Methane Hydrate Resource Assessment Offshore Western Ireland

Padraic Mac Aodha[1*]

Colin Brown[1]

Art Johnson[2]

[1]Department of Earth and Ocean Sciences, NUI, Galway, Eire.

[2]Hydrate Energy International, 612 Petit Berdot Dr. Kenner, LA, USA.

**pmacaodha@nuigalway.ie*

Table of Contents

Executive Summary

Methane hydrate is a naturally occurring crystalline substance formed from a mixture of water and methane under the correct pressure and temperature conditions. It has a high energy density with approximately 170 litres of methane trapped in every litre of hydrate. The Irish designated area contains two large deep water basins, Rockall and Porcupine, which have suitable conditions for the formation of methane hydrate. This study assesses the potential for the formation of commercially extractable deposits of methane hydrate in these basins.

The hydrate stability zone (HSZ) is that portion of the sedimentary accumulation in the basins, in which the temperature and pressure conditions are suitable for hydrate formation. The two main factors governing thickness of the HSZ are the seabed temperature and the geothermal gradient. Using the data available for these factors, the variation of the HSZ with depth was calculated for the Porcupine and Rockall Basins. The calculated HSZ increases in thickness from 0 m at about 700 m water depth, to 650 m in the Rockall Basin and to 720 m in the Porcupine Basin. These figures are based on poorly constrained hydrothermal and geothermal data and local variations can be expected.

A geological model for the formation of commercial deposits of hydrate was created. This model necessitates the presence of a thermogenic source of methane, a migration pathway to the HSZ and reservoir quality sands and gravels in the HSZ, with sufficient pore space to allow high concentrations of hydrate to form. Both basins have evidence of active hydrocarbon systems capable of providing a thermogenic source of methane so this study focused on assessing the presence and quality of migration pathways and reservoirs.

The assessment was carried out using commercial seismic data, divided into short sections for review. Each section was rated based on the thickness of its HSZ, migration pathways available and the reservoir quality in the HSZ. The three parameters were scored on a scale of 0-1 and the results multiplied by each other to give an overall risk assessment, or prospectivity value for that location. The overall prospectivity values were gridded to provide maps of prospective areas in the study region.

Several areas score sufficiently well in the risk assessment to be considered prospective for commercial accumulations of methane hydrate. Five areas of particular, two on the northeast, one on the northwest, one in the southeast and one in the centre of the Rockall Basin were selected as showing the most potential. The areas in the northeast are the most prospective. Further work including detailed analysis of existing data and acquisition of new data specifically designed to evaluate hydrate concentrations is recommended.

1 Introduction

This report will document the desk study of methane hydrate resource potential undertaken at the Department of Earth and Ocean Sciences (EOS), NUI, Galway between January and July 2005. The aim of the project is to review the possibility of gas hydrates existing in commercially exploitable concentrations offshore Ireland. The assigned study area was Zone 3 of the Irish Designated Area, defined by the Irish National Seabed Survey (INSS) as water depths of greater than 200 m. In practice only the subset of this area which was considered to be within the hydrate stability zone (HSZ) was assessed.

This study comes at an important time in methane hydrate research. 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 by the petroleum industry has mainly 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.

The project benefited greatly from a knowledge exchange with Art Johnson from Hydrate Energy International. This exchange was documented in a separate report and will not be dealt with here (Mac Aodha *et al.*, 2005).

There is a wealth of geophysical data available from the area of interest; commercial seismic, bathymetry, backscatter, sub-bottom profile, gravity and magnetic. However, none of these data were acquired with the aim of establishing either the presence or concentrations of methane hydrate deposits. Therefore a direct assessment of the presence and concentration of methane hydrate is not possible. This is not unusual in hydrocarbon exploration. In light of this the approach taken is to establish a geological model of the conditions under which commercially viable concentrations of methane hydrate are likely to form. The study area was then assessed based on the presence or absence of these conditions.

A brief introduction to the study area its geographical and geological history and relevant previous research in the area will be presented here. The HSZ will then be discussed with reference to the data and model assumptions made. The geological model for the formation of commercial concentrations of hydrate, and the derived parameters for the risk assessment will be reviewed. The results from the risk analysis will be detailed and discussed. This will be followed by a general discussion reviewing the implications including suggestions for future work.

1.1 Location

The area encompassed by Zone 3 of the INSS, shown in Figure 1.1, contains two major deep water basins; Rockall and Porcupine. Large areas of these basin lie within the HSZ and they have been the main focus of this work. Their location and geological history will now be described with emphases on factors which impact on their methane hydrate prospectivity. Large areas of the Rockall Bank and Hatton Basin also lie within the HSZ. However, an early review of the available data for these areas showed they lacked favourable geological conditions for commercial accumulations of methane hydrate and so this study focused on the Rockall and Porcupine Basins.

The Rockall Basin is a large sedimentary basin lying off the west coast of Ireland and Scotland. It is delineated by the bathymetric expression of the Rockall Trough, which it was called in the literature before the official PAP Nomenclature (Naylor *et al*., 1999). It is 1200 km along its axis and up to 300 km wide. Water depths increase rapidly from 200-300 m on surrounding highs to over 2000 m on the basin floor and approach 4000 m in the south west of the basin. The steep nature of the margins of the basin (especially on the eastern margin) means the majority of the area of the basin lies within the HSZ

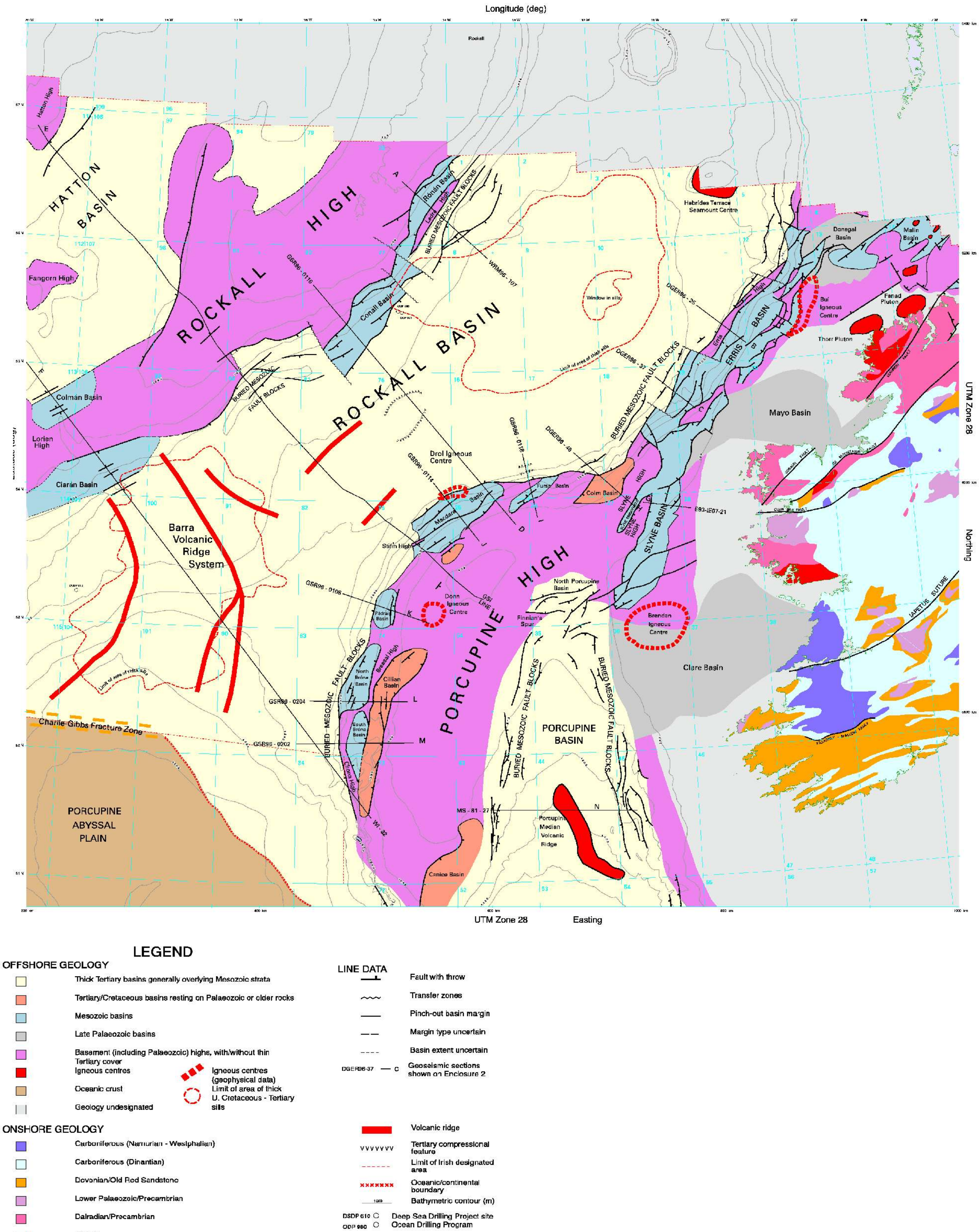


Figure 1.1: *Location map reproduced from Naylor et al., (1999). The study focused on the areas of the Rockall and Porcupine Basins coloured in light yellow (thick Tertiary basins).*

It is bounded by a series of basement highs and Tertiary compression features. To the north east it is separated from the Faeroe Shetland Basin by the Wyville Thompson Ridge. Its eastern margin is made up of the Erris High, Slyne High and Porcupine High which separate it from landward basins of the same names. To the south and south west the boundary between the basin and the Porcupine Abyssal Plain is marked by the Charlie Gibbs Fracture Zone, a large scale transfer zone. To the west the basin is bounded by the Rockall High, which separates the basin from the shallower Hatton Basin on the Rockall Plateau.

The Porcupine Basin lies to the east of the Southern Rockall Basin separated from it by the Porcupine High. It is shallower with water depths increasing from 200 m in the north to 3000 m in the south west. To the east is bounded by the Irish margin and to the south it is bounded by the Goban Spur. The basin opens to the Porcupine Abyssal Plain to the south west.

The basins are part of chain formed along the Atlantic Margin during the early stages of Atlantic rifting. The Atlantic Margin formed as Pangaea split apart in a series of discrete rifting phases starting in the Early Permian. Continental rifting began in the Central Atlantic in the Late Triassic (225-230 Ma; Wilson, 1997) with sea floor spreading taking place by the early Mid-Jurassic (170-175 Ma; Vogt and Tucholke, 1989). It spread northwards with oceanic crust present between Newfoundland and Iberia by 110 Ma (Fig. 5.2C; Cole and Peachy, 1999). The Bay of Biscay and the Labrador Sea opened by 83 Ma (Fig. 5.2D; Cole and Peachy, 1999) and Greenland was separated from the Rockall Plateau by 53 Ma (Srivastava and Tapscott, 1986). Pre-existing lineaments played a pivotal role in defining the orientations of rift axis during the Mesozoic and Cenozoic. Proto North Atlantic rifting for example, took place along a zone of NE-SW Caledonian terrane boundaries that traversed both sides of the present Atlantic during Devonian times (Knott *et al*., 1993).

The lack of well data and the poor quality of seismic data from the basin due to the extensive presence of igneous sills mean the history of the Rockall Basin is still poorly understood. Pre-Cretaceous rifting has yet to be conclusively established for the basin and there are conflicting theories as to the structural style of the basin (e.g., Musgrove and Mitchner, 1996; Corfield *et al.*, 1999). More extensive exploration and a series of wells in its shallow northern part have lead to a better understanding of the Porcupine Basin (Croker and Shannon, 1987, 1995).

1.1.1 Structure

Three main structural trends have influenced the evolution of the Rockall Basin NE-SW, N-S and NW-SE (Corfield, *et al.*, 1999). The first two are the most important in terms of Mesozoic basin development and define the trends of the basin's bounding faults. NW-SE lineaments are interpreted as transfer zones similar to those seen in the Faeroe Shetland Basin. Motion along lineaments of this orientation has served to compartmentalise the basins.

Two contrasting structural styles have been proposed for the eastern margin of the basin. Musgrove and Mitchner, (1996) suggest that faulting is dominantly down to the east. What few down to the basin faults they found, they described as antithetic to those down thrown to the east or similar to broken relay ramps. They put forward a model of reactivation of part of the Caledonian foreland thrust belt. Mesozoic half-grabens formed by extensional reactivation of westward verging Caledonian thrust planes giving rise to the down to the east configuration of the margin.

In contrast, Corfield *et al.*, (1999) stated that faults on the eastern margin displayed considerable down to the basin displacement and throw to the north west. Both sets of authors are in agreement on the down to the basin configuration of the western margin. Mac Aodha (2004) suggested a change in structural style in the basin at the top of the Porcupine High, with down to the basin faulting along the margin of the Porcupine High a down-to-the-east faulting north of this.

Both margins have a chain of perched basins of late Palaeozoic to Mesozoic age most of which sit on the basin margin but some such as the Ronan Basin on the western margin have subsided into the Rockall basin (Corfield *et al.*, 1999; Naylor *et al.*, 1999).

Several major structural lineaments affect the basin and its surrounds. To the south, the Rockall Basin is separated by the Charlie Gibbs Fracture Zone from the Upper Cretaceous oceanic crust of the Porcupine Abyssal Plain. Major long lived Caledonian NE-SW lineaments mapped onshore and considered to have exerted a controlling influence in basin development include the Great Glen Fault system and its splays and the Minch Fault. They help define the eastern margin of the Rockall Basin. NW-SE lineaments of note include the Anton Dohrn Lineament and the offshore extension of the Aran-Waterford lineament. These and other structural features of that trend, do not act as basin bounding faults but rather act to compartmentalise the basins present (Corfield *et al.*, 1999). The Anton Dohrn lineament, which traverses the entire basin, coincides with a change in the orientation of the eastern margin of the basin from N-S in the Irish sector to NNW-SSE in the UK sector.

Despite early assertions that the crust in the basin was oceanic (Roberts *et al*., 1981; Joppen and White, 1990) wide angled reflection studies such as the RAPIDS profiles (O'Reilly *et al*., 1995; Hauser *et al*., 1995) have shown that thinned but unbreached continental crust extends west from Ireland beneath the Rockall Basin and Rockall Plateau to the Hatton continental margin.

The RAPIDS data show a three layer crust beneath onshore Ireland, the Irish shelf and the Rockall High, that has been thinned to two layers under the Rockall Basin, beneath a sedimentary cover of 5-6 km (Fig. 1.2). The RAPIDS profiles also revealed a low velocity layer below the moho interpreted by O'Reilly *et al*. (1996) as serpentinite. The thinning of the continental crust from 30 km, onshore and Rockall Bank, to 5 km, with up to 8 km sediment and water overburden (O'Reilly *et al*., 1994), in the basin requires beta factors in the region *ß* =5-6. Two theories have been put forward to explain how such severe rifting could have occurred without any evidence of crustal rupture or voluminous underplating and igneous intrusion. First is the idea that rifting was multiphase, spread out from the Triassic to the middle Cretaceous. The magnitude of each discrete rifting event would be small (*ß*=2) but the cumulative effect would be large (Walsh *et al*., 1999; Cole and Peachey, 1999).

The second model requires differential stretching of the lithosphere in the region, with the lower crust stretched by a factor of 2-3 while the more brittle upper crust accommodates stretching in the region of 8-10 (Hauser *et al*., 1995). This differential stretching results in the fusing of the middle and upper crustal layers explaining the transition from a three layer crust on the bounding highs to a two layer crust in the basin. Modelling by Perez-Gussinye and Reston (2001) lends some support to this theory. They showed that the entire crust should become brittle at stretching factors greater than 3-3.5 for rift durations of 30-50 My. Taking a lithospheric structure similar to the cratonic model of West Greenland and stretching it for 30 My, they predicted that 4-10 km of the mantle should be partially serpentinised. O'Reilly *et al*., (1996) suggested a serpentinised zone of 5-10 km below the moho along the transverse RAPIDS line which is in general agreement with this.

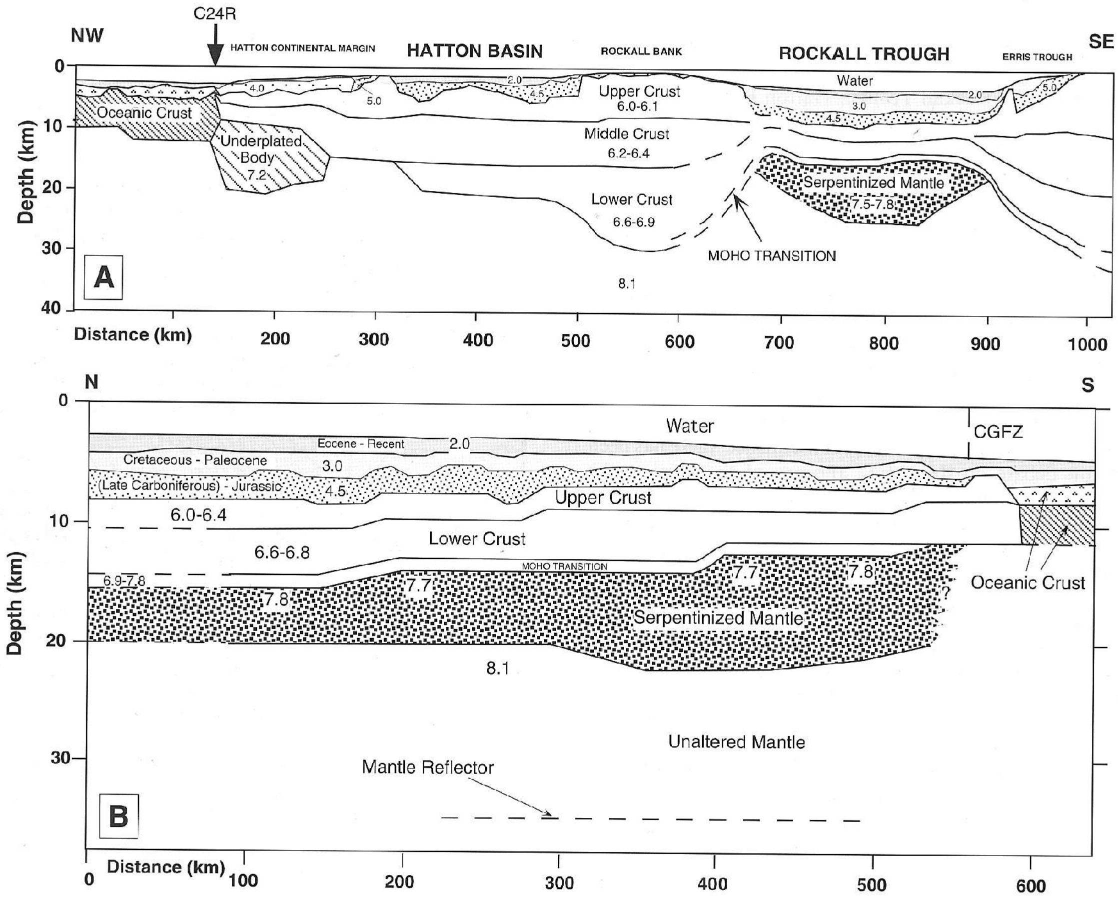


Figure 1.2: *Reproduced from Shannon et al., (1999) (A) Model based on the RAPIDS wide-angled seismic transverse profile from Ireland to the Iceland Basin. Solid interfaces are regions where the model is well constrained by the seismic data. Numbers are seismic P-wave velocities (km s^{-1}). The location of magnetic anomaly 24 (C24R) of early Eocene age is indicated. (B) Model based on RAPIDS wide-angled axial profile through the Rockall Basin. CGFZ=Charlie Gibbs Fracture Zone.*

Reflection lines from the Porcupine Basin show that it is also underlain by continental crust with crustal thickness (including sediment) decreasing from 23 km in the east to 10 km in the west. The basin bounding faults are orientated parallel to the basin margins but are more variable in the north possibly due to the rotation of the Porcupine High away from the continental shelf. (McCann et al., 1995). Both margins of the basin have down to basin faulting.

The level of faulting and the nature of structural control on the basin is important in considering the ability of a region to accumulate commercial deposits of hydrates. Faulting acts as the most efficient pathway to move hydrocarbons up through the system to the HSZ.

For example the gradual nature of the western margin of the Rockall results in a series of smaller faults spread out over a broad area, allowing for efficient migration of methane. The south eastern margin of the Rockall Basin, however, is steep and narrow, controlled by a few large faults. This will only facilitate migration over a narrow area.

1.1.2 Stratigraphy

The absence of well control in the Irish sector of the basin means that stratigraphic interpretations are based on well 132/15-1 on the eastern margin of Hebrides (Musgrove and Mitchner, 1996), Deep Sea Drilling Program hole 610 (Masson and Kidd, 1986) and seismic correlation with the landward Erris, Slyne, and Porcupine Basins. The models produced by Shannon *et al.*, (1999) based on the RAPIDS data showed three distinct sedimentary packages (Fig. 1.2). The lower layer was interpreted as a synrift deposit of possible Permo-Triassic age. It is up to 3 km thick in places but as can be seen on Figure 1.2b this thickness varies. The second layer is considered to be Cretaceous in age (Shannon *et al.*, 1995). To the south of the Charlie Gibbs Fracture Zone it lies on Early Cretaceous oceanic crust. The top layer is a post rift Tertiary sequence which varies from 0.7-4 km in thickness. Whether this model is accepted or not depends on the occurrence of pre-Cretaceous rifting. Well 132/15-1 cored Cretaceous (Hauterivian to Cenomanian) rocks directly on top of what are interpreted from seismic data as crystalline basement (Musgrove and Mitchener, 1996). The well is, however, drilled on a minor high on the margin of the basin and deeper sediment to the west may be of pre-Cretaceous origin. WESTLINE is interpreted as imaging a sedimentary sequence within the Rockall Basin that accumulated following a major rifting event that occurred during the early to mid-Cretaceous (England and Hobbs, 1997). This interpretation is corroborated by the results of EPS data which suggest that Cretaceous sediments lie directly on rocks with basement seismic velocities (Joppen and White, 1990).

More recent sedimentation in post-glacial times has seen the development of large scale fans on the eastern and western margins of the northern part of the Irish sector of the Rockall Basin. There have also been smaller scale slump deposits along the western edge of the Porcupine High. The Feni Drift has resulted in deep water deposition of fine material along the western half of the basin floor (Weaver et al., 2000).

The structure of the sediment pile in the Porcupine Basin indicates a three stage development (Daly, 2002). The pre-rift succession in the basin probably consists of Devonian strata (Robeson et al., 1988). These followed by sediments of late Jurassic to early Cretaceous age (Masson and Miles, 1986) which could be covered by Upper Cretaceous sediments from a post-rift thermal subsidence stage. Finally these are covered by up to 3 km of Tertiary strata. Syn and post-glacial sedimentation has been limited, with a lot of the sedimentary input moving through the Golam channels to form a fan stretching from the mouth of the basin onto the Porcupine Abyssal Plain.

The stratigraphy of the basins is of interest for two reasons; source rocks are needed to provide thermogenic hydrocarbons and reservoir quality sands and gravels are needed in the HSZ to provide suitable reservoirs.

1.1.3 Igneous Activity

Decompression melting due to rifting and the presence of the Iceland Plume have resulted in widespread and voluminous magnetism on the Northern Atlantic Margin (Hitchner *et al.*, 1997). Thick igneous sills are present in large areas of the basin. These are considered to be predominately Tertiary in age (Morton, 1988) but Cretaceous volcanics have also been described from seamounts in the region (Shannon *et al.*, 1995). Musgrove and Mitchner (1996) suggested that since sills inject at subsurface depths where the overburden pressure equals the magma pressure (Einsele, 1985) and, as they are seen throughout the thick Upper Cretaceous section becoming more common where the Cretaceous crustal thinning was the most extreme, some of the sills may be Cretaceous in age. The Barra Volcanic Ridge System (Fig. 1.1) is considered by Scrutton and Bentley (1988) to be Early Cretaceous in age both on the grounds of its setting and stratigraphic considerations.

The second Tertiary wave can be correlated with those in the Faeroe-Shetland Basin and are attributed to volcanism associated with the Iceland Plume. The sills typically occur on seismic sections at 2 sec TWTT below the seabed (Shannon *et al.,* 1995) and act as a significant barrier to the penetration of near vertical incidence seismic energy.

Two large areas are affected in the basin itself. Firstly the area surrounding the Barra Volcanic Ridge System in the south of the basin and secondly an area in the northern sector of the Irish designated area which is as yet unnamed.

Igneous activity in the Porcupine is limited to the Porcupine Median Volcanic Ridge (Roberts et al., 1981). The ridge which runs along the axis of the basin is onlapped by probable Cretaceous strata and appears to be underlain by the Jurassic-Cretaceous unconformity surface (Naylor et al., 1999). Their may be later Tertiary intrusives associated with the ridge.

