. The small GI-gun and MCS streamer were used to acquire seismic traces about every 25 m (the fastest rate possible), with penetration to at least the sea-floor multiple reflection (i.e., upper kilometer or so, on the middle slope)(e.g., Fig. 4). One long line was also done up the east flank with the water gun (fired about every 9 m) and the MCS streamer. MCS data were recorded at 4 kHz, the fastest rate possible with the STRATAVIEW marine controller, to achieve the best possible resolution and continuity of reflections.

The acoustic character of the upper-sedimentary sections on the east and west flanks of the canyon is highly variable and complex. From shipboard monitor records, the uppermost parts of the sedimentary section is characterized by uniformly stratified acoustic units that although locally deformed can be traced over large distances on the upper slope. The underlying stratigraphy in these areas is complex, with more-variable amplitudes and less continuity of reflections.

There is much evidence along transects down the continental slope for local structures and amplitude variations likely caused by strong impedance changes (Fig 4). The polarity of the strong reflections could not be determined in the field, and the cause is unknown (e.g., free gas, sands, hydrates, etc.). The large variability in reflection strength and continuity can in places be directly linked to underlying structures, indicating that materials are, in places, moving vertically into and through the uppermost strata. In the deeper-water areas (e.g., greater than 800 m) where shallow strata are certainly within the hydrate stability zone, some of the observed strong amplitude local features may be either hydrates or products associated with the hydrate system (e.g., migrating gases, authigenic carbonates, bacterial mats, etc.). This is particularly apparent where the sedimentary section is disrupted by diapiric structures, of likely mud/sand composition based on the variable thickness of adjacent buried beds. The piercement features extend to the sea floor and are sometimes denoted by strong amplitudes at the sea floor (in comparison with surrounding sea floor that is a lower-amplitude reflection)(Fig 5).

In general, the cause for the large variability in the acoustic characteristics in many of the field seismic records is not readily apparent, and awaits processing and analyses of the data.

Geometry and extent

The geometry and extent of the gas hydrate stability zone (GHSZ) in the Gulf of Mexico is unknown. The thickness of the GHSZ depends on many factors (e.g., temperature, pressure, salinity, gas content, etc.), and formation of hydrates in the zone requires that adequate gas and water be present. In other areas, the base of the GHSZ is marked by a bottom simulating reflection (BSR) that denotes the location where massive gas hydrates (within the GHSZ) lie above a horizon containing free gas (below the GHSZ). The BSR is commonly cited as evidence for the existence of gas hydrates, although a BSR is not required and commonly does not exist. In the Gulf of Mexico, reports of BSRs are rare (e.g., Hedberg, 1980). The three seismic systems (GI-gun, water gun, and Huntec) were used to look beneath the continental slope for evidences of a BSR, or equivalent acoustic transition at the inferred base of the GHSZ.

In the shipboard records, BSRs like those reported in other parts of the World (i.e., in lower-resolution seismic profiles) are not readily apparent, but may be discovered following data processing. On the flanks of some piercement features, and in the upper part of the sedimentary section where gas hydrates are known, high-amplitude reflections that have cross-cutting geometries are recorded (e.g., Fig. 4). However, the cross-cutting reflections are areally limited and do not extend far beyond the zone of underlying high-amplitude reflections.

Another acoustic characteristics that may point to the base of GHSZ is a "shingling" of reflections with increased amplitudes at shallow depths. Elsewhere than the Gulf, such "shingling" is thought due to free gas trapped beneath the GHSZ in the sedimentary section. In some shipboard records, we see apparent "shingling" that varies from place to place in the unprocessed data due partly to the different center-frequencies of the different seismic sources used. Such localized increases in the amplitude of reflections, laterally and vertically, in the stratified sedimentary section could be associated with local trapping of upward-migrating gases. The trapping mechanism could be hydrates, or could be geologic facies boundaries. The complete analyses await further data processing.

Possible links

There has been much speculation that gas hydrates may be linked to sea-floor failures and slumps -- the reasoning being that when gas-hydrates disassociate the released gas may over-pressure a thin porous (sand) layer that then acts as a decollement for a sea-floor slump. The continental slope of the Gulf of Mexico is characterized by numerous small-scale (hundreds of meters) and large-scale (many km wide) sea-floor failures that are clearly evident in the NOAA swath bathymetry data (Fig 2). Such features have extensive and sometimes complex (e.g., en echelon, down-stepped) headwall scarps that surround the upslope edges of the failure. During the cruise, several tracklines were recorded across the edges of two large-scale failures -- one on each side of the canyon -- to determine possible links with shallow hydrate features. Huntec and GI-gun profiles were recorded across the feature on the west flank of the canyon, and water-gun profiles across the feature on the canyon's east flank.

In swath bathymetry data, the failures seem somewhat similar in size and style of failure. In shipboard seismic profiles, the features both show displacement of the sea floor and faulting of the uppermost sedimentary section, implying relatively young deformation. Huntec profiles, like those shown in Figure 5 for other parts of the margin, show evidence of abrupt failures for the feature on the canyon's west flank. Unfortunately, the Huntec system was inoperable during the survey of the east Canyon flank, but water-gun profiles there indicate similar, albeit possibly broader, failure zones. For both sea-floor features, piercement and/or fold structures may lie close to some segments of the head-wall scarps. At first review, structural deformation resulting from salt tectonics appears to be the dominant cause for the sea-floor failures. However, confirmation of this assessment, and of the potential role, if any, of gases and hydrates in facilitating the degree and/or rate of failure awaits data processing and analysis.

