Gas-Charging of Late Pleistocene Shelf-Edge Delta Reservoirs and Dissociation of Gas Hydrate, Northeastern Gulf of Mexico

by

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ABSTRACT

Stacked and laterally offset clinoform packages associated with lowstand deltas comprise the northeastern Gulf of Mexico shelf edge, from the modern Mississippi River delta to DeSoto Canyon. Within the late Pleistocene Lagniappe delta complex (offshore Mississippi-Alabama), thick sandy prograding clinoform bed sets display strong impedance contrasts on high-resolution seismic, suggesting significant free-gas content. Carbon-14 dating places the Lagniappe delta at the shelf-slope transition about 1 ka before the latest Pleistocene glacial maximum. Thin heterolithic clinoform toes extend down slope to a channel-levee system that feeds bypass sediment to a deep slope fan. In sedimentary units that contain both fluids and gases, laminated sand, silt, and clay units create effective capillary seals that inhibit vertical hydrocarbon migration while focusing lateral and updip transport. Significantly, Lagniappe delta clinoform toes extend down slope into the gas hydrate stability zone, which may act as a regulator of up-dip hydrocarbon migration.

In response to the ca. 100 ka glacioeustatic cycles of the Pleistocene epoch, reduction in hydrostatic pressure and warmer water periodically impact the top of the gas hydrate stability zone, triggering hydrate instability. Rapid decomposition of large gas hydrate reservoirs can dramatically reduce sediment strength and thereby lead to slope failures and canyon/gully formation. Reentrants in the continental margin formed by this process are exploited by falling-to-lowstand deltas as catchments for clinoform toes and by-pass routes for sediment transport to deep-water settings. At more modest rates of gas hydrate decomposition, gas is forced into surrounding sediments where it migrates up-dip along capillary seal limited porous and permeable pathways provided by the heterolithic clinoform toes. It appears that this process provides an early gas charge to the shelf-edge deltas.

Under rising-to-high sea-level conditions and rebuilding of the gas hydrate reservoir, Loop Current intrusions can raise bottom water temperatures on the upper slope (< 1000 m) by 3-10 degrees C, causing near surface gas hydrates to dissociate and, making gas available for up-dip migration. Loop Current impacts are also important for periods of lowered sea level. Presently, gas seeping from truncated clinoforms on the shelf, and ^{13}C-depleted authigenic carbonates in Lagniappe delta cores suggest that hydrocarbon migration is an on-going process at the shelf margin.

INTRODUCTION

Stratigraphy of the northern and northwestern Gulf of Mexico shelf edge records multiple episodes of delta building during periods of lowered sea level (Suter and Berryhill, 1985; Kindinger, 1988; Sydow and Roberts, 1994; Winn et al., 1995; Winn et al., 1998; Anderson et al., 1996, Anderson et al., 2004, and others). Although deltaic systems evolve continuously throughout a glacioeustatic cycle (Suter, 1994), it is generally late falling-stage –to lowstand deltas that significantly prograde the shelf edge and supply sediment to downslope deep-water settings. Generally, where sufficient data are available to reconstruct stratal geometries, late Quaternary shelf edge deltas of the northern and northwestern Gulf appear to be fluvially dominated with some wave modification (e.g. Morton and Suter, 1996).

Recently, detailed sedimentological and biostratigraphic analyses of continuous cores through the Lagniappe delta, along the Mississippi-Alabama shelf edge (Fig. 1), confirm the existence of separate sand-rich fluvially dominated and wave dominated lobes within the same delta complex (Roberts et al., 2003). Because fluvial systems and their drainage basins are highly variable across the Gulf Coast, each corresponding shelf edge delta has its own unique set of characteristics, such as size, stratigraphic architecture, sediment types, and linkage to downslope depositional sites. The smaller systems frequently source intraslope basins (Beaubouef and Friedman, 2000; Beaubouef et al., 2003), while larger shelf edge delta complexes capable of distributing large supplies of sediment seem to control the locations of submarine fans (Winker and Booth, 2000). Sediments are transported downslope in density flows, directly from the distributary mouths, or from delta front slope failures.

Posamentier (2003) notes that 3-D seismic time slices of the continental slope in the vicinity of the Lagniappe delta display numerous narrow gullies that he interprets as the result of hyperpycnal flows originating from the shelf edge delta distributary network. It appears that dominant gullies evolve into channel-levee systems that supply sediments to submarine fans on the middle-to-lower slope, Figure 2 (Fillon et al. 2000). Dip-oriented high-resolution seismic profiles across the shelf edge frequently illustrate deltaic clinoform sets charged with gas, and farther down-slope, thin, closely spaced reflectors linking clinoform toes to slope fans. These thin reflectors, interpreted as turbidite deposits, frequently intersect large growth faults, shallow salt, and “gas chimneys,” as determined from seismic data.

A probable mechanism for charging shelf-edge deltas with gas from decomposing gas hydrates is the subject of this paper. The Lagniappe delta at the Mississippi-Alabama shelf edge is in the study site.

THE LAGNIAPPE DELTA SHELF-SLOPE SYSTEM

Vintage U.S. Geological Survey sparker data acquired on the Mississippi-Alabama shelf and upper slope imaged a set of clinoform reflectors that defined a delta that had prograted to the shelf edge during a period of lowered sea level. This delta, named the Lagniappe delta (Kindinger, 1988), became the subject of an extensive study funded by industry under the auspices of the Gulf of Mexico Shelf-Slope Research Consortium (GOMSSRC). Both high resolution seismic and corehole data were collected to build a better understanding of the

Lagniappe delta's detailed seismic, lithologic, biostratigraphic, and chronostratigraphic framework. Figure 1 shows the Lagniappe delta and the locations of four continuously cored boreholes drilled to "calibrate" the seismic stratigraphic architecture of the delta to age, stable isotope stages, biostratigraphic markers, paleoecologic estimates of water depth, and sediment properties.

The Lagniappe delta was discovered to have developed both its western and eastern lobes at the shelf edge by about 19 ka BP. The major clinoform sets in both parts of the delta are today submerged at about -90 m water depth, not -120 m as predicted for the maximum lowstand by most sea level curves (e.g. Labeyrie et al., 1987; Shackleton, 1987), Figure 3. However, Coastal Studies Institute researchers found a small, lobe at approximately the -120 m level when additional high-resolution seismic profiles were acquired. This lobe, as yet undated, appears to stratigraphically overlie the eastern 19 ka BP lobe of the Lagniappe delta. It is the subject of on-going research.

The GOMSSRC data define the Lagniappe delta as a multilobate depositional system composed multiple clinoform sets, many of which are incised by a complex network of fluvial scours (Sydow et al., 1992; Sydow and Roberts, 1994). Clinoform sets sampled by the four coreholes were found to be composed primarily of sand, and in the case of fluvial scour fill, primarily of graveliferous sand. No canyons were found to be connected to this shelf-edge depositional system, but slope channels were identified downslope within the succession of distal Lagniappe clinoform toes. . Heterolithic graded units characterized the clinoform toe sets in both the MP303 and MP288 coreholes (Fig. 1).

The thin graded bed sets that comprise the clinoform toes can be traced downslope on high-resolution seismic profiles as a series of well-defined and closely spaced reflectors. Cathles (2001), Erendi and Cathles (2001), and Shosa and Cathles (2001) convincingly demonstrate through laboratory experiments that when dealing with two-phase flow systems (gas and liquid) in heterolithic strata, capillary seals develop that effectively eliminate vertical migration. In the case of Lagniappe delta clinoform toes, which are shallow enough to contain both water and free gas, this result implies that gas entering the turbidite strata cannot escape vertically to the seafloor, but must travel updip along permeable components of each turbidite. Data on the Lagniappe delta and recent interpretations concerning its chronostratigraphy, lithology, burial/subsidence history, and biostratigraphy, as well as its seismic stratigraphic framework can found in recent publications by Fillon et al. (2003), Kohl et al. (2003), Kolla et al. (2003), and Roberts et al. (2003).

CONTINENTAL MARGIN GAS HYDRATES

Gas hydrate that forms in natural environments is a frozen mixture of water and gas (mostly methane). The water molecules in hydrates form rigid cages around molecules of methane, or perhaps gas molecules of slightly higher molecular weight (e.g. C^1 – C^5 gases). Gas hydrate formation takes place under special conditions of temperature, pressure, and gas-water composition. These conditions are frequently met along continental margins. Figure 4 illustrates the hydrate stability zone in a typical continental margin setting. The boundary conditions for gas hydrate occurrence and stability at and below the sea floor are determined by water temperature, hydrostatic pressure and the geothermal gradient. Kvenvolden and Lorenson (2001) present a recent estimate of the potential amount gas hydrate currently stored in the world's continental margins. It is enormous, portending equally enormous potential impacts on future energy supplies, continental margin stability, and global climate change.