Igneous bodies influence hydrate accumulations in a couple of ways. They introduce heat into the system increasing the geothermal gradient which will affect the thermal maturity of the hydrocarbon system and the thickness of the HSZ. The strength of this effect will depend on the age and size of the igneous bodies. Igneous bodies particularly sills will act as a barrier to migration of methane up through the sediment section.

1.2 What is Hydrate

In this section a short introduction to hydrate is presented. It is based on Max (2000) and on the knowledge transfer with Art Johnson (Mac Aodha *et al.*, 2005). 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. 1.3). 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 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 world's 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; Englezos and Bishnoi, 1988).

The formation of methane hydrate has the ability to concentrate gas. One litre of methane hydrate 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 per litre of hydrate, 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.

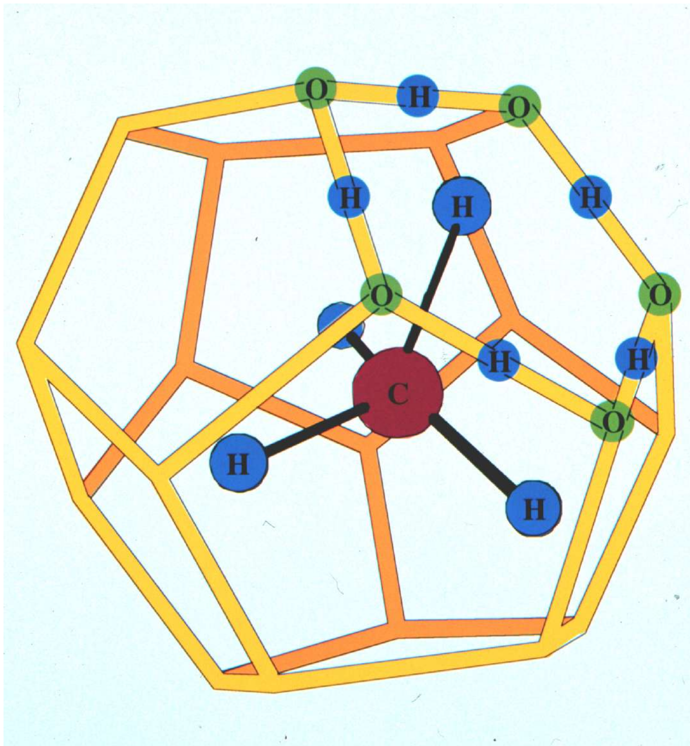


Figure 1.3: *Gas hydrate cage with methane as the trapped molecule.*

Thermogenic gasses (e.g., methane, ethane, propane) are produced when geothermal heat 'cooks' organic matter which has been buried by overlying sediment. The gas composition depends on the thermal maturation process to which the sediments have been subjected. Methane is the main gas 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 HSZ.

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 fall with increasing sediment depth (Fig. 1.4). Figure 1.4 is a schematic graph of the sulphate reduction zone. It does not have a scale as the thickness 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.

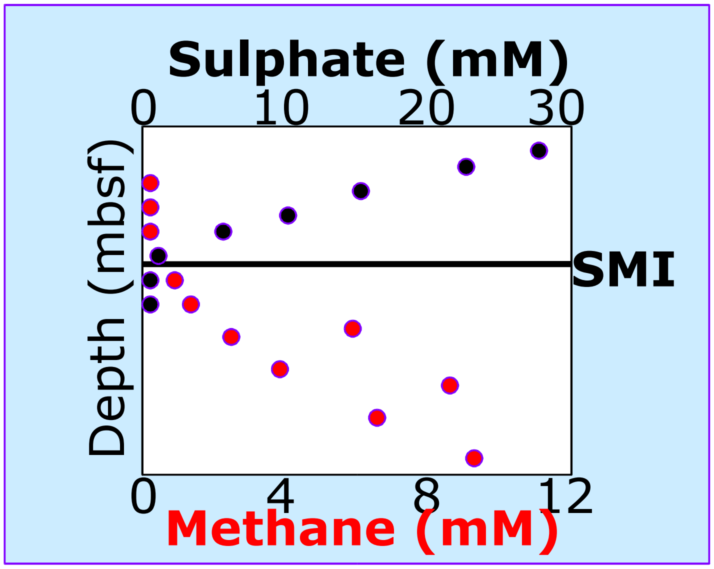


Figure 1.4: *Sulphate reduction zone, showing the levels of sulphate (black dots) and methane (red dots) in an arbitrary thickness of the sedimentary section starting from the sea floor at the top of the graph. The black line marked SMI is the sulphate methane interface. Below this depth, methane will be stable and above it methane will be used up reducing sulphate. mbsf: meters below seafloor.*

Methane hydrate will occur in the pore spaces of sediments where the temperature and pressure conditions lie within the HSZ 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. For example 1-2% hydrate formed in veins or unconnected pore space in 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 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, this resource assessment concentrates on establishing the HSZ, and on assessing the quality of the hydrocarbon play in the area.

2 Hydrate Stability Zone

The HSZ is governed by a number of variables; temperature and pressure are the key controlling factors but, water and gas composition are also factors. Figure 2.1 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 of the composition of the water (difference between pure water and sea water). The successive curves show the effect of the composition of the gases involved.

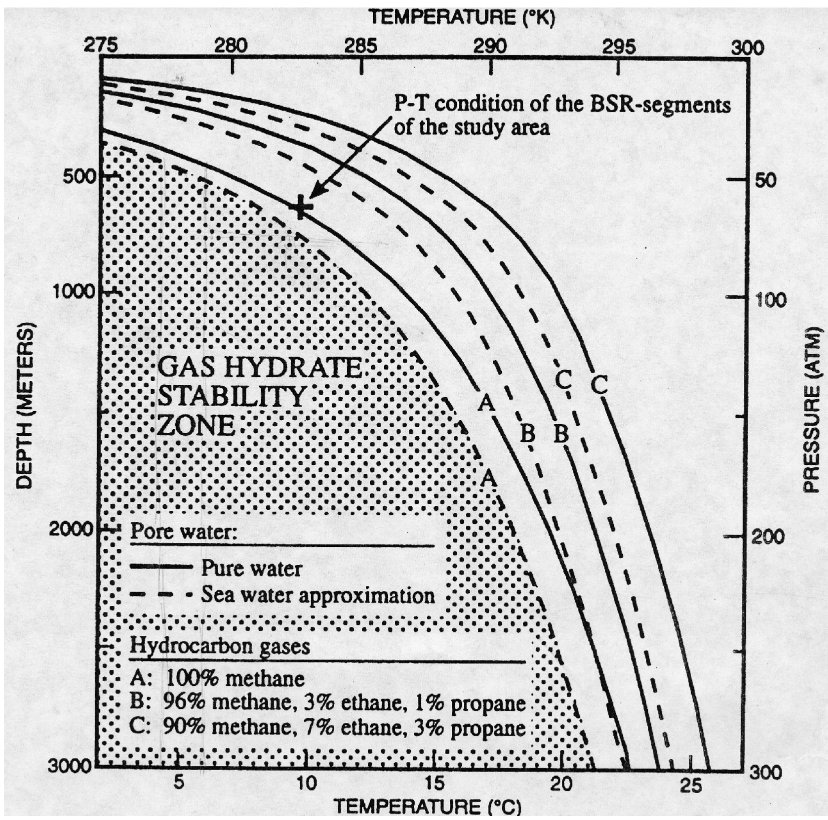


Figure 2.1: *Hydrate stability curves for a range of gas and water compositions.*

By plotting the phase boundary and the hydrothermal seabed profile* on the same curve we can see the temperature/pressure range within which hydrates are stable (Fig. 2.2a).

* The HSZ is controlled by the water temperature at the seabed, how this temperature varies with depth has been called the hydrothermal seabed profile. It differs from the hydrothermal gradient as it describes how the temperature changes with depth up through the water column; hydrothermal seabed profile describes how the seabed temperature changes as depth increases (Mac Aodha *et al.*, 2005).

However, as we are interested in hydrate within the sedimentary column, temperature will start to increase with depth due to the geothermal gradient. Figure 2.2b shows the situation in the sedimentary section at an arbitrary water depth of 1220 m. Hydrate is stable where the sediment water interface is below the intersection of the hydrothermal seabed profile and the phase boundary. However, once below the interface it is the geothermal gradient which governs the temperature. Hydrate will cease to be stable below this phase boundary.

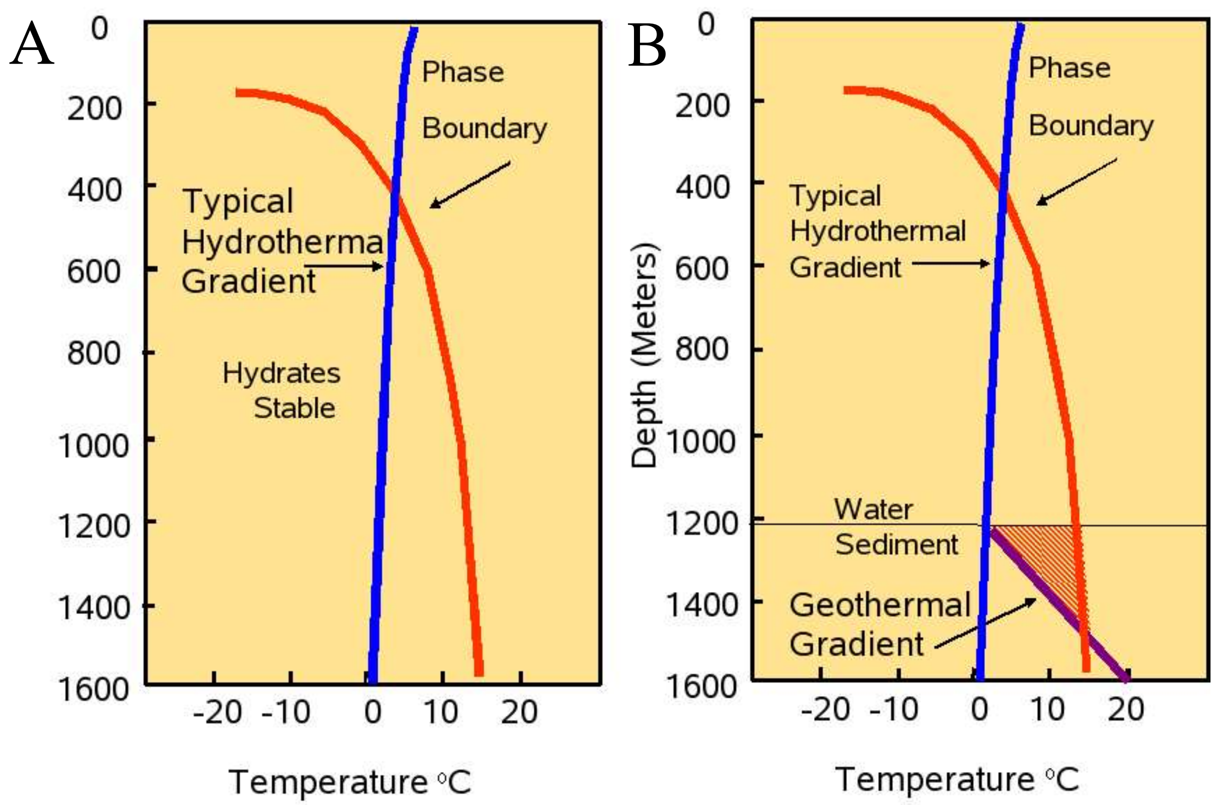


Figure 2.2: *Hydrate phase boundary curves showing the HSZ in the water column and in a sedimentary section at a depth of 1220 m. The area shaded with red lines is the HSZ in the sedimentary section.*

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 seabed profile, geothermal gradient and the gas composition that are the key unknowns.

Of the three unknowns, the seabed temperature has the most available data in the context of the Irish offshore. The INSS took sound velocity profiles (SVP) at regular intervals during their survey of Zone 3 and as part of this, a seabed temperature is recorded. These readings provide good coverage of data points over most of the shallower areas. There are problems in deeper areas, however, where the SVPs do not extend 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 levels 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 (Christian Mohn, *pers. comm.*, 2005). Fortunately other data sets are available and did provide readings down to the sea floor in the deep water areas. These data did not provide full coverage of the stdy area, but did allow us to generate a hydrothermal seabed profile right down to the deepest parts. A hydrothermal seabed profile 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 profiles. Seasonal variations do affect the profile 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 (Christian Mohn, *pers. comm.*, 2005).

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 at regular intervals. This requires that drilling stops for long enough for the temperature to reach equilibrium after the cooling effect of the drilling mud which is circulated through the system. This takes a considerable period of time and full equilibrium status is not usually achieved in offshore wells. Bottom hole temperatures are, however, often recorded but need to be adjusted to take account of this, usually using Horner plots (e.g., Corry and Brown, 1998). Heat flow can vary rapidly over small distances. Faulting, igneous intrusions, salt domes and convective heat transfer via fluids can introduce warmer material from depth. It is very unlikely that sufficient data will be available to delineate the effect of these features on the gradient and it will have to be estimated where they are identified.

As with the hydrothermal seabed profiles the geothermal gradients from the two basins were dealt with separately. Well data from a number of exploration wells in the Porcupine Basin were analysed yielding a geothermal gradient of $30^{o}Ckm^{-1}$. This is in line with industry accepted figures for the basin (Peter Croker, *pers. comm.*, 2005). The Rockall basin is much more difficult. There is only one released well in the basin (two unreleased) which is in the NE corner of the basin in relatively close proximity to the Hebrides Terrace Seamount. The gradient used in this study was 35^{o}Ckm^{-1} which is in line with the generally accepted value for average crustal thickness adjusted for the stretching in the Rockall. This general figure would be expected to vary greatly over the large area of the basin. It should be noted that this figure is lower than that used by Long *et al.* (2005) who used 45^{o}Ckm^{-1} in a recently published study on the UK section of the Rockall Basin and the Faroe-Shetland Channel. This high gradient could be explained by more extensive Tertiary volcanics in the area.

Considering the degree of unconstrained variability in the three parameters mentioned above, the HSZ calculated for the Rockall Basin is more of a rough guide to the areas 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 have 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), Rao (1999) and Unnithan *et al.* (2004).

Figure 2.3 taken from Englezos and Bishnoi (1988) shows the curve that was used to calculate the HSZ. The figure shows three different phase boundary curves for 100% methane hydrate. The curve that was used is the centre curve which is their curve for sea water.

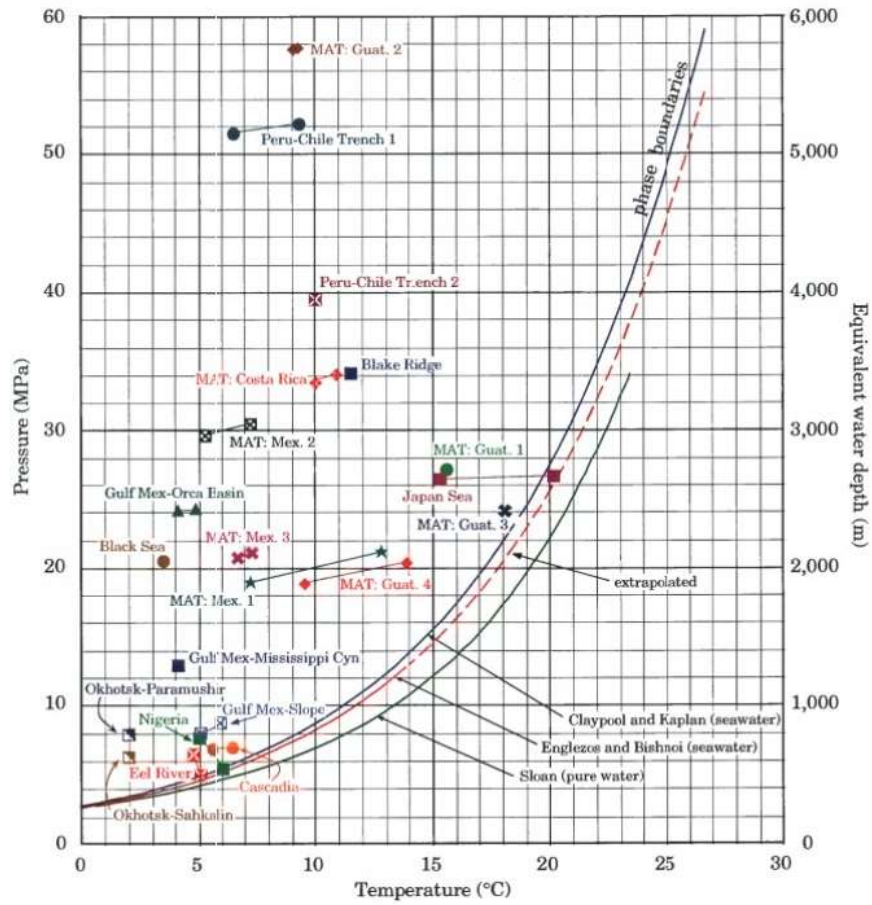


Figure 2.3: *Curves of the phase boundary for pure methane, pure water and sea water (Englezos and Bishnoi, 1988).*

2.1 Porcupine

Figure 2.4 shows the pressure-temperature curves for the Porcupine Basin using the data sources described above. From these curves the HSZ thickness shown in Table 2.1 were estimated.

The graph shows the hydrothermal profile for the Porcupine Basin (blue) as well as the $30^{o}Ckm^{-1}$ geothermal gradient (green). If the depth/temperature combination plots above the phase boundary curve the location will be within the HSZ 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 2.4 represents the phase boundary when there is a mix of 90% methane, 7% ethane and 3% propane instead of pure methane. As can be seen from the figure this will increase the thickness of the HSZ.

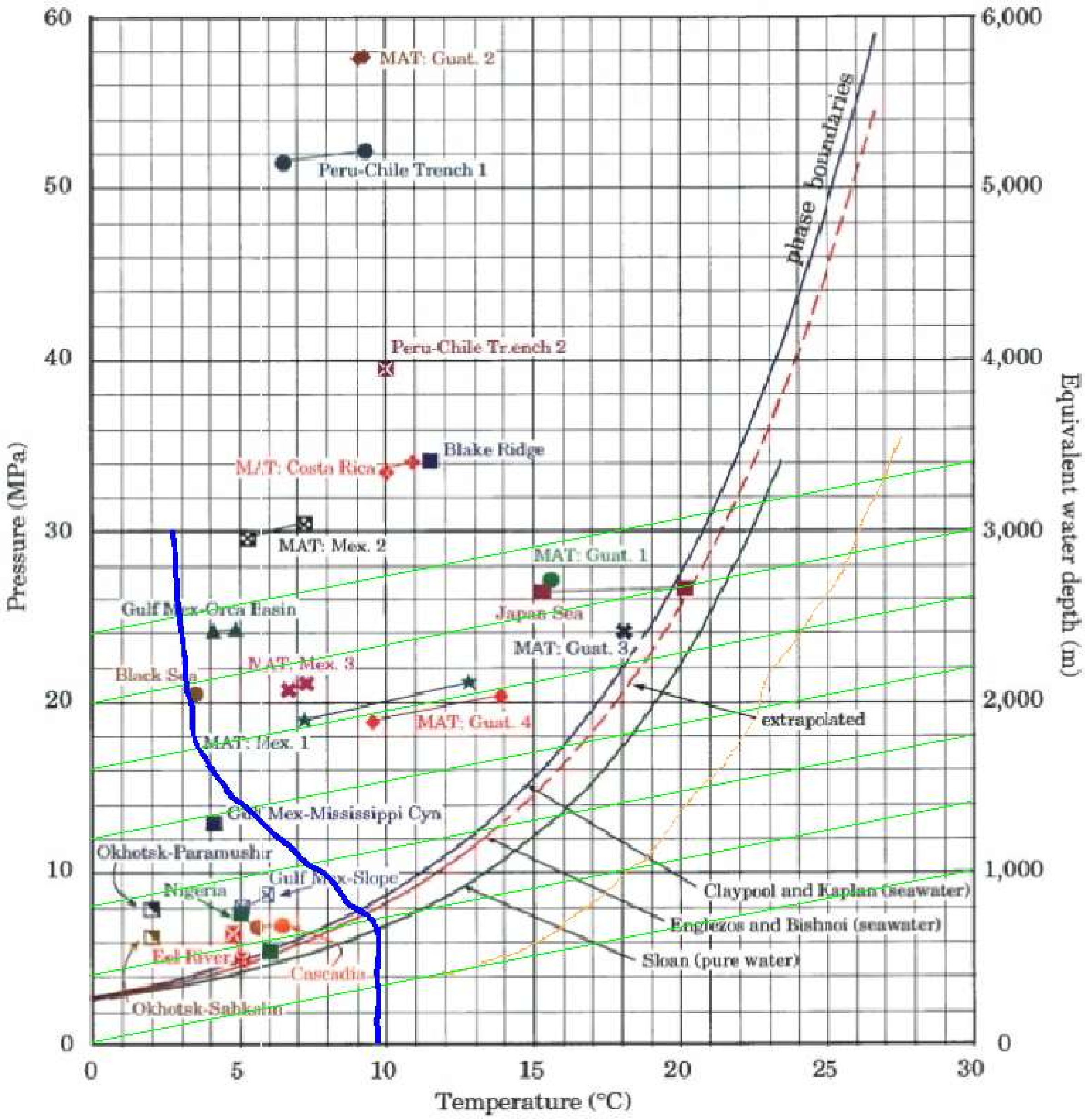


Figure 2.4: *The curves from Figure 2.3 with the hydrothermal seabed profile for the Porcupine Basin (blue), and the geothermal gradient (bright green) overlain. The brown curve is the phase boundary when dealing with a situation where there is 90% methane, 7% ethane and 3% propane.*

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. The result is a time range to use when examining seismic lines to assess reservoir quality and check for possible bottom simulating reflectors (BSRs). Table 2.1 shows the values that were used during the review of the data from the Porcupine Basin.

WD (sec.)	Depth (Meters)	BHSZ (Meters)	BHSZ (m below WB)	Assumed Sed Vel (km s^{-1})	BHSZ (Sec. below WB)	BHSZ sec.
				(2-way)		
0.70	525					
0.80	600					
0.90	675					
1.00	750					
1.10	820	820	0	1.600	0.000	1.100
1.20	900	980	80	1.650	0.097	1.297
1.30	975	1100	125	1.650	0.152	1.452
1.40	1050	1350	300	1.650	0.364	1.764
1.50	1125	1460	335	1.700	0.394	1.894
1.60	1200	1560	360	1.700	0.424	2.024
1.70	1275	1655	380	1.700	0.447	2.147
1.80	1350	1750	400	1.700	0.471	2.271
1.90	1425	1855	430	1.700	0.506	2.406
2.00	1500	1960	460	1.700	0.541	2.541
2.10	1575	2050	475	1.700	0.559	2.659
2.20	1650	2140	490	1.725	0.568	2.768
2.30	1725	2230	505	1.725	0.586	2.886
2.40	1800	2320	520	1.750	0.594	2.994
2.50	1875	2415	540	1.750	0.617	3.117
2.60	1950	2510	560	1.750	0.640	3.240
2.70	2025	2595	570	1.750	0.651	3.351
2.80	2100	2680	580	1.750	0.663	3.463
2.90	2175	2765	590	1.750	0.674	3.574
3.00	2250	2850	600	1.750	0.686	3.686
3.50	2625	3300	675	1.800	0.750	3.688

Table 2.1: *Depths to the base of the HSZ for the Porcupine Basin assuming a geothermal gradient of 30ºCkm^{-1} and a 100% methane gas composition. WD, water depth; BHSZ, base HSZ; WB water bottom.*

The results show that the HSZ starts quite deep for the latitude of the basin at approximately 820 m. This has been attributed to the circulation of warm saline water from the

Mediterranean around the basin which elevates the seabed temperatures. These data can be quality controlled using BSRs where found as they mark an exact position for the base of the HSZ at that location.

