OCCURRENCE OF GAS HYDRATES IN SEDIMENTS IN "EMOBS" FIELDS OFFSHORE WESTERN NIGER DELTA: POCK MARKS AND SEEPAGE SITES.

ABSTRACT

Increased oil and gas exploration activity in the Niger Delta region of Nigeria has led to a detailed investigation of the sea floor status. In this paper, we analyzed the high resolution Side scan sonar and subbottom profiler data in Niger Delta offshore basin to understand the shallow structures and shallow deposits for gas hydrates. Observed mounds and depressions show fluid/gas migration features such as acoustic voids, acoustic chimneys, and acoustic turbid layers. Such fluids are usually rich in low molecular weight hydrocarbons, mainly methane, with small amount of other gases, such as carbon dioxide and hydrogen sulfide. Formation and decomposition of gas hydrate potentially change the properties of marine sediment. In order to understand the evolution and morphological changes of marine cold seeps, it is important to know the occurrence and distribution of gas hydrate in shallow sediment. Gas enclathrated in hydrate also contains important information and is helpful to understand the source of the gas. There are several implications of dynamically forming and disintegrating gas hydrate pin goes on the seafloor. The two most important ones are believed to be: For engineering and anthropogenic seabed usage, i.e., seabed topography changes over time. For biology/environment, i.e., the possibility for enhanced local primary (microbial) productivity.

Keywords: gas hydrate, pockmark, sea floor, lithology, geohazards

INTRODUCTION

Generally, analyses of the occurrence and distribution of gas hydrate deposits show that the fluid venting areas are the potential sites (pockmarks) of gas hydrate accumulation. The areas of fluid venting may be controlled by the tectonic settings of the region. For example, structures formed due to salt or shale tectonics govern the occurrence of gas hydrate in the Niger Delta front. The seismic character of fluid/gas movement like acoustic voids, acoustic chimneys and acoustic turbid layers have been mapped using high resolution seismic data. Hydrocarbon seepages are of great significance to explorationists because they are often direct indicators of the existence of petroleum systems (Ibe and Chuku, 2015). These processes have previously been documented in a wide variety of geological settings using highly specialized underwater vehicles, cruise ships and remote satellite data. The relationship between seabed morphology with shallow gas venting features are well known from Mid Norway, Nile deep-sea fan, Costa Rica and Gulf of Cádiz (Hovland, 1990; Loncke, et al., 2004; Peterson, et al., 2009; Somoza et al., 2003). Therefore, we made an attempt to analyze the seabed morphology, shallow subsurface structures and shallow deposits in offshore basin using high resolution side scan sonar, sub-bottom profiler (SBP) and single beam swath bathymetry data and establish a link between these shallow features with known areas of gas hydrate accumulation and cold seeps. The deep structure obtained from multi-channel seismic data has helped in understanding the geological and tectonic control on the origin of seabed morphology and gas hydrate deposits.

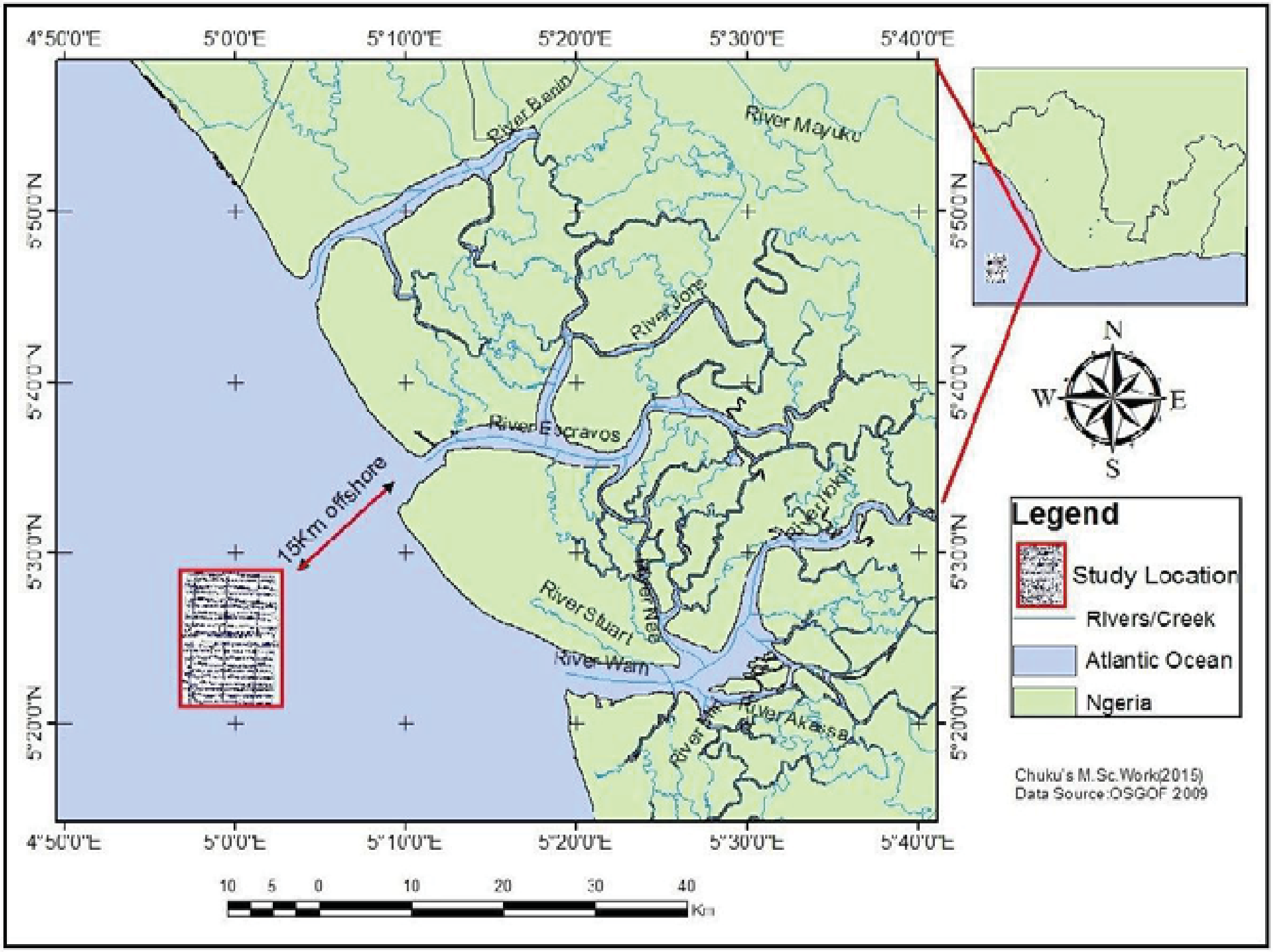


Figure 1: Location Map of the Study Location 15km offshore Western Niger Delta Nigeria (Adapted from Chuku et. al, 2015).

GEOLOGICAL SETTING OF NIGER DELTA

The Niger Delta is situated in Gulf of Guinea on the West central Africa coast and occupies the southern part of Nigeria between latitudes $4^{0}00'$N and $6^{0}00'$N and longitudes $3^{0}00'$E and $9^{0}00'$E. It is bounded in the south by the Gulf of Guinea and in the North by older (cretaceous) tectonic elements which include the Anambra Basin, Abakiliki uplift and the Afikpo syncline. To the East and West respectively, the Niger Delta is bounded by the Cameroon volcanic line and Dahomey

Basin. The study area is a pockmark field as well as gas hydrates located within the Gulf of Guinea on the continental margin offshore Nigeria. This continental margin is undergoing slow deformation by gravity tectonism that initiated in response to both, rapid seaward progradation and loading huge amount of sediment (Damuth, 1994). Distinguished this area into three subareas based on the structural styles: 1) an upper extensional 83 zone, 2) an intermediate translational zone, and 3) a lower compressional zone. The pockmark field studied in this paper is located in the translational zone which is characterized by diapirs underneath. Examples of seismic recordings of shale diapirs in this area can be found in Damuth (1994) and Cohen and McClay (1996).The Nigerian continental margin is an active fluid flux area as indicated from various seafloor features, such as pockmarks, mud volcanoes, gas hydrates and carbonate concretions (Bayon et al., 2007; Brooks et al., 2000; Graue, 2000; Hovland et al., 1997).Formation of such authigenic carbonates is typically attributed to the anaerobic methane oxidation. Pronounced bottom simulating reflectors (BSR), demonstrating the boundary between the base of the free gas underneath, were reported. Such BSRs indicate the presence of gas hydrates related to high methane flux towards shallow sediments caused by fluid migration. In addition, gas chimneys found in the subsurface were proposed to serve as pathways for fast hydrocarbon migration between reservoirs and the seafloor (Heggland, 2003).The pockmark field, comprising the pockmarks A and C studied herein, lies at water depths between 15m and 19m. Pockmark A is a slightly NE-SW elongated seafloor feature with a hummocky topography in the center. The hummocky area corresponds to high singlebeam backscatter which may indicate the occurrence of shallow gas hydrates, free gas and/or authigenic carbonates.

FORMATION OF GAS HYDRATES

(Gas hydrates are ice-like substances that form in deep-sea sediments)

Figure 2 An aggregation of methane ice worms inhabiting a white methane hydrate seen in the Gulf of Mexico, 2102. Studies suggest that these worms eat chemoautotrophic bacteria that are living off of chemicals in the hydrate. *Image courtesy of NOAA Okeanos Explorer Program.*

When gas molecules are trapped in a lattice of water molecules at temperatures above 0°C and pressures above one atmosphere, they can form a stable solid. These solids are gas hydrates. Most gas hydrates are formed from methane (CH4). Methane is the simplest hydrocarbon, and is the primary component of the natural gas that we burn for energy. If you hold a hydrate nodule in your hand and light it with a match, it will burn like a lantern wick. There is fire in this ice! Gas hydrate deposits along ocean margins are estimated to exceed known petroleum reserves by about a factor of three. These hydrate beds leak gases into the water, forming cold seeps on the ocean floor. This hydrocarbon seepage is common on continental margins around the world. Chemosynthetic communities similar to those found at hydrothermal vents form at cold seeps, using hydrocarbons or hydrogen sulfide for carbon and energy. Seep tube worms, mussels, and clams form two-meter-high bushes over kilometer-sized beds. Most seeps are also characterized by high microbial productivity. Hydrates influence ocean carbon cycling, global climate change, and coastal sediment stability. Localized meltdowns have caused massive continental slope failure, which can present a geological hazard for shelf oil and gas production. Massive hydrate dissolution events, releasing vast amounts of the greenhouse gas methane, are possible causes of some of the abrupt climate changes seen in the geologic record. Methane hydrates (or gas hydrates) are cage-like lattices of water molecules containing methane, the chief constituent of natural gas. They may represent one of the world's largest reservoirs of carbon-based fuel. However, with abundant availability of natural gas from conventional and shale resources, there is no economic incentive to develop gas hydrate resources, and no commercial-scale technologies to exploit them have been demonstrated. Gas hydrates can be found under arctic permafrost, as well as beneath the ocean floor. They can also form during drilling and production operations. So far, gas hydrates have provided more problems than solutions. The formation of gas hydrates in deepwater production can hinder operations; managing or preventing their formation in deepwater oil and gas wells and pipelines has been a challenge for many decades, and addressing the existence of gas hydrates is a major part of planning for deepwater drilling and production. However, at some point in the future, gas hydrates could be a potential source of natural gas. When brought back to the earth's surface, one cubic foot of gas hydrate releases 164 cubic feet of natural gas. According to the United States Geological Survey, the world's gas hydrates may contain more organic carbon than the world's coal, oil, and other forms of natural gas combined. Estimates of the naturally occurring gas hydrate resource vary from 10,000 trillion cubic feet to more than 100,000 trillion cubic feet of natural gas. Tapping such resources would require significant additional research and technological improvements.

