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High-resolution seismic-reflection investigation of the northern Gulf of Mexico gas-hydrate-stability zone

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Abstract

We recorded high-resolution seismic-reflection data in the northern Gulf of Mexico to study gas and gas-hydrate distribution and their relation to seafloor slides. Gas hydrate is widely reported near the seafloor, but is described at only one deep drill site. Our data show high-reflectivity zones (HRZs) near faults, diapirs, and gas vents and interbedded within sedimentary sections at shallow depth (< 1 km). The HRZs lie below the gas-hydrate-stability zone (GHSZ) as well as within the zone (less common), and they coincide with zones of shallow water-flows. Bottom simulating reflections are rare in the Gulf, and not documented in our data.

We infer HRZs result largely from free gas in sandy beds, with gas hydrate within the GHSZ. Our estimates for the base BHSZ correlate reasonably with the top of HRZs in some thick well-layered basin sections, but poorly where shallow sediments are thin and strongly deformed. The equivocal correlation results from large natural variability of parameters that are used to calculate the base of the GHSZ. The HRZs may, however, be potential indicators of nearby gas hydrate. The HRZs also lie at the base of at least two large seafloor slides (e.g. up to 250 km^2) that may be actively moving along decollement faults that sole within the GHSZ or close to the estimated base of the GHSZ. We suspect that water/gas flow along these and other faults such as 'chimney' features provide gas to permit crystallization of gas hydrate in the GHSZ. Such flows weaken sediment that slide down salt-oversteepened slopes when triggered by earthquakes.

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Keywords: Gas–hydrate; High-reflectivity zones; High-resolution seismic; Northern Gulf of Mexico; Seafloor slides; Chimney feature

1. Introduction

The upper- and mid-continental slope of the northern Gulf of Mexico is an area with proven oil and gas resources (Brown, 1999), active hydrocarbon seeps and > 50 recovery sites of intact natural gas hydrate (< 6 m below seafloor (mbsf); Sassen et al., 2001). The area is dominated by varied salt-tectonic basin structures, high sedimentation rates, and complex late Neogene stratigraphy with common seafloor failures (Diegel, Karlo, Schuster, Shoup, & Tauvers, 1995; Prather, Booth, Steffens, & Craig, 1998). Gas is abundant, and gas hydrate is widely known within a few meters of the seafloor around mud diapirs and vent sites (Roberts, Wisemen, Hooper, & Humphrey, 1999b). Carbon isotopic properties show that the gas is from both biogenic and thermogenic (i.e. oil-associated) sources. Gas hydrate samples from these sites contain gases of both origins (Sassen et al., 2001). In theory, gas hydrate is stable in the Gulf of Mexico in water depths greater than 300–500 m and to subbottom depths up to approximately 1000 m (Milkov & Sassen, 2000; Sloan, 1998). However, gas hydrate has been observed in cores from subbottom depths greater than a few meters only on the Mississippi fan in 2422 m water depth at DSDP Site 618 (Leg 96). There, small crystals of gas hydrate were observed in cores from the interval 19–38 mbsf (Bouma, Coleman, & Meyer, 1986).

The geophysical evidence for gas hydrate in the region is equivocal. Where gas hydrate deposits are known from submersible observations and coring near-seafloor vents and diapirs, high-resolution seismic surveys show localized strong seafloor reflections and shallow subbottom acoustic wipeout zones (e.g. Roberts, Kohl, Menzies, & Humphrey, 1999b; Sager, Lee, MacDonald, & Schroeder, 1999). Over the same regions, deep-tow side-scan sonar images show zones of high backscatter that are associated with

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diagenetic-carbonate, chemosynthetic-community and gas-hydrate deposits (Cooper, Twichell, & Hart, 1999; Sager et al., 1999; H. Roberts, written commun.), and seafloor reflectance values derived from 3D seismic surveys commonly show varied amplitudes and reversed polarity indicative of near-seafloor gas (Roberts, 1996; Roberts, Cook, & Sheedlo, 1992). Bottom simulating reflections (BSRs), the most commonly cited evidence for gas hydrate, are rare in the northern Gulf of Mexico and documented only on the continental rise of the western and central Gulf of Mexico (Hedberg, 1980; Shipley et al., 1979, fig. 6), even though extensive multichannel seismic-reflection data exist.

Gas hydrate is widely postulated as a potential energy resource and is implicated as a factor in slope stability (e.g. Kvenvolden, 1999). Yet, in the Gulf of Mexico, the distribution of gas hydrate throughout the GHSZ is not known, although estimates of the economic potential are now being made (Milkov & Sassen, 2001). Prior studies in the region focus principally on basin-edge structures with little emphasis on the extensive areas of basin flanks and centers.

In 1998 and 1999, the US Geological Survey (USGS) conducted high-resolution seismic investigations of the Mississippi Canyon (Fig. 1(B) and (C)) and Garden Banks–Green Canyon regions (Fig. 1(D)) of the upper- and middle-continental slope to study regional subbottom distribution of gas hydrate deposits and associated free gas and their effects on slope stability. Tracklines crossed several continental slope basins, including areas of known occurrences of gas hydrate, shallow water-flows, chemosynthetic communities, and seafloor slides. The region location names we use (Fig. 1(B)–(D)) correspond to names of lease block areas defined by the Minerals Management Service (MMS, 2002). Lease block areas have irregular shapes and orientations, and to avoid confusion we use standard geographic coordinates and regional names in this study. For our discussion of geologic features, the Garden Banks region is approximately the western half Fig. 1(D) and Green Canyon region is the eastern half.

Our study found widespread occurrence within the upper 500–700 m of the sedimentary sections of chaotic units with disrupted reflections that have high reflectivity that can be diffuse in places. We refer to these as high reflectivity zones (HRZs). The report shows examples of the high-resolution seismic data across HRZs and discusses possible causes of these zones with regard to likely concentrations of free gas that in turn may be a source for gas hydrate deposits in the GHSZ. The report also describes evidence for fault and stratigraphic conduits, and evidence for the coincidence of HRZs with deep-seated faults, diapiric structures, shallow water-flows and decollements beneath seafloor slides in the study areas. These may be important features in explaining fluid/gas flow through the GHSZ and hence the distribution of possible gas hydrates.

2. Geologic framework

The complex geologic setting of the northern Gulf of Mexico results largely from interactions of active salt tectonics, rapid sea-level-driven sedimentation, and gravity slope-failures (Diegel et al., 1995; Prather et al., 1998). The resulting suite of minibasin and ridge features (e.g. Fig. 1) are being actively modified by deep-seated (kilometers) and shallow (meters) faults that are being buried by debris flows and hemipelagic draped deposits. Sediment types and deposition rates are highly variable in the minibasins, depending on fluvial input to the adjacent shelf and slope, and on input from slope failures. The resulting structure and stratigraphy of the GHSZ is complex as exemplified in most seismic-reflection sections shown herein. The greater the resolution of the seismic-reflection data examined, the greater the variability observed.

In general, the basins are areas of salt withdrawal and the intervening ridges are areas of salt piercement or structural folds (Rowan, 1995; Figs. 1 and 2). Slope head-wall scarps (i.e. the heads of canyons) are regions of slope failures and subsequent erosion. Structural pathways for upward migrating fluids and gases are most common along ridge crests, tops of isolated diapiric highs, edges of basins and close to slope failures—locations where faults extend to near the seafloor. These areas are marked by seafloor mounds, pockmarks, authigenic carbonate deposits, gas hydrate, debris flows, chaotic reflection zones and other features related to water and hydrocarbon seeps (Roberts, 2001; Roberts & Carney, 1997). Basins commonly have cyclic sections of chaotic sediments overlying laminated sediments, and these sections have been deformed by downslope movement in widespread slides and debris flows (Berryhill, Suter, & Hardin, 1987).

2.1. Seismic surveys

Extensive seismic surveys have been conducted in the northern Gulf of Mexico, but most are proprietary, and do not cover broad regions with high-resolution seismic data. Prior published seismic-reflection surveys across these regions by the USGS (e.g. Berryhill et al., 1987; EEZ-SCAN 85 Scientific Staff, 1987) and others (e.g. Weimer, Crews, Crow, & Varnai, 1998) are either not in digital format or are of lower resolution than required for this study. High-resolution seismic-reflection surveys have been described from areas around gas hydrate deposits (e.g. Roberts et al., 1999a,b; Sager et al., 1999), but do not extend across basin flanks and centers.

The 1998 survey in the Mississippi Canyon region (Fig. 1(B)) was a collaborative effort between USGS and the University of Mississippi Marine Minerals Technology

