Investigation into potential gas hydrate and gas zones off the South African coastline

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Abstract

Abstract Gas and petroleum products are important to modern life and, as peak oil is reached, the search is on for alternative fuel sources. A natural gas hydrate, also known as a clathrate, is formed when a gas molecule (such as methane) is trapped in a lattice of ice. Once considered oilfield nuisances, they are now being considered as an alternative fuel source. I asked whether any indications of hydrates, and gas, were present off of the South African coastline within Block 2. Two hundred and sixty (260) pre-processed seismic lines and eighteen (18) well reports were provided by the Petroleum Agency of South Africa (PASA) for review and study. Within these, evidence of gas was abundantly clear. The presence of gas, and thus a gas source, is a good indicator that - should the other formation conditions be present - hydrates could occur in this area within the Gas Hydrate Stability Zone (GHSZ). Unfortunately, no bottom simulating reflectors (BSRs) - the clearest indicator of gas hydrates - were found. These findings do not, however, confirm the absence of gas hydrates as where there is gas, there may be hydrates. The field of hydrate research is still new in terms of technology and practical applications, and the means to extract and produce hydrates is still expensive. However, in the drive for more sources of power to supply a growing demand, the South African government has already drafted a plan to develop infrastructure for future gas market developments. When developed, this infrastructure could potentially make use of the gas found within Block 2 and its surrounds and, as the technology to detect and extract methane hydrates becomes more mature (and associated costs to extract and produce it drop), it may prove to be a valuable additional future resource as well.

Plagiarism declaration

I know the meaning of plagiarism and declare that all of the work in the dissertation, save for that which is properly acknowledged, is my own.

B. K. Smith

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Chapter 1

Introduction

1.1 Background

Gas and petroleum products are important to modern life - for power, fuel, food or light. Drilling for hydrocarbons occurs in areas where the geological conditions for the generation and collection of oil and gas prevail. While oil and gas are drilled and transported, a phenomenon - gas hydrates - was noticed in the offshore pipelines, Arctic fields and high-pressure underground storage facilities. A gas hydrate, also known as a clathrate, is formed when a gas molecule (such as methane) is trapped in a lattice of ice (Figure 1.1). Once considered oilfield nuisances, they are now being considered as an alternative fuel source.

Research, exploration and exploitation of gas hydrates is a relatively new field. Hydrates were previously identified for avoidance as they could pose safety hazards in drilling, often associated with sub-marine geohazards. It has also been suggested that the natural storage and release of gas hydrates may have been associated with climate changes.

Hydrates are constrained by three main factors: a low temperature; a high pressure; and the amount of organic matter present. This restricts them to Polar waters, continental shelves and Polar permafrost and tundra. The zone where hydrates may form is known as the Gas Hydrate Stability Zone (GHSZ).

Despite holding a large volume of gas under pressure, gas hydrates are difficult to extract safely and efficiently. This technological drawback means that experimental production wells are limited and are either national or international collaborative projects. Gas hydrates have been produced from test wells at Messoyha (Russian permafrost), Mallik (Canadian permafrost) and Nankai (deep water trough off Japan). To commercially exploit gas hydrates as a resource, the test wells have to work and, more specifically, areas of hydrates need to be identified. Technological drawbacks mean that this is expensive.

This dissertation is focussed on identifying possible sources of hydrates within the South African context. In order to do this we need to understand more about gas hydrates, how they form and where they are likely to be found.

1.2 What is a hydrate?

Hydrates have been known to scientists for almost 200 years but mostly as a curiosity. In the 1930's a more serious study of the phenomena began when a discovery was made that gas pipelines, especially in cold climates, were being plugged with this substance owing to the fact that the pipelines often supported the thermodynamic conditions necessary for hydrate formation (Demibras, 2010). The problem of pipeline blockages increased in the 1970's when plugging in even the largest diameter pipelines from offshore, Arctic fields, or in the wells from high-pressure underground storage facilities, was reported (Atilhan *et al.*, 2012). Hydrates are sometimes referred to as "Fiery Ice" or "burning snowballs" for their ability to burn spectacularly. This phenomenon is caused when the gas hydrates dissociate - due to decreasing pressure or increasing temperature - and the ice lattice collapses, releasing the methane which can then be ignited (HeriotWatt, 2013). This process is shown in Figure 1.2.

Gas hydrates, or clathrates, are formed when a gas molecule such as methane is trapped in a lattice of ice - a clathrate, as shown in Figure 1.1. Clathrate comes from the Latin word meaning to encage and is one of a class of compounds where larger molecules are encircled by cages of different molecules (Collett, 2004). Methane clathrates, as opposed to clathrates of larger molecules such as propane or isobutane, appear to be the most common form found in nature (Burwicz *et al.*, 2011; Collett, 2004), and can be either biogenic (formed by microbial decay of organic matter) or thermogenic (formed by thermal cracking of sedimentary organic matter into hydrocarbon liquids and gas) in origin (Demirbas, 2010b).

1.3 How do they form?

Bacterial gas formed during early diagenesis of organic matter can become part of a gas hydrate in continental shelf sediment. Similarly, thermogenic gas leaking to the surface from a deep

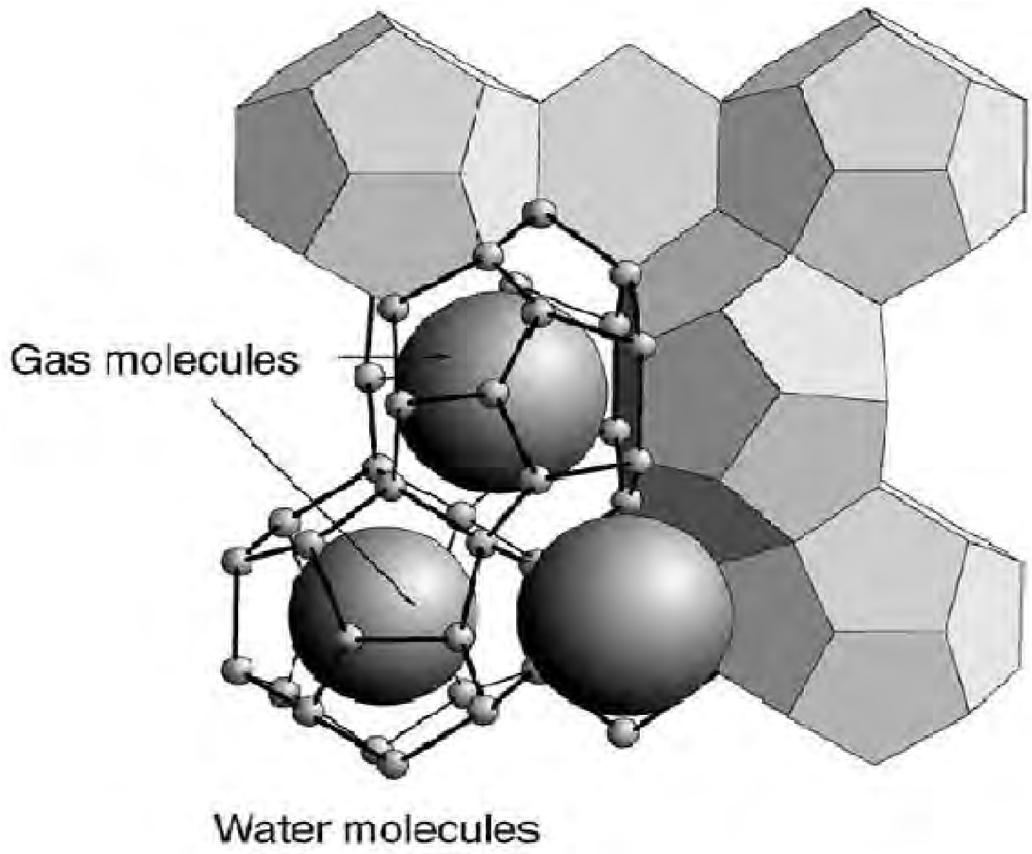


Figure 1.1: Model of a clathrate. A cage of water molecules surrounding a gas molecule (potentially methane).

thermogenic gas accumulation can form a gas hydrate in the same continental shelf sediment (Demirbas, 2010a; Sloan. Jr, 1998).

While the precise mechanisms of gas hydrate formation and decomposition still remain unclear (Saito and Suzuki, 2007), accepted knowledge agrees that the formation of gas hydrate is controlled by four main factors: Temperature, depth / pressure, sedimentation rate and amount of organic matter.

The first factor needed for hydrates to form is a low temperature, between 0° C and 10° C (273K - 283K) which is most likely to be found beneath permafrost on land and below the colder bottom waters in a marine setting. Secondly, a high pressure must be present - greater than 3Mpa - which is usually found offshore in sediments which are more than 300 m in depth below the sea surface, according to Kvenvolden (1999). Another important factor that needs to be present is organic matter; this should be present in amounts of greater than 1%. In addition to these major factors, a high sedimentation rate of greater than 1 cm per thousand years has

Figure 1.2: Gas hydrate burning as the methane within the ice lattice, released (dissociated) through either a decrease in pressure or an increase in temperature, is ignited (Left:(GNSScience, 2009))(Right:(Reardon, 2013))

also been shown to be significant in some cases (Chazelas *et al.*, 2006). This approximates to more than 10 metres per million years. The porosity of the sediments may contribute to a far lesser degree (Behseresht and Bryant, 2012).

The formation factors are balanced against one another as shown by the phase diagrams in Figure 1.3 A and B (after Collett (2004)). As depth, and thus pressure, increases below the ground surface (Figure 1.3A), there may be a formation of hydrates. The solid red line of the phase boundary establishes the upper / shallower boundary of the methane hydrate. Temperature and pressure, furthermore constrains the deeper boundary of the zone of gas hydrate through the geothermal gradient. The geothermal gradient (represented on the diagrams as a dashed red line) describes the rate at which temperature increases as depth below the ground surface, or seafloor increases. This rate varies depending on geographical location and mineral composition of the surrounding rock or sediment and determines the thickness of the hydrate layer, the lower the temperature / depth gradient, the thicker the layer. The base of the gas hydrate layer (blue dashed line) is determined by the point at which the phase boundary crosses the geothermal gradient, as hydrate will not remain stable if its icy lattice is heated to the point at which it dissociates. Above this temperature (below the base of the gas hydrate) free gas, or gas and water may be found within the sediments. The grey, dashed line shows 0° C (273K) for reference in both diagrams and cuts the phase boundary in both cases at ~300 m (approximately 3MPa).

There are some minor variations when it comes to the interaction of formation factors in marine hydrates. As with the explanation of Figure 1.3A, pressure increases with depth - below the sea surface and then below the seafloor (Figure 1.3B) - providing the conditions necessary for the formation of hydrates. Once again the solid red line of the phase boundary defines one margin of the zone of gas hydrate. Gas hydrates do not form in the water or ocean due to the low concentration of methane (Borowski, 2004) and thus the upper, or shallower, limit is the water / sediment interface. The red dashed line represents the hydrothermal gradient through the water column, which has a small negative temperature / depth gradient compared to the relatively large positive geothermal gradient below the seafloor. The geothermal gradient determines the deeper extent of the methane hydrate, as determined by the point at which it crosses the phase boundary. The y-axis on Figure 1.3B was mislabelled by Collett (2004) as the "Depth (meters below **seafloor**)". This could clearly not be the case as the water / sediment interface is clearly marked on his figure, as well as the fact that, if accurate, the zone of gas hydrate would be found between 1.2 km and 1.5 km beneath the seafloor surface - a depth that would undoubtedly be associated with a temperature too high to sustain hydrate.

After initial formation, the continued presence of gas hydrates is controlled by the Gas Hydrate Stability Zone (GHSZ), where the conditions are balanced to develop and sustain gas hydrates. Even though the conditions of temperature and pressure may be favourable for hydrate occurrence, they may not always occur due to the lack, or cessation, of one of the three driving mechanisms. As schematically illustrated in Figure 1.4B the stratification of the GHSZ in marine environments may display the following characteristics, in order of depth: water, watery sediments, sediments with hydrate within their pore space, base of the hydrate stability zone, free gas within permeable and porous strata.

1.4 Where are they found?

Gas hydrates can broadly be found in three major settings where the factors controlling their formation combine to create the most favourable or stable environment: high latitude South and North Polar waters; the continental shelves or slope; and in the Polar permafrost or tundra, as seen in Figure 1.5. More specifically, Kvenvolden and Lorenson (2001) state that natural gas hydrate occurs worldwide in oceanic sediment of continental and insular slopes and rises of active and passive margins, in deep-water sediment of inland lakes and seas, and in polar sediment on both continents and continental shelves. In aquatic sediment, where water depths exceed about 300 m and bottom water temperatures approach 0° C, gas hydrate is found at the

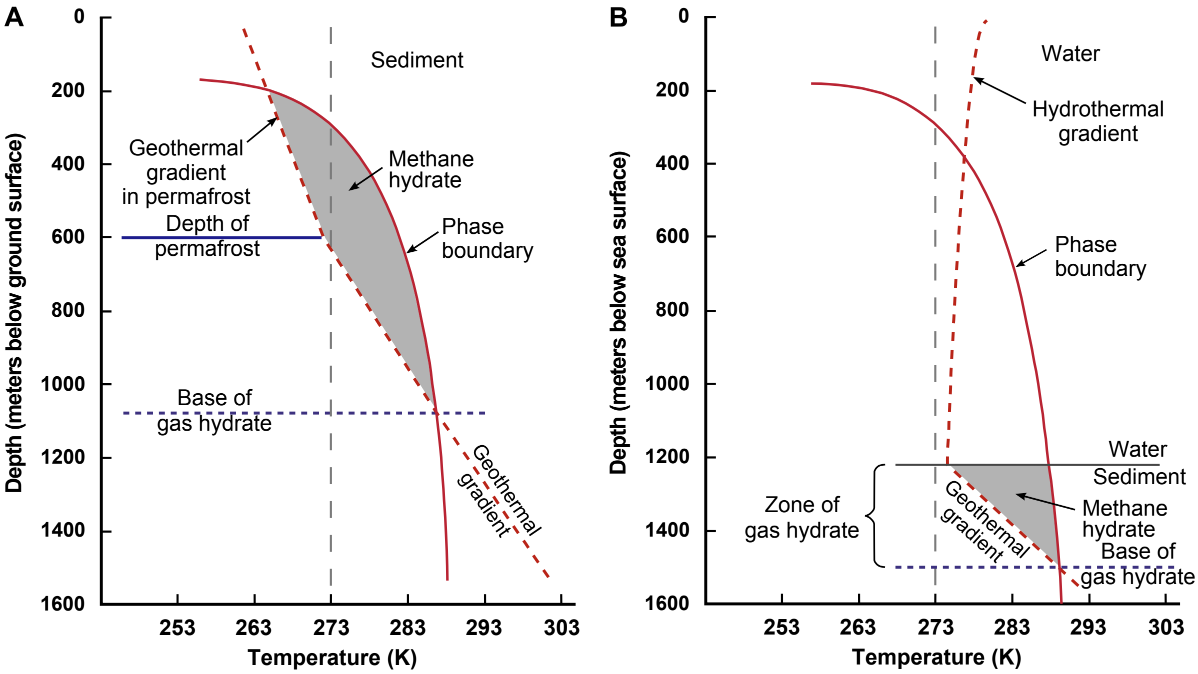


Figure 1.3: Phase boundary diagrams demonstrating the gas hydrate stability field in grey by showing the depth-temperature zone in which methane hydrates are stable in A) a permafrost region and B) an outer continental margin marine setting (after Collett (2004)). The grey dashed line shows 273 K / 0° C for reference.

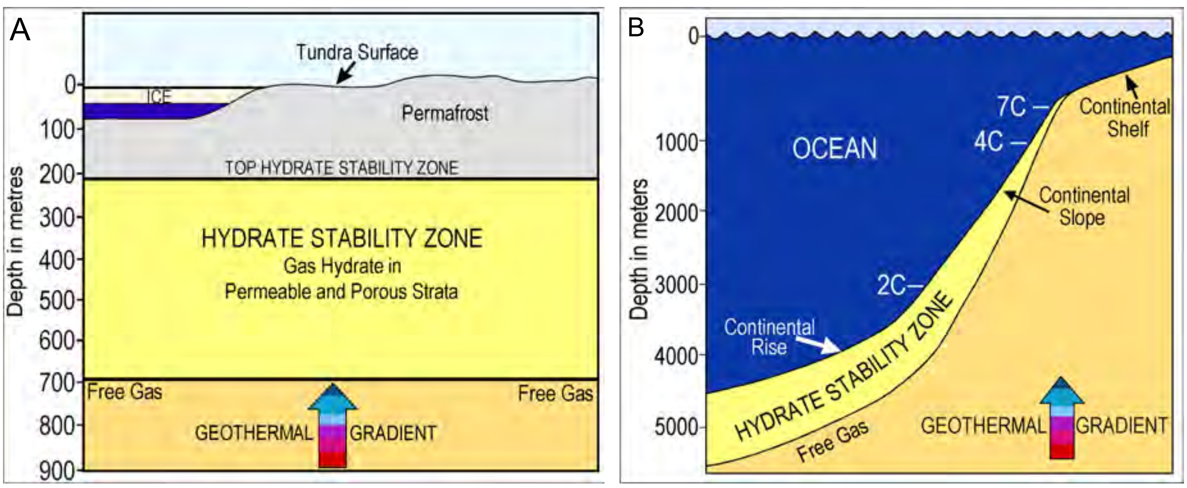


Figure 1.4: Schematic of the Gas Hydrate Stability Zone, graphically depicting the result of applying the phase diagrams in Figure 1.3. The Hydrate Stability Zone is shown in light yellow within the A)Arctic and Antarctic tundra and B) the marine environment (ICGH, 2006).

seafloor to sediment depths of about 1100 m. In polar continental regions, gas hydrate can be present in sediment at depths between about 150 m and 2000 m (2 km).

Some evidence of gas hydrate has been seen in cores from the ODP (Ocean Drilling Program) wells that were drilled off the south-western coast of South Africa in the South Atlantic Ocean at various sites on Leg 40 (DSDP:TheShipboardScientificParty, 2007).

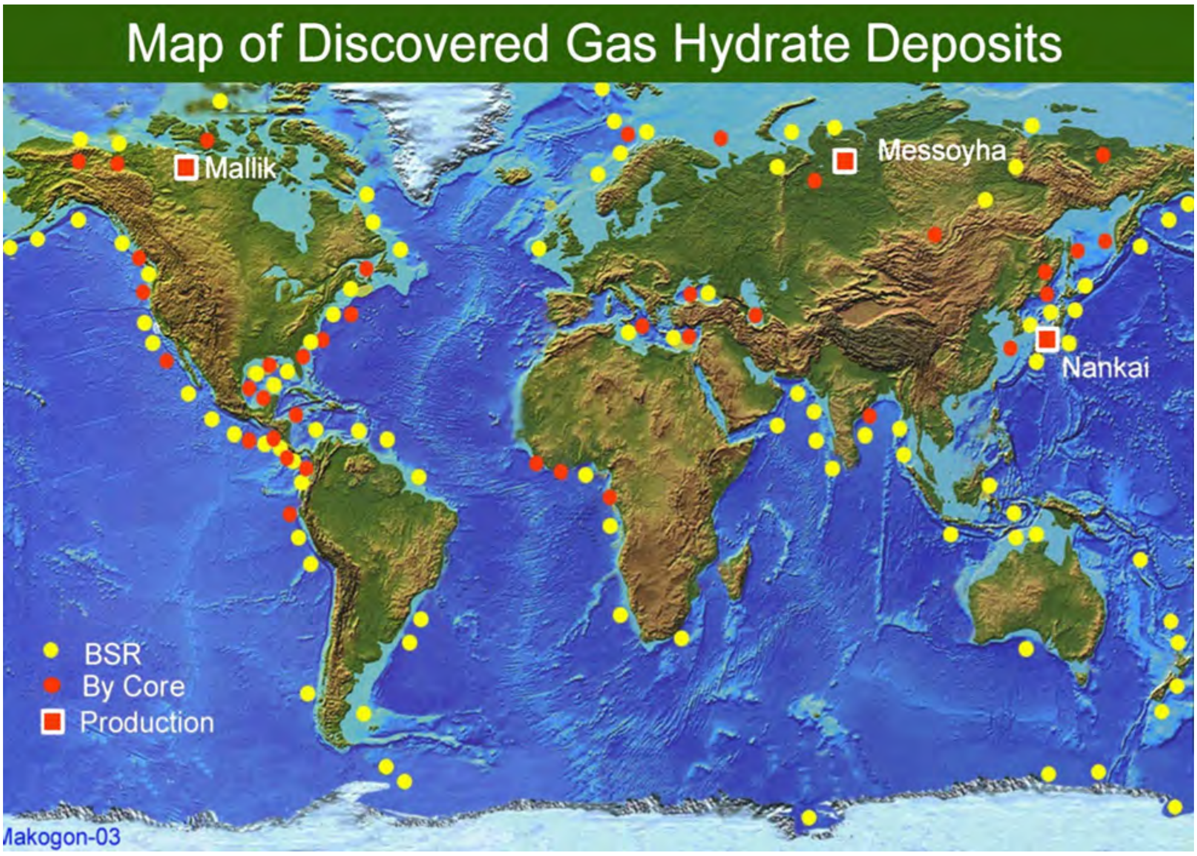


Figure 1.5: Worldwide Distribution of Natural Gas Hydrates (Kvenvolden and Lorenson, 2010). The yellow dots represent gas hydrates discovered by the presence of a BSR, the red dots indicate where gas hydrate was present in a cored sample , and the red squares show areas where wells for gas hydrate production have been drilled.

The processes that control the local extent of gas hydrate distribution and growth are not fully known, and research in this field continues. Cores from the Ocean Drilling Program (ODP) leg 204, 9 sites on the Cascadia Margin in 2002, showed some fractures within the core that were filled with gas hydrates. Some gas hydrate tubes were seen which could provide a conduit for gas to flow through. This leg was specifically undertaken in order to investigate gas hydrates within a region that they were known to occur (NationalResearchCouncil, 2011; Ruppel, 2011).

Fluids in general tend to migrate along planar surfaces but do not move in one sheet like a mud or lava flow, rather behaving like a river on a plain - with no sheet flow, only discrete channels. When conditions are favourable, hydrate tubes form through which free gas can flow. Gas hydrates tend to be more pore filling (matrix supported) than cementing, and migrate along fractures, taking advantage of larger grained or porous layers. This would appear as an anisotropic physical property (ICGH, 2006). This informs the distribution patterns within the sediments at the general locations shown on the map.

Migration of gas through the hydrate and sediment, as well as the migration of dissociated hydrate (now gas), has been shown to be controlled to a large extent by the type of sediment it is found in, such as coarse grained clean sand, silty or clayey sand, or even silt or clay. Grain size affects capillary invasion vs fracturing and may influence production (Santamarina and Jang, 2009). Methane fluxes, or releases of methane from the ocean or lake floor, occur and have been recorded on echo sounder data and studied in various parts of the world where hydrates exist. Periods of seismo-tectonic activity have been found to trigger an increase in these fluxes (Obzhirov, 2009), either through activation of existing faults or creation of new ones. Methane gas has also been shown to accumulate below the GHSZ and percolate through it to the seabed, where it flares into the water column (Xiaoli and Flemings, 2006). As the free gas migrates through the gas hydrate stability zone some of it may be transformed into hydrate, depending on the gas saturation and salinity status of the sediment within this zone.

1.5 Gas hydrates: friend or foe?

Kvenvolden (1999) stated that the three major potential effects on human welfare from gas hydrates are: as a factor in global climate change, as a potential energy source and as sub-marine geohazards. Of these three he only considered the hydrates as a marine geohazard to be of immediate importance. The effects of dissociating hydrate on the atmosphere were seen to be negligible due to the ameliorating effect of the hydrosphere and biosphere. When the paper was published no one had yet worked out how to effectively, or even possibly, remove hydrates from the ground to a useful effect. This has since changed and production is possible, if not economically viable just yet.

In terms of conventional oil exploration at the moment, however, gas hydrates represent a significant drilling and production hazard. Russian, Canadian, and American drilling engineers have described numerous problems associated with gas hydrates, including blowouts and well-bore casing failures (Collett, 2004).

1.5.1 Gas hydrates as a sub-marine geohazard

Hydrates are kept stable in their icy state within the Gas Hydrate Stability Zone (GHSZ), a zone in which the temperatures and pressures keep the hydrate from dissociating into free gas. As soon as the clathrate is removed from these conditions it may expand as it dissociates. This is one of the most dangerous expressions of gas hydrates as an immediate geohazard. When the sediment is confined in a core sample, well or pipe it may cause material to explosively shoot free when the pressure differential is significant enough to counter the plugging effect of the other sediments or liquids. In such a manner it may pose a significant safety risk as a geohazard.

A natural geohazard on a larger scale would be slope failure due to destabilisation of sediments as shown in Figure 1.6a. This has been put forward as a possible mechanism for the slope failure resulting in the Storegga Slide off of the coast of Norway approximately 7250 ± 250 years ago (Haflidason *et al.*, 2004) which led to substantial tsunamis. Hydrate dissociation is probably only one of several factors influencing this event, only making a local contribution to the slope failure (Bryn *et al.*, 2005). This is supported by the fact that Mienert *et al.* (2005) dated the main phase of hydrate dissociation at between 12 500 and 9000 years ago, which pre-dates the Storegga Slide by more than 1000 years. Further massive failure in the area is unlikely in the near future as Bunz *et al.* (2003) state that the extent of the present day hydrate distribution is limited to a small area on the Northern flank of the Storegga submarine slide, owing to the glacigenic lithology and the shallowing and pinching out of the GHSZ.

A sudden release of gas (Figure 1.6a) may not only contribute towards slope failure, but also liberate many bubbles into the ocean in a confined area, potentially destabilising any infrastructure above it; as when a shallow gas pocket is (usually unintentionally) struck by a drill rig. The occurrence of methane hydrate within the pore space may affect the strength of the methane hydrate sediment, according to experiments conducted with artificial methane hydrate production (Li *et al.*, 2011).

1.5.2 Gas hydrates as a factor in climate change

Many people are concerned that gas hydrates, especially those containing methane which is a potent greenhouse gas, pose a risk to the Earth in terms of aggravating climate change. Two triggering mechanisms for hydrate release most focussed on are: warming and sea level fall.

Warming is not really an issue for the release of hydrates as the only zone really affected would be that in the mid- to shallow- waters of 500 m - 700 m. Methane would only be released along the edges of the system, near the hydrate-gas boundary, where the hydrate is not very stable to begin with. In the deep waters of the Antarctic, the bottom water is at about -1° C (the coldest bottom of the deep oceans are normally about 2.5° C) and the hydrate stability zone goes down to about 300 m (as opposed to 500 m in some areas) (W. Wood, pers. com). Based on isotope records in ice cores, measuring the distinct deuterium / hydrogen (D/H) isotope ratios associated with marine hydrates, Sowers (2006) suggested that marine hydrates were stable during the last glacial termination as well as the warming periods at the end of the Older and Younger Dryas (~14 700 and ~11 500 years ago respectively). The source of the higher methane levels during the last glacial cycle may potentially be an increase in methane from wetlands, which become more extensive in a warmer environment leading to a related higher atmospheric methane emission contribution.

Sea level fall would be an issue, as this would lower the pressure at the sea floor and be more of a contributor to degassing/dissociation than warming by bottom water which would have to be significant enough to propagate through the sediment column to the gas-hydrate boundary. Hydrates at the ocean floor are solid - they are fixed in the hydrate stability zone. The unstable areas are near the edges of the system when it dissociates to gas (W. Wood, pers. com). This destabilization and release into the atmosphere is graphically represented in Figure 1.6. There are two possible feedback loops that can be applied to the situation where a drop in sea level occurs. The negative feedback cycle has as its premise that as the sea level falls (due to glaciation or other sea level fall) there is less pressure on the sub-marine hydrates which then dissociate, become released into the atmosphere as greenhouse gasses and raise the earth's temperature. This higher temperature would melt the glaciers, raising the sea-level once again and stabilise the sub-marine hydrates due to the increased pressure. The positive feedback loop contends that the rise in temperature would melt the permafrost. This would release more greenhouse gasses in the form of methane which would further raise the temperature, repeating the cycle.

While their formation, location and stability field are now better understood, the full effect of hydrates de-gassing into the ocean or atmosphere is still debated. The debate is between those that claim the gas from the dissociated hydrates will enhance, and maybe speed up, climate change in a runaway positive feedback cycle (Haq, 2001) as illustrated in Figure 1.7; and those who say it is a natural occurrence for hydrates to periodically release into the ocean or atmosphere and that they are, in fact, far more stable than previously thought (Reagan *et al.*, 2010).

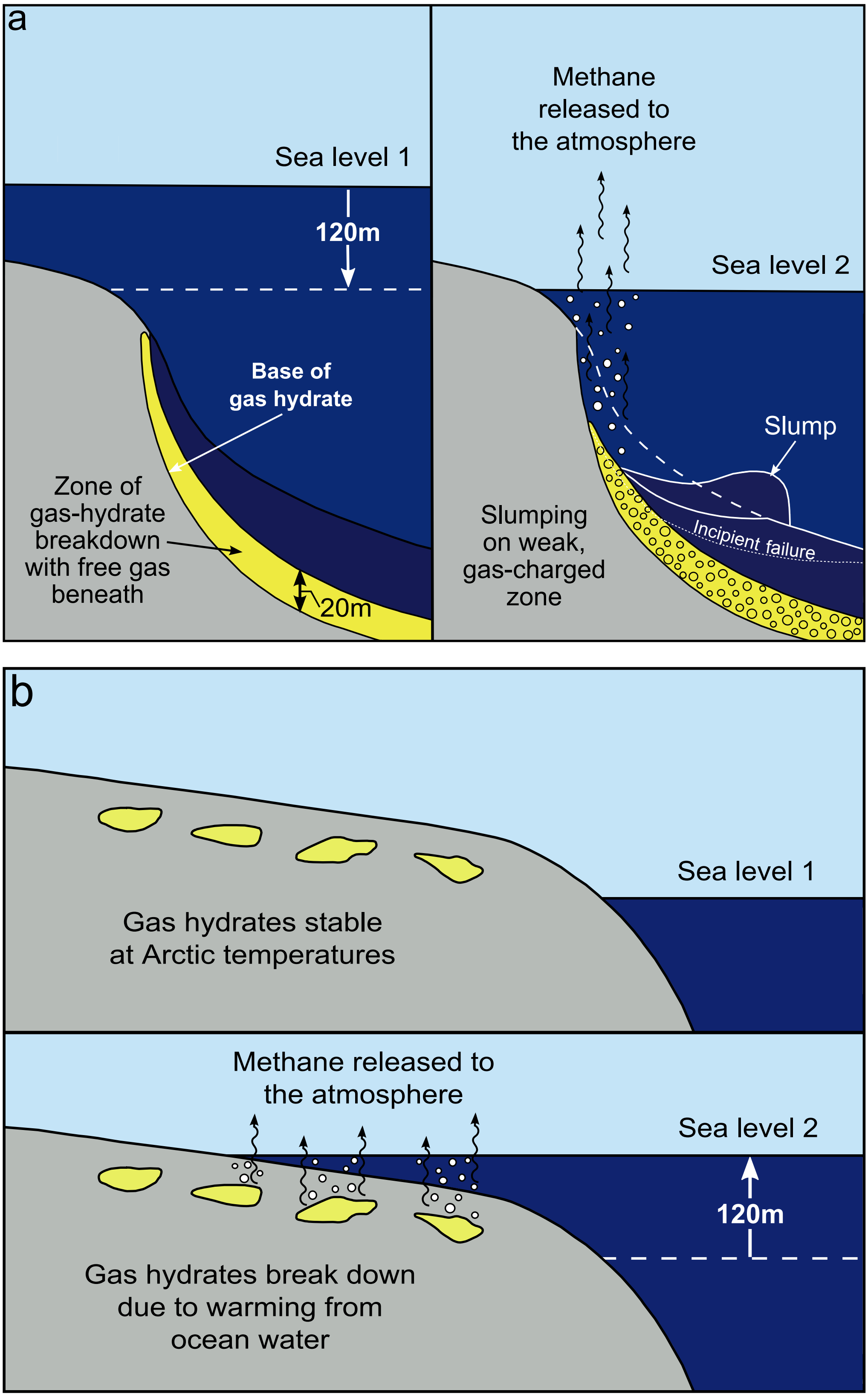


Figure 1.6: Projection of possible degassing of oceanic a) and terrestrial b) gas hydrate layers due to sea level rise or fall (image: U.S. Geological Survey [USGS])

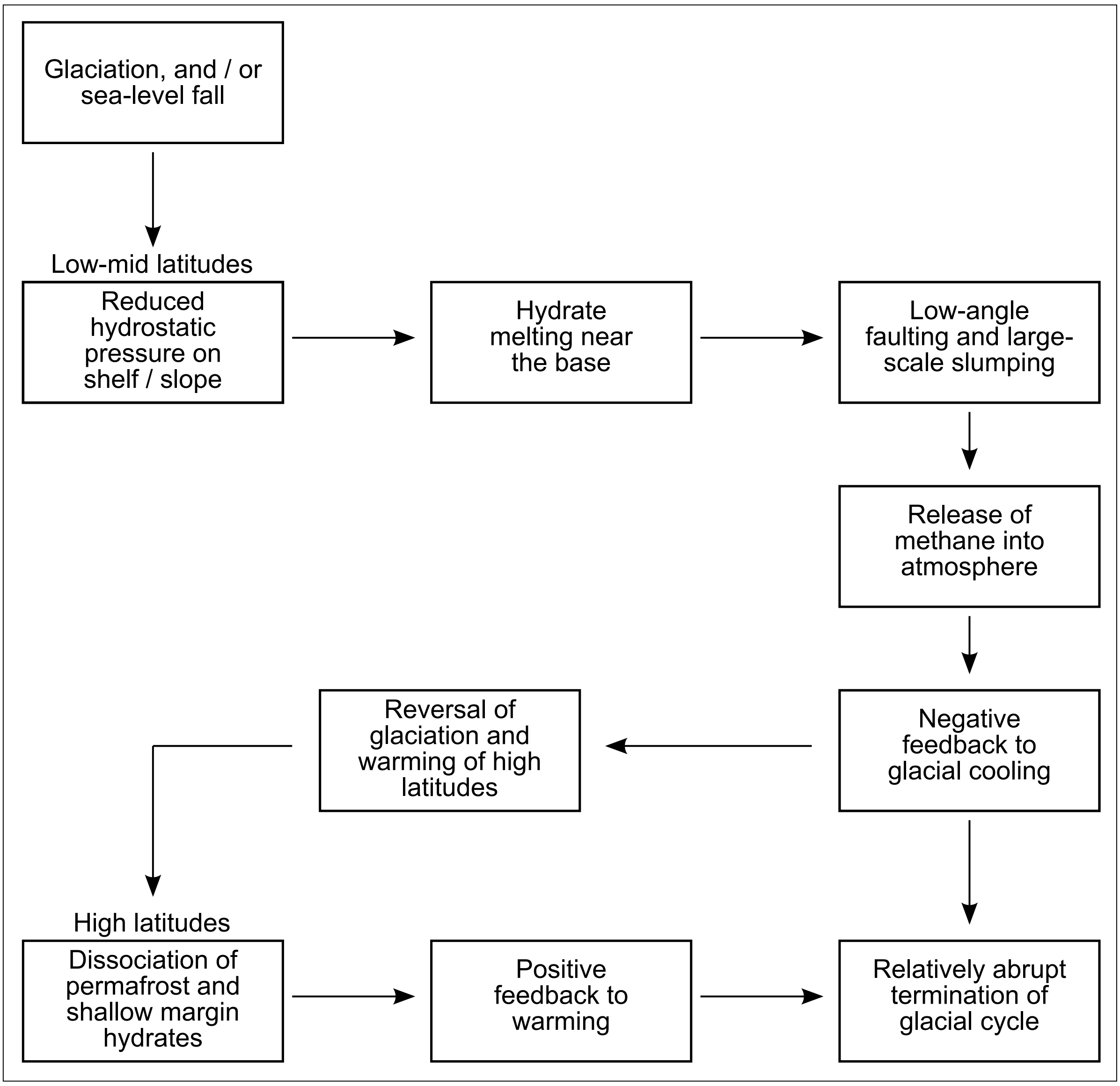


Figure 1.7: The negative-positive feedback loop model of sea level fall, hydrate decomposition, and climate change (reversal of glaciation and rapid warming) through methane release in the low and high latitudes (Haq, 2001)

1.5.3 Methane hydrate as an energy source

As gas hydrates are formed under high pressures and low temperatures they will expand as they rise to the surface and become less pressurised and warmer, a process known as dissociation: a chemical process by which temperature or pressure changes cause a group of molecules to be separated into simpler groups (Collett, 2004). The commonly cited "energy density" ratio for methane hydrate is 164:1, indicating that 164 unit volumes of methane at standard pressure (1 atm) and 0° C will be released from 1 unit volume of hydrate (assuming 96% of all cages are occupied by gas molecules). In the subsurface, this ratio is largely independent of depth because gas hydrate is nearly incompressible at the pressures where gas hydrate is stable on Earth (Boswell *et al.*, 2010). One m^3 of hydrate should yield approximately 164 m^3 of gas.

Hydrates are estimated to represent over half of the available organic carbon source in the world; 10 000 - 11 000 Gigatons (Gt), according to Demirbas (2010a), shown in Figure 1.8. Recoverable and non-recoverable fossil fuels, the main component of our present energy consumption in the form of oil, gas or coal, are estimated to be only half of this amount. As traditional fossil fuels become scarce or more expensive to refine, a potentially extensive and rich source of organic carbon would become worthwhile to pursue. The United States' Department of Energy (DOE) considers an approximate 1% recovery rate of methane from the known methane hydrate reserves within the United States (estimated at over 2000 trillion cubic feet [TCF]) would be enough to satisfy its consumption demand for the next eighty years (Editorial, 2007).

Mallik Research Well, located within the permafrost zone of the far north of Canada, is presently being used to test the reliability and accuracy of down hole logging tools with reference to gas hydrates as well as trying to produce hydrates through a de-pressurization technique. Many engineering and logistical challenges are still to be overcome especially when trying to produce safely and efficiently from marine reservoirs or those beneath the delicate permafrost. Messoyah, in Russia, and Nankai, off the coast of Japan, also have methane hydrate programs in place to produce methane from known gas hydrate locations (Nagakubo *et al.*, 2011).

CO_2 can replace the methane molecule within the hydrate structure. The guest molecules, such as methane or carbon dioxide, are of an appropriate size such that they fit within cavities formed by the host material (Editorial, 2007). This provides a direct contrast to the notion of hydrates being a negative influence in anthropogenic climate change. There is hope that future techniques will be able to release the methane and store the carbon dioxide, thus providing energy whilst sequestering carbon (Farrell *et al.*, 2010). Laboratory tests are being conducted to create gas hydrates to observe their various properties, measure them and model their behaviour.

Kvamme *et al.* (2007) experimentally demonstrated that it was possible to inject CO_2 into a methane hydrate within a sandstone reservoir and transform that natural gas hydrate into a CO_2 hydrate (thus sequestering the other greenhouse gas, CO_2) and release the methane held in-situ. This released methane/natural gas could then be harvested and the carbon dioxide could be safely stored for a long time as CO_2 hydrate, which is considerably more thermodynamically stable than its methane counterpart. Ersland *et al.* (2009) expanded on this idea, focussing on capillary effects, the presence of liquid channels and the connectivity of pores and channels

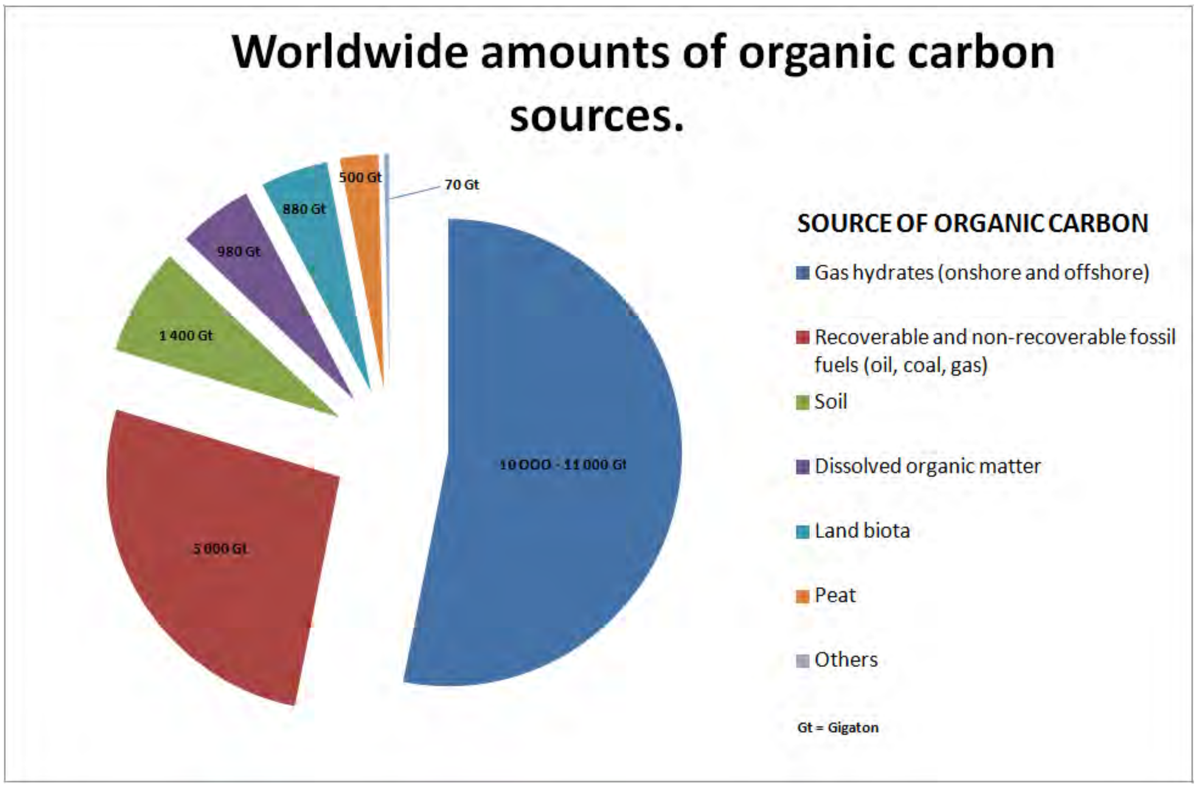


Figure 1.8: Simplified Earth Carbon Distribution from table in Demirbas (2010a). The estimated amount of gas hydrates (offshore and onshore) of about 10 000 to 11 000 Gigatons is shown in blue. In contrast, the recoverable and non-recoverable fossil fuels, in red, are half of that at 5 000 Gigatons.

within the reservoir rock. Their findings confirm the earlier experiments and strengthen the case for possibly using methane hydrate reservoirs to sequester carbon dioxide.