Gas hydrates are of great importance for a variety of reasons. In offshore hydrocarbon drilling and production operations, gas hydrates cause major, and potentially hazardous flow assurance problems. Naturally occurring methane clathrates are of great significance in their potential for as strategic energy reserve, the possibilities for CO2 disposal by sequestration, increasing awareness of the relationship between hydrates and subsea slope stability, the potential dangers posed to deepwater drilling installations, pipelines and subsea cables, and long-term considerations with respect to hydrate stability, methane (a potent greenhouse gas) release, and global climate change.

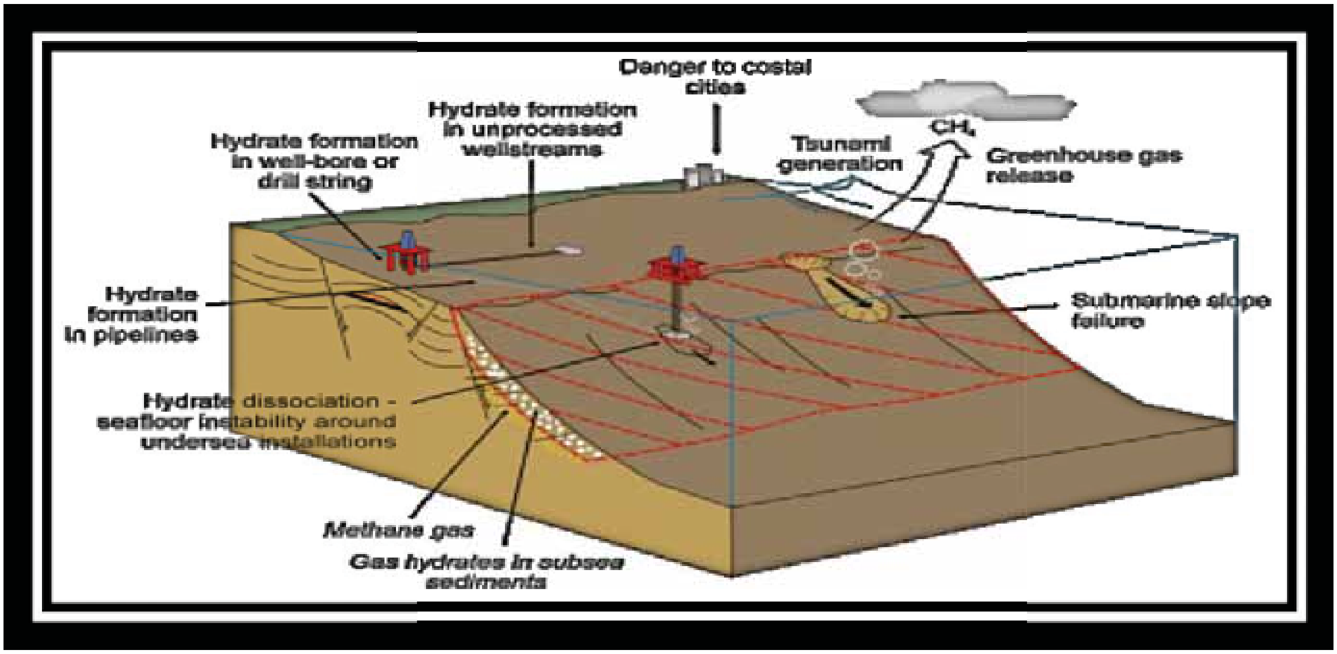


Figure-3 Major issues of gas hydrates.

HYDRATES IN OFFSHORE HYDROCARBON PRODUCTION OPERATIONS

DRILLING

In drilling, record water depths are continuously being set by oil companies in the search of hydrocarbon reserves in deep waters. Due to environmental concerns and restrictions, water based drilling fluids are often more desirable than oil based fluids, especially in offshore exploration. However, a well-recognized hazard in deep water offshore drilling, using water based fluids, is the formation of gas hydrates in the event of a gas kick. In deep-water drilling, the hydrostatic pressure of the column of drilling fluid and the relatively low seabed temperature could provide suitable thermodynamic conditions for the formation of hydrates in the event of a gas kick. This can cause serious well safety and control problems during the containment of the kick. Hydrate formation incidents during deep-water drilling are rarely reported in the literature, partly because they are not recognized.

The formation of gas hydrates in water based drilling fluids could cause problems in at least two ways:

- Gas hydrates could form in the drill string, blow-out preventer (BOP) stack, choke and kill line. This could result in potentially hazardous conditions, i.e., flow blockage, hindrance to drill string movement, loss of circulation, and even abandonment of the well.
- As gas hydrates consist of more than 85 % water, their formation could remove significant amounts of water from the drilling fluids, changing the properties of the fluid.

This could result in salt precipitation, an increase in fluid weight, or the formation of a solid plug.

- The hydrate formation condition of a kick depends on the composition of the kick gas as well as the pressure and temperature of the system. As a rule of thumb, the inhibition effect of a saturated saline solution would not be adequate for avoiding hydrate formation in water depth greater than 1000 m. Therefore, a combination of salts and chemical inhibitors, which could provide the required inhibition, could be used to avoid hydrate formation.

PRODUCTION

The ongoing development of offshore marginal oil and gas fields increases the risks of facing operational difficulties caused by the presence of gas hydrates. A typical area of concern is multiphase transfer lines from well-head to the production platform where low seabed temperatures and high operation pressures increase the risk of blockage due to gas hydrate formation ~~(Figure 2)~~. Other facilities, such as wells and process equipment, can also be prone to hydrate formation.

Different methods are currently in use for reducing hydrate problems in hydrocarbon transfer lines and process facilities. The most practical methods are:

- At fixed pressure, operating at temperatures above the hydrate formation temperature. This can be achieved by insulation or heating of the equipment.
- At fixed temperature, operating at pressures below hydrate formation pressure.
- Dehydration, i.e., reducing water concentration to an extent of avoiding hydrate formation.
- Inhibition of the hydrate formation conditions by using chemicals such as methanol and salts.
- Changing the feed composition by reducing the hydrate forming compounds or adding non hydrate forming compounds.
- Preventing, or delaying hydrate formation by adding kinetic inhibitors.
- Preventing hydrate clustering by using hydrate growth modifiers or coating of working surfaces with hydrophobic substances.
- Preventing, or delaying hydrate formation by adding kinetic inhibitors.

HYDRATES IN THE NATURAL ENVIRONMENT

Hydrates as a Potential Energy Resource

Two factors make gas hydrates attractive as a potential energy resource: (1) the huge volumes of methane that is apparently trapped as clathrate within the upper 2000 m of the Earth's surface, and (2) the wide geographical distribution of gas hydrates.

Natural gas is widely expected to be the fastest growing primary energy source in the world over the next 20 years. In the U.S. Energy Information Administration's International Energy Outlook 2002 (IEO2002) reference case, worldwide gas consumption is projected to almost double to 162 trillion cubic feet in 2020 from 84 trillion cubic feet (standard conditions) in 1999. Given the attractive features of gas hydrates, and the growing demand for natural gas, it seems reasonable to conclude that gas hydrates could serve as a future energy resource.

A number of schemes for methane hydrate exploitation have been proposed, although at present, technical and economic considerations restrict production to experimental tests only. The Japan National Oil Company (JNOC) has been a pioneer in this field, having already drilled experimental wells in the Mackenzie Delta of Northern Canad with ambitious plans for further test wells in sediments of offshore Japan.One interesting branch of research in this area is the possibility of CO2 sequestration. CO2 hydrate is thermodynamically more stable than methane hydrate, so the possibility exists for sequestration of CO2 into existing seafloor clathrates, whereby yielding methane. This process is particularly attractive, as it would act as both a source and a sink with respect to greenhouse gas emissions.

HYDRATES AS A GEOHAZARD

The aspect of gas hydrates which has the biggest implications for human welfare at present is their potential as a geohazard. Of particular concern is the danger posed to deepwater drilling and production operations, and the large body of evidence which now exists linking gas hydrates with seafloor stability. With conventional oil and gas exploration extending into progressively deeper waters, the potential hazard gas hydrates pose to operations is gaining increasing recognition. Hazards can be considered as arising from two possible events: (1) the release of over-pressured gas (or fluids) trapped below the zone of hydrate stability, or (2) destabilization of in-situ hydrates.The presence of BSRs has previously been a cause of concern, as they could be considered evidence for the existence of free gas (possibly at high-pressure) beneath. More recent analysis suggests however, that as long as excess water is present, there should not be a build-up of gas pressure beneath. This is because, at the base of hydrate stability, the system approximates to 3-phase equilibrium, where pressure is fixed (generally at hydrostatic), and temperature occupies the available degree of freedom. This means that any excess gas will be converted to hydrate, returning the system to its equilibrium pressure (assuming there is no major barrier to the mass transfer of salt). This case is likely to predominate in many hydrate-bearing sediments, although gas seeps and mud volcanoes, common to thermogenic hydrate areas (e.g. Gulf of Mexico, Caspian Sea), could be considered evidence for excess gas and pore-fluid pressures at shallow depths.In the absence of gas traps, hydrates still pose a hazard due to their potential for destabilization. This danger is particularly apparent in the case of conventional oil and gas exploration, for which drilling methods contrast quite markedly to the shallow piston-coring approach used by ODP in hydrate areas.

Conventional rotary drilling operations could cause rapid pressure, temperature or chemical changes in the surrounding sediment. An increase in temperature could be caused by a hot drill bit, warm drilling fluids, or later as high-temperature reservoir fluids rise through the well, while the addition of hydrate inhibitors to drilling muds (to prevent hydrate formation in the well-bore or drill string in the event of a gas-kick) could change sediment pore-fluid chemistry. Some, or all of these changes, could result in localized dissociation of gas hydrates in sediments surrounding wells. A similar case would apply to seafloor pipelines, where the transportation of hot fluids could cause dissociation of hydrates in proximal sediments. In a worst-case scenario, clathrate dissociation could lead to catastrophic gas release, and/or destabilization of the seafloor. The hazards associated with drilling in gas hydrate areas are exemplified by cases from the Alaskan Arctic, where subsurface permafrost hydrate destabilization has resulted in gas kicks, blowouts, and even fires.

HYDRATES AND SEAFLOOR STABILITY

A significant part of the gas hydrate geohazard problem is related to how they alter the physical properties of sediment. If no hydrate is present, fluids and gas are generally free to migrate within the pore space of sediments. However, the growth of hydrates converts what was a previously a liquid phase into a solid, reducing permeability, and restricting the normal processes of sediment consolidation, fluid expulsion and cementation. These processes can be largely stalled until the BHSZ is reached, where hydrate dissociation will occur.