During interglacial periods of high eustatic sea level similar to the Holocene, methane, and to a lesser extent other thermogenic gases, migrate into continental margins where they combine with water under conditions of low temperature and high hydrostatic pressure to form gas hydrate. Most evidence for the charging of continental margins with gas hydrate is indirectly interpreted from marine seismic reflection profiles. Anomalous bottom simulating reflectors (BSRs) that may cut across true stratigraphic reflectors can be identified in seismic profiles from most continental margins. These anomalous reflectors correspond to the phase boundary at the base of the hydrate stability zone (Fig. 3). They develop in response to acoustic impedance contrasts between gas hydrate bearing strata above and strata containing free gas below, resulting in a negative reflection coefficient. Bottom simulating reflectors exhibit a characteristic reversed polarity signal.

Repeated high frequency glacioeustatic changes in sea level punctuate the late Pleistocene. ~ These cycles, characterized by a progressive saw-tooth drop in sea level to a maximum lowstand followed by a rapid rise to a highstand, lasting ~100 ka, are convincingly demonstrated by many lines of evidence (e.g. Kennett et al., 2003). Researchers now generally believe that these eustatic cycles, reflecting global ice volume and climate change, may be directly related to charging and discharging of the continental margin gas hydrate reservoir (Paull et al, 1991; Haq, 1999; Kennett et al., 2003). Geoscientists argue that as eustatic sea level falls dramatically in association with periods of maximum glaciation, methane is released to the water column and atmosphere creating a "greenhouse"feedback effect that initiates atmospheric warming, melts glaciers, and thus reverses the eustatic sea level fall. Methane is a much more efficient greenhouse gas than carbon dioxide, both in short term (decadal) and longer (millennial) time scales.

In addition to being implicated in global warming, glacial retreat, and sea level rise, the release of methane from the continental margin gas hydrate reservoir has some other important geological implications. Potentially, the most important of these is the probable relationship between gas release and destabilization of sediments in continental margins, leading to slope failure and submarine landslides (Thiery et al., 1998; Mienert and Posewang, 1999; Clennell et al. 2000; Driscoll et al., 2000). The timing of major slope failure episodes within the eustatic cycle is not well constrained, but during the latest ~100 ka cycle, the rapid drop in sea level between the end of oxygen isotope stage 3 (~30-35 ka BP) and the oxygen isotope stage 2 glacial maximum (~18 ka BP) is a likely time period (Fig. 3).

Another important geologic impact of hydrate destabilization is that gas is made available for migration into reservoirs updip of the hydrate stability zone. During a sea level fall, when hydrostatic pressure decreases and bottom water temperatures increase sufficiently to cause gas hydrate dissociation at the upper end of the stability zone, significant quantities of gas will be released into surrounding sediments. Catastrophic releases lead to the slope instability problems discussed above, but slower hydrate decomposition, which is probably most common given the thousands of years over which even rapid glacioeustatic sea level falls develop, releases gas less catastrophically. Gas that is released gradually and trapped in the subsurface, migrates up dip within porous and permeable strata, driven by buoyancy and hydraulic forces and confined by capillary seals until it is discharged through faults and other migration pathways to the seafloor, or until it reaches a reservoir quality shelf-edge sand where, potentially, even at relatively shallow depth it can be trapped by capillary seal development at a facies boundary.

The sealing capacity of capillary seals in couplets composed of coarse and fine laminae is additive, so within laminated section consisting of hundreds of couplets, which in total might be only a few tens of feet thick, dynamic seals of considerable competence can be maintained. Cathles (2001) concludes that, because each capillary barrier at each fine layer is independent of others in the section, seals restraining hundreds of bars of overpressure could be constructed of hundreds of fine sediment layers, each with the few bars of capillary pressure drop observed in his laboratory experiments (Shosa and Cathles, 2001).

Relic pockmarks, mud volcanoes, and other fluid and gas expulsion features of the shelf edge and upper slope may have been formed by gas migration and escape from the sea floor driven by this process. The same process may also have charged clinoform beds on the shelf and upper slope which contain sufficient free gas to be essentially white body reflectors of acoustic energy.

Loop Current Effects on Gas Hydrate Stability

Surface layer physical oceanography of the Gulf of Mexico is dominated by the Loop Current. Direct intrusions of this warm water current and its eddies on the shelf edge and upper slope, as shown in Figure 5, routinely elevate temperatures at the seabed by as much as 3° - 10°C in upper slope settings. Roberts et al. (1999) have shown, through in situ experiments, that exposed and shallow subsurface gas hydrate deposits decompose in response to thermal impacts by warm Loop Current water. Direct encounters of the Loop Current and its eddies with the upper slope have a dwell time over any given point of about 3-5 weeks. The surficial water mass dominated by the Loop Current is about 800-1000 m thick. Even during modern highstand conditions, therefore, the upper part of the gas hydrate stability zone is thermally pulsed by direct Loop Current intrusions and associated eddies. Eddy formation occurs at a frequency of one to three per year. Warm eddies separate from the Loop Current in the eastern-central Gulf and travel westward along the shelf edge where they eventually encounter the east Texas continental shelf. There they are trapped, lose energy, and finally disappear. This repeated behavior means that at least once and perhaps as many as three times a year gas hydrate in the surficial sediments is exposed to elevated temperatures. The methane hydrate, which is the most vulnerable hydrate phase to thermal pulses on the upper slope, will decompose during these events creating free gas. If in a favorable stratigraphic setting, this gas is available for updip transport.

Numerical simulations of the Loop Current during the latest Pleistocene glacial maximum and paleoecological evidence from GOMSSRC coreholes suggest that the Loop Current is also active during periods low sea level (Welsh, 1996; Fillon et al., 2004; Kohl et al., 2004). Assuming a rather constant supply of gas from the subsurface, it is possible that surface and near surface gas hydrates form and decompose at the frequency of thermal pulses provided by the Loop Current and its eddies across the entire northern and northwestern upper continental slope of the Gulf at both highstands and lowstands of sea level. This mechanism acts as a thermal pump that potentially makes gas available for updip migration to shelf edge reservoirs. The assumption of a constant supply of gas from the subsurface, however, may not be valid. Lower sea levels will lower fluid pressures in deeper strata, potentially allowing capillary seals to migrate upward, creating additional reservoir space for deep gas to fill. This might diminish the volume of gas supplied at the base of the hydrate stability zone during lowstands. Without adequate replenishment, the periodic dissociation of hydrates at the top of the hydrate zone by thermal pulses might be more likely to produce catastrophic slope failure.

EVIDENCE FOR GAS-CHARGING OF SHELF-EDGE DELTAS

Extensive high resolution seismic and core studies of the Lagniappe delta at the Mississippi-Alabama shelf edge reveal that the sand-rich clinoform sets comprising the delta are acting essentially as strong white body reflectors. Rather than producing strong lithologic reflections from conformable stratigraphic interfaces within the clinoform sets, the bulk of returning acoustic energy appears generated diffusely within the upper portion of each set of clinoform toes. Acoustic shadow or "blanking" zones are identified beneath the high amplitude diffuse reflections.

Three different lines of evidence strongly suggest gas-charging as the cause of these unique seismic responses in Lagniappe delta sediments: (1) the diffuse high amplitude areas and associated acoustic blanking zones on high resolution seismic profiles, (2) plumes of gas leaking from truncated clinoforms into the water column, observed on both echo sounder and seismic records (), and (3) ^{13}C depleted diagenetic carbonates in cores linking carbonate concretions and foraminiferal test fillings to hydrocarbon gas. Seismic evidence for this relationship between deltaic deposits and free gas is illustrated in a dip-oriented profile across the eastern shelf edge lobe of the delta (Fig. 6). Note the acoustic blanking and very irregular high amplitude zones in the upper and middle parts of the shelf-edge clinoform toe sets at the right of the profile. In contrast, the more irregular zones of strong diffuse reflections beneath mid-outer shelf clinoform sets imaged in the middle of the profile suggest vertical migration of free gas out of clinoform toes. This response is illustrated in greater detail near the western end of the strike line shown in Figure 7. In these very irregular vertical migration fronts we may be seeing evidence of gas escape from sedimentary facies in which there are insufficient fine-coarse laminae sets to provide an adequate capillary seal, resulting in the gas leakage from truncated clinoforms into the water column.

Many seismic profiles show that some clinoform reflectors, usually defining the boundary between clinoform sets, present an unusually high amplitude response. Many of these reflectors represent the final reflection horizon of a clinoform set. Switching the locus of Lagniappe delta deposition through changing distributary dominance produces characteristic toplap-downlap relationships between clinoform sets (Sydow et al., 1992). When such a switch takes place, sediment that collects on the final clinoform surface is finely laminated and fine-grained as determined by correlation of sediments in continuous coreholes to seismic reflectors (Fillon et al., 2000). It appears that gas migrates through the sand-rich clinoforms, but collects within (in capillary seals) and beneath these less permeable laminated clay drapes, creating the high amplitude patterns clearly apparent in both Figures 6 and 7 and most other seismic profiles through this delta. Because these laminated drapes are generally too thin to provide competent capillary sealing, often a foot or less in thickness, gas escapes and migrates vertically to the next laminated section or to the seafloor.