1.6 Current hydrate research

The history of this research is fairly new. A conference for hydrate researchers from all over the world is held every two years - Fiery Ice From the Seas, International Workshop on Methane Hydrate Research and Development. Starting in 2000, the workshop brings professionals together from government agencies, universities and industry to share their thoughts and methods for research, exploration, detection, evaluation and extraction.

Interest in methane hydrate as an energy resource was initially ignited in the 1960's by Russian scientists who claimed contribution from hydrates during conventional gas drilling in the Messoyakha field, Siberia (Demirbas, 2010a). The U.S. was a leader in the 1970's in this area. In mid-1990's, two countries, with a large energy demand but limited resources (Japan and India), began to explore the possibility of extracting methane from hydrates (Editorial, 2007). The Ocean Drilling Program began to look specifically for marine gas hydrates in 1992 (Demibras, 2010; NationalResearchCouncil, 2011). The United States' research effort got a significant boost with the passage of the Methane Hydrate Research and Development Act in 2000. Under the Act, the U.S. Department of Energy coordinated a five-year effort by the federal agencies "to promote the research, identification, assessment, exploration, and development of methane hydrate resources". Advances in the basic understanding of hydrates have occurred during these 5 years, including several hydrate-specific expeditions in the Arctic and in the deep water on the continental shelves around the world according to an editorial in the Journal of Petroleum Science and Engineering (2007). As additional years have passed, further technical advances have been attained as well as an increase in general knowledge about hydrates and how they function.

Previously gas hydrates were only associated with potential oil- or gas-field drilling and were almost exclusively seen as a hazard - something to be avoided at all costs due to the potential disaster that could follow a gas kick, a sudden influx of dissociated gas and overpressure leading to a blow out (Collett, 2004). At the present time much is being done to discover these areas independently of conventional petroleum exploration.

A global map, derived from data accumulated by Wood and Jung (2008), can be seen in Figure 1.9. It shows the thickness of the potential Gas Hydrate Stability Zone globally, varying between 0 m and 500 m. From this map one can see that there is the potential for hydrates to occur globally - except, generally, on the continents, shallow continental shelves, the deep parts of the South and East Pacific and central Indian oceans, and the hotter mid-oceanic ridge areas. The only difference is in the thickness of the GHSZ. This does not mean that hydrates will be found in all of these locations, merely that should the conditions for gas hydrate formation be present locally, the potential thickness of the hydrate would be as indicated.

1.6.1 Hydrate indicators in seismic data and beyond

Seismic data indicating gas hydrate presence could be any one, or combination, of: bottom simulating reflectors (BSR), polarity reversal, amplitude attenuation zones or blanking zones (gas masking), reduction in velocities immediately below the hydrate zone, gas chimneys or gas seeps, mud volcanoes, sea floor hydrate mounds or pock marks. Attitudes as to what the indicators of gas hydrates are, are changing. Traditionally, the major indicator was seen to be the bottom simulating reflector shown on the seismic record. BSRs are an interface; this

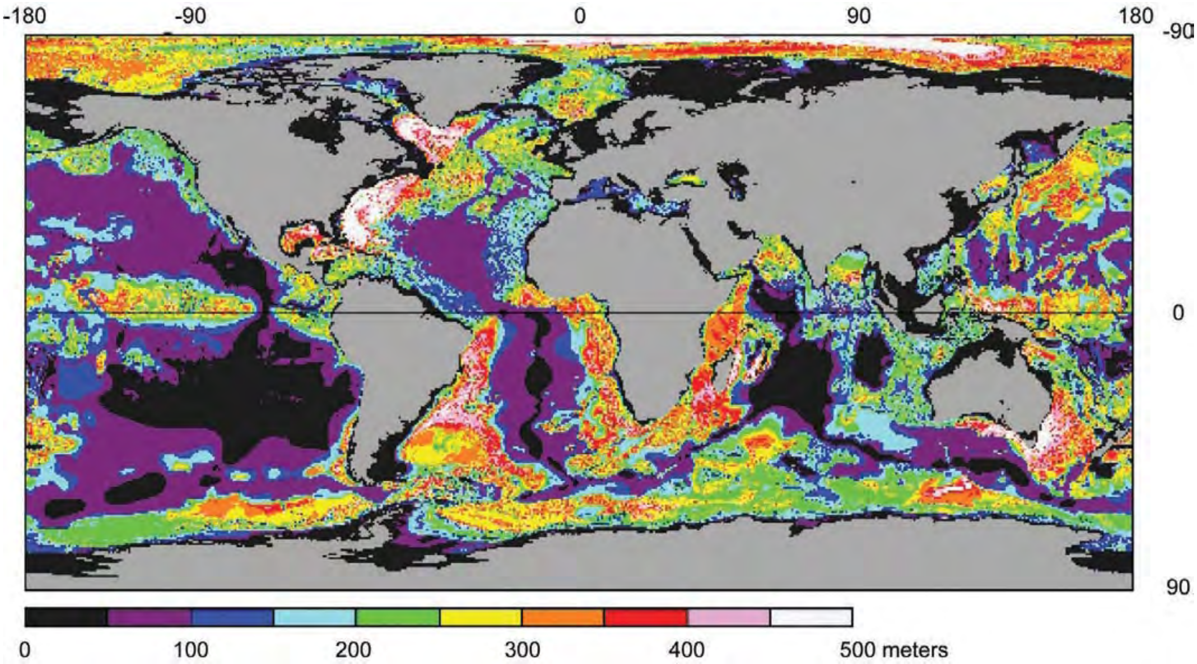


Figure 1.9: World Methane Hydrate Stability Zone (MHSZ) Thickness (Wood and Jung, 2008) showing the potential thickness of gas hydrate in 50 m increments. Ranging from 0 m in black (insufficient organic matter in deep ocean basins, high temperatures along mid-ocean ridges and insufficient pressure on continental shelves) to a maximum of 500 m in white (mostly on certain continental slopes and rises)

phenomenon is caused by the strong contrast in the sound velocities and densities between the methane hydrate bearing sediment and the free gas bearing sediment below it (Hyndman and Spence, 1992; Plaza-Faverola *et al.*, 2012). The resulting reflection follows the shape of the interface between the ocean floor and the water column. The bottom simulating reflector (BSR) interface lies at the base of the gas hydrate stability zone.

In Figure 1.10, a seismic section from the Blake-Bahama Ridge is shown above an interpretation of the same section. A BSR can be seen on the seismic section in the form of a strong reflector at about 4.25 s two-way travel time (TWT) that mimics the seafloor reflector above it at approximately 3.5 s TWT. The interpreted section clearly shows this BSR, in red, cutting across the interfaces denoting strata. This cross-cutting relationship with dipping reflectors is important in distinguishing a BSR from a stratigraphic reflector within the rock or sediments.

BSRs may not always indicate the presence of hydrates, and conversely hydrates are not always associated with BSRs. An area of sufficient contrast between layers could be the cause of a BSR. The diagenetic conversion of Opal-A to Opal-CT (different versions of quartz) results in a decrease in porosity and this sudden increase in cementation can cause a strong, BSR-like, reflector (Berndt *et al.*, 2004). Evidence from drilling on the Blake Ridge, off the coast of the

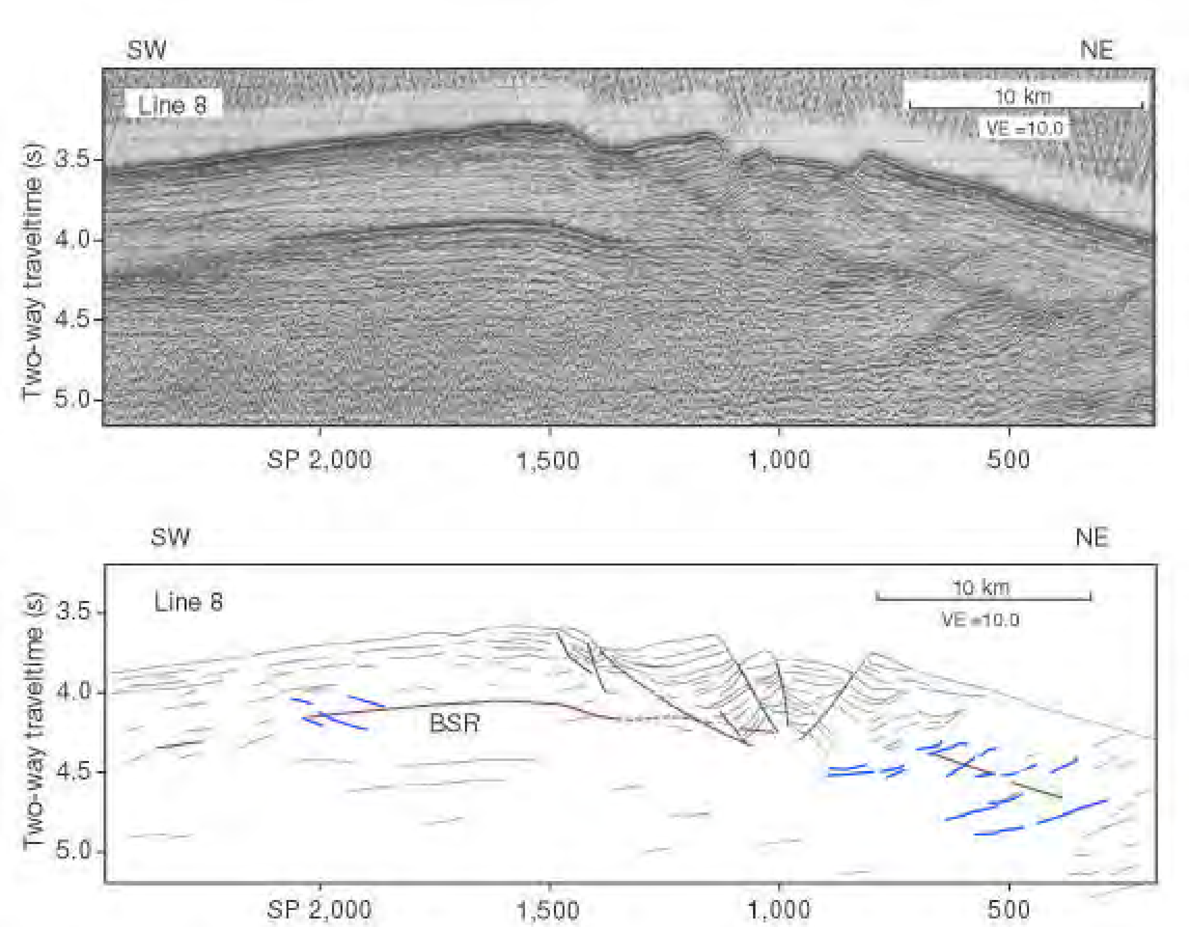


Figure 1.10: Bottom Simulating Reflector (BSR) in red on a seafloor slump in the Blake-Bahama Ridge as shown on a seismic section and interpreted (Sloan. Jr, 2003) The blue highlighted lines represent the strata that are being cross-cut by the BSR, a key indicator that the 'BSR' is not merely another reflector.

USA, has shown that no BSR, a weak BSR and a strong BSR all corresponded to the same 5% methane hydrate layer (ICGH, 2006). This shows that the belief that 'if there is a hydrate, there must be a BSR' is not always correct, as emphasised by Rajput *et al.* (2012). Another belief was that if there was free gas migrating upwards, there must be a hydrate. This has also been shown to not always be the case. Different methods of detecting hydrates should be investigated and combined with the traditionally accepted indicators to provide a more rounded, and hopefully more accurate, detection method.

Seismic attribute analysis is an analytical software tool used not only to locate hydrates, but other geological features as well. It allows for quick and accurate identification of a variety of geological features and is especially useful in large datasets. Seismic attribute analysis is often used in conjunction with other mathematical tools such as neural networks or genetic algorithms in order to maximise the information gained from modern seismic lines. When processing and interpreting seismic data, inferences about the actual geology are made based on the response gained from the geophysical sensors. Features tend to have certain attributes that define them. These seismic attributes are often initially tested in a trial-and-error mode with a particular attribute, or combination of attributes, then being selected as the general descriptor of a geologic object (Meldahl *et al.*, 2001). It is important to note, however, that the seismic attribute does not definitively identify a *specific* geologic object, but rather any seismic position with a similar attribute response. As gas chimneys or other migration pathways are often found in conjunction with gas hydrates - providing access to between hydrates and deeper sources of methane (Aminzadeh *et al.*, 2001; Chun *et al.*, 2011) -, these are also features to be sought out in the seismic data when attempting to locate hydrates.

Attributes that characterize gas chimneys are vertical or sub-vertical zones of blanking (disturbances in the seismic data) where the amplitude of the seismic signal is reduced i.e. low amplitude (Meldahl *et al.*, 2001). Seismic attributes helping to identify the BSR are seismic velocity, blanking, attenuation, reflection strength and instantaneous frequency. These characteristics can also assist in qualifying whether the BSR is related to hydrates (Sain and Gupta, 2012). Velocity models on pre-stack data show high velocities in the hydrate bearing layer above the BSR and low velocities in the free gas bearing sediments below the BSR (Vargas-Cordero *et al.*, 2010; Sain *et al.*, 2011). As with any geophysical interpretation caution should be exercised in blankly applying these attributes without consideration of geological setting (Loreto and Tinivella, 2012) and other surrounding features which may help to inform any interpretations or algorithms.

More intensive or advanced processing techniques may be applied after conventional processing (filtering, stacking velocity analysis, stacking and post-stack time migration) has identified the BSR and thus potential hydrate-bearing sediments. Techniques such as those employed by Vargas-Cordero *et al.* (2010) can be used to quantify and give a potential estimate of gas hydrate and free gas in the sediments.

A less conventional method is to look at communities of chemosynthetic organisms such as mussels or clams. Clams would survive near where methane seeps to the surface of the seafloor. As the vent decayed and stopped producing gas the clams would die. These dead clam fields provide an indicator of where the hydrate used to have a surface expression. Living clams would show where the vent is now. By looking at both the dead and living clam communities researchers could track the movement of the vent. The progress of a gas hydrate layer can be tracked by the degassing events or a trail of dead clam communities (ICGH, 2006; McGee *et al.*, 2008). The seep that once fed the clams has moved onwards to feed a new colony - leaving the old one to wither and die. By tracing these dead colonies one can deduce where the seep has moved and subsequently the possible extent of the hydrate bed.

Chemical and microbiological indicators are also able to help determine the presence of methane, and thus, indirectly hydrates. Among these are: methane enrichment with depth, sulphate reduction with depth, higher concentration of total organic carbon (TOC) in cores, the abundance of sulphate reducing and sulphate fermenting bacteria and isotopic indicators such as the enrichment of $\delta^{18}O$ (Tomaru *et al.*, 2007).

1.6.2 Detection and exploration (country-level)

Aside from the seismic methods already mentioned, detection tools used include; DTAGS (Deep Towed Acoustic Geophysical Sensors); methane 'sniffers'; sea floor sensors; specialised tools on ROVs; and more. The array and accuracy of tools being used to identify and quantify gas hydrates is growing as understanding and the knowledge base increases. Many countries worldwide are investigating their possible hydrate reserves, and the potential for extraction of hydrates found within their waters or beneath the permafrost. Whilst investigations into palaeo-climate, palaeo-sea levels or palaeo-oceanography add an historical perspective, they do not inform the present existence of hydrates in the area. The conditions required to maintain gas hydrate in sediments are short-lived when compared to other geological processes which is why more exploration and analysis is required to build a wider and more detailed model of their specific formation environments and local constraining factors. Many gas hydrate programmes are undermanned and there is a bias towards national programmes which tends to impede international partnership development. There are also language barriers between industry and the research community (ICGH, 2006). This being said, there are several successful international partnerships with the large extraction testing projects, and regular conferences and workshops endeavour to bridge any actual and perceived gaps between those researching the resource and those attempting to commercialise and profit from it. The Proceedings, 7th International Conference on Gas Hydrates (ICGH, 2010) stated that, within the next decade, gas from hydrates could be realistically seen as a viable economic product.

Within the United States much hydrate research is being carried out (Rath, 2006), with many agencies co-operating on various research foci such as: energy exploration, platform and pipeline stability, geoacoustic sediment properties, global warming, ocean carbon modelling and atmospheric modelling. The National Oceanic and Atmospheric Administration (NOAA) is investigating the effects and the potential of gas flux to the atmosphere, the U.S. Geological

Survey (USGS) and Naval Research Laboratory (NRL) are developing innovative equipment and techniques to collect and analyse samples of gas hydrate from the sea floor.

Several other countries that are looking into hydrates include Canada, Russia, the UK, India, Japan, Taiwan, Germany, New Zealand and more recently Korea and China. Countries with long coastlines and conditions that could possibly be conducive to the formation of hydrates that are not looking into that field at present include Australia and South Africa. According to Clennell (2006), in the case of Australia, the country does not have a national gas hydrates program as (proven) hydrates have been uncommon on the Australian Continental Margin and the country has large reserves of conventionally trapped natural gas and thus not much incentive to find more (gas) at the present time. There is Australian interest in research in hydrocarbon seepage studies which have encountered natural gas hydrates, as well as background research on hydrates relating to the planned future expansion into deep and ultra-deep water drilling. South Africa also does not have a national hydrates research and development program - the South African Government: Department of Energy and its State Owned Enterprises (RSA_DoE, 2013; SANEDI, 2013) focus on fossil fuels, nuclear power, and renewable and alternative fuels to supply the country's energy needs. Natural gas is considered as a fuel source that is undergoing rapid expansion. Unconventional energy sources such as gas hydrates are not presently being studied or explored, though the Department of Mineral Resources (DMR) is investigating the potential exploitation of shale gas (an unconventional resource) in the Karoo (DMR, 2012). South Africa, like Australia, has no (proven) hydrates, and it has viable, land based, mineral deposits and energy sources such as coal and natural gas; this would seem to indicate that there is no immediate need to investigate a potential additional energy source. Gas and gas hydrates are, however, a much cleaner form of fuel than coal and could supply a significant amount of power as well as not being subject to the same environmental problems as shale gas. These reasons alone should mean that natural gas hydrates should be researched more diligently and urgently.

A collaborative research program led by Natural Resources Canada (NRCAN) and Japan Oil, Gas and Metals National Corporation (JOGMEC), and supported by the Aurora Research Institute attempted to produce hydrates at the Mallik research well site in the Mackenzie Delta. This field program was successfully completed in April 2008 (Yamamoto and Dallimore, 2008). Their research and development objectives were to evaluate de-pressurisation as a practical mode of stimulation for gas hydrate production; to employ state of the art well engineering and monitoring instrumentation to regulate and quantify gas hydrate dissociation. The Canadian and Japanese partners were also attempting to improve specific extraction techniques and had 60 - 70 days of extended production, culminating in six days of continuous gas production from the Mallik gas hydrate reservoir (GSC601, 2012). This onshore production test produced between 2000 m^3 and 4000 m^3 of gas per day (JOGMEC, 2013a).

Russia has plenty of conventional (proven and well established) energy resources available to them and thus not much need for unconventional resources like gas hydrates. Even so, they do have a limited gas hydrate program which mostly focuses on theoretical research and gas hydrate prediction and prevention (Yakushev, 2006). There are many oil and gas lines that flow though cold environments and it is important to prevent hydrates forming in these. Of specific importance is the need to predict and avoid hydrates when drilling for oil, especially through the relict permafrost. A well known oil and gas company drilled through the permafrost causing the release of natural gas, the well became too unstable and had to be capped.

Britain, with access to some of the North Sea oil fields, also has an interest in hydrates, especially as a potential hazard. Through exploration they have made many discoveries, as well as having several national institutions working on gas hydrate research (Berndt, 2006; HeriotWatt, 2013). Through these research programmes, scientists have found indicators of potential hydrate zones to be high angle faulting, seen in seismic sections, and turbidite flows. The hydrate was concentrated in the course grained turbidite sand layers. By using logging while drilling (LWD) and measurement while drilling (MWD) the pressure in the well can be monitored and should it change by more than 100 psi the drilling will be stopped. Other discoveries were that sandy sediment containing gas hydrates is often surrounded by more clayey sediments and that hydrates were not located at the bottom simulating reflector (BSR) seen on the seismic section, but significantly higher. High resolution logs from LWD showed better data than traditional wire line logging as the data could be obtained before the sediment was heated by the drill bit. This information could assist others exploring for, and trying to more accurately evaluate, hydrate resources.

Japan's methane hydrate exploitation program started under the Ministry of Economy, Trade and Industry (METI) in 2001 (Masuda, 2006). As part of a thorough exploration and development plan the program has divided its objectives into three phases. Phase 1 comprises: research (exploration techniques, dissociation methods and modelling, production technologies and environmental impact assessment); identification of potential gas hydrate fields offshore Japan and selection of an offshore production test site; and development of production technologies through onshore production tests. Phase 2 would involve the implementation of the findings from Phase 1 and initiate an offshore production test in Japanese waters as well as conduct ongoing feasibility and environmental impact studies. Should the previous two phases be successful, Phase 3 would develop technologies for commercial gas production from hydrates. The first Phase was successful as gas hydrates were found in the Nankai Trough, which is a fore arc region situated on the continental shelf, and the collaboration with Canadian researchers on the production test well at Mallik was a success in 2008. The Japan Oil, Gas and Metals National Corporation (JOGMEC) has, in March 2013, completed a flow test and confirmed gas production in the Nankai Trough area (JOGMEC, 2013b). The provisional production test produced volumes of gas of approximately 20 000 m3/day over 6 days. (JOGMEC, 2013a).

India initiated a National Gas Hydrate Programme in 1997 which was reconstituted, together with all institutes and organizations, in 2000 under the coordination of the Directorate General of Hydrocarbons (DGH) and is researching the possibility of finding large deposits in the deeper waters off of their coasts (Sethi, 2006; ICGH, 2006). This would provide energy relief to their growing economy. Major areas of study are concerned with how, why and where gas hydrates occur. The most important regions being investigated are: the Krishna Godavari Basin, where massive quantities of gas hydrate have been found; the Kerala Konkan Basin, where no hydrates have yet been found and the BSRs seen were found to be due to diagenesis; the Andaman area, where deep BSRs have been seen as well as good quality disseminated hydrate associated with volcanic ash; and finally the Mahanadi Basin, where seismic records have shown very good potential BSR and free gas quality but good gas hydrates have not been found - just some disseminated in the pore spaces (ICGH, 2006). Much work is being done by different research teams and organizations in India to investigate (DGH, 2010; Sain and Gupta, 2012) and map (Sain *et al.*, 2011) gas hydrates that have been discovered in these basins - for the advancement of exploration and exploitation. In order to quantify this potential resource, different processing techniques are being applied to historical as well as newly acquired seismic data. Ojha and Sain (2008) have utilised traveltime inversion and amplitude versus offset (AVO) modelling, coupled with rock physics theory in order to appraise the ratio of gas hydrates to free-gas and gain a quantitative assessment of the gas hydrates in place. Riedel and Shankar (2012) utilised different seismic techniques to estimate and assess the probability of hydrate location and concentration: a combination of impedance inversion and the running-sum of the seismic similarity attribute across the GHSZ. Wang *et al.* (2013) are employing geostatistical inversion in order to estimate gas hydrate saturation in a fractured reservoir previously analysed by Riedel *et al.* (2010). These and other processing techniques, such as genetic algorithms, have also seen use and been quite successful in identifying and quantifying India's gas hydrates. On the physical side, a technique for imaging cores with infra red radiation has been developed in India. When imaged, the gas hydrates within the core sample will appear red against the surrounding sediment.

Previous research into hydrocarbons within the north western exploration blocks offshore South Africa has largely focussed on gas in its various forms, rather than gas hydrates. Within the Orange Basin itself, exploration began in 1974 with the discovery of the Kudu gas field offshore southern Namibia (Muntingh and BrownJr., 1993), and exploration into its oil and gas potential, on both sides of the border, has continued since then (PASA, 2007). The focus of this research has mainly been on hydrocarbon generation, migration and seepage (Anka *et al.*, 2009) as this is doubtless where commercial value can be extracted. Ben Avraham *et al.* (2002) and Viola *et al.* (2005) had a different focus and instead looked into the occurrence of mud volcanoes off the west coast of South Africa, along with the possibility of gas hydrates.

Much work has recently been done by various researchers from the GFZ in Potsdam in conjunction with South African academic institutions. Kuhlmann *et al.* (2011) investigated Blocks 3 and 4, to the south of this study area, for gas generation, migration and leakage. This followed on from research published the previous year (Kuhlmann *et al.*, 2010) on how passive margin evolution may control this leakage. Continuing with the investigation into controls on natural gas leakage (and passive margin evolution), Boyd *et al.* (2011) investigated further north, in Block 2, and whilst this was in the same area as this study the focus was almost exclusively on gas. Hartwig *et al.* (2012) also focussed on fluid escape, but limited to a specific Eocene event evidenced by widespread paleo-pockmarks seen in the data. In a comparative study of basins on the margins of the South Atlantic, Marcano *et al.* (2013) looked at the major factors controlling hydrocarbon generation and leakage. Although BSRs were identified in the central segment basins - the Lower Congo Basin and the Brazilian Margin - they were not identified in either of the southern segment basins represented by the Orange Basin and the Colorado Basin.

1.6.3 Sampling and evaluation

A tool being successfully used to sample gas hydrates obtained through coring is the pressure core. This method is used to assess methane hydrate as a geohazard as well as by researchers to determine the amount, and structure, of hydrates within the sediment. In the past, normal, unpressurised cores were used for determining the amount of hydrate within the sediment. This proved to be inaccurate as when the cores were raised, any hydrate within them would begin to dissociate and therefore the readings acquired were often lower than the actual amount (Lee *et al.*, 2013). The cores also became pressurised as the hydrate dissociated and could provide a hazard to the scientists and deck hands aboard the ship when they explosively left the core casing.

Using the pressure core technique, the core may either be degassed within a sealed environment, in order to accurately assess the hydrate (or rather, methane) content of the core, or an X-ray image of the core can be taken whilst still 'in-situ' within the core barrel - as seen in Figure 1.11. During sampling, other techniques used in preserving the possible hydrate cores include: immersion in liquid nitrogen at Arctic temperatures or storage at methane hydrate pressure and ambient Arctic conditions (Kneafsey *et al.*, 2011). Pressure cores have been developed and refined in order to obtain samples at hydrate depth and pressure and maintain those conditions for storage and transfer (if required) before final analysis (Abegg *et al.*, 2008). The Chinese Geological Survey team and partners have concluded a gas hydrate research cruise in the South China Sea (ZHANG *et al.*, 2014). A similar method to the straight X-ray of a pressurised core was used: an X-ray CT scanner (which can be aboard a research ship). The image displayed is in grey-scale with the hydrate showing up as white. The drilling operations from this cruise also yielded a variety of physical examples of the different gas hydrate morphologies - massive, laminated, nodular, veined and disseminated. Physical samples are an important tool in evaluating gas hydrates. Images of these samples can be seen in Figure 1.12.

Obtaining pristine physical samples also allows a variety of geophysical, geomechanical and geochemical tests be run. The relationship between the water flow regime and the distribution, formation and dissociation of hydrates can be characterised by the isotopic composition (δD and δ^{18}O) and chloride concentration of pore waters (Tomaru *et al.*, 2007). It has been discovered that gas hydrates are enriched in deuterium (D), relative to the ambient water, due to the preferential crystallization of D-rich water during hydrate formation (Hesse *et al.*, 2000). The δD value of pore water thus appears to be a sensitive indicator of gas hydrate occurrence. Another geochemical reaction occurring within the pore water during hydrate formation is the enrichment of δ^{18}O and subsequent decrease in Cl^-; this effect has been used to estimate the gas hydrate content within the sediments (Matsumoto and Borowski, 2000; Tomaru *et al.*, 2004). These chemical reactions would be impossible to accurately quantify without physical samples.

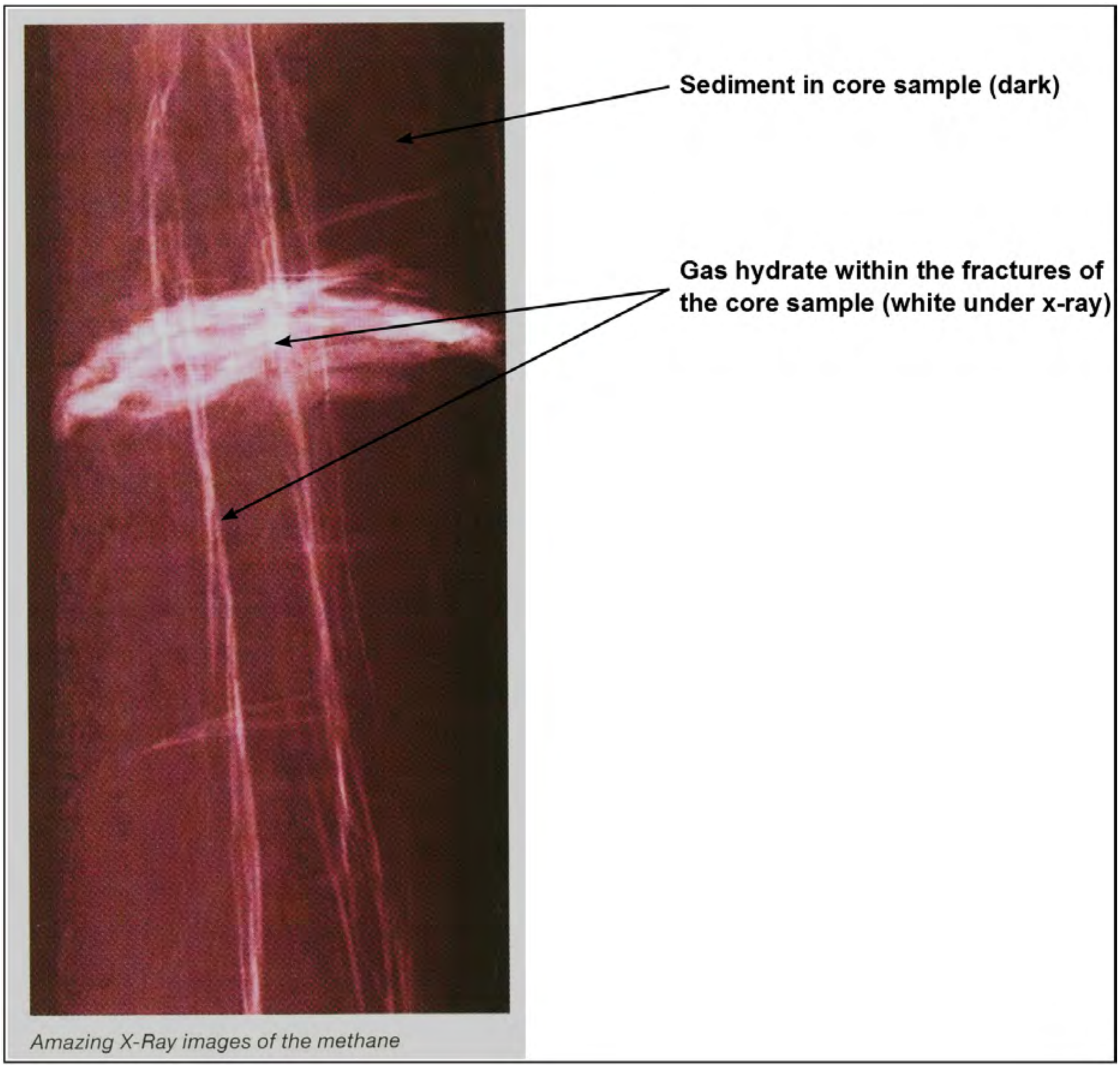


Figure 1.11: X-Ray of Gas Hydrate in a pressure core (CrossSection, 2006)

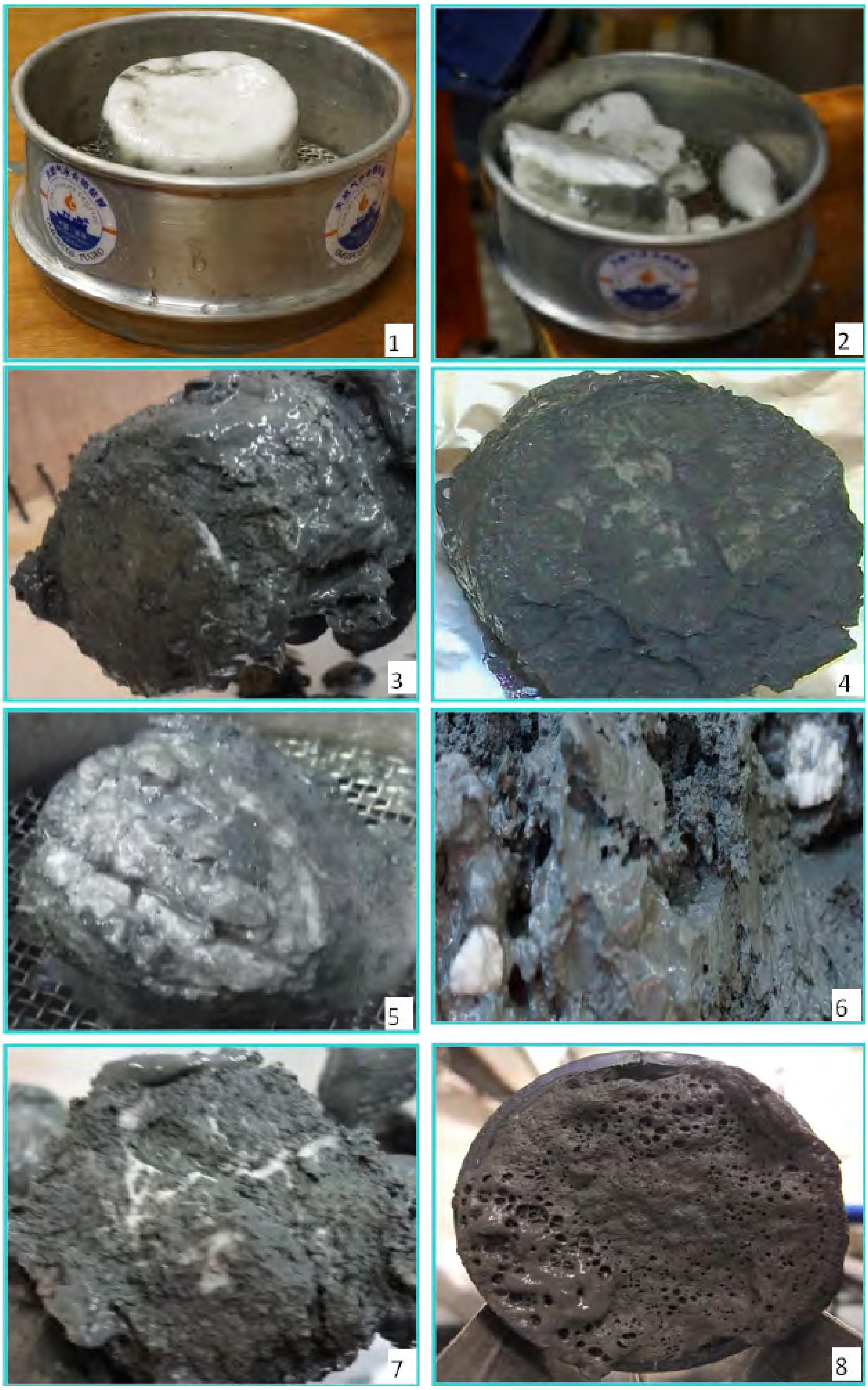


Figure 1.12: Samples of gas hydrate displaying different morphologies. Gathered from the GMGS2 drilling sites in the South China Sea (ZHANG *et al.*, 2014). Massive hydrate (1 and 2); laminated hydrate (3 and 4); nodular hydrate (5 and 6); hydrate veins (7) and disseminated hydrate (8).

1.6.4 Technologies for extraction

The bulk of the literature on gas hydrates, particularly an understanding of how and where they occur, how they are constrained and how to extract them, is relatively recent, with the greatest advances happening in the last 20 to 30 years. There are many areas within this field that are only sparsely covered and others which are only now being investigated as the technology to analyse and understand these sediments is invented or developed to a usable level. The traditional production methods and approaches of the mainstream oil and gas industry were not compatible with what was required to successfully exploit this unusual resource (Boswell, 2009).

The test well at Mallik is using a de-pressurisation technique to extract hydrate from beneath the permafrost, schematically shown in Figure 1.13. This appears to be the most common form of extraction used (Rutqvist *et al.*, 2009), but does have associated problems. Research by Santamarina and Jang (2009) has shown that there is a quantifiable relationship between grain size and likelihood of producing sand rather than gas. Furthermore, an additional problem suggests that the ratio of sand to clay particles within the surrounding reservoir rock also plays a part in the success of methane production from gas hydrates. These factors need to be taken into account when assessing the viability of a hydrate prospect as an energy source. As with any hydrocarbon, many variables play a role in the ultimate exploitation of the resource: Availability, accessibility, cost to produce, price per unit, comparative cost of other fuel sources, reliability of extraction techniques, ability to integrate with existing infrastructure, degree of technical expertise required, etc. Hydrates will not be produced on a wide scale until these factors combine to make it profitable to do so.

Three different methods of extraction have been posited: 1) thermal injection, 2) de-pressurisation (as with the Mallik test well) and 3) inhibitor injection (Figure 1.14). The thermal injection technique introduces steam or hot water to the well which is terminated in the hydrate stability zone. The raised temperature leads to the dissociation of the hydrate which then rises up the well. The de-pressurisation technique drills below the hydrate zone into the zone of free gas. The well is then perforated at the appropriate depth and the pressure differential enables the gas to rise up the well. The inhibitor injection method is similar to thermal injection except that, instead of steam or hot water, an inhibitor such as methanol is injected into the target zone resulting in the gas rising from the well. Yuan *et al.* (2013) conducted experimental laboratory studies using different types of solutions (NaCl, Na_2SO_4 and ethylene glycol), various water temperatures and differing flow rates to determine the optimal conditions for maximum gas

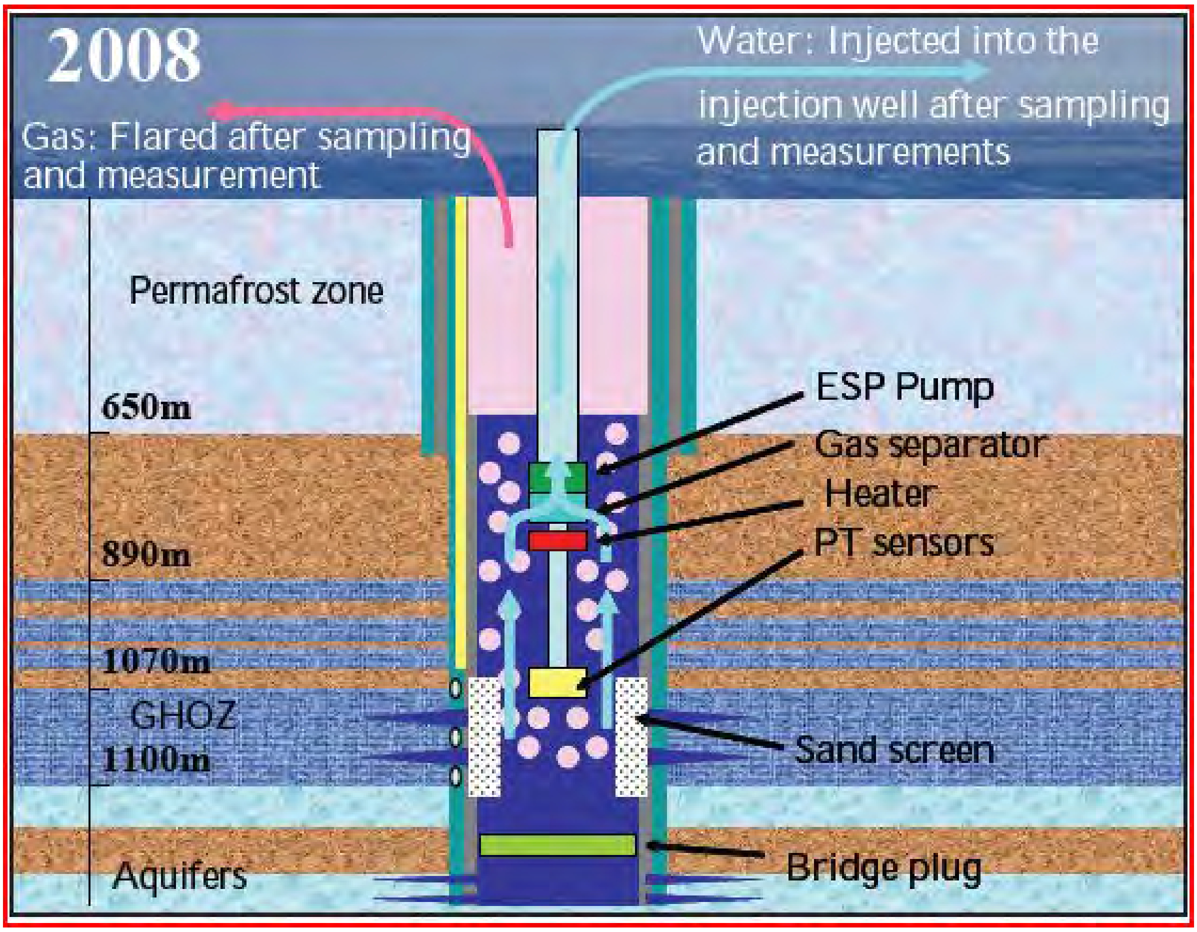


Figure 1.13: Schematic of the de-pressurisation system of the 2008 completion for the Mallik test well (Yamamoto and Dallimore, 2008).

extraction. The prohibitive costs of test wells mean that a large amount of simulation and laboratory work are necessary before techniques can be field tested.

JOGMEC successfully produced gas from the Nankai Trough utilising the de-pressurisation technique. The site was selected based on seismic and well data collected from 2001-2008 (Yamamoto, 2013), lessons learned from the Mallik test well (which applied the same technique) were applied and drilling was staged from the *Chikyu* drilling vessel. The pressure in the well was lowered and approximately 120 000 m^3 of gas was produced. Production was terminated after an increase in sand production after 6 days. In the same way that JOGMEC learned and applied lessons from the Mallik test and gained further data for future testing and production wells, so too can South Africa use the existing information (obtained by other national programs) and build on it to jump start its own program.