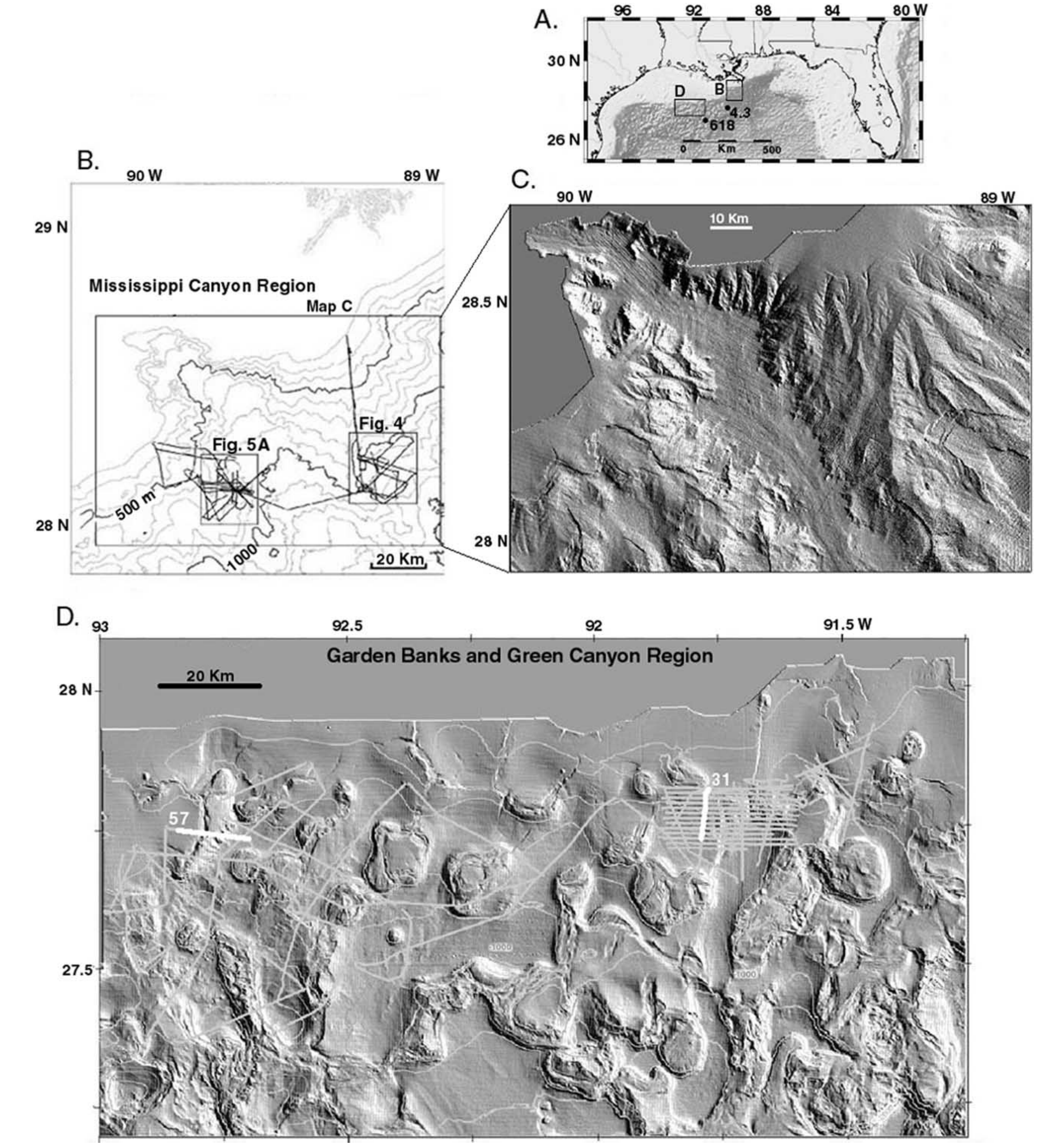

Fig. 1. Index maps for USGS high-resolution seismic-reflection cruises. (A) Location map with ODP Site 618 and $M = 4.3$ earthquake; (B) Bathymetry and 1998 cruise tracks; (C) NOAA Swath bathymetry for the 1998 study area; (D) NOAA Swath bathymetry with 1999 cruise tracks.

Center. Multichannel high-resolution seismic-reflection data were acquired using a 35 in.^{3} dual-chamber airgun (i.e. GI-gun) or 15 in.^{3} water gun sources and a 250 m-long 24-channel solid-core streamer. The data imaged to depths >1300 m subbottom with nearly 5 m resolution. Single-channel data were recorded by a Huntec deep-tow boomer towed at 100–200 m subsea-surface, and achieved penetration greater than 200 m subbottom and 0.25 m vertical resolution. A detailed ocean bottom seismometer survey was also conducted on the west side of the Mississippi Canyon in an area where seafloor gas hydrate deposits are known (Neurauter & Bryant, 1990). The 1999 USGS cruise in the Garden Banks and Green Canyon region (Fig. 1(D)) acquired multichannel high-resolution seismic-reflection

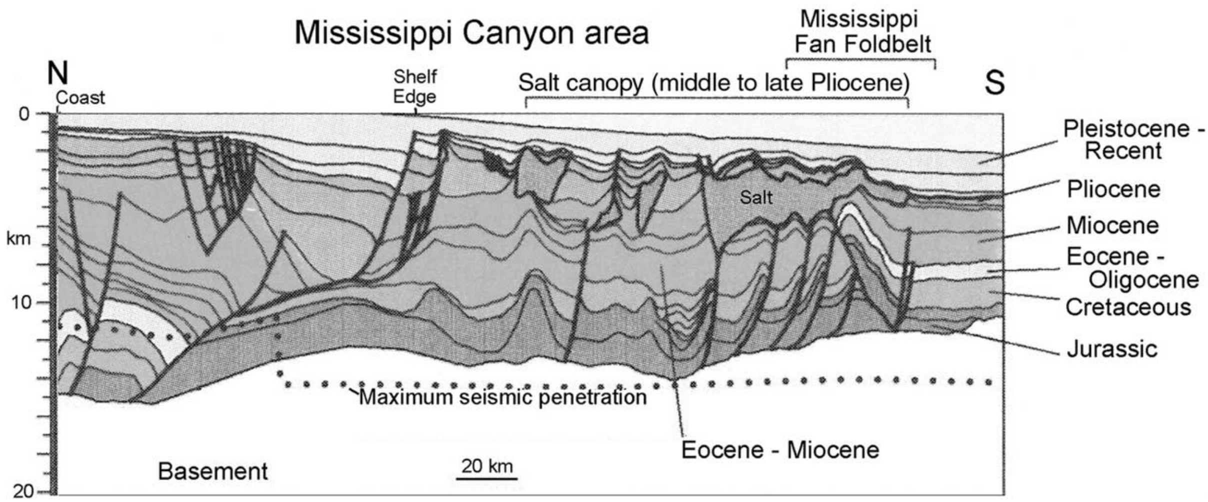

Fig. 2. Geologic section across the northern Gulf of Mexico shelf and slope in the Mississippi Canyon region illustrating typical salt features and stratigraphy of the study regions, adapted from Peel, Travis, and Hossack (1995).

data with the same water gun and streamer as used 1998; and, Huntec deep-tow boomer data and deep-tow side-scan and chirp-seismic data were also recorded. The chirp seismic data penetrated to about 40 m subbottom with a resolution of about 0.1 m. Additional information are available from Cooper, McGee, Hart, and Pecher (1998) and McGee, Cooper, Pecher, Grace, and Buchannon (1998) for the 1998 cruise, and from Cooper et al. (1999) and Foster et al. (1999) for the 1999 cruise. Data processing for the water-gun multichannel data is described in Lee, Hart, and Agena (2000). Images and digital data for multichannel seismic-reflection data from both cruises are available on the World Wide Web (Hart, Cooper, Lee, & Agena, 2002).

2.2. Gas-hydrate-stability zone

The thickness of the GHSZ is controlled by many factors that include water depth, bottom-water temperature, pore-water salinity, gas composition, subbottom temperatures, and the presence of overpressure zones and salt diapirs (Milkov & Sassen, 2000). In the Gulf of Mexico, these factors are all highly variable in space and time, and most are poorly known over large areas of the slope. Hence, estimates of GHSZ thickness for the Gulf of Mexico can vary widely.

We calculate gas hydrate stability curves using methods of Sloan (1998) for pure methane and two thermogenic gas compositions for samples recovered within our study regions (Fig. 3(A)). For the Garden Banks and Green Canyon region we use a composition that is the average of five measurements of vent gas at Bush Hill (about 27.79N and 91.25W) reported by Sassen et al. (1994, table 1). For the Mississippi Canyon region, we use a composition from gas-hydrate samples recovered in piston cores (Anderson, Sloan, & Brooks, 1992). Usual procedure is to use vent gas composition for estimating GHSZ thickness (Milkov & Sassen, 2000), but we do not have vent gas measurements for the Mississippi Canyon region. Here, the hydrate has a composition nearly identical to that for the Garden Banks and Green Canyon region, and the 93.4% methane composition lies in the middle of the 90–96% methane range assumed by Milkov and Sassen (2000) for their calculations of GHSZ thickness in the northern Gulf of Mexico. For descriptive purposes in the figures, we cite the above thermogenic gas compositions as ‘Bush Hill gas’ and ‘Mississippi Canyon gas’.

Gas hydrate compositions are highly variable across the northern Gulf of Mexico slope (e.g. Milkov & Sassen, 2001) and in some cases gas hydrates have low-methane percentages (71–85%) whereas the nearby vent gases have high-methane percentages (90–96%) (Sassen et al., 1999). As an extreme example, we also show the $P-T$ curve for a thermogenic gas with 61.9% methane obtained from gas-hydrate samples in Green Canyon (Anderson et al., 1992), to illustrate the potentially large variability in $P-T$ conditions for hydrate stability. Such a vent gas composition is not known, but if this gas composition were to be found at depth in reservoir gas, then GHSZ thicknesses would be significantly greater than that for the two gases with 93.4% methane that we show in Fig. 3(D).

For the calculations, we also use water temperatures compiled by NOAA (2001), and assume a subbottom temperature gradient of 25 °C/km and uniform pore-water salinity of 35‰ (Milkov & Sassen, 2000). Fig. 3(B) shows how the thickness of the GHSZ is estimated, and Fig. 3(C) and (D) shows how the thickness relates to seismic-reflection sections in two-way reflection time and to depth sections in meters.

The curves in Fig. 3 show that the GHSZ is thinnest for pure methane gas. For thermogenic gases, the GHSZ is thicker and can occur in shallower water depths. For example, in 1.0 s of water (i.e. 750 m), the estimated thickness of the GHSZ for pure methane gas is 300 m, but the estimated thickness for thermogenic Bush Hill gas is

