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Modeling Near Surface, Gas-Induced Seafloor Deformation Using Thin Plate Mechanics in the Thunder Horse Oil Field, Gulf of Mexico and Ninilchik Field, Cook Inlet Basin, Alaska

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Abstract

Seabed topographic expressions such as pockmarks and domes caused by the vertical migration and accumulation of methane are found in muddy, cohesive sea beds around the world. These surface features range from 10-1000 m in diameter and 1-20 m in relief (Judd and Hovland, 2007). The mechanics of soft, cohesive sediment deformation due to overpressure from rising gas is not well understood or quantitatively defined despite the hazards they present to offshore drilling. Shallow gas pockets and overpressured sediments formed by the migration of subsurface gas to the seafloor can cause drilling blowouts, resulting in the release of large amounts of methane into the atmosphere that may contribute to climate warming. Barry et al., (2012) took initial steps to quantitatively define the sediment deformation caused by the upward pressure of rising gas against an impermeable sediment layer. They observed that the deformation to clay-bearing, cohesive sediments could be characterized by elastic thin plate mechanics up to sediment failure. Thin plate theory, also, could be used to predict the pressures responsible for known sea domes around the world. In this study, shallow gas and associated subsequent deformation to the sediments around them were identified in two study areas: the Ninilchik field along the eastern shore of the Cook Inlet in Alaska and the Thunder Horse Field in the Mississippi Canyon Protraction area of the Gulf of Mexico. Each observable upward doming feature was measured for radius, deflection, and thickness. This information is used in an elastic thin plate equation for calculating pressure (Barry et al., 2012). In the Ninilchik field, all measurements were done by interpretation of 3D seismic data in Petrel® 2011. In the Thunder Horse Oil Field, measurements of the sediment response at the seafloor were collected using a 3D three meter-binned bathymetry survey in Schlumberger’s Petrel® 2011. Nine Gulf of Mexico and three Alaskan gas accumulations were identified and analyzed in this study. In addition,
numerous other gas-related features were observed in the Gulf of Mexico study area including pockmarks, interpreted gas hydrates/outcrops, and subsurface gas that did not affect seafloor surface. By applying Barry et al. (2012) laboratory-derived method for predicting pressures, a range of predictive pressures for twelve gas domes was calculated using two equations based on the amount of observed deflection. Calculated pressures for individual domes ranged from 499-17,696 Pa in the Gulf of Mexico and 261-15,640 Pa in the Cook Inlet. The majority of observed domes displayed a deflection to thickness ratio (w/h) greater than 0.3 suggesting plate stretching during deformation and “flexible” plate behavior. Plate stretching equation best predicts the pressures for these 5 “flexible” domes, compensating for the added stresses created by their large deflections while still predicting comparable pressures (+/- 6%) for “stiff” domes (w/h<0.3) compared to non-plate stretching equation. Domes with the smallest Young’s Modulus (low-end calculations) provided pressures most similar to Barry et al. (2012) and a range of lower pressure values more likely recreated in the subsurface than high-end values. Domes in the Gulf of Mexico were better suited for the application of elastic plate theory due to their more circular plate shape and clay-rich lithology, thus producing more reliable pressure results than the Cook Inlet domes.
Chapter 1. Introduction

Doming of near surface sediments is often a small and easily overlooked mechanical response of the sediment layer to pressure (from a gas accumulation) below. Assuming the sediment layer is both impermeable and perfectly horizontal, gas migrating upward to the surface will become trapped under the sediment layer. In time, the trapped gas will provide enough upward pressure against the layer (seafloor) that it will bend or flex upwards much like the lithospheric response to the weight of ice sheets or mountain chains. While mountains may provide an enormously large force and lithosphere deformation measured on the order of hundreds on meters (Gudmundsson, 1999), sediment domes hundreds of meters in diameter usually grow no larger than 10 meters in relief (Hovland and Judd, 1988) from relatively small overpressures (Barry et al., 2012).

Gas generation, the preferential pathways taken, and the mechanical processes involved with migration have been investigated due to its importance in the energy industry (Algar et al., 2010; Algar et al., 2011; Boudreau, 2012). Overpressured sediments and collections of shallow gas cause seafloor instability that serve as hazards to offshore drilling operations by causing blowouts. Large, instantaneous releases of methane during a blowout or dome collapse contribute a sizeable amount of methane into the atmosphere. The greenhouse effect of methane gas is well known (Jorgenson, 1995) and large additions into the atmosphere may lead to warming temperatures (Archer and Buffet, 2005).

An important step in trying to quantitatively understand the mechanical response of sediment to underlying pressure was taken by Barry et al. (2012) by measuring the amount of pressure responsible for doming. In laboratory experiments, results were then compared against elastic thin plate theory calculations to determine if this theory, normally reserved for hard rock
conditions such as plate rebound (Gudmundsson, 1999) and magma emplacement (Pollard and Johnson, 1973), could satisfactorily characterize and predict soft sediment deformation. The results indicated that the tidal flat sediments from Cole Harbor of Nova Scotia, Canada could be characterized by elastic thin plate theory (behaved elastically) up to the point of sediment fracture and failure when deflection to thickness ratios reached values of approximately 0.2. These results lay a foundation on which predictions can be made about when dome collapse can be expected, whether certain sediments can deflect enough to be considered flexible/stiff, and how much pressure sediments can withstand.

In this study, the methodology of Barry et al., (2012) is applied to near surface gas deposits in two different areas: the Ninilchik field in the Cook Inlet Basin of Alaska and the Thunder Horse Oil Field in the Gulf of Mexico. Gas dome parameters including the amount of deflection of the deformed layer, the thickness of deformed layer overlying the trapped gas, and the diameter of the domes were measured using seismic software. These measurements were used to calculate first-order, predictive pressures for observed domes using thin plate mechanics as well as define and constrain the relationship between the aspect ratios of deformation domes and the amount of gas-related overpressure from depth. The purpose of this study is to: (1) determine whether elastic thin plate theory can be applied to predict pressures for gas domes outside of the coastal sediments of Nova Scotia (i.e. different Young’s Modulus’ and tensile strengths); (2) determine whether domes in the Gulf of Mexico and Cook Inlet have the same geometries as the laboratory domes created in Barry et al. (2012); and (3) test whether domes behave as stiff or flexible plates.
Chapter 2. Geologic Overview

2.1 Study Area

This study utilized donated data sets from two geologic areas: the Cook Inlet and Gulf of Mexico. A 3D seismic survey of the Ninilchik Field of the Cook Inlet, Alaska was contributed by Marathon Oil. Marathon Oil and CGGVeritas conducted two separate 3D seismic surveys in the Alaskan basin known as primarily a Tertiary gas play with conventional, four-way structural closures. The two surveys were merged together in 2007 imaging 206 km² of onshore and offshore data along the Cook Inlet. BP Exploration Inc. and C&C Technologies Inc. conducted a geohazard survey in 2001 for a proposed floating production platform in the Mississippi Canyon Area of the Gulf of Mexico with the goals of identifying any seafloor, near-seafloor, or biological community impact risks associated with potential offshore drilling. The data collected allowed for a high resolution view of the top 30-50 meters of the subsurface and detailed imaging of the seafloor conditions and outcrops.

2.2 The Cook Inlet and Ninilchik Field

The Cook Inlet is a forearc basin that sits between the southern portion of mainland Alaska to the west and the Kenai Peninsula to the east. Ninilchik Field is located on the western coast of the Kenai Peninsula about 145 km southwest of Anchorage, Alaska (Figure 1) and has been a target for gas production since the 1950’s (Carter and Adkinson, 1972). Producing formations in the Cook Inlet and Ninilchik Field range from the Late Oligocene Hemlock formation to the Mid Miocene Beluga Formation due to their organic coal rich layers that provide the source for the targeted methane gas (Fisher and Magoon, 1978).
Figure 1. Location and setting of the Cook Inlet. The Cook Inlet, oriented northeast to southwest, sits between the parallel Bruin Bay and Border Ranges faults (Swenson, 2001). The Cook Inlet has a thick, highly faulted Mesozoic and Tertiary section that produces and traps biogenic gas, creating favorable conditions for gas-induced doming.
The Cook Inlet forearc basin is oriented northeast to southwest as part of the Pacific continental margin that has remained active since the Jurassic (Magoon, 1994). Tectonic activity and subduction has created a highly faulted basin system with two basin-parallel faults, the Bruin Bay and Border Rangers fault, and the Castle Mountain Fault to the north surrounding the inlet (Figure 1). The 320 km long and 96.5 km wide trough-like basin sits between the Alaska Range Mountains to the northwest and the Kenai-Chugach Mountains ranges to the east (Kirschner and Lyon, 1973). The Castle Mountains to the north and Chugach Mountain Range to the east provide sources for the sediments that filled in the basin.

The present day basin and sediment deposition began to take form in the Late Jurassic with heavy sediment loading along the western half of the basin due to the uplift of the northern Alaska Range (Kirschner and Lyon, 1973). Following this initial deposition from the north, the Kenai-Chugach Mountains were uplifted from the Late Cretaceous up to the Tertiary leading to alluvial fan deposition from the east. Rapid deposition of sediments from the surrounding mountain chains led to basin deepening and fluvial deposition from the northeast (Hartman et al. 1972).

Tertiary deposition, of which the Kenai group makes up nearly 80%, was deposited primarily as a braided fluvial system although lacustrine, estuarine, and alluvial fan environments have also been identified (Boss, et al., 1976; Jones and Detterman, 1966). Originally, sedimentation came from Western Canada and the interior province of Alaska (Kirschner and Lyon, 1973) and was deposited into a depocenter to the northeast of the current basin. A distinct shift in sedimentation occurred as the highlands of Alaska Range became the source of sedimentation and moved the depocenter further southeast to its present location. Further north and closer to the sediment source(s), the Tertiary section reaches thicknesses
upwards of 8 km while generally thinning to the south. Biogenic gas generation declines at temperatures above 80°C, restricting gas to the top half of the Tertiary (Head et al., 2003). A two to three kilometer Tertiary section is observed in Ninilchik Field. It is described as a non-marine, interbedded sandstone, conglomerate, and coal bed group with abundant volcanic fragments stemming from the uplift of the southernmost portion of the Alaska Range in the Tertiary (Hayes et al., 1976). Within these formations are large anticlines that create the typical four-way closure required for a structural trap. Transpressional forces responsible for much of the observed deformation and folds within the basin are sourced from the combination of the collision of the North American and Pacific plates along the Alaska-Aleutian subduction zone and the Yakutat block collision to the east (Haeussler et al., 2000).