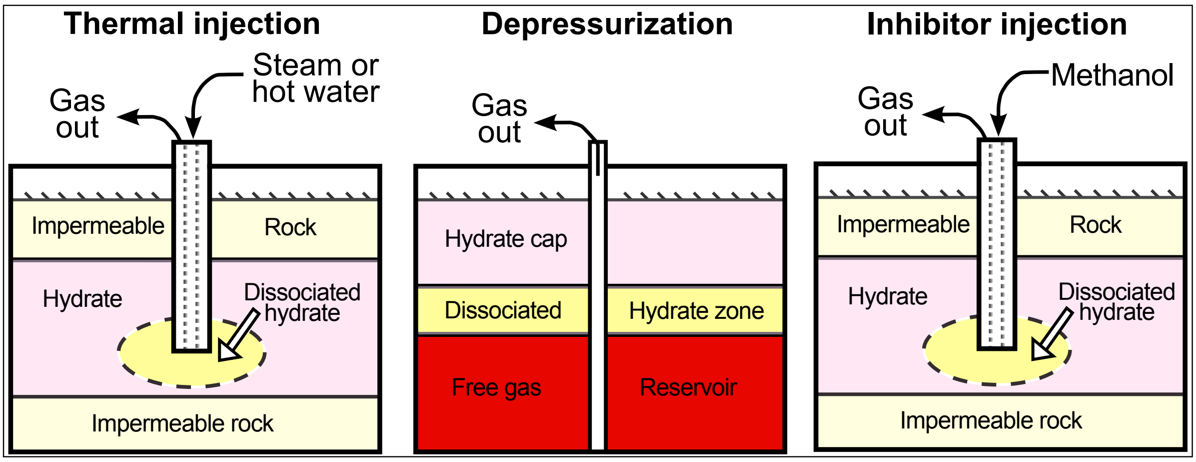


Figure 1.14: Schematics of the three main processes to be used for extracting hydrates: Thermal injection, De-pressurisation and Inhibitor injection (Collett, 2004; Demibras, 2010).

1.7 Proposal and research aims

As shown above gas hydrates are a possible, viable, source of energy. This dissertation examines the possibility of discovering potential gas and gas hydrates in Block 2 off the west coast of South Africa. This block contains the necessary conditions for the presence of hydrates but no hydrates have been found yet. Several potential hydrate indicators have been reported or noted in the area: mud volcanoes (Ben Avraham *et al.*, 2002; Viola *et al.*, 2005), gas shows in the test wells drilled, and abundant evidence of gas in the form of chimneys. I have analysed for the presence of gas and gas hydrates by using previously acquired seismic lines and wells from the Petroleum Agency of South Africa (PASA), gathered from various surveys between 1976 and 2003. The data was displayed and inspected for indicators of gas hydrates - mostly Bottom Simulating Reflectors (BSRs) which are, to date, still the most reliable indicator of hydrates. Gas escape features were also looked for as hydrates are often fed from deeper gas sources. The question is then, are the hydrate indicators sufficient to justify South African investment in a hydrate research program given the current extraction technology and return value?

Chapter 2

Methods

2.1 Study area

The location of the seismic lines and wells used for this study is within Block 2, in the south eastern Atlantic, on a passive margin off of the west coast of South Africa (Figure 2.1).

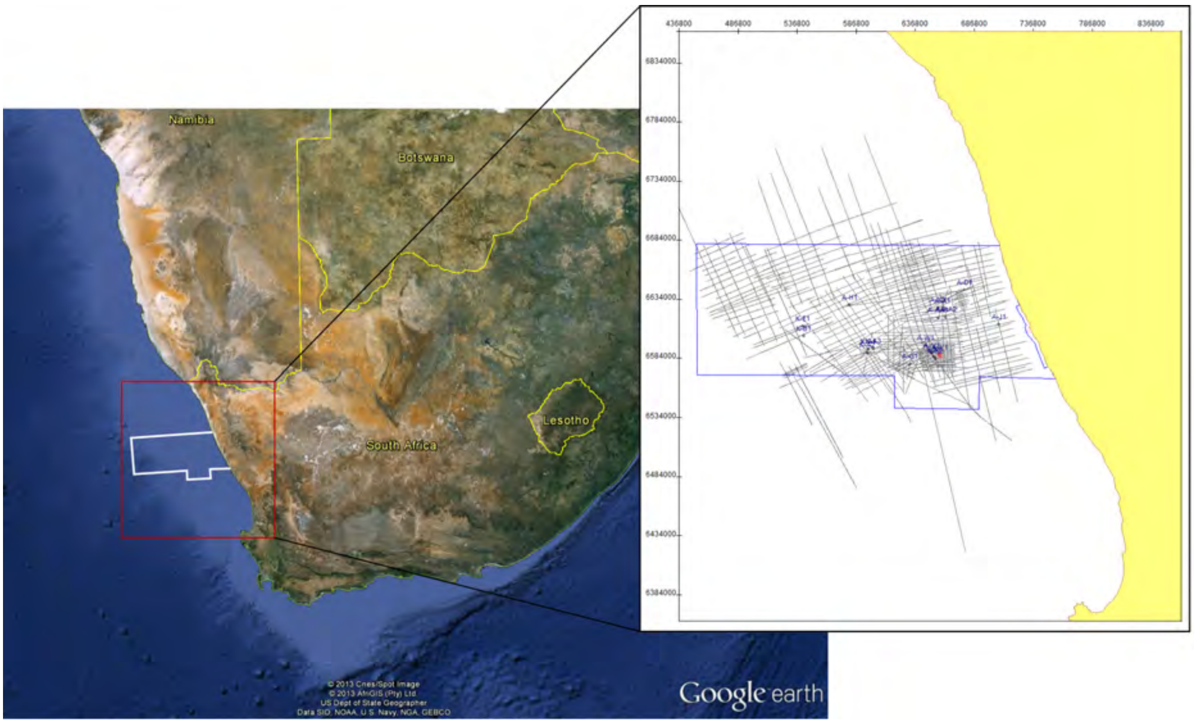


Figure 2.1: Block 2 study area (in white) in the Atlantic Ocean, off the west coast of South Africa. Inset shows the location of the seismic lines and wells within Block 2.

Block 2 straddles the middle to upper reaches of the Orange Basin, one of the main depo-centres on the west African margin. Owing to the basin's setting and geological history, it has been extensively surveyed for oil and gas deposits. The Orange Basin was formed within a divergent plate boundary beginning approximately 132 - 134 Ma (Reid *et al.*, 1991). The sedimentary geology found within Block 2 was formed when the African and South American plates moved away from each other during Gondwana's breakup (Late Jurassic to Early Cretaceous) forming the South Atlantic Ocean. This extension made space for siliciclastic, lacustrine infill (Gerrard and Smith, 1982) within the coast parallel grabens and half-grabens created during the Rift phase. This mechanism is illustrated in Figure 2.2 which shows the rift, and then drift, of the continental plates and the resultant grabens and half-grabens that were formed as a consequence of this pull-apart motion. Block 2 is located almost entirely on a wide shelf, along a passive continental margin and has had sedimentary input from two terrigenous sources: 1) Fluvial - from the Orange River as well as 2) Aeolian deposits - from wind systems blowing off the continental arid to semi-arid regions adjacent to the Basin (Christensen *et al.*, 2002). Sedimentation rates, a potentially significant factor in hydrate formation according to Chazelas *et al.* (2006), were high during the rift and early drift phases - between 135 m per million years and 30 m per million years (Tinker *et al.*, 2008; Kuhlmann *et al.*, 2011) shown in Figure 2.3.

Whilst these early geological processes are separated by hundreds of millions of years from the relatively recent process of hydrate formation, they provide a vital foundation. Of the four major components of hydrate formation, two deal with modern environmental conditions - temperature and pressure. The other two components - sedimentation rate and organic matter - deal with early geological processes which provide the elements required for gas generation and subsequent hydrate formation. Gas is a prerequisite for hydrates.

The present onshore climate is arid to semi-arid. The Orange River is large and originates far inland, making it the perfect mechanism for extensive sediment transport, and offshore deposition. This drainage, combined with other coastal watersheds during the late Creaceous, provided large bodies of terrigenous sediments (Séranne and Anka, 2005; Gallagher and Brown, 1999). Sandy sediments, particularly those with an organic component, are ideal precursors for future oil and gas generating regions. Combined with the trapping graben and half-graben structures and the amount of time that the sediments have had to compact and lithify, the conditions are favourable for hydrocarbons. Wells in this area show the presence of gas, and gas has been produced from wells at Ibhubesi (Sunbird, 2013) within Block 2, though no hydrates have been found yet.

The cold Benguela Current runs from south to north, along the wide western continental shelf off the coast of South Africa to the warmer waters off Angola. There has been a cold surface palaeocurrent off of this coast since the late Albian (Néraudeau and Mathey, 2000; Francis and Frakes, 2009). Looking at the present oceanic conditions, water temperatures in the slightly shallower (i.e. not seabed) intermediate waters, at approximately 750 m, were found by Richardson and Garzoli (2003) to be between 5° C and 7° C. A layer of North Atlantic Deep Water (NADW) occupies the depth range of 1750 m - 3750 m (Saunders and King, 1995; Arhan *et al.*, 2003). The different water masses are characterised by their distinctive salinity, temperature, dissolved oxygen content and nitrate nutrients. The boundaries between them are, in this case, more clearly distinguished by the latter two identifiers. The water temperature would continue to drop from the intermediate waters through to the deep waters, according to the hydrothermal gradient for the area (as illustrated in Figure 1.3), and the colder waters at the seabed would provide the cooler temperatures needed for an environment of present gas hydrate stability. These water masses have a larger, more regional, footprint and do not provide a specific temperature profile for the Orange Basin at a particular site (unless that site co-incides with an existing sampling location). When multibeam or seismic surveys are conducted in a particular area, a CTD (Conductivity, Temperature, Depth) probe is sent through the water column to the seabed to obtain an accurate, and site-specific temperature and salinity profile.

The region around the Benguela Current is known as the Benguela Current Upwelling System (BCUS) and is an area high in biotic productivity and rich in marine life. The biotic productivity originated in the late Miocene, approximately 10 Ma (Robert *et al.*, 2005; Robinson *et al.*, 2002; Siesser, 1980) and has generally intensified, with some periodic changes, over time. Berger *et al.* (1998) showed that the sediments in this area have high total organic carbon (TOC) with concentrations ranging from 2% to 20%; this could be the rich source of organic material needed for generation of ‘new’ hydrocarbons. On the other hand, the Walvis Ridge protrudes out into the Atlantic north of the town of Walvis Bay, Namibia and may separate relatively rich oil and gas fields to the north of it from relatively sparse shows to the south. The ridge could have stopped the transport of some organic rich sediments from the north to the south on the poleward counter-current. The sources of the hydrocarbons in the Orange Basin are much older than the present biotic productivity, however (Soekor, Pty; Boyd *et al.*, 2011).

This is a passive margin and deposited material has been accumulated to great thicknesses. The sedimentation rates within the Orange Basin have been constrained by various studies and are well presented in Figure 2.3. In this figure different sedimentation rates for the western South African margin are shown: the red line represents the more conservative estimate of sedimentation rate from Tinker *et al.* (2007) and the higher estimate from Kuhlmann *et al.* (2010) is depicted with the black line.

The thermal evolution of the Orange Basin and it's tectonic subsidence history are discussed by Hirsch *et al.* (2010), whilst Maystrenko *et al.* (2013) provide a thermal model of the entire South west African continental margin. The South African section of this model was further substantiated by tying it to existing features observed in deep refraction seismic experiments by Hirsch *et al.* (2009). The thermal model showed that, at just 1 km beneath the surface the temperature was between 5° C and 15° C on the seaward side of the Orange Basin to 30° C - 35° C on the landward side. At 3 km depth, the temperature on the seaward side of the basin, along the continent-ocean boundary, had risen to between 10° C to 20° C. The crustal thermal gradients help to constrain the possible lower boundary of the Gas Hydrate Stability Zone.

Block 2 exhibits strong elements of both the rift and drift phase of basin development as evidenced by the coast-parallel, north-south trending horst and graben structures and the onlapping and discontinuous reflectors. A generalised Chronostratigraphy of the Orange Basin according to PASA (2007) is shown in Figure 2.4 and illustrates the various depositional patterns seen in the rock record, specifically the various high stand and low stand conditions experienced during the rift and drift phases. This sequence informs the interpretation of the seismic and well data by putting the sediments into chronological context, as well as giving a rough estimation of sediment type by observing the morphology of the seismic interfaces.

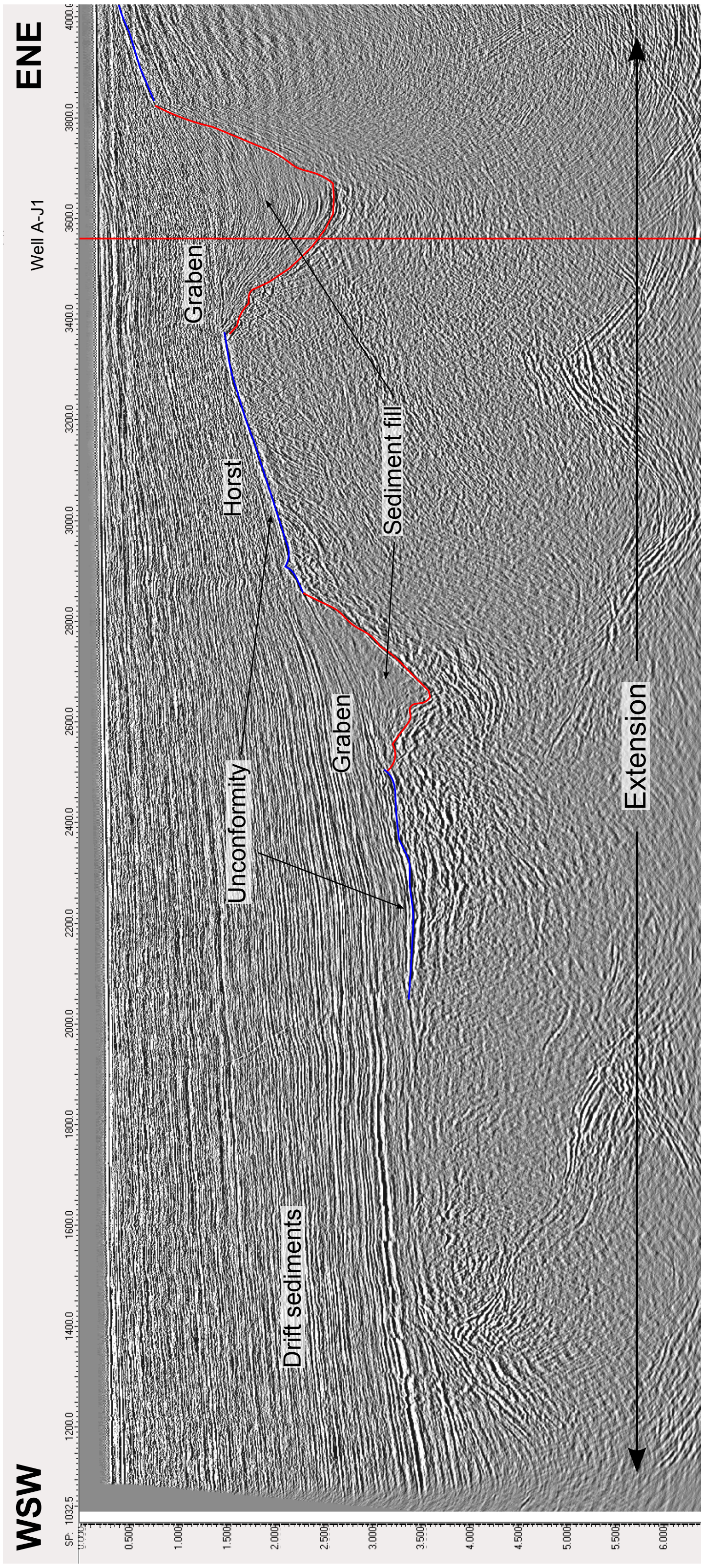


Figure 2.2: Example of extension, between South America and Africa, with the Rift phase creating a succession of dipping horst (blue) and graben / half-graben (red) blocks which are subsequently filled with rift sediments and volcanics and unconformably overlain by the Drift sediments (Line SA92-163).

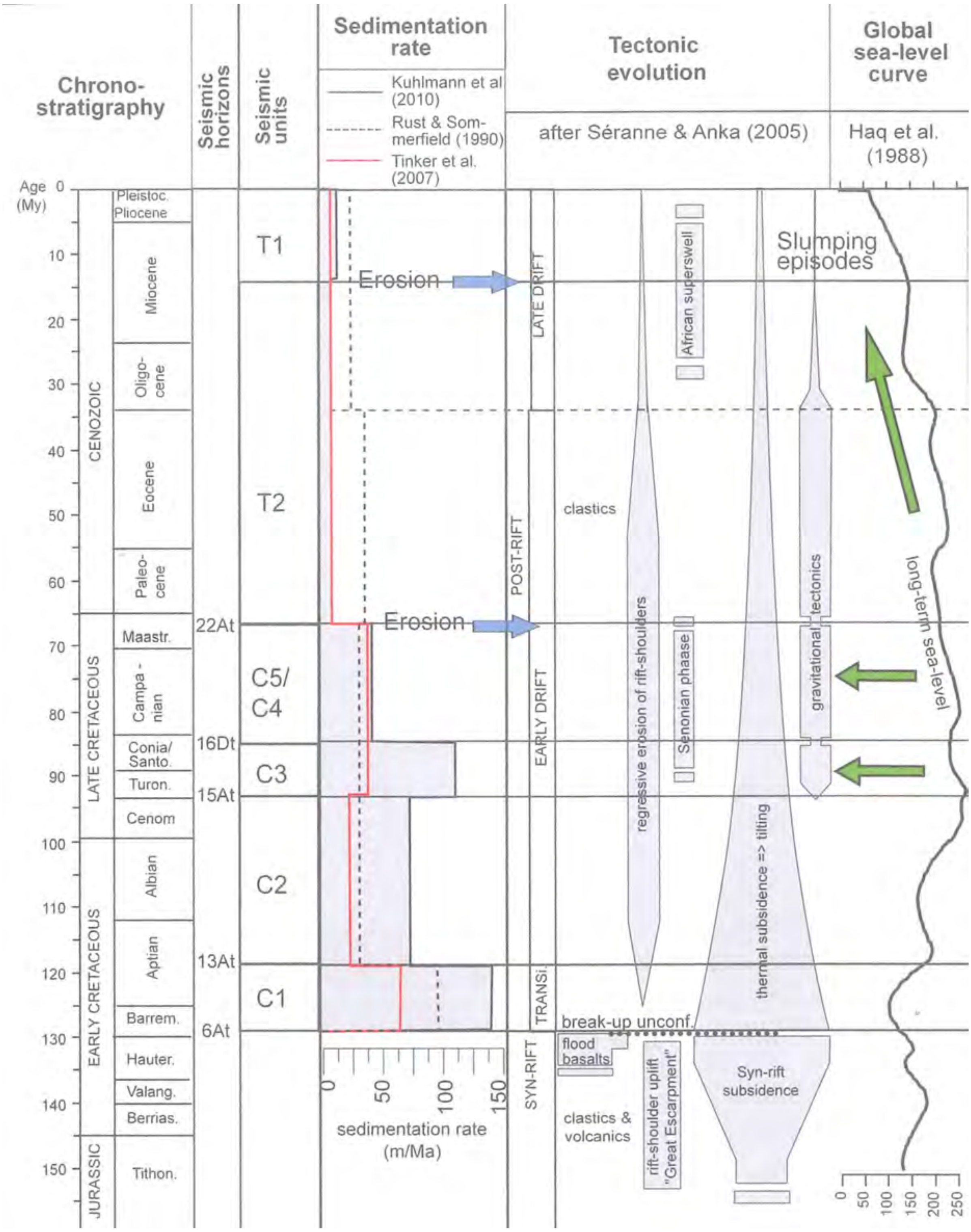


Figure 2.3: Chronostratigraphic chart combining sedimentation rates derived from the study area (Kuhlmann *et al.*, 2011) together with the local tectonic evolution and global sea-level curve for the western South African margin. The red line shows that during the mid-Cretaceous, approximately 130 million years ago, to the late-Cretaceous, approximately 65 million years ago, the sedimentation rate was high (between 25 m and 60 m per million years). These high rates, combined with the lower sea level and thermal subsidence during the early drift stage, mean that a large sediment wedge was laid down at the right time to have possibly matured into a present-day source rock.

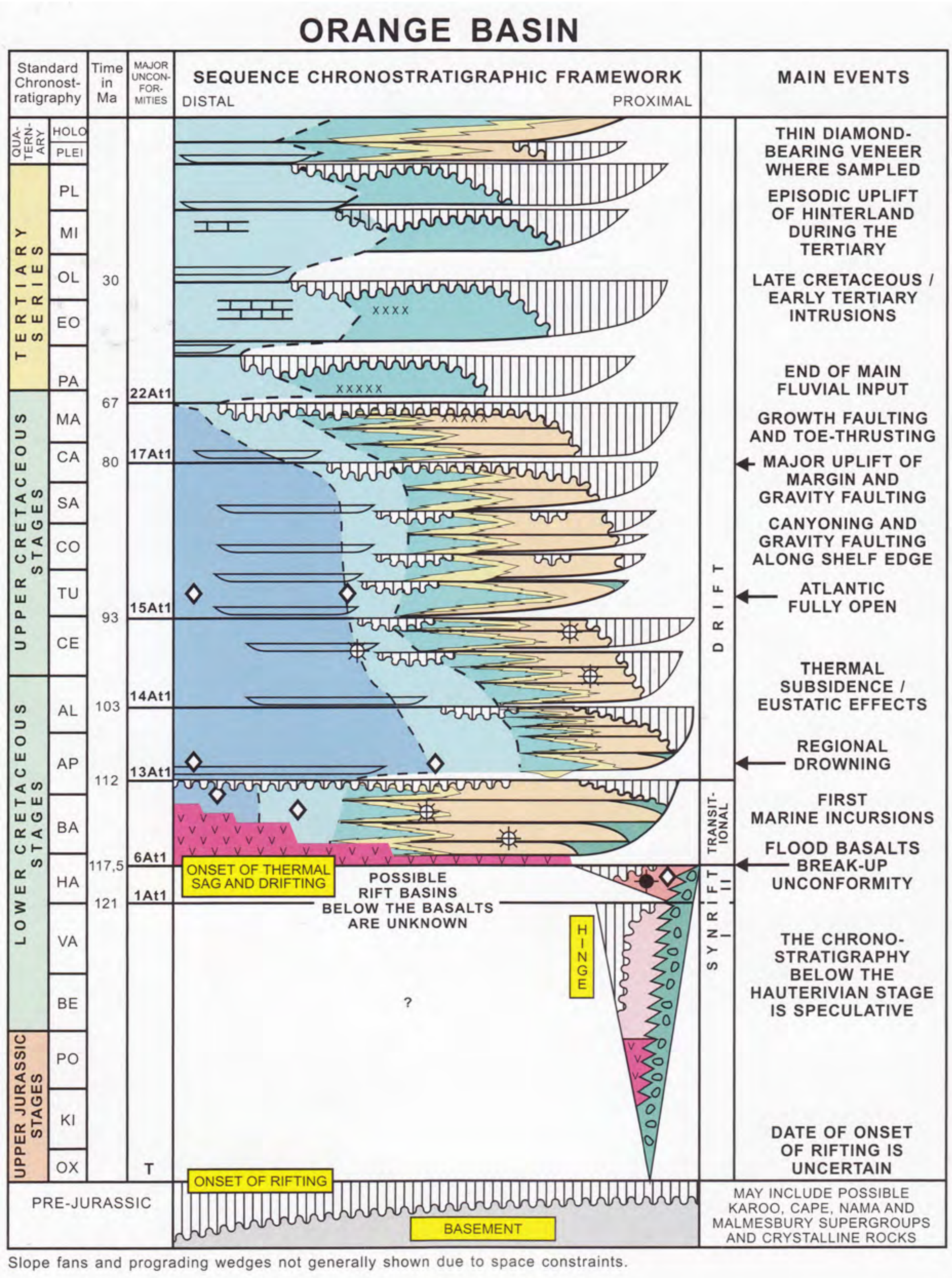


Figure 2.4: Generalised Chronostratigraphy of the Orange Basin (PASA, 2007) broadly showing the main events influencing the type and pattern of sedimentation within the basin from its formation to present-day.

2.2 Data collection

The data used in this study was acquired through the Petroleum Agency of South Africa (PASA) who curate all data from surveys undertaken by various companies. They combine these surveys and analyse the data in order to provide recommendations to companies bidding on the various blocks off the South African coast line.

The seismic line data was acquired over 21 different surveys between 1976 and 2002, each with its own regional focus within Block 2. The well data was from well reports by Soekor and Forest Oil, spanning drilling dates from 1979 to 2003. The companies who initially acquired the seismic line data were responsible for the processing. The 2-D, time-migrated, SEGY data for the appropriate lines was then integrated into an IHS (Information Holding Services) Kingdom Suite project and used for further interpretation for the purposes of this dissertation.

Two hundred and sixty (260) lines and eighteen (18) well reports were provided by PASA for analysis. A listing of these, including their locations, is provided in Appendix A and Appendix B as well as illustrated in Figure 2.1. Each line was loaded into IHS Kingdom Suite and inspected for indications of gas or elements which would suggest the presence of gas hydrates. Where noted, these were marked and annotated for global analysis of the data-set. Well log reports were also examined and compared to the seismic line through which they passed as well as attempting to identify any trends that became apparent.

2-D reflection marine seismic data is collected, using a sound source, usually an air gun, which creates seismic waves which are propagated through the water and the sub-surface, and are reflected off various stratigraphic interfaces, and recorded by hydrophones. A schematic of the physical acquisition process can be seen in Figure 2.5. The seismic collection process in terms of hardware (ships, streamers and air guns) is fairly standardized, however the processing and refining of that data depends largely on the software packages used at the time of collection and processing, as well as the individual operator's interpretation and application of the statistics and corrections. The information from the hydrophones is recorded and sent to a computer and analysed by seismic software to produce seismic sections as well as various statistics for time of returns, velocity, elevation, refraction, amplitude, power and signal-to-noise ratio amongst others. A common processing sequence is the following: Noise attenuation is first applied to the signal, then a Common Mid-Point (CMP) sort and Deconvolution are applied to the traces. After this Velocity Analysis is conducted and Normal Move-Out (NMO) stacking velocities are computed and applied to the traces which are then Stacked (likely using the CMP method). These stacks then undergo various processing adjustments (according to the velocities computed for the sedimentary package that they are travelling through), further Deconvolution, Migration, Filters and Scaling. The computed statistical parameters are utilised in an iterative manner by the software - moderated by an operator - in order to produce the clearest, most logical image of the subsurface.

The SEGY geophysical data obtained from PASA had already been processed, though the interpretation and analysis for this project is original. The seismic sections were displayed and interpreted using the IHS Kingdom Suite software package.

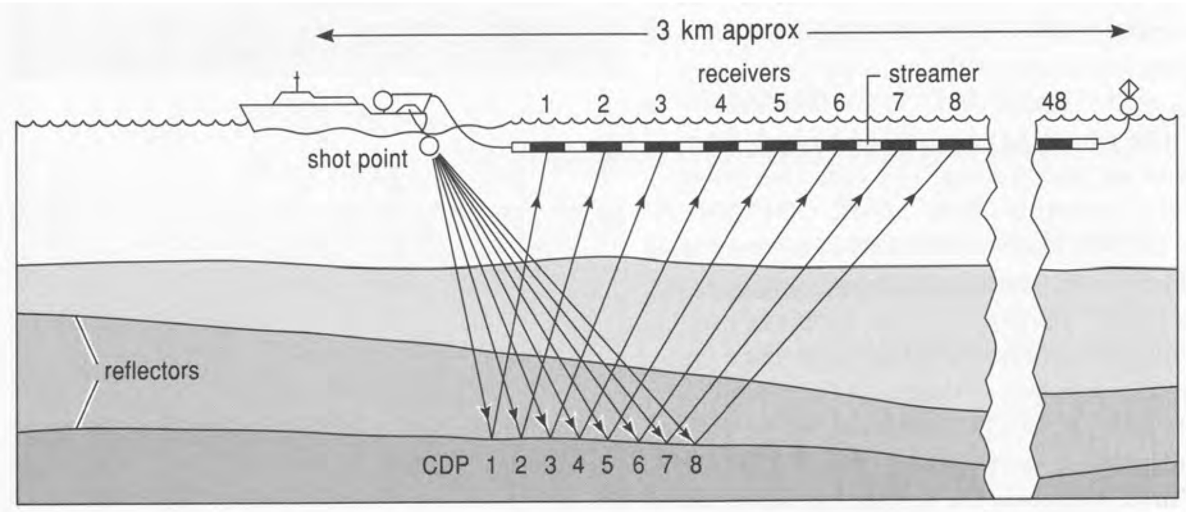


Figure 2.5: Schematic representation of a seismic streamer for marine surveys (Mussett and Khan, 2000).

Of the indicators of gas hydrate seen in the seismic section, the bottom simulating reflector (BSR) is the most reliable. The seismic properties of a BSR are that it 1) simulates the shape of the seafloor above, 2) cross-cuts other seismic reflectors, 3) displays polarity reversal with respect to the seafloor and 4) may have enhanced reflections below it. These properties are caused by the velocity and density differences in the various media that the seismic signal travels through. The seafloor is a particularly strong reflector due to the large difference in the speed of a sonic pressure wave (V_p) as it passes from water to sediment - the V_p in sediment is higher than that in water, as well as the large difference in density (ρ) between water and sediment. The BSR is likewise a strong reflector due to the difference in V_p and ρ between hydrate bearing sediment and a free gas zone, and as the signal is now travelling from a region of higher V_p and ρ (hydrate bearing sediment) to a region of lower V_p and ρ (free gas bearing sediment) the polarity is the opposite of that at the seafloor. This also illustrates why, if there is no significant accumulation of free gas below hydrate-bearing sediments, there may be hydrates present but no evidence of a BSR on the seismic section. Figure 2.7 illustrates the seismic response from seafloor, through the gas hydrate and BSR to below the free gas zone.

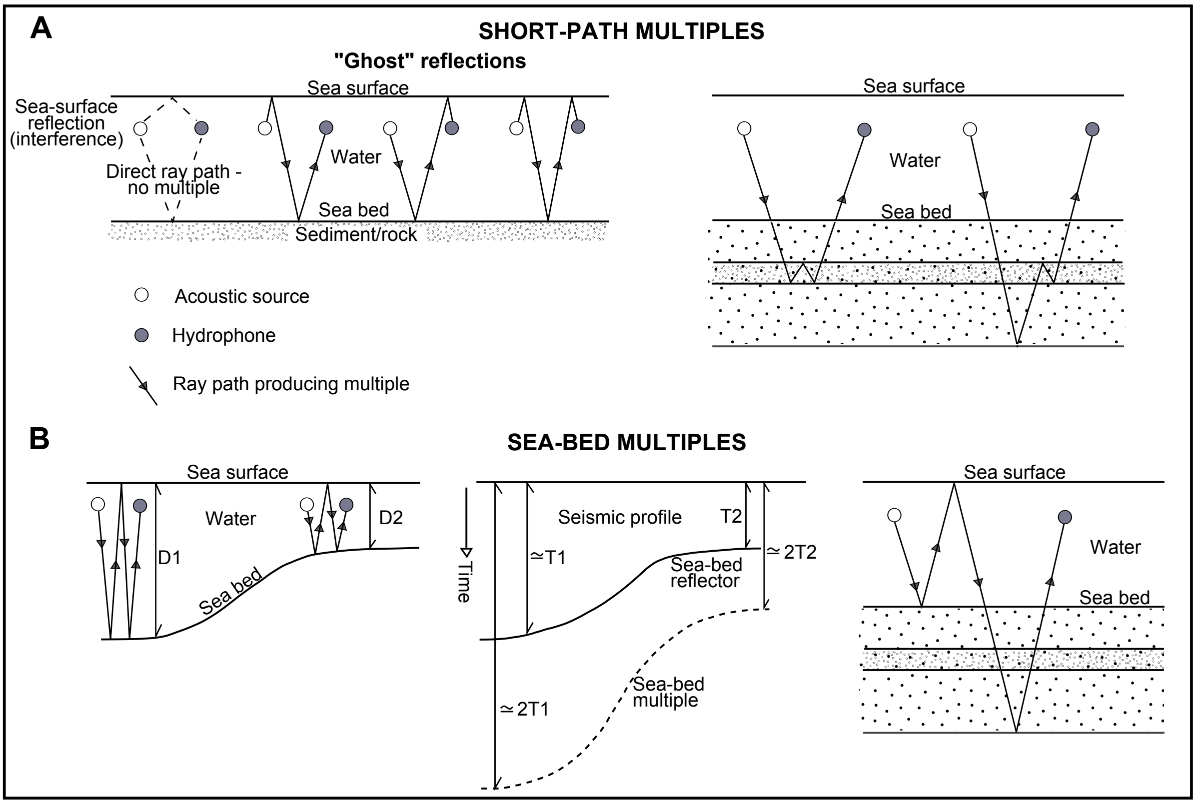


Figure 2.6: A) Short-path multiples produced by reflectors at the sea bed, sea surface and within sediments. B) Sea-bed multiples (long-path multiples) produced by reflections at the sea bed and the sea surface. The schematic representation in the bottom centre shows how a sea bed multiple appears on a seismic section (modified from Stoker *et al.* (1997)). Where the sea bed is flatter, the multiple is almost parallel (making it hard to distinguish BSRs within that zone). However, the multiple exaggerates the relief of the sea bed making the process of identifying it easier in areas of higher relief.

A seabed ‘multiple’ occurs when multiple reflection paths combine to create spurious arrivals (Mussett and Khan, 2000) on the seismic section. This is a reflection that is not caused by one lithological interface, but rather by anomalous ray paths in the geophysical acquisition process producing a horizon that imitates one above it at a specific distance (Stoker *et al.*, 1997). Depending on the water depth, this phenomenon must be borne in mind as a possible source of error or artefact on the seismic section at the approximate area of interest. As strong multiples arise from particularly strong reflectors, which reflect a lot of sonic energy, the strongest and most commonly observed form of multiple is the seabed multiple. This is unfortunate when the feature being searched for (BSR) has a defining characteristic of imitating the form of the seabed - the same effect that is displayed by a seabed multiple. A graphical depiction of multiple creation is shown in Figure 2.6A & B. Processing of the data-set by applying NMO and stacking attempts to mitigate multiples by enhancing the stratigraphic reflectors and decreasing the effect of any multiple reflections. This does not eliminate the multiple in many cases and care must be taken when interpreting a seismic section to not equate the multiple with real geology.

Gas chimneys are also associated with gas hydrates (Sun *et al.*, 2012). Seismically, gas chimneys tend to display as blank regions. This is caused by the acoustic signal being scattered by the velocity and density differences between the gas-saturated sediments and the surrounding water-saturated sediments. A similar effect can sometimes be seen in the free gas zone beneath the BSR. Gas chimneys are, as the name implies, constrained horizontally and extend vertically through the seismic section, cutting through the generally horizontal to sub-horizontal structure of the surrounding horizons. They usually start in the area of gas generation and propagate through the surrounding sediments tapering upwards. Gas chimneys occasionally coincide with a raised portion of the seabed (mud volcano), or a roughly circular depression (pockmark) showing a surface expression of the underlying gas. An example of chimneys within the dataset can be seen in Chapter 3 (Figure 3.2).

Mud volcanoes are an indicator of gas or or gas hydrates. Sauter *et al.* (2006) showed discharge in the form of a huge methane plume comprising hydrate-coated methane bubbles and hydrate flakes. Gas plumes can sometimes be seen in the water column of a seismic section in the form of a highly reflective, diffuse mass, above the strong seafloor reflector. They are more readily seen on high-frequency seismic sections, but may also be observed on conventional 2-D data. The mud volcano itself will appear on the seismic section as a raised, often triangular shaped profile on the seafloor. They are also sometimes associated with gas chimneys.

Expression of gas hydrates in the form of methane hydrate mounds (as prominently seen in the Gulf of Mexico) will display on the seismic section as a raised area on the seafloor profile, underlain by diffuse and chaotic reflectors. Visual inspection, through Remotely Operated Vehicles (ROVs) is a better way to view this feature.

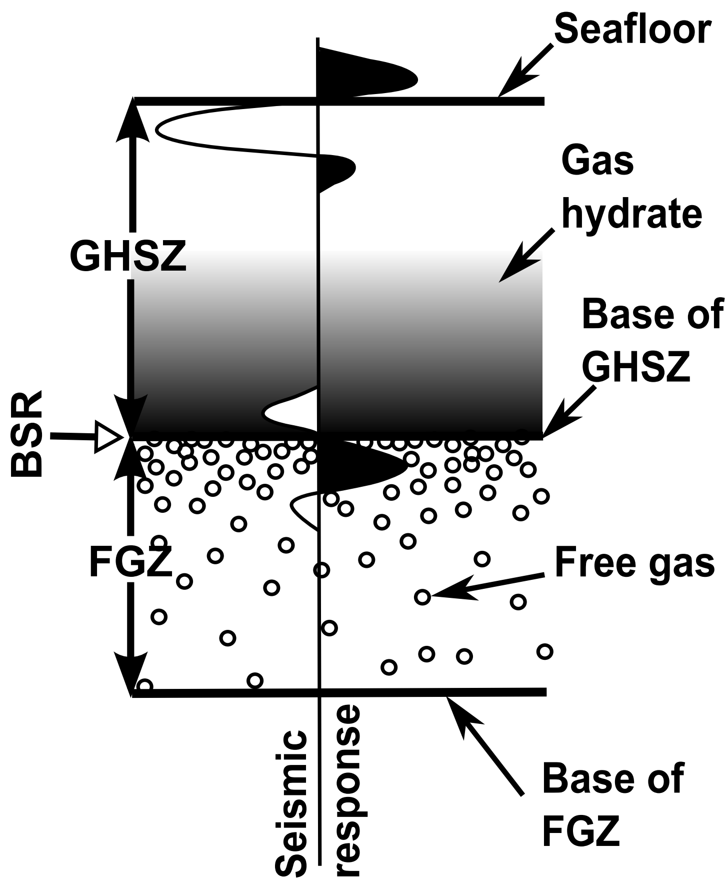


Figure 2.7: Illustration of how a bottom simulating reflector (BSR) is shown on the seismic response in a submarine sedimentary section containing gas hydrate and free gas. The BSR marks the base of the Gas Hydrate Stability Zone (GHSZ) shown above it in shaded grey, and the upper limit of the Free Gas Zone (FGZ) which occurs below. The polarity reversal between the seismic response at the seafloor and the BSR is clearly shown. Modified from Haacke *et al.* (2007).

2.3 Interpretation

The SEGY data was interpreted using the IHS Kingdom Suite software package which provides a 2-D visual representation of the seismic profile itself. These profiles were then visually interpreted for the presence of hydrate indicators (BSRs) and gas indicators (chimneys, blanking, chaotic reflectors, mud volcanoes). Tables of the well reports and seismic line properties were created to facilitate this process and help to find common denominators and any trends that would become noticeable.

Chapter 3

Results

Two hundred and sixty (260) seismic lines and eighteen (18) well reports (Soekor, Pty; ForestOil, 2000-2003) were provided by PASA for review and study. These are shown in Figure 3.1. Of 18 well reports from Soekor and Forest Oil, spanning spudding dates from 1979 to 2003, none showed evidence of gas hydrates though almost all showed some evidence of gas, not necessarily in any commercially useful quantities however.

The well reports predominantly stated that the reservoirs were water saturated or had only poor gas shows; well A-Y1 was the exception as it showed a moderate to good percentage of moveable gas in one of the reservoir sandstones - a much higher yield than any of the others. The well report received for well A-K1 was actually a well **test** report which, despite testing, failed to produce commercial quantities of either oil or gas. However, in the initial stages of the second attempt at starting to produce the well, there was a delay "caused by the flowline becoming blocked with ice". Whether this ice was simply frozen water or of a hydrate nature is not elaborated on, but it bears noting. On average, during the testing period, well A-K1 produced more water than oil (at a ratio of between 1.3 bbl (barrel) / bbl to 1.7 bbl / bbl) and average gas flow rates of only 4.19 to 13.31 MMSCF (Million Standard Cubic Feet) / day. The conclusion was that some condensate was produced, and that the significant quantities of water production were due to the gas-water contact having been perforated. This report for A-K1 is the only one citing physical measurements of the hydrocarbons present. A summary of the observations of the reports on the various wells is found in Table 3.1 with a more detailed description in Appendix A.

Eight (8) seismic lines were corrupted or incorrectly processed or were terminated before their depicted end point; 3 of the 8 had location problems where the shot points of the seismic section were reversed for part of the way compared with the map, which led to the horizons in one section appearing to be dipping towards the coastline (in contrast with those surrounding it which dipped away). This did not, however, significantly negatively impact the interpretation as a whole. The damaged lines were ~3% of the total number of seismic lines and were in the vicinity of alternative seismic lines from different surveys. A further eight lines were significantly, or almost wholly, out of the Block 2 survey area. The locations of the individual surveys can be seen in Appendix C.

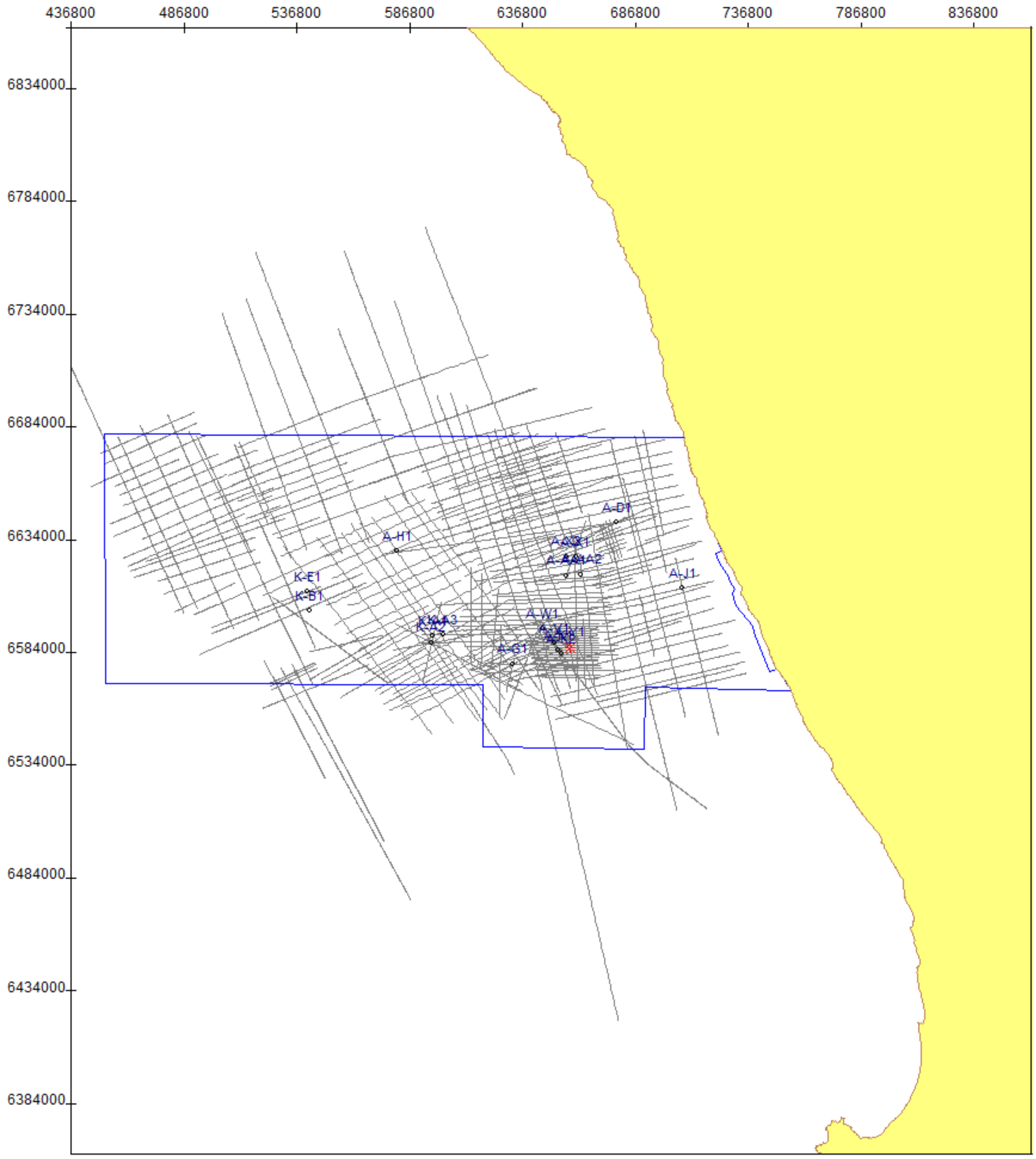


Figure 3.1: Location of all of the seismic lines and wells examined within Block 2 (blue outline).