Special processing

One objective of the cruise was to acquire seismic data at ultra-high sampling rates (up to 200 kHz) to give precise definition of waveforms (i.e., defined by a minimum of 10 samples per wavelength, equivalent to 5 times Nyquist sampling) for retaining phase and true-amplitude information and for gaining greater vertical and spatial resolution than possible from Nyquist sampling. Faster sampling rates also eliminate the need for anti-aliasing filters, to accurately preserve the 0.5-4.0 kHz seismic frequencies of interest to this study. Underway seismic data were routinely recorded, one seismic-system at a time, at the maximum possible rates attainable by the recording system, for the record length and shot interval being used. The sampling rates were: 4 kHz for water-gun and GI-gun MCS (24-channel) data recorded by the Strataview system; 33 kHz for water-gun and Huntec data recorded by the two-channel Mudseis system; and 9 kHz - 80 kHz for water-gun and Huntec data recorded by the single-channel SeaScope system. Seismic signatures were recorded by the SeaScope system at 200 kHz during a stationary test. Due to time and space constraints, special processing was not possible at sea.

The highly sampled data will be used in particular to determine true relative-amplitudes for the uppermost sedimentary section, for use in estimating reflectances, acoustic impedances, and physical properties of the gas-hydrate stability zone. In one set of experiments, seismic data were collected along approximately the same trackline using each of the four seismic sources (2 GI-guns, water gun, Huntec) and the different receiver systems (2 different towed arrays and low-frequency OBS). Data were recorded with only one seismic source operating, to eliminate the possibility of acoustic "cross-talk". The profile crossed Mississippi Canyon Lease Block 798, where Neurauter and Bryant (1989) had previously reported a hydrate mound underlain by zone of high-amplitude reflections (gas?). The new seismic profiles from the same area show additional mounds, a possible BSR, and likely mud diapirs (Figs. 4a,b and 5). Towed-array data from this experiment will be processed at MMTC to derive estimates of reflection coefficients from a multiple-quotient analysis (Missiaen et al., 1996), to study frequency dependence of reflection coefficients for the hydrate stability zone based on the different seismic sources. For the OBS data, the variable response of the two different OBS recording systems will be assessed to look at near-field response of possible hydrates in the underlying sedimentary section.

Large-offset seismic: OBS experiments

Seismic techniques for remote detection of gas hydrates and associated shallow gas are focusing on two observations that can be addressed with OBS studies:
1. Gas hydrates are assumed to increase compressional (P-) wave velocity of sediments. Within a given lithology, regions of high gas hydrate concentration are expected to be marked by elevated P-wave velocity (V_p). Free gas, on the other hand, is known to drastically decrease V_p (e.g., Domenico, 1977)
2. Compressional to shear (S-) conversion has been observed at a layer with high gas hydrate concentration on the Blake Ridge offshore South Carolina (Pecher et al., submitted) most likely caused by a sharp contrast in S-wave velocity (V_s).

The goals of the present OBS study were to use three-component instruments:
1. To determine the three-dimensional (3-D) P-wave velocity field around an area were gas hydrates were reported at the seafloor, and
2. To acquire possible P-to-S converted waves.

The experiment was done over a mound in Mississippi Canyon block MC798. Gas hydrates have been reported in a core from this mound (Neurauter and Bryant, 1989). Seismic reflections in single channel seismic data beneath the seafloor promise adequate ray-coverage for this experiment (Fig. 3A).

Two OBS deployments were made. During the first and main experiment, six OBSs equipped with 4.5-Hz geophones were deployed at 1.5 km spacing along two N-S-lines near the hydrate mound. An OBS was not placed directly on top of the diapir to avoid possible risks due to any brine pools that are commonly observed on similar hydrate mounds. Five profiles (two N-S, two E-W and one NW-SE) approximately 10 km long were shot with a 35/35 in^3 generator-injector (GI) airgun. Reflections at ~1.25 and ~1.5 sec. two-way traveltime were expected to generate clear arrivals in the OBS data. Ray coverage should be sufficiently dense to calculate a 3-D distribution of V_p within the 1.5-km-by-1.5-km square between the southern and central OBSs above the deeper reflection. V_p can be computed in 2-D along the shooting lines in a larger region.

A sixth line was shot in NW-SE direction, with the a 105/105 in^3 GI gun. This source generated a stronger and lower-frequency (and lower-resolution) signal than the small GI gun. The large GI gun signals should facilitate detecting the usually relatively weak P-to-S converted waves. The orientation of the line was chosen to give near horizontal layers, to accurately determine the fine V_s structure of converted waves via applying 1-D waveform analyses.

For the second experiment, three OBSs equipped with 100-Hz geophones were deployed at 600 m spacing along an E-W line across the hydrate mound. A 15 in^3-watergun was used, as it generates higher frequencies (above 500 Hz) than the GI guns. The goal was to observe reflections from the Holocene sediment drape, and thus obtain a very high resolution velocity profile in the uppermost 50-100 m beneath the seafloor near the mound.

Summary

A new suite of very high resolution seismic profiles and Ocean Bottom Seismometer transects were recorded in the Mississippi Canyon region of the Gulf of Mexico to study the characteristics, evolution, and potential impacts of the gas hydrate system. The new highly sampled seismic data should, after processing and enhancement, provide greater resolution of subsurface structure and stratigraphy in the gas hydrate stability zone than previously known. Such data will hopefully illustrate the relationship between vertically-migrating fluids/gases known in the Gulf, and the distribution of gas hydrates and associated features (e.g., sediment failures, velocity anomalies, hard grounds, etc.).

Acknowledgments

The financial support and cooperation of the MMTC is gratefully acknowledged. In particular, we appreciate the efforts of MMTC's Dr. Thomas McGee who as co-chief scientist promoted and helped conduct the cruise. Because MMTC policy precludes cruise reports from presenting preliminary science observations, Dr. McGee chose to produce a separate detailed cruise-operations report for MMTC (McGee et al., 1998) and to not be an author herein, where preliminary observations are discussed. MMTC funding was through the Minerals Management Service of the Department of Interior. Funding for USGS was from the USGS Coastal and Marine Geology Program. The OBS work was funded by the Department of Energy.