Figures 6 and 7 illustrate that as sea level rose across the shelf from the last glacial maximum, approximately 18 ka BP, clinoforms of the shelf edge delta were truncated, a characteristic clearly displayed on seismic records throughout the Lagniappe delta. Gas introduced to the base of these deltaic deposits through updip migration is transported through the sandy clinoforms until a permeability barrier is encountered where it may accumulate, as described above. It is apparent that some gas migrates through the clinoform wedge and exits at the seafloor into the overlying water column. During the collection of seismic profiles over the eastern Lagniappe delta and older delta lobes to the east, several active gas seeps were detected as bubble streams in the water column on echo sounder and high-resolution seismic profiles.

Figure 7 also shows the surface of an older delta directly east of the Lagniappe delta is irregular (compare with surface in Figure 6). These irregularities are interpreted as carbonate buildup on truncated deltaic clinoforms. The side-scan sonar image shown in Figure 8 clearly delineates these features. It is now well known that microbial utilization of hydrocarbon, both crude oil and gas, frequently produces ^{13}C-depleted Ca-Mg carbonates in the form of nodular masses in sediments, crusts, and mound-like buildups (Roberts and Aharon, 1994). These carbonates can form the hard substrates on which other organisms may attach and grow. The carbonate pinnacle trend even farther to the east, opposite the Alabama coast, may represent biogenic growth on such substrates that have vertically accreted through multiple sea level cycles (Ludwig and Walton, 1957; Laswell et al., 1990).

Finally, during the analysis of sediments recovered from coreholes through the Lagniappe delta observation of ^{13}C-depleted carbonate nodules and cements inside of foraminifera tests strongly support a hydrocarbon gas involvement in carbonate cement formation in these cases (Fillon et al., 2004 and unpublished data, Gulf of Mexico shelf-slope Consortium). On the continental slope where hydrocarbon seepage is a common phenomenon around the flanks of intraslope basins, authigenic carbonates in the form of nodular masses in the sediment, cemented crusts, and impressive mound-like buildups are indicators of microbial activity related to sulfate reduction and anaerobic methane oxidation or oxidation of higher molecular weight gases. These reactions increase alkalinity by production of bicarbonate, which stimulates Mg-Ca carbonate precipitation. The carbonate molecules incorporate ^{12}C from the hydrocarbons, giving them a characteristic ^{13}C-depleted isotopic signature. Carbonates analyzed from the Lagniappe delta corehole samples display the “isotopically light” signature indicating a strong link to hydrocarbon gases, predominantly methane.

SUMMARY AND CONCLUSIONS

Recent studies of the shelf-to-slope transition in the northwestern and northern Gulf of Mexico have demonstrated that the shelf edge is constructed largely of laterally offset and stacked deltas that were deposited during periods of falling-to-low sea level. These localized depocenters are linked to downslope deep water “confined” slope fans or “unconfined” basin floor fans through a variety of turbidite-filled conduits ranging from gullies-to-canyons. Where core data are available, clinoform beds within the lowstand shelf-edge Lagniappe delta display excellent reservoir quality. Based on currently ongoing studies, they are considerably more sand-rich than their highstand counterparts.

High-resolution seismic reflection profiles across shelf-edge deltas of the northern Gulf frequently display the diffuse high amplitudes and blanking effects of gas in the middle to upper portions of clinoform sets. Also, gas is frequently observed in the water column on seismic and echo-sounder profiles above shelf-edge deltas. Side-scan sonar data indicate that gas is leaking from clinoforms truncated by the ravinement process associate with a relative sea level rise after delta deposition. The most resistant clinoforms are the sites of low relief carbonate buildups.

In the deep-water province of the Gulf of Mexico, thin turbidite packages link shelf edge deltas to slope aprons and deep basin floor fans. These thin turbidites are thought to originate at the shelf edge during lowstands. The heterolithic nature of turbidites suppresses vertical migration through capillary sealing, but encourages lateral up-dip migration into the thick clinoform wedges that are the fundamental growth units of deltas at the shelf edge.

Laboratory and field studies have demonstrated the importance of capillary sealing in pressure compartmentation of sedimentary basins and in inhibiting vertical migration. Growth faults and shallow salt masses focus fluid and gas migration from the deep subsurface into shallow stratigraphic units including turbidites that are connected up dip to shelf edge deltas. A potential source of gas in these systems is gas hydrates. These unusual frozen compounds of gas (mostly methane) and water have been identified from continental margins throughout the world's oceans. Sensitive to temperature and pressure, they collectively represent an enormous potential energy resource. At high stands of the sea they are generally stable, but at falling-to-low sea level stands when hydrostatic pressure on the upper slope is reduced and warm surface waters impinge on the shelf slope transition, gas hydrates decompose releasing hydrocarbon as to the ocean, atmosphere, and surrounding sediments. Destabilization of upper slope hydrates also can cause slope instability leading to submarine landslides, slumps, and canyon formation, especially if decomposition is a rapid process.

Under modern highstand conditions in the northern Gulf of Mexico, near surface gas hydrate deposits of the upper continental slope are periodically impacted by warm water from the Loop Current and its eddies. The Loop Current affects the upper ~1000 m of the water column. During the direct impingement of the Loop Current or one of its eddies on the upper slope, the normal bottom water temperature of 4-7 °C may be elevated to 14-18 °C. These higher temperatures may persist for over 30 days before the Loop Current or eddy shifts position. Such thermal loading events cause near-surface gas hydrate decomposition and gas formation. Loop Current impacts should be even greater during falling-to-lowstand conditions when warmer surface layer waters contact the hydrate stability zone. If this process supplies gas to clinoform toe-set turbidite packages, up-dip migration of gas may occur. The heterolithic nature of turbidites suggests that capillary seals develop in these strata forcing lateral migration. Presently, the upper depth limit of the gas hydrate stability zone for gas hydrates composed of mixed gases (mostly methane with minor amounts of other thermogenic gases) can be as shallow as 300 m in the Gulf. Therefore, periodic thermal loading by the Loop Current can affect gas hydrates in the 300 m – 1000 m depth range.

Concluding Points

1. The shelf edge in the northern and northwestern Gulf of Mexico is composed of stacked and laterally offset deltas deposited during periods of falling-to-low sea level.
2. A detailed study of the Lagniappe (ancestral Mobile River) delta indicates thick reservoir quality sands in the incised fluvial facies and shelf edge clinoform sets.
3. Sediment by-pass from the shelf edge to deep water occurs by delta front instability and hyperpycnal flows. Slope to basin floor deposition sites are connected to shelf edge deltas through conduits ranging from gullies to canyons.
4. Distal extensions of shelf edge clinoforms (clinoform toes) are composed of heterolithic turbidite deposits. The laminated nature of distal clinoforms suggests that capillary seals may develop nearby limiting vertical migration and forcing up dip lateral migration.
5. High-resolution seismic reflection profiles suggest that shelf edge clinoform sets are charged with gas, perhaps as a product of up-dip migration through distal turbidite deposits.
6. Growth faults and faults associated with shallow salt can provide migration pathways to the turbidite packages which provide conduits for charging shelf-edge deltas with hydrocarbons.
7. Reduced hydrostatic pressure related to lowered sea level releases free gas from gas hydrate deposits in the continental margin, which may cause slope instability including canyon or gulley formation and also may supply gas for charging of shelf-edge delta reservoirs.
8. During both highstands and lowstands, periodic thermal loading of the Gulf's upper slope by the Loop Current destabilizes near-surface gas hydrate deposits and may provide gas for up-dip migration through distal clinoform toes to thick sand-rich clinoform sets at the shelf edge.
9. Gas-charging of shelf-edge deltas appears to be an on-going process.

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REFERENCES

Anderson, J.B., A. Rodriguez, K. Abdulah, L.A. Banfield, P. Bart, R. Fillon, H. McKeown, and J. Wellner, 2004, Late Quaternary stratigraphic evolution of the northern Gulf of Mexico: A synthesis, *in* J.B. Anderson, and R.H. Fillon, eds., Late Quaternary Stratigraphic Evolution of the Northern Gulf of Mexico Basin: SEPM Special Publication No. 79, p. 1-24.

Anderson, J.B., K. Abdulah, S. Sarzalejo, F. Siringan, and M.A. Thomas, 1996, Late Quaternary sedimentation and high-resolution sequence stratigraphy of the east Texas shelf, *in* M. De Batist and P. Jacobs., eds., geology of Siliciclastic Seas: Geological Society of London Special Publication 117, p. 95-124.