Anticlines throughout the basin and in Ninilchik field (Figure 2) are characterized as being asymmetrical and exhibiting steeply dipping northwest and southeast flanks (Boss et al., 1976) within the Tertiary sediments. The Ninilchik anticline sits below the shoreline on the Kenai Peninsula with numerous faults affecting the hydrocarbon trapping structure. The interbedded sandstones, siltstones, and coal layers within the anticline provide a working petroleum system of reservoir, source rock, and seal making the Cook Inlet an attractive oil and gas basin. However, the regularly changing depositional environment of the Cook Inlet has led to complex stratigraphy that makes seismically imaging a challenge due to the large velocity differences between gas, coal, and sediments (Perz, 2001).

Due to the prolific faulting caused by the stresses of an active margin (Figure 3), methane gas created by the biogenic degradation of coals (Kelly, 1963) in the Cook Inlet is quite mobile despite the abundance of impermeable coal layers. Once the generated gas is released from the coal layers it begins migrating through the many and often complex sand reservoirs along the
braided, fluvial channel. In addition, clays within the formations can act as permeability barriers, creating potential stratigraphic traps. The combination of these factors create many complicated and unpredictable reservoir systems that make the correlations between wells difficult and successful hydrocarbon production challenging (Sampson, 2012). The hydrocarbon and gas migration system becomes even more complex due to the deformation processes that has created

Figure 2. Anticlines in the Cook Inlet. Figure taken from Haeussler and Saltus (2011) illustrating the dozens of northeast-southwest oriented anticlines of the Cook Inlet (Haeussler and Saltus, 2011). Ninilchik field circled in red.
Figure 3. Tectonic framework of Cook Inlet. The convergence of the Pacific plate with the North American plate and microplate collision of the Yakutat Block (Sampson, 2012). Ninilchik field (in red) sits near the three-way, oblique plate collision and subsequent transpressional stress field.

the many recent Plio-Pleistocene faults through the Ninilchik field. The faults create conduits for gas migration. Vertical migration of gas is evidenced by the gas chimneys and shallow gas accumulations that are of interest to this study (Figure 4).

2.3 Kenai Group Stratigraphy

The shallow gas accumulations found in Ninilchik Field are all within the upper 300 m of sediment, averaging a depth of approximately 240 m or less at the peak of the “gas head” (package of sediments exhibiting high amplitude reflectors interpreted as being gas-saturated). The deformed sediments trapping the gas are interpreted as the Plio-Pleistocene Sterling
Formation or more recent unnamed glacial till (Figure 5) that make up the most recent sediment in the Cook Inlet.

Figure 4. Shallow gas accumulation Inline 232. Shallow gas is identified based on the amplified reflectors and distorted reflectors known as a “chaotic zone” or “washout”.

The Kenai Group as highlighted in Figure 5 is made up of four Tertiary formations that overlie the West Foreland Formation. The Hemlock formation is the oldest of the Kenai Group and contains a substantial oil reservoir in the Cook Inlet referred to as the Hemlock zone. In the northern Cook Inlet, the Hemlock can be found at depths greater than 5 km according to well data and is identified by a predominate mix of sandstone, conglomerate, and carbonaceous shale interbedded with coal seams and lignite streaks (Kelly, 1963).
Figure 5. Kenai group stratigraphy (modified from Swenson, 1997). The Kenai Group is Tertiary in age, consists of several oil and gas targets in the Cook Inlet, and the Sterling formation is the reservoir for the shallow gas identified in this study.

Above the Hemlock sits the Tyonek formation, a highly productive reservoir in Ninilchik field comprised mainly of sandstones, conglomerates, and siltstones. The most distinguishing characteristic of the Miocene-age formation is the frequently occurring, continuous coal beds at the base of productive sands (Clay and Adkinson, 1972) that average 4.6 m in thickness. Permeability in the sand packages ranges between 3 and 250 milidarcies (mD) (Brimberry et al., 2001) that allows for gas migration while the siltstone layers within the sands act as migration barriers.

Much like the Tyonek, the Beluga formation is another thick package containing high quality sand reservoirs with favorable porosity and permeability for hydrocarbons. Sandstones,
siltstones, and frequent, thin coal layers of less than 2 m are found in the 762 m section.

The most recent and uppermost portion of the Kenai Group is the Sterling formation. The Plio-Pleistocene formation contains partially clay-cemented sand packages upwards of 15.25 m thick. Despite the presence of kaolinite and smectite clays, porosities in sand packages still average around 25% (Brimberry et al., 2001) making them attractive targets for drilling (Boss et al., 1976). On the Kenai Peninsula and near the Ninilchik field study area, the Sterling is relatively thin, thickening to the north where it has been a proven gas reservoir (Bruhn et al., 2000).

Most recent deposition, above the Kenai Group, consists of glacial till and detritus. Erosion of the Alaskan Range and alluvial processes contributed to the approximately 150-300 m thick section of till found in the Ninilchik field (Haeussler et al., 2000).

2.4 Gulf of Mexico and Mississippi Canyon Area

The hydrocarbon potential of the Gulf of Mexico and the global economic impact it produces has led to a wealth of research and data spanning the basin. While a sea of geophysical data has led to many different interpretations of the Gulf and its evolution to present day form, most authors are in agreement that the beginning of the Gulf began in the Late Triassic with the initial breakup of Pangea (Salvador, 1991). From Late Triassic to Middle Jurassic, the widening Gulf underwent phases of rifting which formed rift valleys and stretched continental crust. The first evidence for a seawater connection to the Gulf from the Pacific Ocean are widespread, thick salt deposits of Middle Jurassic age that can be divided into two regions within the basin (Figure 6) (Salvador, 1987). The two distinct salt deposit regions, separated into the Northern Gulf of Mexico salt basin and the Campeche salt basin, are a result of the contemporaneous seafloor
spreading and continental extension associated with the Yucatan block rotation (Bird, 2005) (Figure 6). This seafloor spreading and plate movement led to the Gulf of Mexico’s current day form. The most accepted theory today is that the Yucatan Peninsula block rotated counterclockwise away from the North American plate along a single transform boundary beginning around 160 Ma to form the basin we see today (Bird, 2005).

The northern Gulf has experienced extensive sediment and salt movement as is evident by the Mid-Jurassic anticlines, domes, and diapirs along the entire Texas-Louisiana slope (Mann, 1987). Salt migration can uplift, deform, and fault the sediments above it making the salt responsible for bathymetric highs, near surface salt deposits, and highly complicated stratigraphy found in the Gulf. Salt diapirism has even been linked to authigenic carbonate outcrops (Lee et al., 1989).

Sedimentation into the basin during the Cenozoic was dominated by five major North American fluvial axes, providing the majority of basin infill found on the northern margins (Galloway et al. 2000). The Mississippi Canyon Area is characterized by a delta flank-submarine fan systems tract. Vast amounts of sands and sediments were transported downslope by depositional channels and turbidites into lobes on the deep basin floor (Galloway et al., 2000). The combination of a thick, Cenozoic sedimentary section, huge amounts of organic matter, and halokinesis resulting in fault pathways creates conditions favorable for leaky petroleum systems and gas seeps.

Gas seeps in the Gulf of Mexico are common and have been studied using echo-sounders and side scan (Hart et al., 2008), electromagnetic surveys (Ellis et al., 2008), and even a joint drilling project (Ruppel et al., 2007). These data support the idea that methane gas domes are
vent-related features where buoyant gas moves upwards along faults to the surface. Trapped gas can uplift the seabed, creating bathymetric mounds (Wood et al., 2008).

Figure 6. Evolution of the Yucatan block rotation. A) The initial position of the Yucatan block 160 Ma. B) 150 Ma: A mantle plume becomes active, creating seafloor spreading and dividing the salt. C) 140 Ma: The Yucatan has fully rotated to its present position. (Bird, 2005)
Chapter 3: Data and Methods

3.1 Data

In this study, two data sets were investigated. Marathon Oil donated a 3D seismic survey shot and processed by CGGVeritas in the Ninilchik Field in the Cook Inlet of Alaska. In the Gulf of Mexico, BP Exploration Inc. and C&C Technologies, Inc. conducted a geohazard survey including multibeam bathymetry, side scan sonar, and 2D subbottom profiler data to detail the seafloor surface and shallow subsurface.

3.2 Cook Inlet 3D Survey

An original 2003 seismic survey was merged with a more recent 2007 adjacent seismic survey by CGGVeritas to provide the 206 km² 3D cube (Figure 7) over Ninilchik field used in this study. Both surveys covered portions of the onshore and the offshore area with receiver lines oriented northwest to southeast and source lines oriented perpendicularly, northeast to southwest. The receiver interval for both surveys was 402 m but the source interval varied from 2003 to 2007. The source interval for the original 2003 survey was 100 m onshore and 50 m offshore while in 2007 the source interval was 50 m for both. Air guns provided the source offshore while dynamite was used onshore.

Because the final product is a combination of two separate surveys taken 4 years apart, a 5D interpolation processing technique was applied by CGGVeritas to correct for any acquisition problems caused by the terrain along the shoreline (Figure 8). Using a combination of inline, crossline, frequency, and offset data, gaps within the survey are interpolated with surrounding data to create a complete gap-free survey (Sampson, 2012).
Figure 7. Ninilchik two part survey. Outlined in red is the extent of the individual surveys (CGGVeritas report, 2009). The transition from purple to yellow/green lines marks the current shoreline. Observable gaps within the data are due to acquisition problems while shooting in the difficult Alaskan terrain.

The final Ninilchik field seismic cube, after merging the two surveys and applying the 5D interpolation, contains 1120 crosslines, 365 inlines, and an onshore bin size of 25x33.5 m. The survey’s total capture time was 5,000 milliseconds with a 2 millisecond sample interval. The survey frequency range was 30-50 Hz and a true resolution, based on ¼ wavelength, between 15.25-31 m (CGGVeritas, 2009). Depth conversion for the survey was completed by CGGVeritas by constructing an anisotropic velocity model built using RMS interval velocities based on the pre-stack time migration survey.
Figure 8. 5D Interpolation. A look at the survey before 5D interpolation (top) and after (bottom). Gap issues in the survey related to tough terrain were resolved using known geophysical data at two lines and interpolating between them to fill in holes.
3.3 Cook Inlet Subsurface Gas

All interpretation of the Ninilchik field seismic volume was done in Schlumberger's Petrel® 2011 software. The initial step of identifying any subsurface gas was done in a 2D interpretation window beginning with the first crossline to the north and interpreting every tenth crossline for the entire 1120 lines. Gas was identified based on low frequency, high amplitude reflections, the “washout” of the seismic signal below, “gas chimney” presence, and the depth at which the reflectors are found. Because gas in the Ninilchik field has been found to be biogenic and generated from coal layers within the Tertiary (Fisher and Magoon, 1978), depths below this interval were not closely investigated.