The efforts of the ships's crew, the USGS/MMTC science-support staff, and the Geoforce and Bear Cove technicians to ensure a safe and productive cruise are gratefully acknowledged. The Institute of Marine Sciences, Gulf Coast Research Laboratory is thanked for providing gratis four days of ship time for mobilization and demobilization aboard the R/V "Tommy Munro". We thank also Rebecca Cooper for her work in compiling data and preparing maps, and Michael Hamer, Carolyn Degnan, Nancy Soderberg, and Dave Twichell for their help with preparation of swath-bathymetry maps. The Minerals Management Service, New Orleans, provided valued assistance accessing data used in site selections. Union Pacific Resources of Fort Worth, Texas, gave the necessary permission to install seismometers on the sea floor in Mississippi Canyon Lease Block 798.

References

Anderson, A.L., Sloan, E.D., and J.M. Brooks, 1992, Gas hydrate recoveries in the Gulf of Mexico: What is the shallow water depth limit for hydrate occurrence?, Proceedings 24 th Offshore Technology Conference (1992), Paper 6853, 381-385.

Domenico, S.N., 1977, Elastic properties of unconsolidated porous sand reservoirs. Geophysics, 42, 1339-1368.

Goodwin, R.H., and D.B. Prior, 1989, Geometry and depositional sequences of the Mississippi Canyon, Gulf of Mexico, Journal of Sedimentary Petrology, 59/2, 318-329.

Hedberg, H.D., 1980, Methane generation and petroleum migration, IN Roberts., Q\W.H., and R.J. Cordell (eds), Problems of Petroleum Migration, Amer. Assoc. Petroleum Geologists Studies in Geology No. 10., Tulsa, pp. 179-206.

Kvenvolden, K. A., 1993, Gas hydrates -- geological perspective and global change, Rev. Geophys, 31(2), 173-187.

McGee, T., Cooper, A.K., Pecher, I., Grace, C., and R. Buchannon, 1998, Operations Report for Cruise M1-98-GM, 8-19 June 1998, Marine Minerals Technology Center internal report, 21 p.

Missiaen, T., McGee, T.M., Pearks, D., Ollier, G., and F. Theilen, 1996, An interdisciplinary approach to the evaluation of physical parameters of shallow marine sediments, IN De Batist, M., and P. Jacobs (eds), Geology of Siliciclastic Shelf Seas, Geological Society Special Publication No. 117, London, pp. 299-322.

Neurauter, T.W., and W.R. Bryant, 1989, Gas hydrates and their association with mud diapir/mud volcanoes on the Louisiana continental slope, Proceedings 21st Offshore Technology Conference (1989), Paper 5944, 599-608.

Pecher, I.A., Holbrook, W.S., Lizarralde, D., Hutchinson, D.R., Wood, W.T., Hoskins, H., and Stephen R.A., submitted, Shear waves through methane hydrate-bearing sediments -- Results from a combined walkaway-VSP and OBS experiment offshore South Carolina. J. Geophys. Res.

Weimer, P. et al., 1998, Sequence stratigraphy of Pliocene and Pleistocene turbidite systems, northern Green Canyon and Ewing Bank (offshore Louisiana), northern Gulf of Mexico, AAPG Bulletin, 82/5B, 918-960.