Beaubouef, R.T., V. Abreu, and J.C. Van Wegoner, 2003, Basin 4 of the Brazos-Trinity slope system, western Gulf of Mexico: The terminal portion of a late Pleistocene lowstand systems tract: *In* H.H. Roberts, N.C. Rosen, R.H. Fillon, and J.B. Anderson (eds.) Shelf Margin Deltas and Linked Downslope Petroleum Systems: 23rd Annual GCSSEPM Foundation Bob F. Perkins Research Conference, p. 45-66.

Beaubouef, R., and J. Friedman, 2000, High-resolution seismic/sequence stratigraphic framework for the evolution of Pleistocene intraslope basins, GCSSEPM Foundation 20th Bob Perkins Research Conference, p. 40-60.

Cathles, L.M., 2001, Capillary seals as a cause of pressure compartmentation in sedimentary basins: Proceedings GCSSEPM Foundation 21st Annual Research Conference, Petroleum Systems of Deep-Water Basins, December 2-5, p. 561-572.

Clennell, M.B., A. Judd, M. Hovland, 2000, Movement and accumulation of methane in marine sediments; relation to gas hydrate systems. *In:* Max, M.C. (Ed.), Coastal Systems and Continental Margins, Kluwer, Dordrecht, p. 105-122.

Driscoll, N., J.K., Weissel, J.A. Goff, 2000, Potential for large-scale submarine slope failure and tsunami generation along the US mid-Atlantic Coast: Geology v. 28, p. 407-410.

Erendi, A. and L.M. Cathles, 2001, Gas capillary inhabitation to oil production: Proceedings GCSSEPM Foundation 21st Annual Research Conference, Petroleum Systems of Deep-Water Basin, December 2-5, p. 597-608.

Fillon, R.H., H.H. Roberts, and B. Kohl, 2000, Stratigraphic framework and origin of shallow geohazards on the upper slope, northeastern Gulf of Mexico: Proceedings 32nd Annual Offshore Technology Conference, OTC Paper 12073, p. 1-14.

Fillon, R., B. Kohl, and H.H. Roberts**,** 2004, Late Quaternary deposition and paleobathymetry at the shelf edge-slope transition, ancestral Mobile River delta complex, northeastern Gulf of Mexico, *in* J.B. Anderson and R. Fillon (eds.), Late Quaternary Stratigraphic Evolution of the Northern Gulf of Mexico Basin, SEPM Special Publication No. 79, p. 109-140.

Haq, B.U., 1999, Methane in deep blue ea, Science, v. 285, p. 543-544.

Kennett, J.P., K.G. Cannariato, I.L. Hendy, and R.J. Behl, 2003, Methane hydrates in Quaternary climate change – The clathrate gun hypothesis: American Geophysical Union, Washington, D.C., 216 p.

Kindinger, J.L, 1988, seismic stratigraphy of the Mississippi-Alabama shelf and upper continental slope: Marine Geology, v. 83, p. 79-94.

Kohl, B., R.H. Fillon, and H.H. Roberts, 2003, Biostratigraphy of a Pleistocene shelf-edge delta system, northeastern Gulf of Mexico: Recognition of delta subenvironments: *in* H.H. Roberts, N.C. Rosen, R.H. Fillon, and J.B. Anderson (eds.) Shelf Margin Deltas and Linked Downslope Petroleum Systems: 23rd Annual GCSSEPM Foundation Bob F. Perkins Research Conference, p. 785-816.

Kolla, V., R.H. Fillon, H.H. Roberts, B. Kohl, and B. Long, 2003, Late Pleistocene sequence stratigraphy of the shelf-edge and upper slope in the Viosca Knoll Area of the northeast Gulf of Mexico: *in* H.H. Roberts, N.C. Rosen, R.H. Fillon, and J.B. Anderson (eds.) Shelf Margin Deltas and Linked

Downslope Petroleum Systems: 23rd Annual GCSSEPM Foundation Bob F. Perkins Research Conference, p. 79-90.

Kvenvolden, K.A. and T.D. Lorenson, 2001, The global occurrence of natural gas hydrate: *in* C.K. Paull and W.P. Dillon, Natural Gas Hydrates, Occurrence, Distribution, and Detection: American Geophysical Union Geophysical Monograph 124, p. 3-18.

Kvenvolden, K.A. and L.A. Barnard, 1983, Gas hydrate of the Blake Outer Ridge, Site 533, Deep Sea Drilling Project Leg 76: Initial Reports, Deep Sea Drilling Project Leg 76, p. 353-365.

Labeyrie, L.D., J.C. Duplessy, and P.L. Blanc, 1987, Variations in mode of formation and temperature of oceanic deep waters over the past 125,000 years: Nature, v. 327, p. 477-481.

Laswell, J.S., W.W. Sager, W.W. Schroeder, R. Rezak, K.S. Davis and E.G. Garrison, 1990, Mississippi-Alabama marine ecosystem study: Atlas of high-resolution geophysical data, Minerals Management Service, OCS Study MMS 90-0045, 40 p.

Ludwig, J.C. and W.R. Walton, 1957, Shelf-edge calcareous prominences in northeastern Gulf of Mexico, Bulletin American Association of Petroleum Geologists, v. 41, p. 2054-2101.

Morton, R.A., and J.R. Suter, 1996, Sequence stratigraphy and composition of Late quaternary shelf-margin deltas, northern Gulf of Mexico: American Association of Petroleum Geologists Bulletin, v. 80, p. 505-530.

Mienert, J., and J. Posewang, 1999, Evidence of shallow-and deep-water gas hydrate destabilizations in north Atlantic polar continental margin sediments, Geo-Marine Letters v. 19, p. 143-149.

Paull, C.K., W. Ussler III, and W.P. Dillon, 1991, Is the extent of glaciation limited by marine gas-hydrate? Geophysical Research Letters, v. 18, p. 432-434.

Posamentier, H.W., 2003, A linked shelf-edge delta and slope-channel turbidite system: 3D seismic case study from the eastern Gulf of Mexico: *in* H.H. Roberts, N.C. Rosen, R.H. Fillon, and J.B. Anderson (eds.) Shelf Margin Deltas and Linked Downslope Petroleum Systems: 23rd Annual GCSSEPM Foundation Bob F. Perkins Research Conference, p. 115-134.

Roberts, H.H, J. Sydow, R.H. Fillon, and B. Kohl, 2003, Late quaternary shelf-edge deltas from northeastern Gulf of Mexico and eastern Borneo (Indonesia): A comparison: *in* H.H. Roberts, N.C. Rosen, R.H. Fillon, and J.B. Anderson (eds.) Shelf Margin Deltas and Linked Downslope Petroleum Systems: 23rd Annual GCSSEPM Foundation Bob F. Perkins Research Conference, p. 843-848.

Roberts, H.H., W.J. Wiseman, Jr., J. Hooper, and G. Humphrey, 1999, Surficial gas hydrates of the Louisiana Continental slope, initial results of direct observations and in situ data collection: Proceedings Offshore Technology Conference, Paper OTC 10770, p. 1-12

Roberts, H.H. and P. Aharon, 1994, Hydrocarbon-derived carbonate buildups of the northern Gulf of Mexico continental slope: A review of submersible investigations: Geo-Marine Letters, v. 14, p. 135-148.

Roberts, H.H. and T. Whelan, III, 1975, Methane-derived cements in barrier and beach sands of a subtropical delta complex: Geochimica et Cosmochimica Acta, v. 39, p. 1085-1089.

Shackleton, N.J., 1987, Oxygen isotopes, ice volume and sea level: Quaternary Science Reviews, v. 6, p. 183-190.

Shosa, JD. And L.M. Cathles, 2001, Experimental investigation of capillary blockage of two phase flow in layered porous media: Proceedings GCSSEPM Foundation 21st Annual Research Conference, Petroleum systems of Deep-Water Basin, December 2-5, p. 725-740.

Suter, J.R., 1994, Deltaic coasts *in* R.W.G. Carter and C.D. Woodroffe (eds), Coastal Evolution: Late Quaternary Shoreline Morphodynamics: Cambridge University Press, p. 87-121.

Suter, J.R., and H.L. Berryhill, Jr., 1985, Late Quaternary shelf-margin deltas, northwest Gulf of Mexico: American Association of Petroleum Geologists Bulletin, v. 69, p. 77-91.

Sydow, J. and H.H. Roberts, 1994, Stratigraphic framework of a late Pleistocene shelf-edge delta, northeast Gulf of Mexico: American Association of Petroleum Geologists Bulletin, v. 78, p. 1276-1312.

Sydow, J., H.H. Roberts, A.H. Bouma, and R. Winn, Jr., 1992, Constructional subcomponents of a shelf-edge delta, northeast Gulf of Mexico: Transactions Gulf Coast Association of Geological Societies, v. 42, p. 717-726.

Thiery, R., R. Bakker, C. Monnin, 1998, Gas hydrates; relevance to world margin stability and climate change. *In:* Henriet, J.P. Mienert, J. (Eds.), Geological Society Special Publication, v. 137, p. 161-165.