Delineation of gas accumulations and deformed layers was accomplished in the 3D interpretation window in Petrel® 2011 (Figure 9). Three accumulations were found within the Ninilchik field (Figure 10). Each gas accumulation was then measured for diameter, thickness of “gas head”, orientation, volume, and axis ratio or symmetry. All three accumulations displayed variable shapes and sizes that make the application of just one theory for predicting pressure insufficient. As seen in Figure 15, the northern most mapped accumulation, AKGAS3, does not display a circular dome shape with good axis symmetry. Rather, the gas exhibits a linear or beam shape with an axis ratio of nearly 10:1 in favor of the northeast-southwest axis. This shape makes it a poor candidate for a circular plate and was instead treated as an elastic beam when calculating pressure.

In addition to measuring the extent of gas-saturated sediments, the deflected layers of sediment atop each accumulation were measured for diameter, thickness, and amount of deflection to be used to calculate pressure. These values were taken using the ruler tool in the seismic software in a 2D interpretation window for increased accuracy (Figure 11).
Figure 9. Cook Inlet seismic cube. Interpretation, gas identification, and measurements of gas accumulations were accomplished using a combination of 2D and 3D windows to help resolve the extent of gas accumulations. Incorporating all three dimensions allowed for a complete measurements of the gas-saturated sediments.

Diameter for each dome was measured using the ruler tool after the extent and 3D shape of each accumulation had been mapped (Figure 10). Diameter measurements were done north-south and east-west and averaged for calculations. Because the equations call for a circular plate, axis symmetry is important for reliable results. Deflection was measured in a 2D seismic slice (Figure 11) by first identifying the uppermost, gas-saturated reflection that has been flexed upwards and then measuring the offset from the peak deflection down to the undisturbed baseline.
of the same reflection. This distance is represented by the vertical yellow line in Figure 11.

Thickness of the overlying layer was defined as the distance between top of the gas–saturated sediments and the uppermost reflector that is interpreted to have been deformed by gas.

Figure 10. Cook Inlet gas accumulations. Three separate gas accumulations were discovered in the Ninilchik data set with their locations within the survey displayed above. The extent of the gas-saturated sediments were mapped as a horizon to display size and shape.
Figure 11. Measurements within Petrel® 2011 software. Pictured above is inline 234 of the gas accumulation AKGAS2 in a 2D interpretation window. The green line is a horizon illustrating the shape of the feature and in yellow, an example of typical measurements made for deflection (vertical line) and diameter (horizontal line) of a dome. Vertical exaggeration is almost 3 to 1.

3.4 Mississippi Canyon Geohazard Survey

The 146.6 km² study area is located in the north-central portion of the Gulf of Mexico (Figure 12) approximately 113 km southeast of the southern tip of Louisiana. It sits near the base of the Mississippi Fan near the Sigsbee Plain (Roberts and Bouma, 1990) on the lower continental slope.

The BP survey covered all or portions of Blocks 776, 777, 778, 822, 731, 732, 733, 734, 735, 775, 779, 819, 820, 821, 823, 824, 865, 866, and 867 (Figure 13). After searching the entire
Figure 12. Survey area within the Mississippi Canyon. BP conducted a geohazard survey in the southeast quadrant of the Mississippi Canyon for a proposed floating production platform. (BP Exploration Inc.)
Figure 13. Survey tracklines. The map of the entire 146.6 km² survey area broken into four topographic zones. Circled in black is an approximate 10 km² portion of the survey that contains almost all the subsurface gas and related features.
survey, only Blocks 731, 732, 733, 775, 776, 777, 819, and 820 contain interpreted subsurface gas or gas-induced surface features based on gas related seismic signatures (acoustic void zones, higher amplitude reflectors, etc.). This area is the focal point of this study and seafloor features found in this area include faults, authigenic carbonate outcrops, pockmarks, possible gas hydrates, one 137 x 222 m gas expulsion crater (Jim Thomson, Personal Communication, 2012), and gas domes.

The BP survey covered all or portions of Blocks 776, 777, 778, 822, 731, 732, 733, 734, 735, 775, 779, 819, 820, 821, 823, 824, 865, 866, and 867 (Figure 13). After searching the entire survey, only Blocks 731, 732, 733, 775, 776, 777, 819, and 820 contain interpreted subsurface gas or gas-induced surface features based on gas related seismic signatures (acoustic void zones, higher amplitude reflectors, etc.).

All mapping in this study used the projection Universal Transverse Mercator Zone 16N, central meridian 87° 00’W, a false easting of 1,640,416.67’ at the central meridian, and a false northing of 0.00’ at 00° 00’N. Primary lines of the survey were oriented in a northwest-southeast direction at a spacing of 200 meters. Tie lines were shot perpendicular to the primary lines and were variably spaced. In the northwestern portion of the survey where buried gas is present, tie lines were spaced 500 meters apart while tie lines in the southeastern portion of the survey were spaced 1,000 meters apart.

Seafloor sediments over the entire survey area are interpreted as silts and clays based on parallel layered, alternating amplitude strength reflectors in SBP data (BP Geohazard Assessment, 2002). Beneath the horizontally-layered silts and clay, approximately 23 to 27 m depth, are mass movement deposits found generally to the west of the survey area and have almost no association with the shallow gas. Recorded water depths in the survey area ranged
from approximately 1,610 m in the northern region of the survey down to 2,011 m at the southern tip. With over 305 m difference in water depth, noticeable changes in sea floor gradient were observed and were used as part of the criteria to divide the study area into four different topographic zones (BP Geohazard Assessment, 2002) (Figure 13): a zone of east to southeast-sloping seafloor in the southeastern portion, a zone of smooth seafloor due to mass movement deposits erasing topography, the northeast corner with strong changes in slope, and an area of hummocky seafloor.

The seafloor in the southeastern portion of the survey subtly slopes east to southeast at a gradient of 0.5° to approximately 2°. It is absent of any significant seafloor features.

The mass movement deposits portion of the survey is a large area not confined to a geographic region or quadrant but found where mass movement deposits underlie horizontally layered sand and silts packages. It spans the northwest corner of the survey and continues south along the western edge until pinching out to the east into the middle of the survey (Figure 13). The mass movement debris is responsible for removing any previous seafloor topographic relief and cuts through portions of the hummocky deposits suggesting more recent deposition. Several of the gas-related surface features discussed in this study, including the large gas expulsion crater and zone of small pockmarks, are found within this zone.

In the northeastern region, seafloor gradients change dramatically and water depths range from 1,706 m to 1,945 m. The seafloor slopes 1° near the top and 8° at the base of the slope. No evidence of shallow gas or seafloor related features is found in this region.

Hummocky seafloor regions, like the mass movement deposits, are not confined to just one area and can be found in two separate areas of the survey. The areas include parts of the
northern region and along the southwestern margins. The hummocky seafloor is associated with localized topographic highs and lows in the bathymetry data, typically never reaching more than 7.6 m in relief. While regions exhibiting a hummocky seafloor have gentle slopes between 1° and 7°, the hummocky nature of the seafloor is linked to massive debris flows north of the area (BP Geohazard Assessment, 2002). Several outcrops, gas domes, and numerous surface faults are found in this region.

3.5 Mississippi Canyon Survey Area Stratigraphy

The 2D subsurface data were collected for approximately the first 30.5 m of sediments using an autonomous underwater vehicle (AUV). A CHIRP survey using two hydrophones was used for acquiring the subbottom profiler data at a frequency band between 2 and 8 kHz. The majority of the survey area is interpreted as horizontal clay and silt layers disrupted by amorphous mass movement deposits along the western half of the survey. The subsurface is categorized into 3 distinct sedimentary sequences that are cut into by the mass movement deposits in the northwest (BP Geohazard Assessment, 2002).

Sequence 1, the uppermost layer, ranges from 4.5-9 m in thickness, generally thinning to the east. This layer is comprised of horizontal, soft silt and clay layers that sit on top of mass movement debris flows, where present, in the western portion of the survey area that makes up the focus region of this study. In sub-bottom profiler (SBP) data, the layers are depicted as faint, parallel reflectors just beneath the seafloor (Figure 14). The base is marked by a pair of high amplitude reflectors and one fainter reflector referred to as the “triplet”. This sedimentary signature sits below an unconformity and is found throughout the survey area, making it an ideal marker for the base of Sequence 1. All shallow gas found in this study has migrated to and
Figure 14. Subbottom image of subsurface. Sequence 1 is characterized by two horizontal, prominent reflectors within the first 9 m of the subsurface before encountering the “triplet” that marks the start of Sequence 2. Sequence 2 is approximately 10.6-13.7 m thick and is characterized by numerous parallel reflectors that often contain “Eifel Tower” structures (Jim Thomson, Personal Communication, 2012)
become trapped in Sequence 1 layer. The top of Sequence 2 begins below the unconformity and ranges in thickness from 10.6-13.7 m. The base is marked by an erosional unconformity. The sedimentary sequence is distinguished by high amplitude, closely spaced, parallel reflectors throughout. The dewatering of shallow sediments in Sequence 2 creates a focused acoustic signal in a concave shape that resemble the Eiffel Tower (Figure 14) (BP Geohazard Assessment, 2002). In the northwest, Sequence 2 is often underlain by the acoustically transparent mass movement deposits (Figure 14).

In the northwest portion of the survey area, the last layer that can be penetrated by the acoustic signal is the mass movement deposits (Figure 15). The head of this large debris flow is outside the survey area to the northwest. Flow direction is assumed to be to the southeast, into the study area, with the toe pinching out to the east into the middle of the survey (Appendix A, Figure A29). Acoustically transparent and lacking internal stratification, this section is easily identified located between the other horizontally layered sequences. Thickness of the mass movement ranges from 1-15 m, thickening to the east. The top of the structure is a hummocky surface that could be the result of bulge structures and intrastratal deformation (Figure 14) (BP Geohazard Assessment, 2002). Bulge structures are the product of flow folding due to intrastratal deformation caused by gravitational adjustments due to sediment density contrast and fluid expulsion (O’Leary and Laine, 1996). The small scale folding involved with the bulge structures create concurrent fractures into the layer above that cause inter-layer sediment exchange and possible future fault planes.