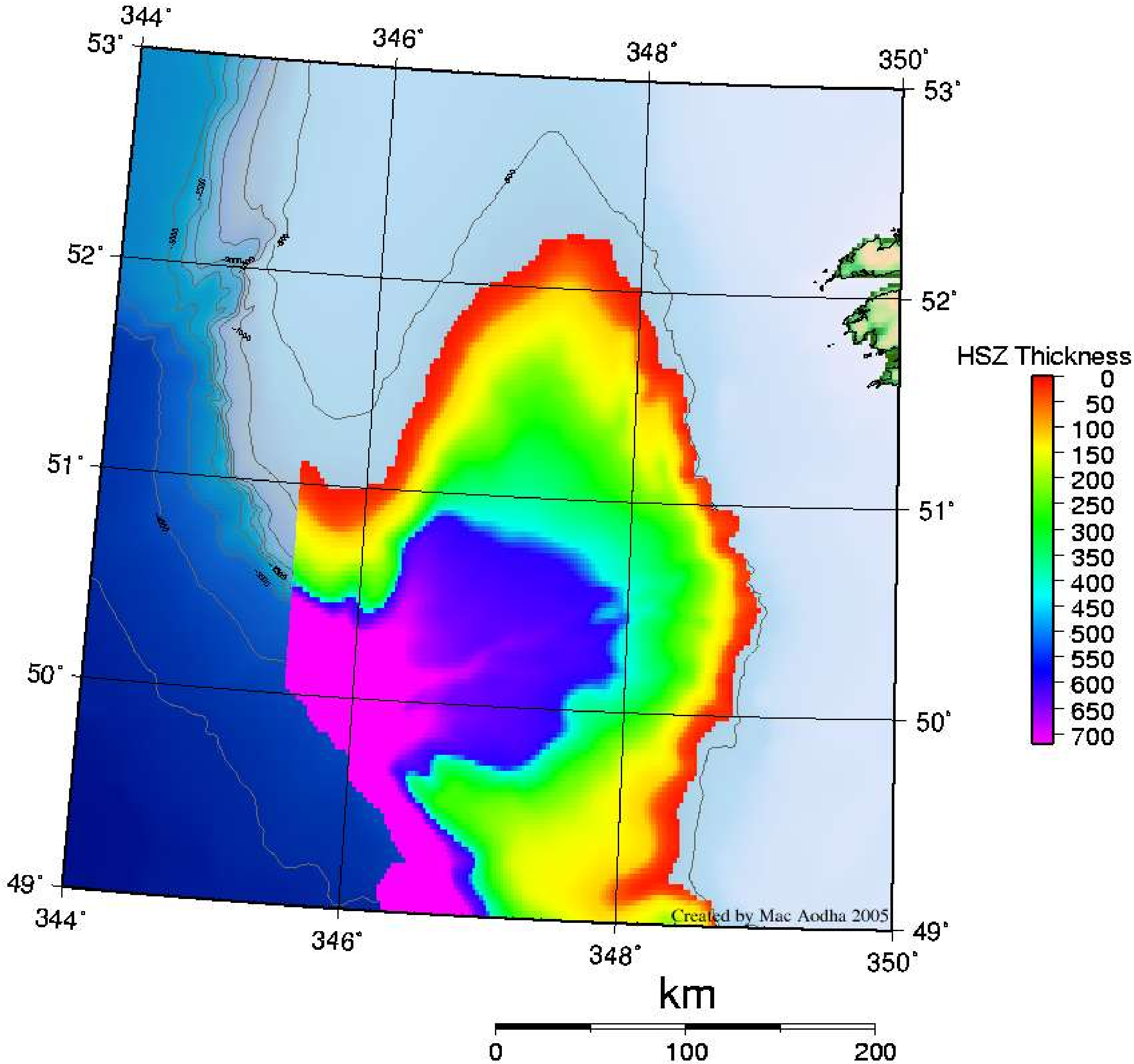


Figure 2.5: Plot of the thickness of the HSZ across the Porcupine Basin. The map was plotted in UTM zone 29.

The thicknesses of the HSZ for the Porcupine Basin are plotted in Figure 2.5. The figure shows that the majority of the southern part of the basin has a HSZ thickness of over 200 m and this increases to over 700 m towards the Porcupine abyssal plane. The results were not extended out onto the abyssal plain as there is a change to oceanic crust once the Charlie

Gibbs Fracture Zone is crossed; the associated change in geothermal gradient means the results from this curve are not valid there.

2.2 Rockall

Figure 2.6 shows the pressure-temperature curves for the Rockall Basin. From these curves the HSZ thickness shown in Table 2 were estimated.

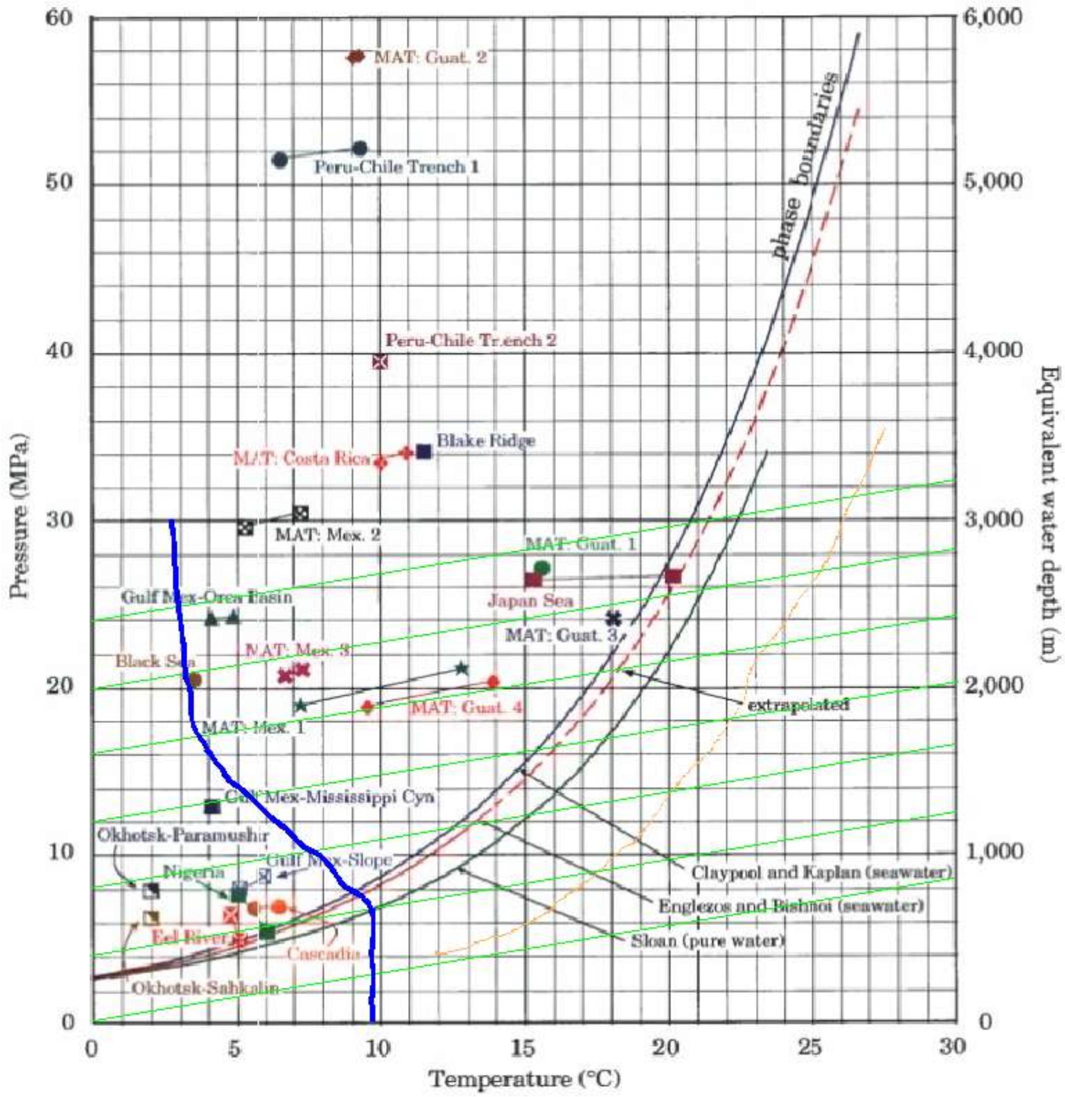


Figure 2.6: *The curves from Figure 2.3 with the hydrothermal seabed profile for the Rockall Basin (blue), and the geothermal gradient (bright green) overlain. The brown curve is the phase boundary when dealing with a situation where there is 90% methane, 7% ethane and 3% propane.*

Table 2.2 shows that a HSZ thickness of over 500 m is possible with the water depths found in the Rockall Basin.

WD (sec.)	Depth (Meters)	BHSZ (Meters)	BHSZ (m below WB)	Assumed sed vel (km s^{-1})	BHSZ (Sec. below WB)	BHSZ (sec)
				(2-way)		
0.70	525					
0.80	600					
0.90	675					
1.00	750					
1.00	760	760	0	1.60	0.00	1.00
1.10	825	875	50	1.60	0.06	1.16
1.20	900	970	70	1.65	0.08	1.28
1.30	975	1100	125	1.65	0.15	1.45
1.40	1050	1240	190	1.65	0.23	1.63
1.50	1125	1340	215	1.70	0.25	1.75
1.60	1200	1460	260	1.70	0.31	1.91
1.70	1275	1560	285	1.70	0.34	2.04
1.80	1350	1650	300	1.70	0.35	2.15
1.90	1425	1760	335	1.70	0.39	2.29
2.00	1500	1860	360	1.70	0.42	2.42
2.10	1575	1965	390	1.70	0.46	2.56
2.20	1650	2050	400	1.73	0.46	2.66
2.30	1725	2150	425	1.73	0.49	2.79
2.40	1800	2235	435	1.75	0.50	2.90
2.50	1875	2320	445	1.75	0.51	3.01
2.60	1950	2400	450	1.75	0.51	3.11
2.70	2025	2480	455	1.75	0.52	3.22
2.80	2100	2560	460	1.75	0.53	3.33
2.90	2175	2640	465	1.75	0.53	3.43
3.00	2250	2720	470	1.75	0.54	3.54
3.10	2325	2820	495	1.75	0.57	3.67
3.50	2625	3140	515	1.80	0.57	4.07

Table 2.2: *Depths to the base of the HSZ for the Rockall Basin assuming a geothermal gradient of 35ºCkm^{-1} And a gas composition of 100% methane. WD, water depth; BHSZ, base HSZ; WB water bottom.*

The table illustrates the effect the increase in the geothermal gradient has on the thickness of the HSZ. If the thicknesses for a depth of 3000 m are compared between Table 2.1 for the Porcupine and Table 2.2 for the Rockall we see that the HSZ is 150 m thicker in the Porcupine. The hydrothermal profile is very similar between the two basins so the difference is due to the 5°C variance in geothermal gradients.

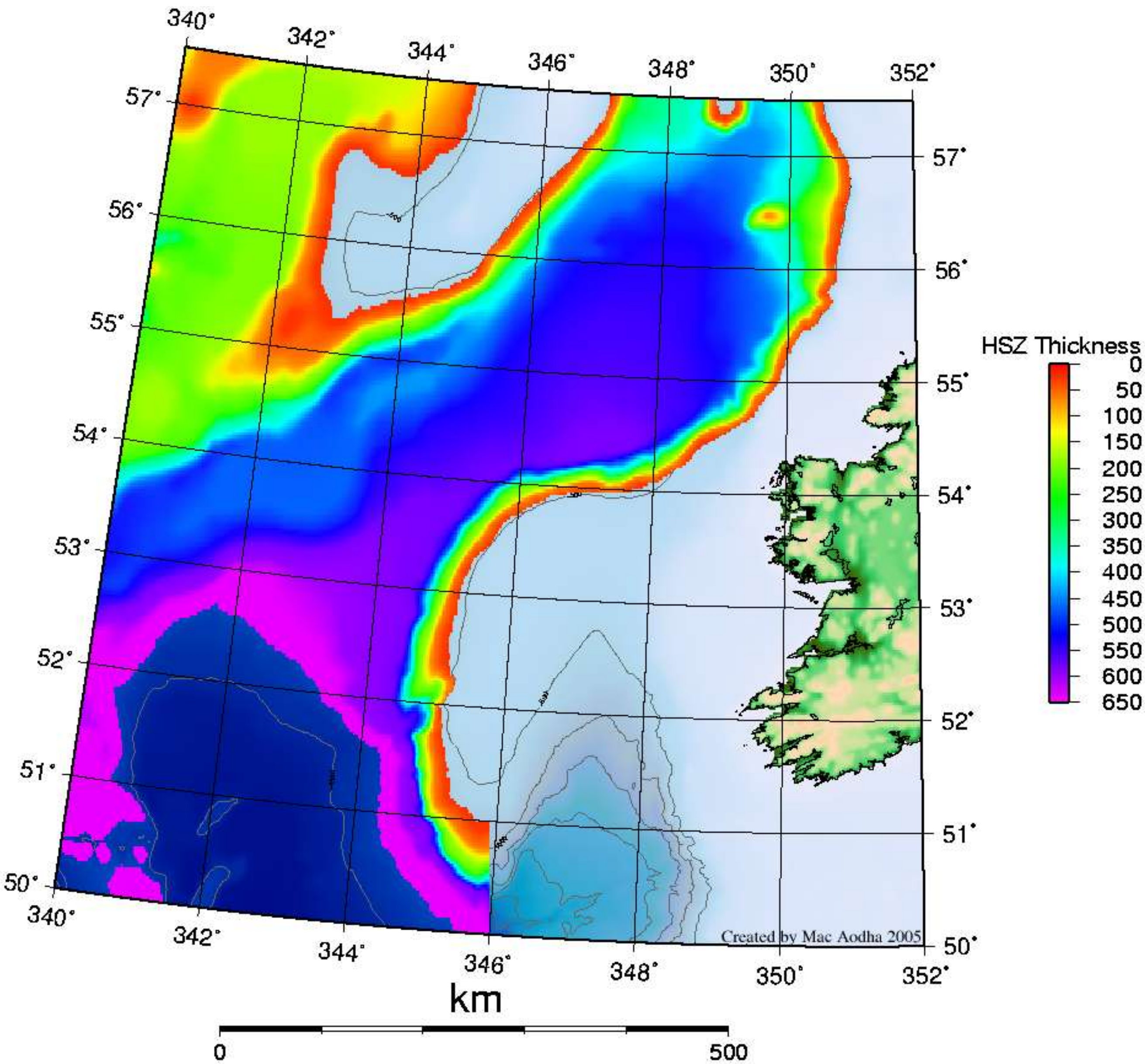


Figure 2.7: *Plot of the thickness of the HSZ across the Rockall Basin. The map was plotted in UTM zone 29.*

Similar to the Porcupine Basin the results from the Rockall Basin show that the HSZ starts quite deep for its latitude at approximately 760 m. This is again attributed to the circulation of warm saline water from the Mediterranean around the basin which elevates the seabed temperatures. It is worth noting that the largest concentration of seafloor temperatures used are from a survey which crosses the Porcupine Bank and descends down into the Rockall Basin. The fact that currents tend to hug the basin margins, means that the data used may not accurately portray the conditions in the centre of the basin or those on the western margin.

The HSZ thickness for the Rockall Basin is plotted in Figure 2.7. There were no seabed temperature data below the depth of 3200 m but the data was extrapolated from the graph to give values down to 4000 m water depth.

3 Risk Assessment

In this section, the methods used to evaluate the methane hydrate resource potential of the study area are discussed. The study focuses mainly on a review of seismic reflection data. The search criteria and bottom simulating reflectors are also discussed.

There are no geophysical data available for the study area that can be analysed to tell us about the presence of hydrate and its concentration. The closest thing is the presence of BSRs on seismic data.

BSRs are commonly accepted evidence for the presence of methane hydrates (Kevenvolden, 2000). 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 classic BSR from the Blake Ridge off the east coast of the US is shown in Figure 3.1. The problem with this image is that it is almost unique in terms of the quality and clarity of the BSR shown. The section 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 3.1. The most common type of BSR is the “string of pearls” type which occurs where sandstones are interbedded with 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 is a series of bright spots where the free gas gathers (Fig. 3.2).

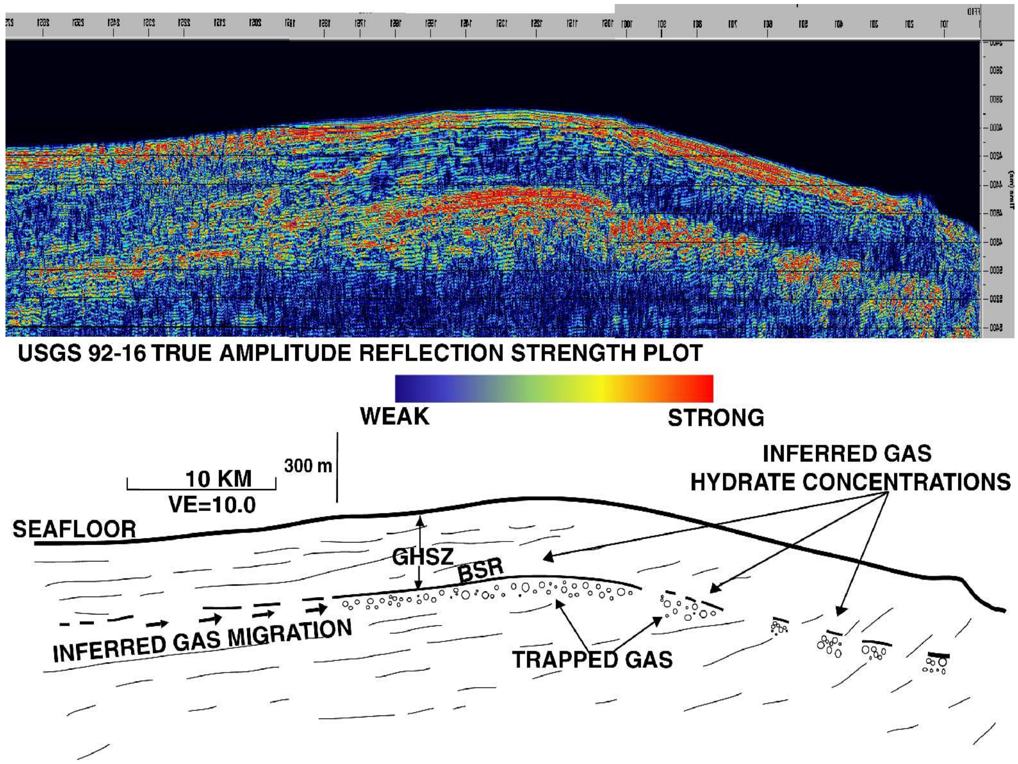


Figure 3.1: *Example of a BSR from the Blake Ridge, with a schematic interpretation below. Image courtesy of Art Johnson.*

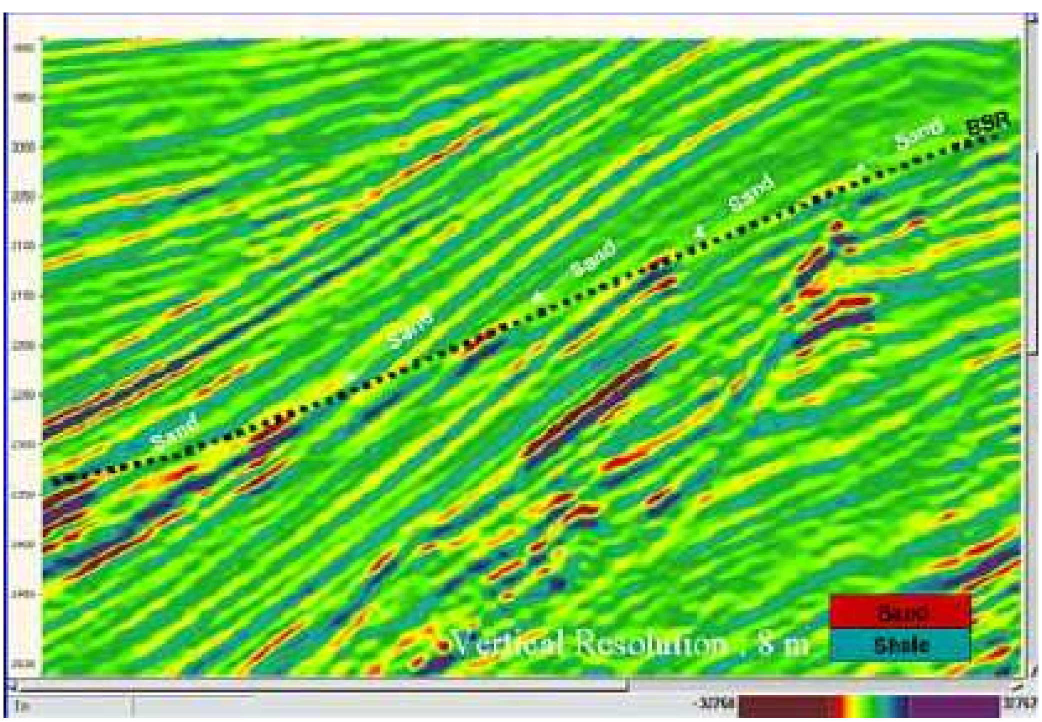


Figure 3.2: *A series of bright spots corresponding to the base of the HSZ in the sand layers, which line up to give a BSR that matches the topography of the seabed. Image courtesy of Art Johnson.*

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 as the HSZ pinches out. In areas where stratigraphy closely matches the seabed this may be the only chance to see a BSR.

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 are present they may bring warmer material up from depth giving local variations in the geothermal gradient and an uneven base to the HSZ. 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 for the absence of BSRs 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 without 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 at 500 ms below the seabed.

Where BSRs are genuinely present there are still problems in their use in exploration for commercial methane hydrate deposits. A BSR will not give information on the concentration of hydrate within the HSZ. The best BSRs are found in shales. (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.) 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 e.g., Gulf of Mexico.

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 biogenic or thermogenic 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 of the thickness of the HSZ 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 nasty looking section but, may 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, but they can be considered tangible evidence for the presence of hydrates.

Taking these factors into account it is clear that just searching for BSRs is not an effective way to conduct a resource assessment. In the absence of direct evidence, the approach taken was to create a geological model which describes the optimum conditions for the formation of commercial deposits of methane hydrate and then assess areas on how well they match those conditions.

The key factors are basically the same as those for a conventional oil and gas play, i.e., an active hydrocarbon system with source, timing, and migration of the hydrocarbons through the sedimentary section to a reservoir within the HSZ. As they can give the best over view of these factors, commercial seismic data were the main focus of our assessment. These do not give direct information on source and timing but these factors have already been proven in the study areas with hydrocarbons confirmed in several wells in the Porcupine Basin and well 12/2-1z in the NE Rockall Basin. On the western side of the Rockall Basin a gas chimney rising from a deep within the section is strong evidence of an active petroleum system in that area as well (Fig. 4.23).

Ideally seismic data would have (i) good resolution in the upper 1-1.5 sec below the seabed to assess the reservoir quality and (ii) sufficient penetration that migration pathways can be assessed. However, this was not the case with some of the data. Commercial seismic data is normally shot and processed to image deeper structures. Therefore, reservoirs in the shallow section are sometimes difficult to identify. One of the problems is that the shallow section is best imaged by higher frequencies. During the late 1980s and early 1990s 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, often the higher frequencies were filtered out at source and never recorded.

The assessment of the seismic data was carried out using a qualitative scale between 0 and 1 for each of the parameters. The higher the value the more suitable is the location is for the presence of hydrate. Each of the values are then multiplied together to give an overall single value on the potential of the area. The main benefit of this method is that, as a single value is obtained, the region can be gridded and contoured based on the potential of each location assessed. A second advantage is that weightings can be given to each of the parameters assessed depending on their importance to the overall objective.

Three parameters were assessed from the seismic sections; the HSZ, migration pathways and reservoir potential.

3.1 HSZ

Of the three the measurement of the HSZ was the most objective. It was assigned a value based on the depth at the location been assessed. As the result is a value between 0 and 1, an upper and lower depth value must be chosen. The lower value was obviously set at the top of the HSZ, e.g., 760 m in the Rockall Basin. The upper value was set where the HSZ reached a thickness of 500 m, e.g., 2600 m in the Rockall Basin. This had the effect that some areas scored 0 where they were above the HSZ and 1 where they were deeper than 2600 m. The value automatically derived from the depth was adjusted where necessary to take account of geological features such as igneous bodies or basement highs which would be expected to change the geothermal gradient in the area. This was a subjective alteration.

3.2 Migration Pathways

Migration pathways are a key element in the formation of an economic methane hydrate deposit as thermogenic methane gas must migrate from the deeper parts of the sedimentary section where it is cooked to the shallow section where the hydrate forms. 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 from 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. This is a subjective measurement but care was taken to ensure that consistency was maintained, particularly between different surveys. This was sometimes very difficult as the quality of the data varied greatly and it is probable that some areas had a higher level of faulting than was revealed by the seismic data. Figures 3.3 and 3.4 below show high and intermediate levels of fracturing respectively. Images of the full range of values which were used as a benchmark for the assessment can be found in Appendix 1.

Figure 3.3 shows a good example from the study area; the upper section (3900-3200 ms) is well faulted offering multiple migration pathways. The lower section (4200-3900 ms) is also perforated by deeper extensions of some of the shallower faults which will allow hydrocarbons to cross the major reflector at 4100 ms.