Welsh, S.E., 1996, A numerical modeling study of the Gulf of Mexico under present and past environmental conditions: PhD dissertation, Department of Geology and Geophysics, Louisiana State University, 206 p.

Winker, C.D. and J.R. Booth, 2000, Sedimentary dynamics of the salt-dominated continental slope, Gulf of Mexico: Integration of observations from the seafloor, near-surface, and deep subsurface: GCSSEPM Foundation Bob F. Perkins Research Conference, p. 1059-1086

Winn, R.D., Jr., H.H. Roberts, B. Kohl, R.H. Fillon, J.A. Crux, A.H. Bouma, H.W. Spero, 1998, Upper quaternary strata of the upper continental slope, northeast Gulf of Mexico: sequence stratigraphic model for a terrigeneous shelf edge: Journal of Sedimentary Research, v. 68, p. 578-595.

Winn, R.D., Jr., H.H. Roberts, B. Kohl, R.H. Fillon, A.H. Bouma, and R.E. Constans, 1995, Latest Quaternary deposition on the outer shelf, northern gulf of Mexico: Facies and sequence stratigraphy from Main Pass Block 303 shallow core: Geological Society America Bulletin, v. 107, p. 851-866.

Figure 1. Bathymetry of the Mississippi-Alabama shelf edge clearly defines seaward protrusions two of which are related to the latest Pleistocene Lagniappe delta. As defined by cores through this delta, clinoforms are composed mostly of sand with shrimp and turbidite deposits in clinoform toes. Although slope channels do not connect to all shelf-edge deltas, many well-defined are present on the eastern Gulf's continental slope. These channels frequently merge doom-slope with channel-levee and slope from systems.

Figure 2. (a) A dip oriented 3-D seismic profile through the oxygen isotope stage 8 (~270 ka) clinoform wedge identified on Figure 1 as VK774. This profile illustrates the linkage of a shelf-edge delta to a channel-levee system downslope. (b) This high resolution seismic profile illustrates both the oxygen isotope stage 8 delta and overlying Lagniappe delta at the present shelf edge. Clinoform toes of both deltas pond sediment against a salt diaper in this profile. Note the "gas signature" particularly in the base of the Lagniappe delta. (c) This X-ray radiograph of a core illustrating thin, stacked turbidite deposits is similar to deposits in clinoform toes of shelf-edge deltas that extend downdip into the hydrate stability zone of the upper continental slope.

Figure 3. A sea level curve of the latest Quaternary eustatic cycle (Labeyrie et al., 1987 Shackleton, 1987) derived from oxygen isotope data. The "saw tooth" fall in seal level from the highstand in 120 ka BP moved fluvial sources of sediment nearer the shelf-edge, increase sediment loading of outer shelf ad slope, and decrease hydrostatic pressure plus increased bottom water temperature on the upper slope hydrate stability zone. As sea level approached the latest Pleistocene glacial maximum deltas formed ad the shelf edge and instability in the gas hydrate reservoir occurred.

Figure 4. This diagram illustrates the theoretical thickness of the gas hydrate stability zone in continental margins as determined by water depth (hydrostatic pressure), water temperature, geothermal gradient, and gas composition. At sea level lowstands, as occurred during the latest Pleistocene glacial maximum, there is a zone on the upper continental slope (shaded area) where gas hydrates are made unstable by decrease hydrostatic pressure and increase bottom water temperature. Winder these conditions gas and water released as products from hydrate decomposition cause sediment instability leading to imitation of slope failures (slumps, debris flows, submarine landslides). This figure is modified from Kvenvolden and Bernard (1983).

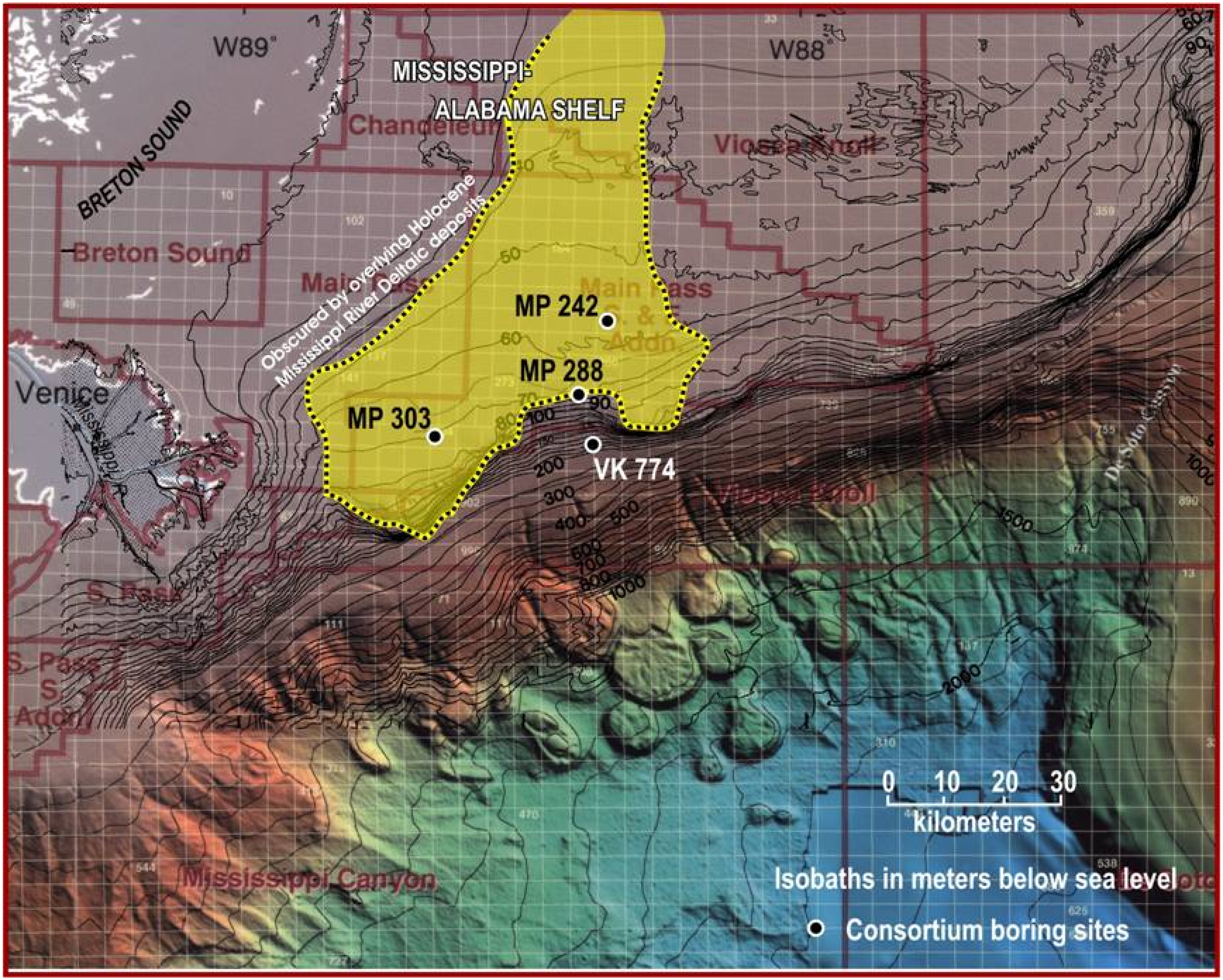
Figure 5. This NOAA AVHRR satellite image of the Gulf of Mexico shows the warm water signature of the Loop Current and eddies that dominate the surface oceanography of the Gulf. This warm surface layer Loop Current structure is about 800-1000m thick. At times of lowered sea level, these warm surface waters impacted parts of the upper slope characterized by hydrate stability during a sea level highstand.

Figure 6. This dip-oriented resolution reflection seismic profile (15 in^3 water gun) designated as CSI-8 on the location map illustrates a lowstand delta at a water depth of approximately -120m, the proposed sea level at the latest Pleistocene glacial maximum. Note the abundance of gas signatures in the lower portions of the clinoform sets and the well-

defined clinoform toes that extend downslope. It is proposed that the thin heterolithic clinoform toes function as conduits for the inpdip imagination of gas into the Lagniappe shelf-edge delta.

Figure 7. This high resolution strike-oriented seismic profile (15 in^3 water gun), designated as CSI-3 on the location map, shows Lagniappe delta deposits (left) onlapping an older wedge of deltaic sediments. Field observations indicate that truncated clinoforms from both deltas and presently leaking gas. The carbonate mounds on older lobes to the east suggest that there may be a link between gas seepage and mound formation. Carbonates with C-13 depleted isotope signatures are produced in both shallow (Roberts and Whelan, 1975) and deep (Roberts and Aharon, 1994) settings as by-products of microbial utilization of hydrocarbons. The fact that gas seepage was detected when this and associated seismic profiles were collected suggests that gas migration into these shelf-edge deltas as an on-going process. Although no samples of this material has been analyzed, it is possible that the carbonates are C-13 depleted and represent by-products of hydrocarbon seepage. Gas seeps were observed on acoustic records from this area.