Outside of the northwest portion of the survey area as the mass movements deposits begin to thin, Sequence 3 can be imaged by the SBP data sitting below the mass movement deposits and an erosional unconformity. It is another layer of closely spaced, horizontal
reflectors that can reach up to 19.8 m in thickness (Figure 14) although attenuation of the acoustic signal often prevents imaging the entire section. Reflectors in Sequence 3 are lower in amplitude than Sequences 1 and 2.

Figure 15. Gas expulsion crater. Line 9 of SBP data contains a crater from a large and instantaneous release of subsurface gas (modified from BP Geohazard Assessment, 2002). In this portion of the survey area, the mass movement deposits span the limits of the acoustic signal.
The marine survey company, C&C Technologies, used their own HUGIN (High Precision Untethered Geosurvey and Inspection System) 3000 Autonomous Underwater Vehicle (AUV) (Figure 16) to collect multibeam bathymetry, side scan sonar, and subbottom profiler data at depth.

Figure 16. HUGIN 3000. The HUGIN 3000 AUV was created in 2000 and is the first AUV designed for commercial applications. This illustration depicts the major components inside the AUV that allow it to collect the many different types of geophysical data associated with the geohazard survey (BP Exploration Inc., geohazard assessment, 2001)

Primary sensors for the data collection include Edgetech’s Side Scan Sonar and Chirp Subbottom Profiler sensors as well as a Simrad EM 2000 Swath Bathymetric System. These geophysical data collection systems are responsible for the data used in this study.

The Simrad EM 2000 Swath Bathymetric System is a multibeam echosounder system operating at 200 kHz that transmits a pulse to create a 200-meter-wide swath underneath the
AUV for seabed mapping. The swath coverage has a maximum angle of 150° and the AUV, coasting 12 m off the seafloor, uses an onboard velocimeter to relay real-time acoustic transmissions data that allows for depth calculations. The echosounder produces 10 pings per second, at 111 beams per ping, to create a final depth resolution of 20 centimeters. This is by far the high resolution data in this study and is the ideal data from which to measure any seafloor topography. This data can be imported into Schlumberger’s Petrel® 2011 software and viewed as a 3D recreation of the seafloor.

The Edgetech Side Scan Sonar sensor is a dual frequency sonar chirp that produces high resolution side scan sonar images of the seafloor by sending out a wide band digital FM signal across the seafloor at 120 kHz and 410 kHz. The raw data can then be processed by C&C Technologies and converted to XTF (eXtended Triton Format) for interpretation using CodaOctopus’ GeoSurvey software.

Shallow, 2D seismic profiles were gathered using the Edgetech Chirp Subbottom Profiler sensor that generates transmit pulses between frequencies of 2 and 8 kHz and a total record length of 300 milliseconds. The HUGINS AUV has a built-in steps to reduce ringing and for the deconvolution of the response to the output pulse. The collected raw seismic data is then converted into SEG-Y files that can be viewed in Schlumberger's Petrel® 2011 software for interpretation. The final data have a resolution of 6-10 cm.

3.6 Thunder Horse Subsurface Gas and Features

The focal point of the Thunder Horse survey is the gas and associated surface relief features in Blocks 731, 732, 733, 775, 776, and 777. While Blocks 819 and 820 contain small isolated occurrences of subsurface gas, they exhibit no associated surface deformation.
The first step taken to ultimately calculate pressure from seabed dome geometries was identifying subsurface gas in 2D subbottom data that can be cross-referenced with BP Exploration Inc.’s own geohazard map (Figure 17). Only primary lines 1-30 of the subbottom data were in SEG-Y format that could be imported into a seismic viewing software like Petrel® 2011. Lines viewed in Petrel® 2011 allowed for greater resolution and spatial awareness within the survey when viewing the subsurface but the files contain a constant depth and start time that is not representative of the water depths during acquisition. This resulted in a nontopographically-corrected seafloor. This prohibited the ability for any true measurements to be taken from subbottom profiler data but remained useful as supplementary data due to the enhanced resolution. The remaining lines were topographically-corrected static images in JPEG form provided by C&C Technologies, Inc that could still be used to identify shallow gas based on seismic washout, acoustic voids, and high amplitude reflectors near the surface. Both types of data were functional for the purpose of this study with the main differences being the correction for seafloor topography and image quality (Figure 18). Because the Thunder Horse field survey was conducted for only shallow depths, the resolution is much greater than a traditional seismic survey like at Ninilchik field. This makes the attenuation of the seismic signal and washout zone beneath the gas much more prominent and easier to identify.

After identifying all shallow gas in the survey, it must be determined if the gas is responsible for any deformation seen at the surface, specifically doming. Surface relief and topography is best visualized using the multibeam bathymetry 3 m binned data which allows for a high resolution, 3D look at the seabed. Subbottom profile data only resolves the seafloor and subsurface directly beneath the AUV tracklines, giving the interpreter a limited view of the data. Bathymetry data (Figure 19) has the advantage of imaging the entire seafloor, filling in the gaps
Figure 17. BP geohazard survey. BP provided their interpretation of the subsurface gas and surface features over the entire survey. Pictured above is a zoomed in image of the northwest corner where most gas-related features can be found. Spotted green: pockmark region. Solid Green: sediment variation associated with gas hydrates. Spotted Purple: possible gas hydrates. Purple: gas hydrates. Brown: outcrops. Yellow: gas expulsion feature. Pink: interpreted acoustic void zone associated with shallow gas.
between tracklines, and allowing for measurements of seafloor features without incorporating calculations between subbottom and side scan sonar data. Side scan data interpretation was done concurrently with the identification of seafloor features in bathymetry data. Using CodaOctopus’ GeoSurvey®, side scan sonar allowed for cross referencing any subtle or poorly imaged relief found in the bathymetry data. The majority of the subsurface gas found in the Thunder Horse field geohazard survey is associated with pockmarks, outcrops, two large gas craters, or no surface expression at all. Of the >60 separate gas effects seen in subbottom 2D data, only nine were related to positive relief domes.

With the domes identified in the bathymetry data and the gas responsible in the subbottom data (Figure 20), 3D measurements could be taken using the ruler tool just as with the Ninilchik field gas accumulations. Location, volume, axis ratio, diameter, and deflection, \( w \), were measured using the bathymetry data while thickness of the deformed layer, \( h \), was
Figure 19. Bathymetry data. The multibeam bathymetric data allows for a look at relative topographic relief on the seafloor. Red and yellows indicate a higher relief while the blues and purples are lower relief. The color scheme was set to highlight the subtle variations in relief between the blues, greens, and yellows which encompass all gas-related features.
measured using 2D subbottom images. Diameter of the Gulf of Mexico domes was measured north-south and east-west from the point at which the seafloor began to slope upwards, across the peak, and down until the seafloor slope was again zero. The two measurements were then averaged for future calculations. Deflection was measured in the 3D bathymetry data by measuring at the edge of the dome (slope=0) to the peak. This change in elevation is equal to $w$. The value for $h$ was measured from the surface down to the beginning of the attenuation of the seismic signal. A washout zone or acoustic void zone in a seismic signal is due to the velocity differences between the trapped gas above and the sediments below. Gas can then be interpreted to be trapped just above the beginning of the attenuating signal. This definition is used in determining where the gas is trapped and the extent of $h$ on top. With these interpreted data, pressure is compared using equations 3 and 4.

Figure 20. Measuring domes using bathymetric data. Bathymetry data (left) illustrating the domes shape and size atop the seafloor. SBP data (right) displays the subsurface and acoustic void zone associated with the dome. Thickness of the elastic layer bracketed in red.
3.7 Gas Dome Background and Theory

Seabed domes are a type of mechanical response to migrating subsurface gas trapped beneath soft clay sediment layers. Gas domes exhibit subtle relief over hundreds of meters that, if not for evidence of shallow gas from seismic amplitude data, could be overlooked. The ratio of dome width to vertical displacement, or deflection, is often greater than 100 to 1.

Table 1. Table of Natural Seabed Domes (Barry et al., 2012). Dome parameters worldwide were compiled from existing publications to compare relative sizes and aspect ratios.

<table>
<thead>
<tr>
<th>Location</th>
<th>Width (m)</th>
<th>Vertical displacement (m)</th>
<th>Layer thickness (m)</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Northern Norway</td>
<td>125</td>
<td>4</td>
<td>Unclear</td>
<td>Plassen and Vorren, 2003</td>
</tr>
<tr>
<td></td>
<td>500</td>
<td>1.5</td>
<td>5</td>
<td>Plassen and Vorren, 2003</td>
</tr>
<tr>
<td></td>
<td>120</td>
<td>3</td>
<td>1</td>
<td>Plassen and Vorren, 2003</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>0.6</td>
<td>Not available</td>
<td>Hovland and Judd, 1988</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>1–2</td>
<td>1–2</td>
<td>Hovland and Judd, 1988</td>
</tr>
<tr>
<td></td>
<td>350</td>
<td>2</td>
<td>Not available</td>
<td>Hovland and Judd, 1988</td>
</tr>
<tr>
<td></td>
<td>600</td>
<td>3</td>
<td>12</td>
<td>Hovland and Judd, 1988</td>
</tr>
<tr>
<td>North Sea</td>
<td>100</td>
<td>1–2</td>
<td>2</td>
<td>Hovland and Judd, 1988</td>
</tr>
<tr>
<td>Irish Sea</td>
<td>400</td>
<td>1</td>
<td>1.25</td>
<td>Yuan et al., 1992</td>
</tr>
<tr>
<td></td>
<td>200</td>
<td>0.5</td>
<td>1</td>
<td>Yuan et al., 1992</td>
</tr>
<tr>
<td></td>
<td>250</td>
<td>2</td>
<td>2</td>
<td>Yuan et al., 1992</td>
</tr>
<tr>
<td></td>
<td>150</td>
<td>1</td>
<td>2</td>
<td>Hovland and Judd, 1988</td>
</tr>
<tr>
<td>Mediterranean</td>
<td>200–300</td>
<td>0.5</td>
<td>Unclear</td>
<td>Dimitrov and Woodside, 2003</td>
</tr>
<tr>
<td>Patras Gulf</td>
<td>150</td>
<td>2–3</td>
<td>25</td>
<td>Haslott et al., 1996</td>
</tr>
<tr>
<td>Iberian Peninsula</td>
<td>20–50</td>
<td>2</td>
<td>Not available</td>
<td>Duarte et al., 2007</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>0.7</td>
<td>Not available</td>
<td>Garcia-Gil, 2003</td>
</tr>
<tr>
<td></td>
<td>150</td>
<td>1</td>
<td>Not available</td>
<td>Jané et al., 2010</td>
</tr>
<tr>
<td></td>
<td>100–200</td>
<td>5</td>
<td>Unclear</td>
<td>Lee and Chough, 2003</td>
</tr>
<tr>
<td>Okhotsk Sea</td>
<td>600–700</td>
<td>10</td>
<td>10</td>
<td>Luan et al., 2008</td>
</tr>
<tr>
<td>Fraser Delta</td>
<td>150</td>
<td>1.5</td>
<td>Not available</td>
<td>Judd and Hovland, 2007</td>
</tr>
<tr>
<td>U.S. East Coast</td>
<td>500</td>
<td>10</td>
<td>Unclear</td>
<td>Hill et al., 2004</td>
</tr>
</tbody>
</table>