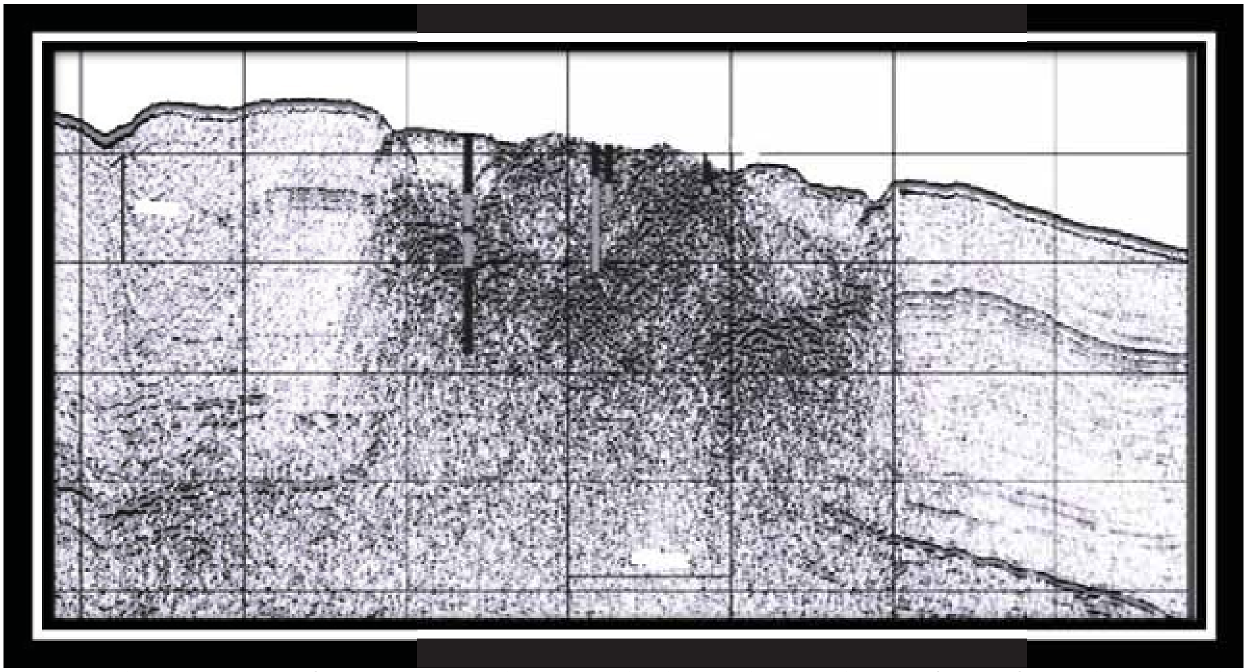
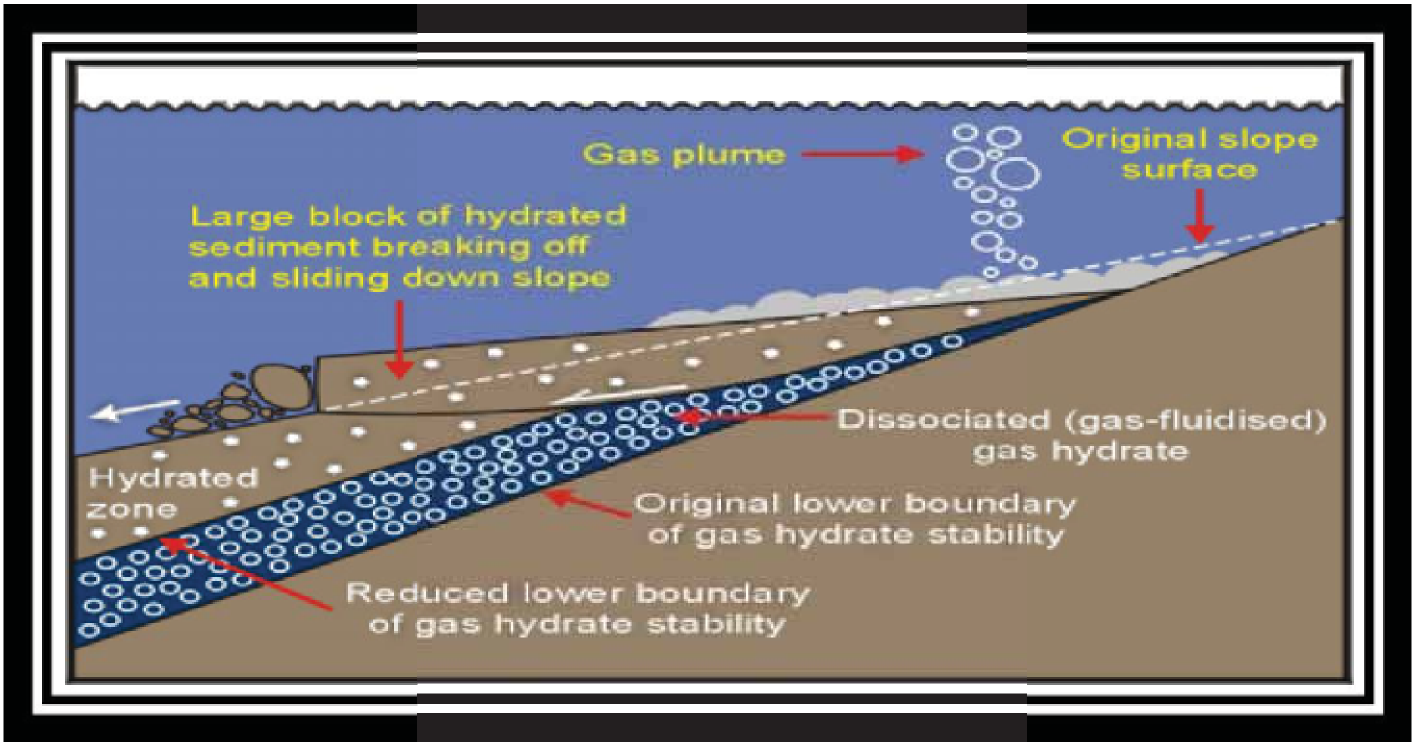


Figure 4 showing a significant contrast between high amplitude chaotic facies from the central part of the pockmark and the low-amplitude sub parallel reflectors of the surrounding sediments.

Dissociation of hydrates can arise through an increase in temperature due to increasing burial depth (assuming continued sedimentation) or an increase in sea bottom-water temperatures, and/or a decrease in pressure (e.g., lowering of sea level). Upon dissociation, what was once solid hydrate will become liquid water and gas. This could lead to increased pore-fluid pressures in under-consolidated sediments, with a reduced cohesive strength compared to overlying hydrate-bearing sediments, forming a zone of weakness. This zone of weakness could act as a site of failure in the event of increased gravitational loading or seismic activity. The link between seafloor failure and gas hydrate destabilization is a well established phenomenon, particularly in relation to previous glacial-interglacial eustatic sea-level changes. Slope failure can be considered to pose a significant hazard to underwater installations, pipelines and cables, and, in extreme cases, to coastal populations through the generation of tsunamis.



~~Figure 5~~ Potential scenario whereby dissociation of gas hydrates may give rise to subsea slope failure and massive methane gas release

HYDRATES AND GLOBAL CLIMATE CHANGE

Methane is a particularly strong greenhouse gas, being ten times more potent than carbon dioxide. Increasing evidence points to the periodic massive release of methane into the atmosphere over geological timescales. However, whether such enormous releases of methane are a cause or an effect with respect to global climate changes remains the subject of much debate. Global warming may cause hydrate destabilsation and gas release through a rise in ocean bottom water temperatures. Methane release in turn would be expected to accelerate warming, causing further dissociation, potentially resulting in runaway global warming. However, conversely, sea level rise during warm periods may act to stabilize hydrates by increasing hydrostatic pressure, acting as a check on warming.

A further possibility is that hydrate dissociation may act as a check on glaciations, whereby reduced sea levels (due to the growth of ice sheets) may cause seafloor hydrate dissociation, releasing methane and warming the climate. The strong link between naturally occurring gas hydrates and the Earth's climate is an increasingly recognized phenomenon. However, there is still little understanding concerning the exact role gas hydrates play in global climate change.

Gas hydrates (or gas clathrates) are non-stoichiometric crystalline solids comprised of hydrocarbon gases trapped within the cavities of a rigid "cage-like" lattice of water molecules. These compounds contain clusters (two or more) of gas-trapping polyhedra formed by pentagonally and hexagonally arranged hydrogen-bonded water molecules. Van der Waals interactions between the trapped (enclathrated) "guest" molecule and the surrounding water cage walls stabilize and support the individual polyhedra forming the hydrate lattice and restrict the translational motion of the guest molecule.

Hydrate structures are classified into three categories based on the geometries of their constituent water cages: cubic structures I and II and hexagonal structure H. Each crystalline structure contains geometrically distinct water cages with different size cavities which typically accommodate only one guest molecule ranging in diameter from 0.40 - 0.90 nm. [2] Structure I (sI) hydrates are the most commonly encountered naturally occurring hydrate structure which encases small diameter molecules (0.40 - 0.55 nm) such as methane or ethane gas. [2] Structures II (sII) and H (sH) hydrates accomodate larger guest molecules, typically propane or iso-butane for sII or combinations of methane gas and nexohexane or cycloheptane, but are less prevalent in nature. For sI hydrates, the unit cell consists of 46 water molecules arranged into two small dodecahedral cages (each with twelve pentagonal faces) and six large tetradecahedral cages (each with two hexagonal and twelve pentagonal faces) Assuming full occupancy, the ideal molar guest to water ratio for an sI hydrate is 1:5.75

Gas hydrates form in high pressure, low temperature environments where sufficient gas and water are present. The hydrate formation requirements restrict the occurrence of natural gas hydrates to two types of geologic locations: i) under permafrost in the polar continental shelves and ii) in sediment beneath the ocean floor The blue sections in the generic curves illustrate regions in permafrost and oceanic sediment where the pressure and temperature conditions and the concentration of methane gas are within the hydrate formation and stability zone. These curves are based on pressure-temperature phase equilibrium data and correspond with reflection seismic data collected in these environments. While several different models have been developed to describe the mechanisms involved in gas hydrate formation, there is a general consensus that the origin of the methane concentrated in naturally occurring hydrates is either microbial (generated by anaerobic decomposition of organic matter) or thermogenic (generated by thermal decomposition of organic matter).

Reflection seismology and recovered core samples are primarily used to estimate methane hydrate reserves. While core samples provide direct evidence for hydrates, they are often difficult to obtain from regions with hydrate favorable conditions. Conversely, reflection seismology is routinely used as an indirect method to detect hydrate deposits in the Earth's subsurface. This exploration technique monitors changes in the velocities of reflected seismic waves to indicate transitions between materials with different densities. The locations of methane hydrate deposits are inferred by identifying bottom simulating reflectors (BSRs) on the seismic profiles. BSRs are interpreted as the boundary between hydrate and free gas regions in the subsurface. In general, estimates based strictly on BSRs are considered speculative since hydrate bearing sediment has been extracted from regions without BSRs and vice versa. Therefore, estimates of the global accumulations of methane hydrates vary over three orders of magnitude (0.15×10^{15} - 3.05×10^{18} m^3 of methane at STP). However, even conservative estimates indicate that a significant amount of methane gas is concentrated in the shallow geosphere.

