Knowledge Transfer between Hydrate Energy International and the Department of Earth and Ocean Sciences, NUI, Galway

HEI

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Introduction

This report will document the topics covered during a transfer of knowledge which took place at the Department of Earth and Ocean Sciences (EOS), NUI, Galway, between the 10^{th} of January and the 4^{th} of February 2005. The principle participants were Arthur Johnson of Hydrate Energy International and Padraic Mac Aodha of EOS. The transfer took place at an early stage in hydrate exploration in Irish waters as part of a preliminary resource assessment by EOS and as such maximum benefit from Mr. Johnson's many years experience in the field was obtained.

The exploration for methane hydrates as a commercial resource is an emerging field. The existence of hydrates in the sediments of continental margins has been well documented. Until recently, however, study of hydrates has focused on the geohazards presented by the deposits. Increased world demand for natural gas, driven by economic growth and a desire to move to cleaner fuel sources, has lead to an increase in prices. This new economic reality, the movement of oil production into ever deeper water and the development of new technologies such as 'gas to liquids', combine to make hydrate extraction viable. With Ireland's large areas of deep water acreage in both the Porcupine and Rockall Basins it is important that we are aware and make full use of these opportunities.

This report will cover the current practices in commercial hydrate exploration, which will be applied to deep water basins of the Irish Designated Area.

An introduction to hydrates detailing how and why they form will be presented along with some points on what is necessary for an economic hydrate deposit. The hydrate stability zone, how it is calculated and the problems with the data involved are then discussed. The features and problems in seismic data which play a crucial role in identifying an economic resource are reviewed. Finally, ancillary pearls of wisdom which have a bearing on hydrate research are documented. Max (2003) covers many of the topics referred to here and is suggested as a good starting point.

What is Hydrate

Hydrates belong to a body of crystalline solids known as clatherates. The name clatherates comes from the Latin for cage, referring to crystalline solids in which a gas molecule is trapped inside a cage of different molecules. Where the cage is made up of water molecules the resulting crystal is known as a hydrate (Fig. 1). Many gases can be used in the formation of hydrates, a notable naturally occurring dangerous example is hydrogen sulphide H_2S. The focus of this study is, however, the assessment of hydrocarbon resource potential and as such it is the hydrocarbon gases of methane, ethane and propane which are of interest. Naturally occurring methane hydrate has been found in the pore spaces of sedimentary deposits on most of the worlds continental shelves and in Arctic regions. The formation of methane hydrate is governed by temperature, pressure, composition of the gas and composition of the water (i.e., salinity).

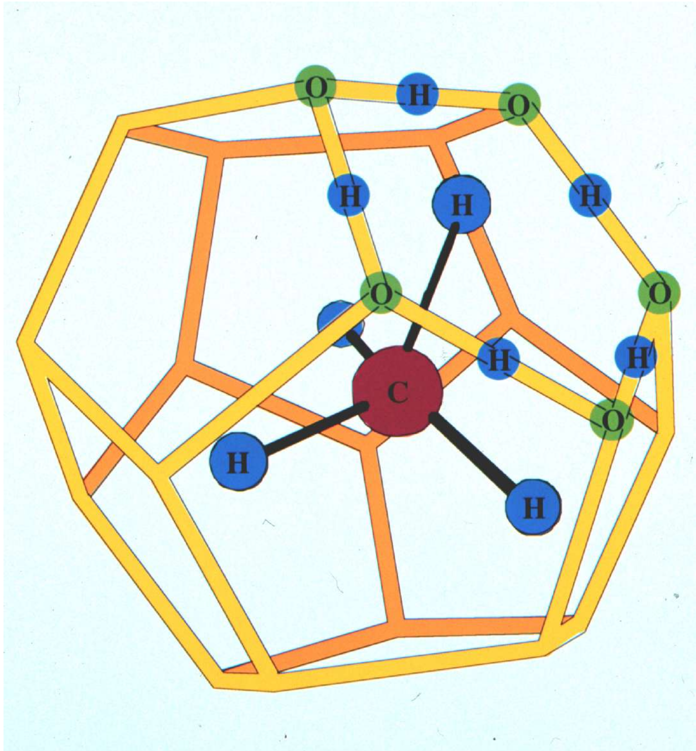

Figure 1: *Gas hydrate cage with methane as the trapped molecule.*

The formation of methane hydrate has the ability to concentrate gas. One litre of methane will contain between 160 and 170 litres of methane at standard temperature and pressure. When this is adjusted for the pressure of a conventional natural gas reservoir, the ratio drops to 2-3 times the volume of methane for the same volume but at much shallower depths.

There are two sources of methane hydrate; biogenic and thermogenic. Biogenic refers to methane which is created by microbial action on organic mater in the shallow sediment. Biogenic methane is purer in nature i.e., other hydrocarbon gasses are not produced. The production rate of biogenic methane is dependent on the influx of organic matter into the system. In order to produce an economically viable accumulation, a high influx is required. Thermogenic gasses are produced when geothermal heat 'cooks' organic matter which has been buried by overlying sediment. The gasses produced will depend on the thermal maturation process the sediments have been subjected to. Methane is the main gas produced but a percentage of ethane and propane is also common. Again, there must be a high flux of hydrocarbon gases in order to form a commercial resource, but here the crucial factor is the migration pathways available to the gas to take it from its buried source rock to the shallow hydrate stability zone.

Methane and sulphate will not coexist. Methane acts as an electron donor for sulphate reduction: $CH_4 + H_2SO_4 \text{-->} CO_2 + H_2S + 2H_2O$. As sulphate is present in sea water the methane must reduce all the sulphate present before it can form hydrate. This gives rise to what is known as the sulphate reduction zone in the upper part of the sedimentary section. The concentrations of sulphate will fall the further into the sediment you go (Fig. 2). Figure 2 is a schematic graph of the sulphate reduction zone. It does not have a scale as it is not constant, it will depend on the flux of methane through the system and flux of sea water (if any) through the sediment to replenish the sulphate levels. The black line marked SMI on the diagram is the sulphate methane interface. Below this depth methane will be stable and above it methane will be used up reducing sulphate.

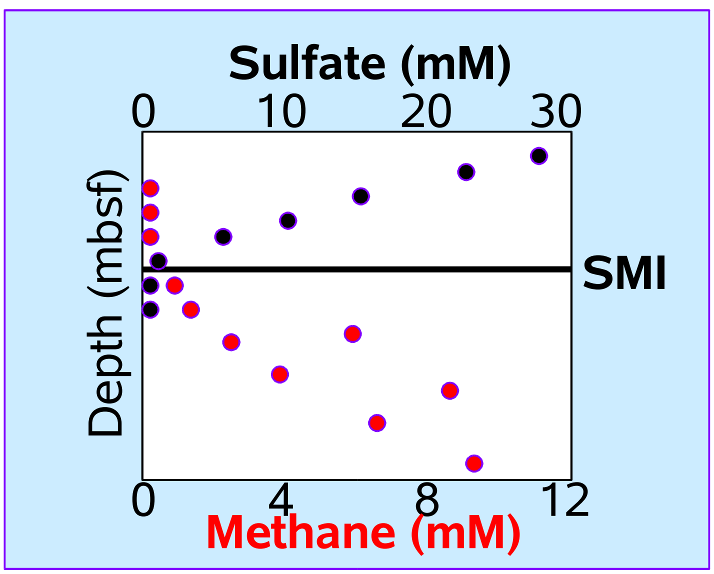

Figure 2: *Sulphate reduction zone, showing the levels of sulphate (black dots) and methane (red dots) in an arbitrary thickness of the sedimentary section starting from the sea floor at the top of the graph. The black line marked SMI is the sulphate methane interface. Below this depth, methane will be stable and above it methane will be used up reducing sulphate.*

Methane hydrate will occur in the pore spaces of sediments where the temperature and pressure conditions lie within the hydrate stability zone and the pore water is saturated with respect to methane (which implies no sulphate). The aim of this project is a resource assessment of gas hydrate deposits. In order for a hydrate deposit to be an economic resource it must occur in a sufficient concentration to enable extraction in a cost effective way. This requires that the hydrates form in a porous sediment/rock with a high degree of permeability. 1-2% hydrate formed in veins or unconnected pore space in a shale will simply not be economic to extract with current gas prices and proposed extraction methods.

The search for economic methane hydrate deposits is therefore very similar to a search for conventional oil and gas deposits. All the key components of a conventional oil/gas play must be present. Current understanding of hydrate systems suggest that biogenic generation alone will not provide a sufficient flux of methane to form an economic deposit. Thermogenic methane input is required. For this, a source rock, a suitable thermal maturation history and a migration pathway to take the methane up to the hydrate stability zone (HSZ) are required. A reservoir rock/sediment in the HSZ with a high volume of interconnected pore space (sand/gravel) is required for suitable concentrations to form. A seal or cap rock is not required as the hydrate will act as its own seal. However, a low permeability layer just above the reservoir rock will slow down the flux of methane through the system, increase the saturation of sea water with respect to methane and provide improved conditions as well as more time for hydrate to form.

Taking all of these factors into account, a resource assessment will concentrate on establishing the hydrate stability zone, and on assessing the quality of the hydrocarbon play in the area.

Hydrate Stability Zone

The hydrate stability zone is governed by a number of variables; temperature and pressure are the key controlling factors but, water and gas composition are also factors. Figure 3 shows how the boundaries of the stability zone will move as temperature and depth increase. The comparison between the dashed curves and the solid black curves show the effect the composition of the water has (difference between pure water and sea water). The successive curves show the effect of the composition of the gases involved.