Table 1 lists the dimensions of gas domes from around the world. The height of deflection associated with seabed domes is small relative to its width (refer to Table 1) due to the low strength of the sediments. This modest relationship is due to the lack of cohesion between soft sediments and the ease at which they fracture (Barry et al., 2012). Soft, un lithified sediments are easily broken apart or fractured making large deflections due to gas impossible. Increasing
the pressure or force against the sediment layer will eventually lead to sediment failure, release of trapped methane gas, and pockmarks. Pockmarks serve as good indicators of past or present mobile subsurface gas (Hovland and Judd, 1988).

Very little is understood of the stability of gas-induced seabed domes and it was not until the rise of deepwater drilling and global warming climate concerns that the domes and the gas trapped beneath them became a subject of interest. In order to avoid hazardous drilling conditions and potential blowouts, shallow gas and shallow gas feature identification is an important aspect of the offshore drilling process. Drilling rigs, platforms, and pipelines must all be placed away from subsurface gas accumulations that could create unstable seafloor conditions. Methane gas released by failed domes contribute to the greenhouse effect in the atmosphere and must be budgeted for in climatic models (Barry et al., 2012).

In order to quantitatively define the stability limits of a seabed dome, a relationship between the force causing deformation, the layer’s response to that force, and the properties of the layer must be understood. Because the seafloor is relatively thin, horizontal, and being deformed by a single force (buoyancy) from one direction, elastic thin plate bending theory can be used (Barry et al., 2012). The study of contact mechanics, the deformation between two objects in contact with one another, originated in the 1880’s with Hertz Law (Coste and Gilles, 1999). Describing rock behavior using contact mechanics and elastic thin plate theory are not new as several studies dating back to the 1960’s have applied thin plate theory to conditions such as the lithospheric response to the weight of mountain chains (Gudmundsson, 1999) and observed man-made bending in rocks (Sun, 1969). Although very few, if any, natural materials or sediments are perfectly elastic, behavior of sediments comprised of mainly clays have been well defined by elastic models (Hamilton, 1976; Barry et al., 2010). Previously, Barry et al.
(2012) assumed that the sediment layer is an elastic, single-phase medium with linear elasticity over all strain rates and used a circular isotropic plate with fixed edges to model deformation in laboratory experiments (Figure 21). Assuming a fixed-edge condition, while not seen in natural domes, is employed for its simplicity in this first-order pressure and allows for direct comparison to Barry et al. (2012) experimental laboratory results.

![Thin plate with fixed-edge condition](image)

**Figure 21.** Thin plate with fixed-edge condition. The figure demonstrates the elastic bending theory to be applied to observed gas domes in each study area. $P$, the pressure from the trapped gas, $w$, the amount of deflection associated with $P$, $a$, the radius of the dome, and $h$, the thickness of the layer being deformed. (Barry et al., 2012)

Small-strain, thin plate theory requires two conditions on the aspect ratio of the dome (Ugural, 1999). First, the plate radius, $a$, must be large in comparison to the plate thickness, $h$ (Figure 21). Previous published works on elastic bending theory such as Ventsel and Krauthammer (2001) suggest an $a:h$ ratio of at least 8:1 is needed for the theory to accurately characterize deformation while results from Barry et al. (2012) lab experiments suggest that the theory applies for $a:h$ ratios as low as 5:1. The second requirement is that the deflection, $w$, must be small in comparison to the elastic layer thickness, $h$. Previously studied domes (Table 1) all have widths, $2a$, that are at least 10 times greater than the deflection. Elastic thin plate theory has been applied to accurately predict pressures in experimental lab domes with a $w/h$ value as high as 0.2 (Barry et al., 2012).
To calculate the pressure responsible for natural seabed doming using elastic thin plate theory, the equation for deflection as a function of the radius for a thin circular, fixed-edged plate under uniform loading (Urugal, 1999) (1) was rearranged to solve for pressure (2),

$$w = \frac{P}{64D} \left( a^2 - r^2 \right)^2,$$

(1)

$$P = \frac{64wD}{\left( a^2 - r^2 \right)^2},$$

(2)

where $P$, pressure, is equal to the total overpressure applied along the bottom of the plate (sediments) minus any pressure from the overlying water and sediment column. $D$ is the flexural rigidity of the plate and is equal to $Eh^3/[12(1 - \nu^2)]$. $E$ is Young’s Modulus of the plate and $\nu$ is Poisson’s ratio. Young’s Modulus is a measure of the finite strength or stiffness of the sediments and can be defined as the ratio of stress over strain. Poisson’s ratio is the ratio of relative transverse contraction strain to the relative longitudinal extension strain in an elastically deformed material. Since clay sediments are assumed to behave elastically (Hamilton, 1976; Barry et al., 2010) in small strain conditions, Poisson’s ratio is equal to 0.5 in all calculations under the assumption that the seafloor is an incompressible, perfectly elastic medium. $r$ is the distance from the center of the dome at which the deflection is the greatest. In nearly all real world cases and in line with our uniform load equation, maximum displacement always occurs at the center of the dome ($r=0$). Substituting in our constant $\nu$ and $r$ values, equation (2) becomes

$$P = \frac{64w\left(\frac{Eh^3}{9}\right)}{a^4},$$

(3)
A second theory is needed when calculating the pressure responsible for larger deflections within seabed domes that cannot be explained in small-strain theory. Plate stretching theory is used when the value of $w/h$ is higher than 0.3 (Ventsel and Krauthammer, 2001). Some works (Ventsel and Krauthammer, 2001; Gould, 2013) have proposed that when the $w/h$ values rise above 0.3, mid-plane tensile stresses develop, adding resistance to deformation that cannot be accounted for in simple elastic thin plate theory. Plate stretching can account for this added resistance and larger deflection values. Barry et al. (2012) lab results in tidal flat Windsor sediments observed sediment failure at $w/h$ values as low as 0.1-0.2 and thus, did not find plate stretching to be a factor in sediment doming. Calculating pressure for a fixed-edged circular “stretched” plate with constant $r$ and $v$ values is shown in equation (4) (Urugal, 1999)

$$P = \frac{16E}{3} \frac{hw}{a^4} \left( \frac{2h^2}{1.5} + w^2 \right),$$  \hspace{1cm} (4).
Chapter 4: Results and Discussion

Investigation through SBP and side scan sonar data of the entire Mississippi Canyon Area resulted in only a 10 km² area in the northwest corner of the survey (Figure 13) containing evidence of gas. The focal point of the survey will be the gas and associated surface relief features in Blocks 731, 732, 733, 775, 776, and 777. While Blocks 819 and 820 contain small isolated occurrences of subsurface gas, they exhibit no associated surface deformation.

In the Thunder Horse field, identified domes were smaller in size than other published gas domes (Table 1), ranging from 97-131 m in diameter. All were roughly circular in shape, displaying similar axis lengths and exhibiting deflections <5 m. The locations of the domes within the survey area were random, with six of the domes found in two closely-spaced groups of three.

Three shallow gas accumulations were identified using the 3D volume of the Ninilchik field in Alaska. Ninilchik domes were buried in the subsurface at an average depth of 240 m within the Sterling formation and ranged from 3,022-4,572 m in diameter. Two accumulations were found within the offshore portion of the data and one onshore. Although thousands of meters long, relief for the underground domes ranged from 38-97 m.

Pressure results are based upon the three gas accumulations with subsequent sediment deformation found in the Ninilchik field data set and the nine seabed domes discovered in the Thunder Horse field geohazard survey. Thunder Horse field features from the Gulf of Mexico are labeled with the moniker “GOMDome” followed by a number. The number and order are for organizational purposes only. Likewise, gas accumulations in the Ninilchik field of Alaska are labeled as “AKGAS” followed by a number for ease of discussion (Table 2).
Table 2: Dome Parameters Used in Calculations