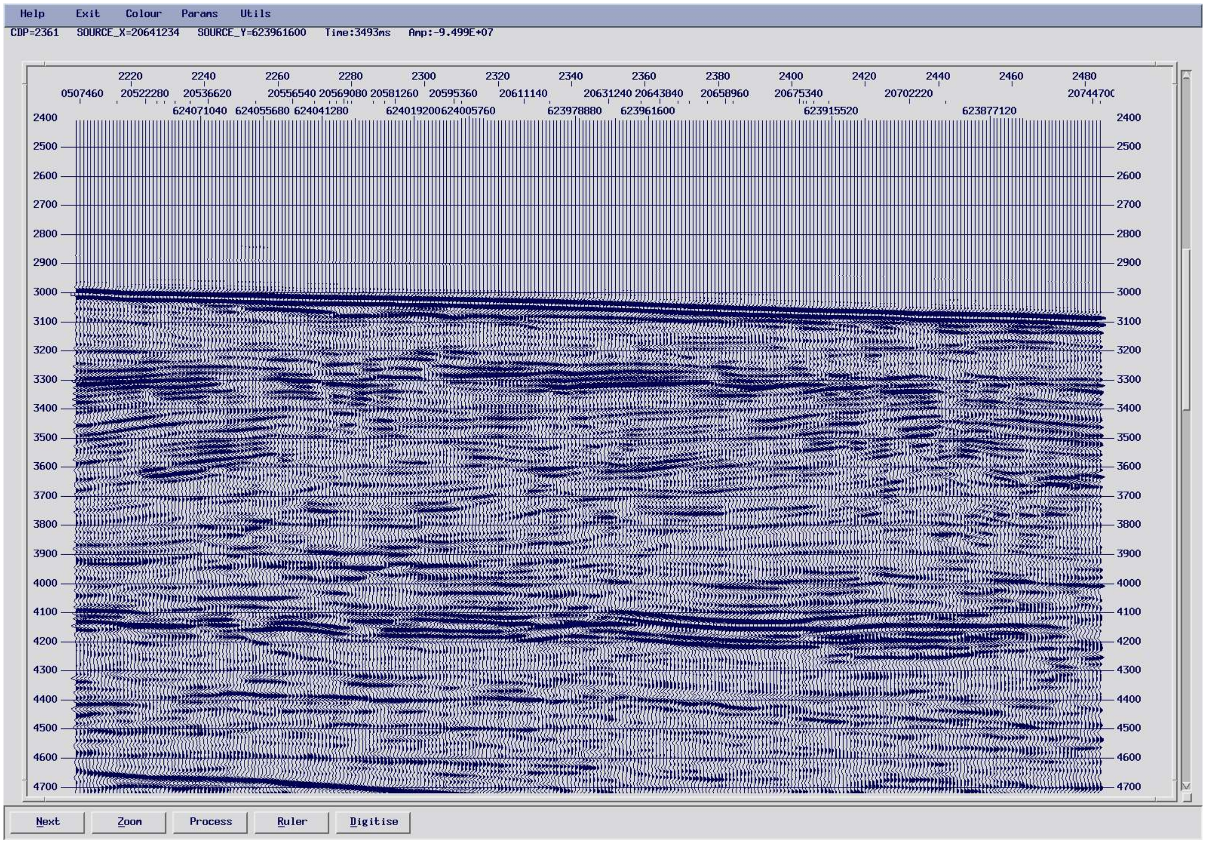


Figure 3.3: *Very well faulted seismic section, offering good migration pathways from source to shallow reservoirs.*

Figure 3.4 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.

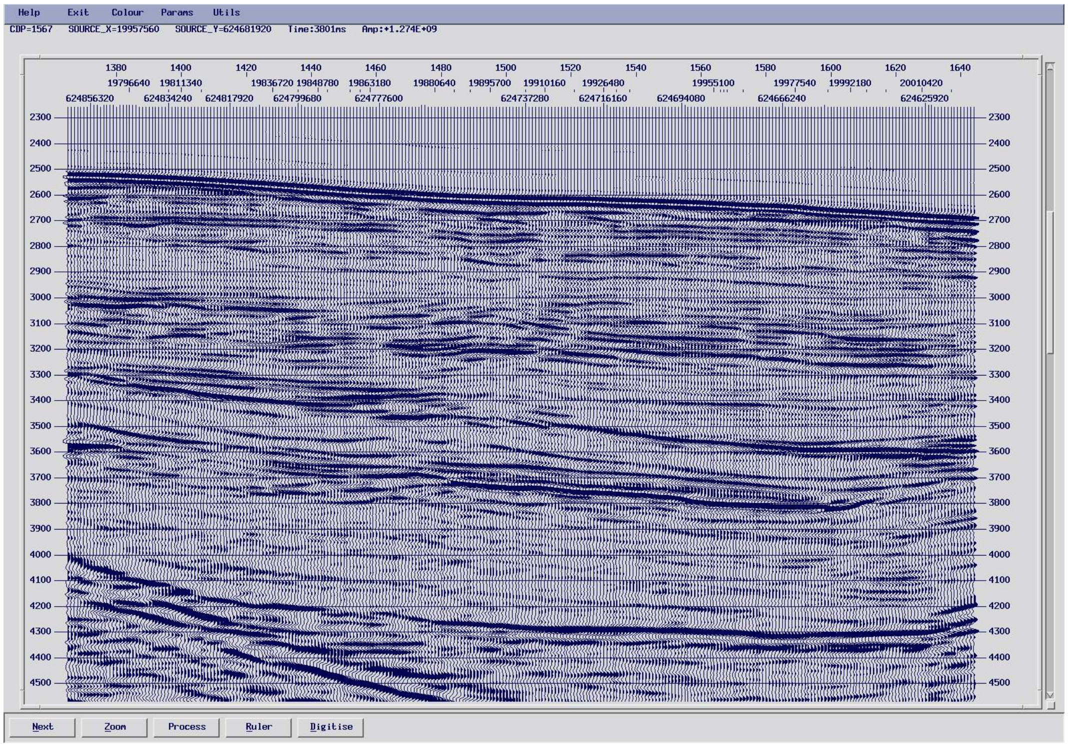


Figure 3.4: *The upper section is well faulted but the strong reflector at 3600-3700 ms remains largely unbroken and is therefore a barrier to hydrocarbon migration.*

3.3 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. However, higher energies are required to bring in coarser material. So 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 imaged by the seismic data. This again is a subjectively measured parameter and as with migration care was taken to ensure consistency across different locations. There were some problems with lack of reflected energy in the shallow parts of some of the sections and examples of this are shown in the results section. Figures 3.6-8 below show examples of some of the reservoirs encountered. Images of the full range of values which were used as a benchmark for the assessment can be found in Appendix 2.

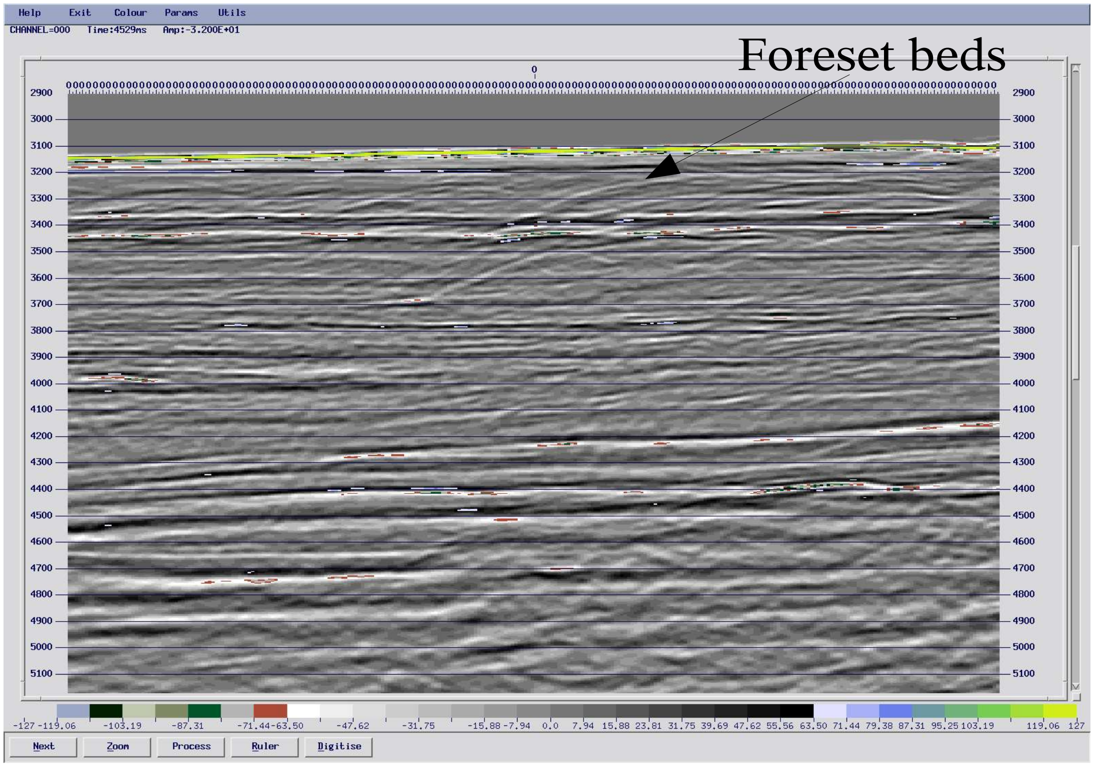


Figure 3.6: *Variable density plot showing foreset bedding in the upper section between 3400 ms and 3200 ms.*

Figure 3.6 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 deeper part of this section (3800-4300 ms) illustrates the difficulties involved in making this kind of interpretation on poorly migrated data. There are dipping features in this section which are not real but the result of diffractions.

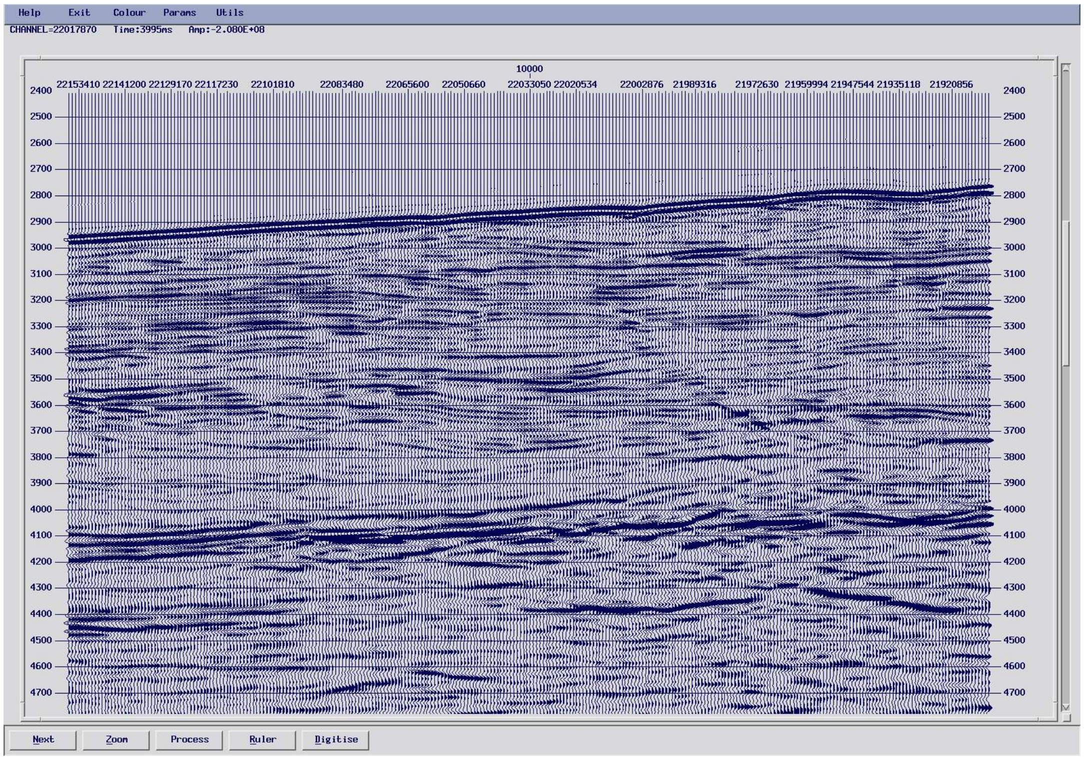


Figure 3.7: *Seismic section showing higher energy sediment in the top 200 ms below the seabed, particularly on the right hand side of the image.*

Figure 3.7 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 3.6, it is distinctly different from the parallel strong reflections seen in the shaley sections of Figure 3.8. 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 3.8 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 ms (left side). There is some evidence of foreset beds in this unit but 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 HSZ. This will allow the pore water to become supersaturated with methane at lower flux rates and thus promote the formation of hydrate.

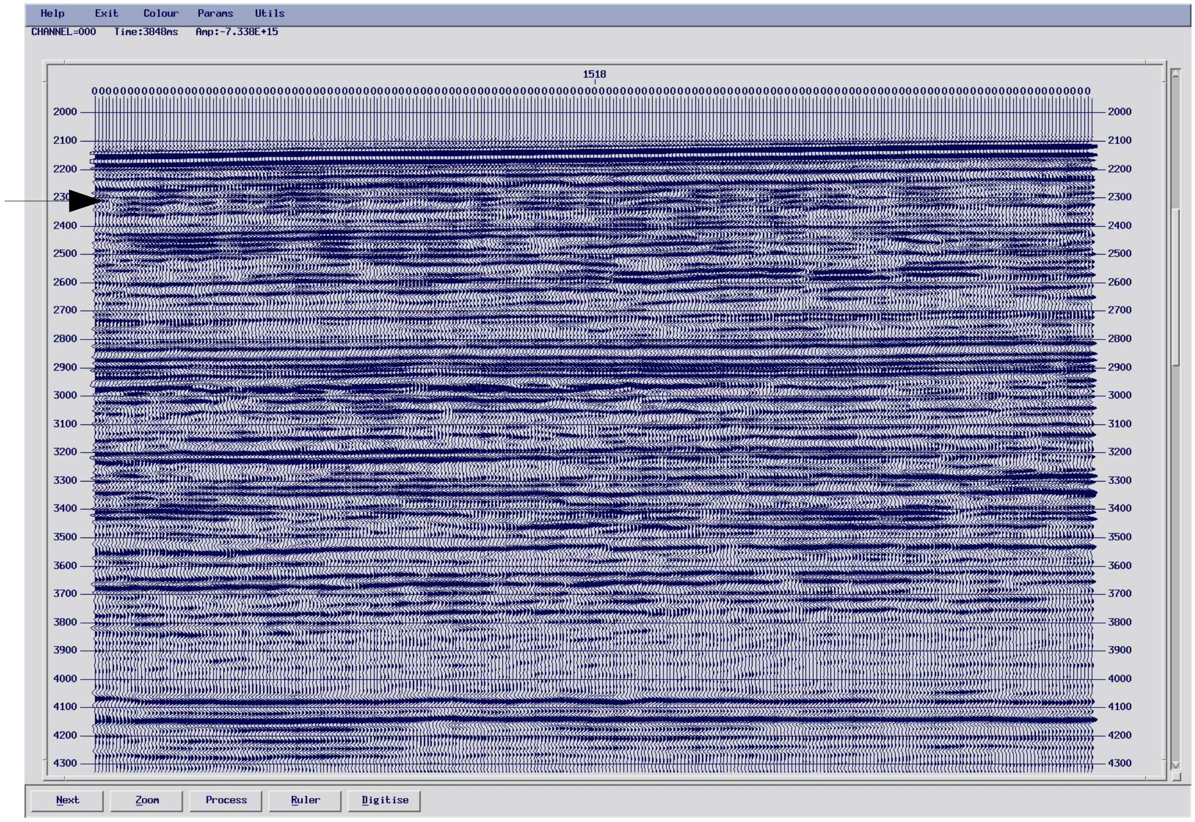


Figure 3.8: *Possible sandstone reservoir overlain by a thin veneer of shale.*

The overall risk assessment result for each of the seismic sections analysis is found by multiplying the values measured by each other giving a theoretical range of 0-1 as in the individual assessments. In practice, multiplying three decimal values together tends to result in low values, e.g., a value of 0.7 out of 1 is prospective for any of the parameters but which scores 0.7 for all three parameters will have an overall risk assessment value of 0.34. This was taken as the general cut off point above which areas are considered to be prospective or merit further study. It should be noted that achieving this value or higher does not mean that the area scored over 0.7 for each parameter.

4 Results

The results or the risk analysis will be documented survey by survey in this section. The Rockall and Porcupine Basins were dealt with separately as they were found to have different HSZs and levels of prospectivity. Maps are presented along with a description of the highlights from the survey in question. Some sample seismic sections from the most prospective areas are also presented.

The seismic lines were split up into 280 common depth point (CDP) sections for analysis with each section reviewed on the basis of the risk assessment parameters detailed above. In all just over 5000 individual sections were assessed for the study. The location of each of the sections was taken from the headers of the seismic traces and converted from a mixture of UTM zones 28 and 29 to digital geographic (latitude and longitude) co-ordinates. The maps in this section are plotted using GMT (Wessel and Smith, 1998) in UTM zone 29.

4.1 1995_08-E95IE07

This survey shown in Figure 4.1 covers a small area on the eastern margin of the Rockall Basin north west of Donegal.

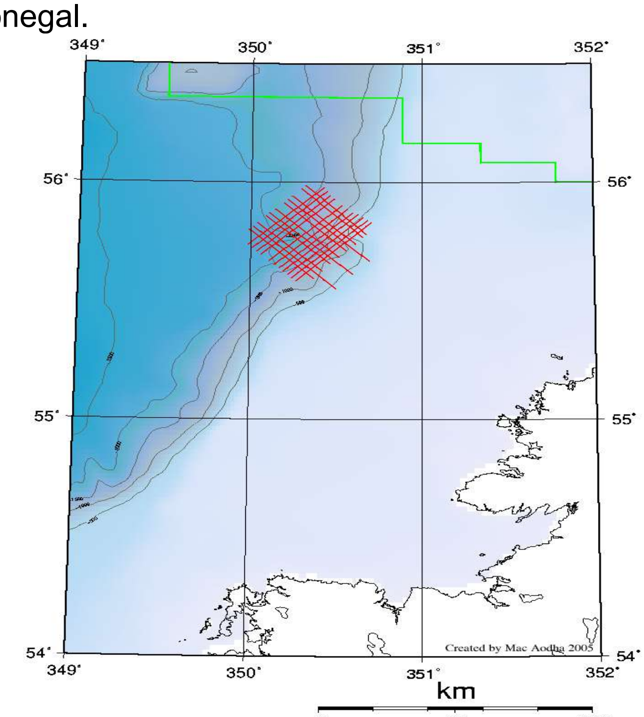


Figure 4.1: *Location map for survey 1995_08.*

The data quality is good in the first 1-1.5 s below the sea floor but drops off below this. It is probable that all the faults were not clearly imaged and therefore, the migration risk assessment values measured will be lower than the true value.

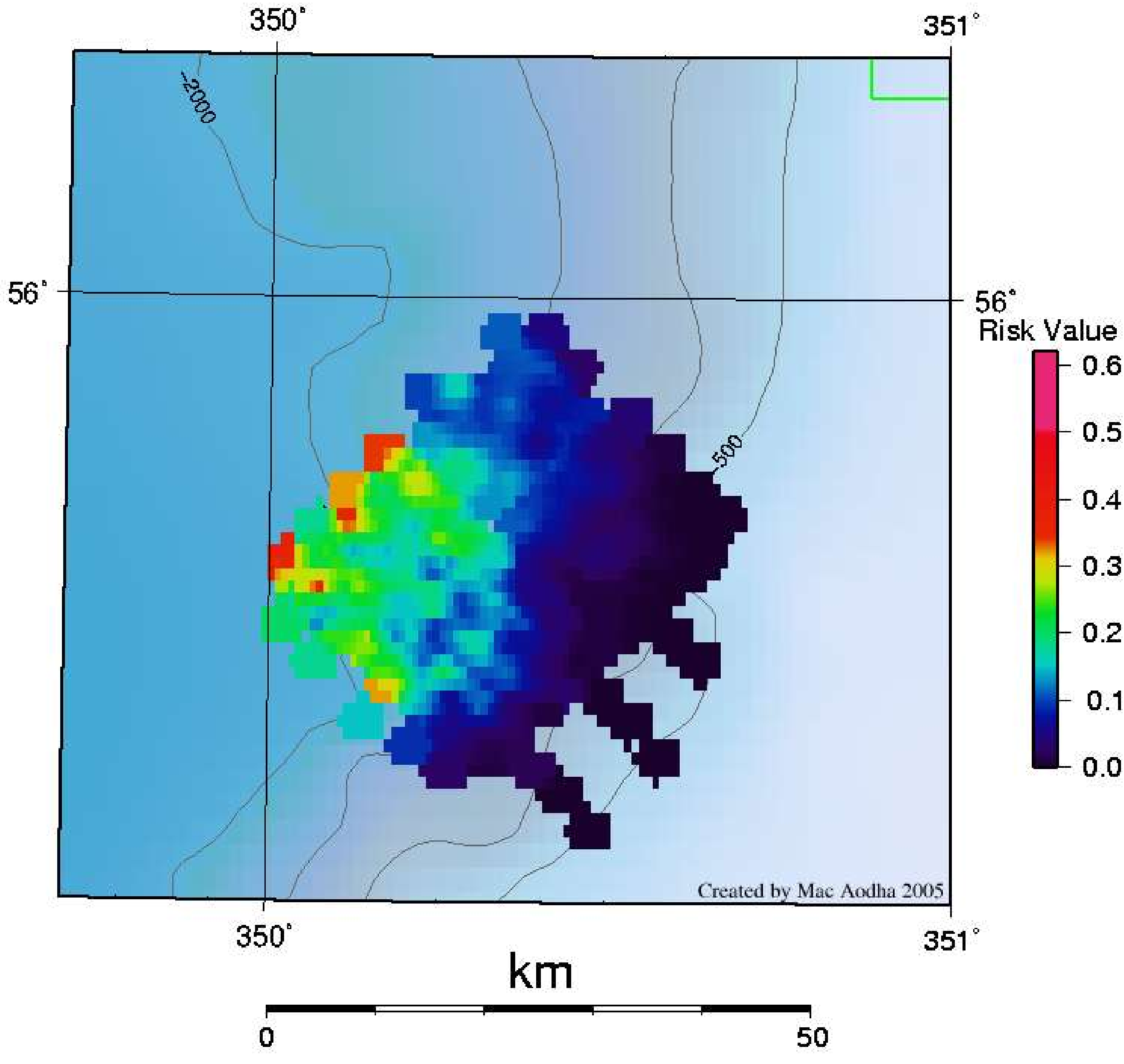


Figure 4.2: *Results of the risk assessment from Survey 1995_08-E95IE07.*

Most of the survey area has some prospect of hydrate formation with 92% of the points analysed lying within the HSZ. However its location on the margin of the basin means that only 6% of the area scored a HSZ assessment of greater than 0.7. The location of the survey on the margin on the basin dictates that there is some faulting as part of the structural control. However, as mentioned above the quality of the data in the lower section was poor and only 13.5% of the sections analysed scored greater than 0.7. This may be an underestimation of the true value. Its position on the basin margin means that it is within transport range of coarser sediment. This is corroborated by the reservoir potential with 20% of the survey scoring over 0.7.

There are a couple of key locations in this survey which have a high potential. Four separate locations scored risk assessment values of 0.34 or higher. Shown in Figure 4.2 they all lie in the western part of the survey where the water is deeper than 1500m and the HSZ is thickest. Figure 4.3 shows the seismic data from one of these locations. The HSZ calculated at this depth is 530 ms below the seabed. The base of the HSZ is at 3400 ms on the right of the image (marked in green). This is deep enough to encounter the dipping reflections on the right of the image between 3200 and 3700 ms which are interpreted as coarser material with good reservoir potential. The upper part of this section is broken by three dipping faults which are a possible migration pathway. While no clear faults stand out on the lower part of the section it is worth noting that main horizons at this level are broken and un-continuous. They would not form an effective seal to stop gas migrating up through the system.