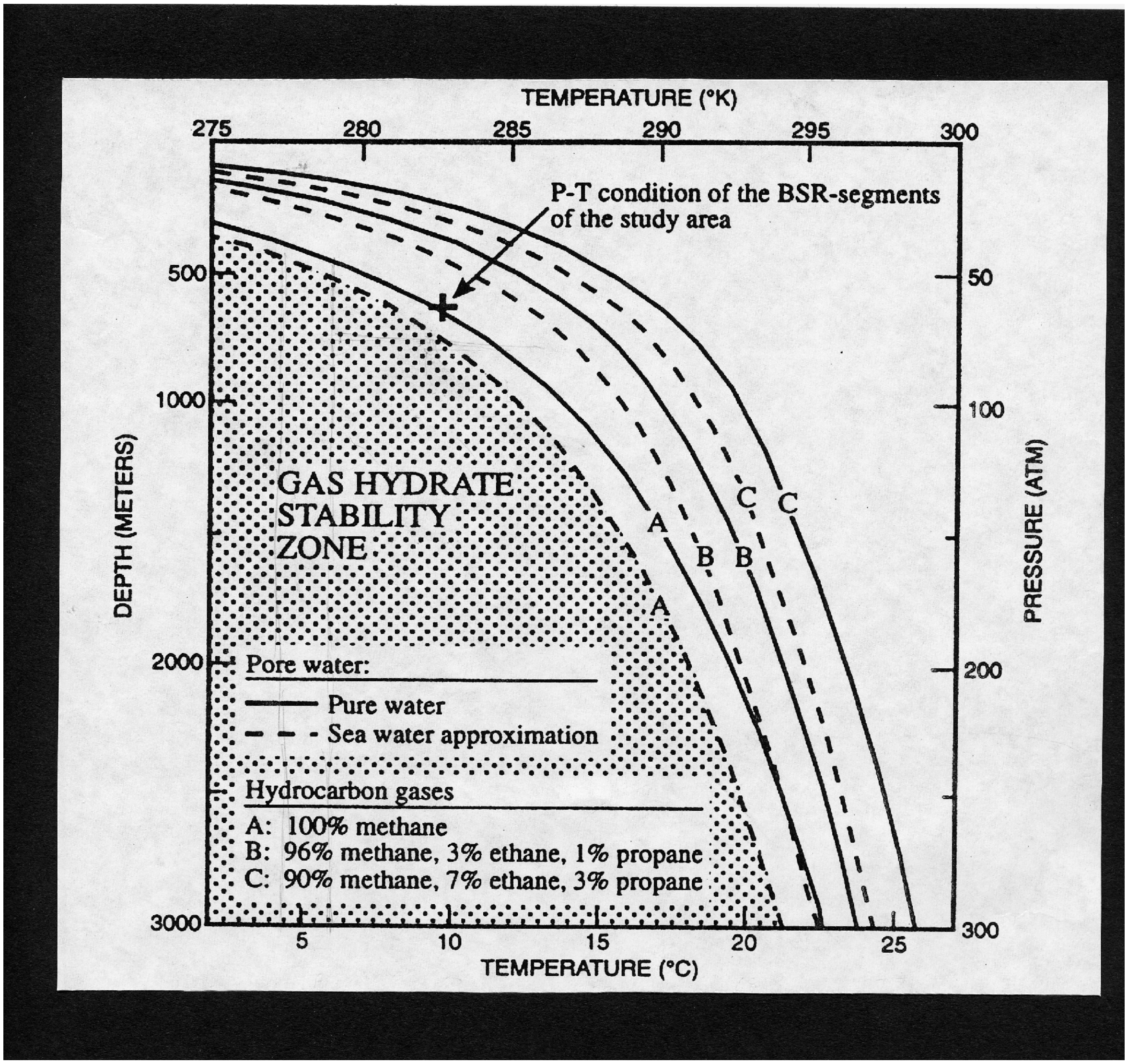

Figure 3: *Hydrate stability curves for a range of gas and water compositions.*

By plotting the phase boundary and the hydrothermal gradient on the same curve we can see the temperature/pressure range within which hydrates are stable (Fig. 4 left). However, as we are interested in hydrate within the sedimentary column, temperature will start to increase with depth due to the geothermal gradient. Figure 4 (right) shows the situation in the sedimentary section at a arbitrary water depth of 1220 metres. Hydrate is stable where the sediment water interface is below the intersection of the hydrothermal gradient and the phase boundary. However, once you go below the interface it is the geothermal gradient which will govern the temperature. Hydrate will cease to be stable once this crosses the phase boundary.

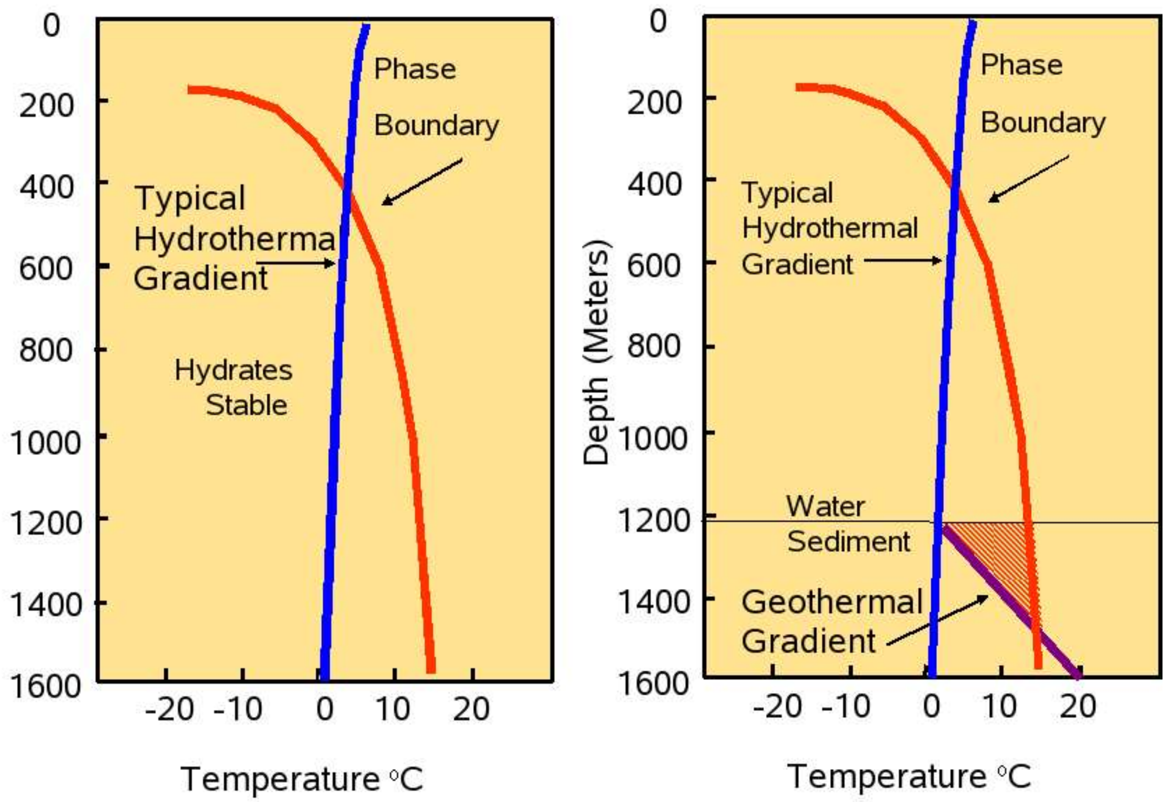

Figure 4: *Hydrate phase boundary curves showing the HSZ in the water column and in a sedimentary section. The area shaded with red lines is the HSZ in the sedimentary section.*

As depth is well defined and the variations in sea water salinity are not sufficient to affect the stability zone in the areas under investigation, it is the hydrothermal and geothermal gradients and the gas composition that are the key unknowns.

(Note: The term hydrothermal gradient is used generally and so is used here. This author does not believe it to be an accurate term as it refers to the change in temperature from the sea surface down to sea floor. However, what is usually measured is the change in temperature at the sea floor as the depth of the sea floor changes. The gradient suggests that it is only the depth which is changing where in fact the x and y co-ordinates also change with the data used. Hydrothermal profile would be a better term.)

Of the three unknowns, the seabed temperature is, at least in the context of the Irish offshore, the easiest to tie down. The INSS took sound velocity profiles at regular intervals during their survey of Zone 3 and as part of this, a seabed temperature is recorded. These readings provide a scatter of data points over the entire area, however, there are problems in deeper areas where the SVP was not lowered all the way to the sea floor. Ideally, temperatures need to be taken exactly at the sea floor. While temperatures may not vary greatly over a 50-100 m interval at other places in the water column it is very common to have fast flowing currents and rapid changes in temperature in the first 5-10 m above the seabed. A hydrothermal gradient is generated by plotting seabed temperatures verses depth. It is good practice to do this separately for separate bathymetric areas as different basins will have different circulation regimes and hence different gradients. Seasonal variations do affect the gradient especially at shallower depths. The variations may not be as simple as warmer in summer and colder in winter. Effects such as increased mixing due to winter storm activity can be more influential than sunlight influx and atmospheric temperature.

The geothermal gradient is much more difficult to establish, especially in a poorly explored area such as offshore Ireland. The only really accurate way to establish the geothermal gradient is to drill a hole in the ground and take measurements as regular intervals. This, however, requires that drilling stops for long enough for the temperature to reach equilibrium after the cooling effect of the drilling mud which gets circulated through the system. This takes a considerable period of time and full equilibrium status is not usually carried out in offshore wells. The bottom hole temperatures that are recorded need to be adjusted to take account of this, usually using Horner plots. Heat flow can vary rapidly over small distances. Faulting, igneous intrusions and salt domes can introduce warmer material from depth. It is very unlikely that sufficient data will be available to delineate the effect these features will have on the gradient and it will have to be estimated where they are identified. The generally adopted procedure is to try to establish a regional gradient for each geologic area and use that, except where distinct features are identified.

Gas composition is also difficult to put a figure on in poorly explored basins. Information can be gleamed from fluid inclusion work, commercial wells, and what is generally known about the nature of the hydrocarbons in the basin.

Considering the degree of unconstrained variability in the three parameters mentioned above, the HSZ calculated is more of a rough guide to the sections which are susceptible to hydrate formation rather than an exact zone.

There are two methods of calculating the HSZ once the data for the variables has been constrained; plot the data points on a phase boundary curve and read off the depths, or enter the values into a formula to calculate the HSZ. In this study, the stability zone was calculated using curves, but, algorithms to calculate the thickness of the zone are to be found in Miles (1995), Tao (1999) and Unnithan *et al.* (2004). Figure 5 taken from Englezos and Bishnoi (1988) shows the curve that was used to calculate the HSZ.