Figure 8. The linear-to-arcuate patterns in this side-scan sonograph represent the expression of eroded clinoforms. The reflective patterns that demonstrate relief above the surrounding seafloor by their acoustic shadows are interpreted as carbonates that have built on resistant truncated clinoforms


W89°
W88°
MISSISSIPPI-
ALABAMA SHELF
BRETON SOUND
Chandeleur
Viosca Knoll
Breton Sound
Main Pass
Main Pass
S. & E.
Addn.
Obscured by overlying Holocene
Mississippi River Deltaic deposits
Venice
MP 242
MP 288
MP 303
VK 774
Viosca Knoll
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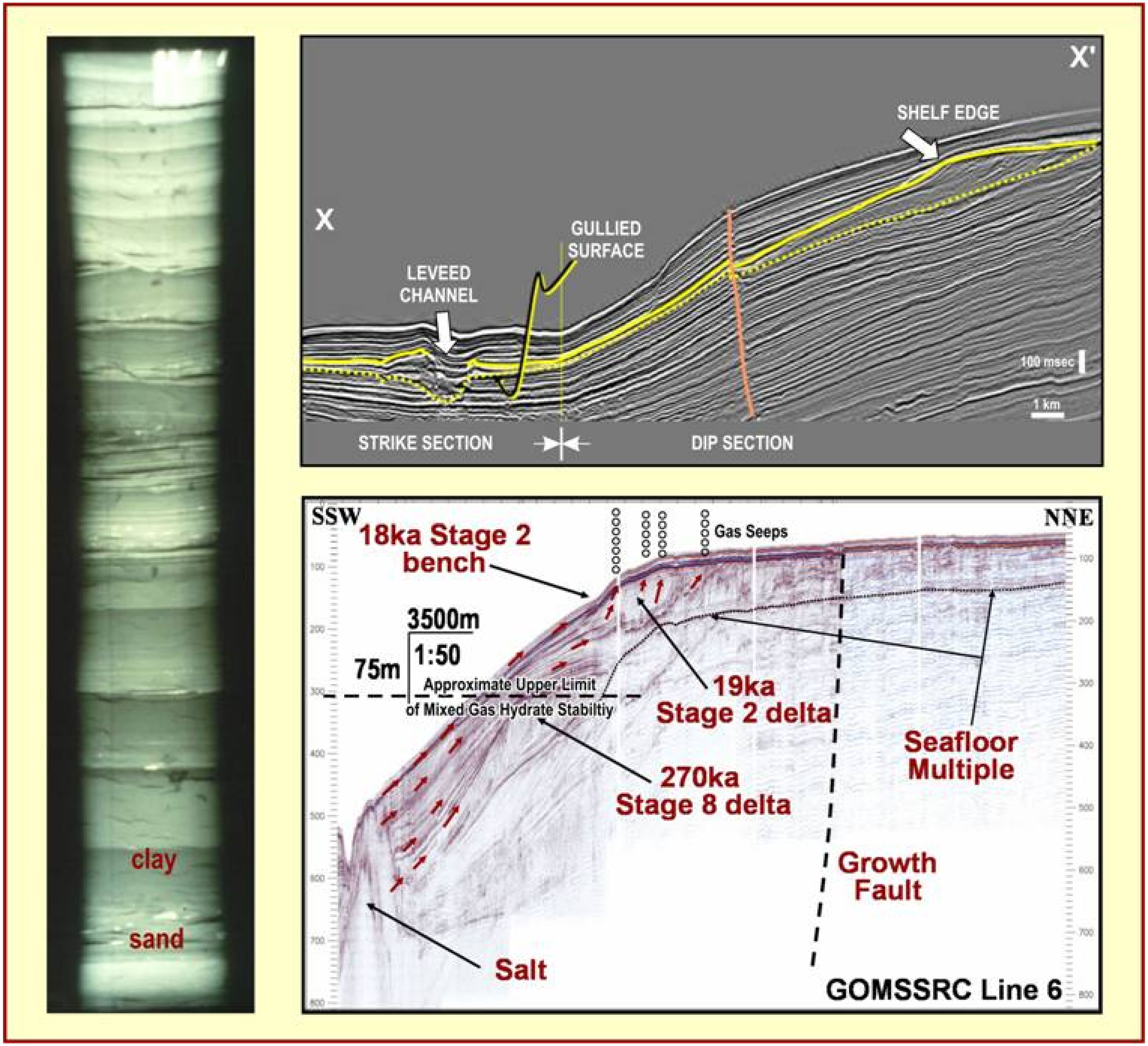
Consortium boring sites