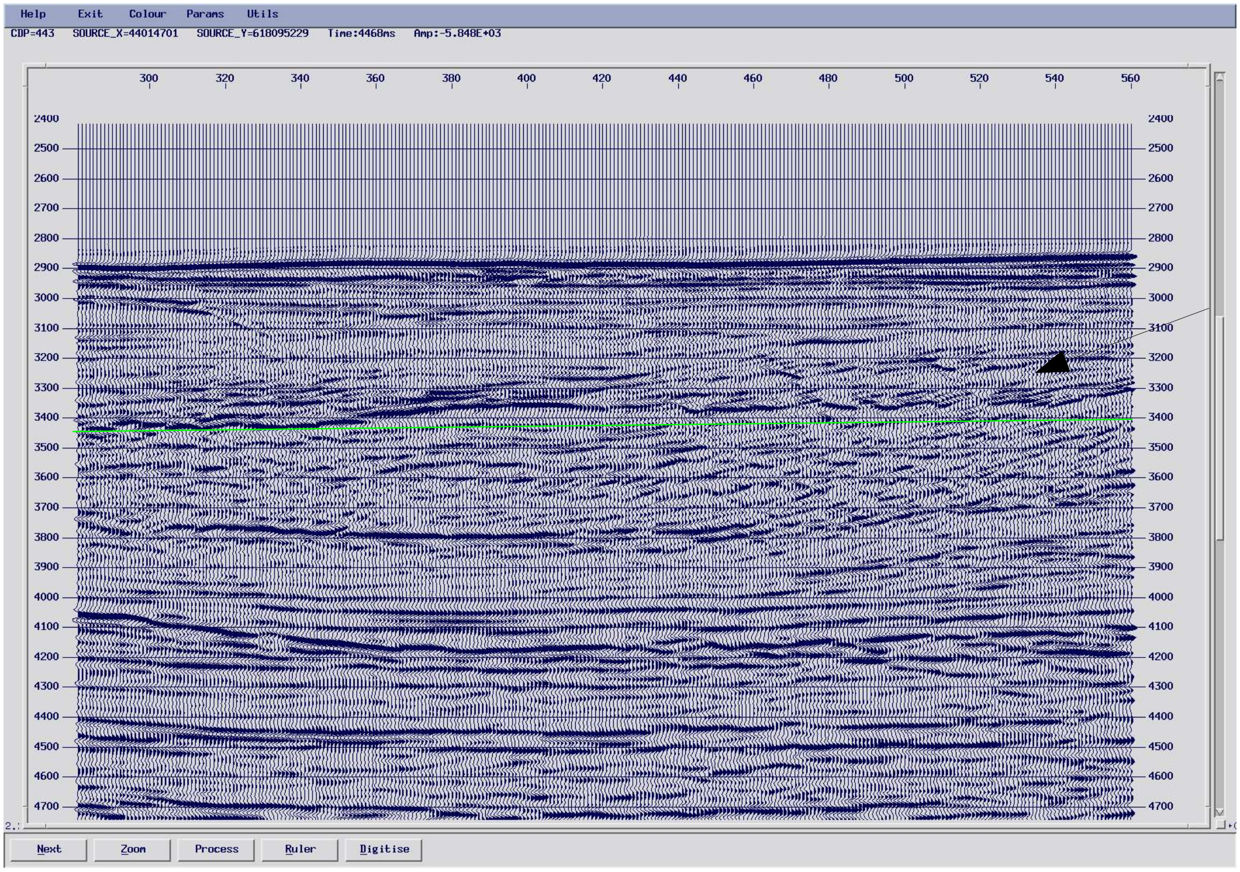


Figure 4.3: *Image from 1995_08 showing possible high quality reservoir. The HSZ was calculated at 500 ms thick for this location. The calculated base of the HSZ is shown in green.*

4.2 1996_01

This survey, shot by GECO-PRAKLA, consists of a series of broadly spaced regional lines along the western margin of the Porcupine Bank with one line extending across the entire Rockall Basin. The location of the lines is shown in Figure 4.4.

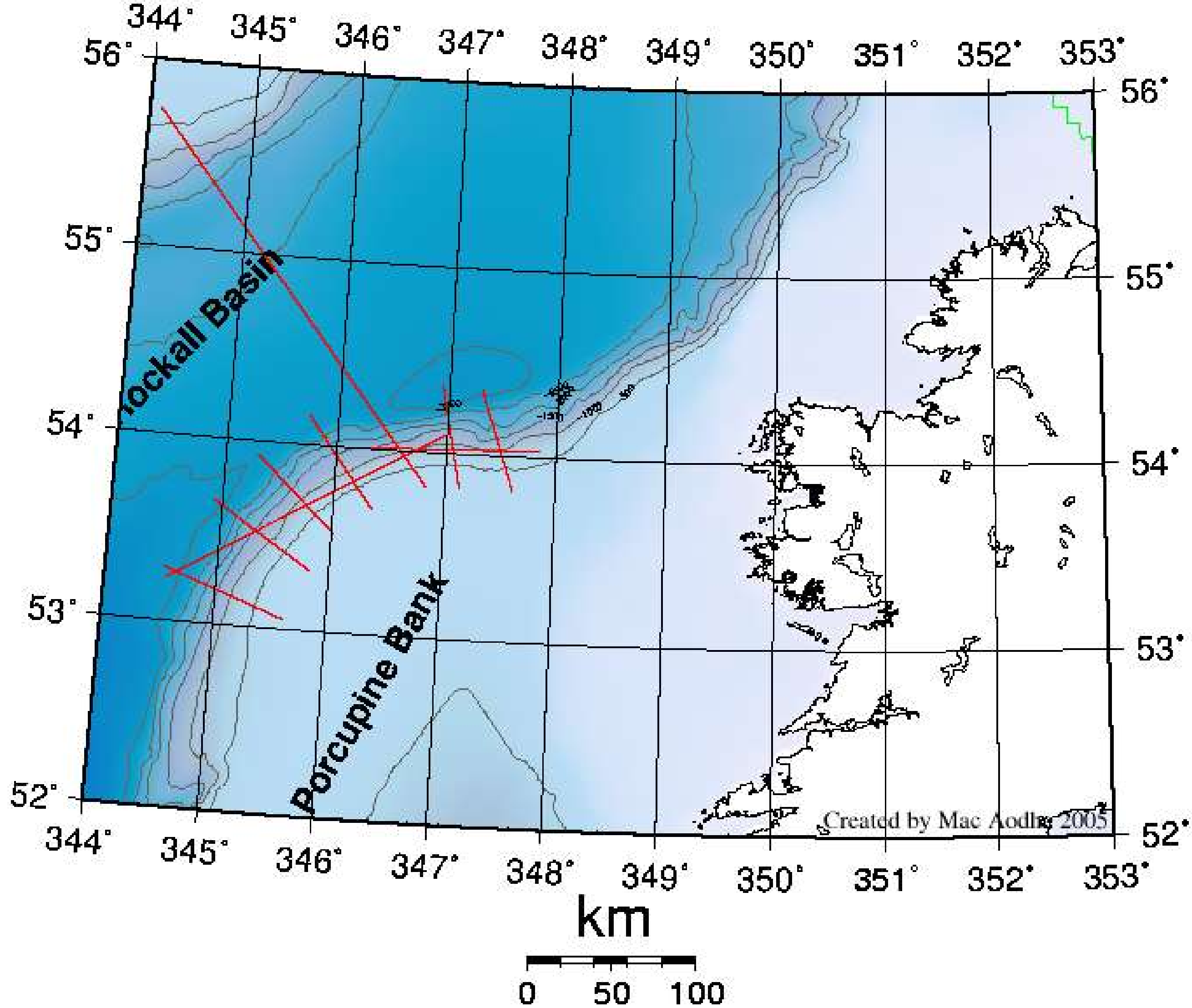


Figure 4.4: *Location map for survey 1996_01.*

The data from the survey are of good quality with features imaged well below the HSZ. This allowed a clear assessment of migration pathways to be made. There is a lack of reflected energy in the upper 300-400 ms of the section particularly in the Rockall Basin. This may be due to the homogeneity of the sediment but it is suspected that some of the higher frequency energy has been removed from the data (or not recorded).

While the area covered by this survey does include some of the shallower Porcupine Bank, 82% of the data points are within the HSZ, with 38% scoring higher than 0.7. Despite the survey crossing the margin only 2% of the data point scored higher than 0.7 for migration.

This can be partly attributed to the structural style of the eastern margin of the Rockall Basin at this location. It is controlled largely by a single localised normal fault system with a rapid transition over a small area. Some of the most useful migration pathways are associated with buried Mesozoic fault blocks (Naylor *et al.*, 1999) just inside the basin. Faulting in the sedimentary succession is much more pronounced in the central part of the Rockall Basin than in the area of the basin proximal to the Porcupine Bank. The reservoir potential is not good in general with only 7% scoring over 0.7. The best potential occurred at the base of the slope. The results are shown in Figure 4.5.

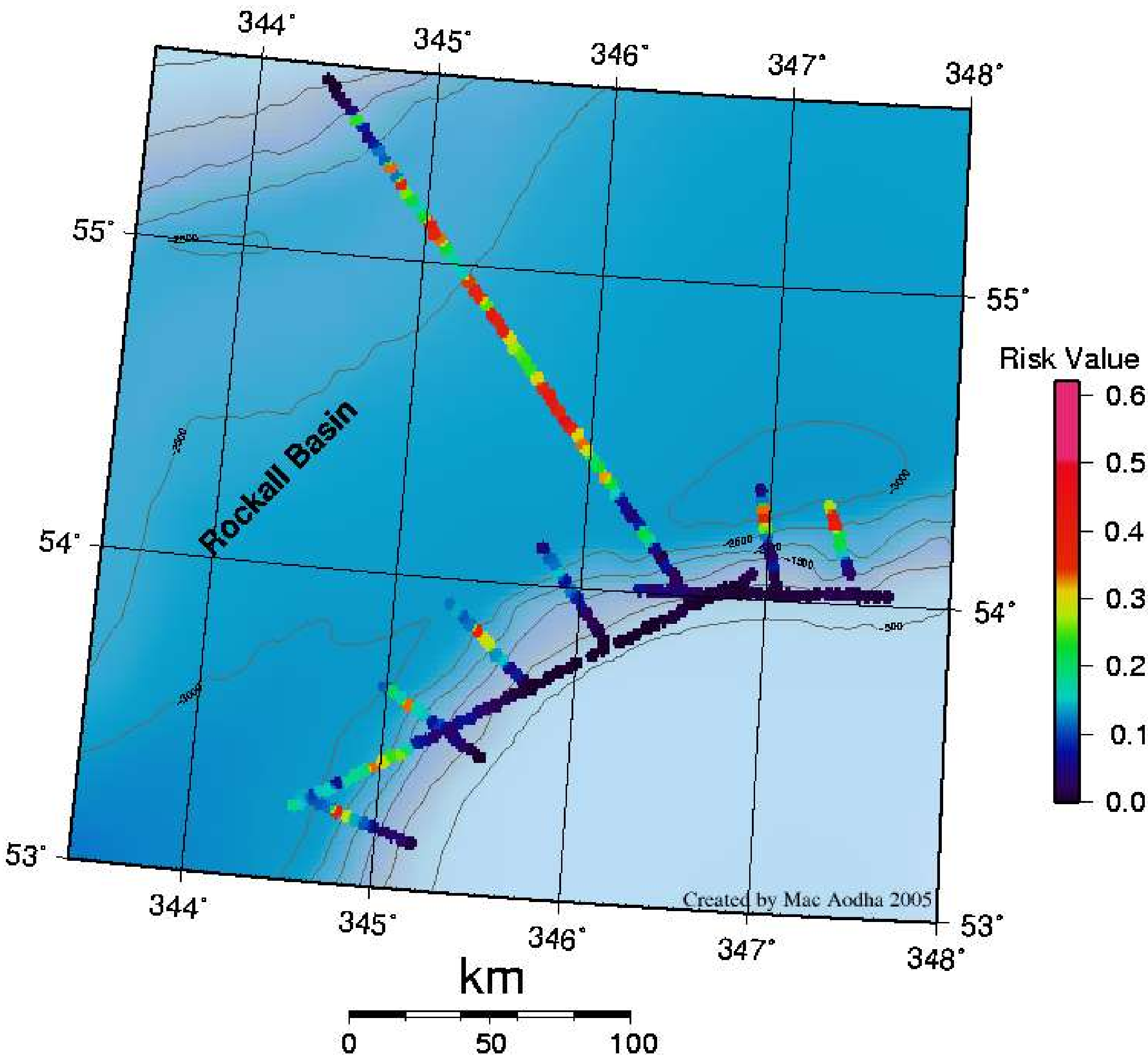


Figure 4.5: *Results of the risk assessment from Survey 1996_01.*

From Figure 4.5 it is clear that there are few discrete locations close to the Porcupine Bank as well as large areas in the centre of the Rockall basin which have good resource potential. GSR96_116, which is the line which crosses the basin, is interesting as it is reveals that, as well as having migration pathways, a large area of the basin has a continuous sedimentary package which may have reservoir potential. The layer (Fig. 4.6) is consistently at about 150-200ms below the sea floor and varies in thickness from 100-400 ms. While this would not be interpreted as the best quality reservoir, it is the most aerially extensive and for the most part lies entirely within the HSZ.

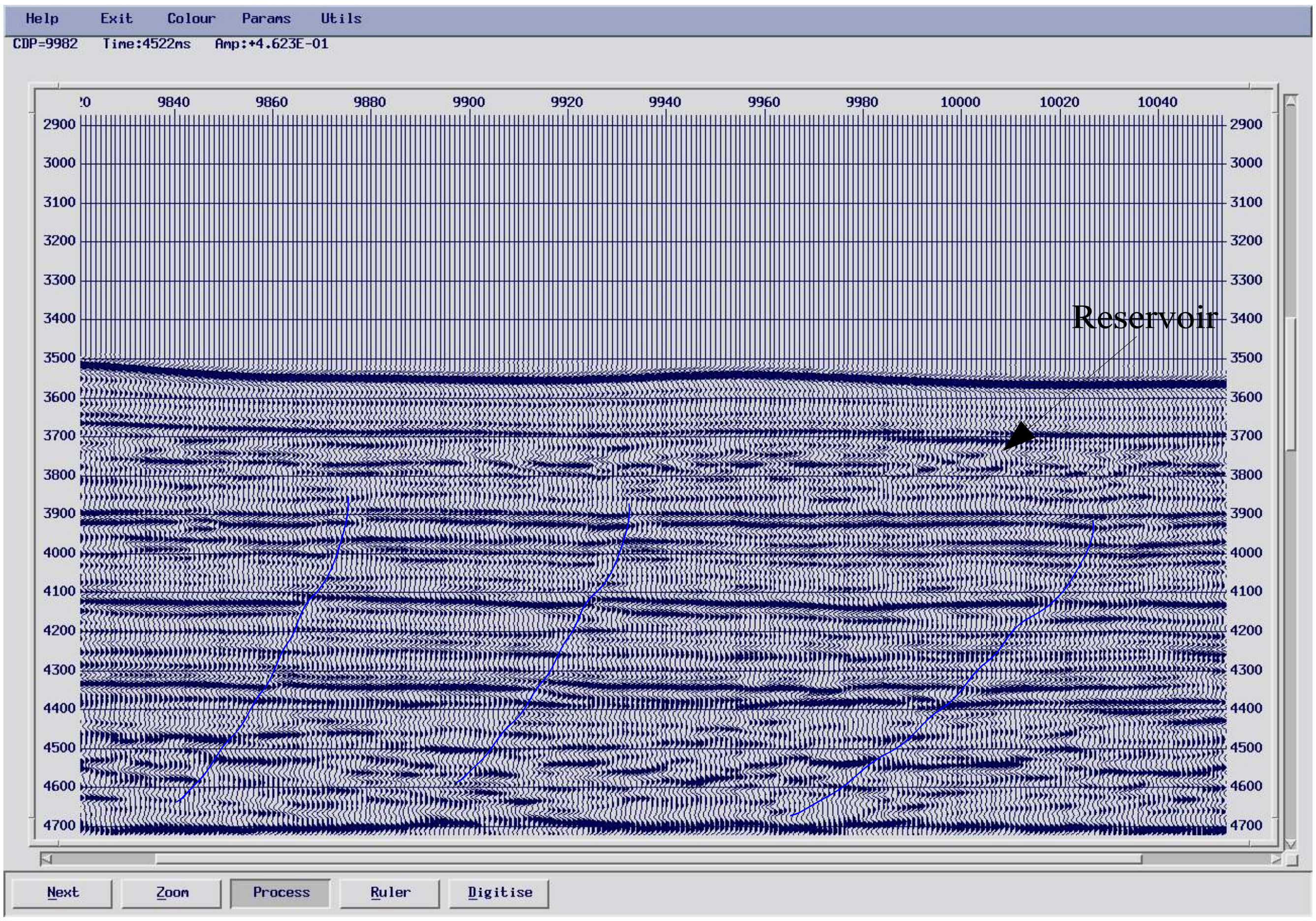


Figure 4.6: *Section of GSR96_116 from Survey 1996_01 showing a 200 ms thick potential reservoir which is extensive in the centre of the Rockall Basin. The image also shows three faults providing migration pathways to the reservoir.*

4.3 1996_03

This Fugro-GeoTeam survey provides a broadly spaced regional overview of the NW margin of the Rockall Basin (Fig. 4.7). It images the gradual margin between the Rockall High and the Basin, including the perched Conall and Ronan Basins.

The data are of good quality with the lower parts of the sedimentary succession clearly imaged and good resolution in the upper section. Some parts have, however, been over migrated, leading to dipping artefacts which obscure some of the section. The problem is limited to a few areas.

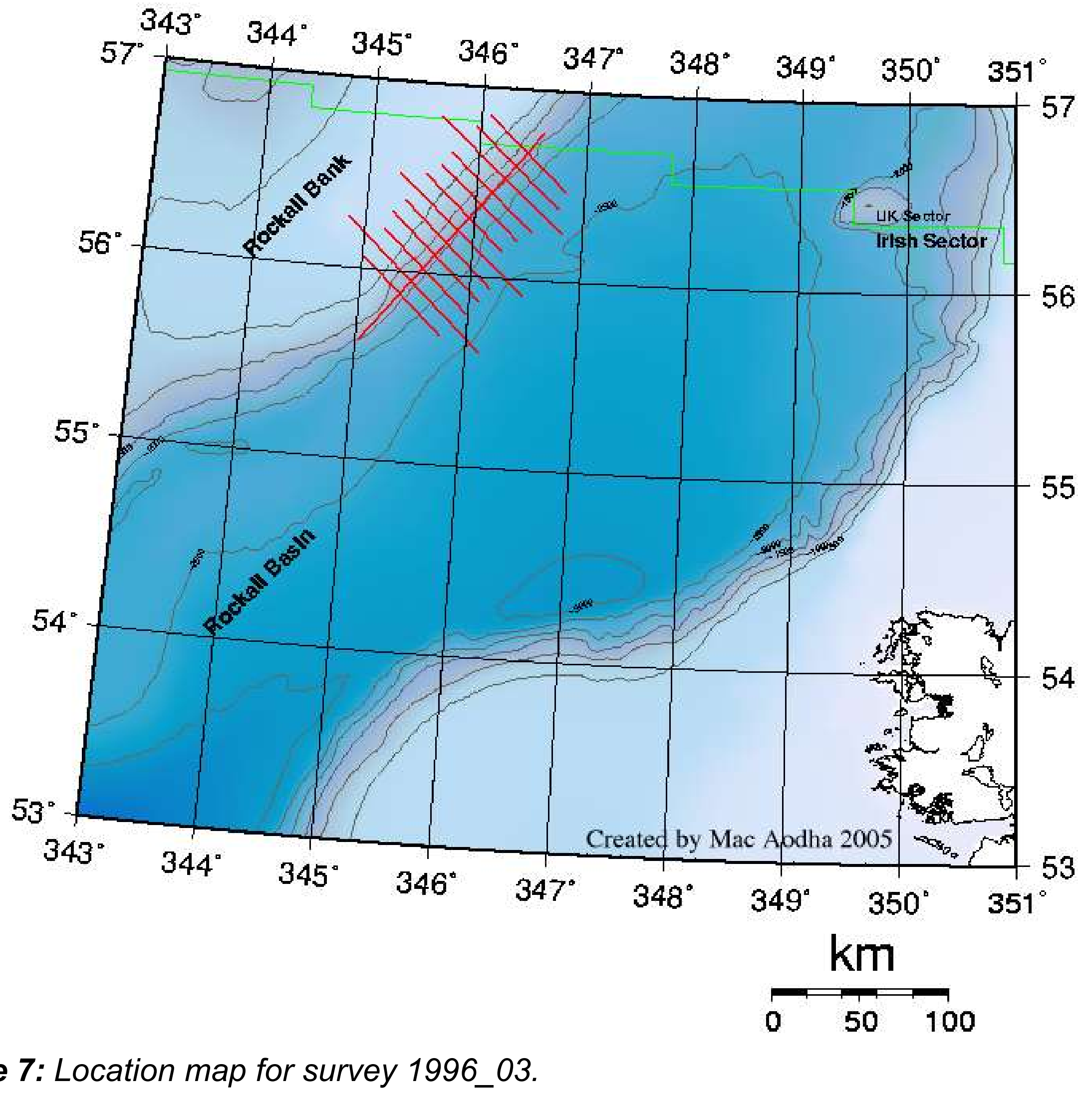


Figure 7: *Location map for survey 1996_03.*

A lot of the survey area is on the upper part of the slope and the Rockall High with water depths of less than 1000 m. The HSZ only scored highly in the eastern ends of the lines; this did, however, count for 20% of the points analysed. The different structural style of the western margin of the basin has resulted in much higher migration scores for surveys on this margin compared with the eastern margin. In this survey 19% of the data points scored 0.7 or better. This score implies a fault system which allows migration right up through the system. The reservoir quality is not as good with only 3% of the area scoring over 0.7. A further 9% did score over 0.6 which, combined with the high migration and HSZ scores, resulted in 9% of the data points scoring greater than 0.34 in the overall assessment. As can be seen from Figure 4.8 these prospective areas are concentrated in the eastern side of the survey.

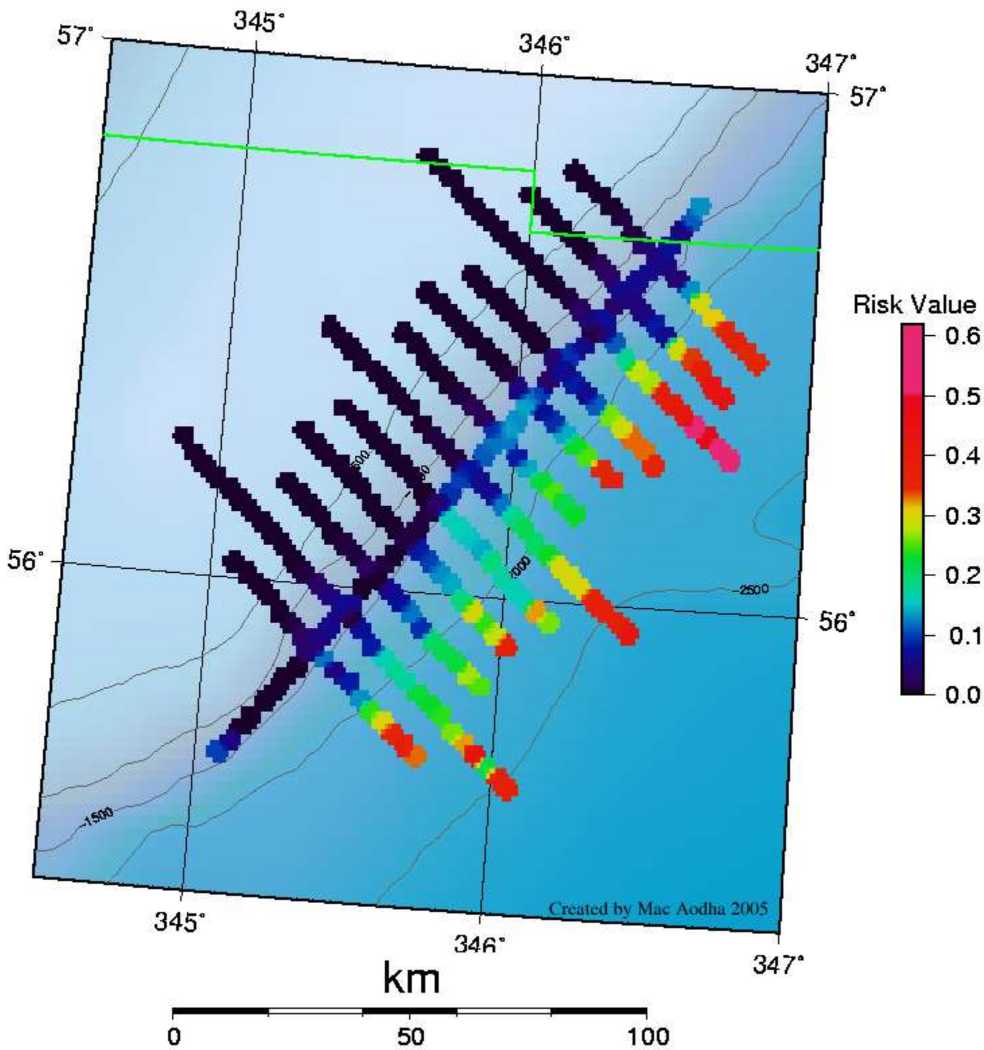


Figure 4.8: *Results of the risk assessment from Survey 1996_03.*

Figure 4.8 shows a broad prospective area in the north east corner of the survey area. This included four particularly high scoring areas (pink) which scored between 0.49 and 0.6. An example from this area is shown in Figure 4.9. The HSZ (green line) at this location is calculated to be 495 m thick which corresponds to 570 ms below the seabed. The section is faulted on both the left and the right of the image and there is an absence of an unbroken reflection which could act as a seal. The upper 200 ms of the sedimentary section, while unclear, is interpreted as having reasonable reservoir potential. Combined with this are units of dipping beds seen between CDP 1080 and 1100 at a depth of 3700-3900 ms and again between CDP 1160 and 1220. While the faulting makes it difficult to properly judge the quality of the lower reservoirs, this is a good example of the high level of prospectivity in the area.