<table>
<thead>
<tr>
<th>Name</th>
<th>average $a$ (m)</th>
<th>axis ratio</th>
<th>$h$ (m)</th>
<th>$a/h$</th>
<th>$w$ (m)</th>
<th>$w/h$</th>
<th>$a/w$</th>
<th>low $E$ (kPa)</th>
<th>low D (Nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GOMDome1</td>
<td>47.9</td>
<td>1 to 1</td>
<td>8.1</td>
<td>5.91</td>
<td>2.4</td>
<td>0.30</td>
<td>19.96</td>
<td>840</td>
<td>4.96E+07</td>
</tr>
<tr>
<td>GOMDome2</td>
<td>55.8</td>
<td>1 to 0.75</td>
<td>6.2</td>
<td>9.00</td>
<td>3.4</td>
<td>0.55</td>
<td>16.41</td>
<td>840</td>
<td>2.22E+07</td>
</tr>
<tr>
<td>GOMDome6</td>
<td>43.3</td>
<td>1 to 1</td>
<td>9</td>
<td>4.81</td>
<td>4</td>
<td>0.44</td>
<td>10.83</td>
<td>840</td>
<td>6.80E+07</td>
</tr>
<tr>
<td>GOMDome3</td>
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<td>1 to 0.75</td>
<td>6.1</td>
<td>8.10</td>
<td>2.4</td>
<td>0.39</td>
<td>20.58</td>
<td>840</td>
<td>2.12E+07</td>
</tr>
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<td>1 to 1</td>
<td>7.5</td>
<td>8.33</td>
<td>4</td>
<td>0.53</td>
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<td>840</td>
<td>3.94E+07</td>
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<td>1 to 0.8</td>
<td>11</td>
<td>5.95</td>
<td>5</td>
<td>0.45</td>
<td>13.10</td>
<td>840</td>
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<td>GOMDome9</td>
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<td>39.60</td>
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<td>1 to 0.67</td>
<td>228.6</td>
<td>10.00</td>
<td>83.8</td>
<td>0.37</td>
<td>27.28</td>
<td>3,000</td>
<td>3.98E+12</td>
</tr>
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<td>1 to 0.195</td>
<td>152.4</td>
<td>11.95</td>
<td>38.1</td>
<td>0.25</td>
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<td>97.5</td>
<td>0.76</td>
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<th>Name</th>
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<th>$h$ (m)</th>
<th>$a/h$</th>
<th>$w$ (m)</th>
<th>$w/h$</th>
<th>$a/w$</th>
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<td>0.14</td>
<td>40.98</td>
<td>3,000</td>
<td>2.43E+08</td>
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<tr>
<td>AKGAS1</td>
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<td>1 to 0.67</td>
<td>228.6</td>
<td>10.00</td>
<td>83.8</td>
<td>0.37</td>
<td>27.28</td>
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<td>152.4</td>
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<td>0.76</td>
<td>15.50</td>
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<td>1.40E+13</td>
</tr>
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</table>
Results from calculating pressure using strictly equation 3, equation 4, and a combination of the two will be plotted against elastic thin plate theory to determine the best fit. Confidence of data and the real world limitations of sediments (cohesion, fracturing, etc.) not accounted for in plate theory must be considered and used to determine unrealistic or questionable results.

4.1 Measurements and Pressure Calculations Using Non-Plate Stretching Equation

To get an initial sense of the pressure values calculated by the elastic plate theory, the first calculations done on the twelve gas domes were calculated using the “stiff” plate equation 3. This assumes that regardless of the $w/h$ value, no additional in-plane stresses were involved adding to the resistance to deformation. Recall, equation 3 for stiff plates is $P = \frac{64w(Eh^3)}{9a^4}$.

Two assumptions must be made when solving for $P$. The first is for the variable $a$. The domes found in this study are not perfectly circular meaning the measurement taken for $a$ depends on the orientation in which it is taken. To mitigate the differences in radius length, two measurements for diameter were taken perpendicular to each other for each dome and averaged together. Axis ratio was also documented (Table 2) demonstrating how much each dome deviated from a perfect circle. All the domes in the Thunder Horse field exhibit an axis ratio of 1:0.7 or higher, meaning the short axis was never less than 70% of the long axis. Ratios of 1:0.75 are considered adequately comparable and an average of the two would result in a confident representation of the true radius. Ninilchik field domes were even less circular than GOM domes and averaging results in less confident pressure calculations.

The second assumption is the value of $E$, Young’s Modulus, for the sediments being deformed. Because $E$ values have not been measured for sediments in each data set, a range of known $E$ values for similar sediments are used. The clays and silts of the seafloor in the Thunder
Horse field are well approximated by fine-grained, near-seabed marine sediments with $E$ values of 840-3,000 kPa (Lavoie et al., 1996). Deformation of the Tertiary sediments in the Ninilchik field predominately consists of sands and clays that can be approximated by $E$ values ranging between the high end of clays and lower end of sands (3,000-60,000 kPa) (Birch et al., 1942). A range of $E$ values for like-sediments is used to bracket pressure calculations.

Table 2 lists the measurements, important ratios, assumptions, and variables needed to calculate pressure for low-end and high-end values for all twelve domes.

Barry et al. (2012) results concluded that deflection of sediments was possible from surprisingly small overpressures ranging from 1-420 Pa for the domes of Table 1. Calculated pressure values for non-plate stretching in Table 3 yielded a range of values spanning over one order of magnitude. For low $E$ values, pressure ranged from 499-14,166 Pa. High end $E$ values ranged from 1,331-50,594 Pa. It should be noted that the $E$ values used in Table 3 were 3-100 times greater than the $E$ values used in Barry et al. (2012). Pressure and Young’s modulus have a direct relationship resulting in expected pressure values 3-100 times greater than for that of the Windsor tidal flat sediments used in Barry et al. (2012) results.

In both low and high cases, the same feature, GOMDome9, was responsible for the highest pressure calculations at more than one magnitude greater than the next closest estimate. GOMDome9’s extraordinarily high value is attributed to its $a/h$ ratio of 2.2 making it by far the thickest plate in the data set. As a “thin” plate is described as having an $a/h$ ratio equal to approximately 8 or higher (Ventsel and Krauthammer, 2001), GOMDome9’s great layer thickness eliminates the possibility of accurately applying elastic thin plate theory. In addition, while a dome is found at the surface (Appendix A, Figure A23), the subbottom data for
Table 3 presents the pressures calculated using the two equations for thin plate mechanics. Pressures were calculated using the measurements listed in Table 2 to obtain a low-end and high-end value for each equation. The right column implemented both equations, using equation 3 when $w/h<0.3$ and equation 4 when $w/h>0.3$. Pressure values highlighted in green indicate domes with $w/h>0.3$ and thus calculated using equation 4 for flexible plates.

<table>
<thead>
<tr>
<th>Name</th>
<th>low $P$ (Pa)</th>
<th>high $P$ (Pa)</th>
<th>low $P$ (Pa)</th>
<th>high $P$ (Pa)</th>
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<td>24,007</td>
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GOMDome9 reveals an expanded section deep within Sequence 2 that cannot be explained as near–surface gas. Although excluded from consideration for future calculated pressures, GOMDome9 serves as an example as to how sensitive the pressure values are to increasing layer thickness.

4.2 Pressure Calculations Compensating for Flexible Plates Using Both Equations

Table 3’s results for equation 3 serve as a first-case baseline for estimated pressure values for each case. The differences between the concept of stiff \((w/h<0.3)\) and flexible \((w/h>0.3)\) plates was ignored for these first calculations. Plate stretching theory or the flexible plate equation incorporates the added in-plane tensile stresses that develop during large deformations. The hypothesis that accounting for this distinction between stiff and flexible plates would better characterize the domes in the study was tested. Table 3 displays results for using equations 3 and 4 for the same cases and geometries except that for all cases in which \(w/h>0.3\) equation 4 for plate stretching was applied.

The average difference between stiff plate behavior \((w/h<0.3)\) versus flexible plate behavior \((w/h>0.3)\) in the six applicable cases (highlighted in Table 3) is a 20.6% increase in pressure (Figure 22). The feature AKGAS2 was the most effected by the plate stretching equation with a 43.5% increase in pressure calculated, almost double the second largest change. This can be answered by the \(w/h\) values of each case. While all cases possess \(w/h\) values over 0.3, AKGAS2’s value of 0.76 makes its deformation approximately 40% larger than the second most deflected feature and thus most susceptible to the compensation in equation 4. This 0.76 \(w/h\) value is so large that it cannot be confidently explained solely by the pressures of trapped gas or by elastic thin plate theory. Future results and discussions will exclude AKGAS2.
Figure 22. Plate stretching equation effect. Pictured above is the difference between pressures for domes using the stiff plate equation (white) and the plate stretching equation (red).

### 4.3 Pressure Calculations Using Only Plate Stretching Theory

Final by pressure calculations were computed using only the plate-stretching equation (Table 3). The results are pressure values that are proportionally higher than stiff plate calculations based on the w/h value.
4.4 Discussion

Because AKGAS3 has one axis over 5 times longer than the next, it is best exemplified as a beam rather than a plate. When viewing the accumulation with interpreted faults, it is interpreted that the gas that created AKGAS3’s linear shape migrated up through the subsurface along a large vertical fault (Figure 23). This fault created the pathway necessary for the buoyant gas to move to the surface until it became trapped due to fault termination or an impermeable layer. The fault-side of the gas accumulation, the northwest edge, cannot be treated as a fixed-edge as in previous calculations. This present the unique scenario for a cantilever beam equation to be implemented and tested against previous methods to determine if, in fact, it presents more realistic results.

The equation for the deflection of a cantilever beam with uniformly distributed load is (Gere and Timoshenko, 1997),

$$w = \frac{qL^4}{8EI},$$

where $I$, moment of inertia, is a new variable that is equal to $b^3h/12$. $L$, in the numerator, is the length of the axis perpendicular to the fixed edge, $q$, is the force per unit length (analogous to pressure), and $b$ is the width of the beam against the fixed edge. By substituting in the values for $I$ and simplifying, for a cantilever beam with uniformly distributed load,

$$q = \frac{2b^3hEw}{3L^4},$$

(6).
Figure 23. AKGAS3 and fault. The interpreted surface displaying the fault displacement is the top of the Beluga formation, just below the Sterling formation where gas accumulations are found. The major northeast-southwest fault (white) through the Ninilchik field sits directly below AKGAS3 (circled in red).

Calculated pressure values for AKGAS3 as a cantilever beam versus the initial computations as a circular plate are presented in Table 4. An average radius was used in the plate equations while the cantilever beam equation makes the distinction between $L$ and $b$.

Table 4. AKGAS3 Beam Theory Results

<table>
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<th>AKGAS3 Equations</th>
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<td>Non-Plate Stretching Circular Plate</td>
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<td>5230</td>
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<tr>
<td>Plate Stretching Circular Plate</td>
<td>274</td>
<td>5476</td>
</tr>
<tr>
<td>Cantilever Beam</td>
<td>2.64E+09</td>
<td>5.28E+10</td>
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</table>
The accumulation AKGAS3 is a unique cantilever beam in the sense that the beam, \( L \), is the short axis when compared to \( b \), the width of the beam. Because AKGAS3 is not the typical description of a cantilever beam, the force required to deform a beam with such a proportionally high \( b \) value is extreme. Although a cantilever beam equation better represents the geometry of AKGAS3, the calculations suggest an unrealistic amount of force required for the observed deflection and deformation cannot be solely explained by buoyant gas forces (Table 4).