Figure 1

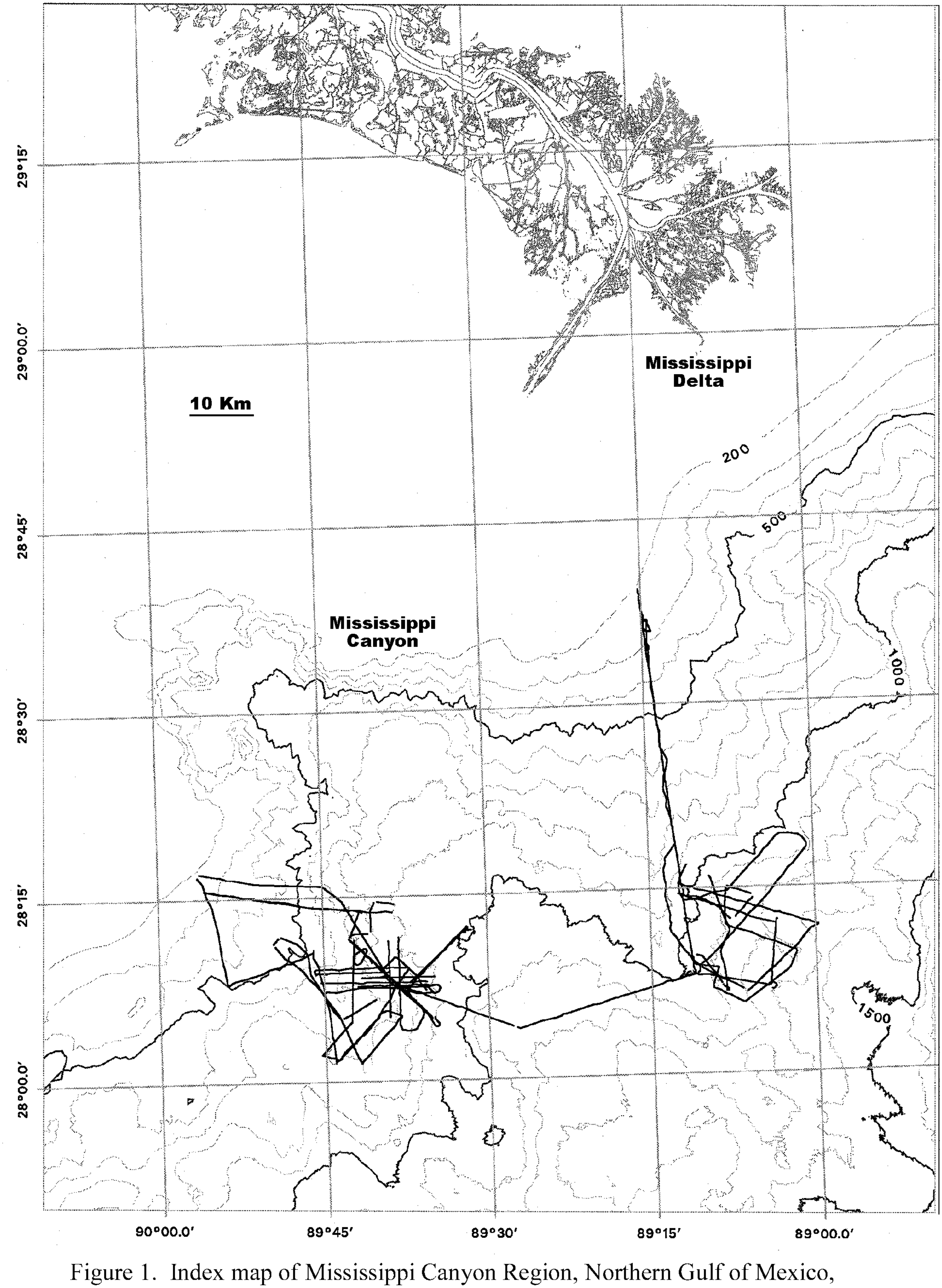

Figure 1. Index map of Mississippi Canyon Region, Northern Gulf of Mexico, showing location of seismic tracklines for cruise M1-98-GM. Bathymetry contour interval is 100 m.

FIGURE 2

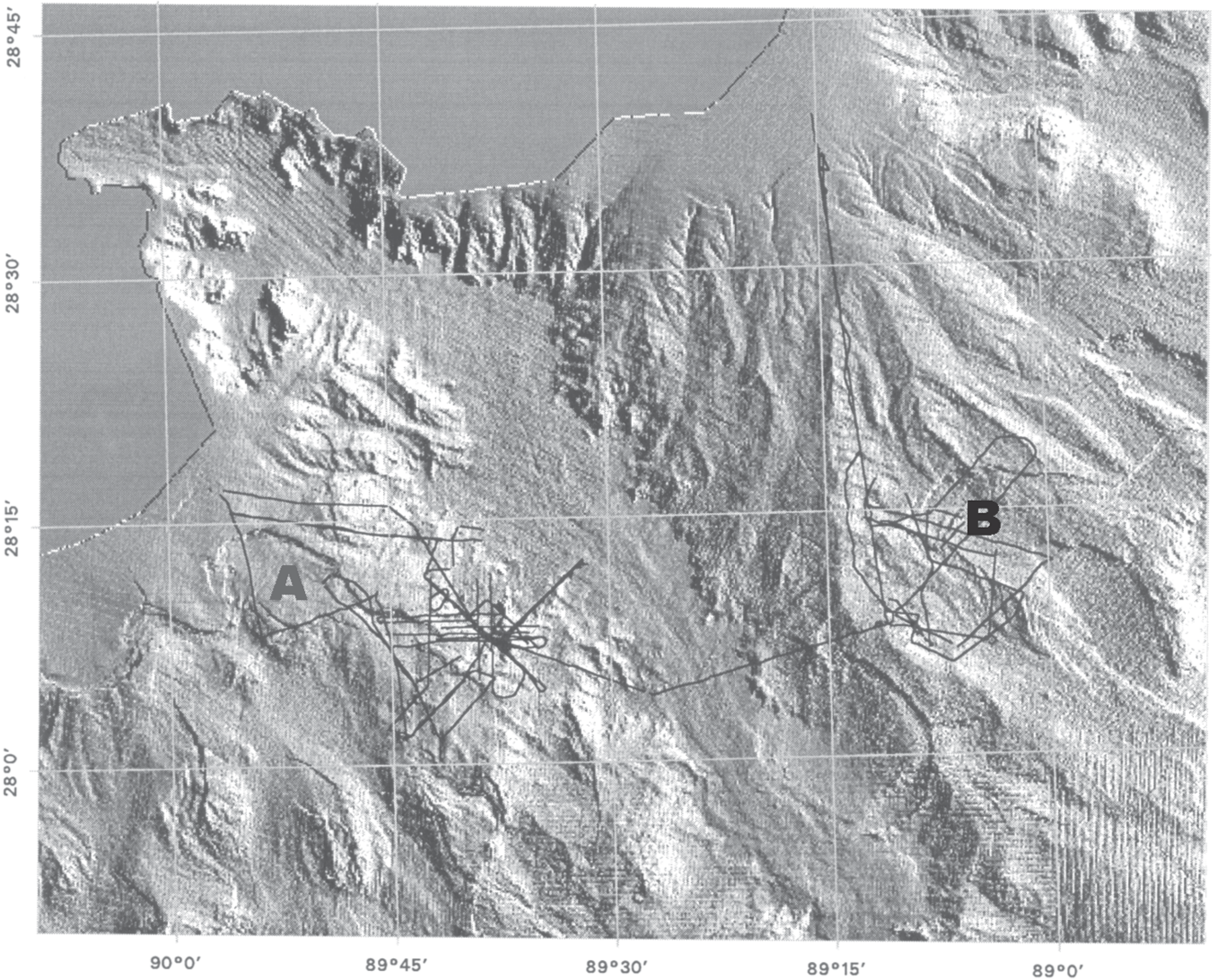

Figure 2. Shaded bathymetic relief map of the Mississippi Canyon region from NOAA seabeam bathymetry data gridded at 100 m intervals. The map covers roughly the lower half of Figure 1, from the 200 m contour seaward. Seismic tracklines are shown to illustrate their relation to sea-floor features. A and B are large sea-floor failure zones mentioned in text, with headwall scarps upslope from the letters.