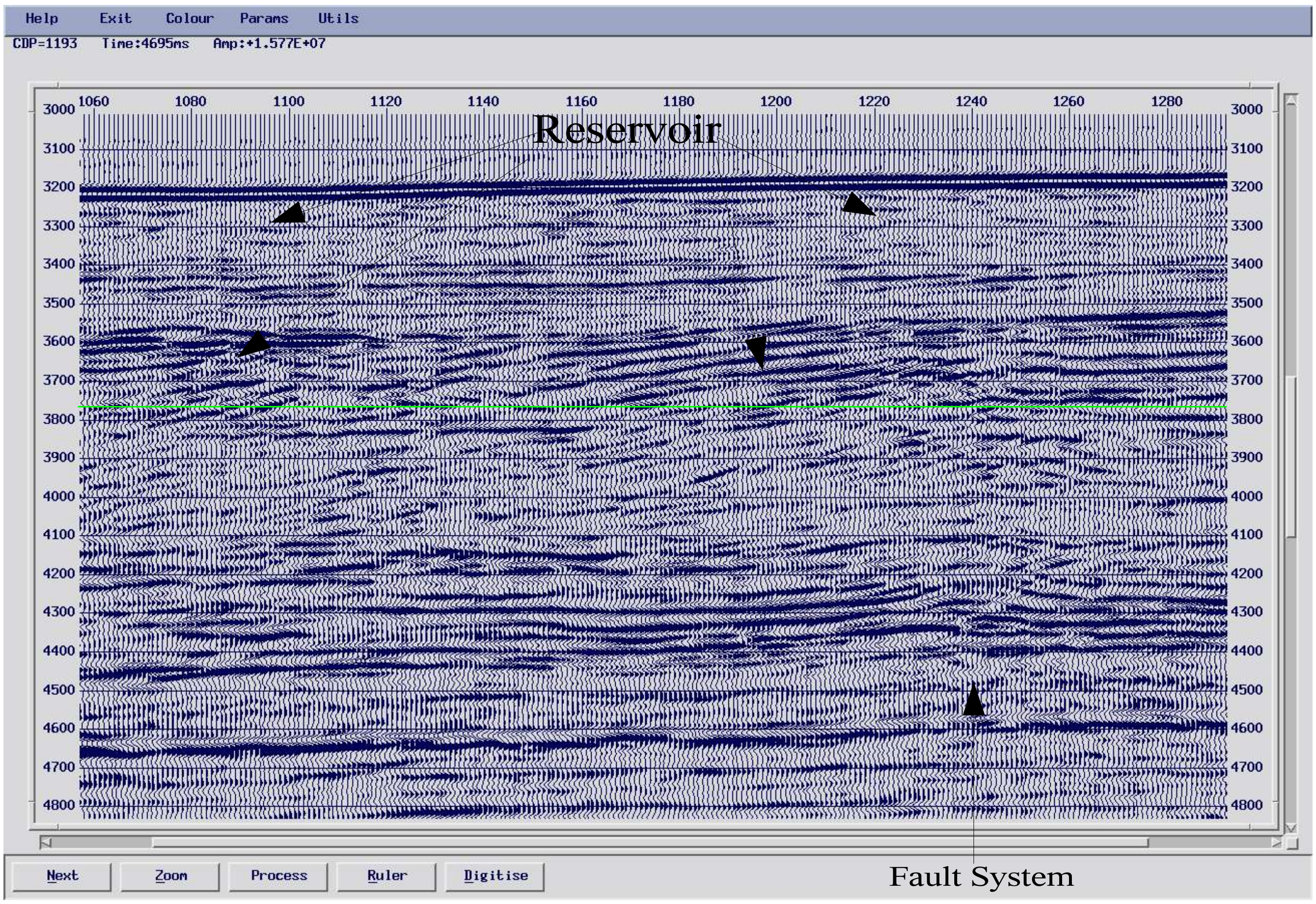


Figure 4.9: *Image of a highly prospective area from 1996_03 showing good migration and reservoir potential in an area with a HSZ 495 m thick.*

4.4 1996_07

This survey shot by Spectrum comprises two distinct subsets INROCK and ISROCK which cover different areas of the eastern Rockall Margin. The two will be dealt with separately.

4.4.1 INROCK

This section of the survey covers an area of the eastern margin of the Rockall Basin just to the south of the boundary between the Irish and UK sectors (Fig. 4.10).

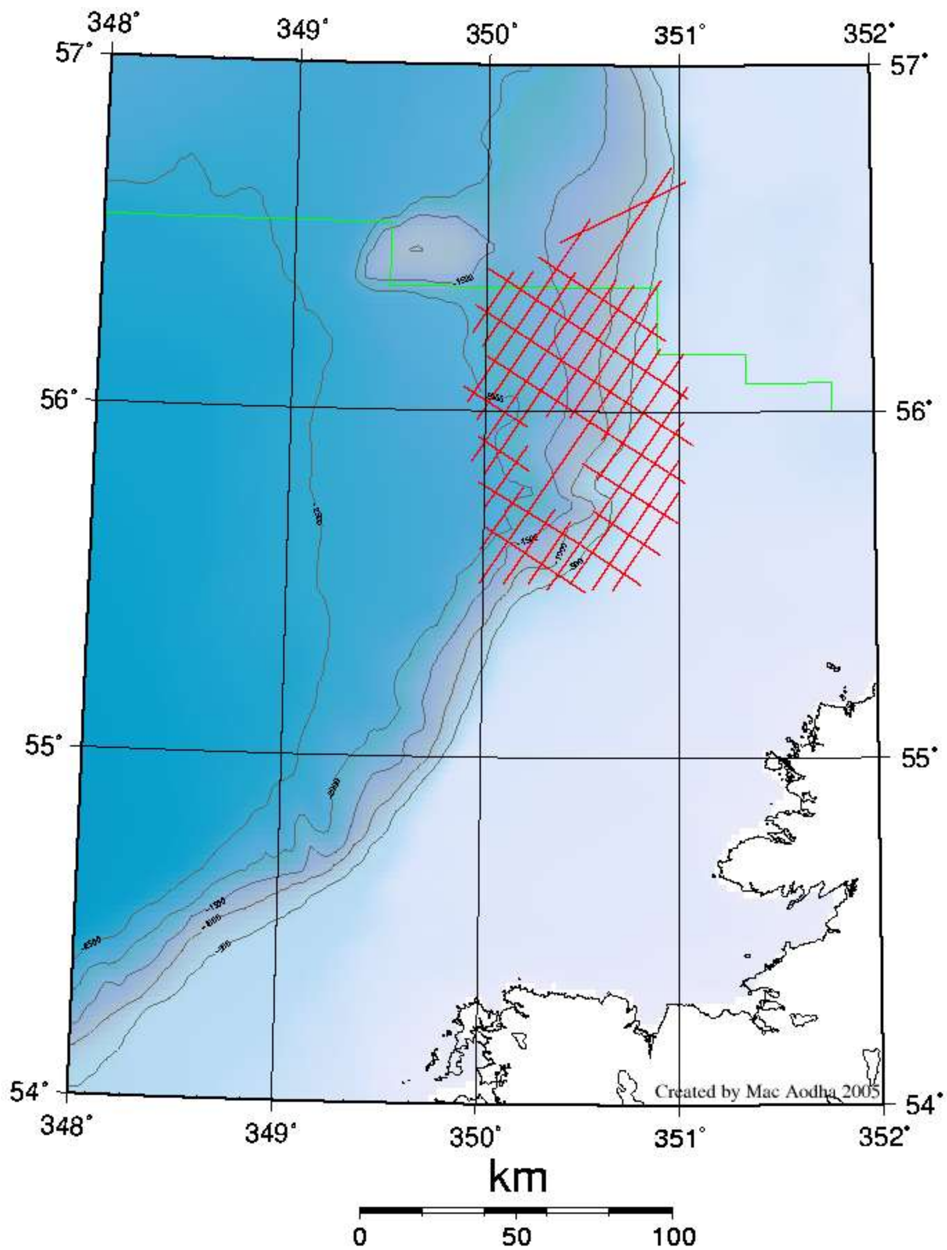


Figure 4.10: *Location map for survey 1996_07 INROCK.*

The data quality is high with good resolution throughout the section. This section of the survey covers an area predominately on the margin and encroaching onto the adjacent shelf. With very little of the area on the basin floor, the HSZ values are generally low. Five percent of the data points scored better than 0.7 compared with 37% which were in areas too shallow to be within the HSZ. The values for migration and reservoir potential were also low both with only 4% scoring better than 0.7. This is reflected in the results showing in Figure 4.11 below with only two small areas in red showing high potential.

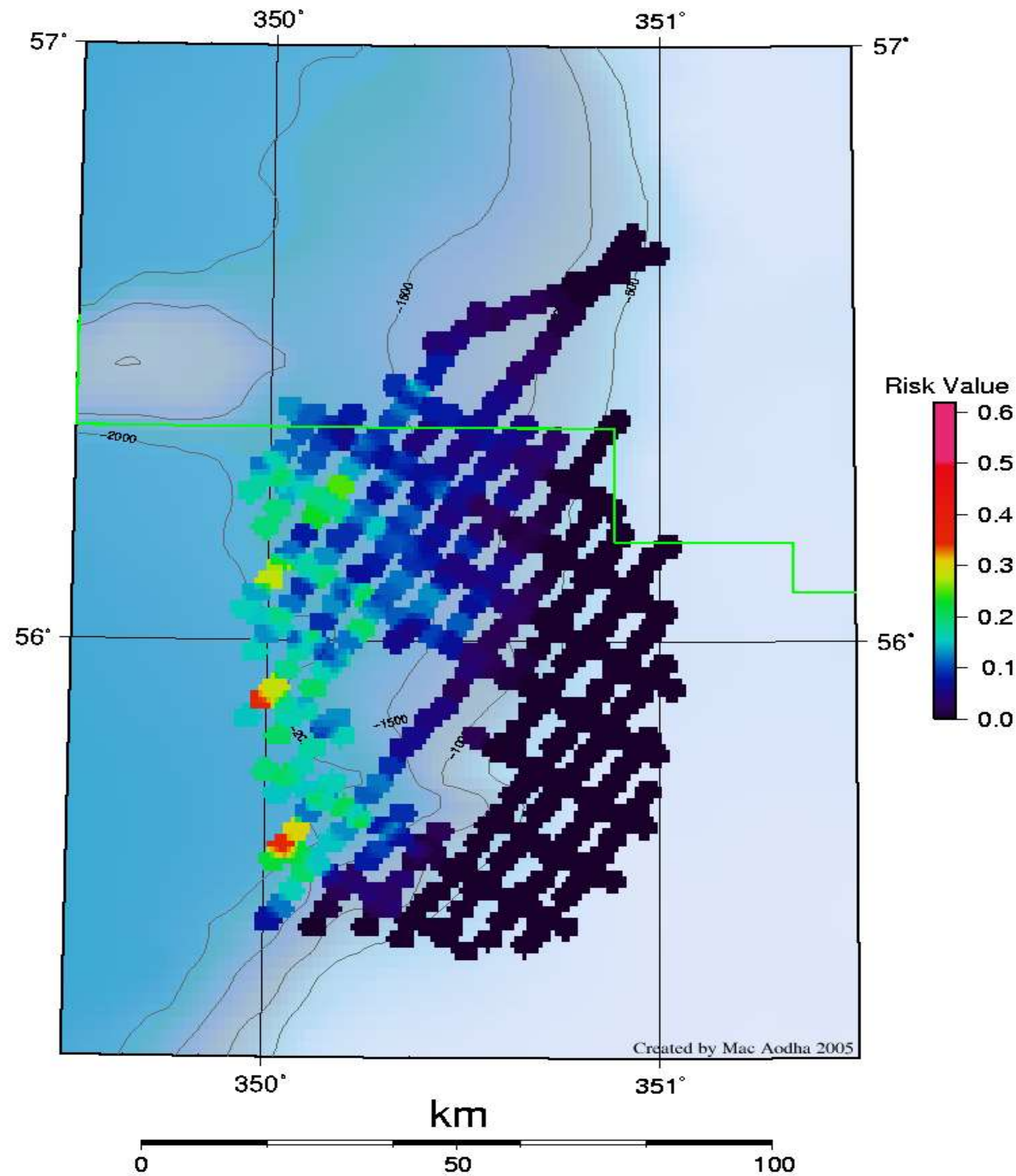


Figure 4.11: *Results of the risk assessment from Survey 1996_07 INROCK.*

4.4.2 ISROCK

This section on the survey shown in Figure 4.12 provides regional coverage of the western flank of the Porcupine Bank. Like the INROCK survey a lot of the data is situated high up on the margin and on the adjacent shelf and hence is not prospective.

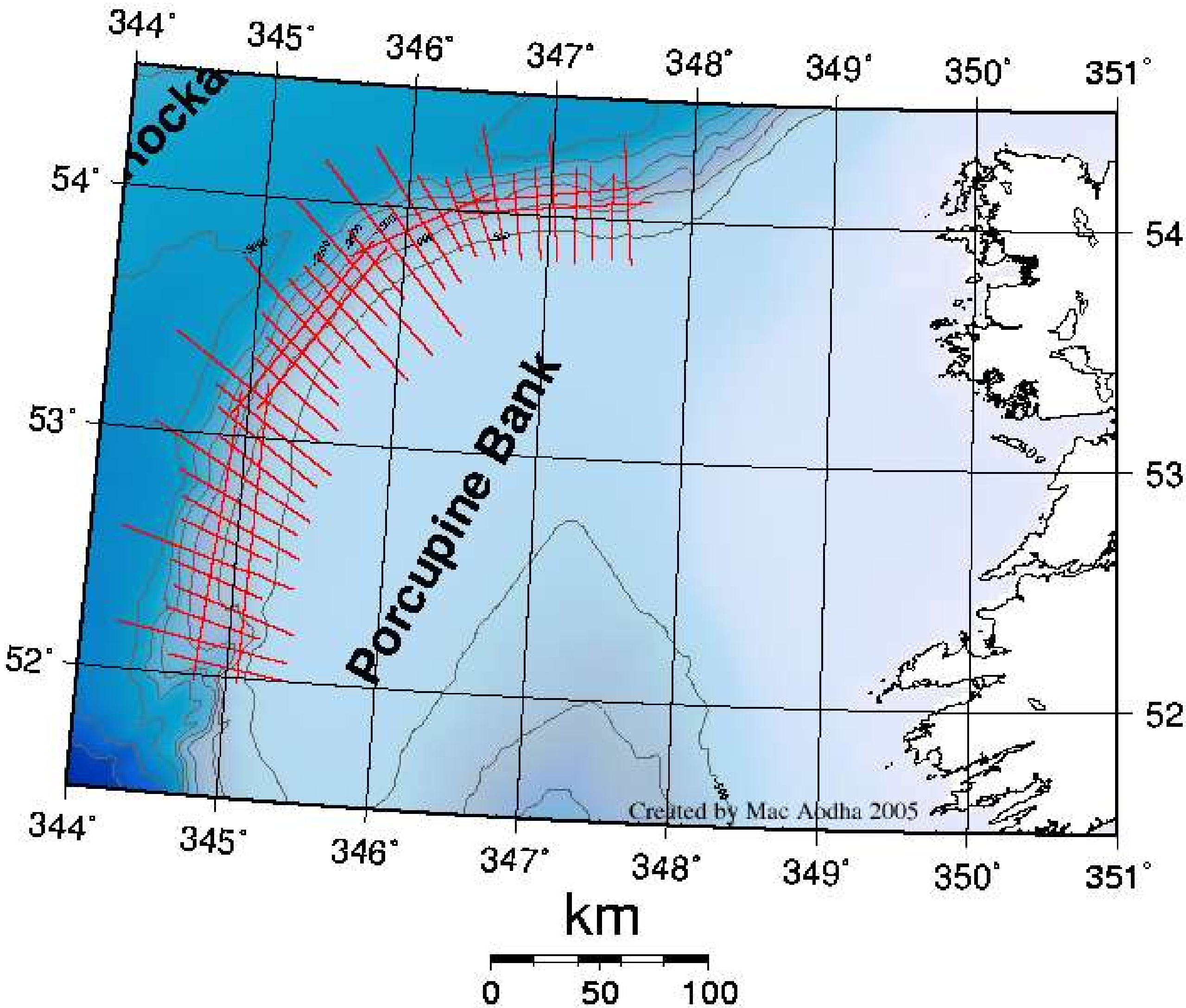


Figure 4.12: *Location map for survey 1996_07 ISROCK.*

The data quality of this part of the survey matches that of the INROCK leg with good resolution throughout the section. HSZ values are not as low as INROCK due to the narrower steeper margin in this part of the basin; 16% of the area scored over 0.7. Migration values were very poor with only one locality out of 789 sample locations scoring over 0.7. This is part of a pattern where migration pathways are in general very poor in the south east of the Rockall Basin. Reservoir potential was also poor with only 12 of the 789 data point exceeding 0.7. This is reflected in the results, plotted in Figure 4.13, which show only two prospective locations, of which at least one is very localised.

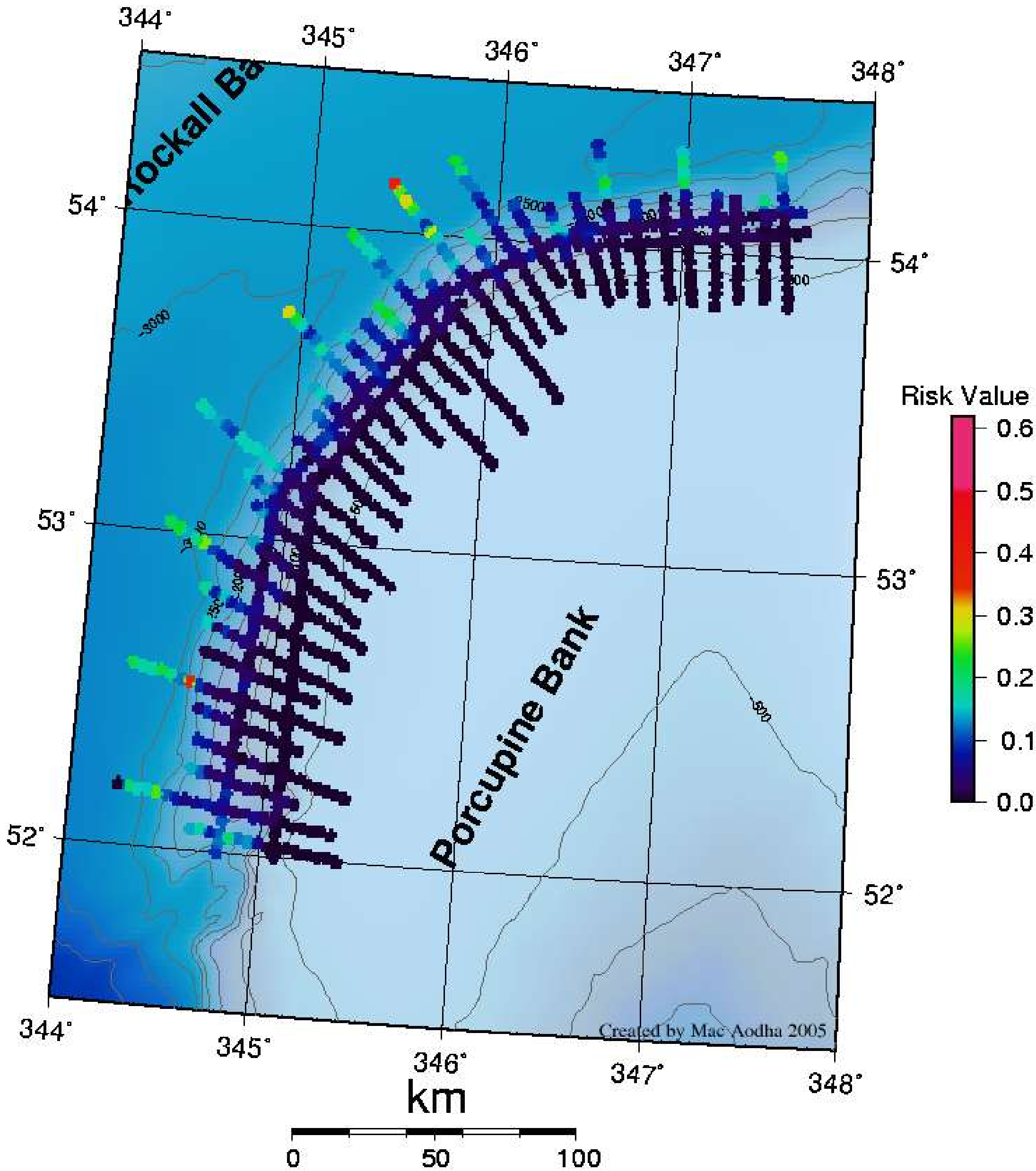


Figure 4.13: *Results of the risk assessment from Survey 1995_08-E95IE07.*

4.5 1996_15

This survey provides regional coverage of the eastern margin of the Rockall Basin north of the Porcupine Bank (Fig. 4.14). Shot by Digicon it stretches much further out into the basin than the INROCK data. The data quality is good in general though best viewed with a 300 ms automatic gain control applied.

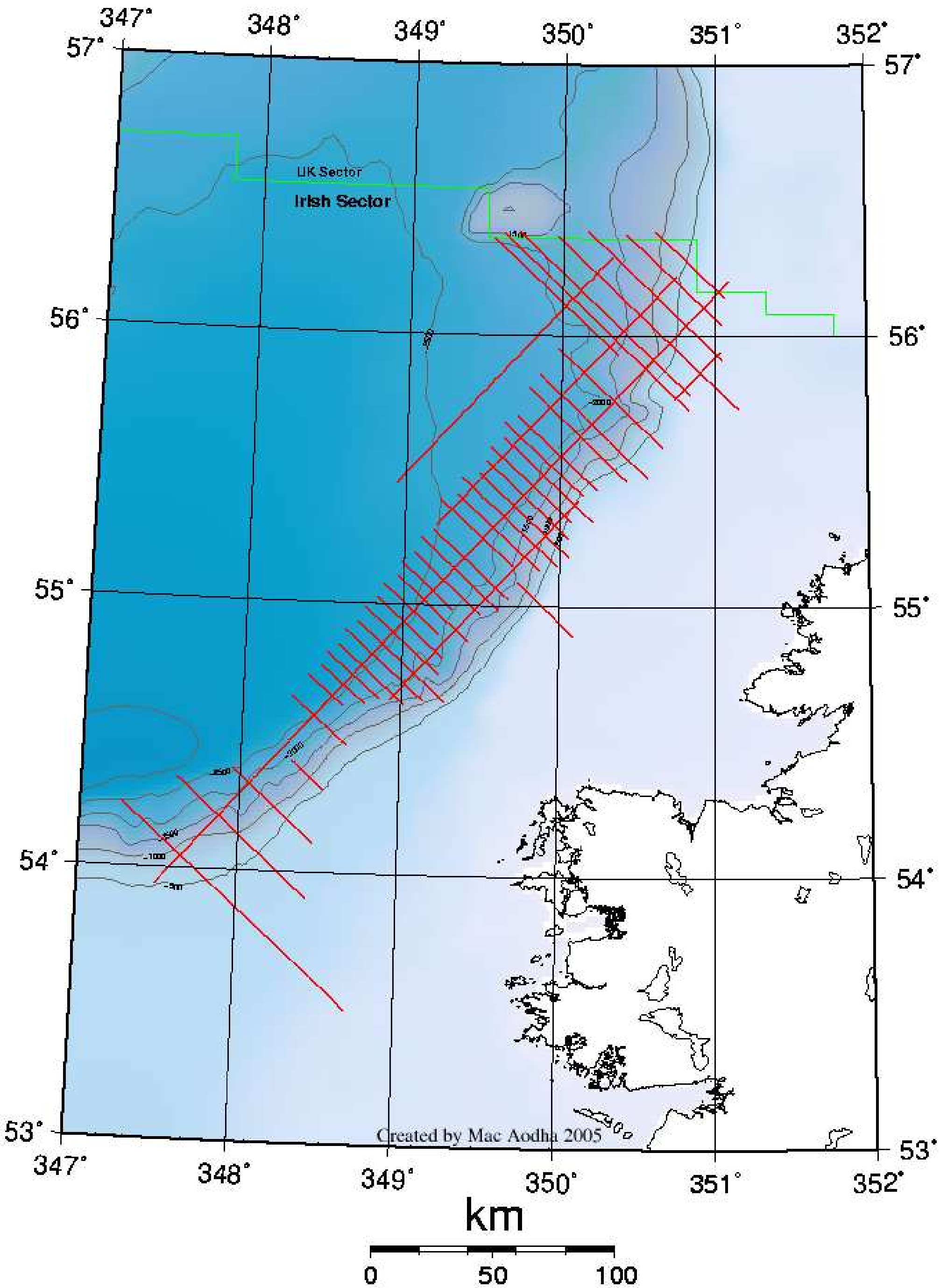


Figure 4.14: *Location map for survey 1996_15.*

The survey extends out to water depths of over 2500 m and this is reflected in the HSZ results with 40% of the data points scoring over 0.7. The migration values were low with only 1% (11 locations) scoring over 0.7 despite the faulting associated with the margin. This area has some of the best reservoir potential found in the study and 13% of the overall area scored over 0.7. The results are plotted in Figure 4.15.