Despite the relative magnitude and global pervasiveness of gas hydrate deposits, the existence of naturally occurring gas hydrates was first recognized in 1965 when a Soviet oil crew located a reservoir of methane hydrates while drilling in Siberia. [11] Prior to this discovery, gas hydrates were only known to occur in the laboratory and within the thermodynamically favorable conditions found in oil pipelines.

Since this discovery, gas hydrates have attracted interest as a potential energy resource.

STRATIGRAPHIC-TYPE SEDIMENTARY HYDRATE DEPOSITS

The most common hydrate deposits on Earth are in the ocean, and are the product of largely one-dimensional processes of organic carbon burial, bacterial methanogenesis, and methane transport in slow fluid flow. Following the terminology of Milkov and Sassen (2002), we will refer to these as stratigraphic-type hydrate deposits.

In the steady state, the maximum concentration of hydrate is found at the base of the stability zone, with bubbles found below (Davie and Buffett, 2001). Typical concentrations of hydrate are a few percent of pore volume, and the amount of bubbles below the stability zone is also a few percent by volume. The layer of bubbles is clearly apparent in seismic sections of the subsurface sediment. Temperature contours within the sediment column tend to parallel the sea floor, and so the layer of bubbles tends to parallel the sea floor as well.Stability zone is referred to as a “bottom simulating reflector” or BSR. Because it is remotely detectable, the distribution of the BSR is one of the best indications of the distribution of hydrates in sediments. Most of the hydrate deposits on Earth correspond to the stratigraphic type, and hence the estimates of the global inventory of hydrates are based on the physics or on the observed distribution of these types of deposits. Estimates range from 500 to 10 000 Gton C as methane in hydrate globally. The estimates can be compared according to two metrics. One is the area of the sea floor where hydrates can be found, and the other is the inventory of methane, as hydrate and in some tabulation as bubbles, per square meter. Milkov (2004) does a detailed and very thorough comparison of these characteristics of estimates, leaving no need for more than a summary of his results here.

HYDRATES AS FOSSIL FUEL

Another pathway by which hydrate carbon might reach the atmosphere to affect climate is if it is combusted as a fossil fuel. Estimates of the total inventory of methane in hydrate deposits globally are very high, but probably only a small fraction of the hydrate reservoir would be extractable (Milkov and Sassen, 2002). The largest methane reservoir, the stratigraphic disseminated deposit, is the least attractive economically. The concentration of methane is generally too low for economical extraction using current technology. The sediments of the Blake Ridge are impermeable (Kvenvolden, 1999), making extraction even more unlikely, while sediments in the Nankai Trough are more permeable and hence easier to extract (Milkov and Sassen, 2002), which the Japanese intend to do (Kerr, 2004). The other class of oceanic deposits is the structurally-focused deposits, such as found in the Gulf of Mexico (Milkov and Sassen, 2001) and mud volcanoes (Milkov, 2000). Milkov and Sassen (2001) estimate that the Gulf of Mexico contains 40 times as much hydrate methane as conventional subsurface reservoir methane in that area.

The most likely near-term targets for methane hydrate extraction are deposits associated with permafrost soils on land and in the shallow ocean.

Accumulation of marine sediments in the basin probably commenced in the Albian time, after the opening of the south Atlantic ocean between the African and South American continents. Development of proto- Niger Delta, however, started only in the later Paleocene/Eocene, when sediments began to build out beyond troughs between basement horst blocks at the northern flank of the present Delta area. Since then, the delta plain has prograded southwards onto oceanic crust, gradually assuming a convex-to-the-sea-morphology (Evamy et al, 1978).

The development of the delta has been dependent on the balance between the rate of sedimentation and the rate of subsidence (Doust, Omatsola, 1990). This balance and the resulting sedimentary patterns were controlled by the structural configuration and tectonics of the basement (Evamy et al, 1978).

THE GEOLOGY OF GAS HYDRATE

The majority of the hydrate deposits on Earth are composed of biogenic methane, as indicated by its isotopic composition and the lack of other short hydrocarbons such as ethane. Most of the organic matter raining to the sea floor decomposes in the top few centimeters of the sediment, called the zone of early diagenesis. However, the production of methane from this decaying organic matter is usually inhibited by the presence of dissolved sulfate, providing a more energetically favorable respiration pathway. Sulfate is removed from pore waters deeper in the sediment by reaction with methane (anaerobic oxidation of methane, AOM, described above). This reaction prevents sulfate and methane from coexisting at high concentrations in sediment pore waters. Typically both species diffuse toward their mutual annihilation at a well-defined methane/sulfate boundary (Borowski et al., 1996, 1999; D'Hondt et al., 2004). After the depletion of sulfate, methane can be produced from solid organic carbon or by reaction of dissolved organic carbon, notably acetate, carried into the methanogenesis zone by diffusion or pore water advection. Wellsbury et al. (1997) found that heating sediment in the lab, up to 60_C, stimulates the bacterial production of acetate. At Blake Ridge, the concentration of acetate reaches very high concentrations, supplying 10% of the reduced carbon necessary for methane production (Egeberg and Barth, 1998). Bacterial abundances and metabolic rates of methanogenesis, acetate formation, and AOM are extremely high at the base of the hydrate and gas zone, rivaling metabolic rates at the sediment surface (Parkes et al., 2000). Bacterial activity is detected within the hydrate zone as well (Orcutt et al., 2004).

MATERIALS

Side scan sonar, subbottom profiler and echo sounder track lines (24) and sea bed samples were collected in the study area in cruises.

Approximately 27 linear kilometers of side scan sonar and echo sunder data were surveyed using Geo acoustics SSS 941 Tow fish and EA 400 single beam hydrographic echo sounder.

The accurate positioning of the side-scan sonar, subbottom profiler and echo sounder track lines was accomplished by means of a kongsberg sea path 330 receiver(DGPS).The backscatter of the surface sediments (side- scan sonar), coupled with sea bed sample has enabled the distinction of the sea floor pockmarks, gas hydrates and depressions. Water depths measured form echo sounders were used to determine the bathymetric classification and location of the study area within the inner shelf environment of the Niger Delta. Bed forms captured from the sea bed scan were matched with the topographical features to deduce the processes shaping the sea floor environment of the study area. the hypotenuse.

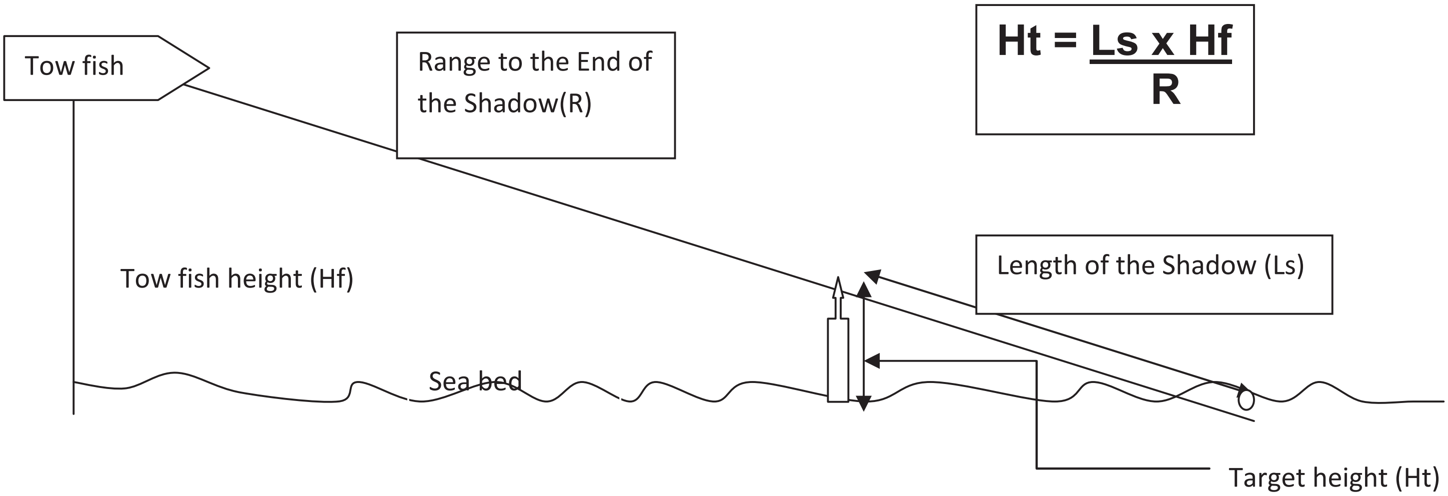


Figure 6: Target height measurements above sea bed.

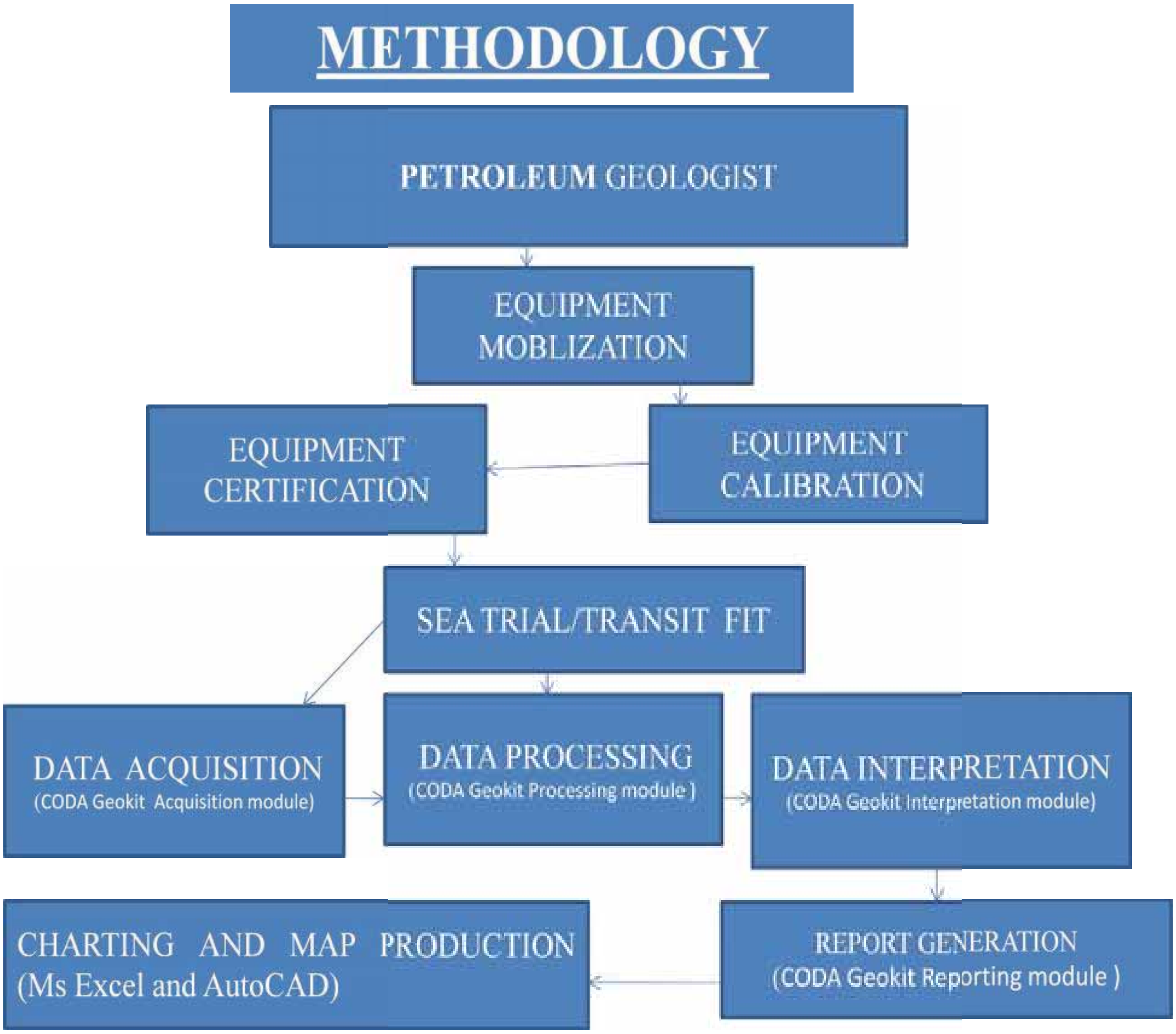


Figure 7: Work flow chart

RESULTS

These consist basically of two sets of data: sub bottom data and side scan data with respect to lithology, pockmarks, sea floor topography, and subsurface stratigraphy and environment of deposition.