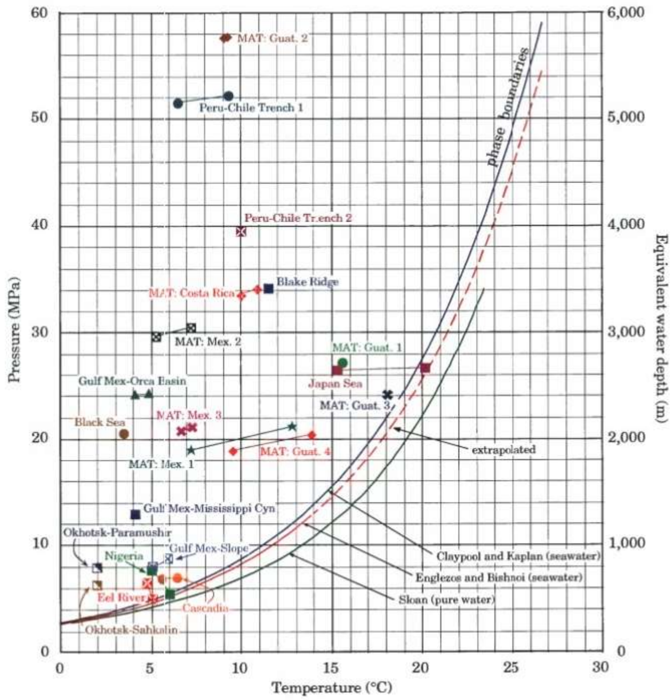

Figure 5: *Curves of the phase boundary for pure methane, pure water and sea water (Englezos and Bishnoi, 1988).*

The figure shows three different phase boundary curves for 100% methane hydrate. The curve that was used, is the centre curve which is for sea water. Two this graph the hydrothermal gradient for the Porcupine Basin (blue) and Zone 3A (red) were added as well as a 20° C geothermal gradient (bright green) to give the graph shown in Figure 6. If the depth/temperature combination plots above the phase boundary curve the location will be with in the hydrate stability zone at the sea floor. The base of the stability zone for the location can be calculated by finding the intersection between geothermal line running through that point and the phase boundary curve.

The brown line on Figure 6 represents the phase boundary when instead of pure methane there is a mix of 90% methane, 7% ethane and 3% propane. As can be seen from the figure this will considerably increase the thickness of the HSZ at this low geothermal gradient of 20° C. However, if the geothermal gradient was higher at say 30° C (probably a more realistic value for areas of the Porcupine Basin) the effect will not be as pronounced, as the slope of the green lines will not be as steep.

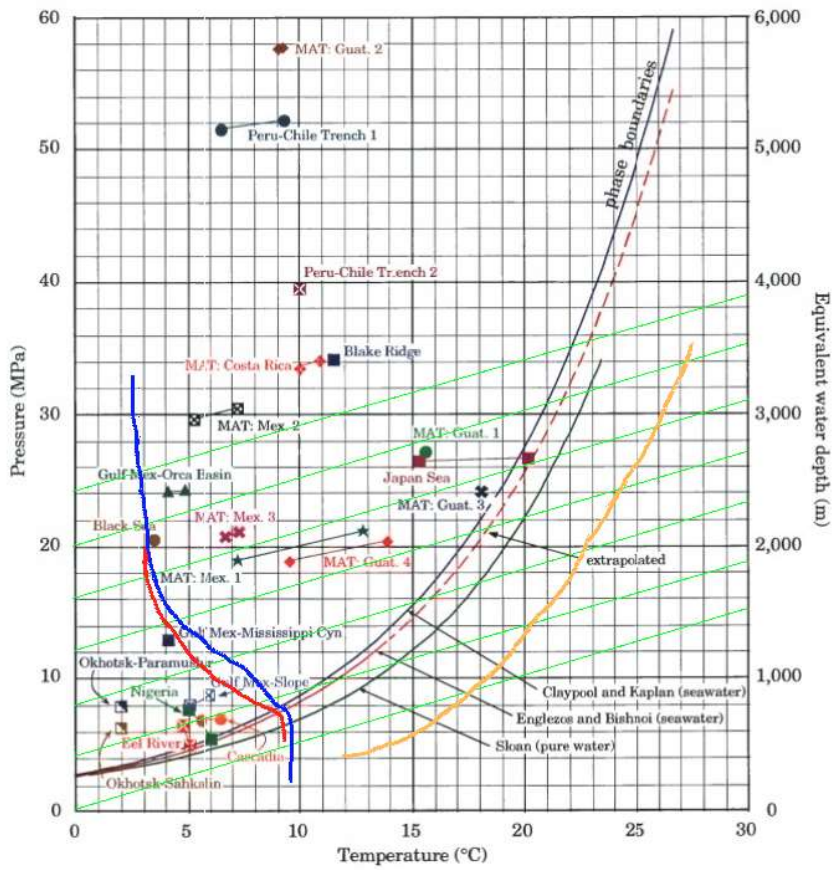

Figure 6: *The curves form Figure 5 with the hydrothermal curve for the Porcupine Basin (blue), Zone 3A (red) and the geothermal gradient (bright green) overlain. The brown curve is the phase boundary when dealing with a situation where there is 90% methane, 7% ethane and 3% propane.*

From the curve the thickness of the HSZ is read off at regular intervals at depths between 400 and 3000 m and the results are used to produce tables of the thickness at various depths. Once the HSZ has been defined, it can be converted from metres to seconds TWTT, using suitable velocities for the sediments in the region. What you get is a time range to use when examining seismic lines in which you can assess reservoir quality and check for possible bottom simulating reflectors (BSRs). Table 1 shows the table that was used during the initial review of the data.

BHSZ Tables

		Porcupine 30 Deg/Km 100% Methane	Porcupine 30 Deg/Km 90% Methane	3A 30 Deg/Km 100% Methane	3A 20 Deg/Km 100% Methane	3A 20 Deg/Km 90% Methane
WD (sec.)	WD (Meters)	Depth to BHSZ (sec.)	Depth to BHSZ (sec.)	Depth to BHSZ (sec.)	Depth to BHSZ (sec.)	Depth to BHSZ (sec.)
0.70	525		0.748			0.816
0.80	600		0.868			0.943
0.90	675		0.982			1.056
1.00	750		1.091		1.047	1.166
1.10	825		1.207	1.136	1.155	1.281
1.20	900	1.225	1.312	1.268	1.276	1.392
1.30	975	1.339	1.424	1.377	1.404	1.512
1.40	1050	1.491	1.539	1.491	1.526	1.627
1.50	1125	1.599	1.644	1.597	1.638	1.732
1.60	1200	1.706	1.751	1.706	1.754	1.837
1.70	1275	1.812	1.857	1.815	1.866	1.942
1.80	1350	1.918	1.963	1.924	1.981	2.050
1.90	1425	2.026	2.066	2.029	2.092	2.159
2.00	1500	2.135	2.172	2.135	2.199	2.268
2.10	1575	2.240	2.277	2.240	2.308	2.378
2.20	1650	2.342	2.381	2.342	2.416	2.487
2.30	1725	2.446	2.486	2.446	2.522	2.593
2.40	1800	2.549	2.592	2.549	2.626	2.700
2.50	1875	2.654	2.696	2.651	2.732	2.804
2.60	1950	2.760	2.797	2.754	2.836	2.908
2.70	2025	2.863	2.901	2.857	2.939	3.012
2.80	2100	2.966	3.005	2.960	3.045	3.116
2.90	2175	3.066	3.110	3.063	3.147	3.220
3.00	2250	3.169	3.214	3.166	3.250	3.324
3.50	2625	3.688	3.726	3.688	3.763	3.843
4.00	3000	4.189	4.234	4.192		

Table 1: *Depths to the base of the HSZ in sec TWTT for Porcupine Basin and Zone 3A with a variety of geothermal gradients and gas compositions (see headers for details).*

These data can be quality controlled using BSRs (see section an BSRs below) where found as they mark an exact position for the base of the HSZ at that location.

Seismic Data

To best describe what is required from seismic data, we must first go back to the key factors we are looking for in assessing hydrocarbon prospectivity. That is, an active hydrocarbon system with source, timing, and migration of the hydrocarbons right up through the system to a reservoir within the HSZ. Ideally seismic data would have good resolution in the upper 1-1.5 sec below the seabed to assess the reservoir quality and with sufficient penetration that migration pathways can be assessed. However, commercial seismic data is normally shot and processed with much deeper objectives. Therefore, migration pathways are often well imaged but reservoirs in the shallow section are much more difficult to identify. One of the problems is that the shallow section is best imaged by higher frequencies. During the late 80's and early 90's there was a large increase in shot fold and streamer length leading to an exponential increase in the data recorded. The increase was greater than the computing infrastructure could deal with at the time, and as there was little interest in the shallow section very often the higher frequencies were filtered out at source and never recorded.

BSRs

BSRs are the commonly accepted evidence for the presence of methane hydrates. The BSR is not caused by the hydrate itself but by the acoustic impedance between the hydrate bearing sediment and the free gas bearing sediment below the phase boundary at the base of the HSZ. Visually, there is a strong reflection parallel to the seabed with the opposite polarity to that of the seabed reflection. A BSR from the Blake Ridge off the east coast of the US shown in Figure 7 has been used so often it could be considered a type section. The problem with this image is that it is almost unique in terms of the quality and clarity of the BSR involved. The section shown in Figure 7 is only a small portion of a very long line over the area. The majority of the line looks like the extreme left hand side of the section where there is very little BSR evidence.

Generally, BSRs are much more subtle than the image shown in Figure 7. The most common type of BSR is the “String of pearls” type which occurs where sandstones are interbedded with a less porous material. Gas migration through the system will favour the more porous sandstones and so free gas will accumulate below the HSZ in the sandstone layers in higher concentrations than in the interbedded layers. What this gives rise to is a series of bright spots where the free gas gathers (Fig. 8).