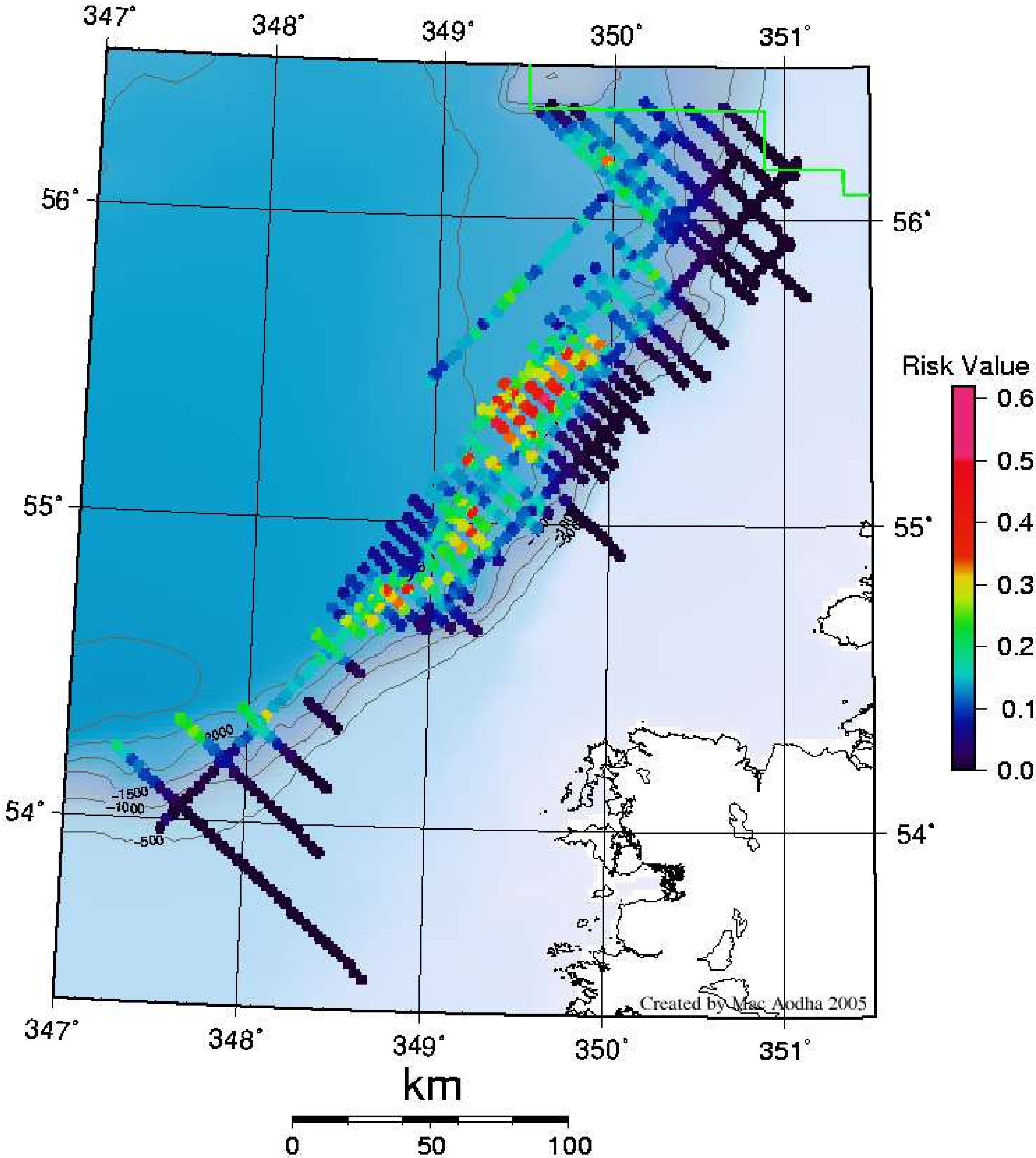


Figure 4.15: *Results of the risk assessment from Survey 1996_15.*

The results show three distinct areas of interest. The largest stretches 40 km between 55.3° and 55.6° N with overall risk assessment values of over 0.5 in some locations. Two other smaller prospective areas lie further south. The area scores well on HSZ with excellent reservoir potential in places, therefore the real controlling factor is the presence or absence of suitable migration pathways. Figure 4.16 is typical of the reservoir potential which exists in the upper section.

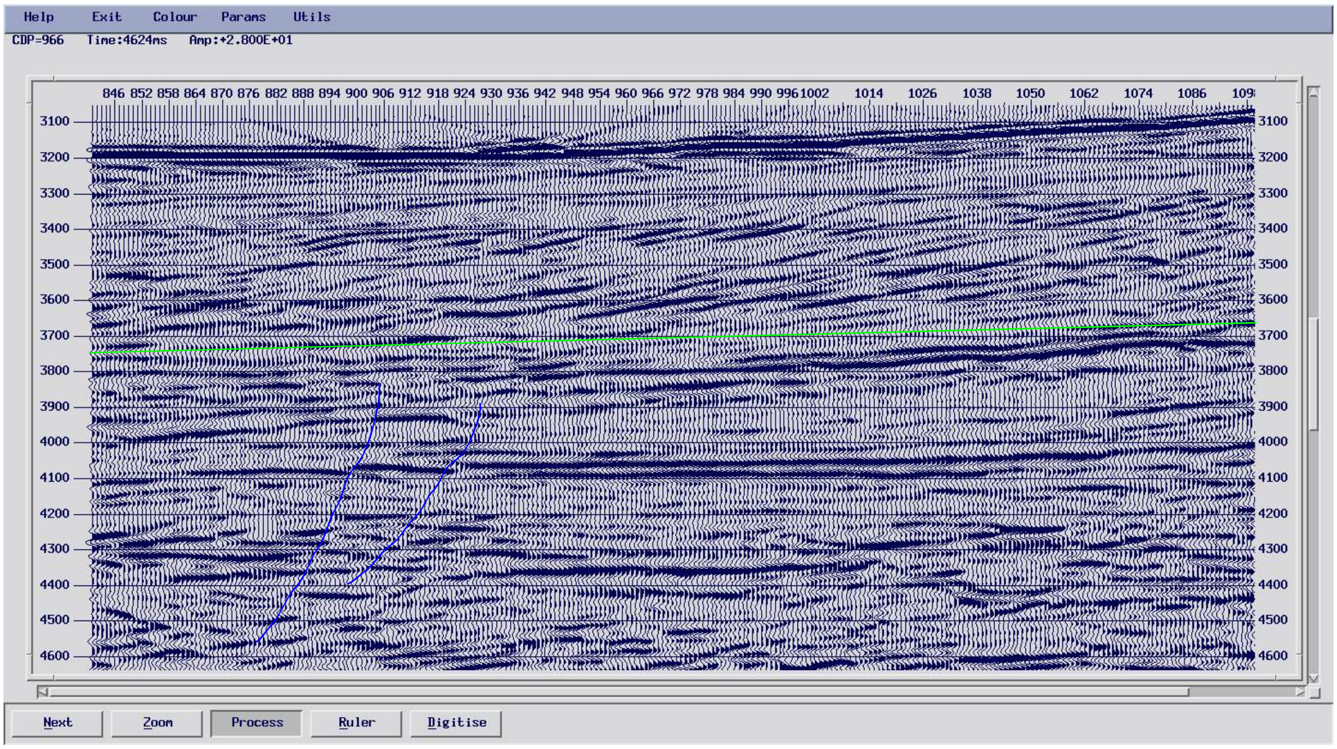


Figure 4.16: *Image of shallow dipping sand/gravel from Survey 1996_15. The HSZ is marked in green.*

The HSZ (green line) calculated for the area imaged in Figure 4.16 is 570 ms below the seafloor. This means that most of the HSZ is comprised of the unit with dipping layers, offering excellent reservoir potential. There is some evidence for two faults (blue lines) below CDP 900 and 912 the reflection just above the 4100 ms line is offset in two places.

The reservoirs in this area are interpreted as prograding lobes of a large fan complex. This offers some explanation as to the lower reservoir values recorded on the lines running parallel to the basin margin compared to those running perpendicular. A parallel line will only record the dipping nature of the beds at the edges of the lobe while the lines perpendicular to the margin (long axis of the lobe and parallel to its build direction) will record the dipping nature right the way through.

4.6 1997_07-STAR97

This small survey was shot by Horizon for Statoil and covers an area to the west of Donegal almost entirely contained within the Rockall Basin (Fig. 4.17). The area corresponds to the central prospective region of the three regions identified in 1996_15; though most of this survey is a little further west both lie on the 55 parallel. The data quality is very good; an AGC of 300 ms was used to highlight the features.

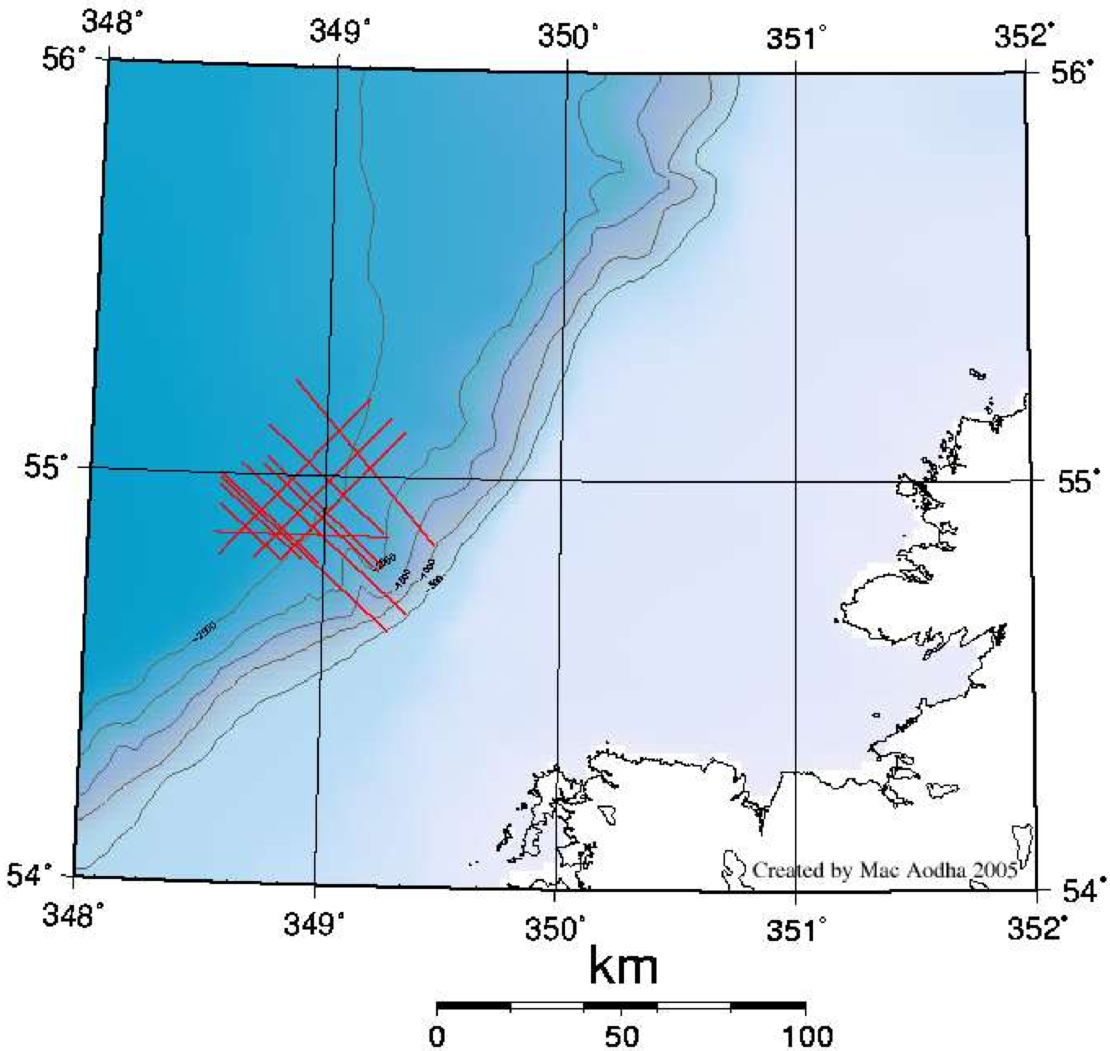


Figure 4.17: *Location map for survey 1997_07-STAR97.*

The HSZ results were excellent with all of the survey within the HSZ and 88% scoring over 0.7. As with 1995_15 over the same area, migration is still the weakest factor, but the results were a lot higher with 10% or the area scoring <0.7. There are two factors behind the higher results; this survey only covers a subset of the 1996_15 area, and more importantly, the data quality is a lot better here and there is better imaging of the faults present. The reservoir potential was very good with 18% of the area scoring over 0.7.

Overall the area shows good level of prospectivity (Fig. 4.18). The target areas are however split up into a number of localised pockets rather than the large areas of high prospectivity seen on 1996_15 further north. This is attributed to a more disjointed set of reservoirs. The fan lobes which make up the reservoirs in this area are either, more distal extensions of those further north or from a closer but smaller local source. These pockets are still in the region of 10-15 km in length.

Figure 4.19 shows one of the potential reservoirs from the survey. The base of the HSZ (green line) for this location is calculated at 530 ms below the seafloor which is deep enough to include most of the unit with dipping layers. The deeper reflections in this image are faulted and un-continuous and are not considered to be effective barriers to migration.

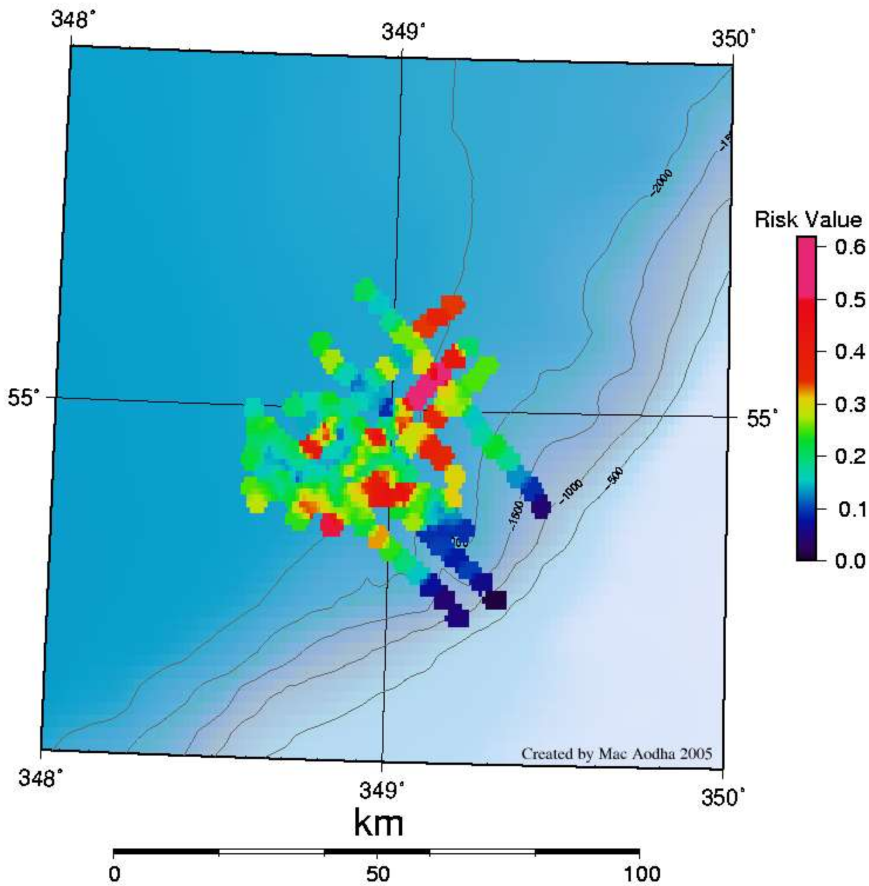


Figure 4.18: *Results of the risk assessment from Survey 1997_07-STAR07.*

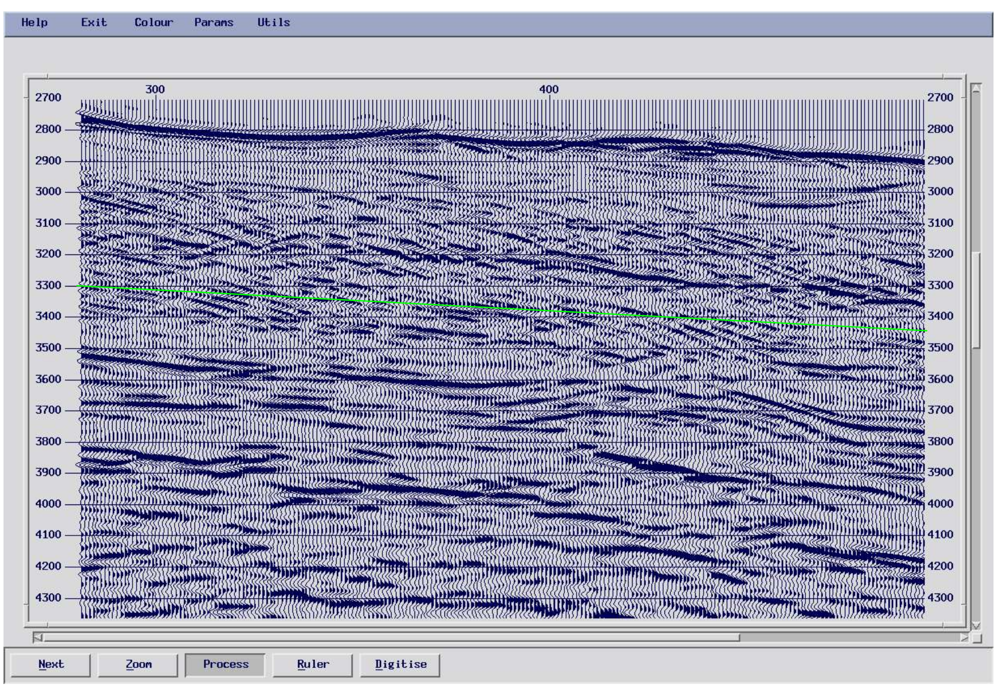


Figure 4.19*: Image showing dipping layers from Survey 1997_07. Green line: HSZ*

4.7 1997_10

This close network of 2D lines was shot by Geco-Prakla for Shell. Situated in the north west. of the basin it covers the perched basins designated Conall and Ronan by Naylor *et al.*, (1999) as well as an area of the basin floor (Fig. 4.20). The data quality is very good with no problems assessing either the migration pathways or reservoir potential.

Most of the survey lies within the HSZ and 39% of the data scoring 0.7 or higher with a maximum HSZ thickness of just under 500 m. The migration pathways on this survey are excellent with extensive faulting across the margin and in the sedimentary layers in the basin. Fifty percent of the data points scored 0.7 or better for migration with the highest overall values in this study. Reservoir potential is the weakest factor with 7% scoring 0.7 or higher. However, with the high migration and HSZ values a lot of the 24% of data points which scored 0.6 or higher for reservoir potential made an overall score of greater than 0.34.

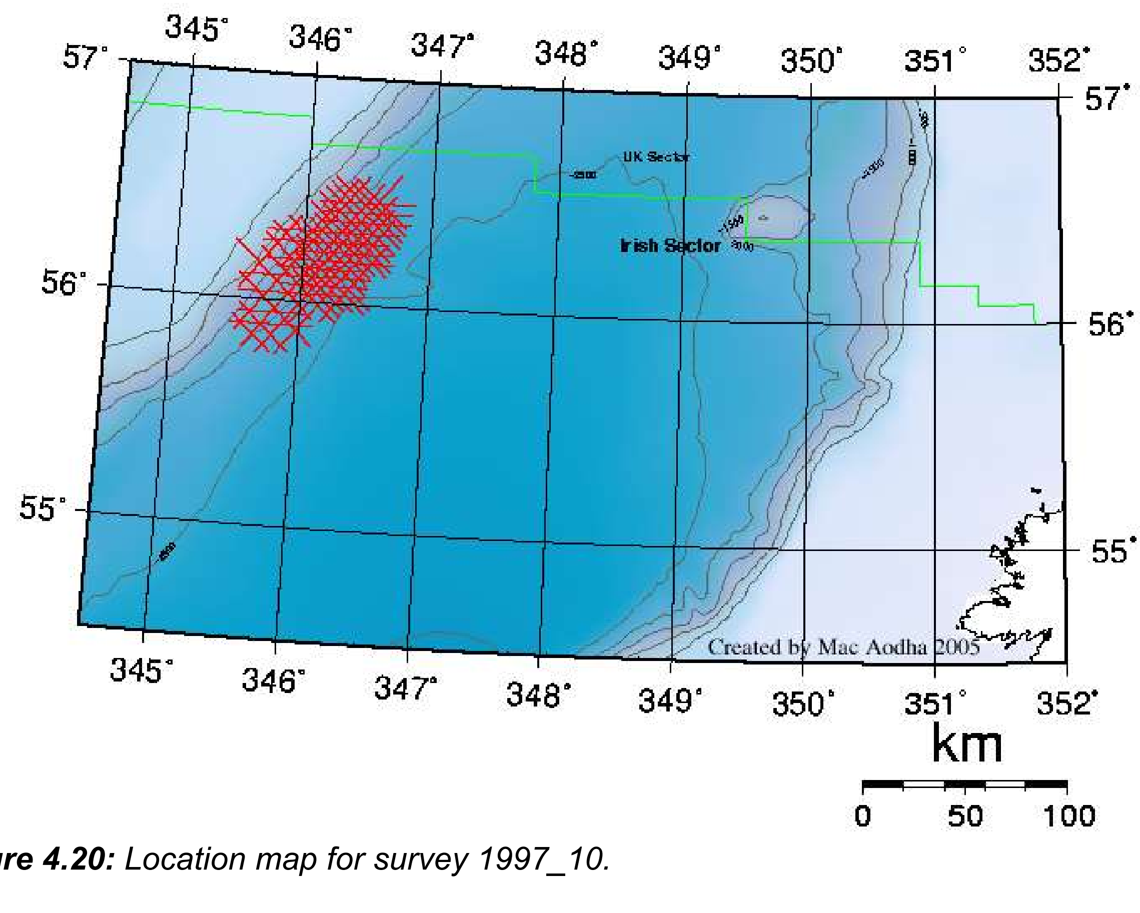


Figure 4.20: *Location map for survey 1997_10.*

The results shown in Figure 4.21 indicate that a large area in the north east of the survey has high prospectivity. There are also some isolated pockets in the south east, the true extent of which is not clear due to the limits of the survey. The results are in good agreement with 1996_3 which is in the same area.

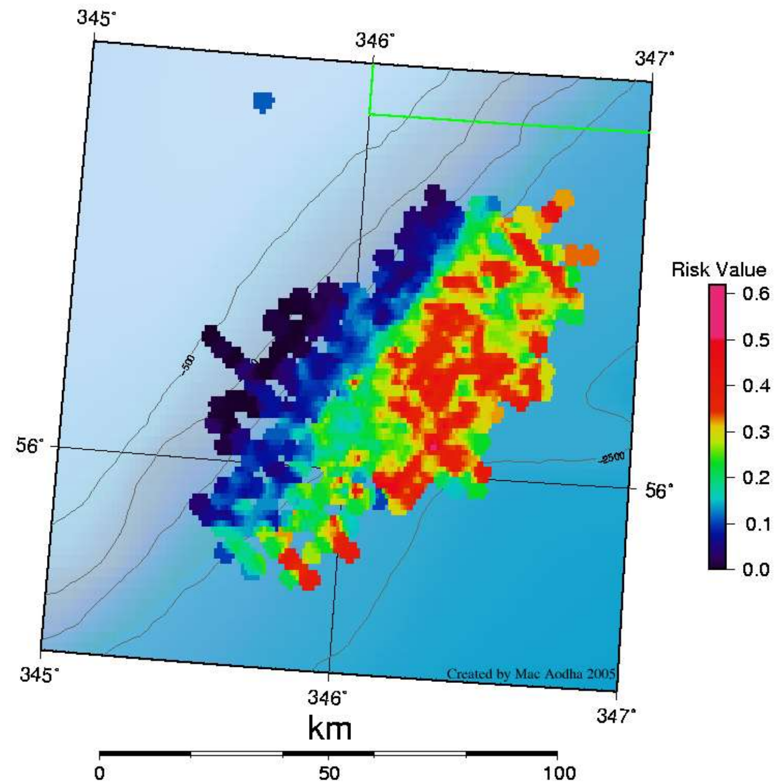


Figure 4.21: *Results of the risk assessment from Survey 1997_10.*

Figure 4.22 shows an example of the extensive faulting which is seen across the area. The fault systems extend right down through the section to the basement block allowing migration right through the system.