Water Depth:

The water depth measured over the study area ranges between 15.7 to 18.3m. The shallowest water depth (15.7m) occurred in south western portion. This bathymetric range indicates that the study area is located within the middle to upper shore face setting of the inner shelf.

Lithology

The side-scan imagery revealed low intensity back scatter dominates the entire study area. This is interpreted as clay and silt with pockets of sand.

Pockmarks

Fluid escape features such as pockmarks which are often associated with gas hydrate and biogenic gas bearing sediments in continental margin settings were observed in the study area. Pockmarks are seabed culminations of fluid/gas escape chimneys which appear as cone-shaped circular or elliptical depressions.

SUB BOTTOM PROFILE

The seismic record of the survey area suggests the presence of the lithified sediments at approximately 20.0m to 25.0m below the sea bed. The prominent seismic stratigraphic interface that separates the lithified sediments from the overlying sea bed sediments was found to shoal towards north east of the survey corridor.

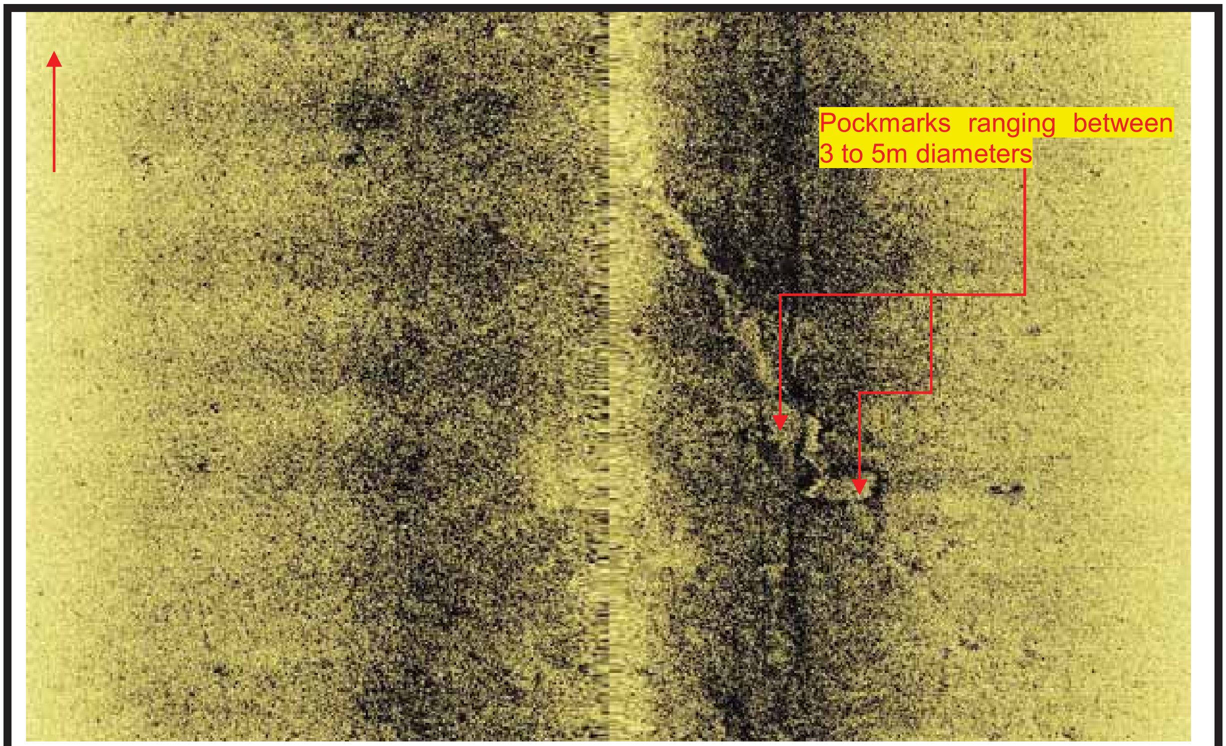


Figure 8 SSS Data extract showing Pockmarks associated with Scar Feature 153m Northwest.

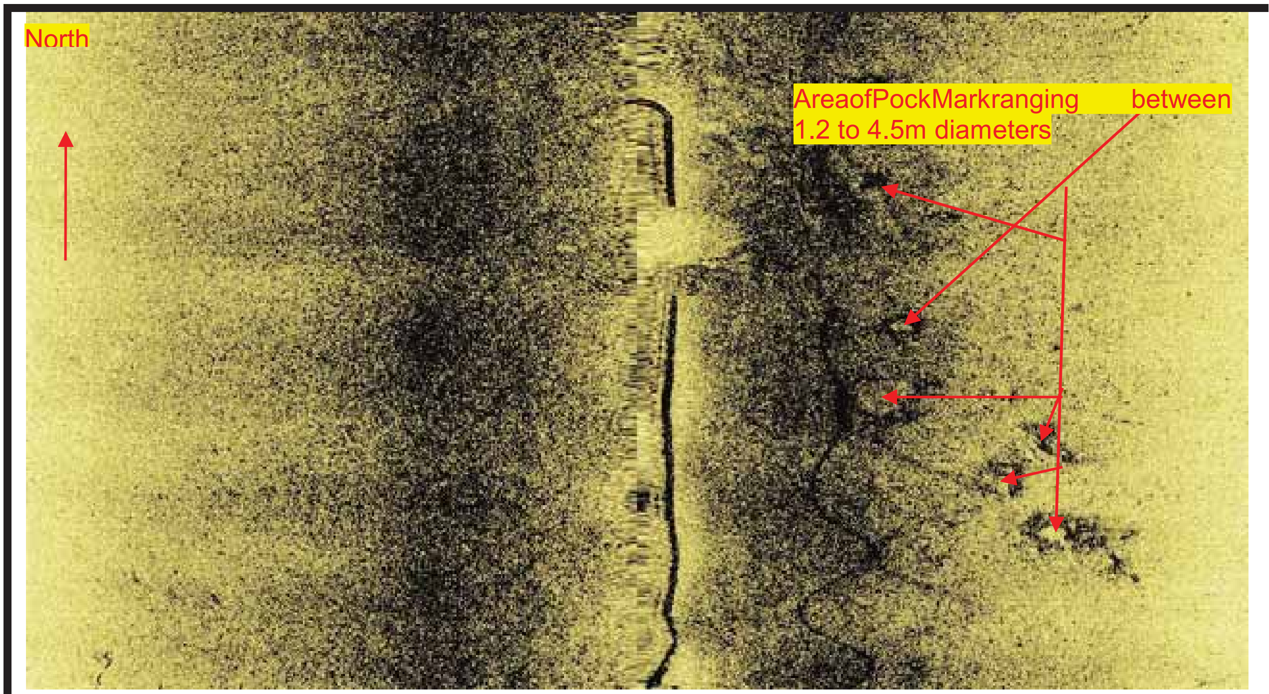


Figure9 SSS Data extract showing Area of Pockmarks within the vicinity.

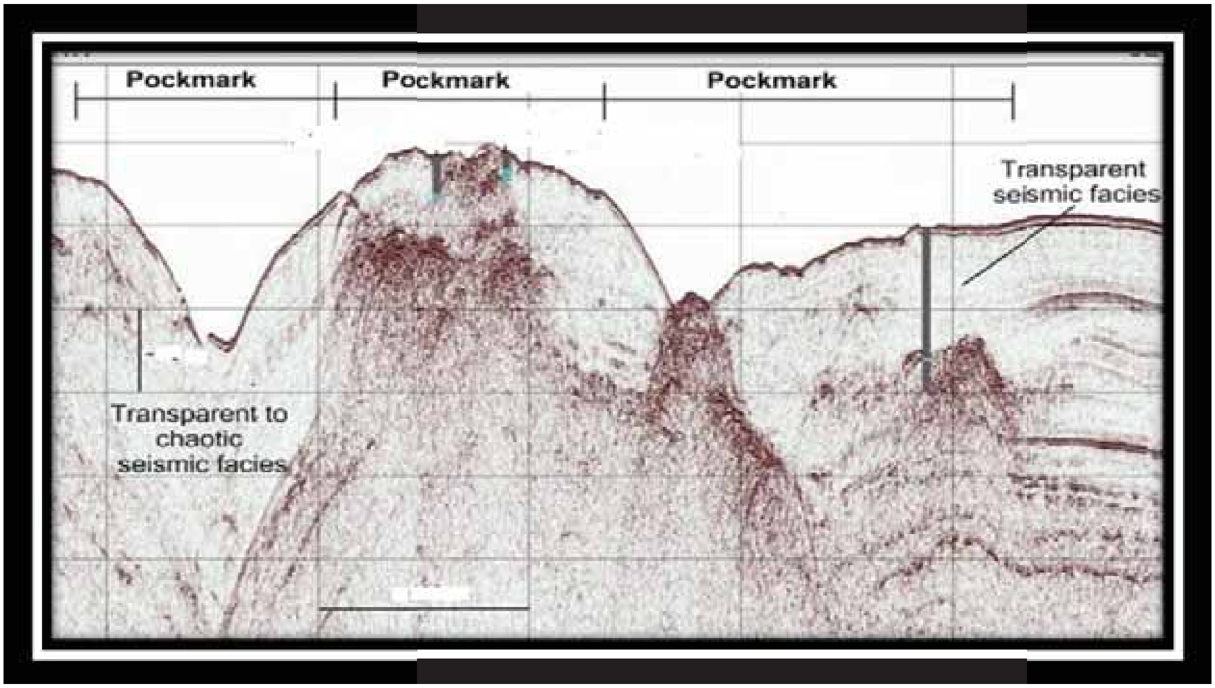


Figure 10. Pockmarks characterized by a reflection free transparent zone to very low amplitude chaotic facies and shallow heterogeneous high amplitude chaotic facies