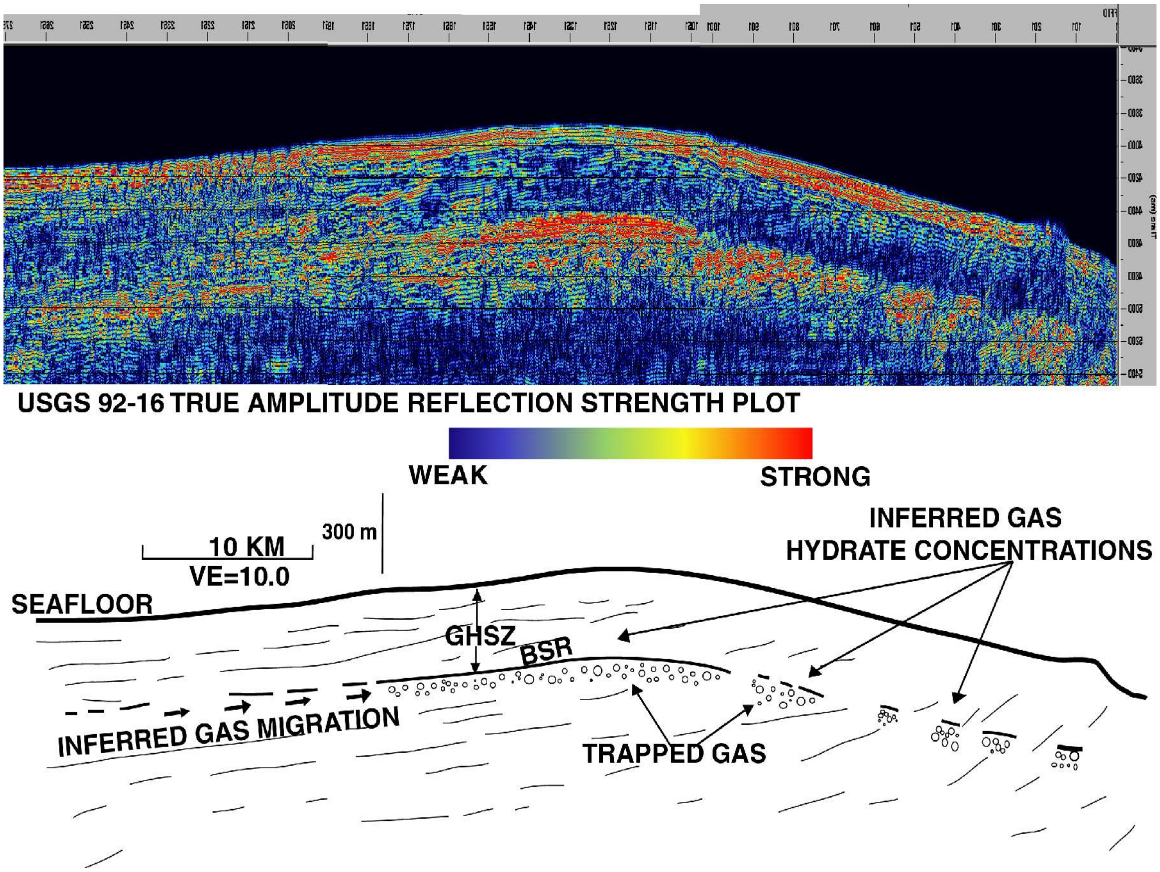

Figure 7: *Example of a BSR from the Blake Ridge, with a schematic interpretation below.*

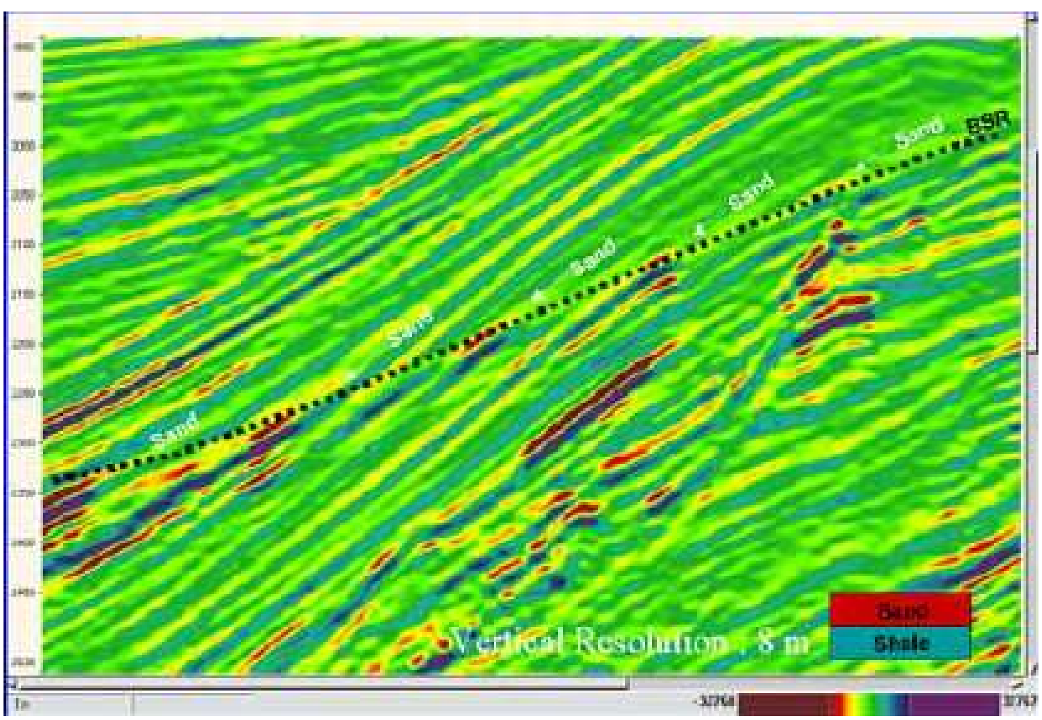

Figure 8: *A series of bright spots corresponding to the base of the HSZ in the sand layers, which line up to give a BSR that matches the topography of the seabed.*

At the upper limit of the HSZ a BSR will not actually be bottom simulating but will come right up to meet the sea bed (Fig. 9). In areas where stratigraphy closely matches the seabed this may be the only chance to see a BSR.

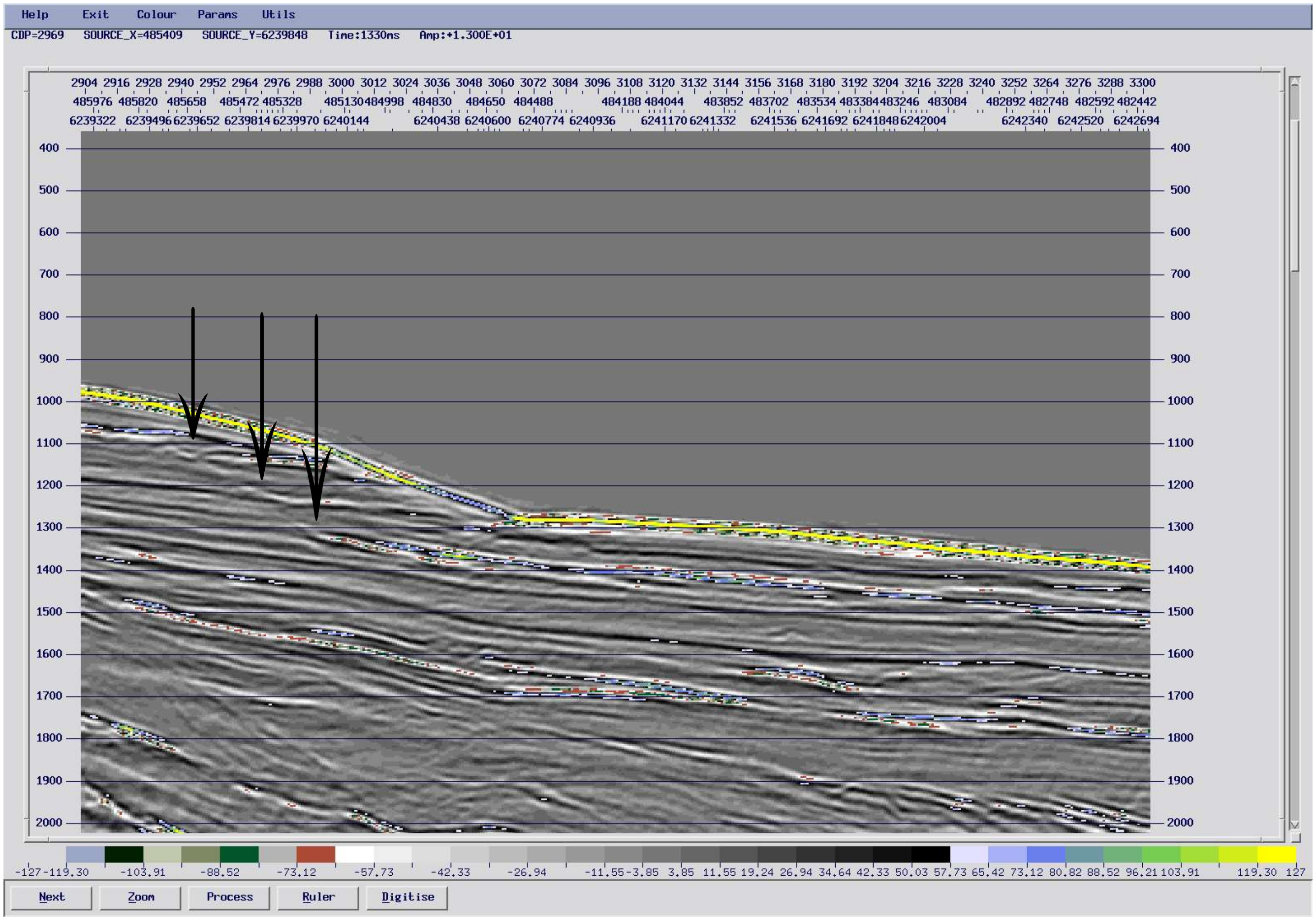

Figure 9: *In the left side of this variable density seismic image there is a feature crossing stratigraphy running right up to the surface. This is interpreted as a BSR at the upper limits of the HSZ.*

BSRs are not ideal tools for hydrate exploration. There are several reasons why a BSR may not be present. A BSR will be lost in shallow stratigraphy if the stratigraphy is parallel to the seabed (quite common in the Irish context). If high frequencies are filtered out during acquisition or processing, the resolution may not be present in the upper section to properly resolve the BSR. Recent deposition, structural changes or variations in the local heat sources will all lead to a changing HSZ with an uneven base, in which case, the BSR may be absent or may not match the seabed. Where salt domes or faults which bring warmer material up from depth are present, there will be large local variations in the geothermal gradient and an uneven base to the HSZ. As stated above the BSR is often not an even reflection but a string of pearls. On 3D seismic surveys, the BSR may only show up on inlines. Finally, probably the most common reason is that there is simply no free gas trapped under the hydrate deposit.