Table 3.1: Summary of well reports for 18 wells. (For details of general geology see Appendix A)

Well	Spudding date	Longitude	Latitude	Depth of well (TD)	Water depth	Gas/oil found
A-AA1	24-Sep-03	30° 33’ 34.91” S	16° 37’ 45.08” E	3324.5m	211.5m	Water saturated
A-AA2	23-Oct-03	30° 33’ 13.28” S	16° 41’ 54.35” E	3171.0m	211.5m	Predominantly Water saturated
A-D1	27-Jun-81	30° 20’ 35.75” S	16° 51’ 38.50” E	3729.8m	168.9m	Poor gas shows. Water saturated
A-G1	30-Apr-88	30° 54’ 58.23” S	16° 23’ 06.27” E	4100m	264m	Low gas levels
A-H1	13-Apr-81	30° 28’ 13.26” S	15° 50’ 46.15” E	3984m	266.1m	Gas shows
A-K1	08-Mar-87	30° 51’ S	16° 35’ E	3681m		Water. Some gas and condensate
A-M1	proposed	30° 29’ 29.66” S	16° 41’ 9.35” E	3422m	206m	
A-T1	proposed	30° 42’ 07.07” S	17° 00’ 03.75” E	3575m	175m	
A-V1	22-Nov-00	30° 49’ 45.88” S	16° 34’ 49.30” E	3714m	242.3m	Problems w/ tool. Abandoned
A-W1	20-Feb-01	30° 46’ 31.10” S	16° 31’ 24.65” E	3511m	245.8m	No shows. Water saturated
A-X1	15-Nov-03	30° 29’ 12.42” S	16° 40’ 19.57” E	3300m	205.5m	Predominantly Water saturated
A-X2	28-Dec-03	30° 29’ 03.56” S	16° 37’ 41.62” E	3478m	207m	Water saturated
A-Y1	07-Apr-01	30° 50’ 48.95” S	16° 39’ 03.81” E	3392m	243.6m	Gas. Moderate hydrocarbons
K-A1	15-Apr-79	30° 48’ 27.50” S	16° 00’ 59.90” E	4819.2m	222.5m	No significant shows. Abandoned
K-A2	10-Sep-79	30° 50’ 03.21” S	16° 00’ 32.78” E	5829.7m	220.4m	Poor gas shows. Water saturated
K-A3	01-Jan-81	30° 48’ 08.55” S	16° 03’ 50.75” E	4676.85m	219.6m	Poor gas shows. Water saturated
K-B1	31-Jan-79	30° 42’ 38.67” S	15° 26’ 52.18” E	4075.8m	354.2m	No oil or gas. Abandoned as dry
K-E1	19-Aug-81	30° 37’ 55.83” S	15° 26’ 03.01” E	4133.7m	318.21m	Dry well with gas shows

3.1 Seismic evidence of gas

The most prevalent indicator of gas seen on the seismic lines was gas chimneys. Some of these were clearly delineated, whilst others were more indistinct - the clarity of the gas chimneys did not appear to be associated with a particular orientation of the seismic line to the coast (either parallel or perpendicular), however the less orthogonal the direction, the more indistinct the structural features. The relative apparent strength of these features could be due to the angle of the survey lines, but it could equally be due to the different years of acquisition and the corresponding changes in recording equipment and hardware or software for capturing the raw data. The seismic data was acquired over 21 different surveys between 1976 and 2002, each with its own regional focus within Block 2. 170 of the 260 seismic lines showed evidence of gas chimneys (weak and defined), gaseous sediments in the form of generalised blanking, chaotic reflectors, fault-associated chimneys or surface features such as mounds - which could be mud volcanoes - and pockmarks. Of this larger number, 111 lines specifically showed the presence of chimneys, either clearly delineated or indistinct, fault-associated or in unbounded columns. The highest concentration was surrounding A-Y1, A-K1 and A-V1 in the south eastern side of Block 2. The A-K1 well test report from March of 1987 did not focus much on the geology of the well, but rather the procedure and flow rates achieved over a three day flow period. The initial wireline tools were lost after being blown up the hole and the wire holding them severed - a clear indication of gas.

Gas chimneys are shown through blanking in the acoustic record when the sound wave is diffused by encountering something which significantly disrupts the surrounding rock or sediment (either gas or gaseous sediments). Chimneys form upwardly narrowing columns which appear to cut through the surrounding horizons, and may result in uplift of those horizons within the chimney. They either terminate before reaching the seabed, or continue upwards until they meet the seafloor reflector. This characteristic can be seen un-annotated in Figure 3.2A and annotated in green in Figure 3.2B on coast-parallel line A87-025. As can be seen on these figures some chimneys are clearer than others. This gas would be too deep to correspond to gas hydrates, but could easily be a feeder source for the formation of hydrates in shallower, cooler sediments. Physical indications of this deep gas were noted in the well report from Well K-E1. It states, in the remarks of the Well-Site Completion Coregraph, that one of the final cores at ~3753 m: “Entire core was bubbling at surface and was sealed and waxed as soon as possible ($\frac{3}{4}$ hr). Therefore the present description is brief and tentative”. The core loggers were likely describing in-situ gas. The core was logged on 30 September 1981 - over 30 years ago - and its location can be seen in Figure 3.3.

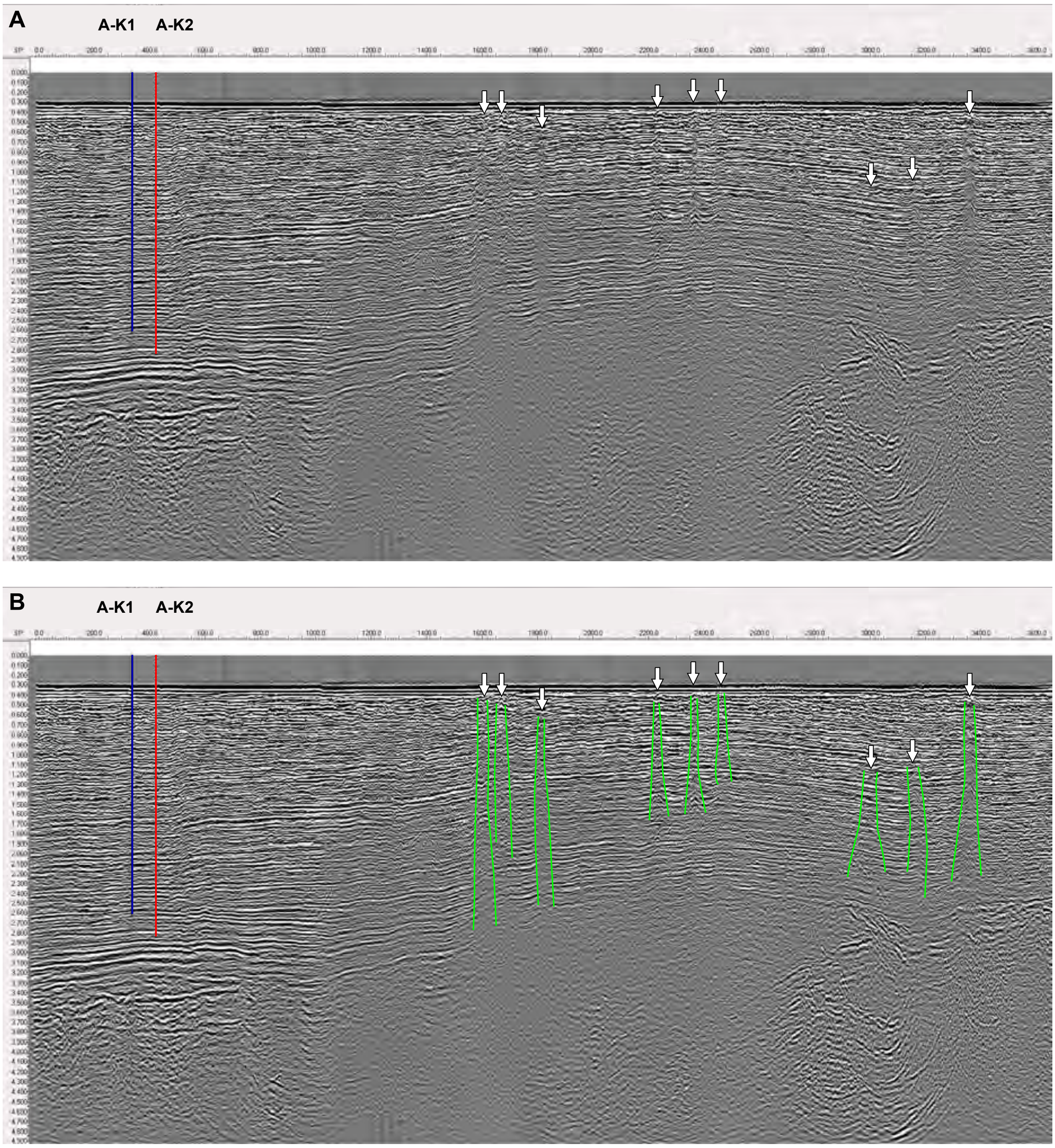


Figure 3.2: A) Image of line A87-025 cutting through Wells A-K1 (in blue) and A-K2 (in red), showing blanking in the form of visible gas chimneys extending from approximately 2.7s TWT (two-way time) to just below the seabed. The chimneys in this un-annotated example are indicated by arrows. B) Annotated image of line A87-025 cutting through Wells A-K1 (in blue) and A-K2 (in red). The Gas chimneys on this coast-perpendicular line are highlighted in green.

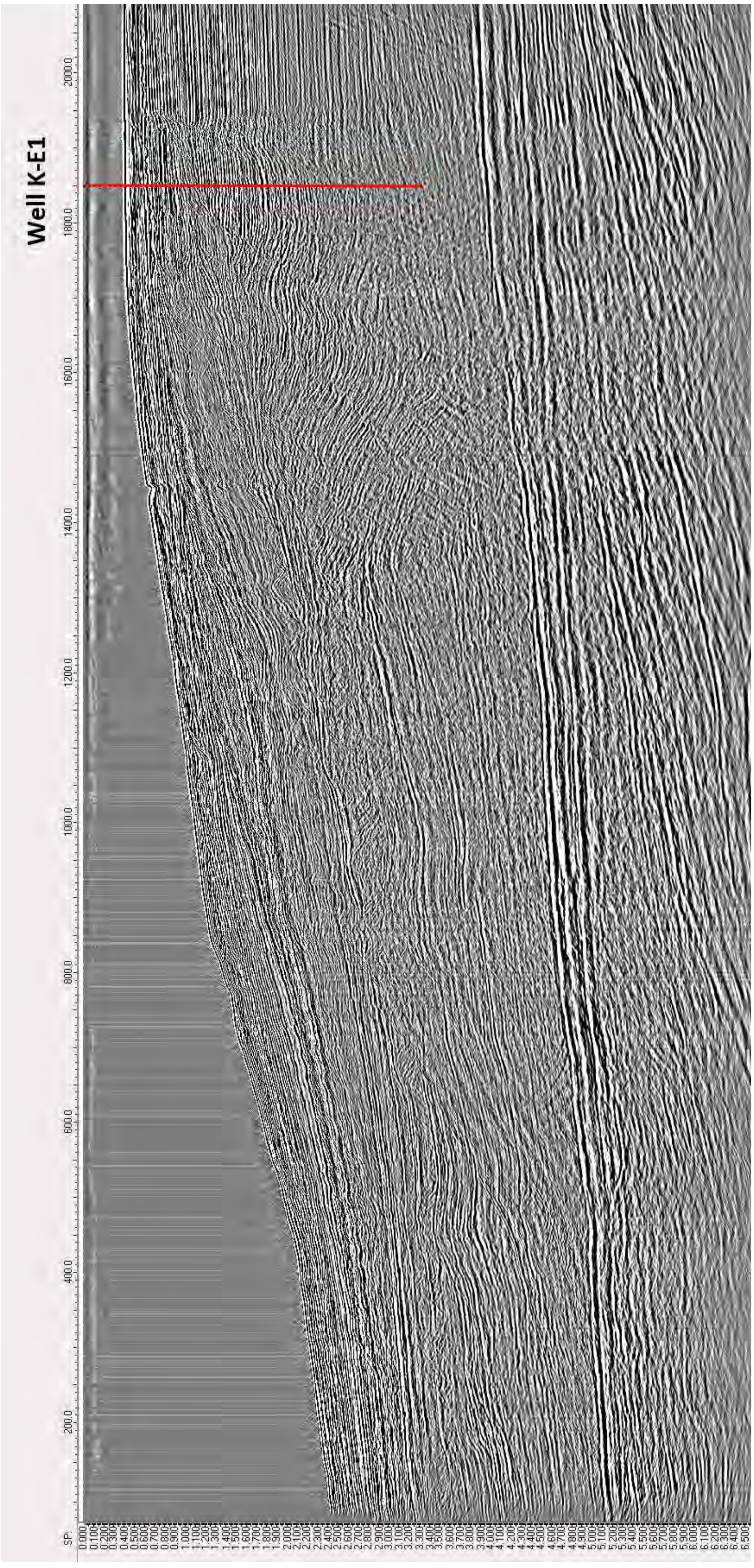


Figure 3.3: Seismic section of line K92-108 through Well K-E1 (shown in red).

3.2 Seismic evidence of gas hydrate

On line AK76-017 in Figure 3.4 (a coast-parallel line towards the southern border of Block 2) a potential BSR was seen, indicated by the cross cutting of the strata. There are indications of gas on the seismic section in the form of chimneys which reach the seabed, a raised section of the seabed (Child's Bank) and the line is also located in the right region geographically - the edge of the continental shelf. Despite all of these indicators, the 'BSR' was concluded to be a seabed multiple (as illustrated and described in Section 2.2). The appearance of a seabed multiple is seen on numerous seismic sections but no clear-cut instances of a BSR (Bottom Simulating Reflector) were noted. These findings do not, however, mean that there are no gas hydrates, as there was abundant evidence of gas - verified by the well log data, numerous gas chimneys, blanking, pushed-up reflections and bright spots. The U.S. Geological Survey (USGS) National Oil and Gas Assessment Team (USGS, 2009) stated that there is evidence to link more deeply buried conventional oil and gas to hydrate accumulations above it and, as Rajput *et al.* (2012) emphasised: the absence of a BSR in a particular area does not indicate the absence of hydrates. Where there is gas, there might be hydrates.

3.3 Features observed within Block 2

When analysing and interpreting seismic data many complimentary factors need to be kept in mind. Features noted need to be viewed in context as well as being critically compared to what is known about geology, in general, and the area being investigated, in particular. Sharp lines are often not of natural origin (except if indicating a fault) and should anomalies such as flares in the water column or chimneys with a suspicious dark spot at their mouth be seen, an alternative explanation should be considered to the immediate: 'gas in the water column' or 'chimney with rock(?) on top'. Knowing how the seismic trace is generated also informs the decision as to whether what is being seen is natural or an error generated by the process that the signal undergoes from the point of collection to the point of final display. A decision is made based on what is more likely to have occurred; given what is being displayed on other lines in the area, other sources of data (e.g. from wells or bathymentric data), the navigation of the vessel at time of collection, the orientation of the seismic line to the geology and and trends noticed in the area.

Following are some of the more significant geological features and trends observed within the Block 2 seismic data. The gas and gas escape features are the most compelling as they provide the strongest supporting features for potential hydrates. A table of the seismic lines and their various attributes is presented in Appendix B. The various surveys were often undertaken with a specific target in mind (potential reservoir, geological anomaly) which is noticeable when observing their areal extent in Appendix C. This localisation is particularly evident when viewing the surveys individually.

Within the AK76- survey, examples seen in Figure 3.4 and Figure 3.5, there is a localised bathymetric high. It is not seen on all of the seismic lines within this survey, but distinctly rises from the surrounding seabed. The seabed within Block 2 is essentially planar until the shelf is reached. This raised area is known as Child's Bank, and the reflectors below the base of the Bank are distinctly different from the fine to absent reflectors within the Bank itself and on its flanks. This seismic signature could mean that it consists of less consolidated sediments or that it comprises more homogeneous material which does not give rise to strong reflections.

Data from A82 survey and A83 survey looked coarse, with no definition or crispness. This could be due to the angle between the direction that the seismic profile was shot and the dip-direction of the strata. In this case it appears that it is due to a difference in collection or processing. A line from the A83- survey was compared to more recent survey done in the same area, SA92. The seismic lines are parallel to each other and perpendicular to the coast, with line SA92-159 being approximately 7 km - 7.5 km north of A83-024. This direct comparison between surveys of different ages can be seen in Figure 3.6. Almost all of the lines from the A83 survey showed a very strong seabed multiple overprinting the lithological reflectors between approximately 0.400 s and 0.500 s, especially prominent on the shallower sections. These lines are relatively close to the coast, ending between 6 km and 12 km from land, and this is an example of an artefact that could commonly be encountered under these conditions.

Whilst gas chimneys are the most abundant evidence of hydrocarbons within the Block, there are other indicators. Figure 3.7 shows bright spots within the gas chimneys and at the A-Y1 well site. This was the site which showed good indications of gas when drilled. Other gas escape features such as blanking, pockmarks and seabed disturbances associated with gas blanking are illustrated in Figure 3.8. Berge (2013) described possible Hydrocarbon-Related Diagenetic Zones (HRDZ) associated with gas blanking and seabed disturbances which could possibly correlate to Figure 3.8a.

There are N/S (coast parallel) extension faults extending from the edge of the graben structures. These would be easy places for chimneys and gas seeps to form. In Figure 3.9 faults associated with the edges of grabens are seen. Rift and drift processes are the likely causes for these (extensional) faults. Gas is associated with these faults in many of the seismic sections and can also be seen in this case. The anomaly in the water column on Figure 3.9b was initially thought to be a gas plume being fed from the chimney, but, due to its uniformly curved shape, has been attributed to a migration effect of missing data or sea-floor discontinuity in the seismic data instead. A large gas chimney, originating deep below the 13At1 unconformity, trending roughly N/S is seen clearly on sections AK76-001, -003, -005, Figure 3.10. Such a feature is also noted in Aminzadeh and Berge (2013), showing a strong vertical line of seepage offset from a fault in the same general geographic location.

Figure 3.11 shows several geophysical anomalies - features that appear to be real, but are not actually present in the lithology. An object in the surface sediments can distort the seismic reflectors below it and cause the appearance of a gas chimney. A feature which contains the indicators of a gas chimney - columnar with blanking and pull-down attributes, with a pockmark on the seabed perhaps associated with it as a result of gas escape - may in fact not be what it seems. A different interpretation could be that the seabed disturbance created a sharp velocity discontinuity in a small area of the seismic section. When the section was stacked and migrated the smooth move-out corrections did not allow the data to be stacked correctly, the smooth velocity field did not allow it to be migrated correctly, and an anomalous 'chimney' was developed below the pockmark.

Examples of extension in the form of dipping blocks are regularly seen on the coast-perpendicular lines such as SA92-159 as seen in Figure 3.12. Annotated figures of these structures can be seen with the dipping blocks of the palaeo-surface in red and the unconformably overlain (younger) palaeo-seabed surface in blue.

3.4 Map of gas features within Block 2

When interpreting the dataset as a whole, it should be kept in mind that the linearity of the distribution of some of the features may be an aliasing effect, due to the position and location of the lines given to be interpreted. A way to overcome, or compensate, for this would be to gather more data from seismic lines **not** used in this thesis, grid and smooth the available data into *regions* and not specific data points, or to run additional surveys in a closer grid pattern in order to distribute the coverage more easily.

Whilst the surveys provided often ran the seismic lines in a grid pattern on occasion tie-lines were not present, they also did not cover the entire Block. The lack of coverage occurs in three separate areas: the extreme south west corner, the southern portion of the protruding section in the south of the exploration block and the areas close to the coast. The lack of near-shore lines is understandable given the constraints of vessel size and manoeuvrability when trailing a length of seismic streamer. The lack of data in the south west corner and southern portion could be either due to the fact that, based on additional data not available for this thesis, it was decided not to run any surveys in that area, or that the surveys were withheld due to proprietary information or still active exploration rights. The latter explanation is far more plausible when considering that the southern section is directly under an area of intense exploration and clusters of wells from past drilling programs.

Looking at the map of the various types of gas expression seen within the survey area (Figure 3.13) it can easily be seen why the wells were placed where they were, as they correspond to chimney and gas rich areas. Of course, this could also be due to the fact that the area around the wells was more highly surveyed, in preparation for drilling, and consequently more seismic lines were made available for this particular area. Many of the lines overlap as well and could lead to the identical feature being identified multiple times on different lines.

Clusters of faults with associated gas are not surprising in this extensional regime, nor is their coast-parallel NE-SW trend. Gas chimneys within the survey area also appear to follow a similar trend, especially when looking at the large palaeo-chimneys in the north western corner of Block 2. These laterally and vertically extensive chimneys often are terminated in a sub-surface mound at the level of the palaeo-seabed. Also in that area, paralleling this NW-SE line approximately 10 km to the west are another series of large, vertically extensive chimneys, creating seabed mounds at their mouths varying from 1 km to 2.5 km. Two chimneys along this line have a surface expression i.e. they reach, and create a disturbance on the seabed. Many are associated with bright spots and areas of blanking and extreme disturbance of seismic reflectors within the columnar delineation of gas chimney.

Several vertically extensive gas chimneys were observed, almost all in the central south. A few of these reached the surface and were associated with what appeared to be a seabed pockmark. The chimneys which showed seabed surface expression also appeared to be clustered in the far south of Block 2 - many just out of it in Block 3. There was a field of shallow surface pockmarks seen around the gas chimneys along the southern boundary of Block 2. They seemed to be along the edges of the bathymetric high known as Child's Bank. There is also an impressively large collapsed gas chimney in this southern area as well which, as well as being vertically extensive, boasts a very wide top. This feature was clearly seen on three separate lines that cut through it at different places and the mouth was measured between 7 km and 10 km at its widest.

The faults in the west are all of a very short, shallow dipping and clustered nature. These listric normal faults are located on the outer shelf / shelf break slope in an extensional domain. They are proximal to the seabed, though all terminate well before it, often against a palaeo-seabed surface, and may provide some diffuse means of transporting gas from the sediments surrounding them. The faults in the south are deep and associated with the numerous grabens within the survey area. These provide a convenient pathway for fluid migration from the deeper source rocks to the surface or sub-surface.

There are areas of diffuse gas or blanking throughout Block 2, often at depth. These are often associated with gas chimneys, either those reaching the surface or those that terminate before it, as well as with faults or fault-associated chimneys. This abundance of gas is of great importance when looking for possible hydrates. The fact that gas sources for the hydrate are available and that there are numerous existing transport pathways in the vicinity of them is promising indeed.

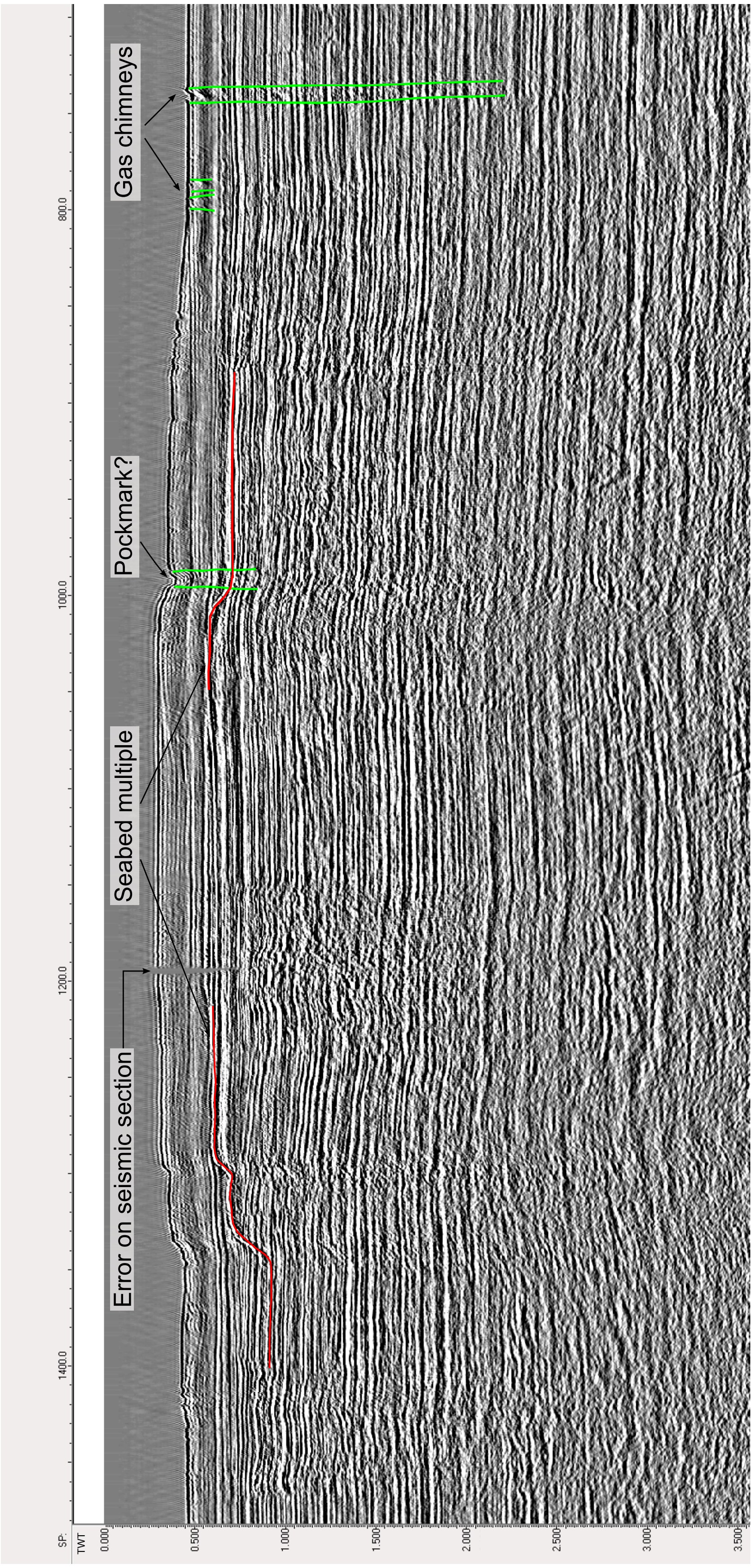
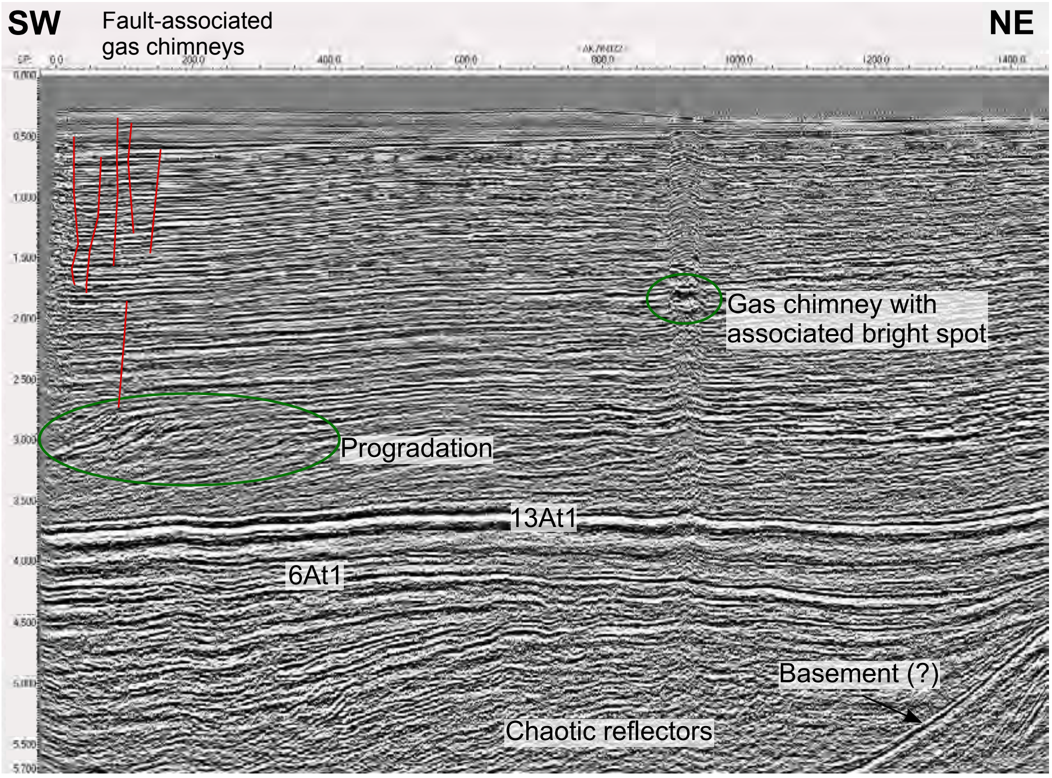


Figure 3.4: Line AK76-017 showing gas chimneys in green, a raised portion of the seabed (Child's Bank) and a possible Bottom Simulating Reflector (BSR) on the left (red) which mimics the shape of the seabed whilst cross-cutting the general strata.



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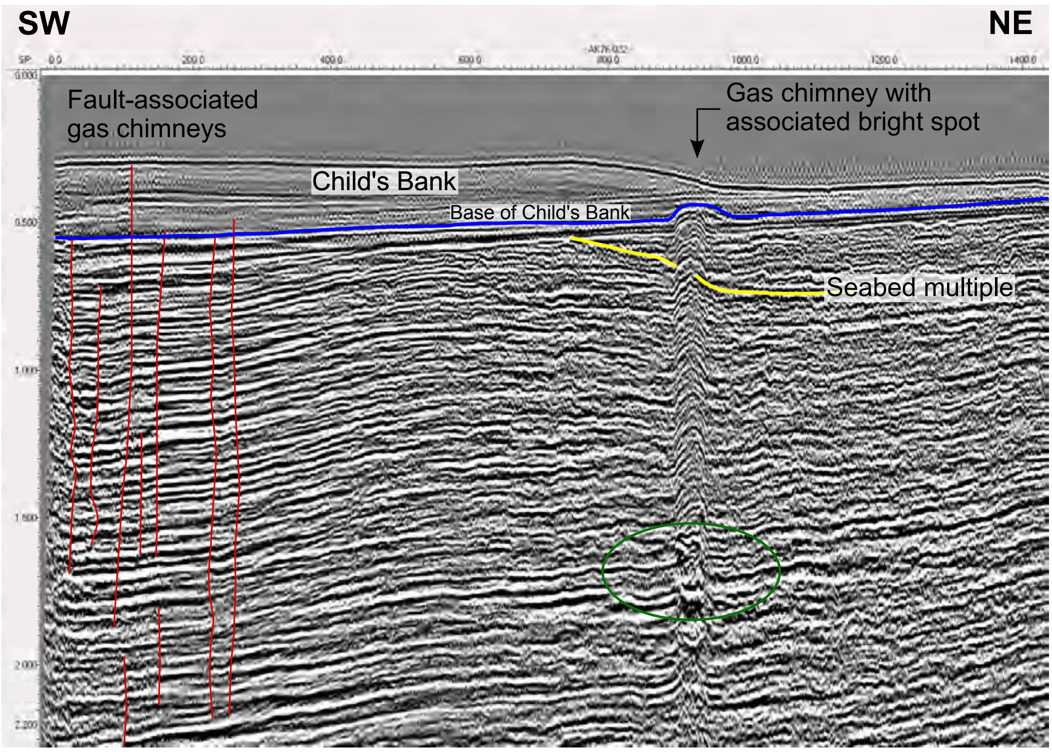
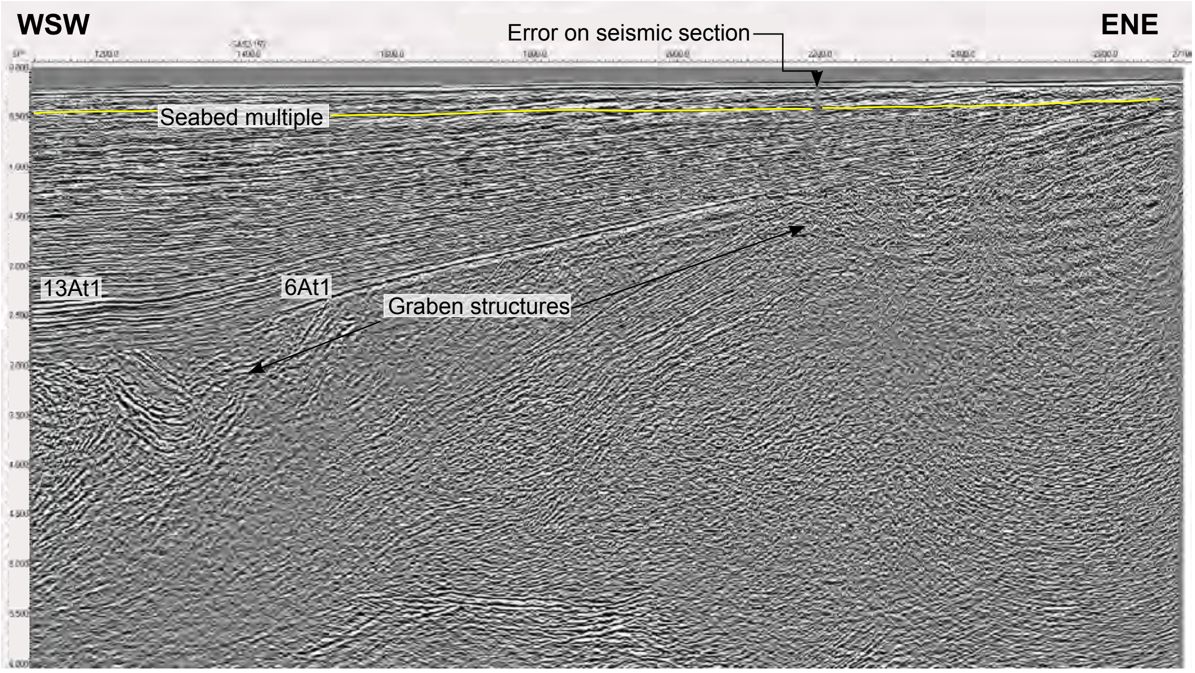


(b)

Figure 3.5: a) Overview of line AK76-022 illustrating a prominent gas chimney with associated bright spot, progradation (resembling cross-bedding in the reflectors) and possible basement in the lower right-hand corner b) A close up version of the line showing the seabed multiple which could easily be mistaken for a BSR as well as the bathymetric high of Child's Bank and fault-associated chimneys in the far left near the surface.



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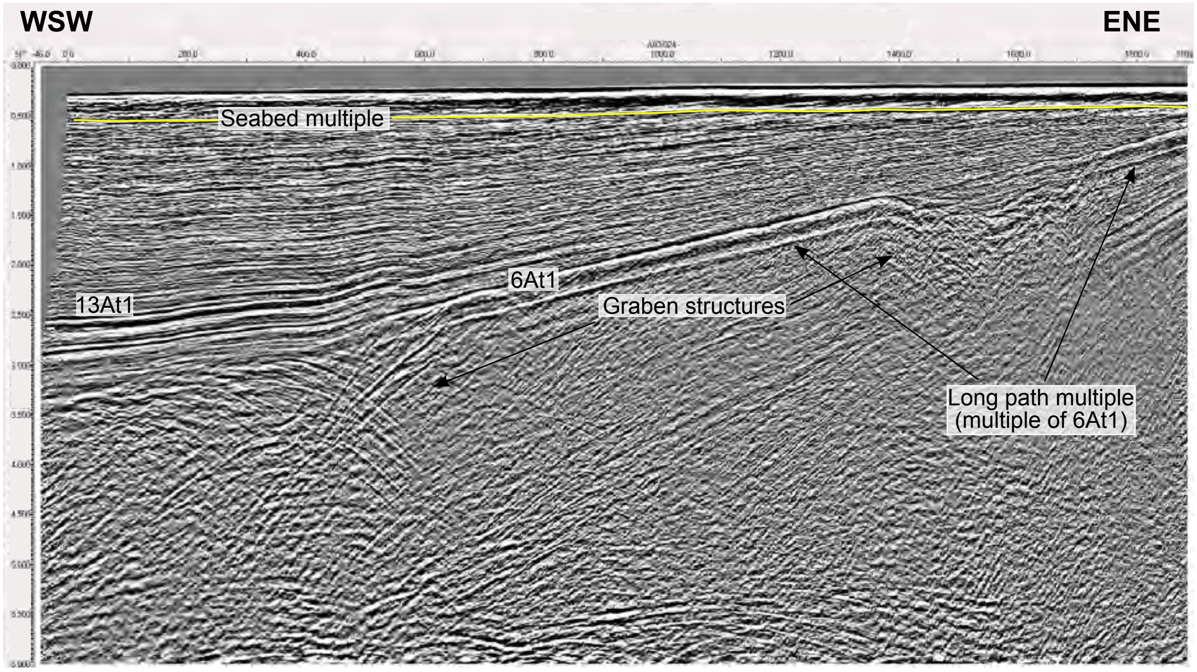
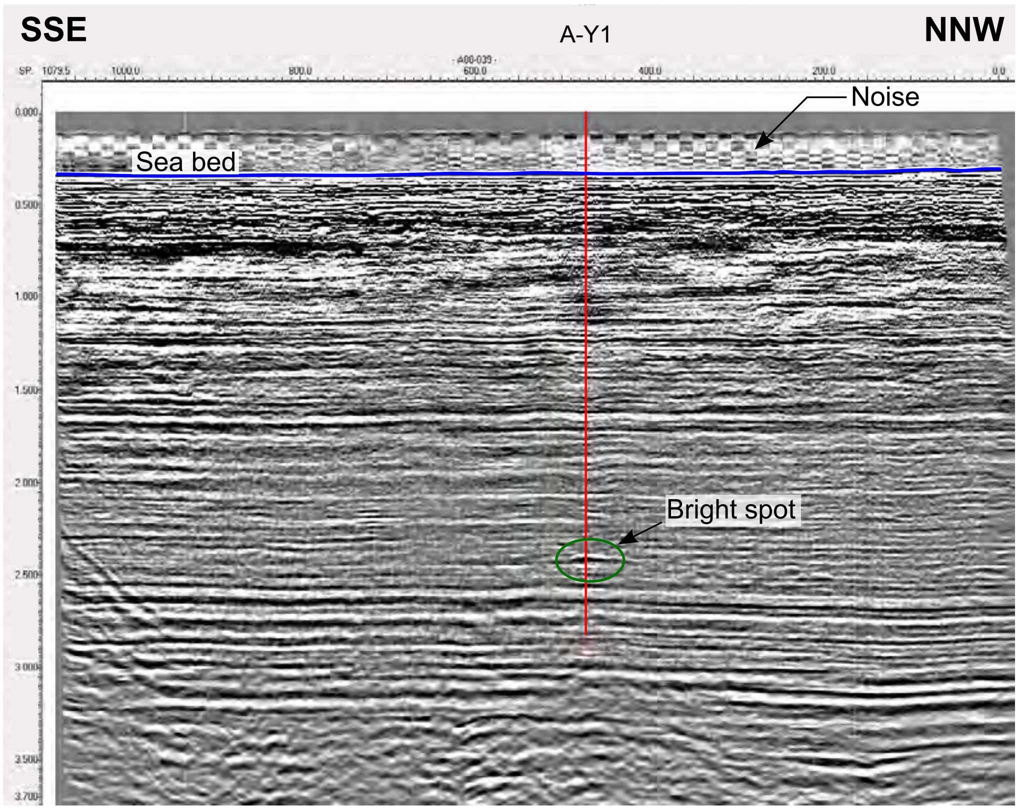


(b)

Figure 3.6: Comparison of two, approximately 7km adjacent, coast-perpendicular lines from different surveys to highlight the difference in quality. a) line SA92-159 is the more recently acquired and lies to the north of b) line A83-024 which is shorter and does not come as close to the coast as the former.