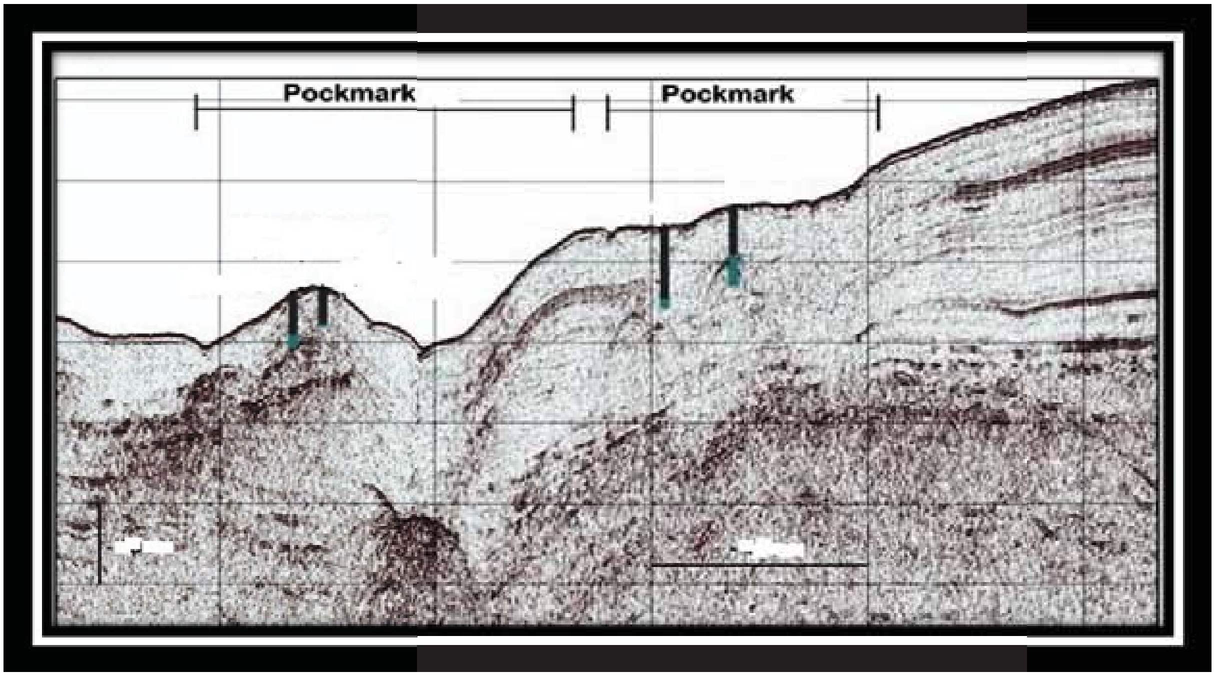
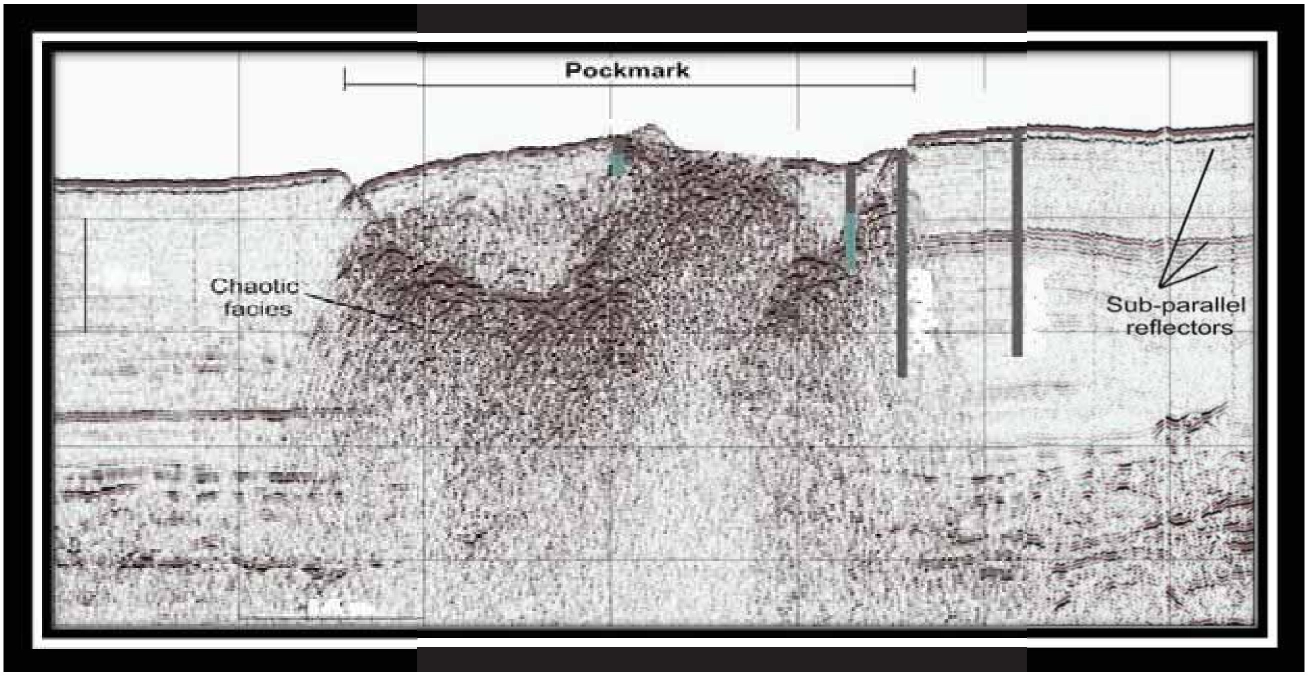
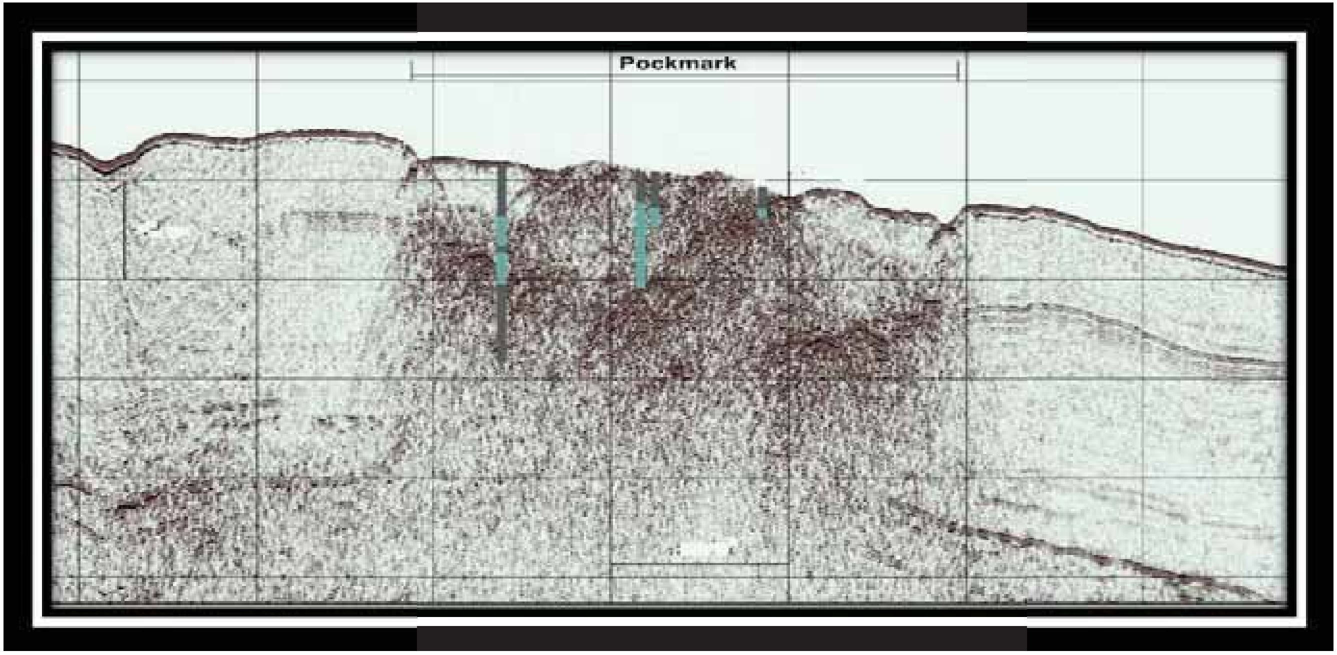


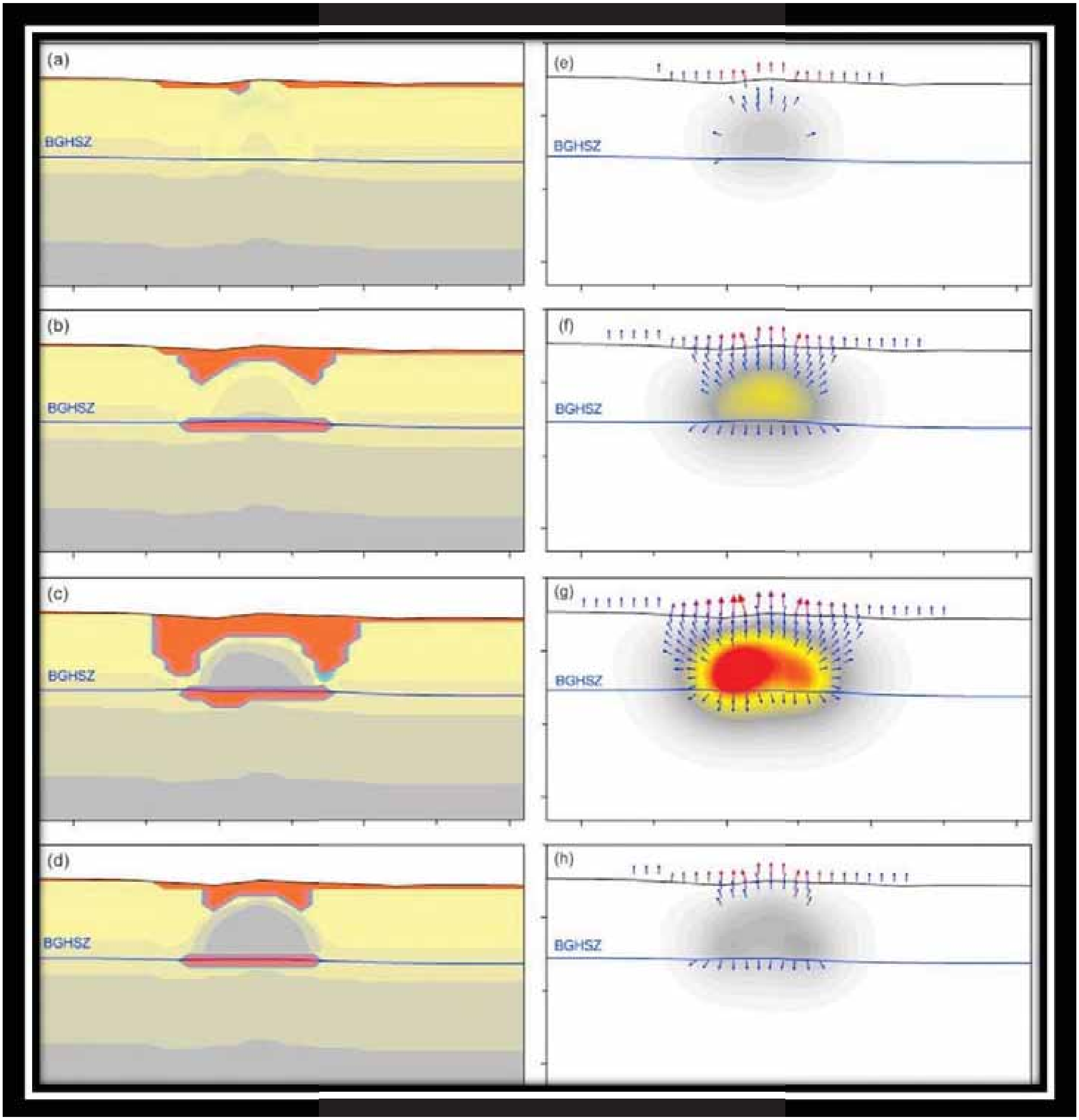
Figure 11 Pockmark is characterized by a reflection-free transparent zone to very low amplitude chaotic facies are projected onto the profile. For shaded areas correspond to hemipelagic sediments, while the blue areas correspond to suspected gas hydrates.