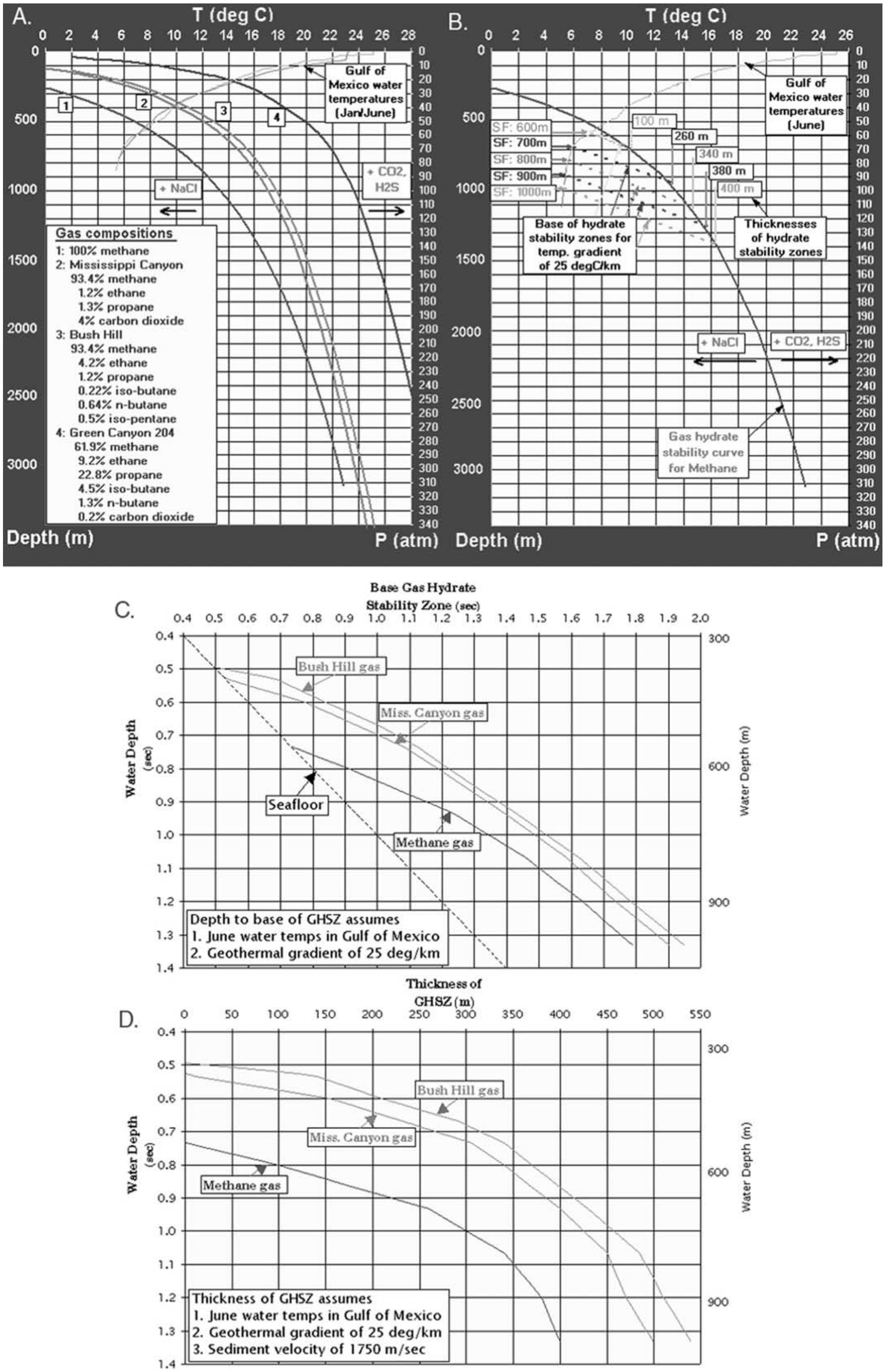

Fig. 3. Gas hydrate stability curves. (A) Stability curves for four Gulf of Mexico gases computed using methods of Sloan (1998) and water temperatures from NOAA (2001), with gas hydrate stable to the left of the curves. (B) Example of how the methane gas curve is used to compute the thickness of the GHSZ for (C) and (D); (C) Curves showing the thickness of the GHSZ in different water depths, with scales in seconds of two-way reflection time—for easy comparison with seismic-reflection records; and (D) Same as curve (C), except GHSZ thickness is in meters.

455 m thick. The curves for thickness of the GHSZ that we show on the seismic-reflection profiles are estimates only from Fig. 3, and the real thickness of the GHSZ may be quite different due to the potentially extreme subbottom variabilities in temperatures, salinity, and gas-compositions. We show two estimates for base of GHSZ on each seismic-reflection profile in the report, one for pure methane and another for a thermogenic gas, to illustrate the general range of expected variabilities from gas compositions. Gas hydrate is stable in the sedimentary section from the seafloor down to the base of the GHSZ. The large variability may also help explain why a BSR is not observed on our seismic-reflection data. A BSR originates from the contact between sediments that contain gas hydrate directly above the base of the GHSZ and sediments below that contain free gas (Andreassen, Hart, & McKay, 1997). A highly irregular base of the GHSZ could prevent a continuous and recognizable BSR. Free gas and gas hydrate can exist together in the GHSZ under special conditions of little formation-water and large gas-supply (Sloan, 1998), and such conditions may exist in the Gulf of Mexico.

2.3. Seismic studies—Mississippi Canyon region

We recorded high-resolution seismic-reflection profiles across the east and west sides of the Mississippi Canyon, with a single tie line between the two survey areas (Fig. 1). These areas are characterized by extreme sedimentation rates up to 15–20 m/ky, pelagic drape and mass-wasting (Coleman, Prior, & Lindsay, 1983) over the last 20 ky, when the principal filling of the ancestral Mississippi Canyon and its side canyons occurred (Goodwin & Prior, 1989). The age of the sedimentary sections in the upper 600–700 m (i.e. the estimated GHSZ) in our operating areas is likely no older than late Pleistocene (Goodwin & Prior, 1989).

2.3.1. East side of canyon

The most prominent feature in our data across the east side of the Canyon is a large seafloor slide that is about 15 km wide and at least 15 km long, covering at least 225 km^2 (Fig. 4). The swath bathymetry image of the slide clearly shows extensional faults at the head of the slide and a 1–2 km wide shear zone along the southwest edge of the slide. A seismic-reflection section across the slide (Line 61, Fig. 4) shows that the subbottom is cut by two categories of faults: a suite of high-angle faults that converge with depth and extend off the bottom of the seismic-reflection record, and a set of faults that appear to be related to stratigraphic sliding within the upper sedimentary section. We infer that the high-angle faults are rooted in deep-seated salt that is the principal driving mechanism for the seafloor slide. The shallow faults sole out within a chaotic unit at about 2.2 s subbottom (Fig. 4), and they partly accommodate the slide motion that includes extension near the slide's head and compression near the toe.

Notably, the slide lies within a broader zone of extensional subsidence (i.e. salt withdrawal). The western edge of the subsidence zone is marked by a number of boundary faults, one of which is the probable conduit for a large elliptical diapir depicted in the swath bathymetry data about 3 km south of Line 61. Gas hydrate was cored at the seafloor from the diapir, and is suspected to exist within other smaller seafloor mounds over nearby faults within the slide's shear and extension zones (Sager & Kennicutt, 2000; Sassen et al., 2001).

Within the boundaries of the extensional subsidence zone, a chaotic stratigraphic unit occurs with disrupted reflections and high reflectivity (i.e. HRZ). The top of the HRZ under the slide lies at a subbottom depth of about 500–550 ms (440–480 m), is about 100–150 ms (90–130 m) thick, and generally mimics the seafloor (Fig. 4(C) and (D)). The high reflectivity occurs mostly where reflections are discontinuous and chaotic. The unit can be traced regionally, but reflectivity is greatest under the slide and near large fault zones (Fig. 4). Here, the estimated thickness of the GHSZ, based on projections of curves in Fig. 3 is about 410 m for gas hydrate formed from pure methane gas and 530 m for gas hydrate formed from thermogenic gas. Drilling at multiple sites along the southwest side of the slide during development of the Ursa Field encountered wet sands from about 300–550 mbsf, with overpressure shallow water flows and some gas (Eaton, 1999). Such shallow water-flows are common in the northern Gulf of Mexico (MMS, 2001).

The slide exemplifies large-scale active slope failure common to the Mississippi Canyon area resulting from several causes including salt withdrawal and diapirism, deep- and shallow-extensional faulting, and gravity sliding. Part of the motion also appears to be accommodated along shallow faults that sole out within the chaotic HRZ. The overlap of depths of the chaotic HRZ (Fig. 4(C) and (D)), the shallow water-flows in overpressured sands (Eaton, 1999) and the estimated base of the GHSZ (Fig. 3) suggests to us that massive recent seafloor sliding may be linked with active flows in sand-prone sections with free gas and gas hydrate.

2.3.2. West side of canyon

We recorded high-resolution seismic-reflection data over a strongly deformed area on the west side of the canyon where shallow structures and seafloor deformation are common and gas hydrate is known from seafloor cores (Figs. 1 and 5(A)). Here too we found irregular and diffuse HRZs that lie within the upper 0.6 s subbottom above diapiric structures, along fault zones, laterally within layered and chaotic stratal units bounded by fault, and adjacent to acoustic wipe-out zones. Seismic-reflection lines 7 and 32 (Fig. 5(B) and (C)) cross several diapiric structures and illustrate the extensive high-angle faults, folded sediments, and irregular and common HRZs in the upper sedimentary section. Gas hydrate was cored from the westernmost diapir in Line 32 (Sassen et al., 1994; Fig. 5).

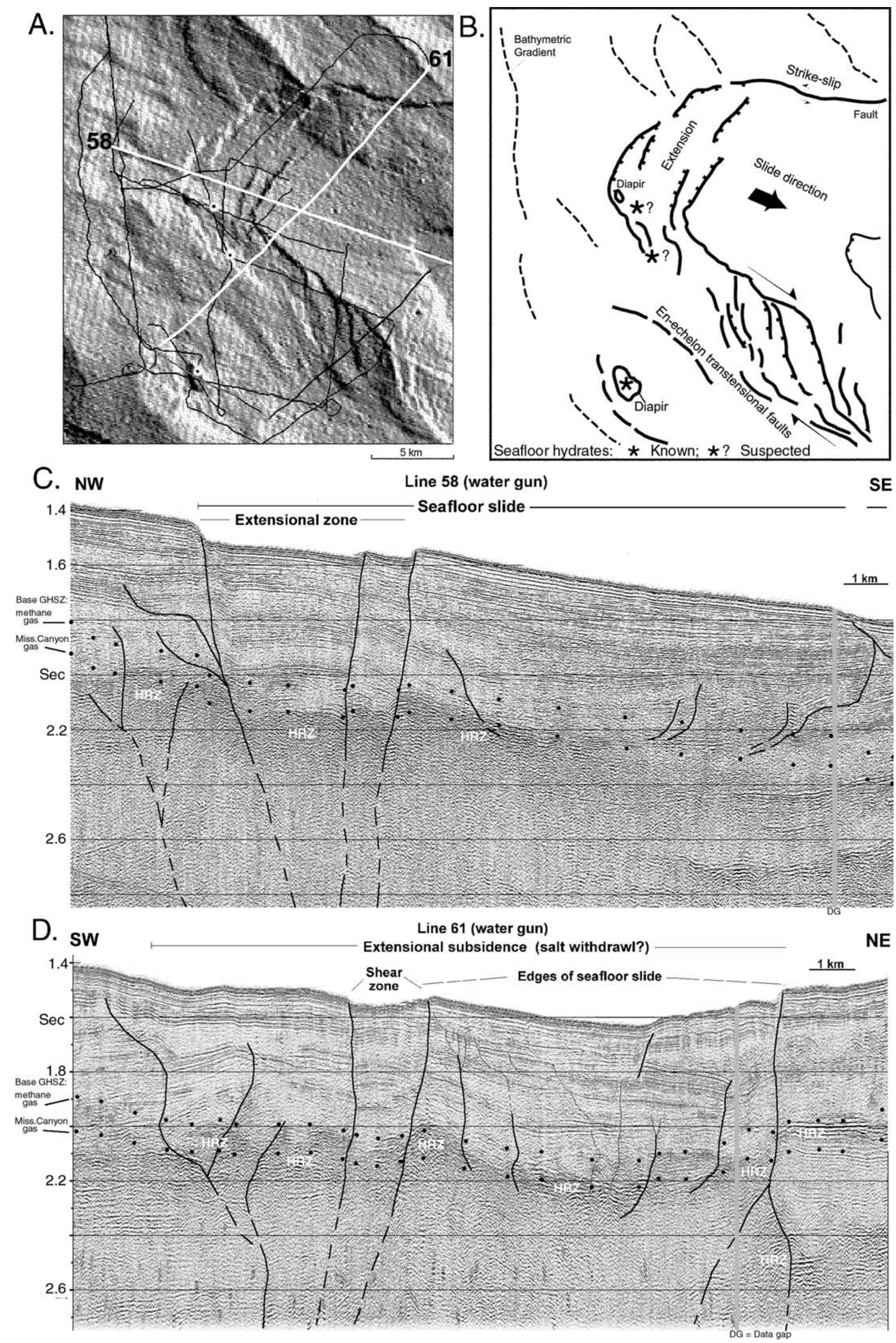

Fig. 4. Survey of a 225 km^2 seafloor slide on the east side of the Mississippi Canyon. (A) Swath bathymetry from NOAA with 1998 USGS tracklines in black and white. See Fig. 1 for location. (B) Diagrammatic sketch of the slide. (C) and (D) Examples of water-gun seismic-reflection profiles down and across the slide. The HRZ with top about 525 ms below the slide is near the estimated base of the GHSZ, and lies along Line 61 at a depth where shallow water-flows were encountered during drilling. At least three gas-hydrate mounds (white circles with dots in (A)) occur in fault zones that delineate the slide and that border the structural depression in which the slide occurs.