From the 12 initial domes used in the pressure calculations, 3 are not consistent with elastic thin plate mechanics. All domes, with the exception of GOMDome9, AKGAS2, and AKGAS3 whom have been previously discussed and dismissed, will be represented unless otherwise specified. The 9 resultant pressure data points calculated from each dome with the three equations (plate stretching, non-plate stretching, and mixed) are plotted along with 72 control data points calculated using plate stretching equation to highlight differences between equations. The two most influential conditions involved in layer doming are the \( \text{w/h} \) ratio, the amount of deflection the layer has undergone, and the \( \text{a/h} \) ratio or thickness of the deformed layer. The elastic thin plate theory plot, which covers the entire range of \( \text{a/h} \) and \( \text{w/h} \) values found in this study, demonstrates the pressure response as it relates to the aspect ratios of each dome (Figure 24). Each equation can be plotted in the same way (Figures 25, 26, and 27) to illuminate any deviations from the theory and determine best fit.

Graphically, there is little difference between the three equations compared to Figure 24 or to one another. This indicates that there is little advantage in making the distinction between stiff and flexible plates with equations 3 and 4 assuming all aspect ratio relationships remain constant. Small pressure values, the purple in Figure 24, are required to deform a thin plate to almost any \( \text{w/h} \) ratio. Six domes from this study, all the domes from Table 1, and most gas-
Figure 24. Elastic thin plate theory. Increasingly “hot” colors represent the higher pressures (Pascals) calculated when w/h and a/h increase. Low pressure values are needed for the deflection of domes with a/h values greater than 8 (thin plates). Pressure begin to increase dramatically when w/h and a/h increase together (the northwest quadrant). Black squares are computed values from a range of a/h and w/h. Pressures were calculated using a low-end E of 840 kPa.

Figure 25. Non-plate stretching equation plot. The nine remaining domes (yellow) are plotted along with the values from Figure 24. Although very similar to Figure 24, small disturbances (waves in the pattern) originate from GOMDome6 (w/h= 0.44) and GOMDome4 (w/h=0.53). Pressures calculated using a low-end E of 840 kPa.
Figure 26. Combination of equations plot. The combination approach, applying equation 3 to all domes with a $w/h \leq 0.3$ and equation 4 for $w/h > 0.3$, eliminated the deviations from the theory seen in Figure 25 and closely mirrors Figure 24. A small deviation at GOMDome1 ($w/h = 0.3$), which lies directly on the border between stiff and flexible plate, is observed suggesting GOMDome1 should be treated as a flexible plate rather than stiff. Pressures calculated using a low-end $E$ of 840 kPa.

Figure 27. Plate Stretching equation plot. Equation 4 has eliminated any problems seen in Figures 25 and 26 and is most similar to Figure 24. There are no observable discrepancies with applying equation 4 to domes with low $w/h$ values. Pressures calculated using a low-end $E$ of 840 kPa.
induced domes due to their gentle slope and large radii would fall into this zone. Pressures begin
to climb drastically as $a/h$ and $w/h$ increase together (trending towards the northwest corner)
peaking at 8,500 Pa for our low $E$ value calculations. This positive relationship has been
previously discussed and is expected as computed $P$ is proportional to $h^3$.

Although visually there is little difference, the math would argue that the plate stretching
equation produces the best results for two reasons. The first reason is that unlike the combination
method, it does not incorporate two different equations, assuring all ratios remain equal. The
second is that the inherent compensational effects produced by equation 4 for the in-plane
stresses for domes with a $w/h$ ratio of less than 0.3 is minimal when compared to assuming stiff
plate behavior (equation 3) across a larger range of deflections and thicknesses. This can be seen
in comparing the data point GOMDome6 in Figures 24 and 25. Due to GOMDome6’s large
deflection and thick layer, calculated pressures will be on the high end of the spectrum, resulting
in a greater difference between equations 3 and 4 than when compared to a thinner, less deflected
dome. This causes a noticeable perturbation due to the equation not accounting for plate
stretching in a case that possesses a high $w/h$ value of 0.44 and a thick $a/h$ value of 4.81.

Equation 4, plate stretching method, can produce better comprehensive pressure calculations
over a range of deflections due to the small variance on the low end.

This reasoning is based on the idea that near-surface cohesive sediments can be deformed
at ratios higher than the 0.13-0.2 $w/h$ failure point cited in Barry et al. (2012) for Windsor tidal
flat sediments. To withstand larger deflections, the deforming layer would require a higher
tensile strength or more cohesive sediments to avoid sediment collapse. In the Gulf of Mexico,
where sediment $E$ values are already more than 3 times the values used for Windsor sediments,
this could be accomplished by the previously stated cementing nature of gas hydrates or the
cohesive nature of a possible hemipelagic mud layer covering the seafloor. Cementation of the grains increases the tensile strength of the sediments and can reduce fracturing that leads to dome failure. Further experimentation and research of the doming capability of gas hydrates and partially cemented clays are needed as increased cementation can reduce flexibility in the layer. A muddy, clay-rich sealing layer would result in increased cohesion between the greater number of grains, theoretically strengthening the domed layer and increasing the resistance to sediment failure. Ninilchik field domes, although sandier than the Gulf of Mexico domes, are buried at shallow depths and thus more compacted than sediments at the surface. It is because of this that they could withstand more deformation and require much more gas pressure to form.

Once the \( w/h \) value of tested domes in the Barry et al. (2012) study reached their failure point (0.13-0.2), the sediment layer began to fracture vertically, resulting in a reduction of \( h \) (and thus \( P \)), and a decrease in the measured pressure compared to calculated theoretical pressure was observed. Considering all but one dome in this study has \( w/h \) values higher than this threshold, possible fracturing within the domes could recreate the same pattern seen in Barry et al. (2012) and actual pressure values could be far less than predicted by the theory.

The calculated values for pressure are presented based on a low end \( E \) value and a high end \( E \) value for typical sediments similar to the ones found in each location. Compared to the pressure results calculated for the domes in Table 1 in Barry et al. (2012), it is reasonable to suggest that the low end \( E \) value of 840 kPa used for the Gulf of Mexico domes is more representative of the sediments. Low end values more closely align with the calculated pressures of other worldwide domes from Barry et al. (2012), whereas high end pressure values are generally 4-8 times larger. Those high end values are not predicted in other known domes of similar sediments. Although, gas hydrates are found within the study area in the Gulf of Mexico
that could be part of the gas accumulation/dome system that would contribute to the stability of the sediments and give credence to such high $E$ values. Given the relatively small size of the domes found in the Thunder Horse field (tens of meters in diameter), it is unlikely that the limited volume (Appendix A, Figure A30) of sediment within the dome would contain enough gas (gas saturation) to produce the high pressure numbers associated with large $E$ values. More information such as porosity, gas saturation, and the physical properties of methane would be needed to determine if such large values could be valid.

Two equations, both for clamped-edged circular plate deflections, were used to quantify the pressures based on the amount of deflection observed. The clamped-edged condition is used for direct comparison to Barry et al. (2012) results. While these comparisons are important within this study, the clamped-edge condition is not an accurate representation of the actual seabed conditions. The resulting predicted pressures will be higher, due to the clamp-edges, than actual pressures at the seafloor. Calculations done with different equations for a free-edge condition may be more accurate but less open to comparisons within this study.

Domes with $a/h$ values of 8 or more in this study best fit the elastic thin plate theory plot and produced pressures values similar to other subsurface gas seen in other worldwide examples. This distinction agrees well with other noted limits for thin plates put forth by Ventsel and Krauthammer (2001) and Barry et al. (2012) ($a/h>5$).

Due to geologic differences between the two locations, results from the two locations should be viewed with proper context. It is worth noting the major differences that are found in each data set. The Ninilchik “domes” are thousands of meters long buried at approximately 240 m depth in a transpressional stress regime made up of predominately sands and clays. Seabed domes in the Thunder Horse data set are on the order of tens of meters, found at the surface of
the seafloor, consists mostly of a mix of silts, clays, and hemipelagic mud, and could be influenced by deeper salts. Steps to accommodate any number of unique differences, like the previously discussed beam-shaped AKGAS3 feature, must be considered.

The gas accumulations in the Ninilchik field in the Cook Inlet are less consistent with elastic thin plate theory than their Gulf of Mexico counterparts with only one feature exhibiting the dimensions and characteristics expected by a circular plate deflection. That feature, AKGAS1, was the only data point from Alaska that was not rejected, even though its axis ratio of 1 to 0.67 ranks it the worst among testable domes. The beam-like AKGAS3 did not possess the geometry to be considered a circular plate and was tested independently using beam equation, although yielding unrealistically high results due to its unique width to length ratio. Finally, AKGAS2 was the smallest Ninilchik feature in terms of average radius but displayed the most deflection for a measured w/h value of 0.76. This much deflection raises questions as to whether solely gas can be responsible for such deformation to clays and sandstones at 244 m depth and whether the elastic plate equation can be confidently applied. A more likely explanation is either the active transpressional forces of the Ninilchik Basin caused anticlinal deformation in addition to the presence of gas, an undetected fault or poor seismic signal resulted in a poor measurement (human error), or a combination of all three.

Gaps in the subbottom data coverage in the Thunder Horse data set prohibited precise layer thickness measurements for some dome features. In cases such as GOMDome4, GOMDome5, GOMDome7, and GOMDome10, the nearest available data was used for measurement. The exact amount of error for each case is a function of how much change in layer thickness occurs between the actual dome and the nearest SBP line. Because thickness values range between 6-11 m in all cases, potential errors should range from centimeters to no greater
than 4 m. Calculations and results interpreted on their behalf come with less confidence due to the important relationship between pressure and thickness as discussed.

Pockmarks comprised over half of the surface features identified in the Thunder Horse field data set primarily located interspersed with the domes and craters found in the northwestern quadrant of the survey. An attempt to predict the pressure responsible for their creation based on applying the same principles of elastic thin plate theory used for their counterpart, domes, was hypothesized. The idea founded on the fact that all variables in the equations for domes could be found in pockmarks with the exception deflection. The assumption that depth to the center of the pockmark is equal to the maximum deflection was made to allow for application of the equation.

Despite the abundance of pockmarks identified in bathymetric data, because of their small size (<30 m), only a the small number of pockmarks were imaged by SBP data. Additional SBP data is required to test this hypothesis.