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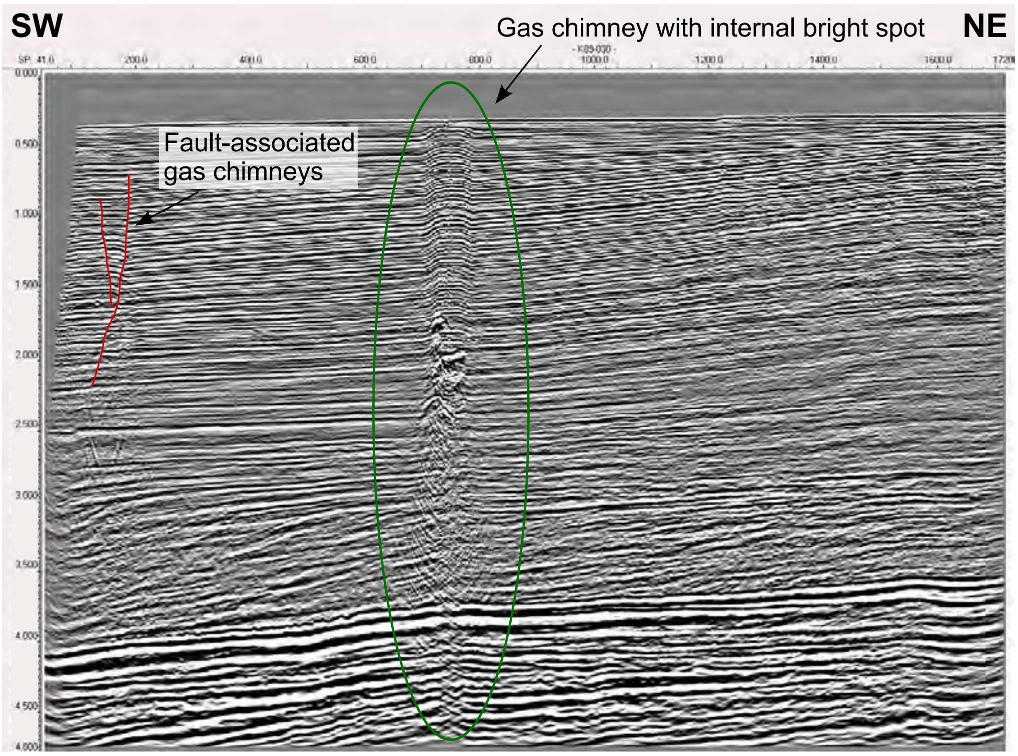
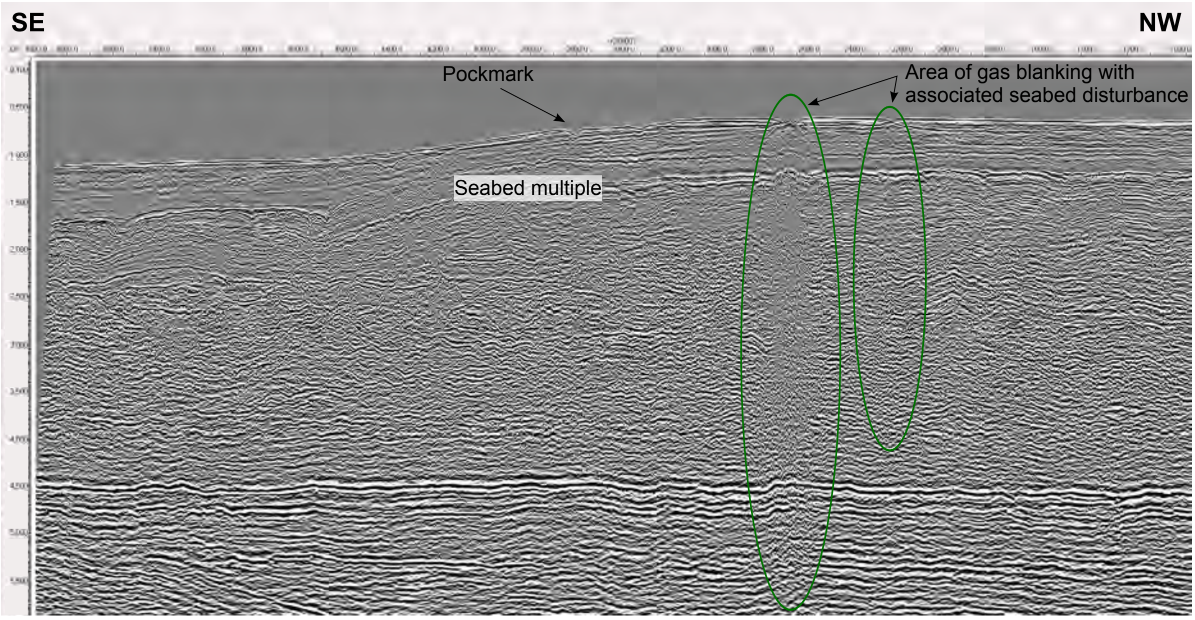


(b)

Figure 3.7: a) Coast-(sub)parallel line A88-039 is not of good quality, but intersects well A-Y1 in which gas was found during test drilling. The well intersects a potential bright spot which is one of the geophysical indicators for gas. b) Vertically extensive gas chimney with internal bright spot and pushed-up reflections. Fault associated gas escape features prominent in the SW on coast-(sub)perpendicular line K89-030.



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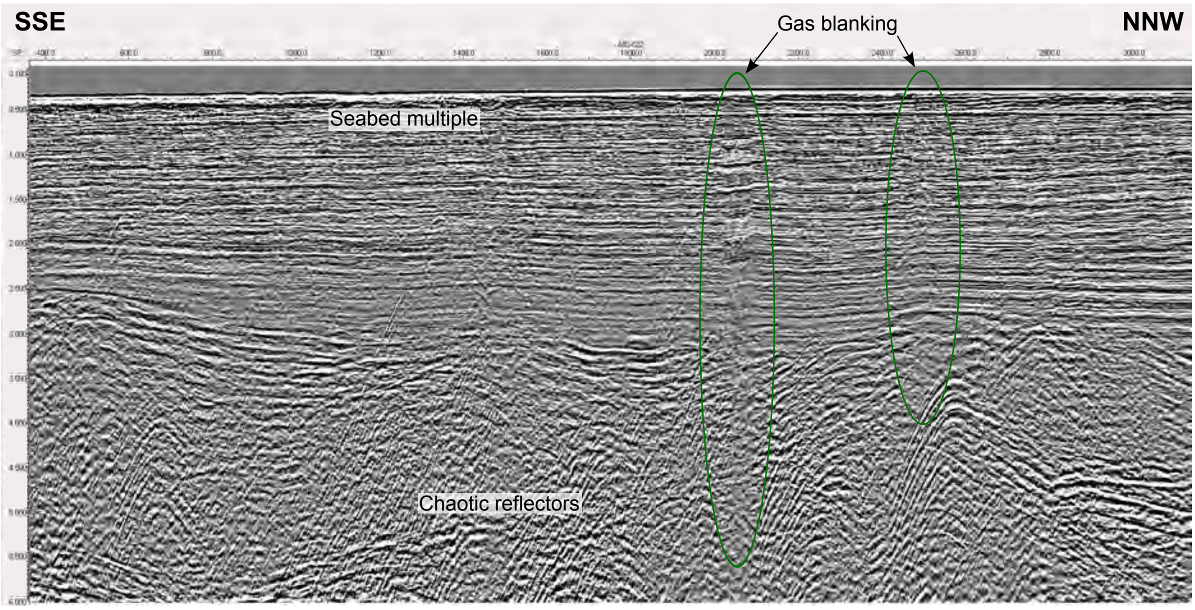
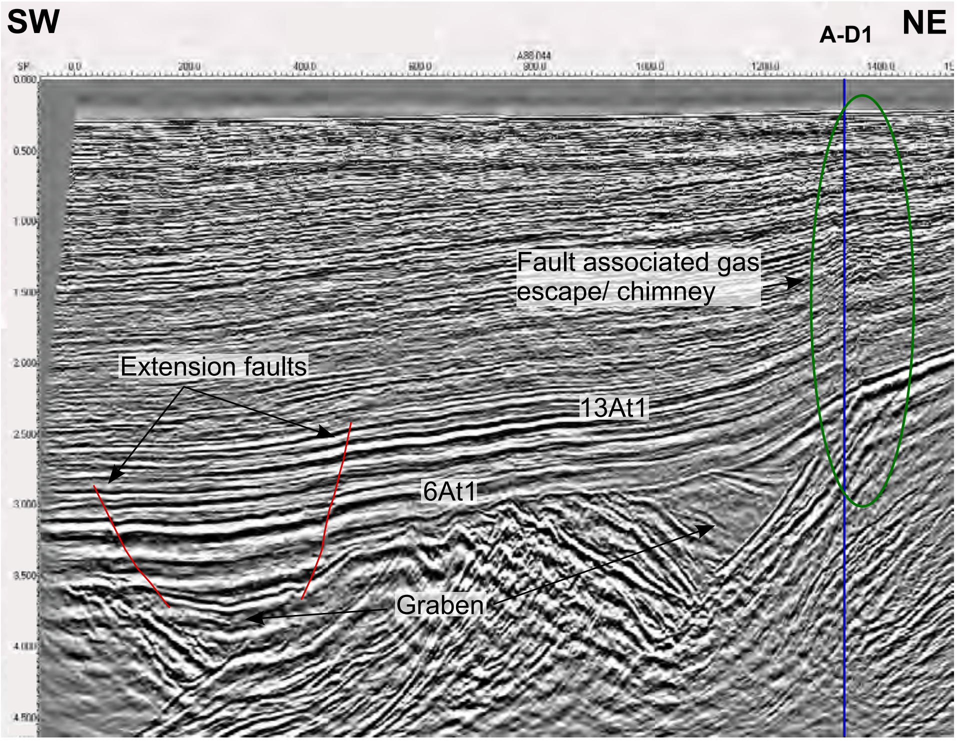


(b)

Figure 3.8: a) Gas blanking with associated seabed disturbance - possible Hydrocarbon-Related Diagenetic Zone (HRDZ) as described by Berge (2013) - on coast-(sub)parallel line K99-001 b) Gas blanking seen on more proximal, coast-parallel, line A83-022. In both of these examples a strong seabed multiple can be seen.



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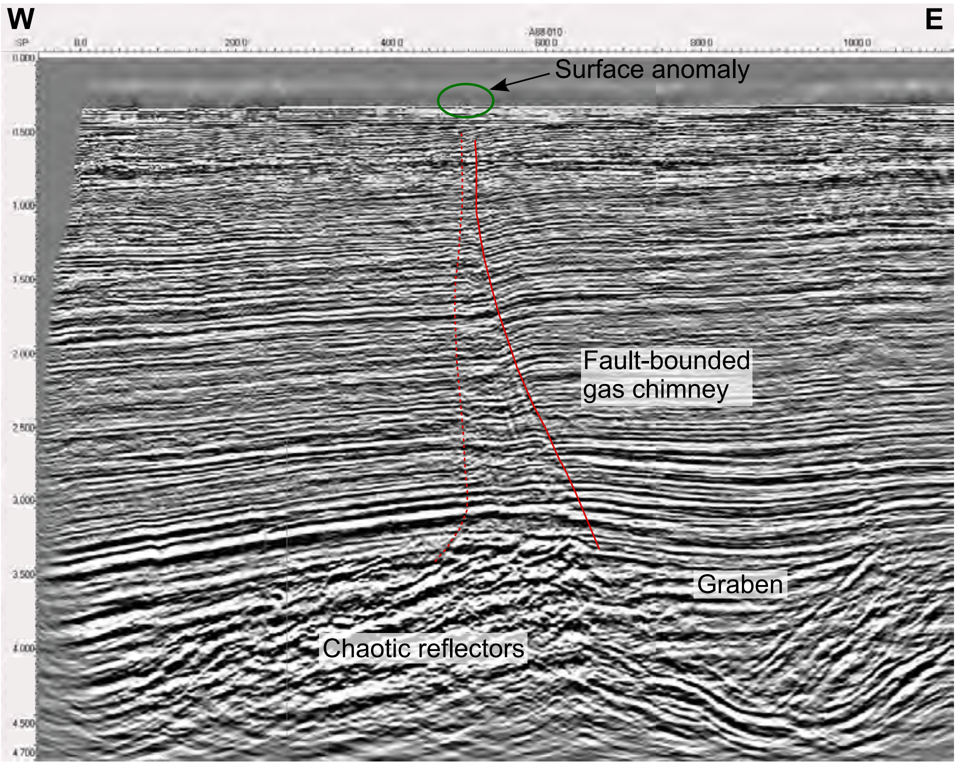
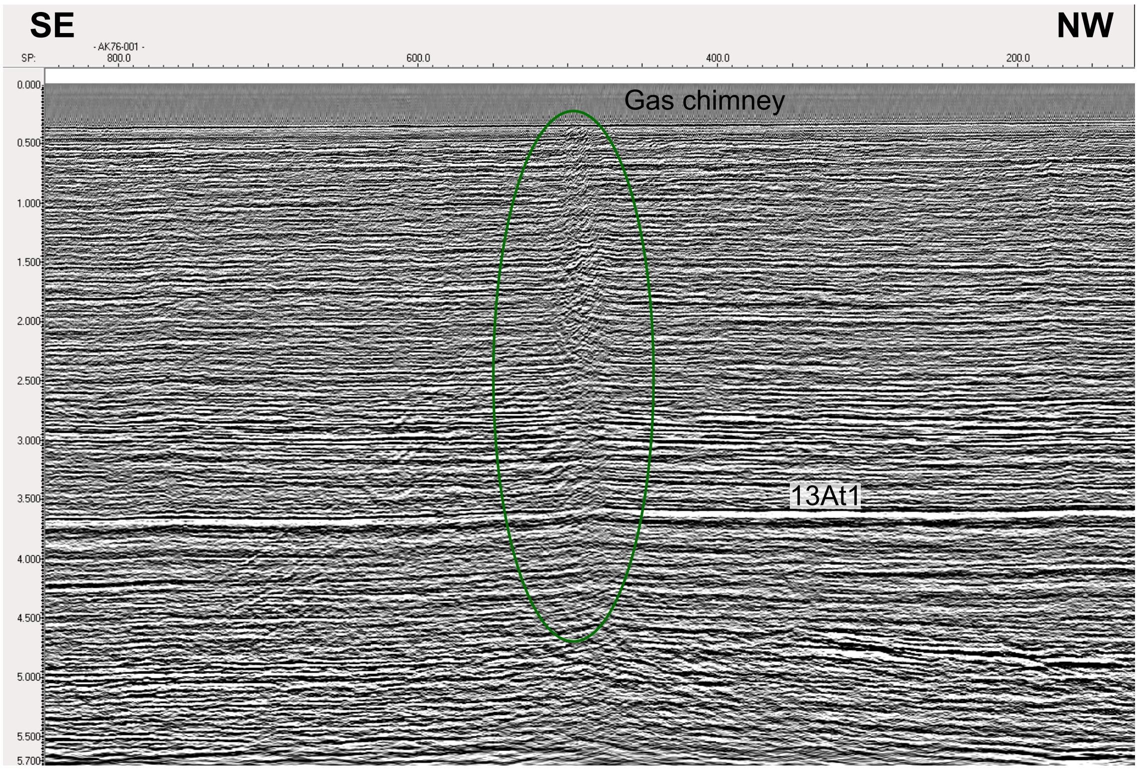


(b)

Figure 3.9: a) Major unconformity surfaces 13At1 and 6At1, extension faults and gas escape / chimney associated with the edges of grabens and Well A-D1 on coast-perpendicular line A88-044. b) Another line from the A88 survey block (A88-010) showing the fault-bounded gas chimney, the fault at the edge of the graben structure is likely from drift creating extensional faults. The anomaly in the water column was initially thought to be gas, but has subsequently been attributed to an insufficient stacking velocity being applied to the seismic data.



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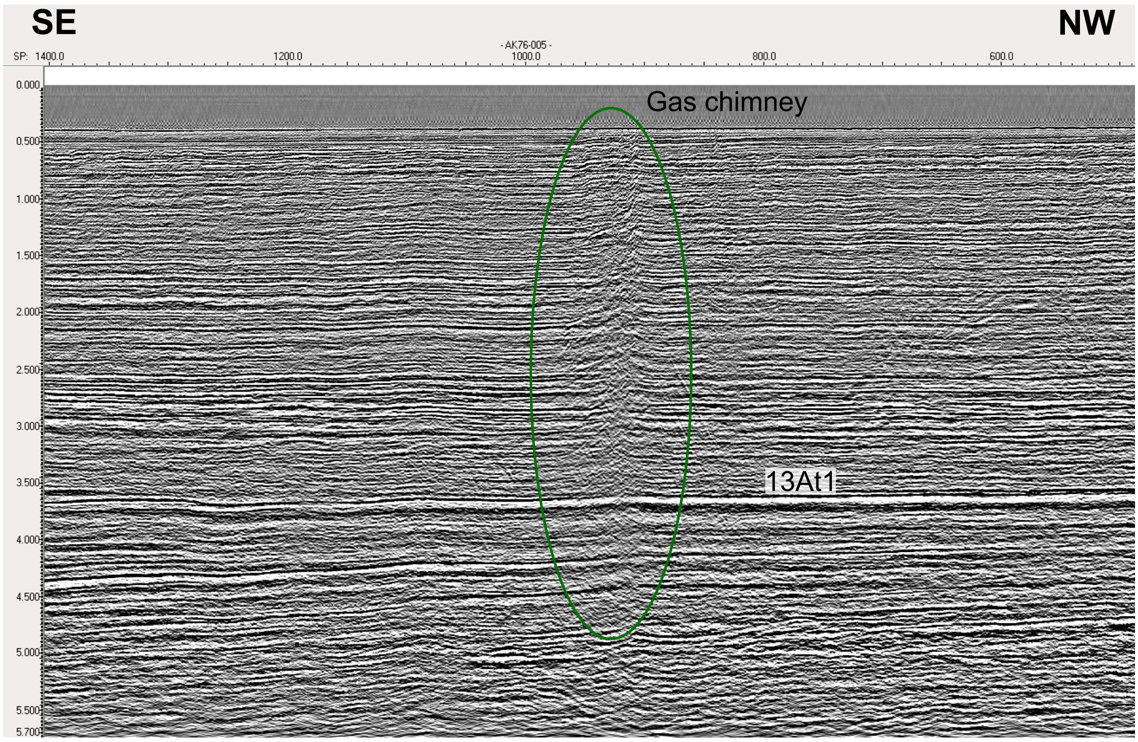
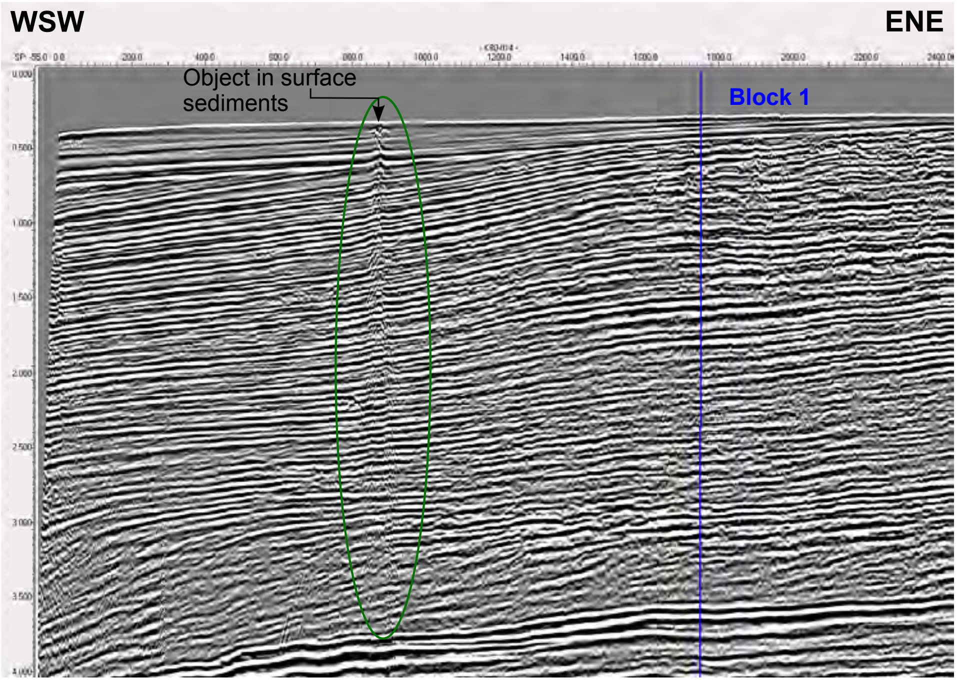


(b)

Figure 3.10: Large, areally extensive, gas chimney with a source below the 13At1 unconformity. This chimney is seen to trend roughly N/S and can best be seen in lines AK76-001 (a), -003 and -005 (b). The distance between the chimney on line AK76-001 and line AK76-005 is approximately 20km N/S. Such a chimney, or series of chimneys, is also noted in Aminzadeh and Berge (2013), showing a strong vertical line of seepage offset from a fault in the same general geographic location.



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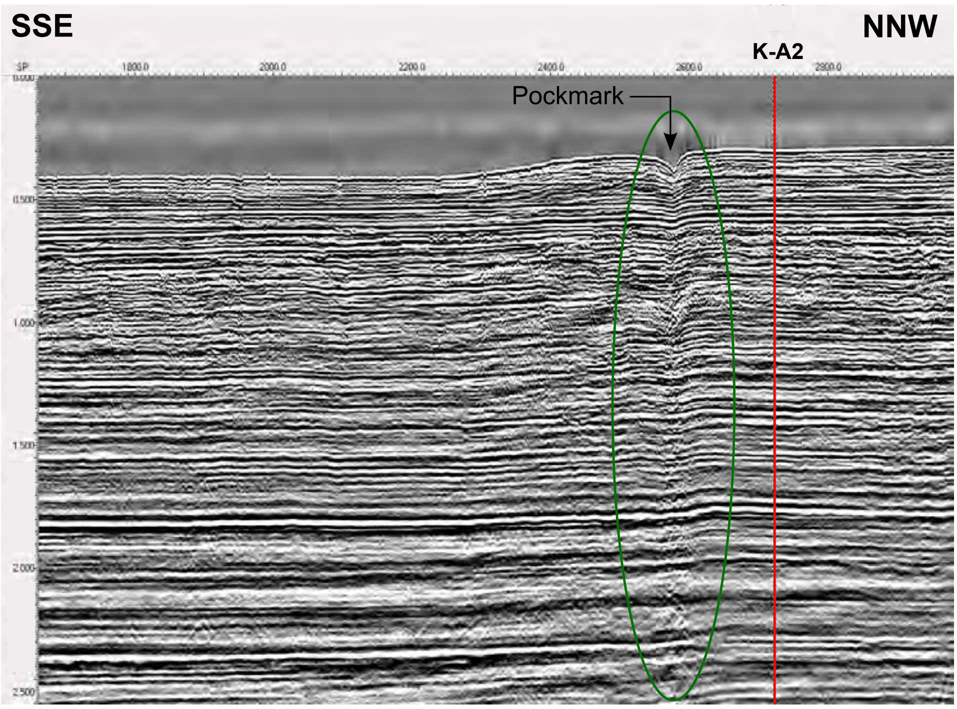

(b)

Figure 3.11: Illustration of phenomena which would cause geophysical anomalies not present in the lithology. a) line K80-014 shows how an object in the surface sediments can distort the seismic reflectors below it and cause the appearance of a gas chimney. The blue line represents the approximate northern boundary of Block 2. b) Line A88-083 shows what appears to be a gas chimney (blanking and pull-down attributes), with a pockmark on the seabed associated with it / as a result of gas escape. A different interpretation could be that the seabed disturbance created a sharp velocity discontinuity in a small area of the seismic section and when the section was stacked and migrated, the smooth move-out corrections did not allow the data to be stacked correctly and an anomalous 'chimney' was developed below the pockmark.

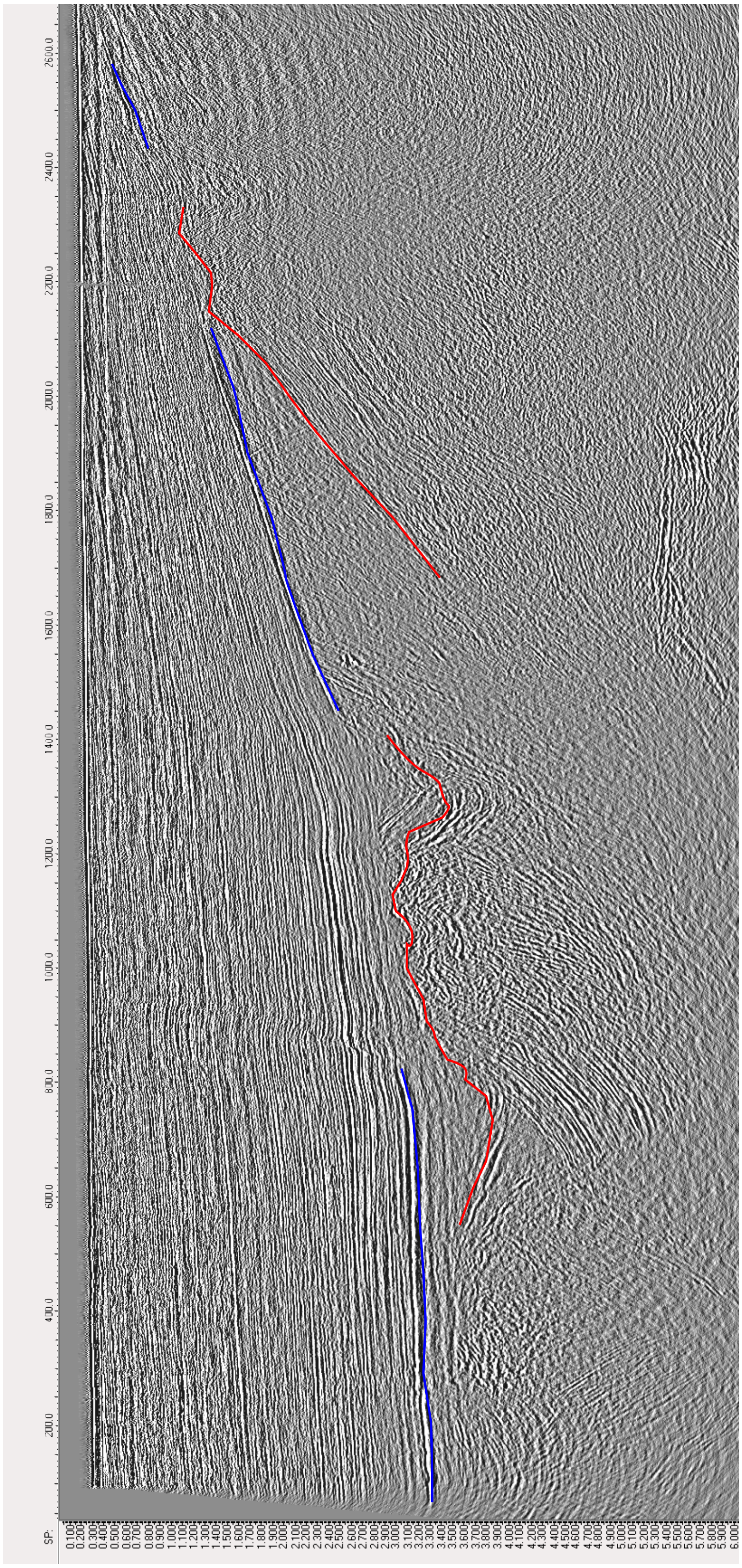

Figure 3.12: Example of extension as shown by the dipping blocks of the horst and graben structures on coast perpendicular line SA92-159.The blue line represents the unconformity surface overlying the eroded palaeo-surface (red) which was pulled apart by rifting and made accommodation structures for sediment to fill in.

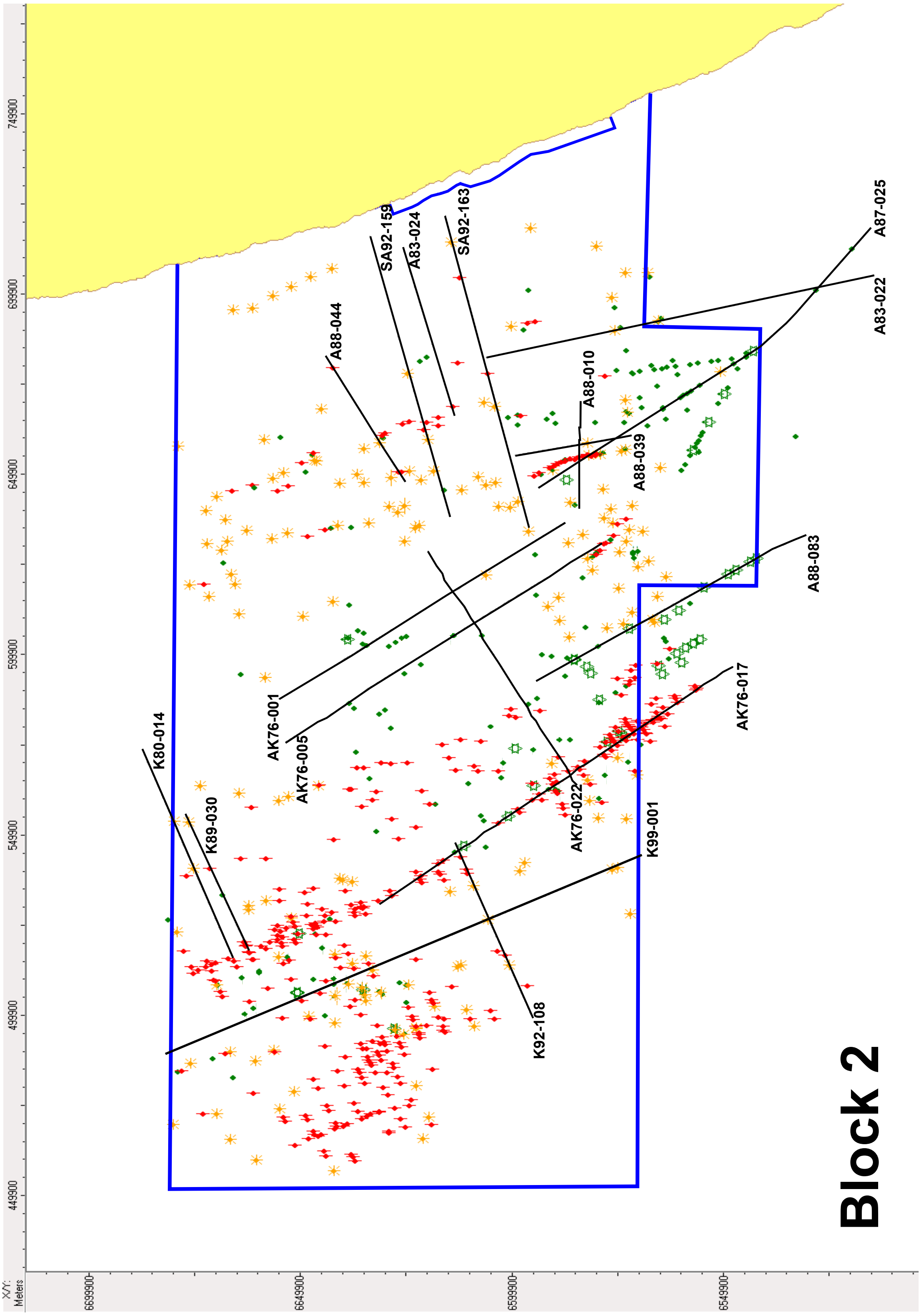

Figure 3.13: Map of areal distribution of various gas features on the seismic lines analysed. These features have been divided into four broad categories: 1) Gas chimneys which reach, and terminate at, the seabed - green stars 2) Gas chimneys which do **not** reach the seabed - green dots 3) Faults or Fault-associated gas chimneys - red dots with a line through and 4) Diffuse gas or gas blanking - gold star-burst. The black lines show the location of the seismic lines used in the data examples.

Chapter 4

Discussion

Within the processed seismic sections and well reports provided, evidence of gas was abundantly clear. The presence of gas, and thus a gas source, is a good indicator that - should the other formation conditions be present - hydrates could occur in this area within the Gas Hydrate Stability Zone (GHSZ). The finding of gas indicators, specifically the presence of numerous gas chimneys and blanking events, was to be expected as there are existing gas wells within the survey area. The Ibhubesi gas field - presently owned by a consortium led by Sunbird Energy (Sunbird, 2013) - lies within Block 2 and may be further developed into the Ibhubesi Gas Project.

Even though definitive evidence of gas hydrates (in the form of Bottom Simulating Reflectors) was not found in any of the sections analysed, it does not mean that hydrates are absent throughout the area.

The work of Boyd *et al.* (2011) also deals with data from Block 2 in the Orange Basin, as this dissertation does. However, that work reviews natural gas leakage features (predominantly gas chimneys) and their relationship with structural and stratigraphic elements within Block 2. It also quantifies the dynamics of the hydrocarbon generation, migration and seepage through the post-rift history of the basin in order to try and understand the relationship between the geology and the gas fluxes in this basin.

The Orange Basin, as mentioned previously, is a known to contain gas, but has not been targeted for investigation of hydrates. This work analyses a different set of data to that used by Boyd *et al.* (2011) and is more focussed on searching for potential *hydrate* indicators that may have been found in conjunction with the gas zones known to occur in the area. Since gas chimneys are often associated with hydrates - in terms of providing migratory pathways from deeper gas reservoirs into the GHSZ (Sun *et al.*, 2012; Aminzadeh *et al.*, 2001; Cathles *et al.*, 2010;

Chun *et al.*, 2011) - these were of particular interest. Gas and gas escape features were targeted and highlighted in this investigation more for the fact that they are predominantly concomitant factors, than for a specific interest in their origin or controls. The relationship between gas and gas hydrates is inseparable and thus any investigation into one involves the other.

Gas chimneys can clearly be seen on several of the lines within the data-set. These often follow faults in the geology making them more linear and dyke-like rather than cylindrical. This linear nature could impact on the clarity of the chimneys on the seismic record, depending on the angle of the transects to the feature. There are what appear to be bottom simulating reflectors, though these all turned out to be seabed multiples. In the paper by Ben Avraham *et al.* (2002) it was suggested that BSRs were seen in this study area, but I did not find any conclusive evidence.

Attitudes are changing as to what indicators of gas hydrates are. Traditionally, the major indicator was seen to be the bottom simulating reflector shown on the seismic record. This phenomenon is caused by the contrast in the sound velocities and densities between sediment saturated with clathrate on the one hand, and sediment saturated with free gas or water on the other. The resulting reflection simulates the shape of the interface between the ocean floor and the water column. As mentioned, the bottom simulating reflector (BSR) interface, inferring the base of the gas hydrate stability zone, has long been held to be the definitive hydrate indicator, so why was it not present here? Petersen *et al.* (2007) stated that previous seismic studies showed that the appearance of a BSR on a seismic section had less to do with hydrate above the BSR, and more to do with the the predominance of underlying free gas (which causes a strong P-wave BSR). As gas hydrate has a component of water as part of its structure (gas trapped within a frozen water cage), it shares some similar properties with water. The contrast between hydrate in sediment vs free gas in sediment would thus be greater than the contrast between hydrate in sediment vs water in sediment. Plaza-Faverola *et al.* (2012) claimed that the BSR was detectable by seismic methods due to the free gas zone (FGZ) which they stated was generally less than ~100 m thick. Should this zone not be present within Block 2, or if it is significantly reduced in thickness, this could be a potential reason why a BSR was not seen in the data.

Free gas may not be collecting in any particular area or zone or beneath a hydrate stability zone due to the fact that it is pervasive and dispersed throughout Block 2, within the sediments and rocks, and has far easier avenues of escape than percolating through gas hydrate bearing sediments. There are many faults and gas chimney structures, examples of which were shown in the previous chapter, and gas in the sediments is often guided and constrained by the fault-associated gas chimneys. These can connect the deeper areas of gas generation to the seabed, resulting in methane flares (not seen on these seismic lines) or seeps. Berge (2013) mentions that other common elements in seep associations (apart from having a connection between the reservoir and surface) are the fact that the chimney may have a shallow recharge zone and / or form gas hydrates, and that there might be a topographic anomaly on the seabed.

Gas hydrate could be present at the level of the seabed multiple, and thus the signature from a faint BSR could have been over-printed. The upper-most horizons in the interpreted seismic sections are generally planar and horizontal. A gas feeder source could generate methane which would migrate through the sediments in gas chimneys, or along the numerous observed faults, and generate a shallow gas hydrate within the GHSZ. The gas and hydrate could furthermore be trapped by a surface seal which would be in the same flat and horizontal (gently seaward sloping) orientation as the rest of the lithology. The gas and hydrate-bearing sediments would shoal with the lithology as the coast became more proximal; and the pressure on the hydrates would reduce to the point where they would dissociate and dissipate within the sediments, or migrate to the seabed.

It is unclear why, given the suitability of the conditions and in the presence of all of the other gas indicators, and even the overt presence of gas in the Ibhubesi Field, there were no BSRs found on the seismic lines analysed for Block 2. One reason that they could not be found could be related to a limitation in data collection - these data were collected and processed long ago and the available technology was limited compared to today as a lot of the lines were from 30 years ago. These test wells and seismic surveys were undertaken for the specific purpose of gas and oil exploration and the parameters were aimed at targets at a far greater depth than that at which gas hydrates would be found. The potential hydrate-bearing sediments could be fed by this deep gas source, but the seismic lines may have to be reprocessed with algorithms tailored towards shallower features. A stumbling block of this procedure could be that the initial frequency of collection may not allow for a higher resolution than the one presently available. As the wells were drilled (again looking for a deeper source of hydrocarbons) the top section of the sedimentary package, from the seabed to the depth at which the first well casing was set, would be disturbed or destroyed. Any potential hydrates that were in this zone would either be destroyed, or would be impossible to analyse as geological and geophysical logging would only commence beyond this point.

Aside from hardware and software limitations, it is unclear how the data set itself was processed after acquisition. No indication of filters, values used for velocity analysis or any corrections is given, though this metadata could possibly be made available upon request. The data is assumed to have been generally correctly collected and processed, but even within this limited dataset errors and corrupted data have been noted. The percentage is very small (approximately 3%), but it does indicate that there is always the potential for error to occur and that reprocessing from raw data is sometimes the only recourse, short of re-shooting the seismic line.

A further reason for not finding BSRs, though highly unlikely, could be related to the fact that seismic lines are, by definition, two dimensional. Full coverage is never achieved, and if a small, localised, BSR was present, but at an areal extent of less than that of the spacing between the lines, then it could remain un-imaged. This would not impact on any decisions made to enhance the probability of finding hydrates as, if the BSR and associated hydrate were so confined, they could not be commercially viable in any event. The dataset provided by PASA was limited to a size suitable for an MSc project, as well as being non-proprietary. Additional seismic lines from the region are available, just not for this project, and could be utilised in order to build a more comprehensive model of the area and enhance the proposals made here.

The International Ocean Drilling Program (IODP) and its predecessor, the Ocean Drilling Program (ODP), have contributed to hydrate research in many ways. In 1995, ODP leg 164 - over the Blake Ridge and Carolina Rise - was specifically designed to investigate gas hydrates. This leg provided a wide-ranging dataset including logging data, vertical seismic profiles and geochemical constraints on in-situ hydrate concentrations. Before this leg there was no specific program and gas hydrates were logged as they were encountered (mostly unexpectedly). Since 2005, though, no gas hydrate drilling has been specifically done by the IODP. Government and private-sector operators have taken over the drilling programs in order to assess the possible resource potential of any hydrates present within their waters (or borders), as well as to continue research into hydrates as hazards with new, ever-deeper water, drilling for oil and gas (Ruppel, 2011).

The national research programs mentioned within this thesis were not restricted to analysing (limited) existing 2-D seismic data and well reports. They have conducted dedicated and directed sampling and measurement programs searching for gas hydrates. Test wells and cores have been drilled at promising locations providing data from down-hole instruments and physical samples in the form of pressure cores. Instruments providing data on heat flow, resistivity and porosity, combined with seafloor mapping via multibeam or ROV (Remotely Operated Vehicle) provide a much more comprehensive and integrated picture than what is able to be obtained from limited data from a single tool. The data available for this study offered only a broad-scale overview, and a more focussed investigation, spanning a multidisciplinary variety of techniques, would be required in order to increase confidence in any result obtained as well as to pinpoint areas of specific interest for further research. A suggestion could be for South African researchers to run high resolution seismic lines specifically to look for hydrates, or to have a program in place to report any hydrate indicators observed in future seismic surveys, even if that were not the main focus of the survey. A program of piston coring and remote sensing (via ROV or similar platform) would be required to obtain physical data on the presence and nature of any hydrates present - massive, nodular, veined or disseminated - as well as utilising geochemical methods to search for the presence of methane gas. A database could be generated from these reports and surveys, and when combined with standard bathymetric and positional surveys, the locations of any potential hydrate fields could be narrowed and further targeted. Technological developments and increasing fuel costs mean that previously unfeasible fuel sources are now accessible, either through more advanced mining techniques or research, or corporate funding.

The presence of gas can be taken as well established; not just from the examination of the present seismic lines, but also previous and continuing investigation into Block 2 and adjacent blocks along the South African coastline. The trends in gas chimneys, especially noticeable when looking at neighbouring lines within a particular survey, are highlighted in Aminzadeh and Berge (2013) where seeps associated with faults within the same geographic area as this study are investigated. Berge (2013) shows that by using modern techniques - neural network analysis of chimney data in this case - the level of risk in exploring and developing an area for hydrocarbon extraction and production is lowered significantly. This approach of using modern software and more sophisticated techniques can be extrapolated and applied to the exploration and detection of possible hydrate fields. By combining not only 2-D seismic data, but pressure core information, high resolution seismic surveys, 3-D seismic surveys and a variety of methane or gas seabed detection tools (chemical "sniffer" tools on ROVs) a far more comprehensive determination can be made as to the economic viability of any given prospect or area.

As Block 2 is further explored for more conventional hydrocarbons, should the search for gas hydrates within this area continue, or is the effort required more than the potential return is worth? I believe that, with access to more modern surveyed seismic lines, it would be viable to continue the examination. These lines have already been surveyed and the initial capital outlay has been spent, so the only expenditure incurred in this case would be the time spent on analysing or re-processing them. The older the data, the greater the chance of it being sub-optimal or in error; either human or technical. This is especially true when transferring and transforming the data sets from older versions of software (or from paper form) to more modern software in order to integrate historic and present day information. The more modern lines would have potentially greater resolution, noise attenuation and would be conducted with a larger number of channels. This is not to say that errors in collection or processing can't happen with modern surveys, just that there is more data redundancy.

Techniques and equipment have changed and improved over the years and it is now computationally possible to do more than ever before. Modern seismic acquisition processes mean that operators are able to focus on a wider range of patterns as the resolution of the seismic data is so much higher. Collected data is able to be manipulated far more quickly and easily through the increased computing power and different software packages that we now have access to. With this greater computing power and storage capacity, larger volumes of seismic data may be collected, including that which would have once been considered superfluous and discarded due to a limitation in capacity. Modern datasets contain far more information than their older counterparts, providing the opportunity to reprocess collected data for a large number of permutations - optimizing the data for a specific area of interest. Hydrocarbon industry knowledge has increased in general and, by virtue of increased academic attention on the subject, the knowledge surrounding features and indicators of hydrates has increased too. As the definition of gas and hydrates changes, so too does the attention being paid to possible occurrences on the seismic record.

Worldwide there are national programs for research and development combining industry and government departments - the costs of essential initial research are often mitigated by the involvement of a financially interested commercial partner. However, if the exploitation of gas and gas hydrates from the west coast of South Africa becomes commercially viable, the rights to the fields' development and production would be far more valuable than at present, as well as providing a source for cleaner power than the country now has. The impact to the country's economy in terms of job creation, energy security and technological skills is significant.

Shale gas and the methods used to extract it, specifically hydraulic fracturing (fracking) of the tight shales, is also unproven within the context of our South African geology (DMR, 2012). With all of the potentially harmful factors that need to be mitigated, as well as the strong opposition to the extraction process, an alternative could be to investigate and invest in offshore gas and potential gas hydrates as a future source of energy. Gas is cleaner than coal and, if kept at pressure, a resource which provides a large amount of energy for the physical space it occupies. There is also less potential negative impact as, unlike 'land' with its multiple other uses for settlement or agriculture, the seabed is not inhabited (by people) and issues such as subsidence and ground water contamination have far less impact. There may also be a positive impact of producing gas hydrates if, as you extract the methane (CH_4), Carbon Dioxide (CO_2) is sequestered in its place (Kvamme *et al.*, 2007; Farrell *et al.*, 2010). The drilling risks and HSE (Health, Safety and the Environment) factors for conventional gas are well established and understood, compared to fracking. The extraction techniques for gas hydrates to build on, and utilise as a framework, are the presently available methods and technologies used for conventional gas extraction.