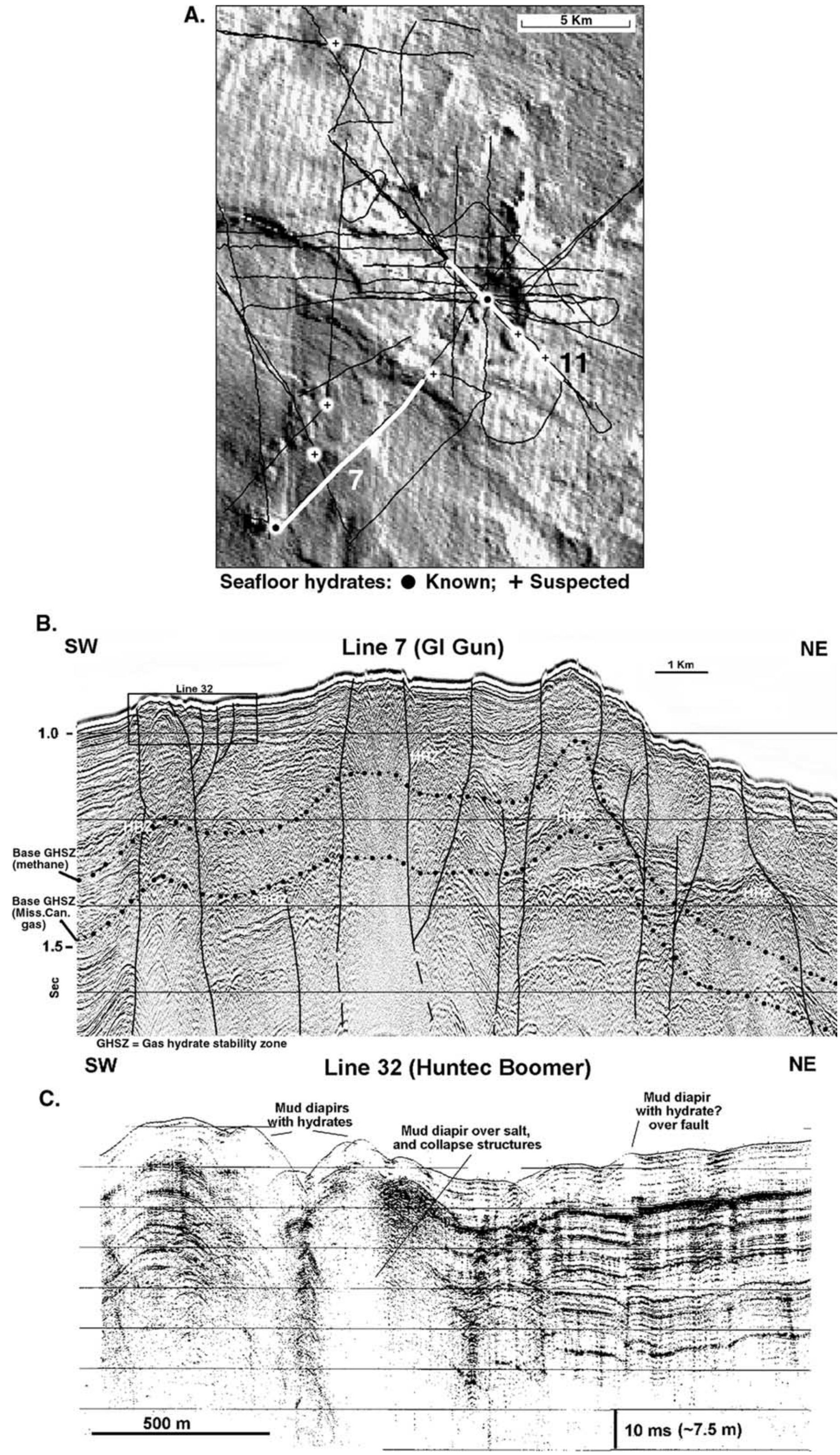

Fig. 5. Map and seismic-reflection data from the west side of the Mississippi Canyon. (A) Swath bathymetry data from NOAA showing locations of 1998 USGS tracklines, known and suspected seafloor gas hydrate deposits, and seismic-reflection lines shown in Figs. 5(B), (C) and 6. See Fig. 1 for location. (B) High-resolution seismic-reflection profile (GI-gun) across typical diapiric and fault structures, deformed sediments and subbottom HRZs. The estimated bases of the GHSZ for the two gas compositions are based on gas hydrate curves in Fig. 3. (C) Boomer seismic-reflection data across folded sediments, faults, and mud diapirs with known gas hydrate deposits. Acoustic wipe-out zones and HRZs may both contain gases (and gas hydrate), but at likely different fluid/gas flow regimes.

In other areas of the Gulf of Mexico's upper continental slope where acoustic wipe-out zones and diffuse HRZs (by our definition) are seen, massive deformation, flow units, gas hydrate and diagenetic carbonates are found within the near-seafloor sediments (Roberts, 2001). Such deposits may also exist in the vicinity of Line 32 near faults that extend to the seafloor and be the conduits for fluids/gases.

Along Line 7 (Fig. 5(B)), the HRZs occur throughout the upper sedimentary section and do not systematically correspond with the estimated depths for the base of the GHSZ for either gas hydrate formed from pure methane gas or from thermogenic gas. Rather, they occur both below and within the estimated GHSZ. And, here like elsewhere we have surveyed, the geometry of HRZs is controlled more strongly by locations of stratigraphic horizons and faults than by the position of the estimated gas hydrate stability boundaries. At the NE end of Line 7, HRZs are offset at faults yet appear to be crossed at high angles by the estimated base of the GHSZ. In other places such as the sides of diapirs, the dips of the HRZs and estimated base of the GHSZ are similar—which may be fortuitous or co-genetic. The similarity is difficult to explain without better knowledge of the true position of the base of the GHSZ. If gas is, as we suspect, the cause of the high reflectivity, then localized concentrations of upward migrating gas are likely moving into shallow reservoirs adjacent to faults (e.g. Losh, Eglinton, Schoell, & Wood, 1999). And, if the HRZ lies within the GHSZ then adequate gas is moving upward to coexist there with gas hydrate.

A detailed seismic survey, including ocean bottom seismometers, was conducted during our cruise across a small semi-circular basin where Neurauter and Bryant (1990) cored gas hydrate from a seafloor mound that directly overlies a shallow HRZ (Figs. 1(B) and 6(A); Cooper et al., 1998). The high-resolution profiles across this area (Fig. 6) show that many near-vertical faults extend to the seafloor and delineate different reflection packages—some with zones of enhanced reflectivity and others with diminished reflectivity. In the higher-resolution Huntec boomer data, the upper 90 ms subbottom is characterized by acoustic 'chimney' features with diffractions and abrupt reflectivity changes that cut through the layered section (Fig. 6(A) and (B))—features that as suggested elsewhere (e.g. Andersen & Bryant, 1990) may denote local accumulations of gas (and gas hydrate). Directly below (i.e. between 90 and 200 ms subbottom), the boomer data show few reflections in an apparent 'wipeout' zone directly above the HRZ. Strata here may be deformed or contain gas (and gas hydrate), as suggested for 'wipeout zones' in other parts of the Gulf of Mexico (e.g. Roberts et al., 1999a).

Initial results of the ocean bottom seismometer data indicate that free gas exists beneath the gas-hydrate-bearing mud diapir (Jaiswal, Zelt, & Pecher, 2001), but the depth-distribution and velocity structure are still under study. The HRZ at about 200 ms subbottom could be the reservoir for gas that is cut by faults along which fluids/gas/sediment move up to the seafloor, where the mud mound with gas hydrate is documented (Neurauter & Bryant, 1990). The estimated bases of the GHSZ for both methane and thermogenic gases lie below the HRZ (Fig. 6(C)). If the HRZ contains free gas, then gas hydrate should exist also in the HRZ. Alternatively, the true base of the GHSZ could be shallower and lie near the top of the HRZ. One way to achieve such a shallower estimated depth for the base of the GHSZ, would require pure methane gas, a higher temperature gradient of 35–40 °C/km (i.e. higher heat flow), and higher seafloor velocities of about 1950 m/s than we assume in calculations graphed in Fig. 3. Increasing subbottom salinities would also tend to make estimated depths to base of the GHSZ shallower than shown in Figs. 3 and 6, by shifting gas-hydrate-stability curves to the left. Regardless, we suspect that gas and gas hydrate exists in the subbottom above the HRZ and beneath the seafloor gas hydrate mound (i.e. in the upper 200 ms subbottom).

2.3.3. Mississippi Canyon transect

A high-resolution seismic-reflection transect across the Mississippi canyon region compiled from 1998 USGS seismic-reflection tracks is shown in Fig. 7–foldout, and illustrates structure and stratigraphy of the upper sedimentary section and the GHSZ, in areas that are noted for both high sedimentation rates and unstable slopes. All but the easternmost part of the transect was recorded with the airgun seismic source—the other with the watergun source. The down-slope transect segments were designed to look for BSRs, especially in water depths of 300–600 ms where they might be expected to come to the seafloor. Good data were recorded and complex stratigraphy observed but no evidence of BSRs was observed anywhere along the transect.