clay
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X
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SHELF EDGE
GULLIED SURFACE
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100 msec
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STRIKE SECTION
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NNE
Gas Seeps
18ka Stage 2 bench
3500m
1:50
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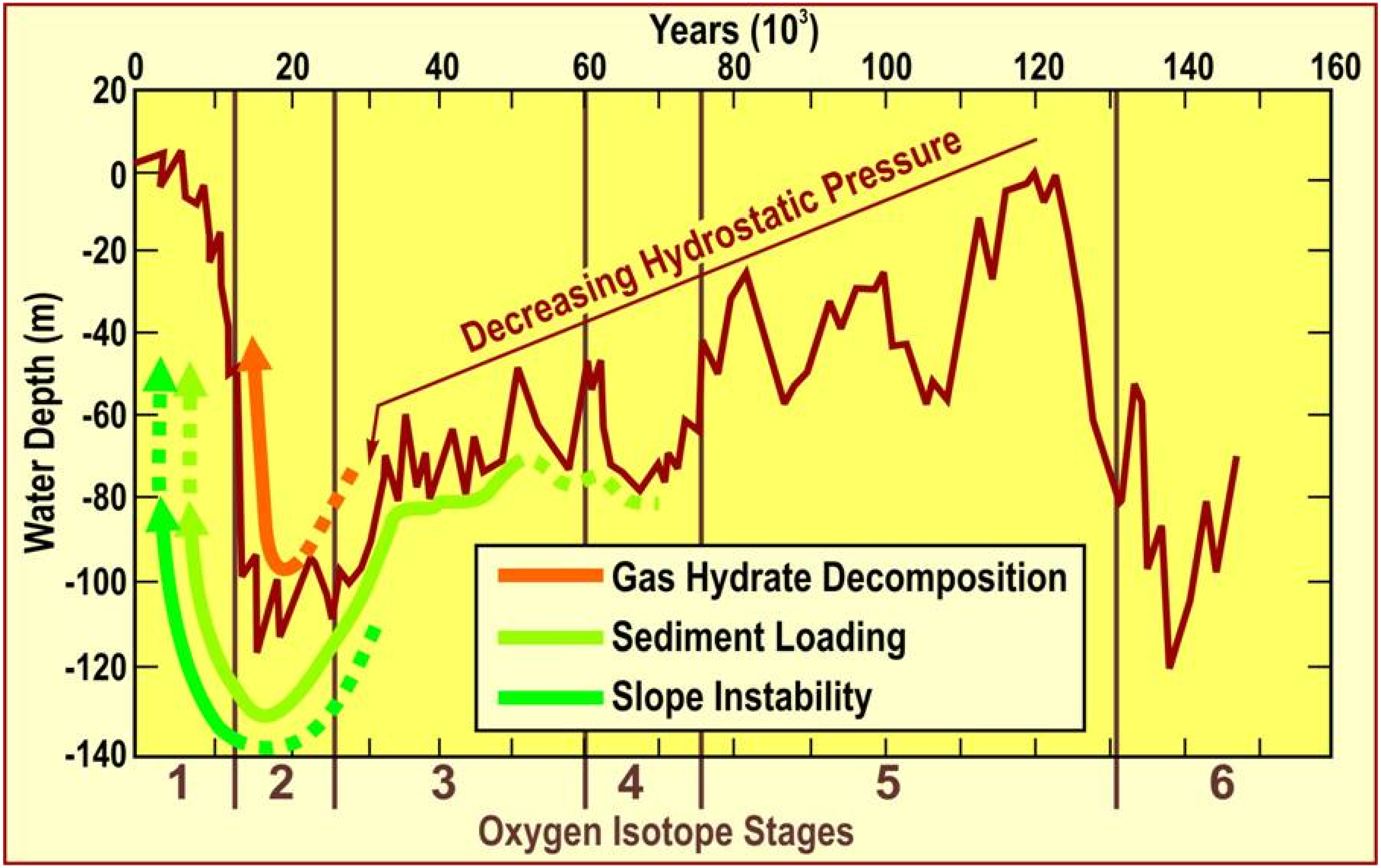
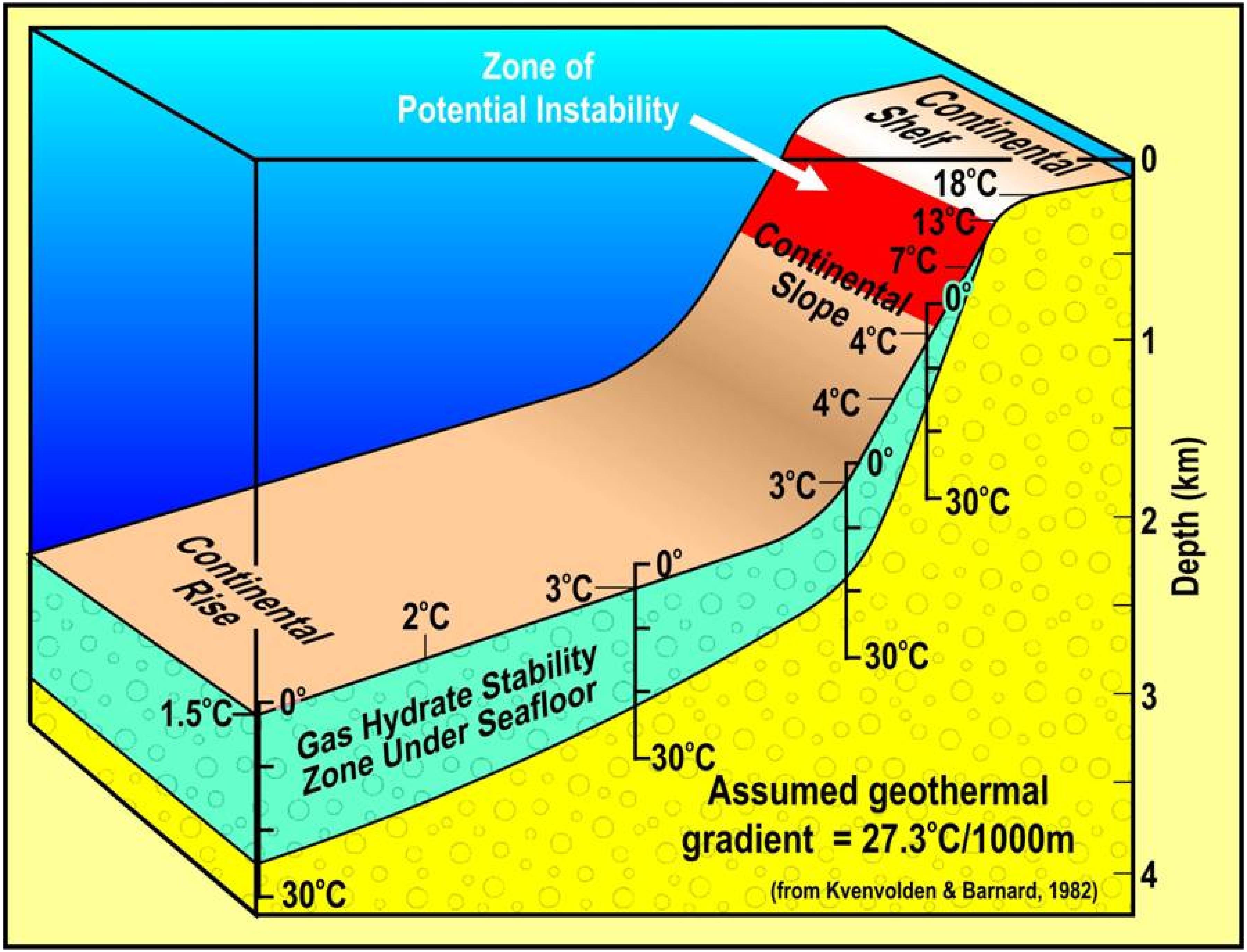
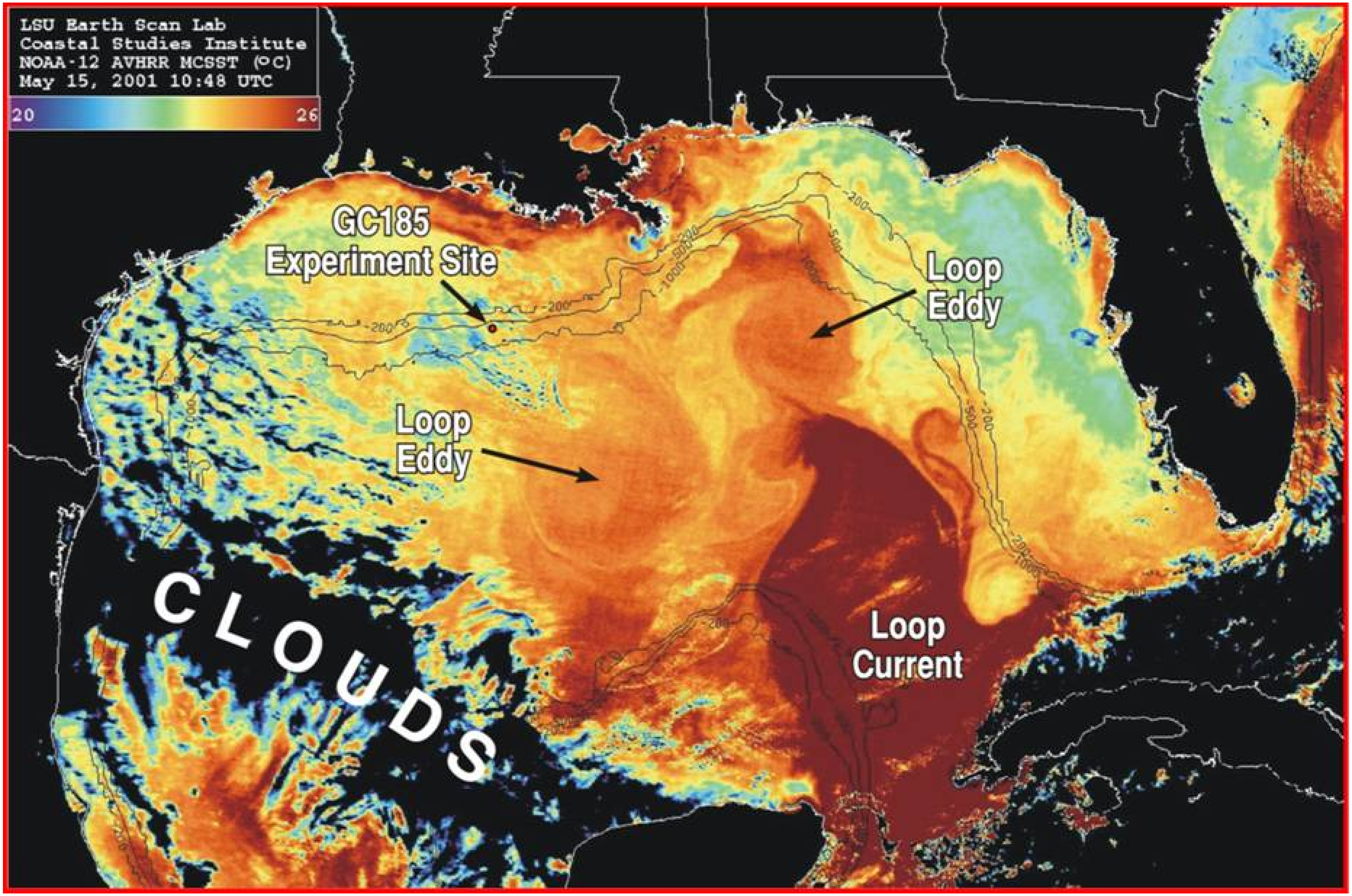
270ka Stage 8 delta
Growth Fault
Salt
GOMSSRC Line 6



Years (10^3)
0
20
40
60
80
100
120
140
160
20
0
-20
-40
-60
-80
-100
-120
-140
Water Depth (m)
Decreasing Hydrostatic Pressure
Gas Hydrate Decomposition
Sediment Loading
Slope Instability
1
2
3
4
5
6
Oxygen Isotope Stages



Zone of
Potential Instability
Continental
Shelf
0
18°C
13°C
7°C
Continental
Slope
0°
4°C
1
4°C
0°
3°C
30°C
2
Depth (km)
Continental
Rise
0°
3°C
2°C
30°C
Gas Hydrate Stability
Zone Under Seafloor
1.5°C
0°
30°C
3
Assumed geothermal
gradient = 27.3°C/1000m
4
30°C
(from Kvenvolden & Barnard, 1982)