False BSRs are caused by a variety of reasons e.g., an unconformity or other stratigraphical features which trap free gas can mimic a BSR with out the need for hydrate. The BSR is after all due to the free gas and not the hydrate itself. Stratigraphic boundaries and seafloor multiples can be mistaken for BSRs if care is not taken. The processing and presentation parameters used to view the line can also play tricks; an automatic gain control of 500 ms for example creates a very good false BSR.

Where BSRs are genuinely present there are still problems in their over use in exploration for commercial methane hydrate deposits. A BSR will not give information on the concentration of hydrate within the HSZ. The Japanese exploration program recently spent $100 million drilling in offshore Japan targeting BSRs and repeatedly drilled uncommercial shales with only a few percent hydrate. It was not until they drilled in the same areas outside the BSRs that they found anything commercial. The reason for this is simple, the best BSRs are found in shales. In basins where shallow stratigraphy matches the bathymetry of the seabed, it will be impossible to distinguish a BSR from the stratigraphy. The absence of BSRs does not imply the absence of hydrates. BSRs are rare in many basins known to contain hydrates.

Having said that, BSRs do have a valid role to play. They do represent strong evidence that the area in question is within the HSZ and there is suitable gas in the system. It does not indicate whether the gas is boigenic or theremogenic in origin. Perhaps the most important clue offered by a BSR is that, assuming the area is reasonably stable in terms of heat flow and recent deposition, it gives a direct measurement of the base of the HSZ. This in turn can be fed back into the calculations carried out in calculating the thickness of the zone and can be used to adjust them as necessary.

Where high frequencies have been recorded in the data it is possible to apply certain filters to enhance the usefulness of the seismic data. Filtering out the low frequencies will result in a very nasty looking section but, will leave a distinctive combination of an opaque area corresponding to the HSZ above a fuzzy noisy area resulting from some free gas below. These are not BSRs senso stricto, they have clear reflections, but they can be considered tangible evidence for the presence of hydrates.

Review Parameters

There are three key elements to a methane hydrate resource that can be identified from seismic data; potential reservoirs, migration pathways and BSRs or other evidence of free gas. How useful the data is will be governed by the resolution and its depth of penetration, which are themselves inter-related. Each of these factors will be examined in turn with examples from data reviewed during the knowledge transfer.

Migration Pathways

Migration pathways are a key element in the formation of a economic methane hydrate deposit as the thermogenic methane gas involved must migrate from the deeper parts of the sedimentary section where it is cooked to the shallow section where the hydrate form. Faulting is by far the most efficient way to move hydrocarbons up through a system. This is particularly true when dealing with hydrate as it represents the last stage in the hydrocarbon migration before it escapes in to the ocean and atmosphere. Porous sediments also facilitate hydrocarbon migration but this is usually local and very often largely lateral and is unlikely to provide a pathway form source to a very shallow reservoir.

The ideal situation is one where a series of linked fault sets are found throughout the system perforating all the major boundaries which might act as a seal. Figure 10 shows a good example; the upper section (3900-3200 ms) is well faulted offering multiple migration pathways. The lower section (4200-3900) is also perforated by deeper extensions of some of the shallower faults which will allow hydrocarbons to cross the major reflector at 4100 ms.

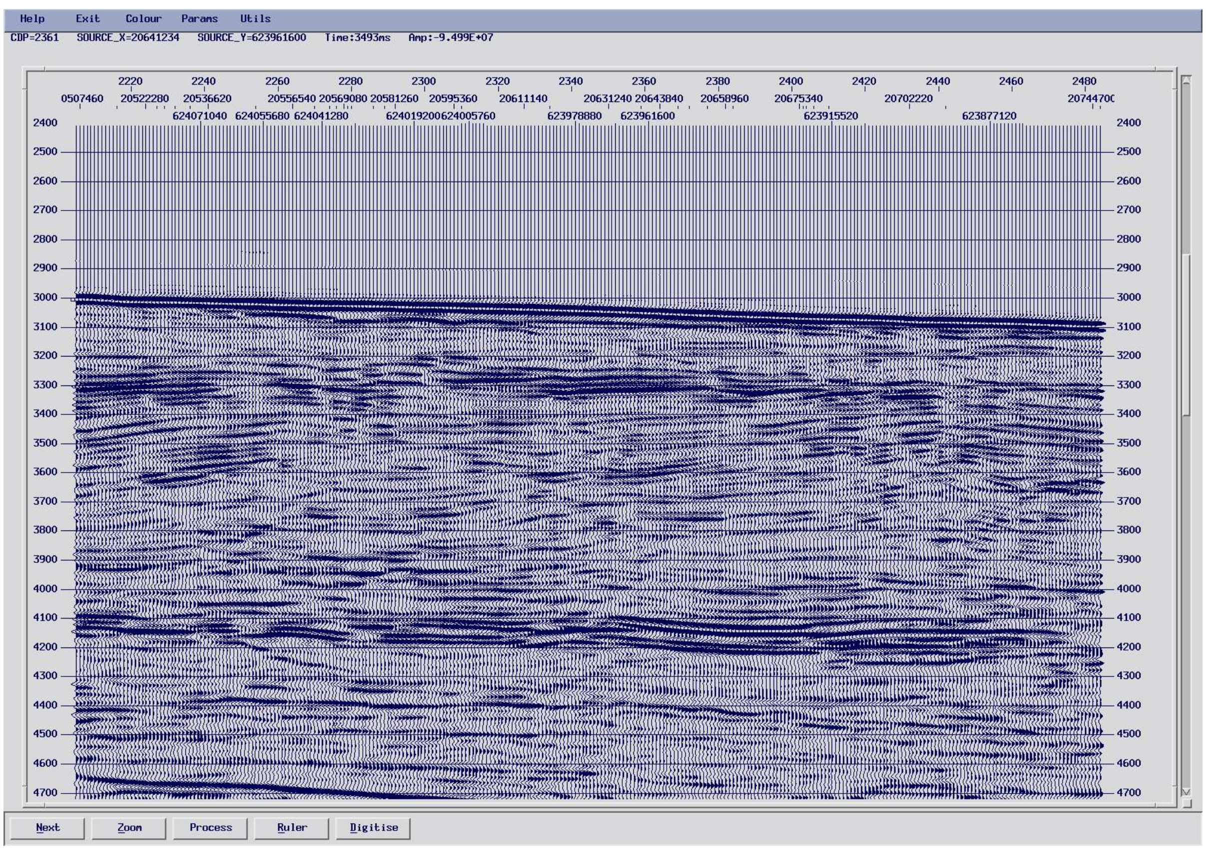

Figure 10: *Very well faulted seismic section, offering good migration pathways from source to shallow reservoirs.*

Figure 11 shows an example where faulting is well developed in the upper section down to 3400 ms but there is little evidence of it penetrating the reflector at 3600-3700 ms. It remains largely intact and a barrier to the migration into the upper section.

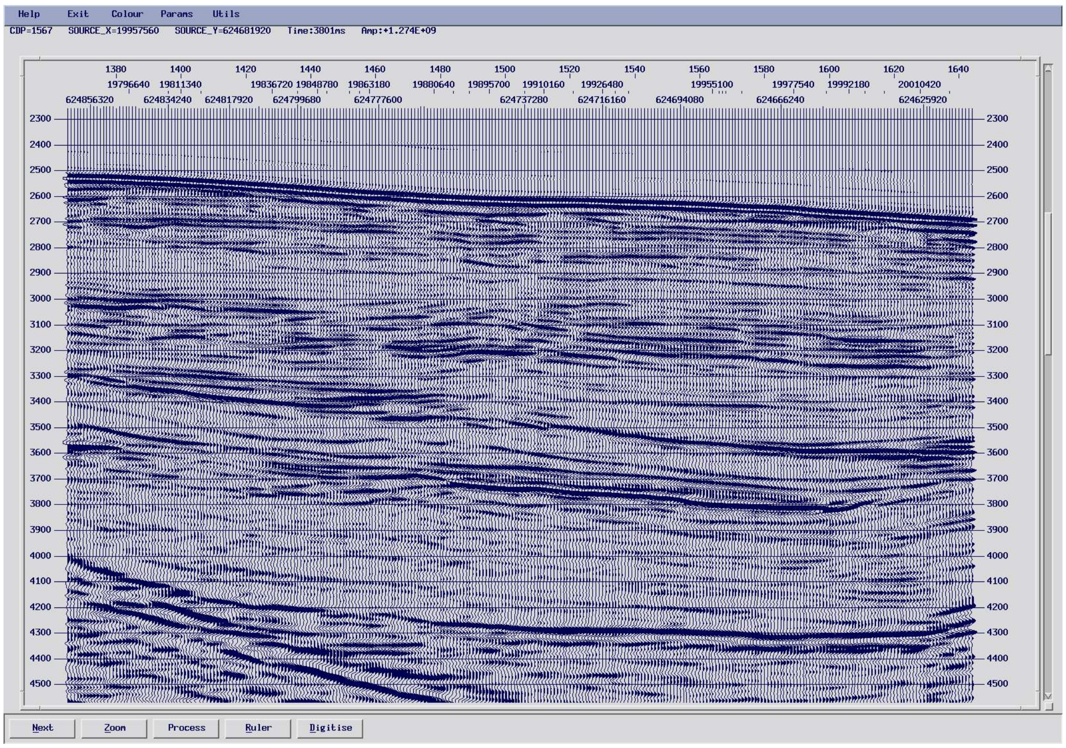

Figure 11: *The upper section is well faulted but the strong reflector at 3600-3700 ms remains largely unbroken and is therefore a barrier to hydrocarbon migration.*

Reservoirs

Suitable reservoirs require the presence of sands or gravel in the HSZ. In order to transport these grain sizes offshore to suitable depths, a higher energy depositional environment is required than for shales. This will show up on seismic sections as foreset beds or a generally complicated internal structure to the stratigraphic units. It is possible to get sandstones interbedded with shale in a flat lying sequence. Higher energies are required however, to bring in coarser material. If the beds are thick enough it is probable that this high energy will lead to the development of an internal structure which will be picked up on the seismic data.