The South African Department of Energy talks about future development in gas, stakeholders and international partners as well as the designation of a national authority for the Clean Development Mechanism (CDM) - an authority that will assess projects and pursue the CDM's stated goals. As South Africa is classed as a developing country, this means that the CDM affords it certain opportunities. One of these is that the CDM can be an effective tool of technology transfer if investments support projects that replace the aging and inefficient technology surrounding the finite resource of fossil fuels, and create new industries in environmentally sustainable technologies (RSA_DoE, 2013). The South African National Energy Development Institute (SOC) Ltd. (SANEDI) is a state owned enterprise tasked with research into the energy field that will "advance South Africa's development, increase human capacity and eventually lead to commercialisable intellectual property" (SANEDI, 2013). At present none of these research projects highlights gas hydrates either as an energy source or an avenue of potential future investigation.

If, after searching though archived data, BSRs are found, it must be emphasised that these only imply hydrates and do not guarantee them. As with all hydrocarbon exploration what is inferred from seismic needs to be confirmed by a more tightly directed survey at higher resolution and coring or drilling. The outlay required for a program of that nature is required if the country's present and future energy demands are to be met; as well as if a cleaner source of fuel is required in order to comply with the Kyoto Protocol and other similar global legislation designed to mitigate climate change.

Chapter 5

Conclusions

Although no definitive indications of hydrate were found, the field of hydrate research is still a new and exciting one in terms of technology and practical applications. New experiments are being devised and implemented and new theories tested continually to progress the knowledge. The vast majority of these programs are undertaken by ‘first world’ countries in areas where hydrates may be better defined. The reasons for this are twofold: the technology needed to explore and exploit hydrates is expensive and, as yet, not a commercialized product; and (as with oil and gas finds) the more significant, proven and larger reserves will be the first ones tapped due to the higher profit: risk ratio. However, as natural resources are finite, it is worthwhile to keep in mind all of the possible energy sources available.

South Africa is a country of significant mineral wealth which is well explored as well as well defined. The history of mining goes back hundreds of years and the resources are by no means exhausted yet. However, there is a power problem in South Africa at the moment - not a problem of resources, but a problem of infrastructure and a problem of sustainability. There is a pressing need not for a *source* of power (as we have significant supplies of coal), but for a source of *clean* power. The South African government website (RSA_DoE, 2013) refers to the Kyoto Protocol and the need to reduce carbon emissions in a bid to mitigate the anthropogenic changes to the global climate presently occurring. The need for a new power source is not as much economically pressing, though that is always a concern for any country, but rather environmentally pressing - traditional energy sources such as coal and oil are dirty when burned, gas is significantly cleaner (de Gouw *et al.*, 2014). Those charged with the growth and prosperity of our nation should learn from the energy lessons of the past: the poor planning and delay in constructing the infrastructure necessary to generate and deliver power to those who require it means that even when the energy resources are available (in the form of coal), the ability to use them in order to generate and distribute the needed electricity is not. Delay is too costly on all fronts when there is the possibility of a new, clean, energy source being discovered and developed. Research should be carried out now; assign the resources to investigate and delineate its location, develop a plan to estimate its extent and viability, collaborate with other countries and programs which have already tackled some of the fundamental obstacles and difficulties in exploration and production and build on their knowledge. Then, when the technology for hydrate extraction has been refined and is commercially proven, South Africa will be ready and waiting to reap the benefits rather than struggling to catch up with a continually increasing energy demand. The case for **gas** production is even more straightforward as the technology to extract and produce this resource is presently available and mature. The infrastructure to generate power from gas, and to distribute it, is the common component required for both of these energy sources (gas and gas hydrates), and needs to be given a high priority if these resources are to be used to help cut carbon emissions and comply with regulations that will ultimately lead to a cleaner world.

The National Gas Infrastructure Development Plan has already been drafted to provide the government with a blueprint for the development of an infrastructure for future gas market developments (RSA_DoE, 2013). As the technology to detect and extract methane hydrates becomes more mature, the associated costs should drop. Instead of being a hazard to be avoided, perhaps the fiery ice could be seen as a potential future resource as well.

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Appendix A

Table 1: Detailed description of well reports for 18 wells within Block 2

Well	Company	Spudding date	Longitude	Latitude	Depth of well (TD)	Water depth	Gas/oil found	General geology
A-AA1	Forest Oil	24-Sep-03	30° 33’ 34.91” S	16° 37’ 45.08” E	3324.5m	211.5m	Water saturated	Albian aged sandstones. Fluvial to upper deltaic progradational sequence. Argillaceous sediments interbedded with sandstones. Reservoir sandstones intersected at 3212m bRT - water saturated.
A-AA2	Forest Oil	23-Oct-03	30° 33’ 13.28” S	16° 41’ 54.35” E	3171.0m	211.5m	Predominantly Water saturated	Albian aged sandstones. Fluvial to upper deltaic progradational sequence. Argillaceous sediments interbedded with sandstones. Reservoir sandstones intersected at 2956.8m bRT - water saturated.
A-D1	Soekor	27-Jun-81	30° 20’ 35.75” S	16° 51’ 38.50” E	3729.8m	168.9m	Poor gas shows. Water saturated	Sandstones within a faulted graben structure. Lower part of graben-fill sequence comprises metamorphosed sediments (predominantly mica-amphibole-schist). Residual gas-saturation, otherwise water saturated sandstones.
A-G1	Soekor	30-Apr-88	30° 54’ 58.23” S	16° 23’ 06.27” E	4100m	264m	Low gas levels	Upward-coarsening middle- and inner shelf argillaceous sandstones. Sandstones of generally low porosity. Potential source rock shales not developed at this location. Evidence of thin gas-bearing sandstones. Other sandstone bands have moderate to higher water-saturations.

continued . . .

Well	Company	Spudding date	Longitude	Latitude	Depth of well (TD)	Water depth	Gas/oil found	General geology
A-H1	Soekor	13-Apr-81	30° 28’ 13.26” S	15° 50’ 46.15” E	3984m	266.1m	Gas shows	Gentle domal structure. Sandstones of the Upper Cretaceous deposited in middle- to outer shelf, upward shallowing environment during high-stand conditions. Prograding sub-marine fan complex. Correlate very well with KA boreholes. Sandstones are predominantly water bearing, but some encouraging gas shows.
A-K1	Schlumberger / Soekor	08-Mar-87	30° 51’ S	16° 35’ E	3681m		Water. Some gas and condensate	Fractured sandstone. (Well test - not a lot of non-technical data).
A-M1	Soekor		30° 29’ 29.66” S	16° 41’ 9.35” E	3422m	206m		RECOMMENDATION TO DRILL. Middle Albian, late low-stand, incised-valley gas play. Primary target: gas-filled, stratigraphically trapped fluvial sandstones. Secondary targets are: structurally trapped sandstones within a series of stacked, fault-controlled closures.
A-T1	Soekor		30° 42’ 07.07” S	17° 00’ 03.75” E	3575m	175m		RECOMMENDATION TO DRILL. Situated on a major hinge zone and comprises a series of stacked fault-controlled closures, overlying the eastern edge of a large half-graben. Two primary targets are: 1) stacked shallow-marine and tidal channel sandstones and 2) stacked channel and barrier bar sandstones. Secondary targets could include: sandstones from marginal marine and barrier bars, braided streams or fan delta sandstones and conglomerates.

continued . . .

Well	Company	Spudding date	Longitude	Latitude	Depth of well (TD)	Water depth	Gas/oil found	General geology
A-V1	Forest Oil	22-Nov-00	30° 49’ 45.88” S	16° 34’ 49.30” E	3714m	242.3m	Problems w/ tool. Abandoned	Upper to Lower Cretaceous. Meandering fluvial system. No significant gasses or shows in most lithologies sampled. Some reservoir sands showed moderate water saturation.
A-W1	Forest Oil	20-Feb-01	30° 46’ 31.10” S	16° 31’ 24.65” E	3511m	245.8m	No shows. Water saturated	Upper to lower Cretaceous meandering fluvial system. Mid Albian age large meander channel sand structure. No significant gasses or shows. Reservoir sandstone considered wet with very poor to no moveable hydrocarbons.
A-X1	Forest Oil	15-Nov-03	30° 29’ 12.42” S	16° 40’ 19.57” E	3300m	205.5m	Predominantly Water saturated	Albian aged sandstones. Fluvial to upper deltaic progradational sequence. Argillaceous sediments interbedded with sandstones. Main reservoir sandstones intersected at 2944m bRT - predominantly water saturated. Thin sandstones below - encouraging gas, but too thin to be productive.
A-X2	Forest Oil	28-Dec-03	30° 29’ 03.56” S	16° 37’ 41.62” E	3478m	207m	Water saturated	Albian aged sandstones. Fluvial to upper deltaic progradational sequence. Argillaceous sediments interbedded with sandstones. Prospective reservoir sandstones intersected at 3042m bRT to 3478m bRt - all water saturated.

continued . . .

Well	Company	Spudding date	Longitude	Latitude	Depth of well (TD)	Water depth	Gas/oil found	General geology
A-Y1	Forest Oil	07-Apr-01	30° 50’ 48.95” S	16° 39’ 03.81” E	3392m	243.6m	Gas. Moderate hydrocarbons	Upper to lower Cretaceous meandering fluvial system. Mid Albian age large meander channel sand structure. Generally no significant gasses or shows, apart from a poor gas show in one interval. Reservoir sandstones showed moderate-good and poor-moderate percentage of moveable hydrocarbons with a moderate water saturation.
K-A1	Soekor	15-Apr-79	30° 48’ 27.50” S	16° 00’ 59.90” E	4819.2m	222.5m	No significant shows. Abandoned	Cretaceous sequences of argillaceous sediments and sandstones deposited in a middle- to outer shelf, upward-shallowing environment during high-stand conditions. Principal target reservoir not reached due to technical difficulties. Thin sandstones did have some gas shows - not economic.
K-A2	Soekor	10-Sep-79	30° 50’ 03.21” S	16° 00’ 32.78” E	5829.7m	220.4m	Poor gas shows. Water saturated	Lower Cretaceous sandstones and argillaceous sediments. Primary reservoir target was water saturated, channel-fill type sandstones underlain by siltstones, sandstones and claystones - pelagic shale section with incalcated, thin turbidite sandstones.

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Well	Company	Spudding date	Longitude	Latitude	Depth of well (TD)	Water depth	Gas/oil found	General geology
K-A3	Soekor	01-Jan-81	30° 48’ 08.55” S	16° 03’ 50.75” E	4676.85m	219.6m	Poor gas shows. Water saturated	Offshore Cretaceous sequences of sandstones and argillaceous sediments. Prograding sub-marine fan complex from 2714m - 4100m, overlying argillaceous sediments with sandstone interbeds representing distal turbidite facies. Primary reservoir target sandstones were water saturated.
K-B1	Soekor	31-Jan-79	30° 42’ 38.67” S	15° 26’ 52.18” E	4075.8m	354.2m	No oil or gas. Abandoned as dry	Upper Cretaceous. Deposited in a regressive slope environment. Turbidites are present in 5 main zones. Sandstones are of shoal or turbidite origin (turbidites developed on the front of a delta). No commercial oil or gas was discovered. Well abandoned as dry.
K-E1	Soekor	19-Aug-81	30° 37’ 55.83” S	15° 26’ 03.01” E	4133.7m	318.21m	Dry well with gas shows	Upper Cretaceous sequence. Distal elements of both high-stand and low-stand tract developments. Zone of ””growth”” faulting extending along the axis of the Orange Basin depocentre. Shelf sandstones were principle reservoir targets. Gas shows present likely migrated up fault planes or within the fault compartment from a deeper, more mature, source rock interval.

continued . . .

Well	Company	Spudding date	Longitude	Latitude	Depth of well (TD)	Water depth	Gas/oil found	General geology

Appendix B

Table 2: Description of seismic lines within Block 2

Survey line name	Orientation	Indications of Gas	Indications of hydrate	Well on line	Comments
A76-001	NW-SE	Gas Chimneys ±15, some appearing to continue to the seabed. One is laterally extensive, approx 10km aross at the mouth, slumping in the central portion and overlain by a layer of flat surface sediments.			
A76-002	WSW-ENE	Maybe a few 1-2 weak chimneys.			
A76-003	SSE-NNW	Approx 6 gas chimneys.			
A78-001	SSE-NNW				
A78-003	SSE-NNW		Potential shallow BSR at 5.5ms was seabed multiple.		
A78-005	NNW-SSE				
A78-007	SSE-NNW	Approx 15 non-distinct gas chimneys.			
A78-008	WSW-ENE				
A78-009	SSE-NNW				
A78-010	WSW-ENE				
A78-012	WSW-ENE				
A78-014	WSW-ENE	Maybe a few (1-2) shallow, weak chimneys.		A-D1	

continued . . .

Survey line name	Orientation	Indications of Gas	Indications of hydrate	Well on line	Comments
A80-019	S-N	Few (2-3) weak chimneys. One is laterally extensive.			
A80-021	SSW-NNE	Maybe non-distinct chmney.			
A80-023	SSW-NNE	Possible gaseous sediments.			
A80-038	WSW-ENE	Possible shallow gas in unconsolidated surface layer.		K-A2	
A80-040	WSW-ENE				
A80-042	WSW-ENE				
A80-044	W-E	Possible gaseous sediments.			
A80-046	NW-SE	Indistinct gaseous sediments.			
A80-048	NW-SE	Large gas chimney and 1-2 smaller, less distinct chimneys.		K-A2	One indistinct gas chimney showing an influence on the seabed in the form of slumping ±3km SE of well K-A2.
A81-018	WSW-ENE				Only part of the line displaying.
A81-019	WSW-ENE				Seismic line corrupted - no image.
A81-020	WSW-ENE				
A81-021	WSW-ENE				
A81-022	WSW-ENE				Well A-D1 just in NE corner of survey block
A81-023	WSW-ENE				
A81-024	SSE-NNW				
A81-025	SSE-NNW				
A81-026	SSE-NNW				
A81-027	SSE-NNW				
A82-015	WSW-ENE				
A82-016	WSW-ENE				

continued ...

Survey line name	Orientation	Indications of Gas	Indications of hydrate	Well on line	Comments
A82-017	WSW-ENE				
A82-018	WSW-ENE				
A82-020	SSE-NNW				
A82-021	SSE-NNW				
A82-022	SSE-NNW				
A82-023	SSE-NNW				A-D1. Shallow. Seabed multiple visible.
A82-025	SW-NE				A-D1. Shallow. Seabed multiple visible.
A82-026	SW-NE			A-D1	A-D1. Shallow. Seabed multiple visible. Well A-D1 intersects unconformity at 2.2s.
A82-027	SW-NE				A-D1. Shallow. Seabed multiple visible.
A82-029	SW-NE				A-D1. Shallow. Seabed multiple visible.
A82-030	S-N				
A82-032	WSW-ENE			A-X2	Target of well A-X2 appears to be a package of Rift sedimentary fill within a half graben between 3.5s and 4.1s.
A82-034	W-E				A-AA1 and A-AA2 are approx 3km north of this line.
A82-035	W-E				
A82-037	W-E				A-W1 is 3km west of start of line.
A82-038	W-E	Possible diffuse gas chimney /dispersed gaseous sediments migrating upwards.			A-V1 is 1.6km south of line.
A82-039	W-E			A-K1	Exceptionally poor seismic line - constant dropping of the signal means image displays as very narrow strips. Section missing along area of interest near wells A-K1 [should cut through], A-K2 (1.5km S) and A-Y1 (1.5km N). General picture or rest of line the same as adjacent parallel lines.

continued . . .

Survey line name	Orientation	Indications of Gas	Indications of hydrate	Well on line	Comments
A82-040	W-E	Possible diffuse gas chimney /dispersed gaseous sediments migrating upwards.			
A82-041	W-E	Possible diffuse gas chimney /dispersed gaseous sediments migrating upwards.			
A83-014	SSW-NNE				Problem at southern end of the line - data missing (either error in nav or other problem as this was the true end of line).
A83-015	WSW-ENE				
A83-016	WSW-ENE			A-H1, A-D1	Line designed to run between wells A-H1 and A-D1 but faulty line. Only initial image until just after the break is gathered (at A-H1 end) and rest of the section is blank. What does display is of poor quality. Slightly more W-E in orientation than lines adjacent to it.
A83-017	WSW-ENE				
A83-019	W-E				
A83-020	SSE-NNW			A-J1	Shallow. Line poorly resolved in the top sediments - could be due to equipment or the sediments themselves being unconsolidated or having a layer of muds at the seabed.
A83-021	SSE-NNW				Shallow. Line poorly resolved in the top sediments - could be due to equipment or the sediments themselves being unconsolidated or having a layer of muds at the seabed.
A83-022	SSE-NNW	Partial blanking and pull-up structures at edge of Block 2.			Shallow. First half of line is out of study area in Block 3.

continued . . .

Survey line name	Orientation	Indications of Gas	Indications of hydrate	Well on line	Comments
A83-024	WSW-ENE				Shallow.
A83-025	WSW-ENE				Shallow. Very short infill line - possibly to investigate area of interest.
A83-026	WSW-ENE				Shallow. Very short infill line - possibly to investigate area of interest.
A83-027	WSW-ENE				Shallow. Line poorly resolved in the top sediments. Reflectors are not well defined in the upper layers (problem with section? / lithology?).
A83-028	WSW-ENE				Shallow. Line poorly resolved in the top sediments. Reflectors are not well defined in the upper layers (problem with section? / lithology?).
A83-029	WSW-ENE				Shallow. Line poorly resolved in the top sediments. Reflectors are not well defined in the upper layers (problem with section? / lithology?).
A83-030	WSW-ENE				Shallow. Line poorly resolved in the top sediments. Reflectors are not well defined in the upper layers (problem with section? / lithology?).
A83-032	WSW-ENE				Shallow. Line poorly resolved in the top sediments. Reflectors are not well defined in the upper layers (problem with section? / lithology?).
A83-033	WSW-ENE	Few (2-3) very weak chimneys. Diffuse gas.			Shallow. Line poorly resolved in the top sediments. Reflectors are not well defined in the upper layers (problem with section? / lithology?).
A83-035	WSW-ENE				Shallow. Line poorly resolved in the top sediments. Lots of parabolic overprintig / interference on the horizontal sediments (bad processing, improper Vs used?).

continued . . .

Survey line name	Orientation	Indications of Gas	Indications of hydrate	Well on line	Comments
A84-010	SW-NE				Shallow. Short line. Strong seabed multiple across whole line. Image quality not the best.
A84-012	SW-NE				Shallow. Short line. Strong seabed multiple across whole line. Image quality not the best.
A84-021	SSE-NNW				Shallow. Image quality not the best.
A87-015	SW-NE	Partial zone of blanking and few pull-up structures. Diffuse gas chimney (maybe?).			
A87-016	SW-NE	Some blanking and pull-down structures in surface tapering cone. Weak gas chimney.			
A87-017	SW-NE	Few (2-3) weak chimneys. Some blanking.		A-G1	Well A-G1 is to the east of the gas chimneys and does not penetrate the unconformity. Line doesn't reach A-V1, but it is 1km from end of line.
A87-018	SW-NE	Few diffuse chimneys (weak).		A-K1	Well A-K1 does not penetrate the unconformity, but appears to be aiming for a small graben-like structure just to the west of a pinch out.
A87-019	SW-NE	Zone of blanking in centre of line below unconformity - gaseous sediments.			
A87-020	WSW-ENE	Gaseous sediments and few very weak gas chimneys (maybe?).			
A87-022	SSE-NNW	Few (2-3) weak chimneys. Some blanking.			
A87-023	SE-NW	Zones of blanking through prominent reflectors. Chaotic reflectors below unconformity (gaseous sediments).			

continued . . .

Survey line name	Orientation	Indications of Gas	Indications of hydrate	Well on line	Comments
A87-024	W-E	Blanking and chaotic reflectors (gaseous sediments between and beneath unconformities).		K-A2	Well K-A2 penetrates the first unconformity at 3.5s, but does not reach the second. There is an error on the seismic section in the east which propogates through the data and mimics a strong gas chimney.
A87-025	NW-SE	At least 10-12 strong gas chimneys. Also gas blaning present at depth.		A-K2, A-K1	Wells A-K1 and A-K2 do not reach the unconformity or the zones of blanking. End of line in Block 3 & curves more to east. Well A-W1 is 1km from SOL, A-V1 is 1km north of line, A-Y1 5km north of line.
A88-002	W-E				Close W-E survey block.
A88-003	W-E				Close W-E survey block.
A88-004	W-E				Close W-E survey block.
A88-005	W-E	Few (2-3) weak chimneys. Some pull-up.		A-G1	Close W-E survey block. Well A-G1 does not penetrate the unconformity. There are a few, very weak, gas chimneys - one to the west of the well.
A88-006	W-E	Possible fault and gas migration/chimney. Flare in the water column / error in velocity applied.			Close W-E survey block. Possible flare in the water column is likely result of wrong velocity applied.
A88-007	W-E	Possible fault and gas migration/chimney			Close W-E survey block.
A88-008	W-E	Possible fault and gas migration/chimney			Close W-E survey block.
A88-009	W-E	Possible fault and gas migration/chimney			Well A-K2 is 400m to north (centre). Close W-E survey block.
A88-010	W-E	Possible fault and gas migration/chimney. Flare in the water column / error in velocity aplied.			Well A-K2 is 400m to north (centre). Close W-E survey block. Looks like gas flare in water could be wrong velocity aplied.

continued ...

Survey line name	Orientation	Indications of Gas	Indications of hydrate	Well on line	Comments
A88-011	W-E	Large gas chimney (possible associated fault) - very triangular with large base, extending from edge of graben.		A-K1	Close W-E survey block.
A88-012	W-E	Large gas chimney (possible associated fault) - very triangular with large base, extending from edge of graben.		A-Y1	Doesn't cut directly through -Y1. Close W-E survey block.
A88-013	W-E	Large gas chimney (possible associated fault) - very triangular with large base, extending from edge of graben.			Close W-E survey block.
A88-014	W-E	Large gas chimney (possible associated fault) - very triangular with large base, extending from edge of graben.		A-V1	Doesn't cut directly through Well A-V1. Well is 200m north of line. Close W-E survey block.
A88-015	W-E	Large gas chimney (possible associated fault) - very triangular with large base, extending from edge of graben.			Close W-E survey block.
A88-016	W-E	Large gas chimney (possible associated fault) - very triangular with large base, extending from edge of graben. Second smaller (though still quite wide) chimney.			Close W-E survey block.

continued . . .

Survey line name	Orientation	Indications of Gas	Indications of hydrate	Well on line	Comments
A88-017	W-E	Large gas chimney (possible associated fault) - very triangular with large base, extending from wewstern edge of graben. Second smaller (though still quite wide) chimney to its west. Third narrower chimney to east - nearly to surface.			Close W-E survey block.
A88-018	W-E			K-A3	Problem with line - not all is displayed (line run E-W and ends about 1/4 way in) Line segment through well K-A3 does not exist. Large gas chimney on western edge of graben-like structure visible. Perhaps same as seen in previous lines (position seems a bit off trend). K-A1 is 1km south of line. Close W-E survey block.
A88-019	W-E	Large gas chimney, triangular shape with wide base. Associated with extension fault rising from western edge of graben.			Close W-E survey block.
A88-020	W-E	2-3 gas chimneys. One large, almost to surface, others less distinct.		A-W1	Well A-W1 cuts through unconformity into chaotic reflectors. Close W-E survey block.
A88-021	W-E	Chaotic reflectors beneath unconformity as well as unconformity disrupted in several places, pulled up in some others - likely gas.			Close W-E survey block.

continued . . .

Survey line name	Orientation	Indications of Gas	Indications of hydrate	Well on line	Comments
A88-022	W-E	Chaotic reflectors beneath unconformity in east, as well as unconformity disrupted in several places, pulled up in some others - likely gas. Gas chimney to east, rising from beneath unconformity.			Small bump/perturbation & divot on seabed where line A88-033 crosses this line. Seen on -033 as well (Surface feature?).
A88-023	W-E	Chaotic reflectors beneath unconformity, in east, as well as unconformity disrupted in several places, pulled up in some others - likely gas. Gas chimney to east, rising from beneath unconformity.			
A88-024	W-E	Chaotic reflectors beneath unconformity, in east, as well as unconformity disrupted in several places, pulled up in some others - likely gas. Weak gas chimney in east.			
A88-025	W-E	Chaotic reflectors and areas of weak blanking (likely gas/ gaseous sediments), disrupted horizons (shifted upwards - gas chimney (weak).			Seabed rises slightly (mound?) on very western edge of line.

continued . . .

Survey line name	Orientation	Indications of Gas	Indications of hydrate	Well on line	Comments
A88-026	W-E	Chaotic reflectors and areas of weak blanking (likely gas/ gaseous sediments), disrupted horizons (shifted upwards - gas chimney (weak).			
A88-027	W-E	Chaotic reflectors and areas of weak blanking (likely gas/ gaseous sediments), disrupted horizons (shifted upwards - gas chimneys (weak), stronger gas cimney in east rising to near-surface.			
A88-028	W-E	Chaotic reflectors. 2-3 weak chimneys disrupting unconformity. Stronger gas cimney in east rising to near-surface.			
A88-029	W-E	Chaotic reflectors. 2-3 weak chimneys disrupting unconformity. Stronger gas cimney in east rising to near-surface [spacially close to well A-AA2].			Well A-AA1 & A-AA2 are both ± 1km south of line.
A88-030	WSW-ENE	Chaotic reflectors. 2-3 weak chimneys disrupting unconformity. Strong gas cimney in east rising from eastern edge of graben-like structure to near-surface.			

continued . . .

Survey line name	Orientation	Indications of Gas	Indications of hydrate	Well on line	Comments
A88-031	WSW-ENE	Chaotic reflectors. 3-4 weaker chimneys disrupting unconformity. Strong gas chimney in east rising from eastern edge of graben-like structure to near-surface.			Well A-X1 800m north of line in vicinity of extension fault-associated chimney.
A88-032	SW-NE	Chaotic reflectors and areas of weak blanking (likely gas/ gaseous sediments)under disrupted horizon of unconformity. Horison pulled down in some areas, pulled up in others.			
A88-033	S-N				Small bump/perturbation & divot on seabed where line A88-022 crosses this line. Seen on -022 as well (Surface feature?).
A88-034	S-N				
A88-035	S-N	Possible gaseous sediments. Below level of unconformity.			Slightly off direct N-S
A88-036	SSE-NNW	Possible gaseous sediments. Below level of unconformity. (possible) weak blanking in sediments above unconformity - could be stratigraphic.			Geographically further than -033 to -035 → near northern boundary of Block 2. Northern half of line out of Block 2.

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Survey line name	Orientation	Indications of Gas	Indications of hydrate	Well on line	Comments
A88-037	SE-NW	Chaotic reflectors and areas of weak blanking (likely gas/ gaseous sediments) under horizon of unconformity.			Really long lone - almost entire block. Close to wells A-V1 and A-K2.
A88-038	SE-NW	Chaotic reflectors and areas of weak blanking (likely gas/ gaseous sediments) under horizon of unconformity. ±4 Weak gas chimney-like structures (correlate with clear chimneys seen on lines perpendicular to this one).		A-K1 [A-V1]	Really long lone - almost entire block. Cuts through wells A-K1 & very close to A-V1 in the south. A-V1 has several of the chimneys to its east and penetrates into the chaotic reflectors beneath the unconformity.
A88-039	SSE-NNW	Bright spot that appears to be intersected by well A-Y1 at ±2.4s. Also areas of blanking & possible chimneys, but not confirmed due to poor quality of seismic line.		A-Y1	Very poor quality line. Sub-parallel. Not much can be clearly seen of well A-Y1 except that it appears to hit a bright spot at 2.4s and (possibly?) at 2.55s.
A88-040	S-N	±6 gas chimneys, most reaching near-seabed, some breaching seabed. Chaotic reflectors in bottom (deep) section of line.			
A88-041	S-N	Many (10+) gas chimneys. These disrupt horizons (pull-up) and reach to near-surface. Very coarse, chaotic reflectors and blanking in association with the bases of some of these gas chimneys.			Line bent, northern end sort of parallel, southern end more N-S. Cuts through all ’perpendicular’ lines 002-032.

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Survey line name	Orientation	Indications of Gas	Indications of hydrate	Well on line	Comments
A88-042	SW-NE	Large (wide-based) gas chimney. Chaotic reflectors and blanking associated with its base.		A-AA1	Large (wide-based) gas chimney rises from chaotic reflectors and area of blanking, passes through well A-AA1 - well depth not shown on seismic line. Does not appear that it would have intersected anything of particular note.
A88-043	WSW-ENE	Chaotic reflectors. Strong (wider-base) gas cimney in eastern half of line rising from eastern edge of graben-like structure to near-surface.			
A88-044	SW-NE	Several vertical disruptions of a series of horizontal reflectors - possible gas escape/gas chimneys or stratigrapic (faults??) Large gas chimney (possible associated fault) on eastern edge of eastern-most graben, extending to near-surface. Chaotic reflectors below unconformity.		A-D1	Well A-D1 adjacent to gas chimney extending from higher, eastern, edge of the eastern graben (extension-fault associated).
A88-045	WSW-ENE	Chaotic reflectors and areas of weak blanking (likely gas/ gaseous sediments) under strong horizon (unconformity). Horizon pulled-up in some areas - presence of gas movement.			More widely spaced, coast-perpendicular block.

continued . . .

Survey line name	Orientation	Indications of Gas	Indications of hydrate	Well on line	Comments
A88-046	WSW-ENE	Chaotic reflectors and areas of weak blanking (likely gas/ gaseous sediments) under strong horizon (unconformity). Horizon pulled-up in some areas - presence of gas movement. Weak gas chimney in east of line.			More widely spaced, coast-perpendicular block.
A88-047	WSW-ENE	±10 strong gas chimneys - some reaching surface sediments, others causing pull-up in unconformity but not reaching surface. Chaotic reflectors (likely gas/ gaseous sediments) under strong horizon (unconformity).		A-H1	Well A-H1 does not reach unconformity, but does intersect some (potentially) disrupted reflectors. Gas chimney close to east of well. More widely spaced, coast-perpendicular block.
A88-048	WSW-ENE	Long gas chimney reaching surface (potential flare in water) on very west of line. Srrong reflector (unconformity) disrupted in several places (pull - up) by gaseous sediments/gas chimneys rising from chaotic reflectors beneath horizon.			Presence of seabed multiple across whole line. More widely spaced, coast-perpendicular block.

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Survey line name	Orientation	Indications of Gas	Indications of hydrate	Well on line	Comments
A88-049	WSW-ENE	Chaotic reflectors (likely gas/ gaseous sediments) under strong horizon (unconformity). Horizon pulled-up in some areas - presence of gas movement. Weak gas chimney in east of line.			Presence of seabed multiple across whole line. More widely spaced, coast-perpendicular block.
A88-050	WSW-ENE	Chaotic reflectors (likely gas/ gaseous sediments) under strong horizon (unconformity). Horizon pulled-up in some areas - presence of gas movement. Gas chimney to east of line - possibly associated with fault - terminates unconformity, does not reach surface.			Presence of seabed multiple across whole line. More widely spaced, coast-perpendicular block.
A88-051	WSW-ENE	Chaotic reflectors (likely gas/ gaseous sediments) under strong horizon (unconformity). Horizon pulled-up in some areas - presence of gas movement. Gas chimney to east of line - possibly associated with fault - terminates unconformity, does not reach surface.			Presence of seabed multiple across whole line. More widely spaced, coast-perpendicular block.

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Survey line name	Orientation	Indications of Gas	Indications of hydrate	Well on line	Comments
A88-052	WSW-ENE	Chaotic reflectors (likely gas/ gaseous sediments) under strong horizon (unconformity). Horizon pulled-up in some areas - presence of gas movement. Some weak blanking.			Presence of seabed multiple across whole line - weak. More widely spaced, coast-perpendicular block.
A88-053	WSW-ENE	Chaotic reflectors (likely gas/ gaseous sediments) under strong horizon (unconformity). Horizon pulled-up in some areas by short gas chimneys (±3) indicting presence of gas movement. Some weak blanking.			Presence of seabed multiple across whole line - weak. More widely spaced, coast-perpendicular block.
A88-054	WSW-ENE	Chaotic reflectors (likely gas/ gaseous sediments) under strong horizon (unconformity) rising in a mound and producing a weak gas chimney extending to surface on east of line. Some blanking.			More widely spaced, coast-perpendicular block.
A88-055	WSW-ENE	Chaotic reflectors (likely gas/ gaseous sediments) under strong horizon (unconformity. Some weak blanking below unconformity.			Small error on line towards west - no signal. More widely spaced, coast-perpendicular block.

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Survey line name	Orientation	Indications of Gas	Indications of hydrate	Well on line	Comments
A88-061					Almost entirely out of Block 2 (in Block 1).
A88-083	SSE-NNW	Many (20) gas chimneys, most all reaching the seabed and ±6 being associated with seabed depressions (pockmarks) The most significant, and deep pockmark is close to the west of Well K-A2 and is associated with the most vertically extensive gas chimney on the section.		K-A2	Some areas of blanking on either side of (main) large chimney in east near well K-A2. Seabed depressions/pockmarks associated with chimneys. Line cuts through corner of southern end Block 2.
A88-104	S-N				Shallow - roughly coast parallel (steeper than SSE-NNW, but not quite true S-N).
AB99-006	SSE-NNW	Few (2-3) weak chimneys. Some pull-up.			Good resolution (fine). Possible channel structure seen.
AB99-008	SSE-NNW	Few (2-3) weak chimneys. One with large triangular base extending to near-surface.			Grp 1. Good resolution (fine). Possible channel structure seen.
AB99-009	WSW-ENE	Few (2-3) weak chimneys. Some pull-down.			Grp 1. Good resolution (fine). Sediments disturbed in layer just below seabed to west/centre - possible slumping.
AB99-010	WSW-ENE	Few (2-3) weak chimneys. Some pull-down. Minor gas blanking.			Grp 1. Good resolution (fine).
AB99-011	SSE-NNW	Few (2-3) weak chimneys. Some pull-up, 2 short potential faults in surface sediments.			Grp 2. Good resolution (fine). Possible channel structures seen.
AB99-012A	WSW-ENE	Few weak chimneys / gas escape features (disruption of horizons). Potential fault in surface sediments (displacement of reflectors).			Grp 2. Good resolution (fine).

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Survey line name	Orientation	Indications of Gas	Indications of hydrate	Well on line	Comments
AB99-013	WSW-ENE	Weak gas chimney. Disruption and pull-up of reflectors.			Grp 2. Good resolution (fine).
AK76-001	SE-NW	Large, vertically exstensive and prominent gas chimney, fed from area of chaotic reflectors (gaseous sediments) below unconformity. Chimney reaches to barely below seabed. Possible feeder chimney / fault-associated seep intersecting at 45° angle from the SE. ±3-4 other, weak chimneys.			
AK76-002	SW-NE	Weak gas chimney. Disruption of reflectors. Potential gas blanking of western 1/4 of line (maybe bad tuning??)			
AK76-003	SE-NW	2 wide gas chimneys that appear to originate together below the unconformity - they split apart as they extend towards the surface, but remain closely adjacent - total combined area of ±4km. Associated strong bright spots in both of these. (Pull-up and pull-down displayed in chimneys.) Near-surface. ±1-2 other, weaker chimneys.			

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Survey line name	Orientation	Indications of Gas	Indications of hydrate	Well on line	Comments
AK76-004	SW-NE				
AK76-005	SE-NW	Large, vertically exstensive and prominent gas chimney, originating below unconformity (13At1). Chimney reaches to barely below seabed with pull-up reflectors) 3-4 other, smaller (vertically and horizontally) gas chimneys, 1 showing an internal bright spot. Reflectors pulled up and more chaotic from just above level of unconformity in SW - possible gaseous sediments.			Well A-G1 is 1.5km to north-east of line
AK76-006	SW-NE	±5 gas chimneys. One deep and associated with small rise in seabed, one (maybe 2) possibly associated with fault. Most reaching near-surface. Pull-up reflectors.			
AK76-007	SE-NW	±4-5 weak gas chimneys / gaseous zones/seeps. Prominent reflector that looks like BSR is multiple generated by gentle mound/rise in the seabed (Child's Bank?) Gaseous sediments noted below the level of the unconformity (chaotic reflectors).		A-H1	Well A-H1 is drilled to the NW of the bathymetric rise - intersects possibly 3 bright spot reflectors. Prominent reflector that looks like BSR is seabed multiple following the gentle mound/rise in the seabed (Child's Bank?)

continued . . .

Survey line name	Orientation	Indications of Gas	Indications of hydrate	Well on line	Comments
AK76-009	SE-NW	±5-6 weak gas chimneys / gaseous zones/seeps. 1 from base of seismc section to SE side of Child's Bank. Prominent reflector that looks like BSR is multiple generated by gentle mound/rise in the seabed (Child's Bank?) Gaseous sediments noted below the level of the unconformity (chaotic reflectors).			Well K-A3 is 800m to north-east of line. Bathymetric rise in the seabed (Child's Bank?). Prominent reflector that looks like BSR is seabed multiple imitating the gentle mound/rise in the seabed in the centre of the seismic line.
AK76-010	SW-NE	±5 gas chimneys. One deep and clear, 2, maybe 3, possibly associated with fault. Most reaching near-surface. Pull-up reflectors.	??? Possible BSR at 0.75s. Flat, like seabed, but reversed polarity and cutting across some stratigraphic interfaces.		Well A-H1 is ±1km south of line. Seabed multiple not to be confused with BSR.
AK76-011	SE-NW	±7-8 weak gas chimneys / gaseous zones/seeps, some fault-associated in the NW. Prominent reflector that looks like BSR is multiple generated by gentle mound/rise in the seabed in the centre of the seismic line (Child's Bank?).Some chaotic reflectors beneath lavel of unconformity - gaseous sediments.		K-A1	Well K-A1 is drilled through the SE 1/4 of the bathymetric rise (Child's Bank), to the SE of the column of gaseous seds & NW of a slight slump in the Bank. Intersects some potential bright spots (?) near bottom of well. Prominent reflector that looks like BSR is actually a seabed multiple imitating the gentle rise in seabed.

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Survey line name	Orientation	Indications of Gas	Indications of hydrate	Well on line	Comments
AK76-013	SE-NW	Large, vertically exstensive and prominent gas chimney, originating below unconformity (13At1) to barely below seabed (with pull-up reflectors) and into the gentle bathymetric high of Child's Bank. ±8-10 other, smaller (vertically and horizontally) gas chimneys, some disrupting surface sediments in SE. Several fault-associated, especially in NW where near-seabed.			Gentle bathymetric high of Child's Bank. There is a pockmark on the SE edge of Child's Bank which may either be a result of what looks like a gas chimney beneath it or, alternatively, the seabed anomaly is causing the percieved disruption in the sub-surface reflectors. Seabed multiple should not be confused by potential BSR.
AK76-014	SW-NE	±6 gas chimneys. Two deep and clear, several sorter, near-surface chimneys possibly associated with fault. Most reaching near-surface. Pull-up reflectors. Bright spots present in deep chimneys at ±1.95s (very prominent upward bowing of reflectors)	94		Seabed had very gentle domal structure in the centre of the line.

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Survey line name	Orientation	Indications of Gas	Indications of hydrate	Well on line	Comments
AK76-015	SE-NW	±10-12 distinct gas chimneys. Some vertically extensive. 1 show clear indication of bright spot within the chimney at ±2.1s. Chimneys show pull-up and pull-down attributes. ±3-5 are fault-associated.			Gentle bathymetric high of Child's Bank. There is a pock-mark on the SE edge of Child's Bank which may either be a result of what looks like a gas chimney beneath it or, alternatively, the seabed anomaly is causing the percieved disruption in the sub-surface reflectors. Looks like fine scouring or de-watering structures in near-surface sediments far SE end of line. Seabed multiple not to be confused with a potential BSR.
AK76-016	SW-NE	±8-10 gas chimneys. 4-5 are well defined and vertically extensive (with pull-up reflectors) and several other weaker chimneys (2-3 may be fault associated). Most reach near surface. 2 are of particular prominence and contain bright spots within them at ±1.5s.	Possible BSR at 0.55s to 0.7s. Imitates domal structure of seabed. Reversed polarity and cross cutting interfaces. Is actually a seabed multiple NOT a BSR.		Seabed has gentle domal structure in south western half of the line and a seabed multiple that should not be confused with a possible BSR.
AK76-017	SE-NW	±10-12 distinct gas chimneys. Most vertically extensive from above level of 13At1, ±3 pass through this reflector with pull-up, sometimes blanking. 1 shows bright spot within chimney at ±2.8s and disturbs the seabed. Chimneys show pull-up and pull-down attributes. ±half are fault-associated. Some chimneys reach to near-surface and others disturb the seabed.	Possible BSR between 0.9ms and 0.6ms is actually a seabed multiple.		There is a bathymetric high in teh centre of the seismic line - Child's Bank - which appears to have stepped sides. This profile is reflected in the sub-surface, but is a mutiple, not a BSR. Stratigraphic reflectors beneath the level of 13At1 and below Child's Bank are gently domal.

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Survey line name	Orientation	Indications of Gas	Indications of hydrate	Well on line	Comments
AK76-018	SW-NE	±6 well defined and vertically extensive gas chimneys, with 2 of these appearing to have some sort of fault association and 1 with associated bright spot at ±2.15s. ±3-4 other, weaker, chimneys (some of which are also fault associated). Most reach near surface.			Seabed has gentle domal structure over south western 3/4 of the line.
AK76-020	SW-NE	5 large, well defined and vertically extensive gas chimneys. 4 reach surface and disrupt seabed sediments. One is much wider (±3.2km), originates in chaotic reflectors well below the unconformity and appears to contain a bright spot within it. Bright spot also present in another defined, vertically extensive, chimney.			Seabed over almost entire line is now gently domed. In a band from ±2.85s to 3.3s in the west there are progradational structures (looks like large scale cross-bedding on seismic section). Error in seismic section slightly east of centre - data missing in wedge from surface to ±0.9s.
AK76-022	SW-NE	3-4 large, well defined and vertically extensive gas chimneys. ±2 reach seabed and one is much larger (correlates with same chimney in AK76-020), originating in chaotic reflectors well below the unconformity and appears to contain a bright spot within it.	??? Possible BSR from ±0.55s to ±0.75s following rise of seabed. Cut by large gas chimney. Actually is seabed multiple.		Seabed over most of SW part of the line is gently domed. In a band from ±2.7s to 3.3s in SW half of line, there are progradational structures (looks like large scale cross-bedding on seismic section) - clearer than in AK76-020. Clear seabed multiple not to be confused with potential BSR.