LSU Earth Scan Lab
Coastal Studies Institute
NOAA-12 AVHRR MCSST (°C)
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Experiment Site
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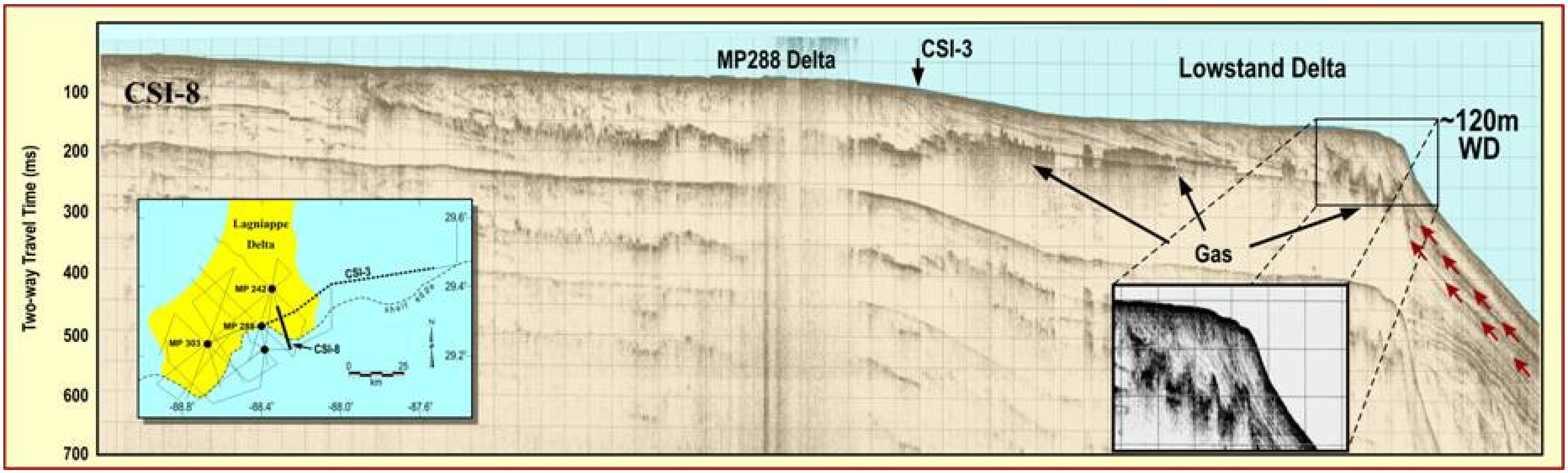
CSI-8
MP288 Delta
CSI-3
Lowstand Delta
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WD
Gas
Two-way Travel Time (ms)
100
200
300
400
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700
Lagniappe
Delta
MP 242
MP 288
MP 303
CSI-3
CSI-8
29.6°
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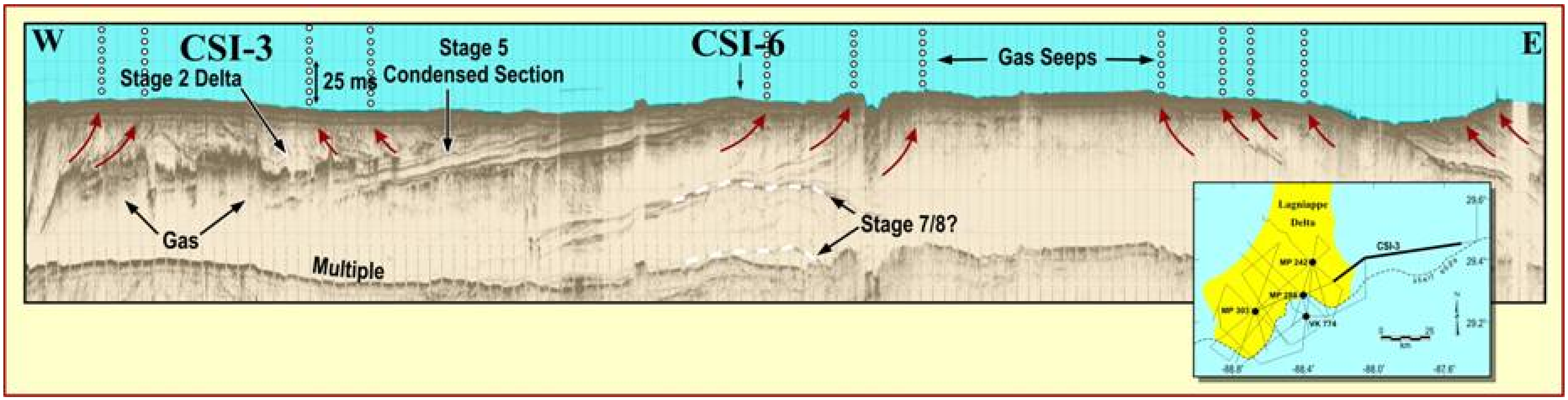
29.2°
-88.8°
-88.4°
-88.0°
-87.6°
0
25
km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Stage 2 Delta
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Stage 5
Condensed Section
CSI-6
Gas Seeps
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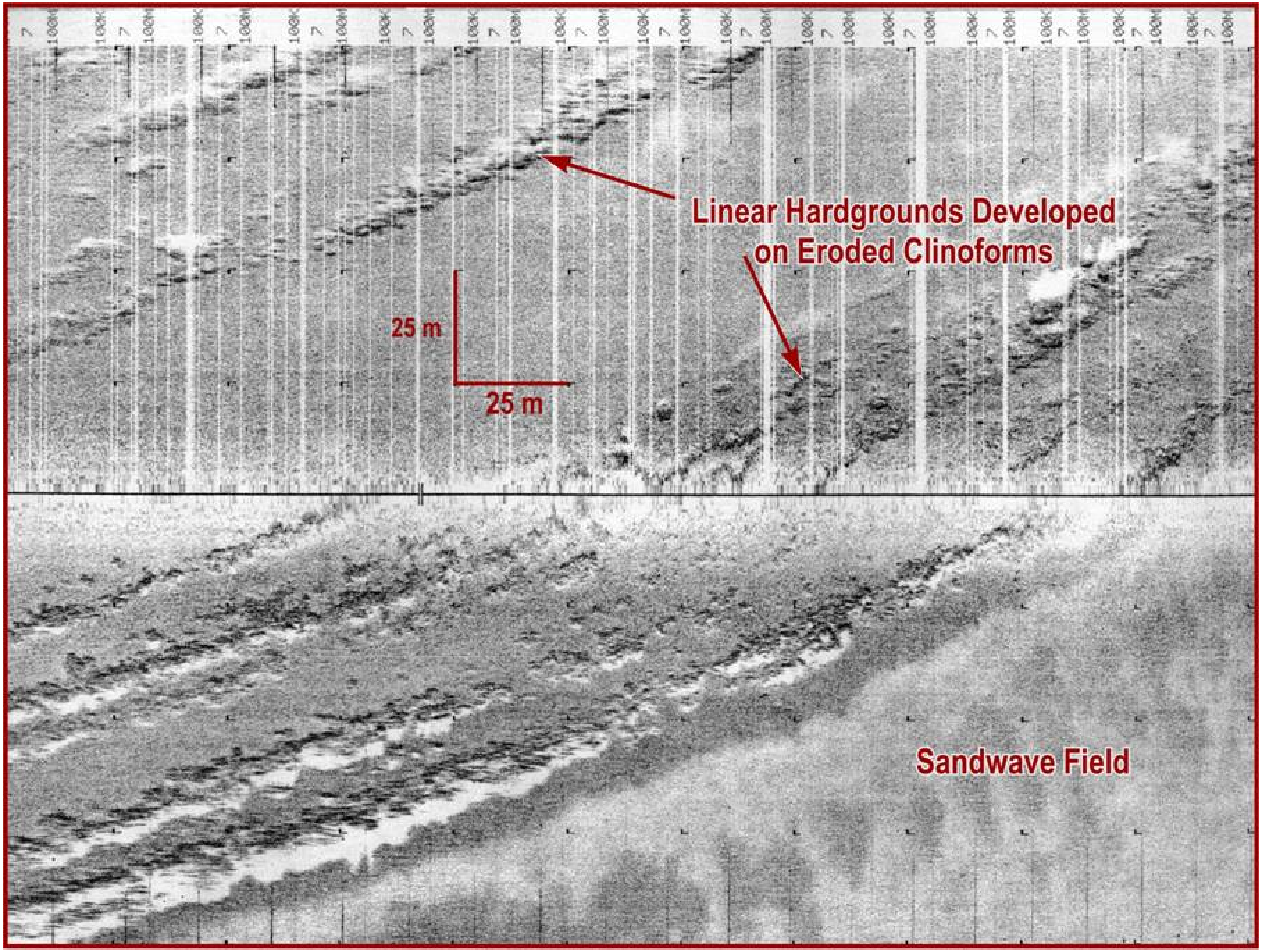
Gas
Stage 7/8?
Multiple
Lagniappe
Delta
MP 242
MP 288
VK 774
29.6°
29.4°
29.2°


Linear Hardgrounds Developed
on Eroded Clinoforms
25 m
25 m
Sandwave Field