Figure 3

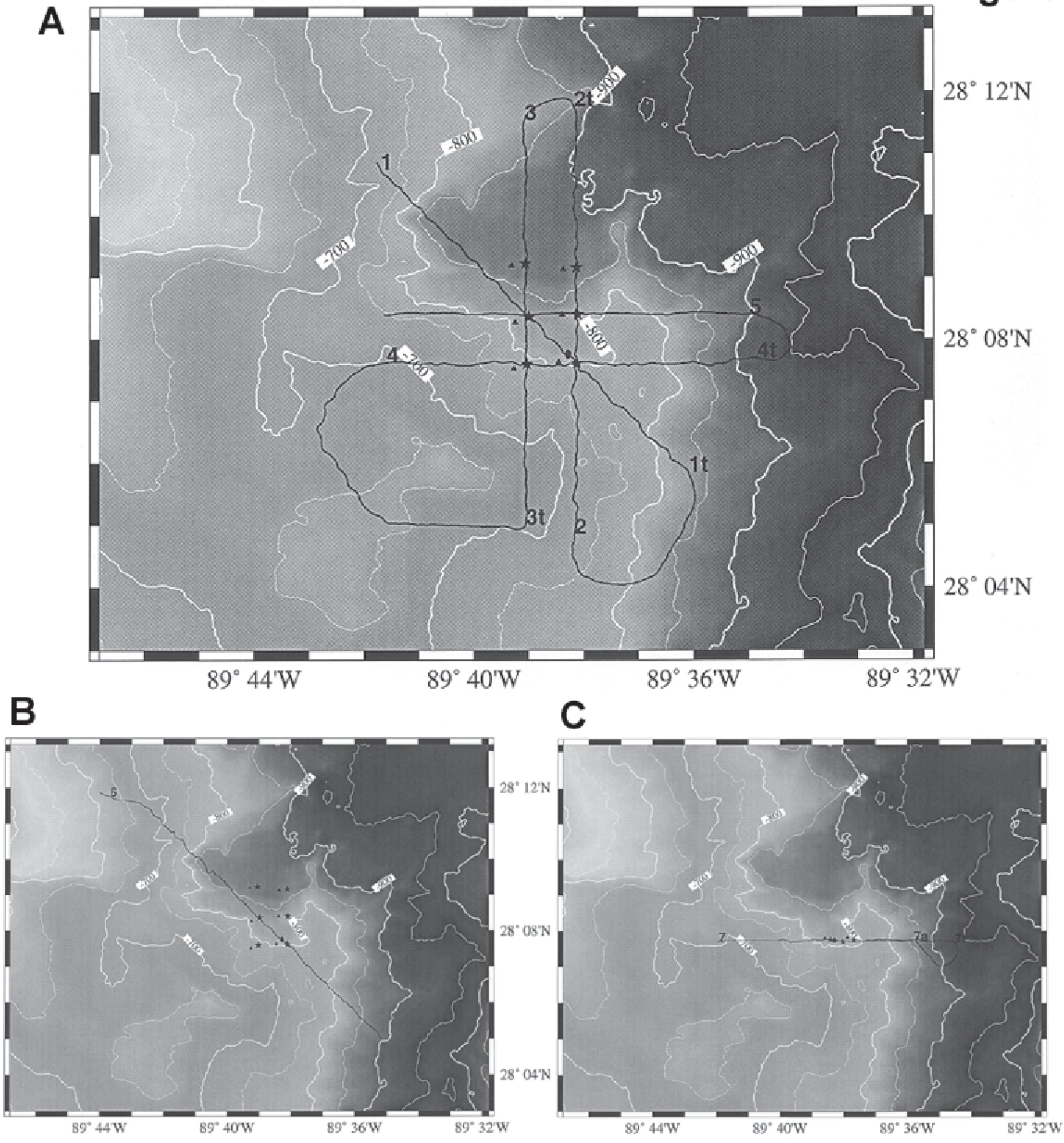

Figure 3. Maps showing the location of Ocean Bottom Seismometers (OBSs) and seismic tracklines for the OBS deployments 1 (A and B) and 2 (C). OBS line numbers are shown. Stars mark deployment positions for OBSs, and triangles are recovery positions. Bathymetry contour interval is 50 m.