The seismic-reflection data (Fig. 7–foldout) shows differences in the numbers of shallow diapirs on the east and west side of the canyon, with more diapirs and shallow deformation on the west side. In part this difference reflects the locations of the tracklines, which were intentionally selected to cross large-scale seafloor failures (west side) and to follow the crest of a thickly sedimented ridge (east side)—to compare potentially different gas hydrate environments. The seafloor failures of the canyon's west side are linked to uplift and faulting of the five prominent and uniformly spaced diapirs (likely salt) and their associated fault systems. The diapirs are deep or below the penetration depth of the seismic-reflection data beneath the Canyon's east side, where shallow stratigraphic complexity is more strongly controlled by depositional and erosional process (e.g. cut and fill) and shallow seafloor slides than by shallow diapiric structures. We readily image faults and stratigraphic features in the high-resolution seismic-reflection data in the upper 500–600 ms (i.e. within the GHSZ), but, are commonly unable to trace or see these features at greater depths for several reasons that include geologic complexity within chaotic layers, some of which have

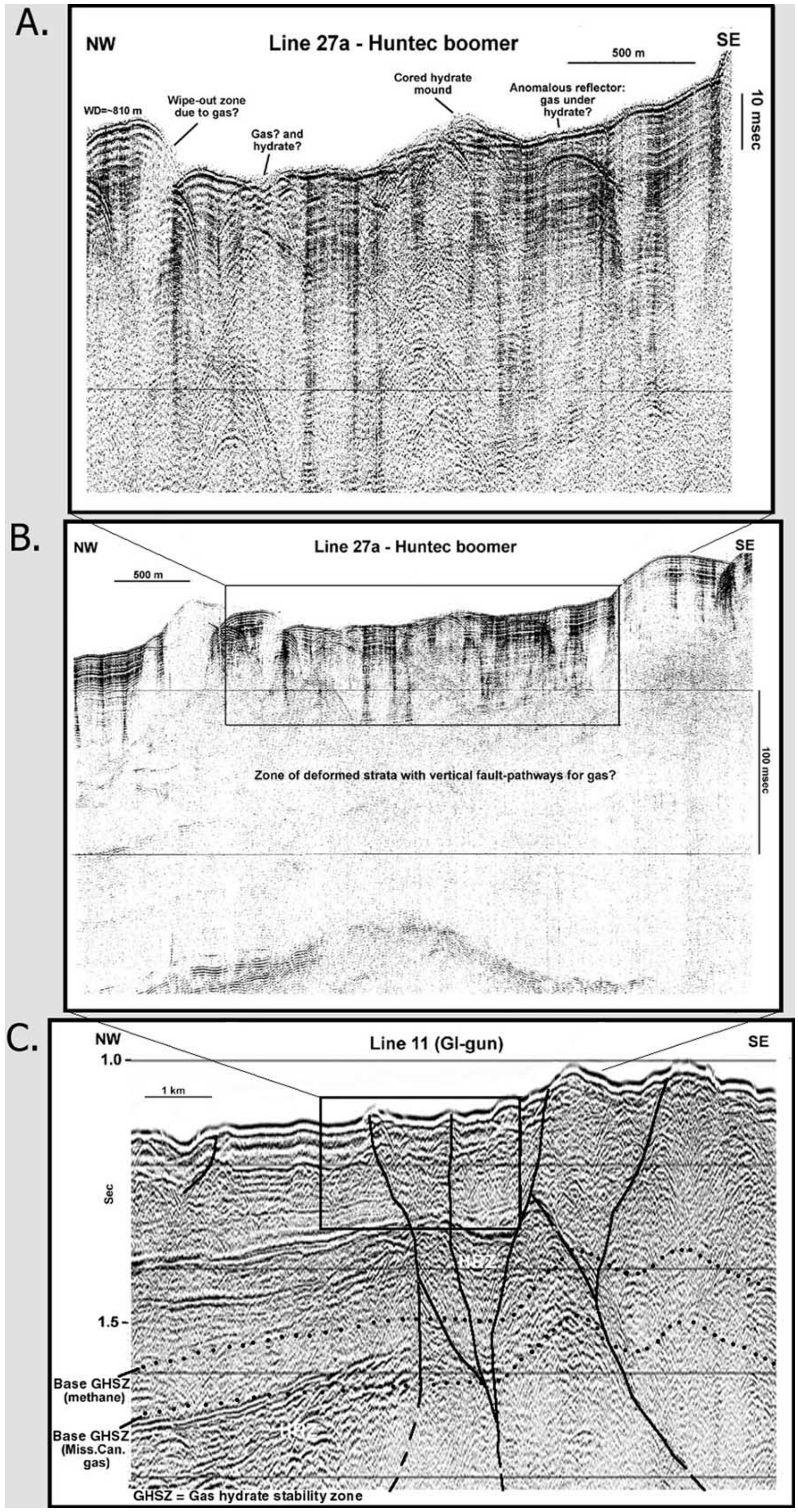

Fig. 6. High-resolution seismic-reflection profiles across a HRZ (200 ms subbottom) and seafloor mound with gas hydrate on the west side of the Mississippi Canyon. (A) and (B) Boomer seismic-reflection data at different scales showing chimney features that may be vertical faults with fluid/gas flows and surrounding gas and gas hydrate, and extending to the seafloor. (C) GI-airgun seismic-reflection data with depths to the estimated bases of GHSZ for two gas compositions. See Fig. 5(A) for location.

high-reflectivity (i.e. HRZs); diminution of the seismic signal below HRZs and other high-reflective horizons; and structural complexities near the diapirs (see also Figs. 4–6).

A prominent characteristic of the shallow stratigraphic section in the GHSZ is the high degree of lateral and vertical variability in the seismic reflectivity, which is more prominent on the western than eastern part of the transect, especially around diapir structures. Beneath the canyon's axis and east side, the most distinctive feature is the extensive HRZ that parallels the seafloor with top at 500–650 ms subbottom (Fig. 7–foldout). This is the same HRZ that lies at the base of the 225 km^2 seafloor slide described above (Fig. 4). The estimated depths to the base of the GHSZ shown on the transect lie above the HRZ. From mid-canyon to mid-slope, the base of the GHSZ for the thermogenic gas (Mississippi Canyon gas) parallels and lies close to the top of the HRZ. Seismic reflectivity within the HRZ is stronger in this region than within the same stratigraphic unit at shallower water depths. Such correspondences suggest that gas hydrate stability may be partly controlling the gas distribution and related reflectivity.

The correspondence we note between the estimated base of the GHSZ and the top of HRZs for the lower half of the canyon's east side is not apparent under the west side, in part because the regionally extensive chaotic unit on the east side is difficult to identify. Rather, areas on the west side of the canyon between and above diapirs are marked by HRZs, and these HRZs lie both above and below the estimated base of the GHSZ. Beneath the west side, the greater shallow structural complexity likely provides more fault pathways to the seafloor for subbottom fluid flows that in turn may result in greater variability in subbottom temperatures, salinities, and gas compositions than under the east side. These variabilities may also mean that our estimates do not accurately trace the real base of the GHSZ, as also noted above (e.g. Fig. 6).

In all areas of the transect, we suspect that HRZs denote the presence of free gas selectively accumulating in stratigraphic reservoir horizons, some of which are the regionally extensive chaotic units. The regional units may be slump and debris-flow deposits or channel-levy deposits that are buried within former (i.e. now partly filled) slope minibasins. Alternatively, they may be thin-bedded turbidites that trap gas by capillary sealing (H. Roberts, written communication, 2002).

2.4. Seismic-reflection studies—Garden Banks and Green Canyon region

The Garden Banks and Green Canyon region (Fig. 1(D)) like the Mississippi Canyon region is also known for locally high sedimentation rates up to 7–11 m/ky for the upper sedimentary section, extensive late Neogene salt deformation, and slope failures with mass-wasting along oversteepened parts of the continental slope (Rowan & Weimer, 1998). Sediment ages in the upper 600–700 mbsf for our estimated GHSZ are likely no older than 0.5 my in the study area (Berryhill et al., 1987; Weimer et al., 1998). As in the Mississippi Canyon region, we acquired both regional and detailed images of the seafloor and shallow subbottom across the basins and rises on the upper- and mid-continental slope. Our goals were to study features of the GHSZ and look for correlations if any between faults, gas and gas hydrate, shallow water-flows and slope failures (Fig. 1(D)).

2.4.1. Continental slope—Green Canyon region

The upper sedimentary section of the continental slope in the Green Canyon region is characterized by layered and chaotic units that are faulted near basin edges, and by slope failures on basin flanks. Deformation is greater near salt structures and on oversteepened slopes. The HRZs are common and may be broad and diffuse with associated wipeout regions, especially where salt-deformation is greatest beneath the uppermost slope (Line 31, Fig. 8). Elsewhere in the northern Gulf of Mexico, on a local scale (e.g. near fault scarps and seafloor mounds) such wipeout zones are documented as sites of gas expulsion, gas hydrate, authigenic carbonates, and/or chemosynthetic communities (Roberts, 2001; Sager et al., 1999). On Line 31, as elsewhere, we infer that the HRZs result from free gas.

Downslope from the diffuse HRZ under the shelf edge (0.4 s water depth, Fig. 8), well-layered reflections at 150–300 ms subbottom have many vertical acoustic chimney features (i.e. small faults) and are encased by chaotic units directly below and above. The underlying chaotic unit has HRZs that are dispersed within chaotic stratal units, and similar to those in other slope basins at about the same depth. Chimney features extend up from this chaotic unit to the overlying chaotic unit, which has low seismic amplitudes and evidence of faulting and sliding (e.g. rotated sediment-blocks, stratal terminations). The shallowest faults in the slide zone sole out along the top of the well-layered unit. Higher-resolution boomer data (Fig. 9) show that many of the small faults along which block sliding has occurred extend upward into the overlying sediments to deform the seafloor. The head of the slide (Fig. 9, Section A) is buried and no longer active, but the middle of the slide (Fig. 9, Section B) shows deformation of the seafloor and suggests to us that the slide is active. The slide is laterally extensive for up to 5–6 km along the basin's slope, as evidence from the seismic-reflection and swath bathymetry data (Fig. 1), hence covering up to 17–20 km^2.