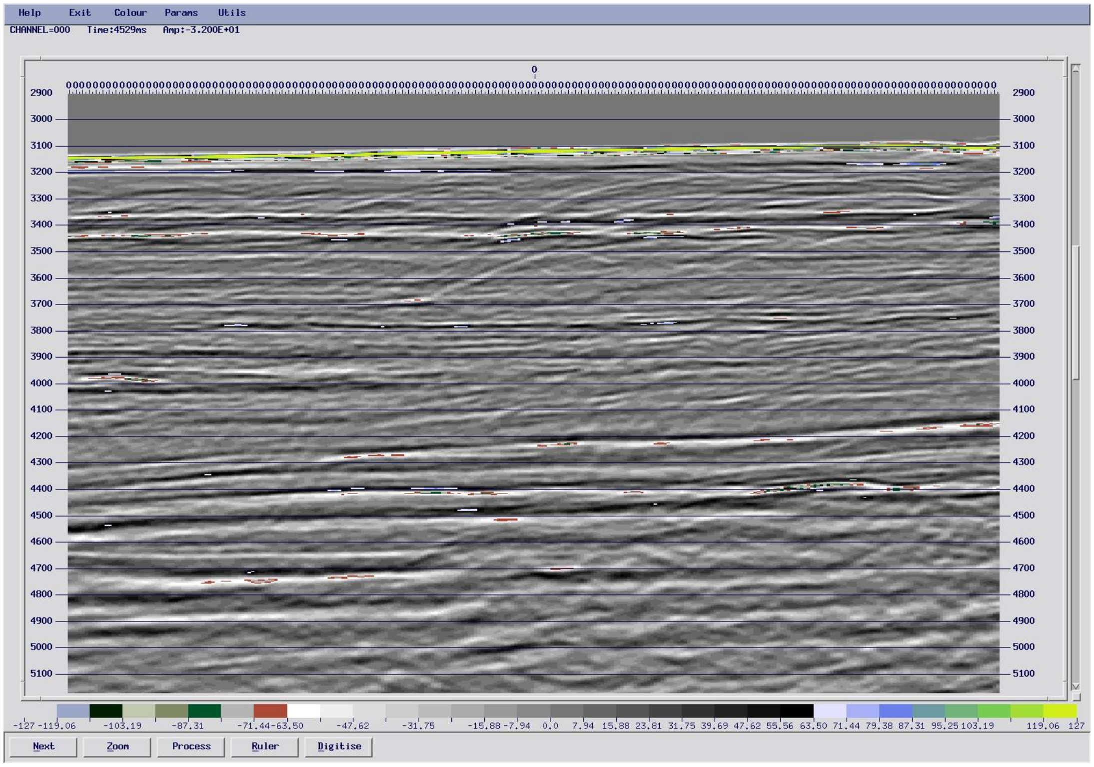

Figure 12: *Variable density plot showing foreset bedding in the upper section between 3400 ms and 3200 ms.*

Figure 12 shows a series of foreset beds in the HSZ, in a band between 3200 and 3400 ms. This internal structure in a thick sequence is indicative of reservoir quality sands and gravels. The section below this illustrates the difficulties involved in making this kind of interpretation on poorly migrated data. There are also dipping features in this section which are not real but the result of diffractions.

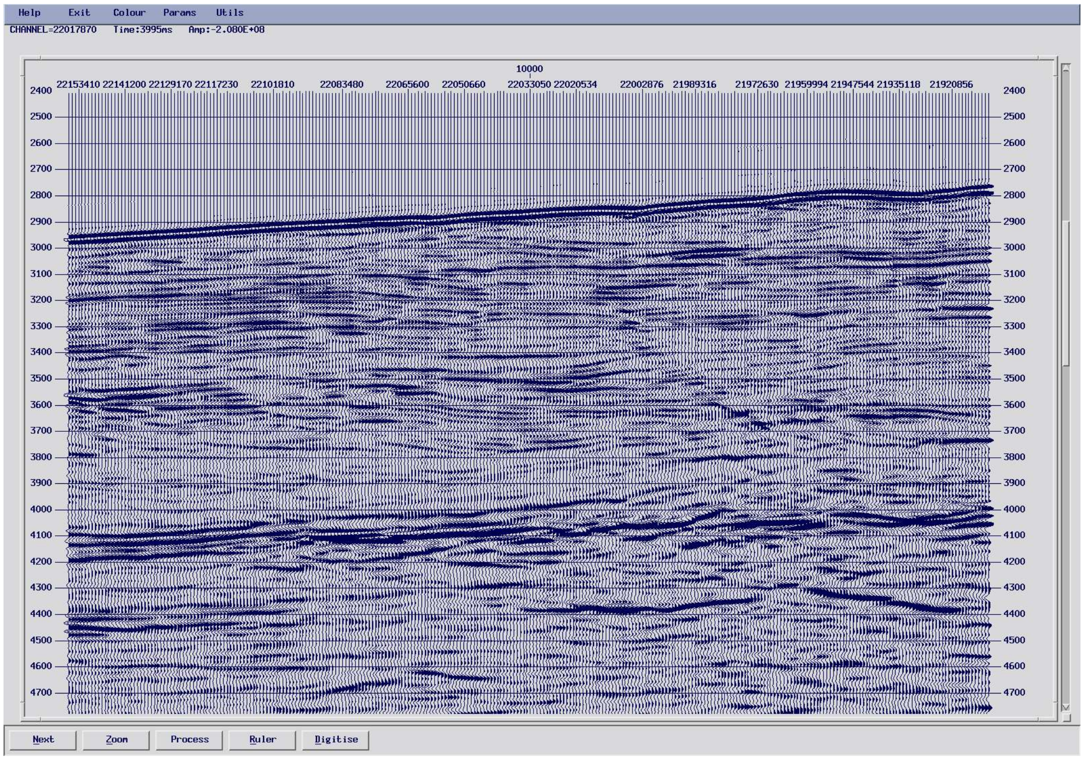

Figure 13: *Seismic section showing higher energy sediment in the top 200 ms below the seabed, particularly on the right hand side of the image.*

Figure 13 shows higher energy sediment in the shallow section up to 200 ms below the seabed, particularly in the right hand side of the image. While this does not have the clear internal structure of the foresets shown in Figure 12, it is distinctly different from the the parallel strong reflections seen in the shaley sections of Figure 14. The chaotic nature of this unit could alternatively have been produced by the slumping of shales and have no reservoir potential. Care must be taken particularly at the foot of slopes.

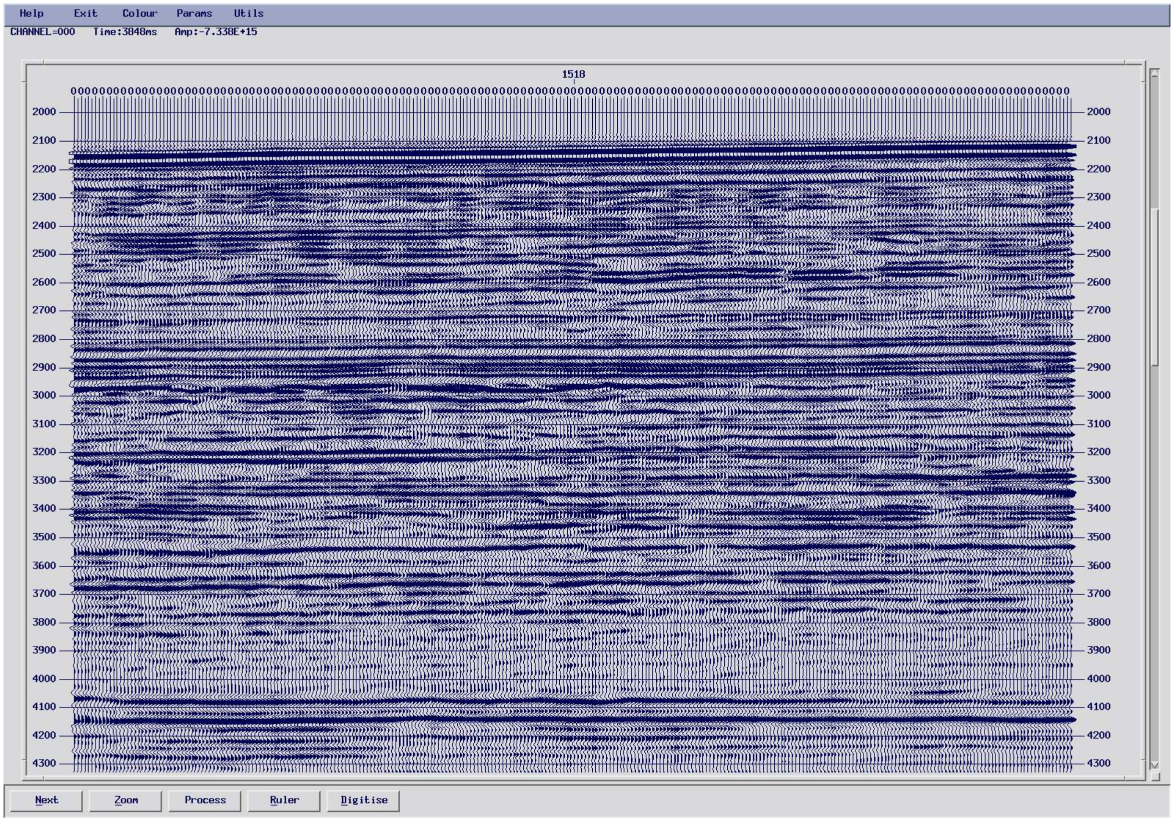

Figure 14: *Possible sandstone reservoir overlain by a thin veneer of shale.*

Figure 14 shows a mixture of sub-horizontal shales, which are clearly represented by the thick parallel reflections and higher energy sandstones. The sandstones are imaged as less coherent units between 2420 and 2280 (left side). There is some evidence of foreset beds in this unit but if present they are not fully resolved by the data. This is an interesting reservoir as the shale layers on top will act as a seal. Hydrate deposits do not strictly need a seal but where one is present, it slows the flux of gas through the system in the key stability zone. This will allow the pore water to become supersaturated with methane at lower flux rates and thus promote the formation of hydrate.

BSRs

The nature and importance of BSRs has already been discussed in this section so only a few examples from the Irish offshore will be shown here. Figure 15 shows a variable density plot with a unit of faulted dipping beds. Cutting across these beds is a high energy reflection of variable strength which is interpreted as a BSR.