~~Figure 12 p~~ockmark showing a significant contrast between high amplitude chaotic facies from the central part of the pockmark and the low amplitude subparallel reflectors of the surrounding sediments and are projected onto the profile locations, shaded areas correspond to hemipelagic sediments, while the blue areas correspond to suspected gas hydrates.



~~Figure 13~~. Pockmark A showing once again a significant contrast between high-amplitude chaotic facies from the central part of the pockmark and the much more continuous seismic facies of the surrounding sediment are projected onto the profile. Shaded areas correspond to hemipelagic sediments, while the blue areas correspond to suspected gas hydrates.



~~Figure 14~~. Iso diffusivity and iso-excess pore pressure contours at calculation step of 4000 years for four different case studies: (a and e) case 1 with an initial hydrate fraction lower than the reference

One presented with a hydraulic diffusivity of the hydrate phase higher than the one used with a heterogeneous initial hydrate fraction distribution, and value equal to 20 instead of the b value of 50 used in the reference calculation

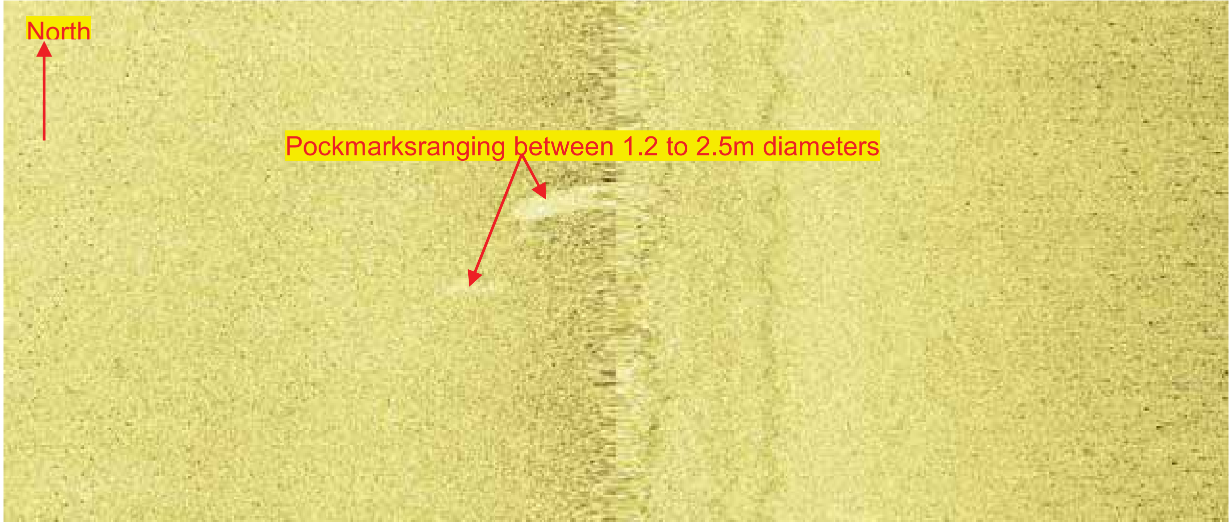


Figure15 SSS Data extract showing Pockmarks on seafloor of study area.

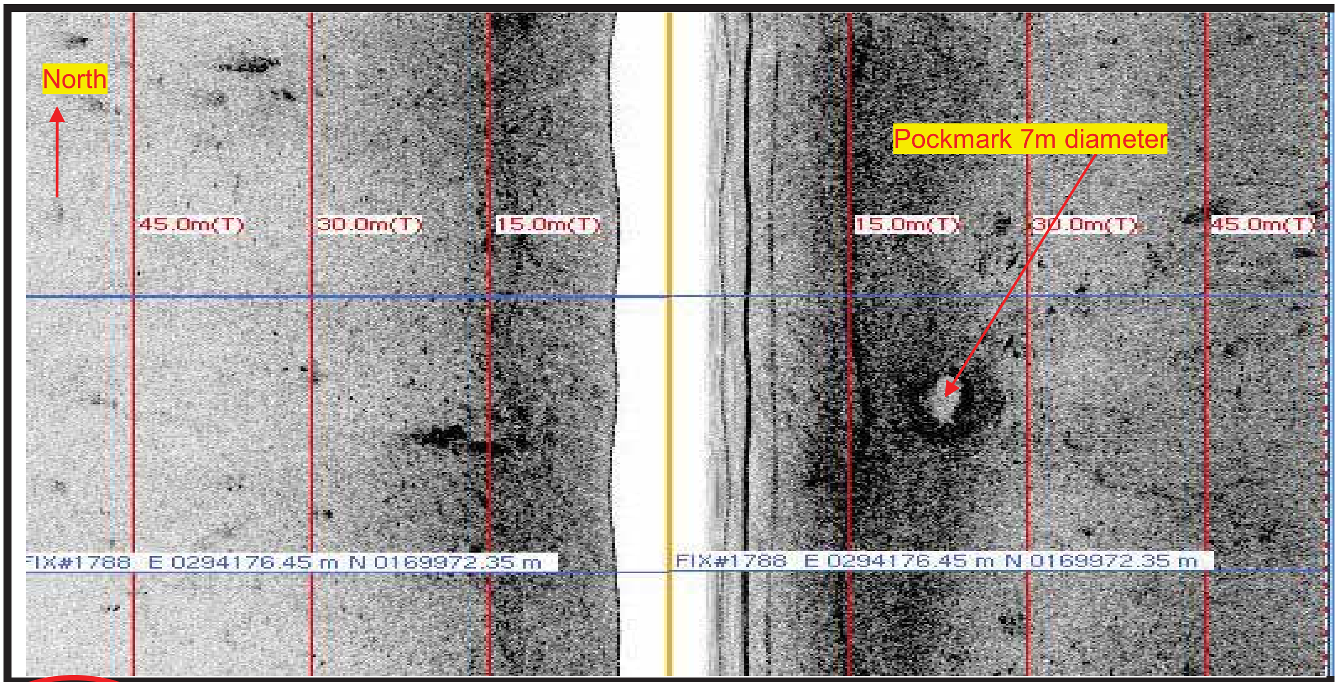


Figure 16 SSS Data extract showing Pockmarks on seafloor of study area.

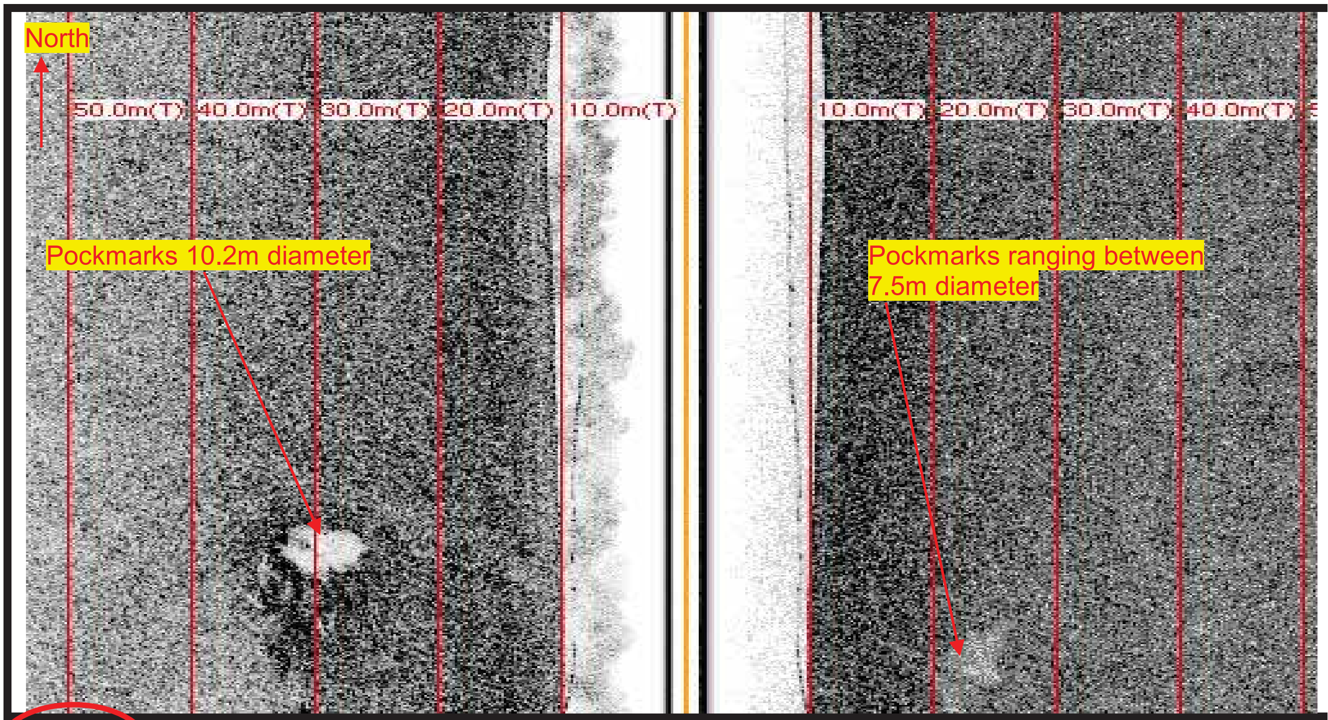


Figure 17 SSS Data extract showing Pockmarks on seafloor of study area …….