On the high-resolution seismic-reflection profiles shown in Fig. 9, the estimated base of the GHSZ for thermogenic Bush Hill gas comes to the seafloor near head of the buried slide (Section A) and the estimated base of the GHSZ for methane gas comes to the seafloor deeper on the slope where there is a structural inflection of the seafloor (Fig. 8). The correlations of the estimated base of the GHSZ and shallow

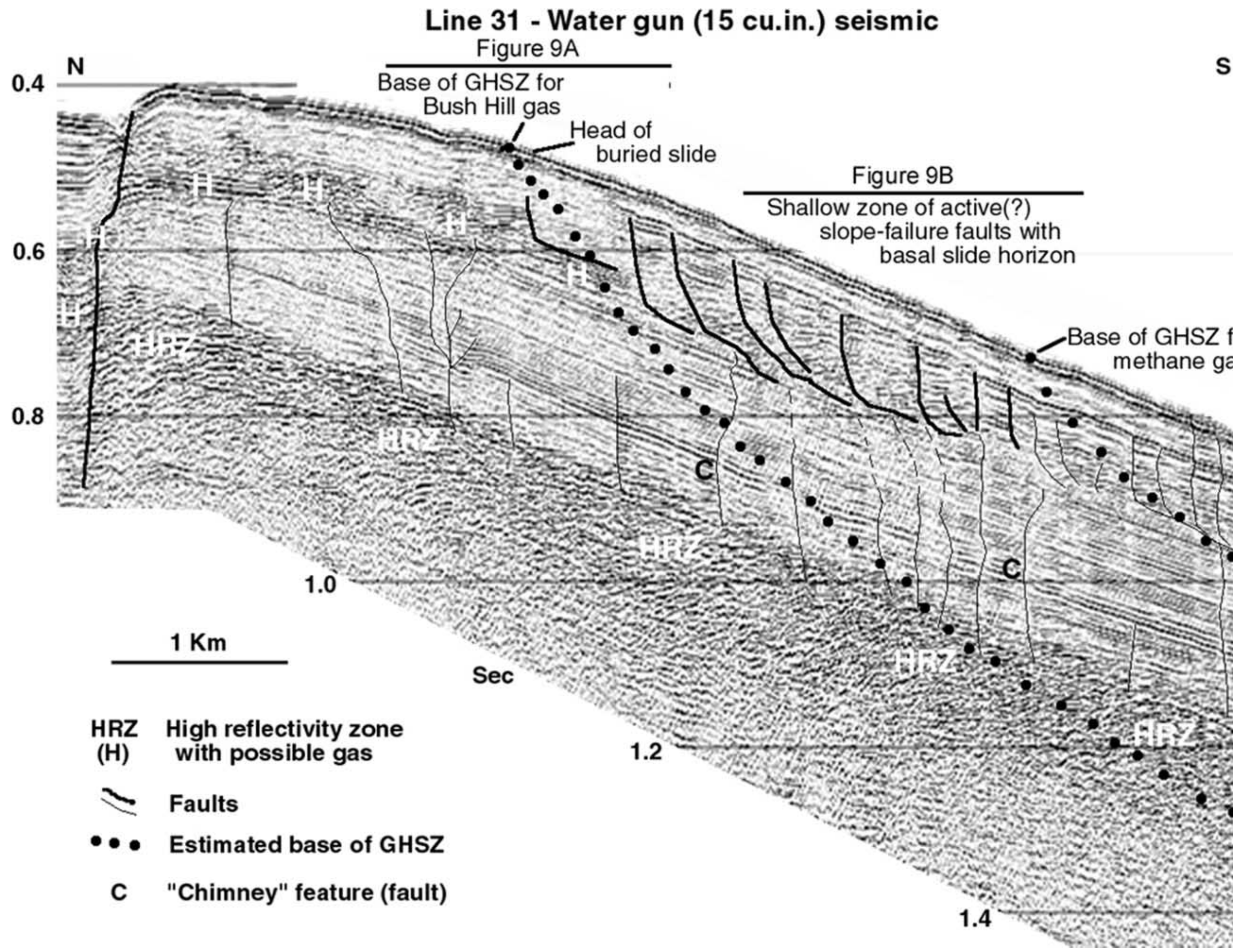

Fig. 8. High-resolution seismic-reflection profile across the upper continental slope in an area of rapid sedimentation showing evidence for a buried slide and deformation of the seafloor over large areas and above a shallow decollement zone (~100 ms subbottom). The HRZs near the shelf edge and beneath the slope (~400 ms subbottom) may be due to gas and/or flows in sandy horizons. Here, the HRZs are stratigraphically controlled rather than following the estimated base of the GHSZ. See Fig. 1(D) for location.

faults may be fortuitous, but warrants further study to determine if the potentially active decollement faults from the head of the slide are linked directly to underlying HRZs by chimney faults, and thereby contain gas and gas hydrate that may facilitate sliding. Below the slide, the estimated base of the GHSZ crosses the sedimentary section with little effect on the seismic reflectivity (Fig. 8). Shallow fluids and gases that we infer are migrating upward along stratigraphic horizons (e.g. chaotic units with HRZs) and structural features (e.g. chimney features) are not being trapped at the base of the GHSZ to create a BSR.

2.4.2. Continental slope—Garden Banks region

The western part of the Garden Banks region (west of 92.5W, Fig. 1) is generally characterized by thinner sedimentary sections than the eastern part of this region, and the sections are less well-layered than in other minibasins that we surveyed. These minibasins also include chaotic and deformed units, but generally at shallower depth across basin flanks and centers than to the east in Green Canyon region. Yet, we observe similar features as elsewhere in the shallow sedimentary section. High-resolution seismic-reflection Line 57 (Fig. 10) across the continental slope of the western Garden Banks region illustrates the laterally extensive diffuse HRZs with discontinuous reflections that occur (a) around faults and diapirs of the uppermost slope, (b) within irregular chaotic units at the base of the continental slope and (c) beneath intraslope basin floors. Along Line 57, the slope has an irregular morphology that results from diapirism, fault-block subsidence and rotation, and sediment sliding. The low-angle shallow-seated fault zones beneath the slope appear to sole out within the HRZs, and are the likely surfaces along which slides occur. The basin floor (SE end of profile) is underlain by a regionally extensive unit with no reflections and may be homogenous chaotic debris-flow and mass-wasting deposits, similar to those noted elsewhere in our high-resolution seismic-reflection data near basin axes. The HRZ near the base of the slope on Line 57 lies close to a drill site with known shallow water-flows (MMS, 2001), but the exact depths to these flows are not openly reported. Hence, the possible correlation of shallow flows and inferred gas-charged slump deposits is equivocal at this location.

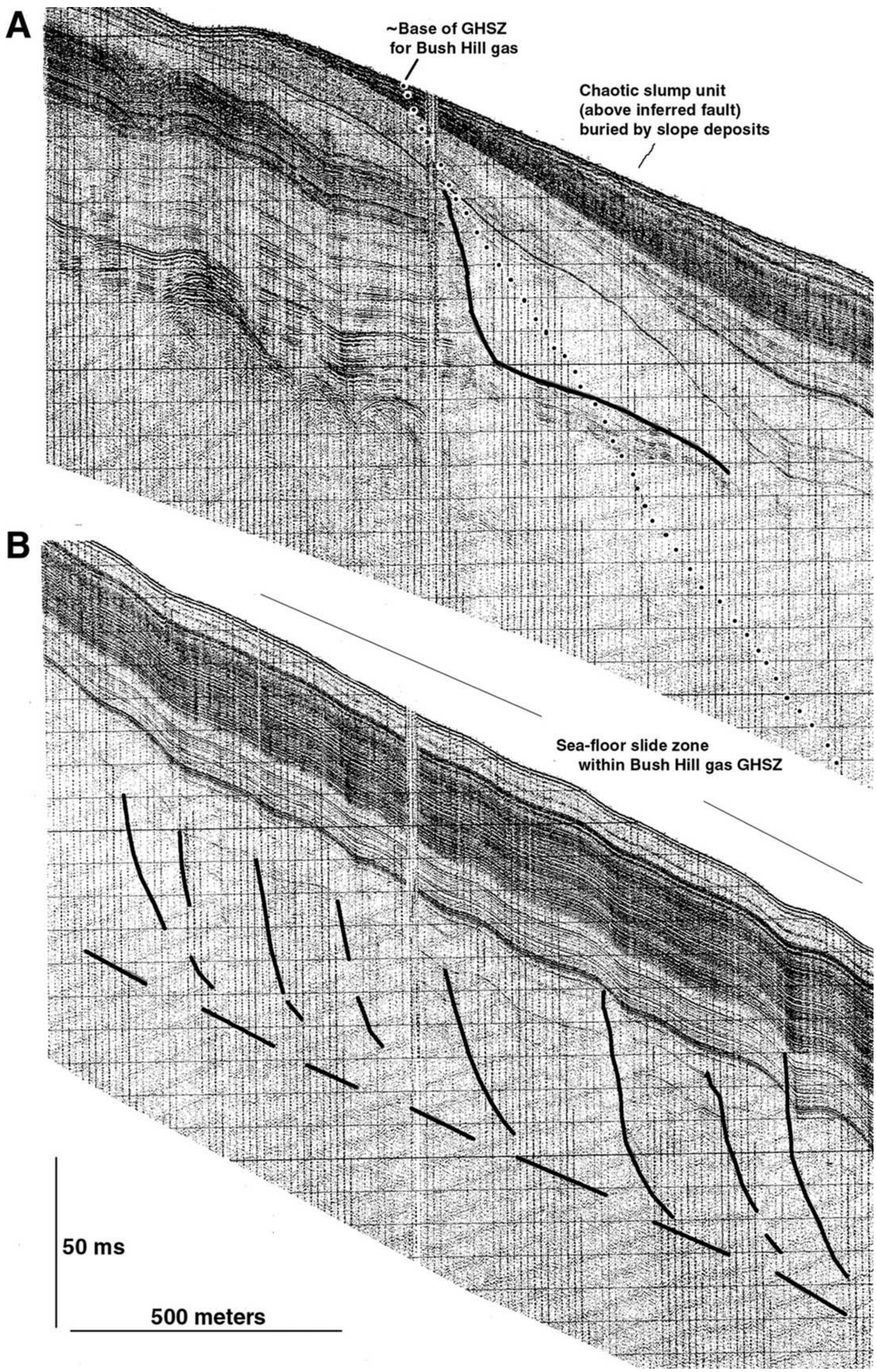

Fig. 9. High-resolution boomer seismic-reflection profiles along the seismic-reflection line in Fig. 8. Reflections at the head of the buried slide are abruptly terminated along a failure zone that occurs coincidentally (?) near the base of GHSZ (Bush Hill gas). Sediments above the slide are deformed to the seafloor suggesting active (?) downslope creep.