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Survey line name	Orientation	Indications of Gas	Indications of hydrate	Well on line	Comments
AK76-024	SW-NE	±3-4 weak gas chimneys. Wide band of chaotic reflectors on SW edge of section (possible gaseous sediments / poor tuning?) most reach near-surface.			Seabed over most of SW half of the line is gently domed. In a band from ±2.75s to 3.25s in SW half of line, there are progradational structures - weaker than in AK76-022.
AK76-026	SW-NE	±4, well defined, vertically extensive gas chimneys (pull up reflectors, 2 may be fault associated). ±2 reach the seabed and disturb sediments. Several other, weaker chimneys, some near-surface, some reach seabed.		K-A2, K-A3	Well K-A2cuts through some progradational structures and through the unconformity. Well K-A3 does not reach the level of the unconformity. Well K-A1 is ±2km north of line (between K-A2 & K-A3). There is a wide column from base to surface of chaotic, disturbed reflectors in the far SW of the line (possible gaseous seds, poss poor tuning).
AK76-028	SW-NE	±6-8 gas chimneys, most reach surface with associated seabed anomalies. 3-4 chimneys in SW most side are fault-associated. 1 (vertically most extensive) is associated with seabed pockmark			Vertically most extensive gas chimney is associated with seabed pockmark - Alternatively pockmark could be responsible for the large vertical disturbance of reflectors (not lithological, but geophysical.) SW 2/3 of the line is gently domed. There is a wide column from base to surface of chaotic, disturbed reflectors in the far SW of the line (possible gaseous seds). Some progradational structures between 2.8s and 3.15s in far SW.
AK76-030	SW-NE	±4-5 gas chimneys reaching to near-surface. 1 vertically extensive and fault-associated. ±3 in SW are vertically shorter and fault-associated.			Distinct column (less wide than previous lines -024, -026 & -028) from base to surface of chaotic, disturbed reflectors in the far SW of the line (possible gaseous seds). Some progradational structures between 2.7s and 3.15s in far SW (less clear than previous lines).

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Survey line name	Orientation	Indications of Gas	Indications of hydrate	Well on line	Comments
AK76-032	SW-NE	±10 strong gas chimneys - some reaching surface sediments, others causing pull-down in unconformity but not reaching surface. ±5 strongly fault-associated chimneys - especially one at southern bounday of Block 2 extending from prograding sediments. Chaotic reflectors (likely gas/ gaseous sediments) under strong horizon (unconformity).			Some progradational structures between 2.7s and 3.1s in far SW.
AK76-036	SW-NE	±10 defined gas chimneys, most having some element of fault-association. ±4 Vertically extensive chimneys - ±3 from area of progradation (outside Block 2, tying in with parallel line to north) and one near NE end, just to the west of Well A-G1, that comes from deep, chaotic area of gaseous sediments below unconformity. This chimney displays pull-down & fault association.		A-G1	Well A-G1 is 300m north of line and does not appear to intersect any distinct anomalies. Progradational structures between 2.3s and 3.1s (in SW, to south of Block 2 boundary). 2/3 of line to south of Block 2 (in Block 3)

continued . . .

Survey line name	Orientation	Indications of Gas	Indications of hydrate	Well on line	Comments
AK76-044	SW-NE	±10 gas chimneys. 1-3 appear to be fault associated. Chaotic reflectors on south-western 20% of line.	Potential shallow BSR at ±0.9s, simulating shelf drop-off - also appears to extend below flat seabed cutting acress dipping stratigraphic reflectors. Actually seabed multiple.		Much longer line. Includes shelf-break / start of continental slope. Eastern 20% of seismic line has chaotic reflectors & disturbed horizons in a defined band from base to seabed, severely disrupting/erasing unconformity - could be result of gas, or poor tuning of seismic line as get to continental shelf. Seabed multiple near shelf edge not to be confused with potential BSR. Line AK76-006 is to the north and AK76-010 is to the south.
AK76-046	SW-NE	±7-8 strong gas chimneys, most having some element of fault-association. Some reach surface, others, near-surface. 2 Vertically extensive chimneys - 1 from area of progradation (outside Block 2, tying in with parallel lines to north and south) and one near NE end that comes from deep, chaotic area of gaseous sediments below unconformity. This chimney displays pull-down & fault association.			Half of line to south of Block 2 (in Block 3). Comes between AK76-032 & AK76-036. Reflectors indicating prograding sediments between 2.65s and 3.25s (in SW, to south of Block 2 boundary).

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Survey line name	Orientation	Indications of Gas	Indications of hydrate	Well on line	Comments
K2002-50	SSE-NNW				Most of line ±90% to south of Block 2 (in Block 3). Much finer resolution than on other seismic lines.
K2002-51	SSE-NNW	Possible gas chimney (short) / pull-up structure.			Most of line ±80% to south of Block 2 (in Block 3). Much finer resolution than other seismic lines.
K80-001	SSE-NNW	±10 clear gas chimneys, ±3 extending from below unconformity (pull-up on intersection). Most reach near-surface - no seabed disturbances. Bright spot in chimney in far south at ±1.8s. Some fault-association in ±3-4 chimneys.			2/3 of line to north of Block 2 (in Block 1)
K80-007	SSE-NNW	4-5 gas chimneys (±3 seem fault associated) below unconformity. ±5 gas chimneys & other areas of blanking & enhanced reflectors (gaseous sediments) above the unconformity in Block 2. Most reach near-surface - no seabed disturbances.			2/3 of line to north of Block 2 (in Block 1). Section ends at 4.9s, others all extended to ±5.8s.
K80-009	SSE-NNW	±2-3 weak, fault-associated chimneys below unconformity (6At1). ±6 gas chimneys & other areas of blanking & enhanced reflectors (gaseous sediments) above unconformity in Block 2. Most reach near-surface & are fault-associated - no seabed disturbances.			1/3 of line above northern boundary of Block 2 (in Block 1).

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Survey line name	Orientation	Indications of Gas	Indications of hydrate	Well on line	Comments
K80-011	SSE-NNW	2-3 weak, fault-associated chimneys below 6At1 unconformity. ±4 clear, fault-associated gas chimneys & other areas of blanking (gaseous sediments) above the 13At1 unconformity in Block 2. One shows seabed expression.			1/2 of line above northern boundary of Block 2 (in Block 1).
K80-012	WSW-ENE	±4 chimneys, all appear fault-associated. Disturbance in near surface sediments (including at seabed) close to where seismic line exits Block 2 - looks similar to Hydrocarbon-Related Diagenetic Zoneabove a chimney - as described by Berge (2013)			90% out of Block 2 (in Block 1). Near surface sediments don't look particularly well consolidated (not as many clear reflectors).
K80-013	SSE-NNW	Many (15-20) clearly defined gas chimneys - all fault-associated in some way - particularly clear in upper sediments in north of line, and in triangular base feeding one of the chimneys. Some gas blanking and chaotic reflectors - gaseaous sediments.			Shorter than other lines parallel to it in this survey - all in Block 2.

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Survey line name	Orientation	Indications of Gas	Indications of hydrate	Well on line	Comments
K80-014	WSW-ENE	Blanking and disturbance of reflectors - gaseous sediments. One very prominent feature - disturbs reflectors in a vertical column like chimney - is likely an artefact caused by an unknown object just below the seabed.			1/4 of line above northern boundary (in Block 1) Section ends at 4.9s, others all extended to ±5.8s.
K80-015	SSW-NNE	±4-6 gas chimneys, 2 in south are strongly fault associated and reach to near-surface sediments. Prominent feature of what appears to be a vertically extensive gas chimney associated with seabed pockmark - Alternatively pockmark could be responsible for the large vertical disturbance of reflectors (not lithological, but geophysical.) Some areas of blanking & disturbed/chaotic reflectors - gaseous sediments.		K-A1, K-A2	Far removed from rest of lines in this survey - to the south. Wells K-A2 and K-A1 appear on this line. K-A2 penetrates to below the level of the unconformity and appears to pass through an area of blanking at ±2.2s. Well K-A1 does not reach the unconformity, but passes through an area of blanking as well as an apparent bright spot and into area of progradation at deepest end of well.

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Survey line name	Orientation	Indications of Gas	Indications of hydrate	Well on line	Comments
K80-016	WSW-ENE	** Bad navigation - data corrupted ** Many faults in upper (closer to seabed) lithology, some have gas chimeys associated with them.			1/2 of line above northern boundary of Block 2 (in Block 1). Problem with application of navigation data to the line from where exits Block 2 to northern end (reflectors appear to slope towards the coast).
K80-018	WSW-ENE	±8 faults - mostly concentrated on far western end - connected with deeper chimneys/seeps (maybe taking advantage of faults). 1 fault reaches seabed in far west of line. Gas blanking present as well as some pull-up structures - gaseous sediments.			Near surface sediments appear unconsolidated due to lack of distinct reflectors as are seen in lithology below this level.
K80-020	WSW-ENE	Areas of blanking (& some pull-up in gas chimneys) and ±6 fault-associated gas chimneys, cluster of 4 in far western side of section. No faults have a surface expression, though they do extend to the near-surface sediments.			Problem with application of navigation on line ±3/4 of way along - bounces to end and back - seismic section looks coherent and can interpret.
K80-022	WSW-ENE	Chaotic reflectors, gas chimney in area beneath unconformity. Areas of blanking (& some pull-up in gas chimneys) above unconformity; and ±7 fault-associated gas chimneys, cluster of 4/5 in far western side of section. No faults have a surface expression, though they do extend to the near-surface sediments.			

continued . . .

Survey line name	Orientation	Indications of Gas	Indications of hydrate	Well on line	Comments
K82-002	SSE-NNW	** Bad navigation - data corrupted ** Gas chimneys (several large) as well as blanking are present, but there are also numerous artefacts (parabolas) as well as a mising-data error at the seabed in the SSE. Do not interpret.			Image of seismic line appears to only start ± 1/3 way along the line. Artefacts and corrupted data, either through loading into original dataset or at time of collection - do not interpret.
K82-004	WSW-ENE	Large zones of gas blanking. Potential chimneys coming off of shallow graben-structure. Chaotic reflectors & several errors / boulders (create parabolas in near-surface sediments) → Poorly processed. Messy.			Short line.
K82-005	WSW-ENE	Large zone of gas blanking on eastern flank and below shallow graben-structure. Chaotic reflectors & possible faults in near surface, though could be errors in processing. → Poorly processed. Messy.			Short line.

continued . . .

Survey line name	Orientation	Indications of Gas	Indications of hydrate	Well on line	Comments
K82-006	WSW-ENE	± 5 fault-associated chimneys in near surface. Large-scale blanking associated with eastern flank (and centre) of graben (pull-down reflectors). Vertically extensive gas chimney with pull-up reflectors associated with is and a potential bright spot.			Short line. Large parabola in east of line - artefact or geology?
K82-007	WSW-ENE	± 4 fault-associated chimneys in near surface. Large-scale blanking associated with graben (pull-down reflectors). Vertically extensive gas chimney with enhanced reflectors and feeding (?) 3 or 4 fault associated chimneys inthe near surface.			Short line. Several large, overprinting, parabola in eastern half of section - geology ? or geophysics artefact?
K82-009	WSW-ENE	± 4 fault-associated chimneys in near surface. Large-scale blanking associated with graben (pull-down reflectors, some are pull-up). Vertically extensive gas chimney with enhanced reflectors and feeding (?) 3 or /4 fault associated chimneys inthe near surface.			Short line. Graben seen in this line is less defined than in previous lines. Several large, overprinting, parabola in eastern half of section - geology ? or geophysics artefact?

continued . . .

Survey line name	Orientation	Indications of Gas	Indications of hydrate	Well on line	Comments
K86-001	WSW-ENE	±5-6 fault-associated gas chimneys. Large area of blanking beneath chaotic reflectors.			3 large pockmarks on seabed to the east of centre - don't influence sediments below shallow unconformity horizon.
K86-002	SW-NE	±5 fault-associated gas chimneys. 2 are vertically extensive. Large area of blanking above unconformity & beneath chaotic reflectors.			Channel below erosional surface (unconformity) that pinches out against another sub-surface horizon at 0.85s, below a large pockmark on seabed in the centre of the seismic section. Pockmark is at base of short rise towards flatter seabed & horizontal sediments.
K86-003	SW-NE	±6-7 fault-associated gas chimneys. Large area of blanking beneath chaotic reflectors above reflector 13At1.			Seabed depression/ pockmark to west of centre.
K89-001	SW-NE	±8 gas chimneys. Most fault-associated, especially in SW. One large, distinct, vertically extensive chimney extending from unconformity to near-surface. Pull up reflectors and bright spots within chimney.			Prograding structures above unconformity. 3 seabed depression/ pockmarks on SW edge of line on rise.
K89-002	SW-NE	2 gas chimneys. 1 large and vertically extensive with pull-up reflectors, reaches near surface, and 1 fault-associated & deeper.			Shorter line.
K89-004	SW-NE	±4 gas chimneys. Most fault-associated, especially in SW, extend from area of chaotic reflectors / blanking (gaseous sediments) and terminate against palaeo-seabed surface between ±0.65s and 0.75s.		K-A1	Well K-A1 appears to hit a bright spot near the bottom of the well.

continued . . .

Survey line name	Orientation	Indications of Gas	Indications of hydrate	Well on line	Comments
K89-005	SW-NE	± 10 gas chimneys - ±6 fault-associated gas chimneys in SW half of line, chaotic reflectors beneath chimneys (likely gaseous sediments source feeder). ±4 weak gas chimneys in NW. Series of slippage related (listrict ?) faults in most SW part of seismic line - just out of Block 2.			15% of line to south of Block 2 (in Block 3).
K89-006	SW-NE	±4 fault associated chimneys in centre and SW part of seismic line. Areas of generalised blanking under fault-associated chimneys (gaseous sediments). Some short, near-surface, anomalies near NE end - could be gas-related, could be errors on seismic.			1/4 of line to south of Block 2 (in Block 3).
K89-007	SW-NE	2 Distinct fault-associated gas chimneys, with chaotic reflectors (gaseous sediments) at their bases, near southern boundary of Block 2.			Half the line out of Block 2 to the south (in Block 3).
K89-008	SW-NE	Some generalised chaotic reflectors - diffuse gaseous sediments.			3/4 of line to south of Block 2 (in Block 3)
K89-024	SW-NE	±6 fault-associated chimneys in SW half of line. Some generally chaotic reflectors - gaseous sediments.			

continued . . .

Survey line name	Orientation	Indications of Gas	Indications of hydrate	Well on line	Comments
K89-026	SW-NE	±5 fault-associated chimneys in far SW, and off centre of line.			Small error on seismic section - missing data in narow wedge shape ±300m from SW end of line.
K89-028	SW-NE	±6 fault-associated chimneys in far SW, and off centre of line.			
K89-030	SW-NE	Very large chimney (in horizontal - ±2km - as well as vertical extent) including several internal bright spots and chaotic reflectors. Pull-up on reflectors surrounding it. 2-3 smaller, fault-associated chimneys in far SW of line.			Some possible aretefacts surrounding large chimney (parabolas) just above the unconformity.
K91-423	WSW-ENE	Shallow (no deeper than ±2.05s TWT) lenticular area of distinct blanking, starting just inside southern boundary of Block 2. Potential gaseous sediments (layer at widest ±0.6s TWT thick).			1/2 of line to the south of Block 2 (in Block 3). Small mound/rise (±25m across) on far eastern side of the line.
K91-428	SSE-NNW	±20 short faults (some may have gas association) in near surface sub-horizontal reflectors. Potential blanking beneath some of these in NW end of line.			1/3 of line to north-west of Block 2 (in Block 1 - maybe). Very good resolution survey. Shows channels (coast perpendicular) in shallower sediments.

continued ...

Survey line name	Orientation	Indications of Gas	Indications of hydrate	Well on line	Comments
K91-429	SSE-NNW	3 Very large and prominent (well defined) chimneys extending from below the unconformity, but most visible effect on horizons from ±2.7s. Pull-up of horizons surrounding 2 of them & internal bright spots. 1 displays surface expression (mud-volcano?) Wide chimney with area of blanking, including bright spot. ±3 smaller & shallower, fault-associated chimneys.			The same feature (wide chimney with area of blanking, including bright spot) can be seen on lines K92-104 and K92-105 in generally same area.
K92-100	WSW-ENE	±15 faults and fault-associated gas chimneys. ±8-10 are extension-fault related. Few areas of localised blanking.			Not the best line - artefacts in water-column and at seabed.
K92-101	WSW-ENE	±15-20 faults and fault-associated gas chimneys. ±8 are extension-fault related. 1 vertically extensive gas chimney, relatively narrow, in far NW (chaotic reflectors & pull-up). Few areas of localised blanking.			Not the best line - artefacts in water-column and at seabed. Palaeo-channels.

continued ...

Survey line name	Orientation	Indications of Gas	Indications of hydrate	Well on line	Comments
K92-102	WSW-ENE	±15-20 faults and fault-associated gas chimneys. Few areas of localised blanking.			Not the best line - artefacts in water-column and at seabed
K92-103	WSW-ENE	Chaotic reflectors. Some weak gas chimneys in east and several shorter, shallow faults with gas-association.			Not the best line - artefacts in water-column and at seabed.
K92-104	SW-NE	Large gas chimney with seabed expression (mound) and wide area of significant internal blanking in near surface. Vertically extensive. Several smaller, fault-associated gas chimneys.			Not the best line - artefacts in water-column and at seabed.
K92-105	WSW-ENE	Large gas chimney with seabed expression (mud volcano & pockmark?) Vertically extensive. Several smaller, fault-associated gas chimneys.			Not the best line - artefacts in water-column and at seabed.
K92-106	WSW-ENE	2 very distinct zones of blanking / disturbance/pull-up which may be gas chimneys, but also may be errors (or error-enhanced).			Seismic section is not the best.
K92-107	SW-NE	±4 faults in shallower sediments - about 2 may be gas-associated.			Not the best line - artefacts in water-column and at seabed. Distinct / distinctive seabed mound/rise (Child's Bank?)
K92-108	WSW-ENE			K-E1	Not the best line - artefacts in water-column and at seabed. Possible dissociating gas / hydrate in one of the well logs. (Some faults, blanking)

continued ...

Survey line name	Orientation	Indications of Gas	Indications of hydrate	Well on line	Comments
K92-109	WSW-ENE				Part of close survey near southern border of Block 2. Channels on palaeo-seabed (coast perpendicular)
K92-110	WSW-ENE				Part of close survey near southern border of Block 2. Channels on palaeo-seabed (coast perpendicular)
K92-111	WSW-ENE				Part of close survey near southern border of Block 2. Possible fault. Lots of channels in shallower sediments (palaoe-seabed/land - coast perpendicular).
K92-130	SSE-NNW				Practically all out of Block 2 - to the south (in Block 3). Tie line for close survey near southern border of Block 2 (-009, -010 & -011).
K93-100	WSW-ENE				Hard to make out seabed. Lots of artefacts & noise in data. Not migrated? Possible half grabens/ poor processing.
K93-102	WSW-ENE				Poorly processed/ much noise. Hard to define seabed. Not stacked? Some channels visible in SW near surface. Faulting/grabens.
K93-103	WSW-ENE				Indistinct seabed. Poor quality line. Possible half grabens. Some incised channels in SW.
K93-104	WSW-ENE				Indistinct seabed. Poor quality line. Possible half grabens. Some incised channels in SW.
K93-125	SSE-NNW	5-6 smaller gas chimneys, quite vertically extensive. 3 with bright spots.			Lots of noise. Some channels?
K93-126	SSE-NNW	1 large, prominent gas chimney. Large area of internal disturbance. Possible surface expression as a seabed mound.			Lots of noise. Some channels? Seabed slopes down to SE. Child's Bank?

continued . . .

Survey line name	Orientation	Indications of Gas	Indications of hydrate	Well on line	Comments
K93-127	SSE-NNW				Incised channels on top of Bank just sub-surface. Some progradational structures in SE (maybe) Poor quality - lot of noise
K93-128	WSW-ENE				1/2 line in Block 1. Poor quality line - no distinct seabed. Not stacked? Possible half-grabens & incised channels.
K93-129	WSW-ENE	Large, vertically extensive gas chimney with seabed expression. Possible flare in water (unclear due to poor line)			Poor quality line. Indistinct seabed & noise in the water column. Possible grabens, faulting and incised channels.
K93-130	WSW-ENE	2 large, vertically and areally extensive gas chimneys. 1 with possible seabed expression & extremely large area of disturbed reflectors			Poor quality line. Indistinct seabed & noise in the water column. Possible grabens & faulting. Gas chimney likely the same as seen in -129
K93-131	WSW-ENE	2 large, vertically and areally extensive gas chimneys with bright spots and internal disturbed reflectors. Terminate just sub-surface, may be associated with sub-seabed mounds			Poor quality line - noise in water column & overprinting data. Gas chimneys likely co-incide with chimneys seen on -129 & -130
K93-132	WSW-ENE				Poor quality line - lots of noise. Incised channels just belw seabed.
K99-001	SSE-NNW	large & vertically extensive gas chimney with surface expression of a mound on the seafloor			Stretches across whole block. Wide area of blanking underneath major surface feature, smaller blanking to NW with similar (though smaller) surface feature.

continued . . .

Survey line name	Orientation	Indications of Gas	Indications of hydrate	Well on line	Comments
K99-002	WSW-ENE	Large gas chimney from below 13At1 & terminating on palaeo-surface at 0.2s below seabed on shelf			Sharp drop off towards SW (shelf break?/ Child's Bank)
K99-003	WSW-ENE				3-4 distinct faults on shelf/bank before if drops off to SW. Could possibly have gas associated with them.
K99-004	SSE-NNW				Very clear palaeo-channel. Coast perpendicular.
K99-005	SE-NW	Several diffuse gas chimneys. Areas of general disturbance due to gaseous sediments.			Prominent mound in SE of seismic line aprox 10km wide
K99-014	SW-NE	Diffuse gaseous sediments.			
K99-015	WSW-ENE				3-4 distinct faults on shelf/bank before if drops off to SW. Could possibly have gas associated with them.
SA92-112	SSE-NNW				Coast sub-parallel. Shallow line. Small error on section.
SA92-118	SSE-NNW				Coast sub-parallel. Shallow line.
SA92-137	WSW-ENE	Diffuse gaseous sediments.			3-4 faults - possible gas association.
SA92-139	WSW-ENE	Diffuse gaseous sediments.			3-4 faults - possible gas association.
SA92-141	WSW-ENE				Gets really shallow in east. Few small errors on the line. ±3 faults from grabens (possible gas association)
SA92-143	WSW-ENE	1 weak gas chimney. ±3 fault-assoc grabens (possible gas)			Gets really shallow in east.
SA92-145	WSW-ENE	±4 fault-assoc grabens (possible gas)			Gets really shallow in east.
SA92-147	WSW-ENE	±5 fault-assoc grabens. 1 weak gas chimney.			Gets really shallow in east. Strong seabed multiple at ±0.35s

continued . . .

Survey line name	Orientation	Indications of Gas	Indications of hydrate	Well on line	Comments
SA92-149	WSW-ENE	±2 weak gas chimneys / fault-assoc grabens.			Gets really shallow in east.
SA92-151	WSW-ENE				Gets really shallow in east. Few small errors on the line.
SA92-153	WSW-ENE			A-D1	Well A-D1 through edge of graben. Gets really shallow in east.
SA92-155	WSW-ENE				Gets really shallow in east.Well A-X2 ±4km to south, Well A-X1 ±5km to south.
SA92-159	WSW-ENE	±4 weak fault-assoc gas chimneys.			Well A-AA1 is 800m to south of line, A-AA2 is 1.8km south. Gets really shallow in east. Small error on the line.
SA92-163	WSW-ENE	5 fault-assoc gas chimneys from grabens.		A-J1	Well A-J1 slightly E of centre of graben. Doesn't penetrate below fill- sediments. Gets really shallow in east.
SA92-167	WSW-ENE	2 fault-assoc graben			Gets really shallow in east.
SA92-173	WSW-ENE	±6 gas chimneys			Gets really shallow in east. Strong seabed multiple at ±0.35s - 0.4s.
SA92-175	WSW-ENE	±3-4 clearer gas chimneys (other weaker)			Triangular shaped error on seabed. Gets really shallow in east. Strong seabed multiple at ±0.35s - 0.45s.
SA92-177	WSW-ENE	±5-8 chimneys (weaker). 1 with apparent seabed expression.			Faulting associated with grabens. Gets really shallow in east.