Figure 4

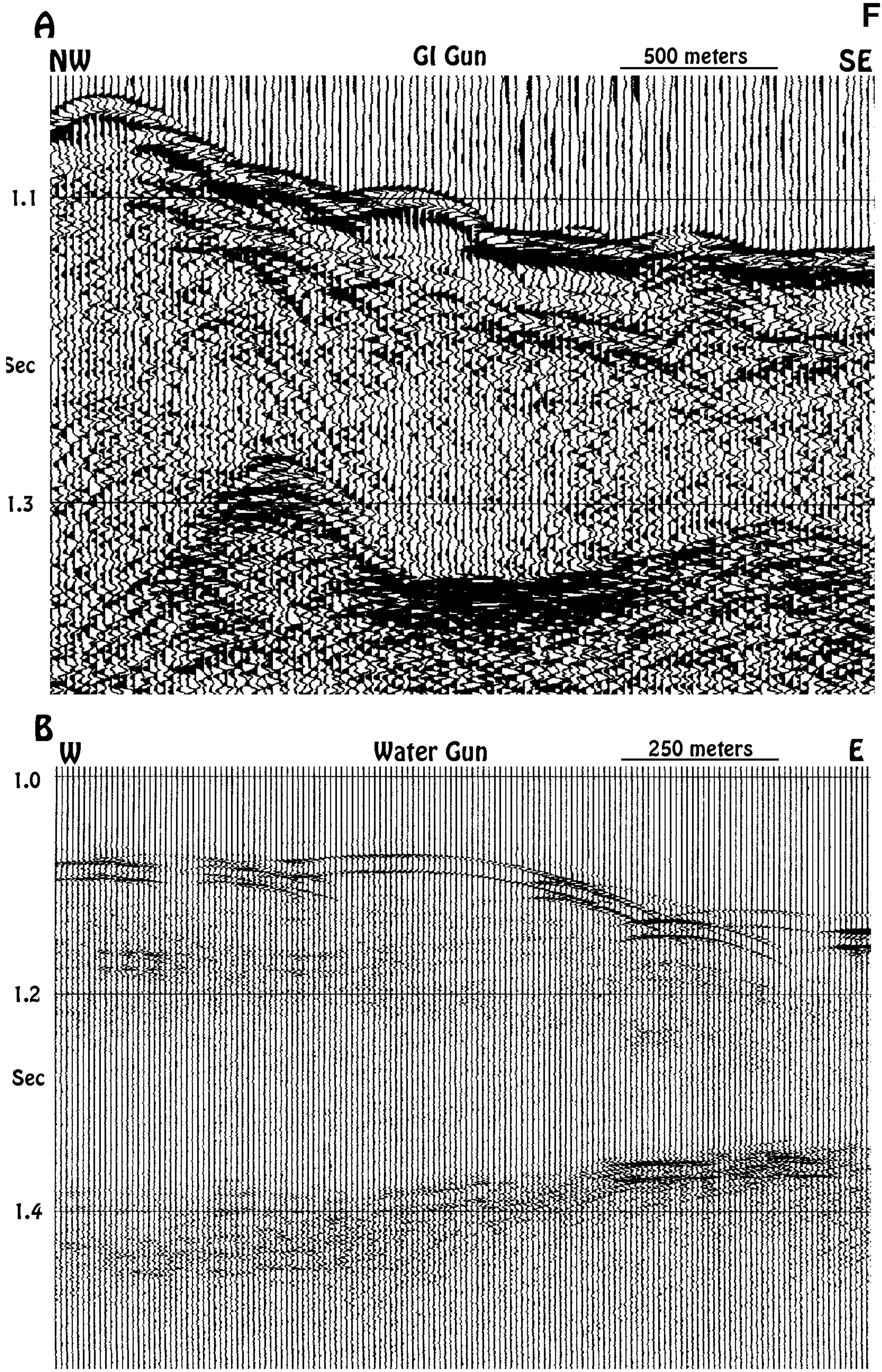

Figure 4. Examples of field records for seismic reflection data recorded during cruise M1-98-GM. Data are single channel with no filtering or Automatic Gain Control applied. (A) GI-Gun (35/35) record from MCS line 11 (OBS line 1) over the hydrate mound area where the OBS experiment was conducted (i.e., over the easternmost sea-floor mound displayed). (B) Water gun record from MCS line 19 near the area of hydrate mounds, showing variable sea-floor and subsurface amplitudes and a high-amplitude "flat spot" that may be free gas.

Figure 5

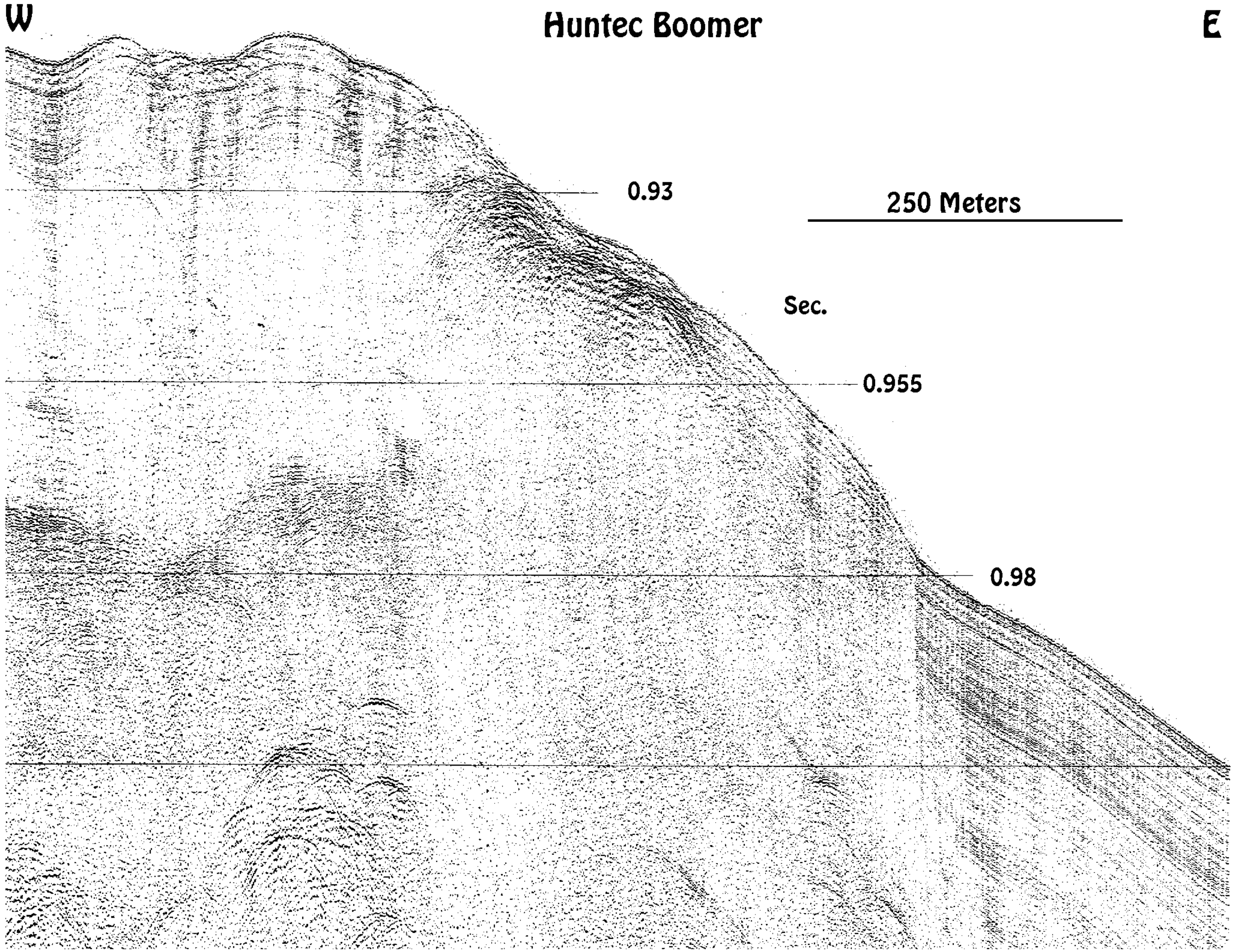

Figure 5. Example of very high resolution Huntec boomer data from line 23 across the west flank of the Mississippi Canyon. The profile crosses a diapiric structure with high-amplitude reflections and acoustic "wipe-out" zone near the sea-floor. Similar acoustic features are found over and near hydrate mounds, suggesting that hydrates could exist here also.