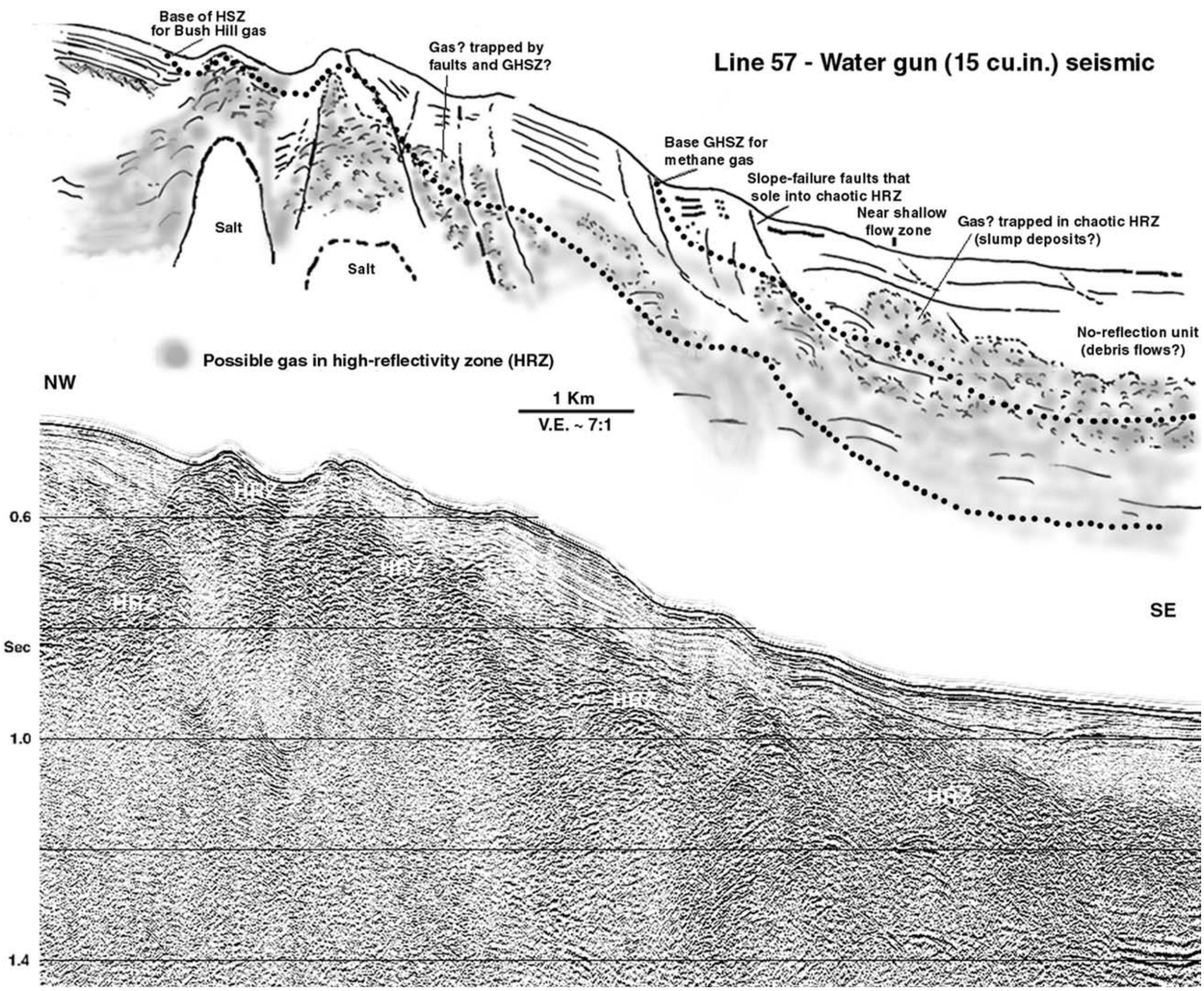

Fig. 10. High-resolution seismic-reflection profile across the upper continental slope in an area of relatively low sedimentation and strong shallow deformation. Extensional slope failures are bounded by deep-seated faults and by likely shallow decollements within chaotic HRZs. Here, the geometry of the top of HRZs more closely follows the estimated base of the GHSZ than beneath the upper slope to the east (e.g. Fig. 8) where layered sediments are thicker. See Fig. 1 for location.

On the uppermost slope near the diapiric fault structures, HRZs lie mostly below the estimated base of the GHSZ for Bush Hill gas (Fig. 10). Downslope, the top of the HRZs follow the general shape of the estimated base of theGHSZ for methane gas, but the high reflectivity lies both below and above (i.e. within the GHSZ for methane). Hence, the relationship of high reflectivity to the estimated base of the GHSZ and the existence of gas hydrate is equivocal at this location. In view of the uncertainties in the parameters used to estimate the base of the GHSZ, the true GHSZ could be shallower and lie above the HRZ. Continuous cores through the GHSZ are the only way to resolve the uncertainty, and such cores do not exist or are not publicly available.

2.4.3. Slope-basins transect

A 150 km-long high-resolution seismic-reflection transect across the upper continental slope of the Garden Banks and Green Canyon study region in water depths of 400–860 m is compiled in Fig. 11–foldout using six of our seismic-reflection lines. The transect crosses five slope basins with sediments that, in the upper 500–600 m (i.e. likely GHSZ), are believed younger than mid-Pleistocene age (Berryhill et al., 1987). The transect illustrates features that are similar to other parts of our study area in which fluid/gas flow and gas hydrate is suspected at shallow depths. The features fall into two general categories: those associated with faults and diapirs at basin edges or intrabasin ridges, and those associated with stratigraphic units across basin flanks and basin centers. The HRZs are observed within both categories. In stratigraphic units, HRZs are more common with high reflectivity near basin-edge structures and within chaotic stratigraphic units near the estimated base of the GHSZ (i.e. areas where gas seeps are common or where free gas might be expected, respectively).

Gas hydrate has been sampled at the seafloor from the tops of two diapiric structures with HRZs along the transect (Fig. 11–foldout), and are likely to be found on the seafloor over other diapiric structures. In basin centers with thick sediments in the eastern two-thirds of the transect, the HRZs generally lie below or close to the estimated base of the GHSZ for Bush Hill gas, but in the west where sediments are thinner, HRZs commonly lie above the estimated bases of the GHSZs. Although some similarity exists between the positions of HRZs and estimated base of the GHSZs across the basins, the relationship is equivocal—a similar argument might be made that HRZs follow regional stratigraphic units that by coincidence mimic the estimated base of the GHSZ.

In the basins, sedimentary units that lie above the regionally extensive stratigraphic HRZs (i.e. above 800 ms subbottom) are generally well layered in the east and more disrupted in the west—with some interbedded deformed units (e.g. slides, Fig. 9) and acoustically opaque units (e.g. channel fill and debris flows, Fig. 10). Locally, these units have enhanced reflectivity that may also result from thin-bedded turbidites and preferential fluid/gas flow in parts of these units. The interbedded deformed units are more common beneath steeper slopes on basin flanks than elsewhere. In many places where chimney features occur they are overlain by 'rumpled' strata resulting from recent (?) creep and or sliding (e.g. Fig. 8) that in turn may be due to vertical movements of deep underlying salt.

The layered sedimentary sections are characterized in many places by near-vertical chimney features of attenuated seismic amplitudes that are most numerous and obvious on the flanks and in the centers of basins with thick sediments. The 'chimneys' are marked by subtle flexures and local vertical seismic-amplitude variations, and in many cases not by detectable vertical displacements of strata. Many chimneys appear to originate or sole in the HRZs near the base of the estimated base of the GHSZs. The chimneys may be compaction or syndepositional faults with upward migration of fluids/gases. Such features are noted by others and cited as being caused in the Gulf of Mexico by gas (e.g. Anderson & Bryant, 1990) and alternatively on the Blake Plateau and the Cascadia margin by vertical zones with elevated velocities due to gas hydrate deposits that cause scattering and destructive interference of seismic energy (Wood & Gettrust, 2001). In either case, localized vertical fluid/gas flow is implied, and where free gas is present within the GHSZ, gas hydrate should be present.

There is no evidence in the transect (Fig. 11–foldout) for a typical BSR with a single continuous reflection, and there is only a tentative correlation between the estimated base of the GHSZ and an underlying HRZ. If the high-reflectivity is caused by gas near the base of the GHSZ, then a BSR might be expected. The absence of a BSR, however, does not prelude the existence of gas hydrate in the sedimentary section, because gas hydrate is found in many other areas where BSRs are not seen (Kvenvolden & Lorenson, 2001).

3. Discussion and conclusions

3.1. Equivocal evidence of gas hydrate

Direct evidence for gas hydrate in our high-resolution seismic-reflection data is equivocal. We are not able to determine seismic velocities or reliably establish reflection polarity; consequently our inferences are based on seismic-amplitude variations in acoustic facies. Such variations are well known to have multiple explanations (e.g. Sheriff, 1975). Yet, the presence of free gas and potentially gas hydrate is also known to have a strong effect on seismic amplitudes and acoustic facies, especially in unconsolidated shallow sand/shale sequences prevalent in the Gulf of Mexico. Seismic reflectivity increases strongly in unconsolidated and saturated sandy units in the presence of small amounts of gas (i.e. 1–2%) due to rapid decreases in bulk density and velocity with displacement of pore waters (Domenico, 1974). And, recent model studies by Huffman (2000, fig. 9) show that reflection amplitudes may increase with decreasing effective stresses in sandy water-flow units at about 0.5 s subbottom, which in the water depths used for the models is close to the base of the GHSZ. Gas is also known to scatter energy and result in either high- or low-amplitudes depending on seismic frequencies (Anderson & Hampton, 1980) and result in 'wipe-out' zones that document where large gas flows exist (e.g. Roberts et al., 1999a).

In the Gulf of Mexico, seismic facies containing gas vary from low-amplitude wipe-out zones (e.g. Roberts et al., 1999a) to chaotic facies with enhanced amplitudes (e.g. Anderson & Bryant, 1990) to bright spots in sand-shale sections (e.g. McConnell, 2000; Roberts et al., 1992). We do not see evidence in our high-resolution seismic-reflection data for BSRs or widespread strongly attenuated blanking zones that are indicators of gas hydrate (e.g. Lee et al., 1993; Shipley et al., 1979), rather we commonly see HRZs with varied shapes and extents in shallow stratigraphic units that lie mostly outside of the estimated GHSZ. In the only documented recovery of deep subbottom gas hydrate in the Gulf of Mexico (i.e. DSDP Site 618), seismic amplitudes are highly varied, from acoustic wipeout near surface (Fig. 12(A)), to stronger amplitudes in minisparker seismic-reflection data where gas hydrate were recovered ('H', Fig. 12(B)), to strongest amplitudes where gassy cores but no gas hydrate were observed (below H, Fig 12(B)). The entire Site 618 hole should be within the GHSZ, assuming either pure methane or Bush Hill gas based on Fig. 3. If the higher reflectivity in the deeper part of the hole where gassy cores were observed is due to small volumes of free gas, then gas hydrate would be expected throughout the core, as was postulated by the Leg 96 shipboard party (Bouma et al., 1986).