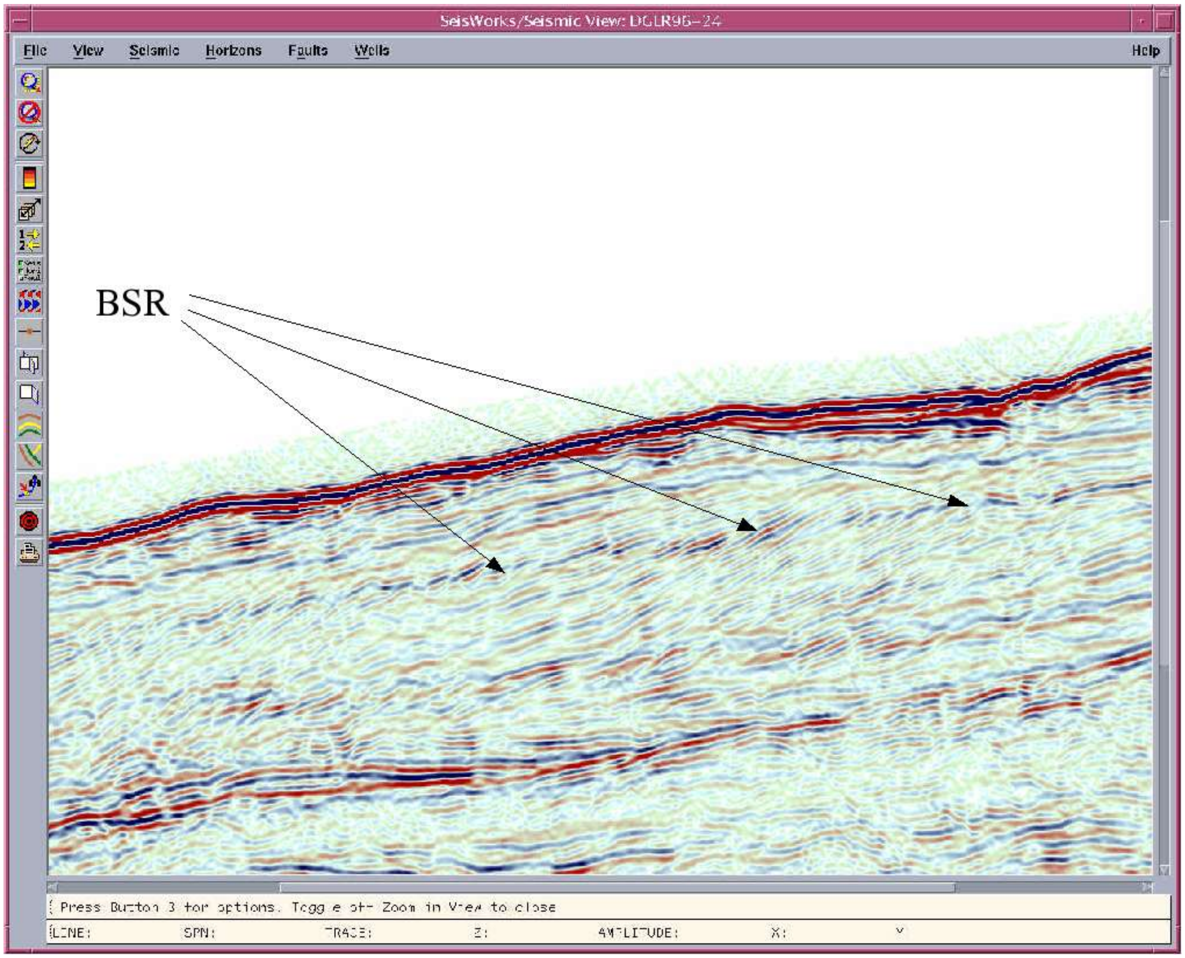

Figure 15: *Variable density plot showing a BSR.*

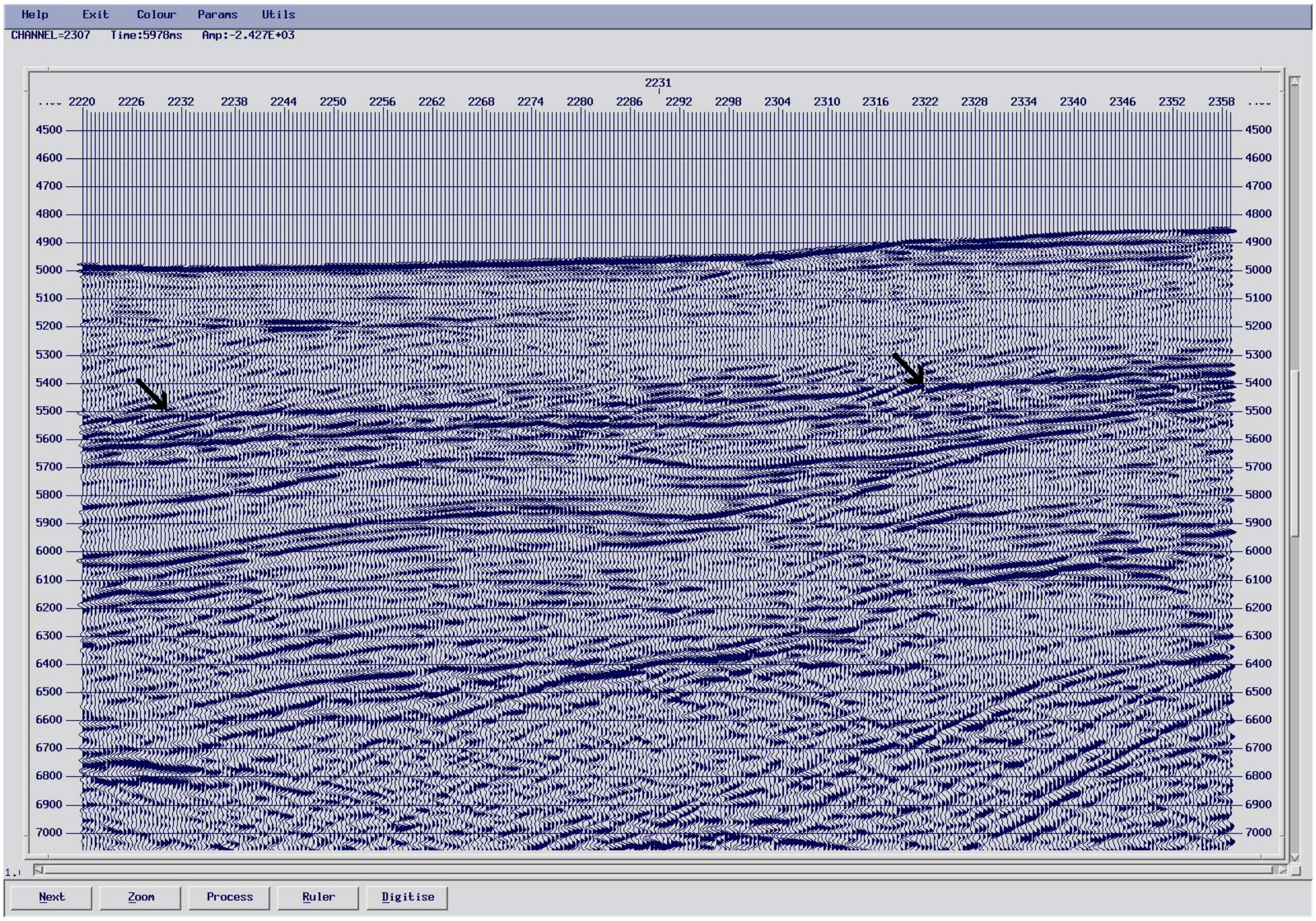

***Figure 16**: Deep water BSR at 5500 ms on the left side of the image.*

The BSR in Figure 16 is much more difficult to spot. It occurs in much deeper water and hence is deeper in the section as the HSZ is thicker there. It is best seen on the left side of the image at 5500 ms where the intensity of the dipping reflections dies out as you cross the phase boundary. This feature could easily be interpreted as an unconformity but careful examination shows the dipping beds continuing in the section above.

Ancillary topics

In this section other topics that were discussed during the transfer of knowledge will be documented. These include; the cementing effect of hydrate; risk assessment for hydrate prospects; and possible extraction methods.

Cementing

This section will look at how the hydrate forms in sediment pore space and the implications for the sediment in terms of seismic velocity, cementation and permeability. The first model for the formation of hydrate in pore space is shown in Figure 17. It shows a situation where the hydrate forms at the boundary between the particles of sediment. In this case the hydrate will have a strong cementing effect. This means that removal of the hydrate will be very destabilising on the sediment. The effect of hydrate on permeability with this model will depend on the percentage hydrate present. This model was found to provide a poor representation of the situation where sandstone is involved. It is considered to be accurate only for shales.

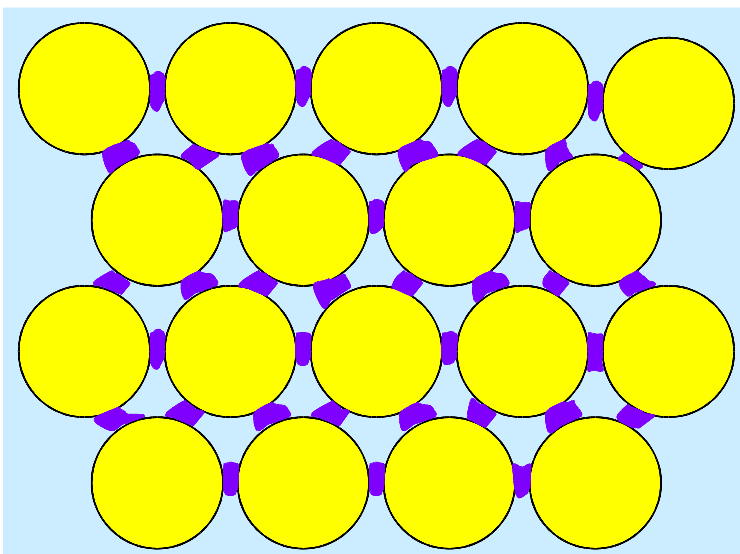

Figure 17: *Model for hydrate formation where the hydrate (purple) forms at the contacts between the particles cementing them together.*

The quartz grains in sandstone are hydrophilic and so the water next to the grains will not be available for hydrate formation. This prevents hydrate from forming between the grains, cementing them together, until very high concentrations of hydrate are reached. Therefore, the model for the formation of hydrate in sandstones is like that depicted in Figure 18, with hydrate forming in pore space. As the sediment remains supported directly by the grains it does not rely on cementation by hydrate for its coherency. The removal of the hydrate will be much less destabilising on the sediment than in the first model. While the hydrate does not cement the grains together, the infilling of the pore space with a solid will stiffen the sediment. The effect hydrate will have on permeability will again depend on the percentage hydrate present.