Steps to improve this study and for future work can be made by acquiring more data to reduce approximations that limited this study. Core or actual sediment samples would be the first step in new data. Cores and direct observation of the domes would help make the distinction between sediment dome and gas hydrate when SBP data is inconclusive. Determining the Young’s Modulus of the sediment through core samples would provide direct calculated pressure values rather than a range. Cores, also, could allow for porosity measurements which would help to determine the gas saturation. This would aid in determining whether the pressure predicted from thin plate mechanics is feasible for domes of differing sizes. Calculated pressure values would be best improved with accurate thickness values for each case. Additional SBP data to directly image each dome would provide accurate thickness values, thus reducing the large error range created by the direct relationship between $h$ and $P$. 
Chapter 5. Conclusions

Two data sets were interpreted using the geophysical data available to find, geometrically describe, and predict pressures using elastic thin plate theory for gentle, gas-induced domes at the seafloor and shallow subsurface. Three shallow gas accumulations with sediment doming were identified in a 3D seismic survey in the Ninilchik field of the Cook Inlet, Alaska. A geohazard survey consisting of multibeam bathymetry, scan sonar, and echo-sounder subbottom data was conducted in the Thunder Horse field in the Mississippi Canyon Block of the Gulf of Mexico where nine seabed domes and numerous other gas-related features (pockmarks, craters, gas hydrates, authigenic carbonate outcrops) were formed.

First-order predictions for the pressures responsible for the observed doming were calculated using a low and high end range of elastic modulus based on the model put forth by Barry et al. (2012).

Three of the original 12 domes were removed from consideration for application of elastic thin plate theory for failing to meet theory requirements: (1) GOMDome9’s \(a/h\) value of 2.2 was nearly four times greater than the acceptable thickness ratio for thin plates \((a/h \geq 8)\); (2) AKGAS2 had a measured \(w/h\) value of 0.76, which considering the properties of a compacted sandstone suggest that the presence of gas alone could not account for such a large deformation; (3) finally, AKGAS3’s axis ratio of 1 to 0.195 is better described as a beam than a plate. Pressure estimates using an elastic cantilever beam for AKGAS3 produced improbably high pressure results.

Calculated pressures from the nine remaining Gulf of Mexico domes ranged from hundreds of Pascals to tens of thousands of Pascals, depending on the assumed elastic properties.
of the deformed sediments. Low-end Young’s Modulus values resulted in more reasonable pressures considering the limitations of gas saturation and the size of domes. These values, also, more closely resembled the calculated pressures from other seabed domes (Table 1) and doming observed in lab experiments (Barry et al., 2012).

Pressures required to produce the domes were calculated using: (1) a stiff plate equation (non-plate stretching); (2) a flexible plate equation (plate stretching equation); and (3) a combination of stiff and flexible based on the w/h value. The difference between stiff and flexible plates is a 20.6% average increase in pressure calculated that is proportional to the amount of deflection. Calculating pressure using only the plate stretching equation produced the best results for the nine domes because it better accounted for the large deflection features while having minimal effects on “stiff” plate features.

The Gulf of Mexico dome, GOMDome1, possesses w/h value of 0.3 which lies directly on the fence between stiff and flexible plates. This value is better expressed as a flexible plate plotted with equation 4 based on Figure 26.

Domes with a/h values of 8 or higher produced the smallest, most reasonable predicted pressures as expected. Due to the power-law relationship between pressure and plate thickness, domes with values of a/h less than 8 require drastically higher pressures to deflect and become increasingly less plausible.

Higher w/h values observed in the Gulf of Mexico domes could be attributed to gas hydrate cementation or the added cohesive nature of a hemipelagic mud layer caking the seafloor sediments. High pressure values are expected in the Cook Inlet due to the higher E value of sandstones when compared to clays and the compaction of sediments due to recent burial. While
gas-related deformation is quite possibly a factor in the subsurface of the Ninilchik field, it is unlikely that the aforementioned deformations in this study are exclusively due to gas. Concerns of the shape and depth of gas-dome complexes, the elastic properties of the sediments being deformed, and regional tectonic forces make it difficult to confidently predict pressures based solely on elastic plate theory inadequate.

The application of elastic plate theory to pockmarks was attempted in the Gulf of Mexico data set with indeterminable results. Data limitations impeded a large sample size and loss of distinct sedimentary layers due to sediment collapse and infill resulted in ambiguous thickness measurements.

Despite their smaller size than other gas dome complexes, the Gulf of Mexico domes were best suited for the application of elastic thin plate theory due to their aspect ratios and high resolution data. The higher $E$ values (840-3,000 kPa) of marine, seabed sediments than those used in the Barry et al. (2012) experiments (30-255 kPa) are theoretically better suited for the theory as it is primarily used in calculations of stiffer materials such as steel. The pressures calculated from these domes may serve as a first approach in quantitatively predicting the pressure involved in subtle seafloor doming in the Thunder Horse field. This knowledge when paired with an understanding of the failure point of marine sediments can assist in predicting and avoiding dome collapses that present a hazard to deepwater drilling operations and an increase in atmospheric methane totals.
References


Appendix A. Gulf of Mexico Data

*Survey lines are not displayed. Planes viewed within the images have no specific orientation and serve only to highlight topography. Vertical relief features are exaggerated 5x. Subbottom data contain cells that are 150 meters in length and 15 meters in depth.

GOMDome1

Latitude: 28°14'22.4230"

Longitude: -088°33'33.5285"

Figure A1. GOMDome1 view from above.
Figure A2. A ground level view of GOMDome1.

Figure A3. Subbottom data for GOMDome1.
GOMDome2

Latitude: 28°14'18.9439"

Longitude: -088°33'31.2704"

Figure A4. GOMDome2 view from above.
Figure A5. A ground level view of GOMDome2.

Figure A6. Subbottom data for GOMDome2.
GOMDome6

Latitude: 28°14'31.7633''

Longitude: -088°32'58.7012''

Figure A7. GOMDome 6 from above.
Figure A8. Ground level view of GOMDome6.

Figure A9. Subbottom data of GOMDome6.
GOMDome3
Latitude: 28°14'43.5467"
Longitude: -088°33'04.0001"

Figure A10. GOMDome3 view from above.
Figure A11: Ground level view of GOMDome3.

Figure A12. Subbottom data of GOMDome3.
GOMDome4

Latitude: 28°12'52.9037"
Longitude: -088°35'29.3595"

Figure A13. DOMDome4 view from above.
Figure A14. Ground level view of GOMDome4.

Figure A15. Subbottom data of GOMDome4. The line above does not directly dissect GOMDome4. This is line 24 of the survey, the closest available data.
GOMDome7

Latitude: 28°14'24.9037"

Longitude: -088°33'41.3187"

Figure A16. GOMDome7 view from above.
Figure A17. Ground level view of GOMDome7.

Figure A18. Subbottom data for GOMDome7.
GOMDome5

Latitude: 8°12′20.5883″

Longitude: -088°37′17.7555″

Figure A19. GOMDome5 view from above. GOMDome5 was found within a large depression pictured above. To the right, the gas expulsion crater can be seen.
Figure A20. A ground level view of GOMDome5.

Figure A21. Subbottom data of GOMDome5. Sediment collapse during the formation of the depression disturbed the shallow sediment layers near the surface. The discontinuous nature of the acoustic signal led to more ambiguous thickness values and lower confidence in final calculations.
GOMDome9

Latitude: 28° 12' 50.8677"

Longitude: -088° 35' 40.6459"

Figure A22. GOMDome9 view from above.
Figure A23. A ground level view of GOMDome9.
Figure A24. Subbottom data of GOMDome9. Unexplained expansion of sediment layers at approximately 45 meters depth in Sequence 2 can be seen in subsurface data. GOMDome9 was excluded from thin plate calculations due to the large thickness of the deformed layer.

GOMDome10

Latitude: 28.243159°

Longitude: -88.548875°

Figure A25. GOMDome10 view from above.
Figure A26. A ground level view of GOMDome10.

Figure A27. Subbottom for GOMDome10. The line and gas featured above are not of GOMDome10 but the closest available data. Line 48 and feature GOMDome6 due to their close proximity and well imaged defined thickness values.
Figure A28. Bathymetry map of the northwestern portion of geohazard survey with Gulf of Mexico dome locations. Numbers correspond to the GOMDome with same number. Locations are approximate and only provide domes location relative to one another. Refer to individual cases for exact locations. “GE” represents the gas expulsion crater.
Figure A29. Extent of mass movement deposits in survey. Mass movement deposits (green) were mapped as part of the shallow geohazard survey. They cover most of the northwestern corner, pinching out to the south and east into the middle of the map (BP geohazard report).
Volume Measurements

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<th>Name</th>
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<th>$h$ (m)</th>
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Figure A30. Volume measurements. The volume of each dome was calculated by treating each dome as a spherical cap and using the equation $V = \frac{\pi h}{6} (3a^2 + h^2)$. If gas saturation is known, this value can be used to determine the volume of gas responsible for doming and how much potential methane could be released upon failure.
Appendix B. Cook Inlet Data

AKGAS1: Longitude: 60.172739  Latitude: -151.507339
AKGAS2: Longitude: 60.108707  Latitude: -151.547658
AKGAS3: Longitude: 60.219152  Latitude: -151.468009

Figure B1. GoogleEarth view of Ninilchik field survey. The location of the seismic survey and individual gas accumulations are overlain on a GoogleEarth image of the Cook Inlet. AKGAS1: red AKGAS2: yellow AKGAS3: black
Figure B2. AKGAS1 view from above.

Figure B3. A combination of crossline and inline planes merge at AKGAS1 (yellow circle).
Figure B4. AKGAS2 view from above.

Figure B5. Inline and crossline view of AKGAS2.
Figure B6. AKGAS3 view from overhead.

Figure B7. Inline and crossline view of AKGAS3. The extent of the gas on the crossline is very limited due to the beam-like shape of the accumulation.
Figure B8. AKGAS3 and fault. AKGAS3’s beam-shaped gas accumulation (red) runs along a large interpreted fault (purple) in the Ninilchik field. The fault allowed for both the gas to migrate upwards and the oblong shape to form.
Vita

Michael Ian Thoma was born in Shreveport, Louisiana in 1988. He graduated from Captain Shreve High School in 2007 and enrolled at Louisiana State University the following Fall. After a freshman year of undecided studies, he declared a Geology major and eventually graduated with a Bachelor of Science in geology in August 2011. Immediately following graduation, Michael decided to pursue his Master’s degree in geology at Louisiana State University with the overall goal of working in the oil and gas industry after graduation. He spent both summers of his Master’s degree working internships as an exploration geologist in onshore Louisiana for Stroud Exploration Co. and Oden & Associates, LLC and offshore Gulf of Mexico for Nexen USA Inc. Michael was offered a full time position as a Graduate Geologist for BHP Billiton in Houston, Texas and plans to begin his career with them in the summer of 2014.