Appendix A: Trackline specifications for cruise M1-98-GM

Julian Day	*GMT Time*	*Start/ End*	*Line No.*	*Line Direction*	*Record Mode*	*Seismic Source*	*Comments*
160	1441	start	1	N to S	MCS	GI gun	35/35 gun used for all but one GI-gun-line.
161	317	end	1				ITI streamer used for all MCS lines.
161	325	start	2	E to W	MCS	GI gun	
161	720	end	2				
161	724	start	3	SE to NW	MCS	GI gun	
161	1609	end	3				
161	1614	start	4	N to S	MCS	GI gun	
161	1906	end	4				
161	1926	start	5	SW to NE	MCS	GI gun	
161	2148	end	5				
161	2212	start	6	N to S	MCS	GI gun	
162	110	end	6				
162	133	start	7	SW to NE	MCS	GI gun	
162	403	end	7				
162	427	start	8	E to W	MCS	GI gun	
162	618	end	8				
162	618	start	9	W to E	MCS	GI gun	
162	805	end	9				
162	823	start	10	NE to SW	MCS	GI gun	
162	844	end	10				
162	1157	start	11	NW to SE	OBS/	GI gun	OBS line 1; "Repeat" line
162	1403	end	11		MCS		
162	1403	start	11A	Circle	OBS/	GI gun	
162	1507	end	11A	turn	MCS		
162	1507	start	12	S to N	OBS/	GI gun	OBS line 2
162	1711	end	12		MCS		
162	1729	start	13	N to S	OBS/	GI gun	OBS line 3
162	1912	end	13		MCS		
162	2105	start	14	W to E	OBS/	GI gun	OBS line 4
162	2322	end	14		MCS		
162	2350	start	15	E to W	OBS/	GI gun	OBS line 5
163	115	end	15		MCS		
163	334	start	16	NW to SE	OBS/	GI gun	OBS line 6; 105/105 cu.in. gun; "Repeat" line
163	625	end	16		MCS		
163	1400	start	17	NE to SW	MCS	W gun	A 15 cu.in. water gun used for all w-gun lines
163	1501	end	17				
163	1504	start	18	SE-NW	MCS	W gun	
163	1610	end	18				
163	1619	start	19	W-E	MCS	W gun	
163	1910	end	19				
163	2000	start	20	SE to NW	SCS-	W gun	One channel of ITI-MCS streamer

163	2309	end	20		SeaScp		
163	2315	start	21	SW to NE	SCS-	W gun	One channel of ITI-MCS streamer
164	2	end	21		SeaScp		
164	23	start	22	E to W	SCS-	W gun	3-element, 1-channel Benthos steamer.
164	401	end	22		SeaScp		
164	624	start	23	W to E	SCS	Huntec	Deep-tow: Source/receiver at about 200 m
164	1123	end	23				below sea surface: range from 160-240 m.
164	1142	start	24	E to W	SCS	Huntec	
164	1204	end	24				
164	1207	start	25	N to S	SCS	Huntec	
164	1244	end	25				
164	1250	start	26	N to S	SCS	Huntec	
164	1317	end	26				
164	1318	start	27	NW to SE	SCS	Huntec	"Repeat" line
164	1757	end	27				
164	1949	start	28	SE to NW	SCS	W gun	Via Huntec streamer; "Repeat" line
164	2230	end	28				
164	2330	start	29	N to S	SCS	Huntec	
165	238	end	29				
165	238	start	30	N to S	SCS	Huntec	
165	338	end	30				
165	357	start	31	W to E	SCS	Huntec	
165	430	end	31				
165	430	start	32	SW to NE	SCS	Huntec	
165	601	end	32				
165	601	start	33	NW to SE	SCS	Huntec	
165	635	end	33				
165	652	start	34	NE to SW	SCS	Huntec	
165	824	end	34				
165	840	start	35	SE to NW	SCS	Huntec	
165	1220	end	35				
165	1224	start	36	NE to SW	SCS	Huntec	
165	1236	end	36				
165	1239	start	37	NW to SE	SCS	Huntec	
165	1404	end	37				
165	1452	start	38	W to E	SCS	W gun	Via Huntec streamer
165	1756	end	38				
165	1827	start	39	SE to NW	SCS	Huntec	Slow fire rate (5-sec): for special processing
165	1948	end	39				
165	1948	start	40	NE to SW	SCS	Huntec	Slow fire rate (5-sec): for special processing
165	2019	end	40				
165	2019	start	41	NW to SE	SCS	Huntec	Slow fire rate (5-sec): for special processing
165	2055	end	41				
165	2103	start	42	SW to NE	SCS	W gun	Via Huntec streamer
165	2332	end	42				