Appendix C

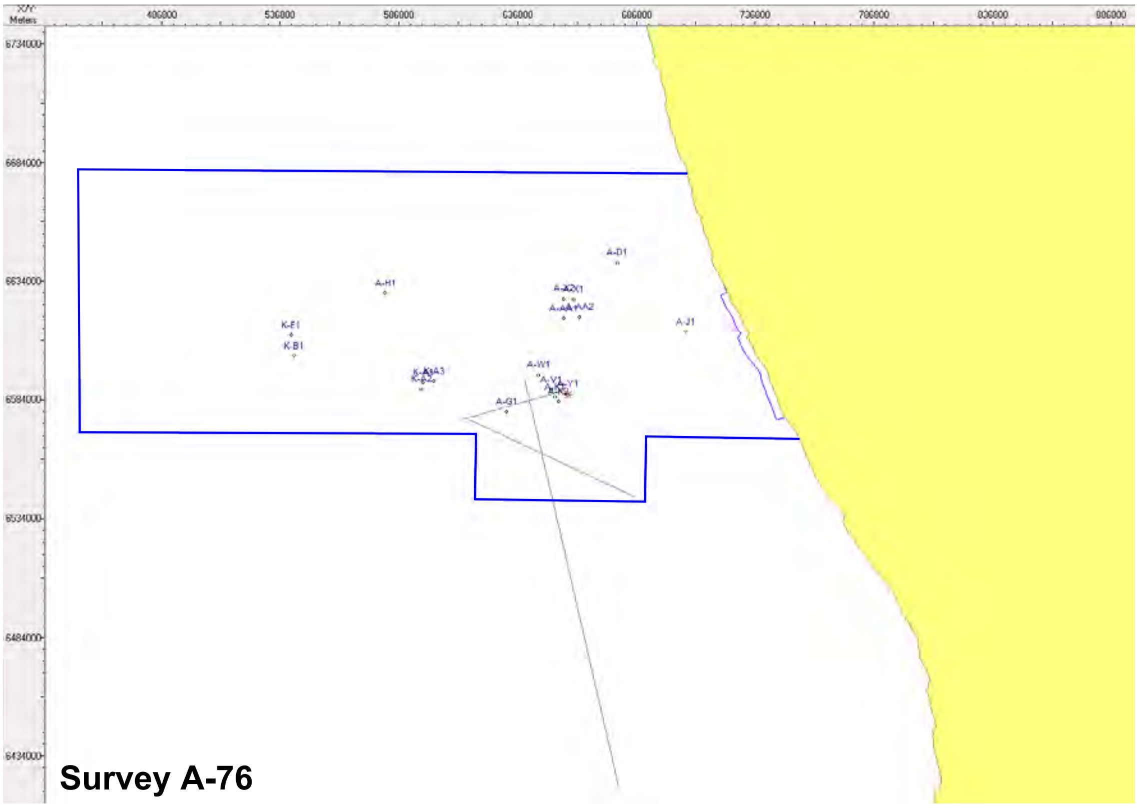

Figure 1: Location of lines provided for survey A-76 in Block 2

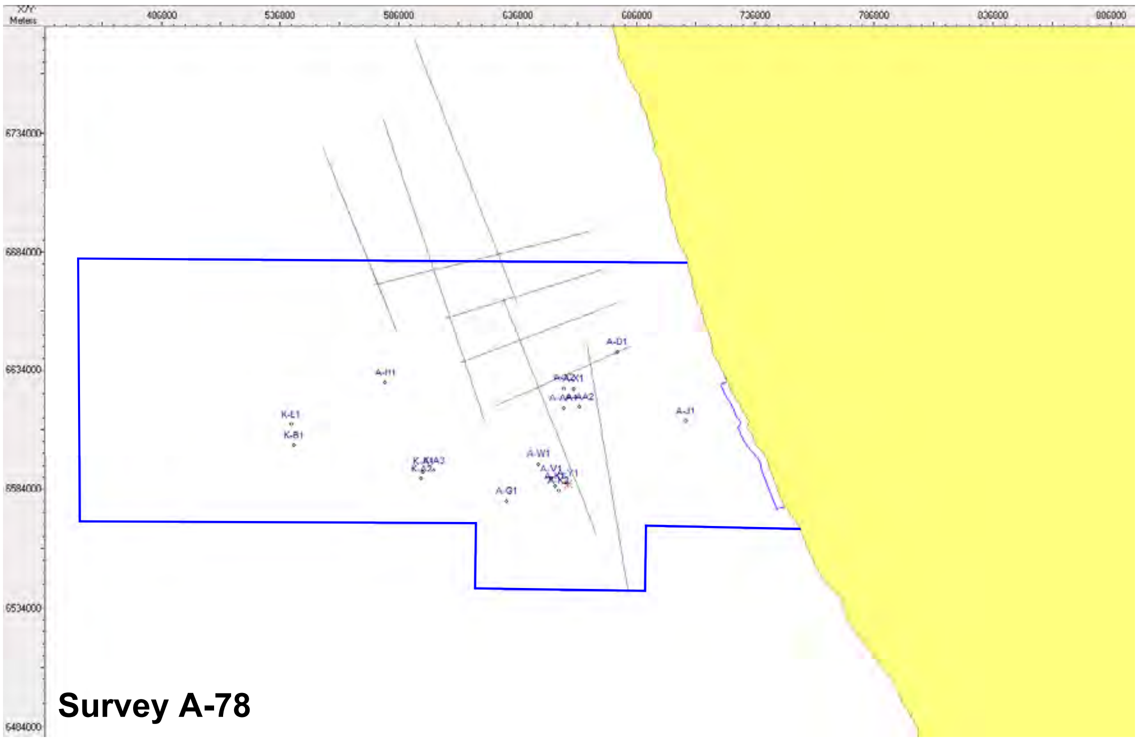

Figure 2: Location of lines provided for survey A-78 in Block 2

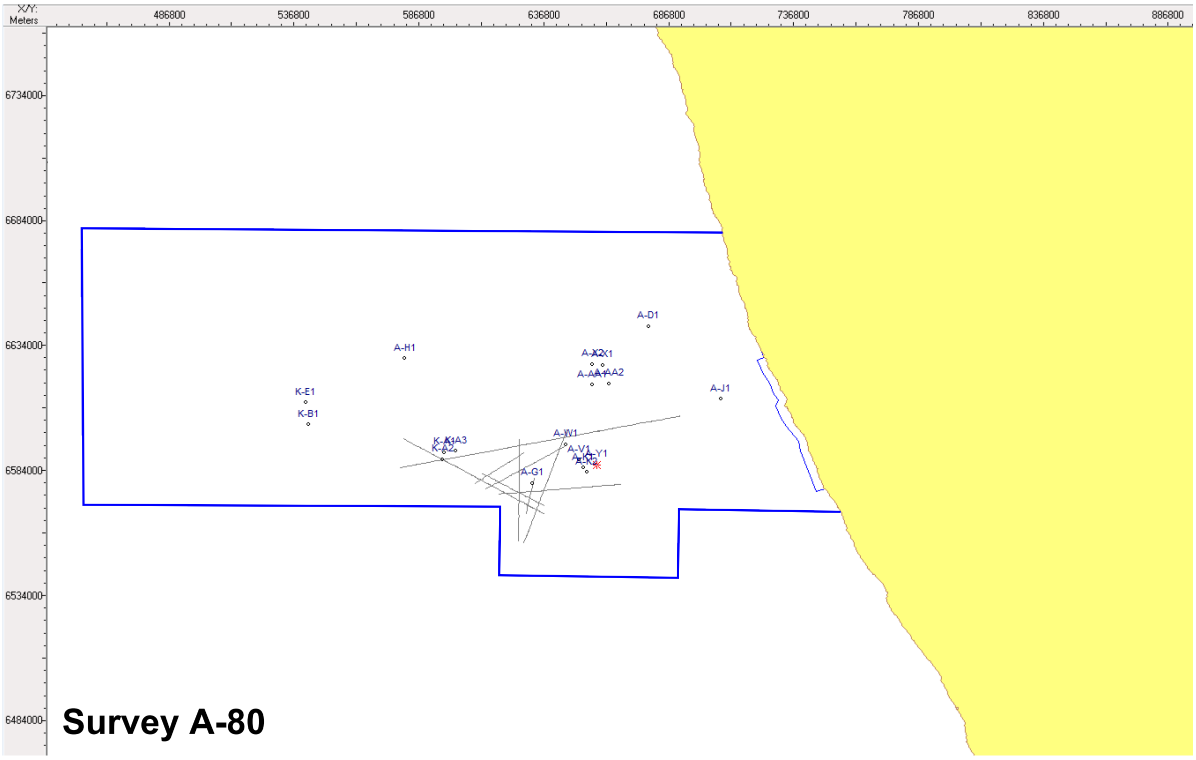

Figure 3: Location of lines provided for survey A-80 in Block 2

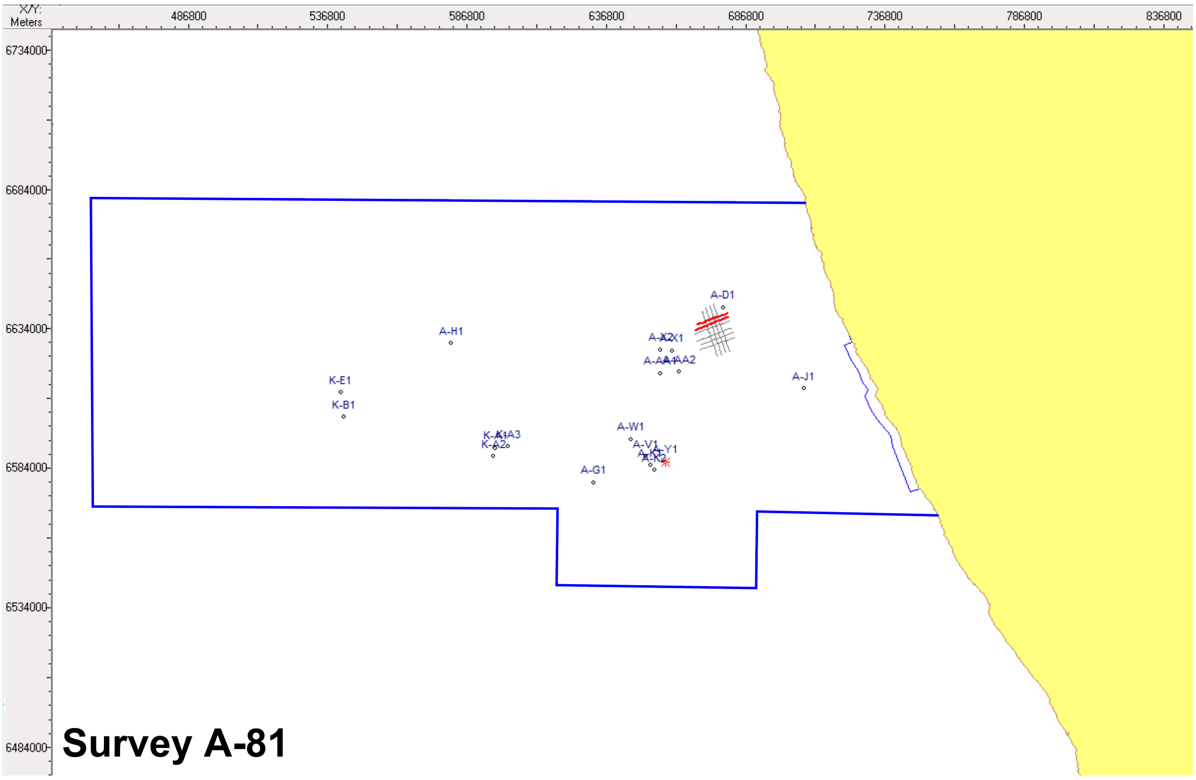

Figure 4: Location of lines provided for survey A-81 in Block 2

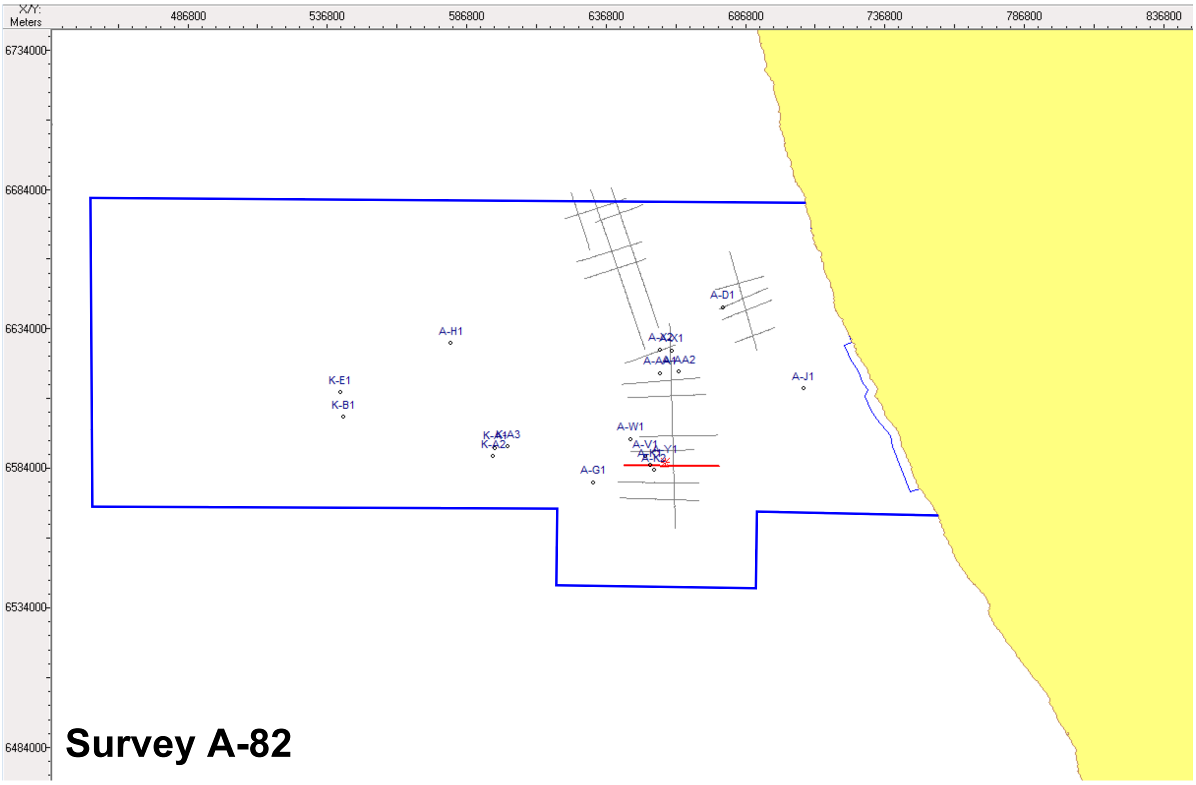

Figure 5: Location of lines provided for survey A-82 in Block 2

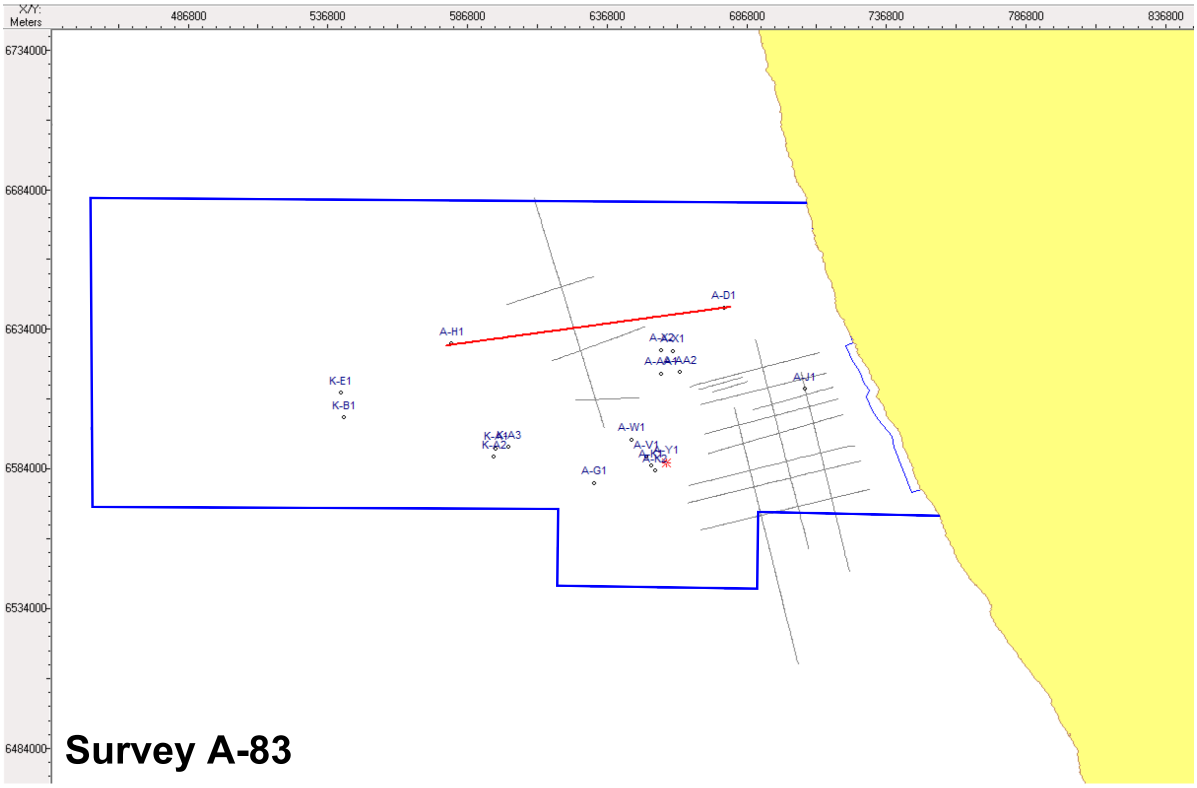

Figure 6: Location of lines provided for survey A-83 in Block 2

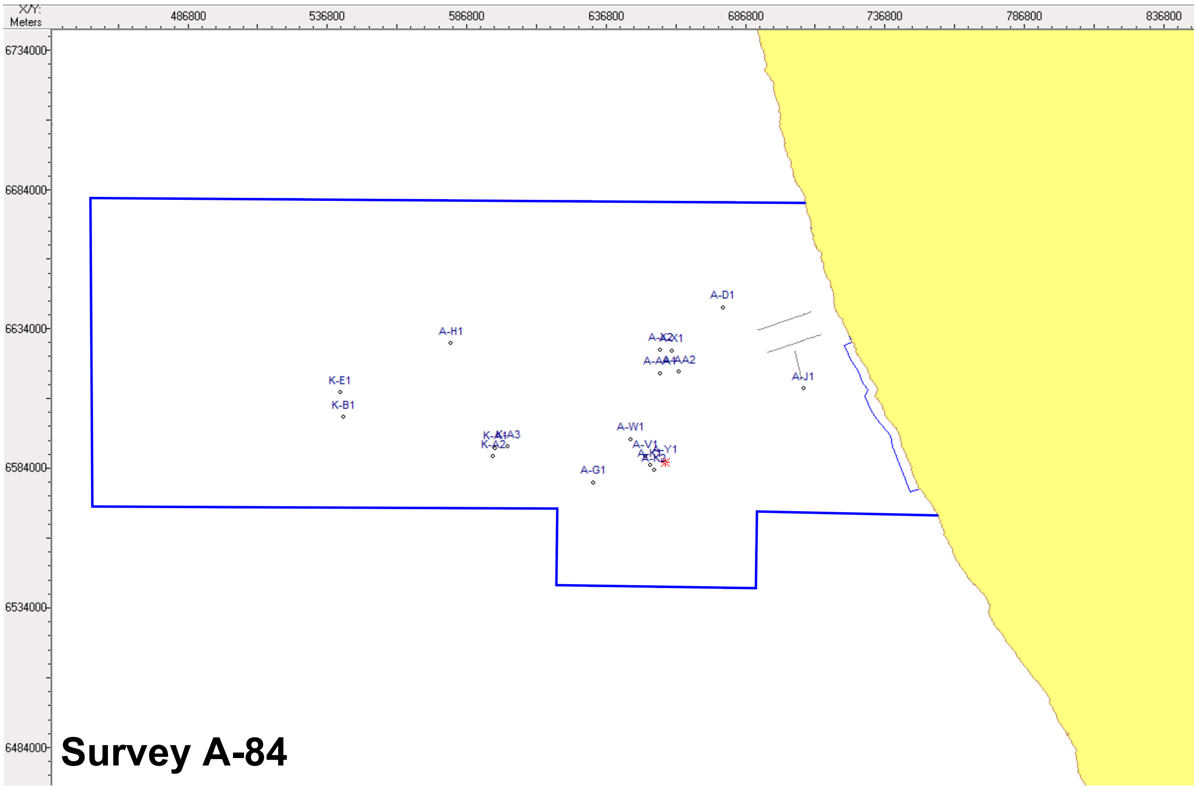

Figure 7: Location of lines provided for survey A-84 in Block 2

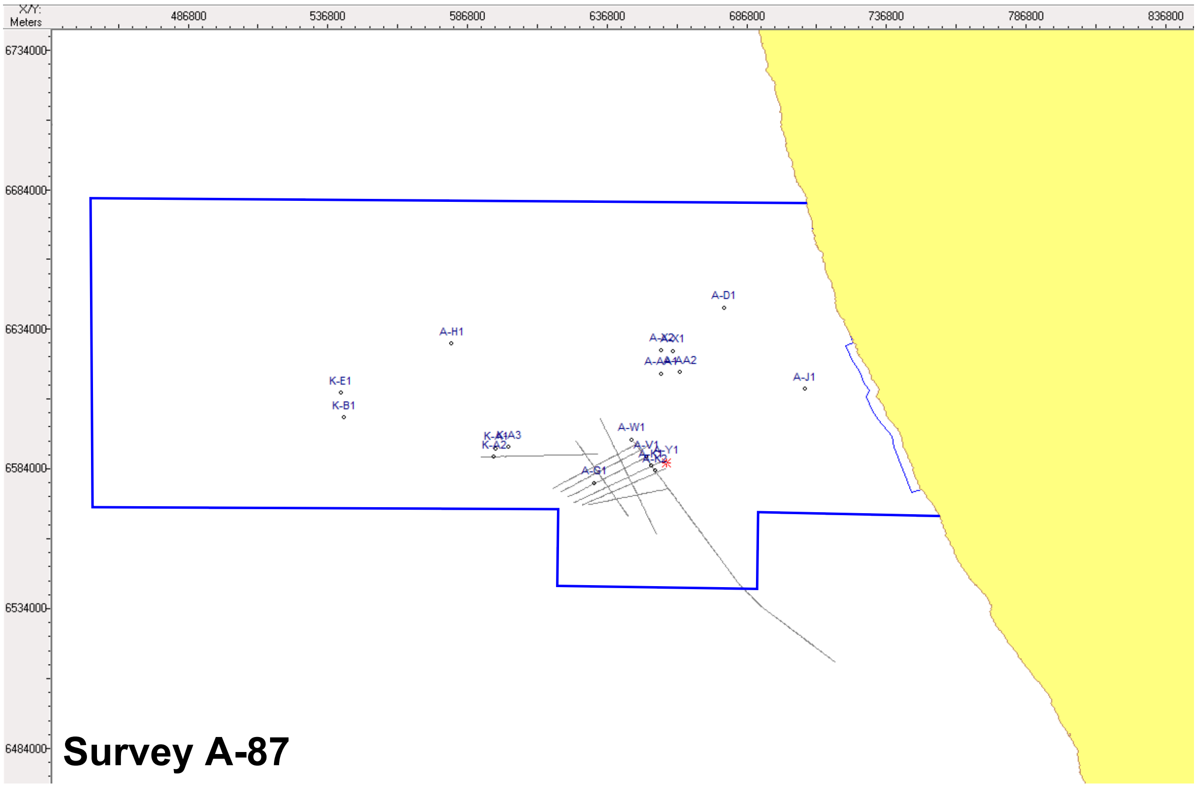

Figure 8: Location of lines provided for survey A-87 in Block 2

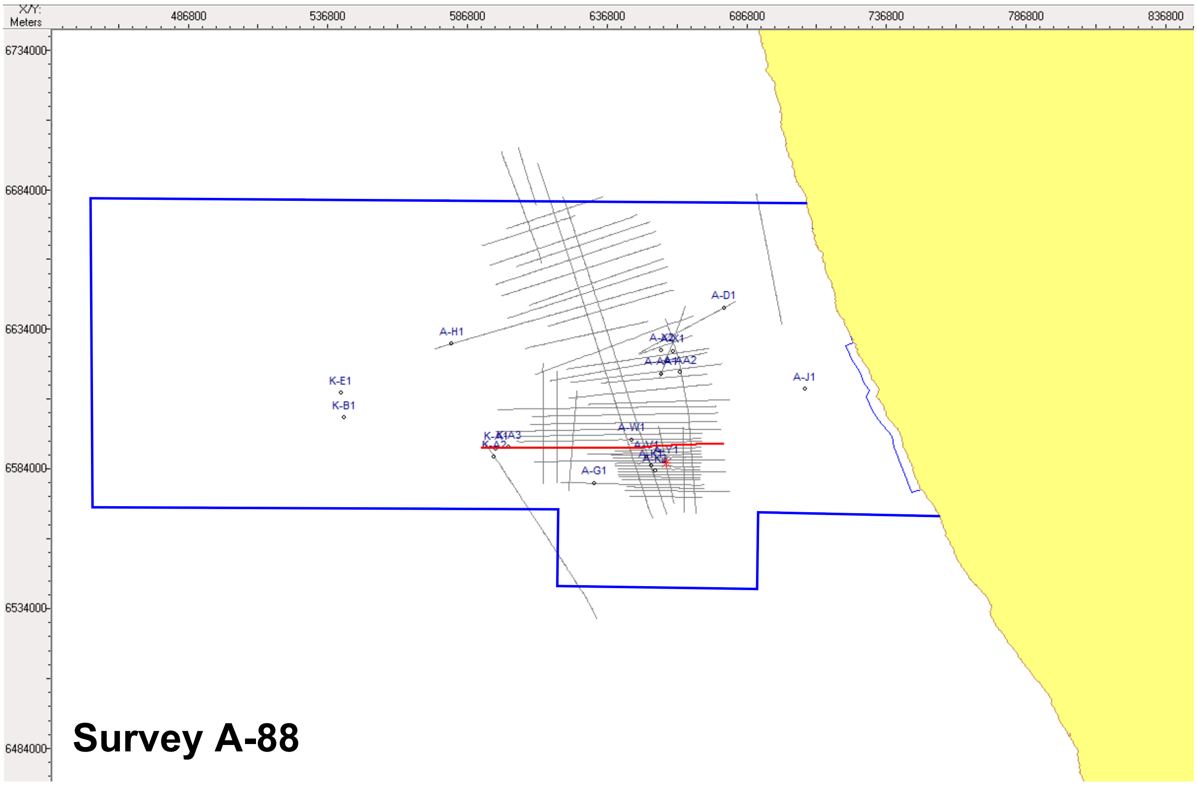

Figure 9: Location of lines provided for survey A-88 in Block 2

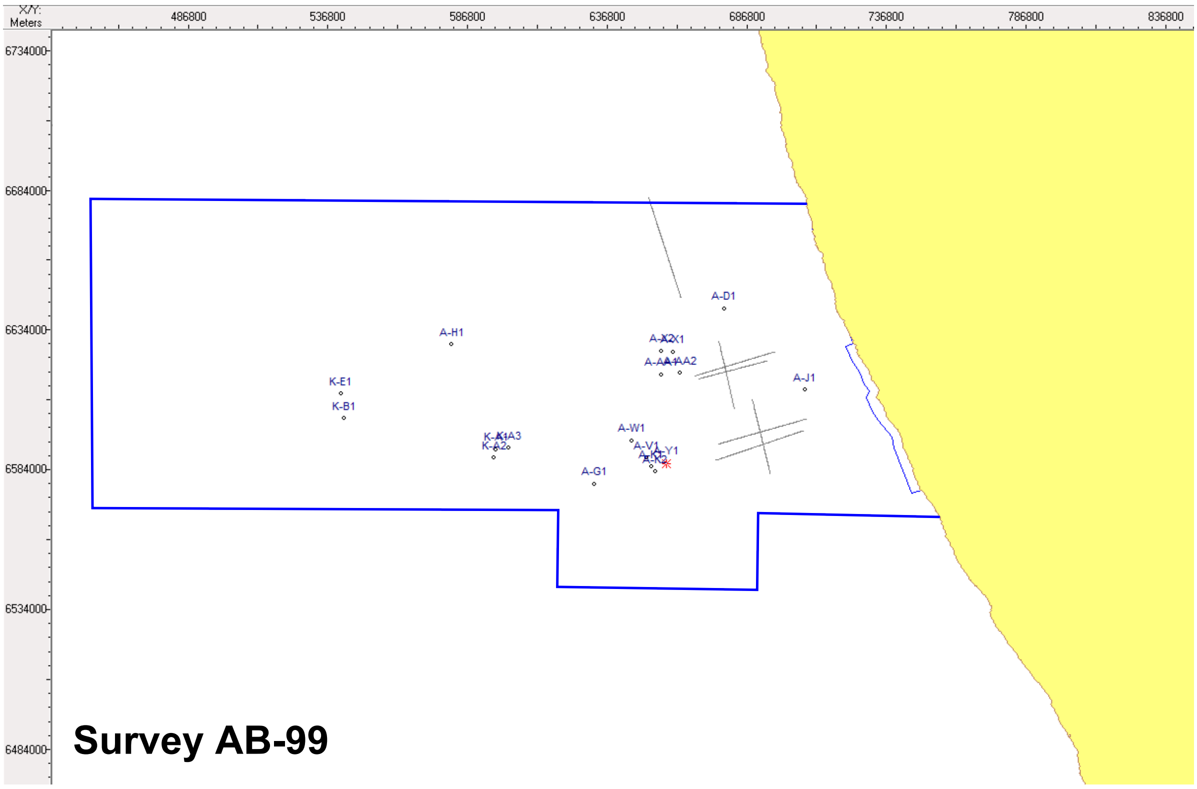

Figure 10: Location of lines provided for survey AB-99 in Block 2

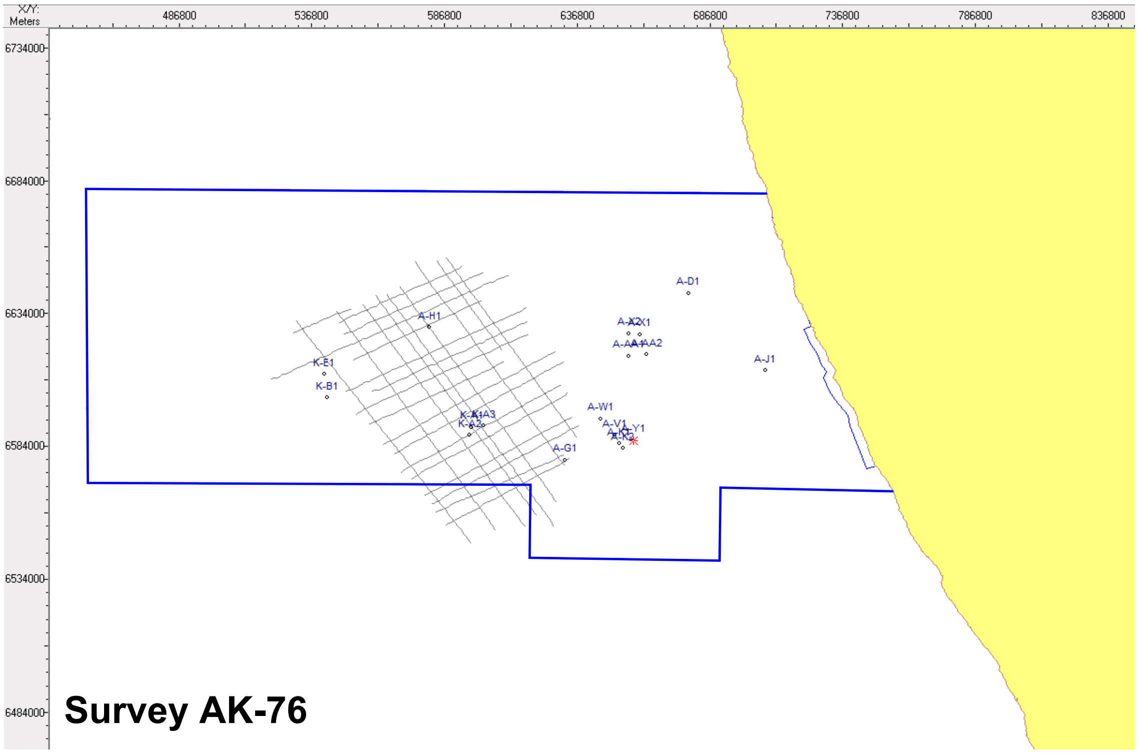

Figure 11: Location of lines provided for survey AK-76 in Block 2

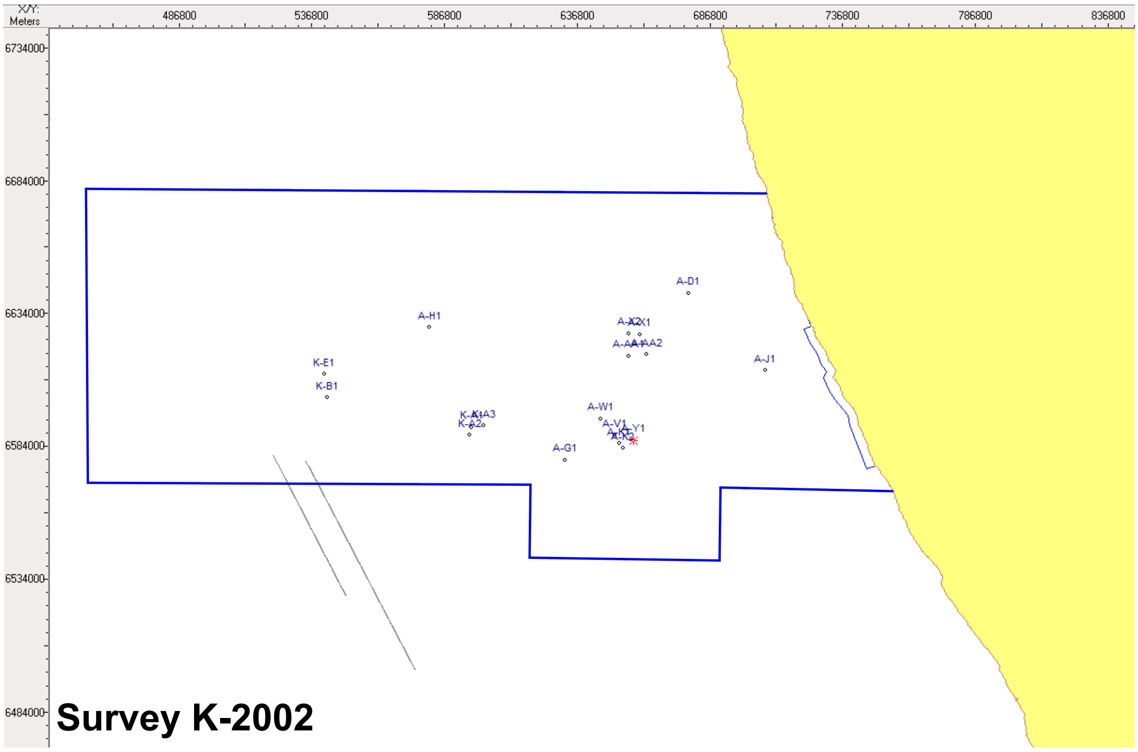

Figure 12: Location of lines provided for survey K-2002 in Block 2

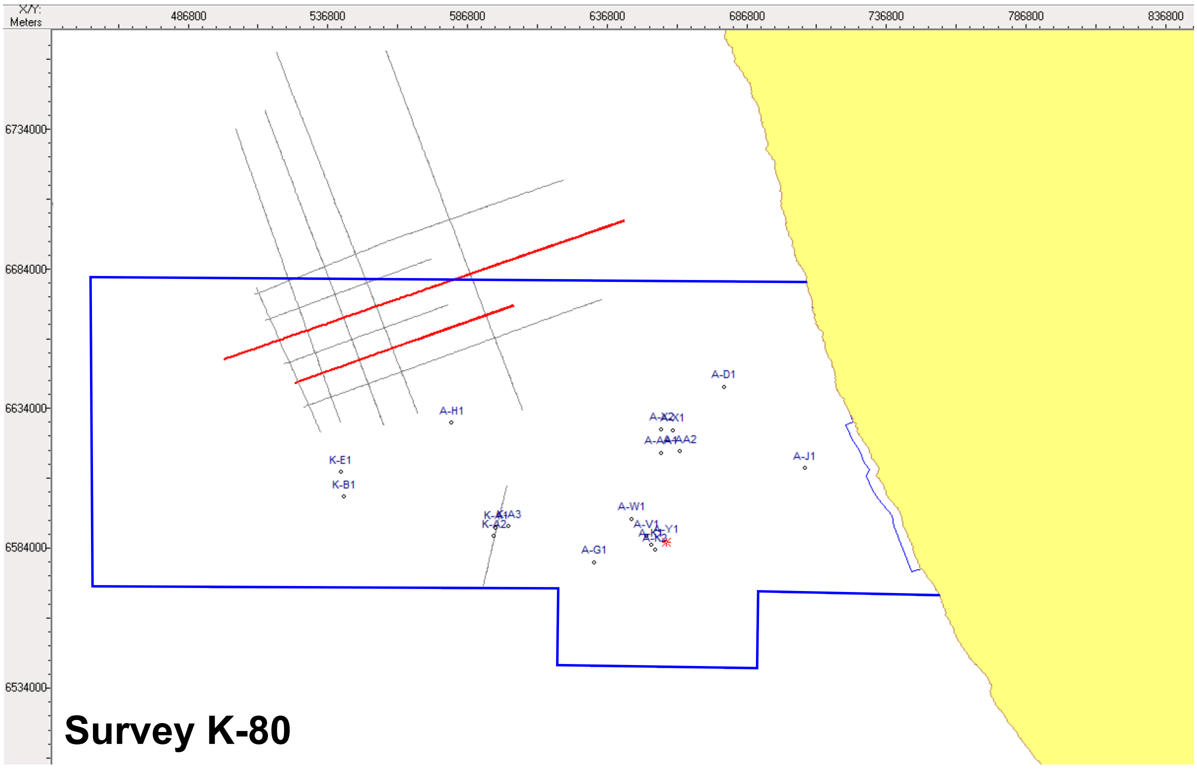

Figure 13: Location of lines provided for survey K-80 in Block 2

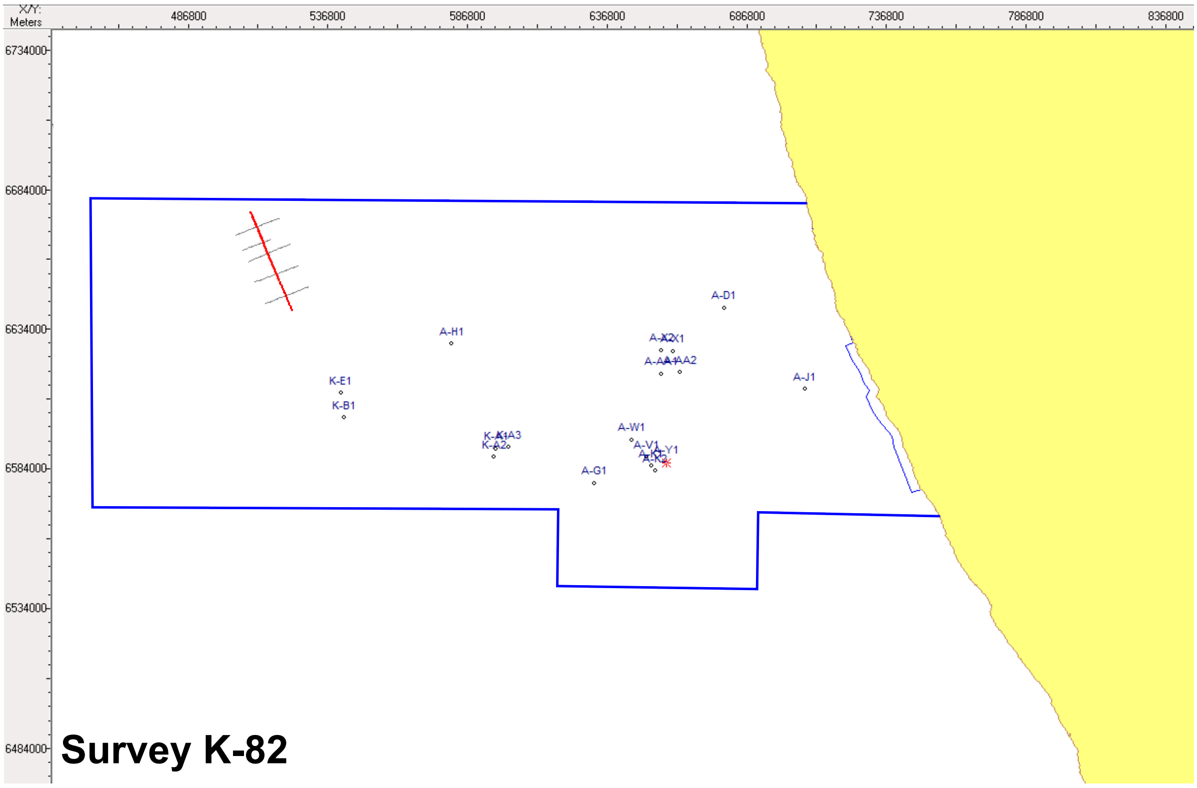

Figure 14: Location of lines provided for survey K-82 in Block 2

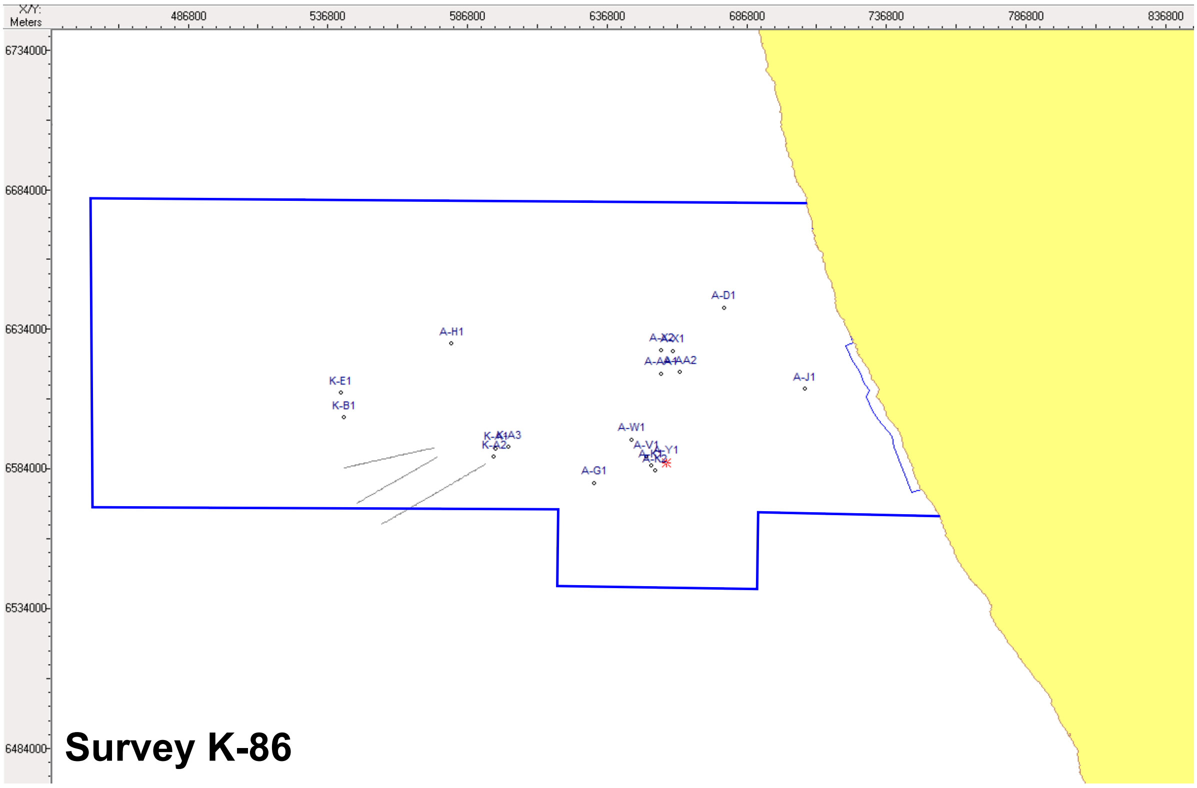

Figure 15: Location of lines provided for survey K-86 in Block 2

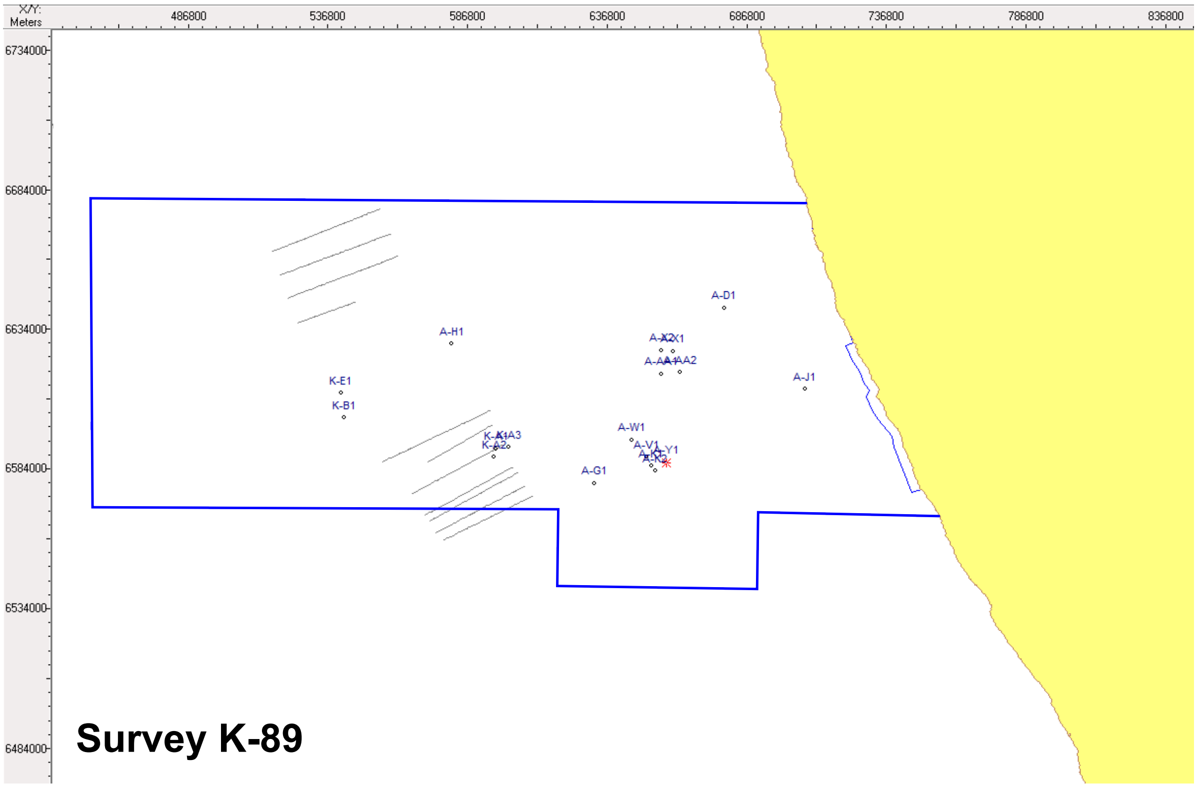

Figure 16: Location of lines provided for survey K-89 in Block 2

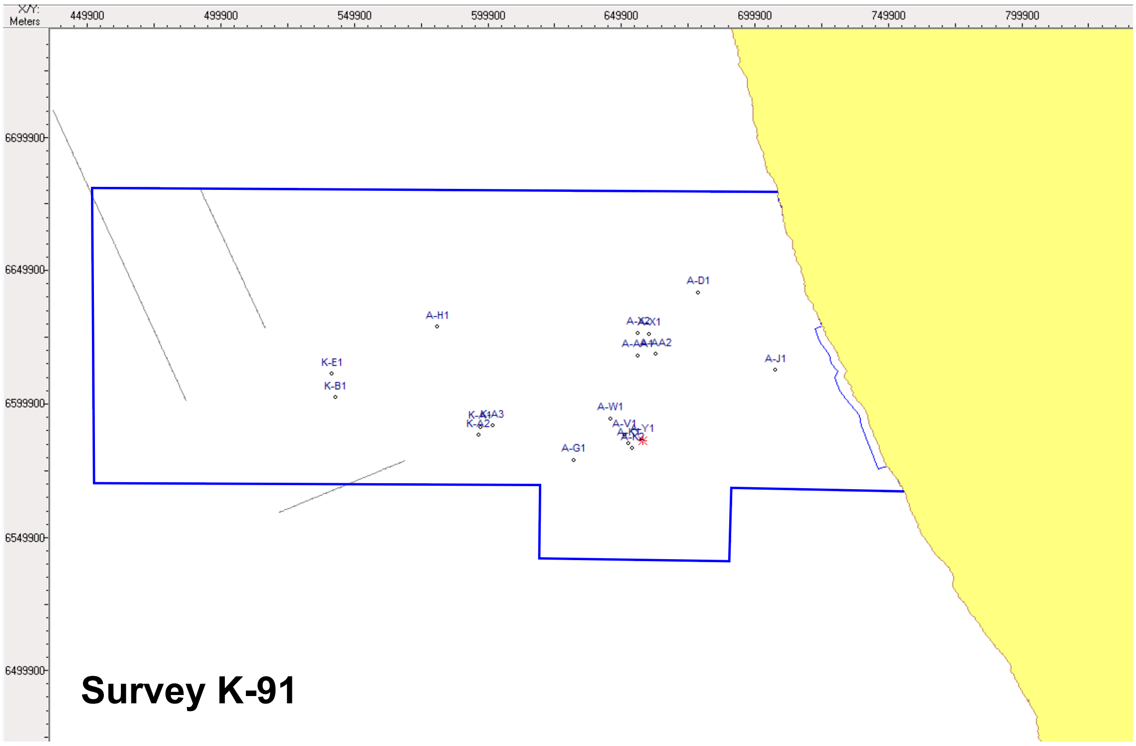

Figure 17: Location of lines provided for survey K-91 in Block 2

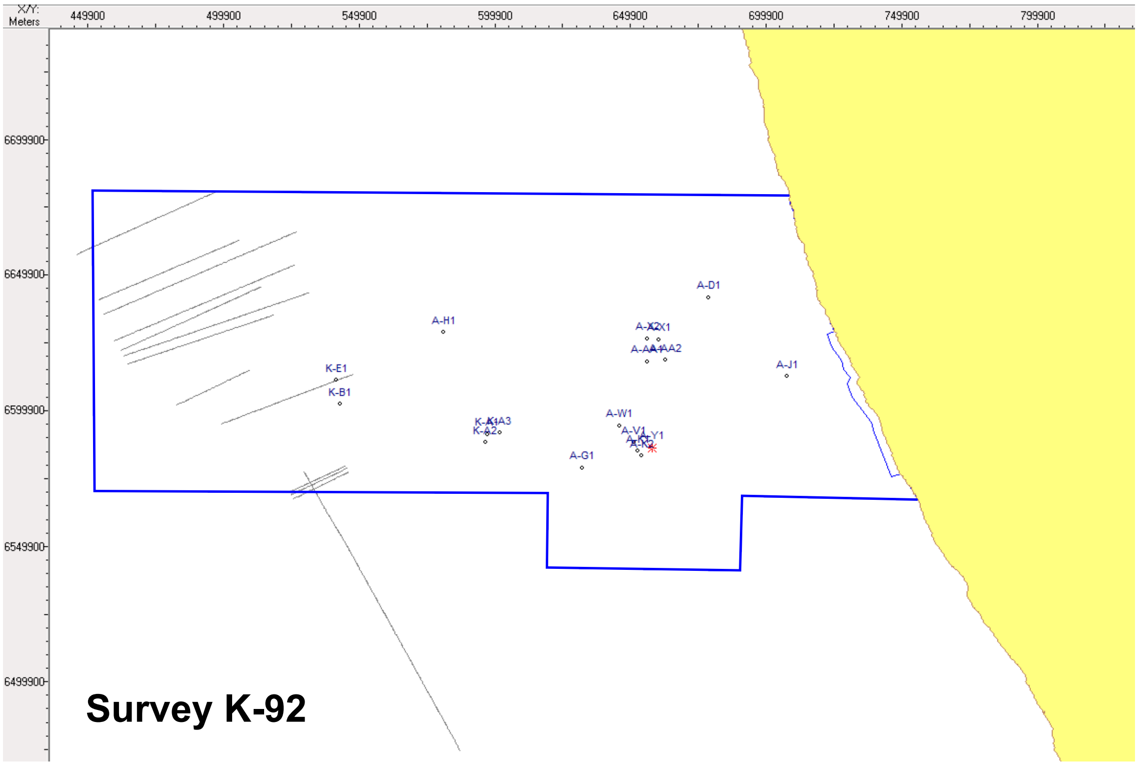

Figure 18: Location of lines provided for survey K-92 in Block 2

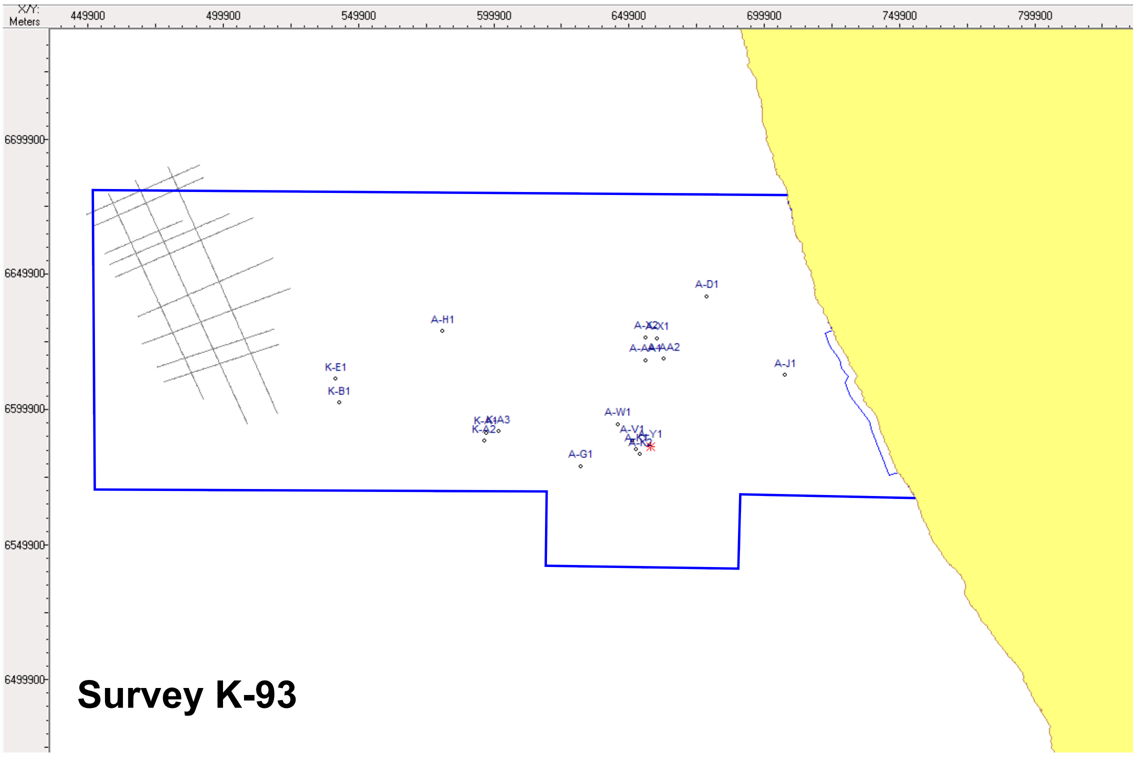

Figure 19: Location of lines provided for survey K-93 in Block 2

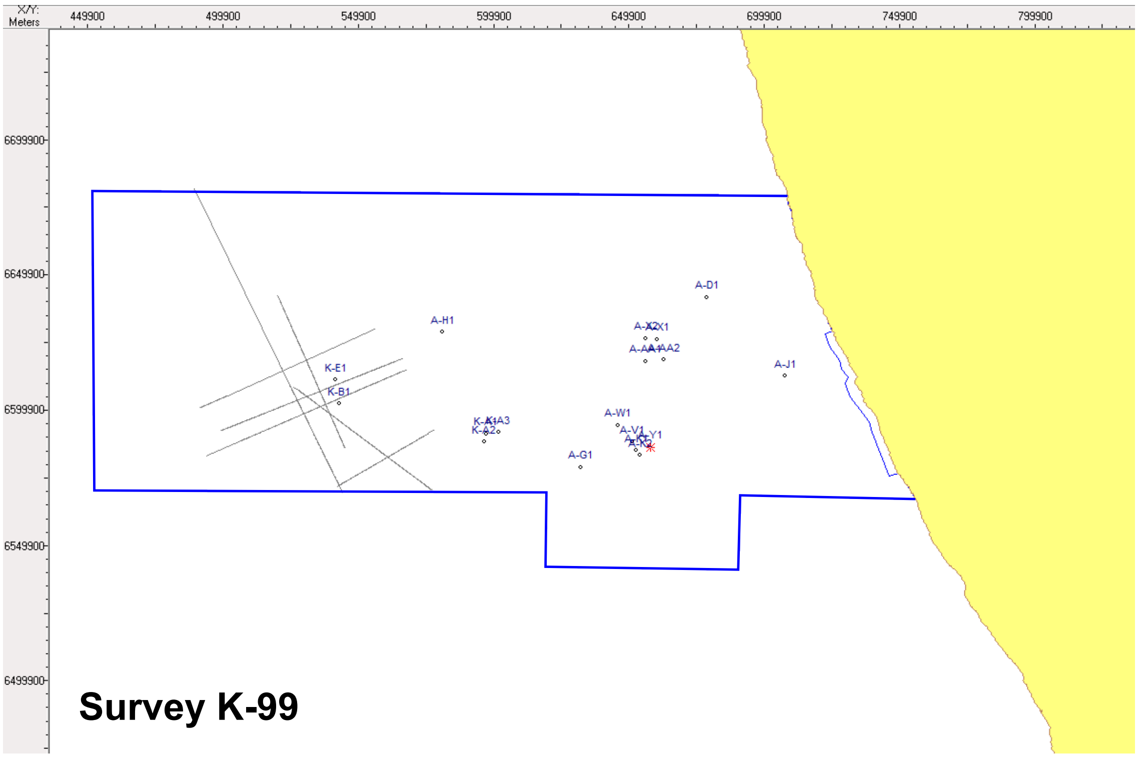

Figure 20: Location of lines provided for survey K-99 in Block 2

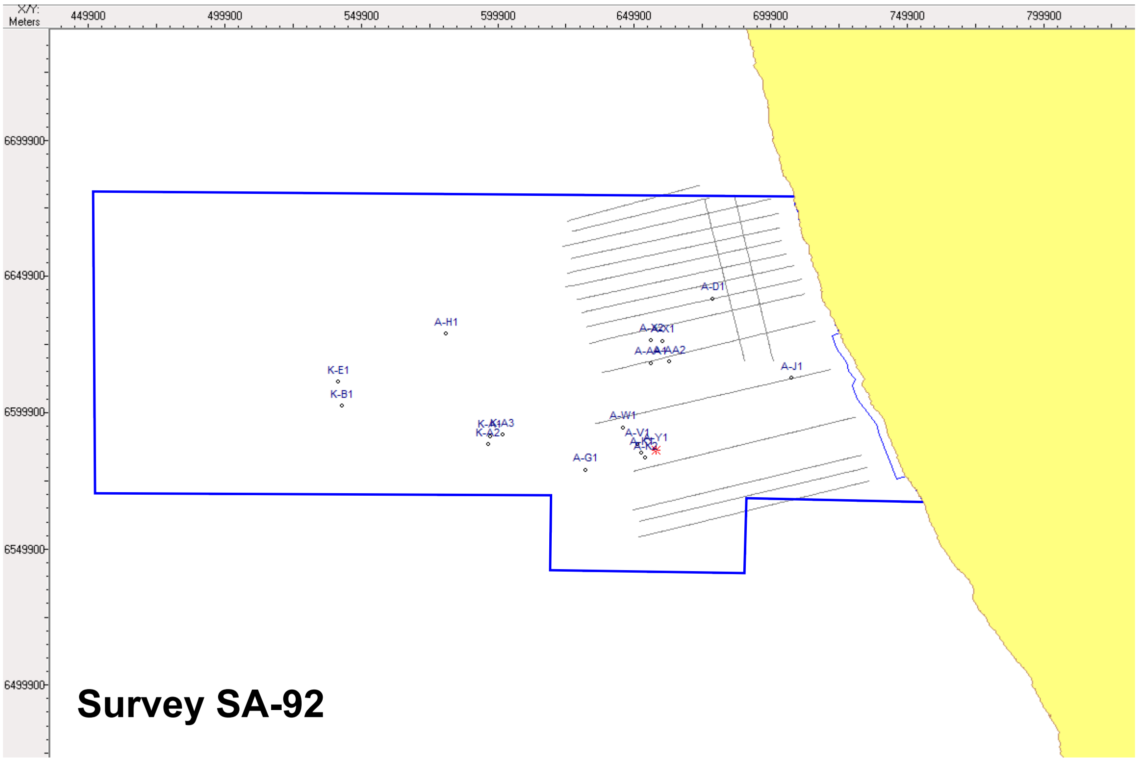

Figure 21: Location of lines provided for survey SA-92 in Block 2