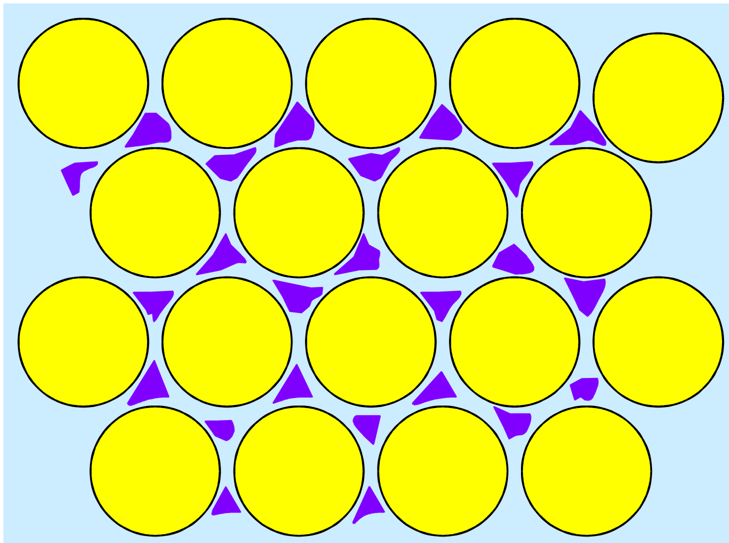

Figure 18: *Model for the formation of hydrate (purple). Hydrate forms in the pore space with very little cementation effect until very high percentages of hydrate are reached.*

The final model of formation is one where the hydrate is formed during deposition and hence makes up part of the support matrix of the sediment (Fig. 19). In this case the hydrate will play a cementing role. As the hydrate is actively supporting the sediment; removing the hydrate will completely destabilise it. This is considered most likely to occur in Arctic deposits where hydrate is stable at surface pressures due to the low temperature.

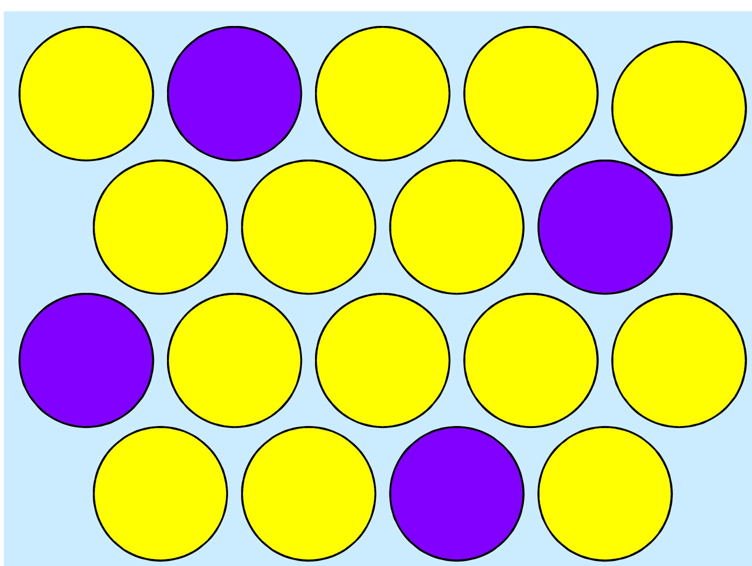

Figure 19: *Model of hydrate formation where the hydrate (purple) is part of the supporting structure of the sediment.*

Risk Assessment

There are two common methods of risk assessment which can be used for aerial delineation of the resource potential in the region of interest. The first method is graphical; three or more colours are used to attribute value to the factors required for an economic deposit (Fig. 20). The resource potential of any area then becomes clear from the graph.

Figure 20: *Graphical method of representing the resource potential of a region. The risk associated with each of the factors involved is roughly quantified and represented graphically. In this image red represents high risk (poor prospect) and green low risk, yellow is intermediate risk.*

The second method is one where each of the parameters involved is given a numerical value. Any range can be used but a value between 0 and 1 is common. The higher the value the more suitable the location is for the objective been assessed. Each of the values obtained are then multiplied together to give an overall single value on the potential of the area. There are several benefits to this over the graphical method, the main one being that as a single value is obtained the region can be contoured based on the potential of each location assessed. A second advantage is that the weightings can be given to each of the parameters measured depending on their importance to the overall objective. If the same values were measured as in the example in Figure 20, area 5 would score a 0.2 on HSZ, 0.7 on stratigraphy and 0.8 on migration giving an overall value of 0.112.

Extraction Methods

In order for methane hydrate to be an economic resource there must be a method of extracting either the hydrate itself or more probably the methane from dissociated hydrate in an efficient manor. As there has yet to be any commercial extraction of methane from gas hydrate, with the exception of the Messoyakha field (north west Siberia), there is as of yet no proven technology or methodology.

Figure 21 shows three possible extraction methods suggested by the USGS. The first method is the most efficient where a well is drilled through the hydrate bearing section to the free gas zone below. The free gas is then pumped out. The pumping causes a reduction in pressure below the HSZ causing gas to dissociate off the base to the hydrate deposit, thus freeing it for extraction. This is the method involved in the Messayakha field.

It should be noted that while there is some debate about the Messoyakha field, it is calculated that 230 bcf of gas dissociated from hydrate was extracted. The field however has not been continually exploited and there are periods of up to 5 years without extraction during which dissociation could have occurred. Questions still remain about whether the rate of dissociation will be sufficient to produce a sustainable flow rate. As the dissociation of hydrate is an endothermic reaction, the system has in effect a natural buffer which acts to keep the hydrate stable. The dissociation of any hydrate from the base of the HSZ reduces the temperature, thus even greater drops in pressure are required before further dissociation can occur.

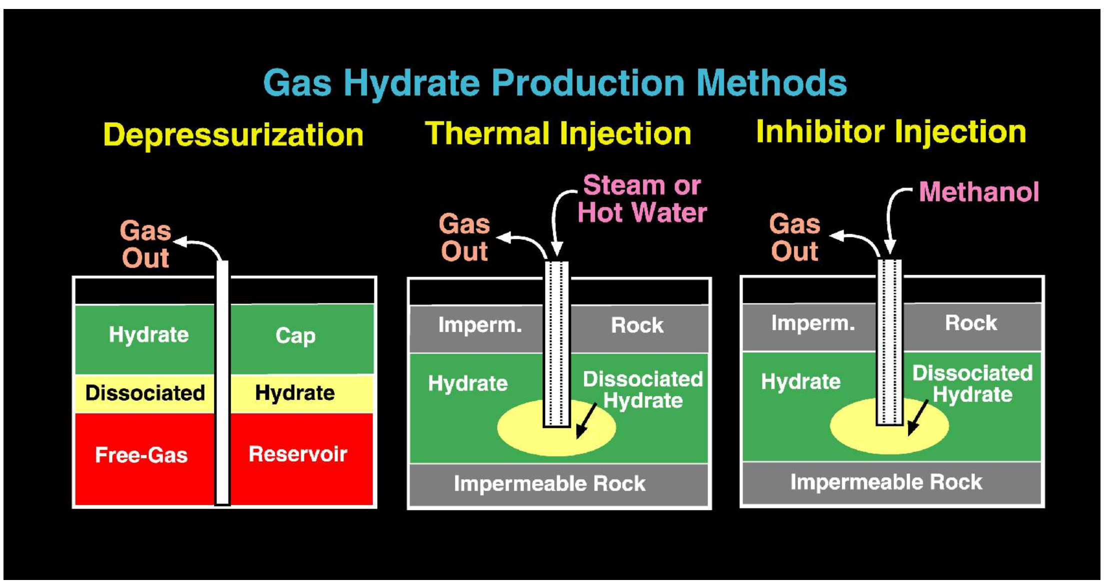

Figure 21: *Possible methods of hydrate extraction put forward by the USGS.*

The second and third methods are similar in ethos. A well is drilled in to the hydrate bearing section and either steam or a chemical is pumped in. This causes the hydrate to dissociate and the gas is extracted. These methods are less efficient as both use energy to heat the water or create the chemical. The chemicals involved are also quite toxic. Two variations on the second method have recently been developed. The first involves the use of a catalytic burner which is lowered in to the well and works by burning a percentage of the free gas as it dissociates. The rate of burn can be controlled by controlling the rate at which oxygen is fed to the system. This has advantages over the pumping of steam or hot water in to the well as there is no loss of heat to the surrounding rock on the way down. The second variation uses of a specific frequency microwave which can again be lowered down the well. While it is still in development it is suggested that the system can target and specifically heat the hydrate without heating the country rock. This would be very efficient in terms of the energy balance of the extraction method.

Summary

The key points learned from the knowledge transfer were.

The search for commercial methane hydrate is very similar to the search for any other hydrocarbon accumulation. The key factors of source, migration pathway and reservoir must be present. A seal is not necessary.

The HSZ is the additional factor in the equation and its definition is the starting point for any exploration. It is governed by the seabed temperature and pressure, geothermal gradient, the salinity of the water and the composition of the gas involved. As most of these key factors will not be well constrained during an initial evaluation. Therefore, the result is a guideline rather than an exact zone.

The evaluation of a region is best done with commercial seismic data. The penetration of sub-bottom profile is not sufficient to cover the entire stability zone. It will not image the migration pathways. Sub-bottom data does have a part to play in reservoir mapping.

The high frequency part of the seismic data is important in resolving the upper section but is often suppressed during standard processing of commercial data, or worse, filtered out at source due to lack of recording capacity.

BSRs are not a good indicator of a commercial hydrate deposit. BSRs are not always present or can be obscured by stratigraphy or other features. Where they are present, they are much stronger in shales which are not viable reservoirs. Where present they do indicate the presence of free gas and thus an active hydrocarbon system. They can be effectively used to verify the HSZ calculated as they will mark the base of the zone.

The method by which hydrate fills the pore space of a sediment depends on the sediment type. In shale it will form at the particle boundaries and act as a cementing agent. In sands it will form in the pore space with no cementing ability until very high volumes of hydrate are present.

There are several suggested methods for exploiting hydrate mainly involving dissociating the hydrate in situ and extracting the resulting gas. These have yet to be fully proven in commercial terms.

Selected Reading

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