165/166	var.	-	43-48	Var.	SCS	Huntec	Short lines: searching for a diapiric structure
166	9	start	49	SW to NE	SCS	Huntec	
166	421	end	49				
166/167	-	-	-	-	-	-	Transit to shelter from high wind/seas
167	2223	start	50	W to E	OBS/	W gun	OBS line 7
168	137	end	50		MCS		
168	921	start	51	N to S	SCS	W gun	Via Huntec streamer
168	1024	end	51				
168	1035	start	52	NW to SE	SCS	W gun	Via Huntec streamer
168	1252	end	52				
168	1306	start	53	N to S	SCS	W gun	Via Huntec streamer
168	1448	end	53				
168	1452	start	54	E to W	SCS	W gun	Via Huntec streamer
168	1656	end	54				
168	1659	start	55	S to N	SCS	W gun	Via Huntec streamer
168	1740	end	55				
168	1744	start	56	NW to SE	SCS	W gun	Via Huntec streamer
168	1843	end	56				
168	1845	start	57	S to N	SCS	W gun	Via Huntec streamer
168	2140	end	57				
169	440	start	58	N to SE	MCS	W gun	
169	821	end	58				
169	821	start	59	NE to SW	MCS	W gun	
169	1040	end	59				
169	1044	start	60	SE to NW	MCS	W gun	
169	1143	end	60				
169	1148	start	61	SW to NE	MCS	W gun	
169	1449	end	61				
169	1449	start	62	E to W	MCS	W gun	
169	1537	end	62				
169	1537	start	63	NE to SW	MCS	W gun	
169	1818	end	63				
169	1838	start	64	NW to SE	MCS	W gun	
169	1946	end	64				
169	1954	start	65	SW to NE	MCS	W gun	
169	2024	end	65				
169	2030	start	66	SE to NW	MCS	W gun	
169	2108	end	66				
169	2108	start	67	N to S	MCS	W gun	
169	2151	end	67				
169	2151	start	68	NW to SE	MCS	W gun	
169	2321	end	68				
169	2321	start	69	NE to SW	MCS	W gun	
170	53	end	69				
170	53	start	70	SE to NW	MCS	W gun	

170	137	end	70				
170	137	start	71	S to N	MCS	W gun	
170	209	end	71				
170	209	start	72	E to W	MCS	W gun	
170	235	end	72				
170	235	start	73	SE to NW	MCS	W gun	
170	325	end	73				
170	325	start	74	S to N	MCS	W gun	
170	1132	end	74				

Appendix B: Specifications for OBS operations on cruise M1-98-GM

OBS Deployment 1:

Julian Day	*Date 1998*	*Time GMT*	*Latitude (North)*	*Longitude (West)*	*Comments*
162	6/11	9:28	28° 08.365’	89° 38.992’	Release OBS 1B
		9:46	28° 07.607’	89° 39.032’	Release OBS 1C
		10:07	28° 07.619’	89° 38.123’	Release OBS 1D
		10:24	28° 08.404’	89° 38.107’	Release OBS 1F
		10:39	28° 09.166’	89° 38.129’	Release OBS 1E
		10:54	28° 09.231’	89° 39.060’	Release OBS 1A
		11:56	28° 10.833’	89° 41.729’	SOL OBS 1 (MCS 11)
		12:00	28° 10.667’	89° 41.615’	OBSs set to start recording
		14:02	28° 05.909’	89° 36.140’	EOL OBS 1 (MCS 11), shoot in turn
		15:05			SOL OBS 2 (MCS 12)
		17:10	28° 11.653’	89° 38.126’	EOL OBS 2 (MCS 12); shoot in turn
		17:25	28° 11.624’	89° 39.039’	SOL OBS 3
		17:28	28° 11.447’	89° 39.093’	SOL MCS 13
		19:12			EOL OBS 3 (MCS 13)
		21:02	28° 07.616’	89° 41.628’	SOL OBS 4 (MCS 14)
		23:21	28° 07.703’	89° 34.884’	EOL OBS 4 (MCS 14), shoot in turn
		23:49	28° 08.394’	89° 34.877’	SOL OBS 5 (MCS 15)
163	6/12	1:15	28° 08.396’	89° 41.729’	EOL OBS 5 (MCS 15)
		~3:00	28° 11.756’	89° 43.657’	SOL OBS 6 (MCS 16)
		6:25	28° 04.905’	89° 35.088’	EOL OBS 6 (MCS 16).
		7:32			Release OBS 1D
		7:54	28° 07.634’	89° 38.451’	OBS Alongside
		8:43			Release OBS 1F
		9:13	28° 08.403’	89° 38.387’	Alongside
		9:36			Release OBS 1E
		10:06	28° 09.133’	89° 38.362’	Alongside
		10:37			Release OBS 1A
		11:12	28° 09.193	89° 39.311	Alongside
		11:41			Release OBS 1B
		~12:15	28° 08.277’	89° 39.241	Alongside
		12:30			Release OBS 1F
		12:59	28° 07.519’	89° 39.272’	Alongside

Notes:
* Data from the OBS disks were downloaded to a PC.
* Intermittent problems: disk drives on PC; GPS clock times; OBS time log; seismic-shot trigger
* OBSs drifted about 500 m from E to W between deployment and retrieval position.

OBS Deployment 2:

Julian Day	***Date 1998***	***Time GMT***	***Latitude (North)***	***Longitude (West)***	***Comments***
167	6/16	20:27	28° 07.776’	89° 37.673’	OBS 2F released
		20:37	28° 07.712’	89° 38.015’	OBS 2E released
		20:53	28° 07.778’	89° 38.405’	OBS 2C released
		22:24			Start shooting
		22:30	28° 07.733’	89° 41.667’	SOL OBS 7 (MCS 50)
		0:45			EOL OBS 7 (MCS 50), shoot in turn
		1:16			On line OBS 7a;
		1:36	28° 07.727’	89° 37.348’	EOL OBS 7a
		2:23			Release OBS 2C
		2:52	28° 07.823’	89° 38.600’	Alongside
		3:14			Release OBS 2E
		3:44	28° 07.746’	89° 38.243’	Alongside
		4:05			Release OBS 2F
		4:34	28° 07.844’	89° 37.882’	Alongside

Notes:
* Only three of the planned six OBSs were deployed due to bad weather.
* An E/W line was chosen to minimize effects of currents observed in the first deployment.
* The eastern part of the profile was shot twice, because of trigger problems.