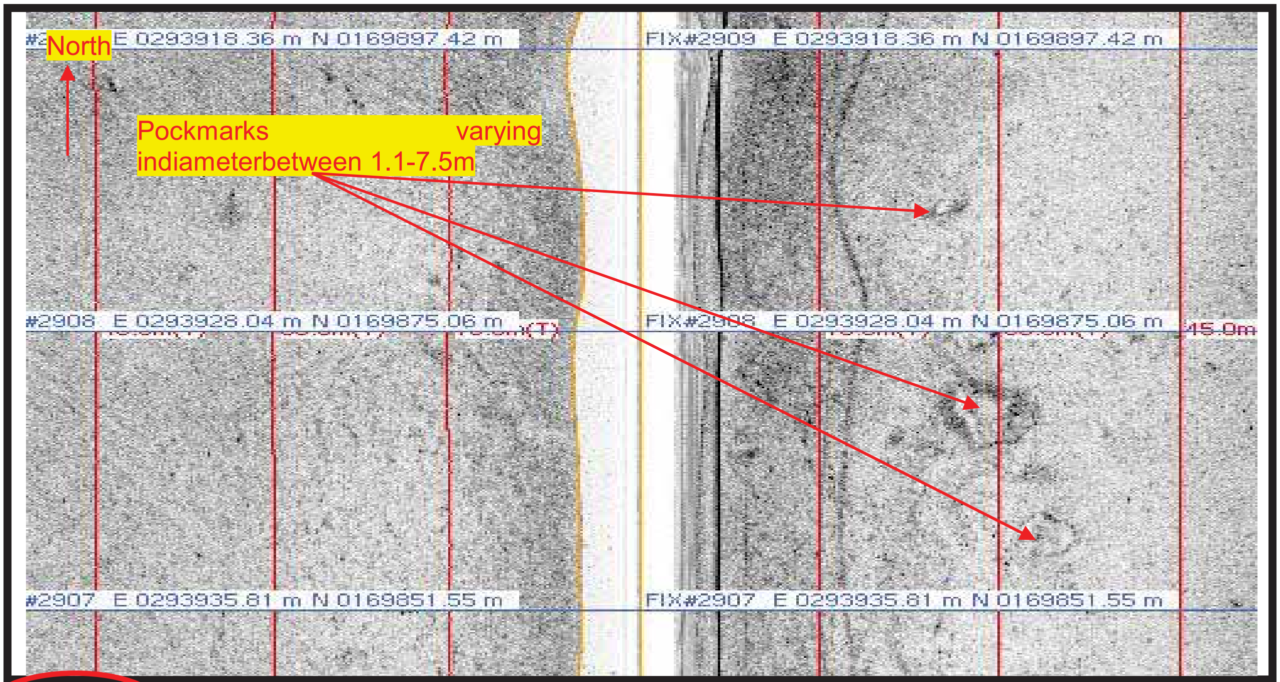


Figure 18 SSS Data extract showing Pockmarks on seafloor of study area ....

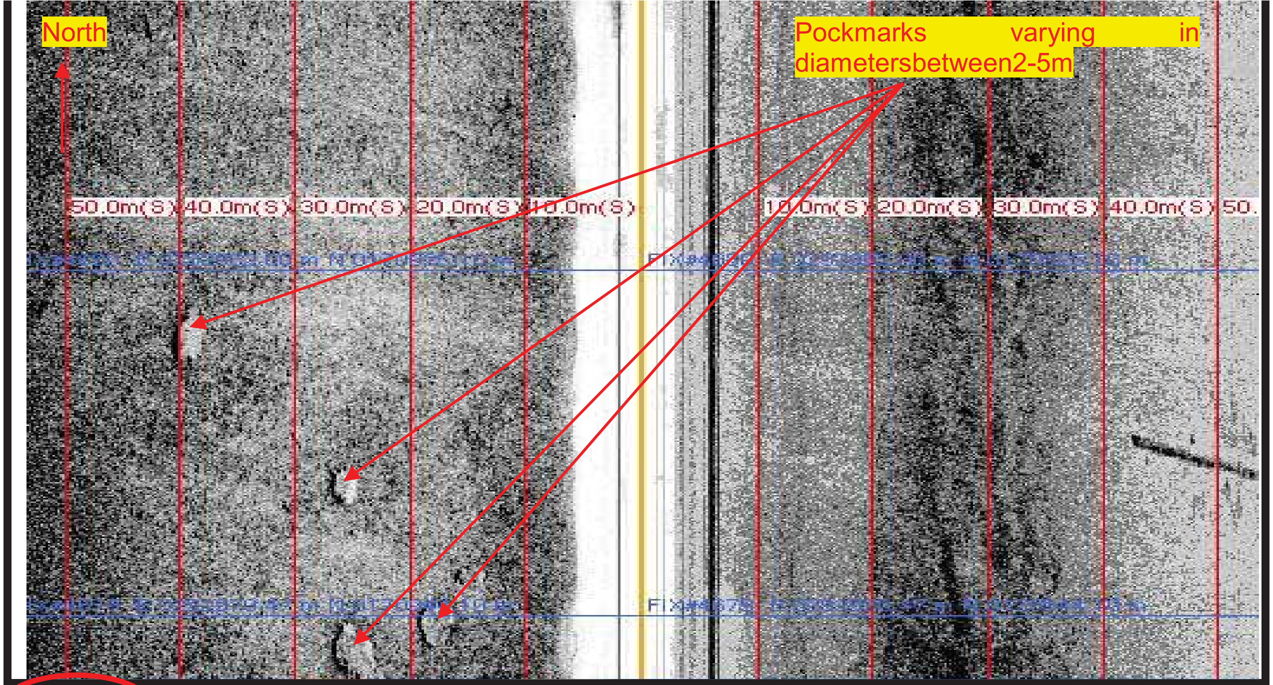


Figure 19: SSS Data extract showing Pockmarks on seafloor of study area

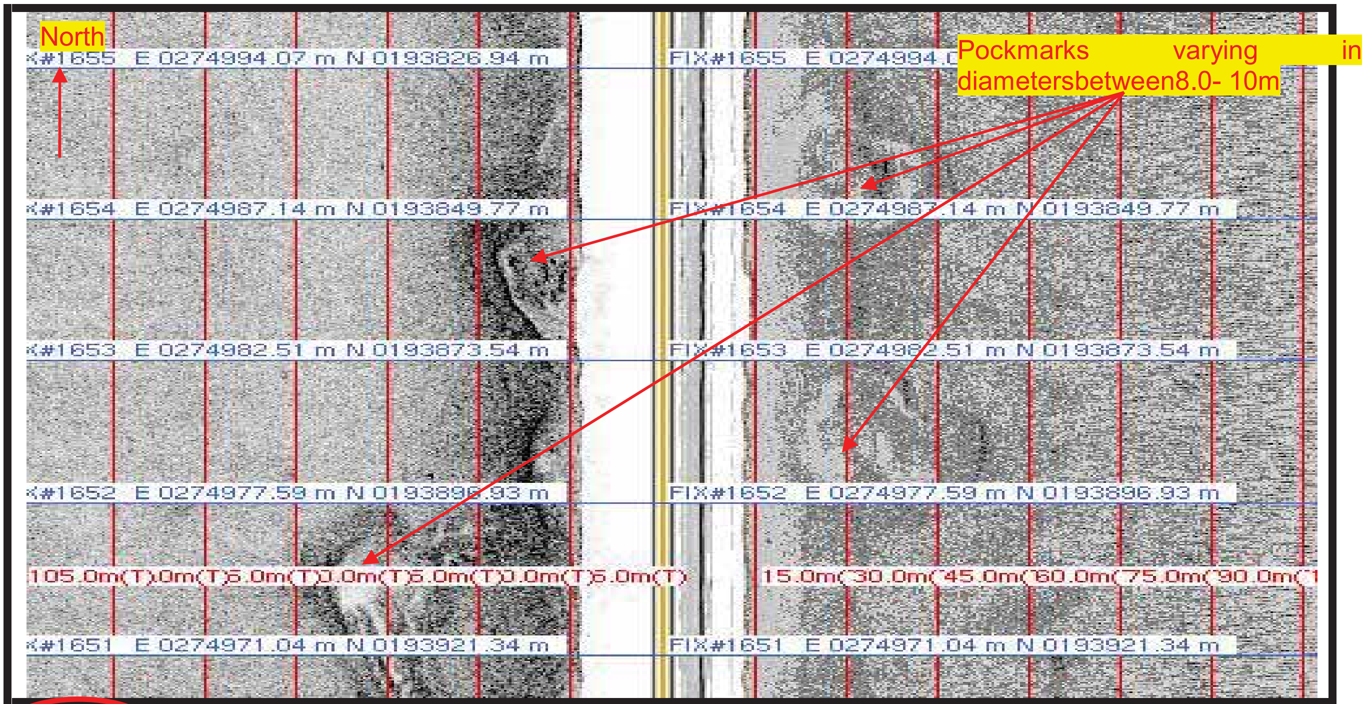


Figure 20 SSS Data extract showing Pockmarks on seafloor of study area

DISCUSSION

Gas hydrate has been commonly found in sediments at the floor or at shallow depth below the seabed of pockmarks located in the hydrate stability zone of continental slopes, but the role of gas hydrate in the dynamics of formation of pockmarks remain questioned. Pockmarks associated with gas (free or dissolved) and gas hydrates are important globally. To assess the methane release from the seabed to the ocean and ultimately to the atmosphere in climatic studies investigating methane as a green house gas [Badr et al., 1991], because methane emissions from pockmarks are a driving force of cold seep ecosystems hosting unique biota [Foucher et al., 2009], and because pockmarks are often found in continental slope areas of fluid driven sedimentary failure of concern to the deep offshore industry.

The Niger delta is areas where many seep related seabed features have been found over the last years in particular during industry exploration mapping at water depths between 500 and 1500 m [Hovland et al., 1997; Brooks et al., 2000; Georges and Cauquil, 2007]. Various studies from the Nigerian continental slope have shown different seafloor sedimentary features such as pockmarks, gas hydrates, slides, mud volcanoes, and carbonate buildups associated with fluid flow [Damuth, 1994; Cohen and McClay, 1996; Brooks et al., 2000; Haskell et al., 1999; Hovland et al., 1997; Deptuck et al., 2003, among others].Heggland [2003] observed gas chimneys above hydrocarbon charged reservoirs. These chimneys are believed to result from hydrocarbon dysmigration (leakage of petroleum from a trap) along fault planes between source rocks of reservoirs and the seabed. All these observations make the Niger delta a prime interest target to study the active interplay of fluid flow processes, gas hydrate dynamics, and seafloor deformation. In this work we focus on a specific area, where very high resolution bathymetry data (autonomous underwater vehicles, or AUV, data from Georges and Cauquil, 2007) acquired recently (Figure 1) show the presence of pockmarks with different shapes and sizes. Some pockmarks are associated to buried channels; others are linked to surface and subsurface faults or to the occurrence of gas hydrates. In this work, we study this last type of pockmark where gas hydrate dynamics could play an important role in the formation and development of pockmarks. We investigate (using various methods: geophysics, geotechnics, and geology) whether the shape and morphology of theses pockmarks could be controlled by gas hydrate dynamics. Finally, we use numerical modeling to validate assumptions and working hypothesis about the possible link between pockmarks formation and evolution and gas hydrate dissolution processes.The investigated area which is characterized by numerous circular to sub circular features lies at water depths ranging from 15 to 18m and is located in the transitional detachment zone.

CONCLUSION

This work is the first one to show pockmarks at different stages of maturation based on seafloor and sub seafloor geophysical data in a relatively localized zone. The SBP profiles show a common internal architecture of the studied pockmarks associated to gas hydrate dynamics: sediments rich in gas hydrate at the central part of the pockmark surrounded by over pressured sediments. The temperature, pressure, and salinity conditions of the studied area demonstrate that sediment deformation linked to the gas hydrate dynamics occurs in the hydrate stability zone. Moreover and based on 3D seismic data and the pseudo 3D micro seismic cube, the sediment deformations (ring shape surrounding the central part of the pockmark seem to be localized in the upper sedimentary layers and are not a direct consequence of deep depressions (Figure 19). Modeling results show that the dynamic of the gas flow through faults is the main cause of the hydrate dissolution and as Rehder et al. [2004] observed the long term survival of gas hydrate must be sustained by sufficient supply of gas dissolution generates excess pore pressure due to the compaction of the hydrated sediments. The fluid flow generated by the excess pore pressure gets around the gas hydrate bearing sediment because of the low permeability of the medium. The loss of the massive hydrate by dissolution at the boundary of the study area and the pore pressure dissipation are accompanied by sediment fracturing surrounding the sediment hosted gas hydrates.

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