In view of all observations from our study regions—that include rapid sedimentation of clastic sand/silt sediments, plentiful gas from thermogenic and biogenic sources, abundant fault and reservoir pathways for upward migration

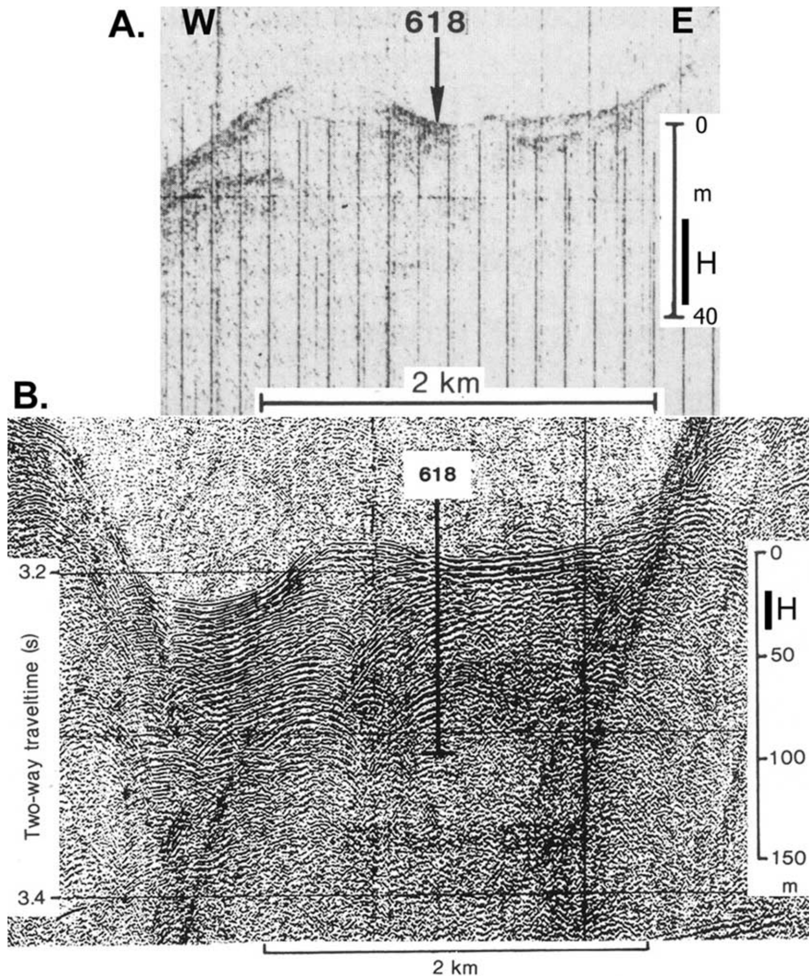

Fig. 12. Acoustic profiles recorded in 1980 across DSDP Site 618 in the Orca Basin in the central Gulf of Mexico (27°00.68′N, 91°15.73′W, Fig. 1(A)). This is the only location in the Gulf of Mexico where gas hydrate (H) has been recovered and documented from depths >6 m below the seafloor. (A) 3.5 kHz bathymetric profile. (B) Minisparker profile. Small gas hydrate flakes were observed in cores between 19 and 38 mbsf. Gassy cores were observed from throughout the hole. Figure adapted from Bouma et al. (1986, pp. 402–403).

of fluids and gases, numerous documented seafloor vent sites with gas and gas hydrate, ubiquitous HRZs that lie below or near areas of known seafloor gas hydrate—we infer that HRZs in the upper sedimentary section are due principally to free gas within thin sandy reservoir beds that are encased in shale and are laterally confined or deformed. Other investigators have cited these areas of high reflectivity and possible gas in high-resolution seismic-reflection data as ‘deformed reflection patterns’ (Berryhill et al., 1987) and ‘seismically amorphous sediment’ (Bouma, Roberts, & Coleman, 1990) or just ‘possibly gassy sediments’ (McConnell, 2000).

We infer that HRZs may sometimes be indicators for subbottom gas hydrate. Where the HRZs lie within the true GHSZ, then gas hydrate would be expected along with the gas. But, we (Fig. 3) and others (e.g. Milkov & Sassen, 2000) do not know the true extent of the GHSZ in the Gulf of Mexico. The HRZs in our data most commonly correspond with stratigraphic units that in some cases locally and regionally track the estimated base of the GHSZ, yet the high reflectivity usually does not cut across stratigraphy. Where the HRZs lie directly below the estimated base of the GHSZ and may encompass one or more stratigraphic horizons, we speculate that at least small amounts of free gas exist in the HRZ and the top of the HRZ may lie close to the true base of the GHSZ. In this case, potentially large quantities of gas hydrate may be contained in the overlying sedimentary section. The interpretation of HRZs as an indicator of nearby gas hydrate is, however, equivocal without knowledge of the location of the true base of the GHSZ. It is important to ‘ground truth’ the seismic-reflection results with seafloor cores and drilling cores that will continuously sample into and through the GHSZ.

3.2. Fault systems, high-reflectivity and slope stability

The deep-seated and shallow rooted faults that we see and infer from the high-resolution seismic-reflection data

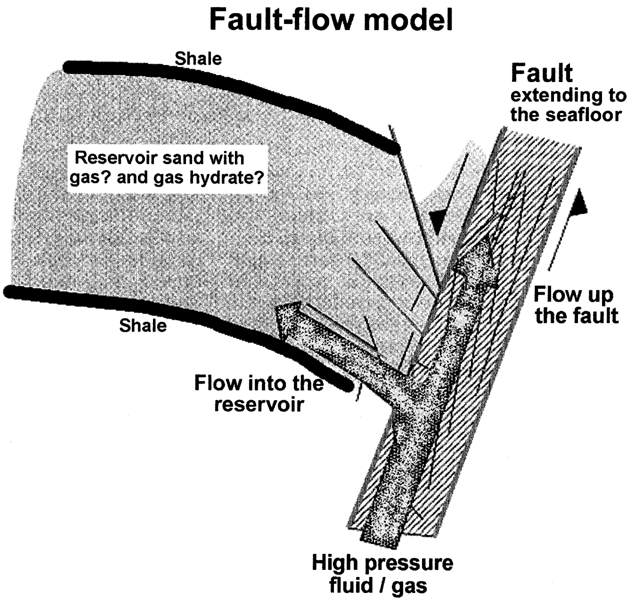

Fig. 13. Model for a fault supplying fluid and gas from depth to a stratigraphic reservoir and the seafloor. Where this system is in the GHSZ, gas hydrate is expected. Modified from Losh et al. (1999).

are the likely conduits for advecting fluids/gases that fill stratigraphic horizons (e.g. Fig. 13) and create the HRZs. Such faults have been noted beneath seafloor fluid/gas seeps and seafloor gas hydrate deposits near structures with HRZs (e.g. Roberts, 2001). Where flows are large at the seafloor and permeabilities of sand horizons within the underlying HRZs of the GHSZ are large, gas hydrate may be solid in thin layers. Alternatively, gas hydrate in the encasing muddy sections may be finely disseminated like that observed at DSDP Site 618 (Bouma et al., 1986).

Nearly all shallow diapirs are associated with HRZs along the crest and flanks, but not all faults have HRZs and hence may not be active fluid/gas conduits. Where deep-seated faults are not present, fluids/gases migrate through the sedimentary section by diffusion and we believe along vertical syndepositional sediment-compaction faults, and then advect into and along stratigraphic reservoirs (Fig. 13). We suspect that the chimney features in the upper sedimentary section are the fault conduits along which fluids/gases may flow upward between reservoir units (e.g. HRZs) in basin areas not cut at shallow depths by deep-seated faults. In oversteepened slope areas, these chimney faults may nucleate into shallow faults that sole out into shallow reservoir units, and that are the surfaces along which slide-blocks rotate and move downslope (e.g. Fig. 8). The interbedded stratigraphic reservoirs and the chimneys within the GHSZ, particularly those near HRZs, potentially hold dispersed and solid gas hydrate depending on reservoir porosities and permeabilities.

In areas of rapid sedimentation and seafloor slides, shallow water-flows are also commonly encountered in drill sites beneath the continental slope, such as described above for the area of Fig. 4. The shallow water-flows occur in water-depths of 450–2100 m and from the seafloor to subbottom depths of 1200 m in unconsolidated sediments with low failure strength and in a state of incipient failure (Huffman, 2000). There may also be a close association of reflectivity variations due to both gas and shallow flows (and potentially gas hydrate) in shallow sandy units, as illustrated in a seismic-reflection section across a suspected shallow flow zone, with high reflectivity (e.g. HRZ; McConnell, 2000, fig. 2).

Gravity is the driving force for slides, with failures probably along the thin (< 1 m thick) horizons and high-angle faults that are likely zones of fluid/gas flows and gas hydrate in the GHSZ. Many of these faults lie directly above or within HRZs. The trigger for slide events on unstable slopes in the Gulf of Mexico may be earthquakes (e.g. Keefer, 1984) resulting from rapid and abrupt salt movements (e.g. uplift rate of 2–4 cm/yr on a diapir in Gyre basin (Bouma et al., 1990)). Seven earthquakes with magnitudes (M) of 3.6–4.9 have been noted under the slope since 1978. One of these, a $M = 4.3$ was sited at 10 km depth under a large salt structure and nearby seafloor slides on the upper continental slope of the Mississippi canyon's west side (12 December, 2000; USGS, 2001; Fig. 1). Currently, large areas of the slope (up to 225 km^2) may be actively sliding (e.g. Figs. 4, 8 and 9), and pose a significant hazard to seafloor structures related to energy exploration and exploitation.

We suspect that free gas, gas hydrate, and shallow water-flows, in thin permeable sandy reservoirs are linked to seafloor slides in areas of the Gulf of Mexico by reducing sediment strength (e.g. Ostermeier et al., 2000). This reduction enhances the probability of shear failure and sliding of thickly sedimented salt-oversteepened slope areas, initially we believe along pre-existing syndepositional faults (e.g. chimney features; Fig. 8). These processes result in shallow structures similar to those observed in other continental-slope regions of suspected gas hydrate (e.g. Popenoe & Dillon, 1996). Continuous core samples through the GHSZ are needed at several locations in the Gulf of Mexico to better document the distribution of gas hydrate and verify inferences from seismic-reflection data.

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