IODP leg 162 drilled location 982 just north of this location and, while hydrate was not recovered, Jansen *et al*., (1995) cited the dissociation of hydrate as a possible explanation for anomalous chlorite readings.

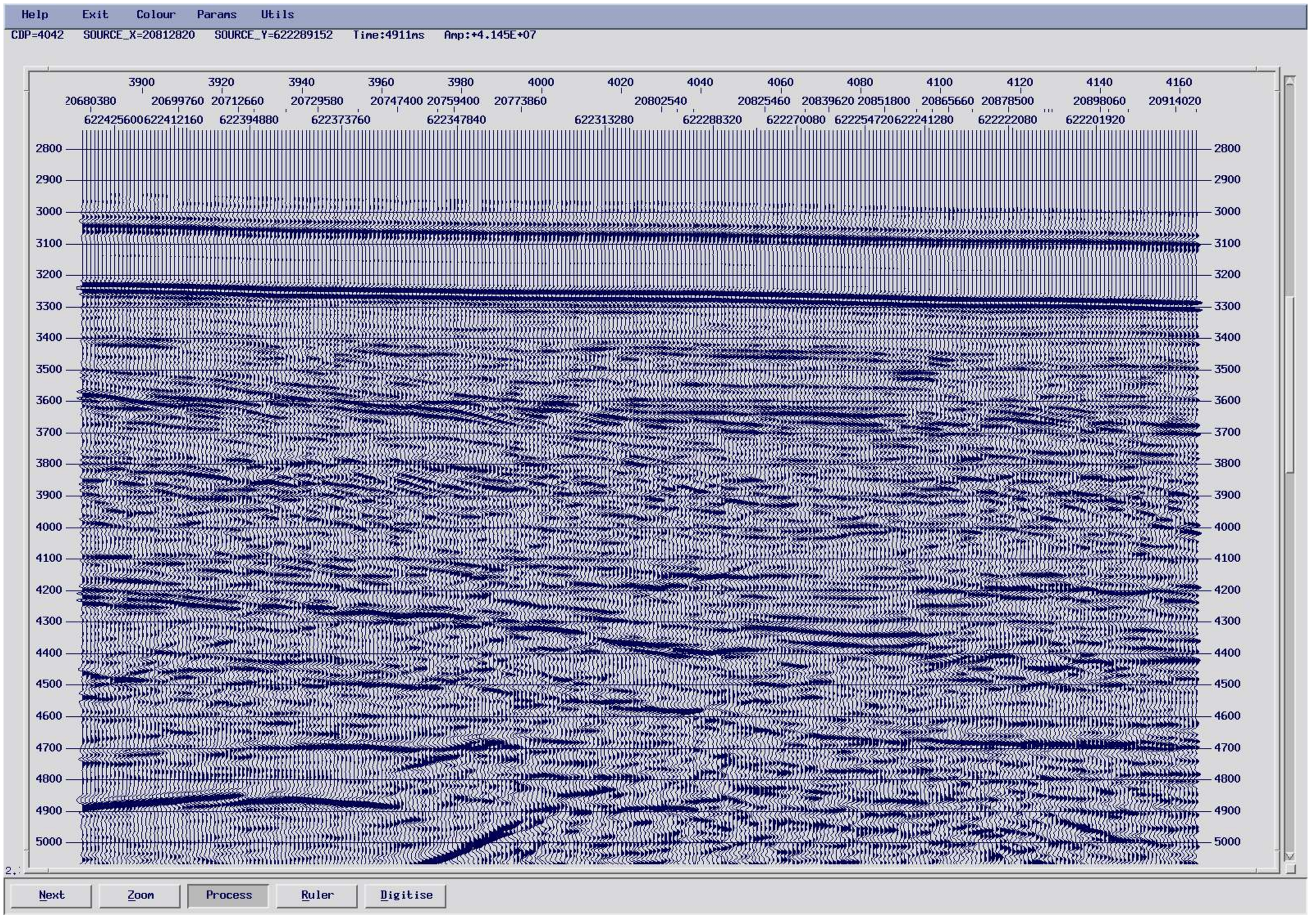


Figure 4.22: *Image for Survey 1997_10 showing the highly faulted nature of the sedimentary section.*

The final point to note from this survey is the presence of a previously recognised gas chimney on line 34 (Fig. 4.23). This suggests an active hydrocarbon system in the area and the ability for these hydrocarbons to migrate up to the HSZ.

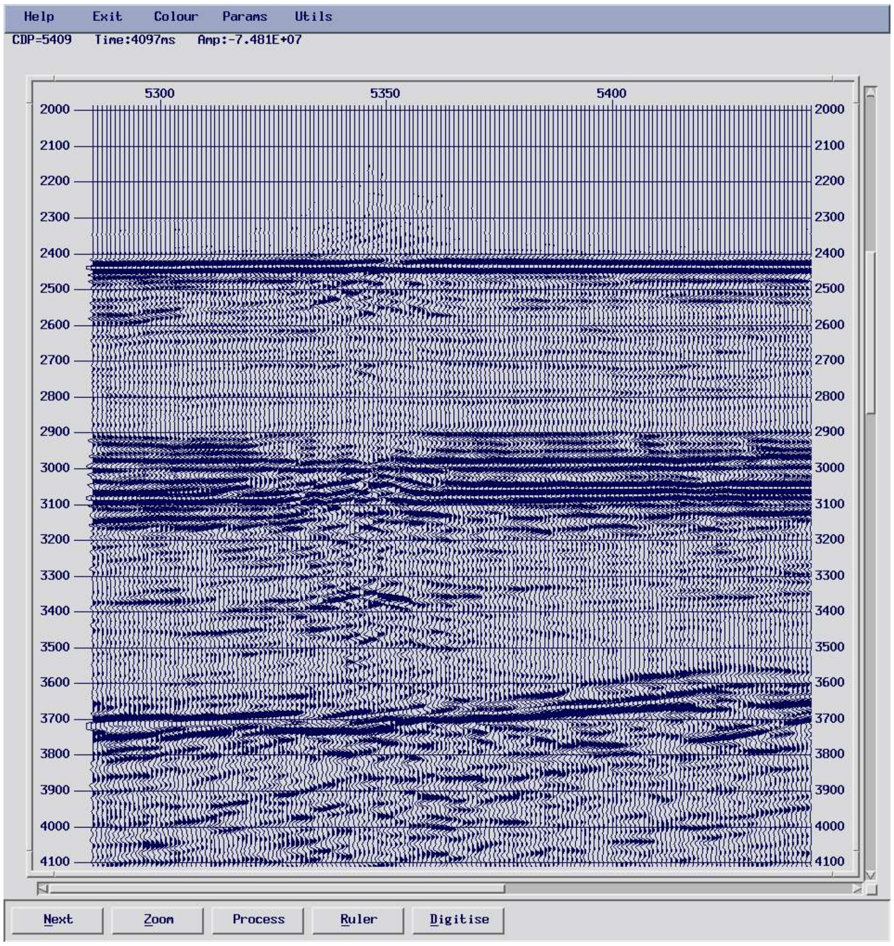


Figure 4.23: *Image from 1997_10 showing as gas chimney.*

4.8 1997_13

This SAGA survey concentrates on a specific area of the western margin of the Porcupine Bank. It mainly focuses on the margin covering a change in water depth from 1000 m to over 3000 m, but does extend some way out into the basin (Fig. 4.24).

Data quality is general good but very little could be discerned where the lines crossed the rapid transition from the basin floor to the steep lower margin.

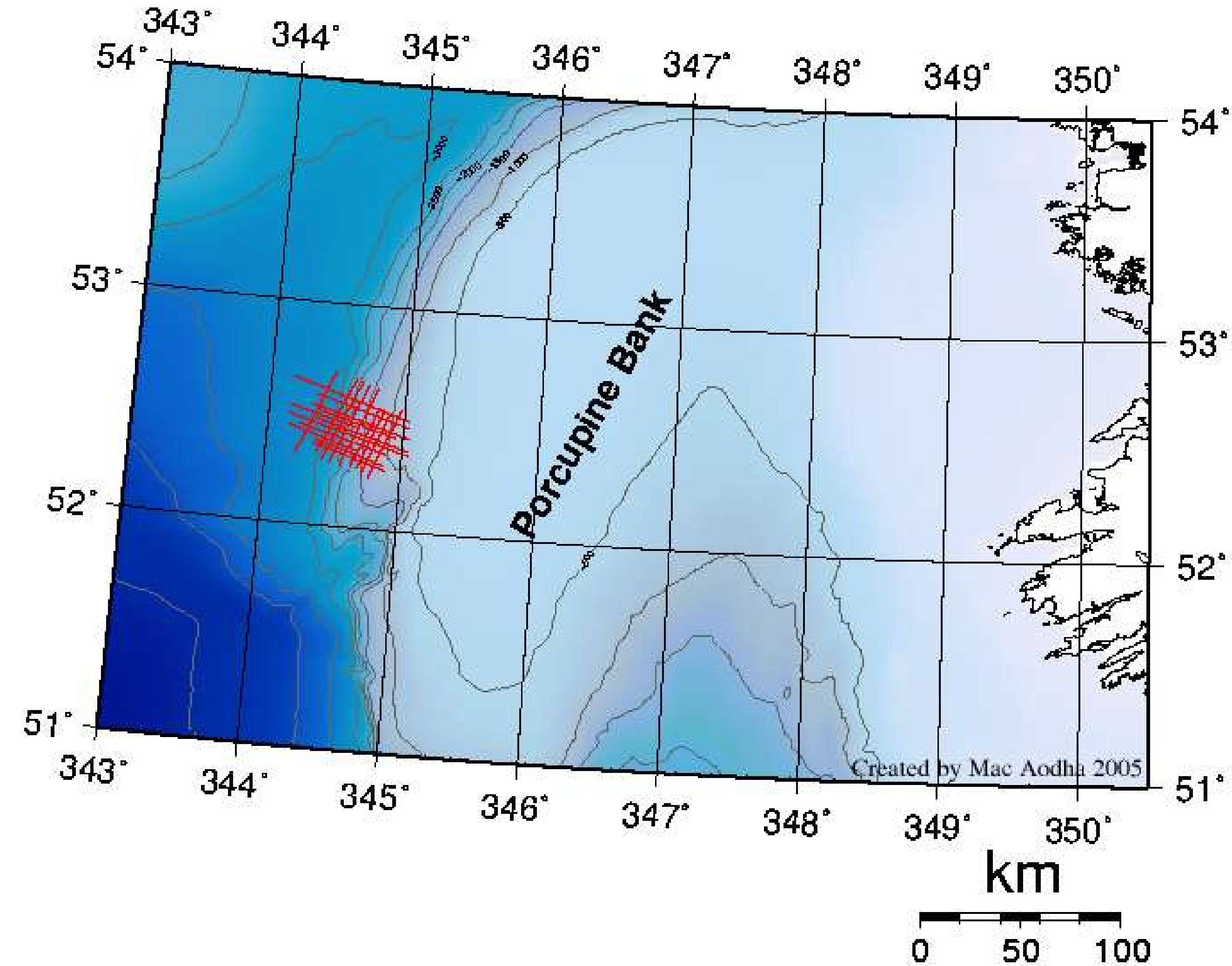


Figure 4.24: *Location map for survey 1997_13.*

The HSZ results are very strong thanks to the rapid increase in depth across the margin; 51% of the area scoring 0.7 or better. Fewer than 2% scored 0.7 or better for migration, however, 12% did score 0.65 or better. Reservoir values are higher than seen elsewhere in this part of the basin but still low with only 9% scoring 0.7 or higher. Where these high results occur they are attributed to a localised sediment influx probably from one of the canyons which cut the margin in this area.

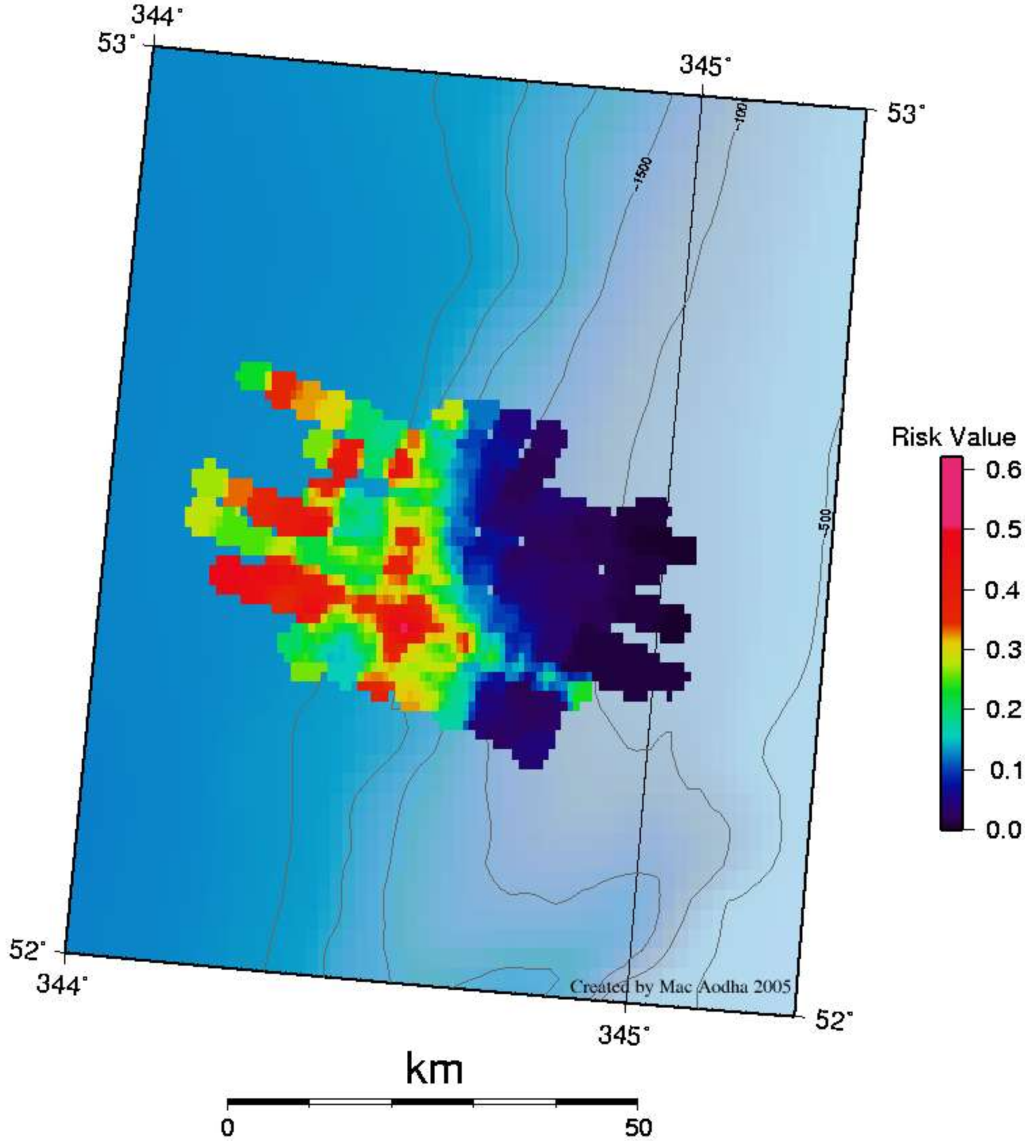


Figure 4.25: *Results of the risk assessment from Survey 1997_13.*

The results (Fig. 4.25) do show a considerable amount of prospective area in the basin itself. The disjointed nature of the prospective areas adds weight to the idea that a local source is creating discrete reservoirs.

4.9 1998_08

This survey slightly overlaps the previous 1997_13 survey and extends further north (Fig. 4.26). Shot by Geco-Prakla for Phillips it provides a tight grid over the survey area.

Data quality is generally good but, as with the previous survey, very little could be discerned where the lines crossed the rapid transition from the basin floor to the steep lower margin.

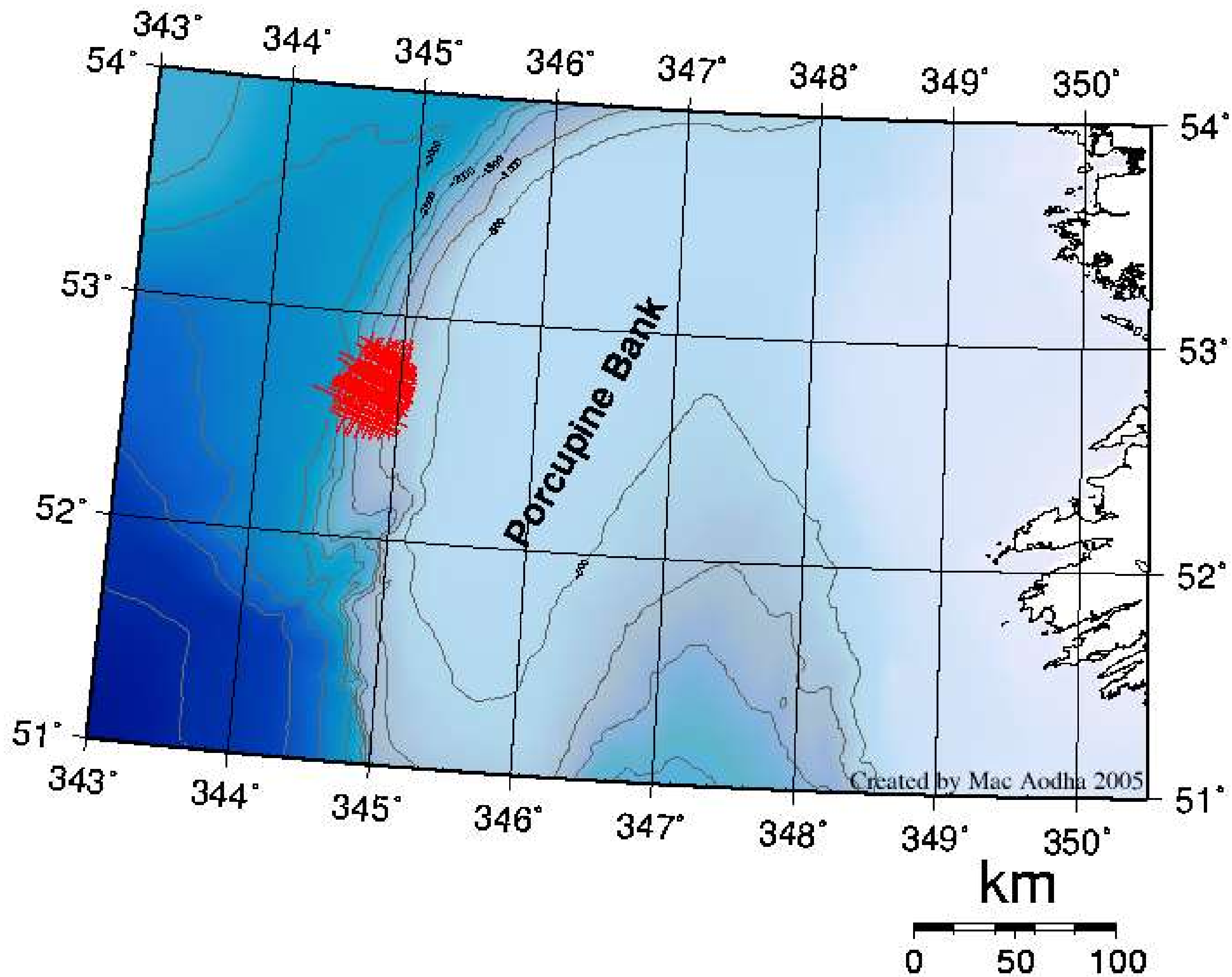


Figure 4.26: *Location map for survey 1998_08.*

This survey only had 18% of data points scoring 0.7 or greater for HSZ. Only 2% scored 0.7 or better for migration. Some of the faulting involved in the structural control of the basin is undoubtedly lost due to the poor quality of the data at the basin margin transition. Only 1% had reservoir potential of 0.7 or higher.

The survey was a little higher up the margin and did not extend as far out into the basin as 1997_07 just to the south, but the deciding factor in why the results shown in Figure 4.27 are so poor compared to 1997_07 is reservoir potential. One potential area of interest approximately 10 km across has been identified but the general outlook for this area is poor.

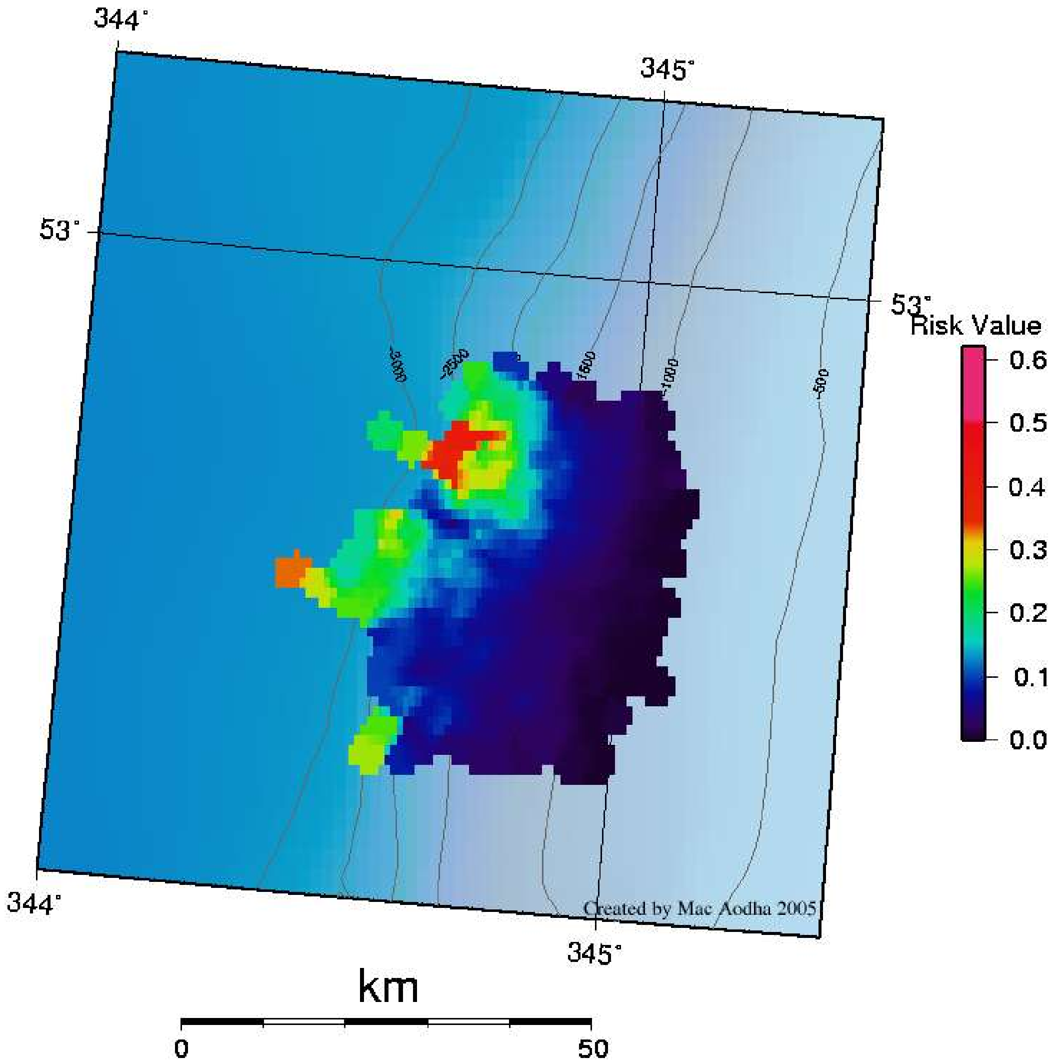


Figure 4.27: *Results of the risk assessment from Survey 1995_08-E95IE07.*

4.10 1998_11

This survey covers an area of the north-eastern margin of the Rockall Basin (Fig. 4.28) already covered by 1996_15 but with a closer line spacing. Unfortunately the survey was shot further up on the margin and does not stretch as far out into the basin.

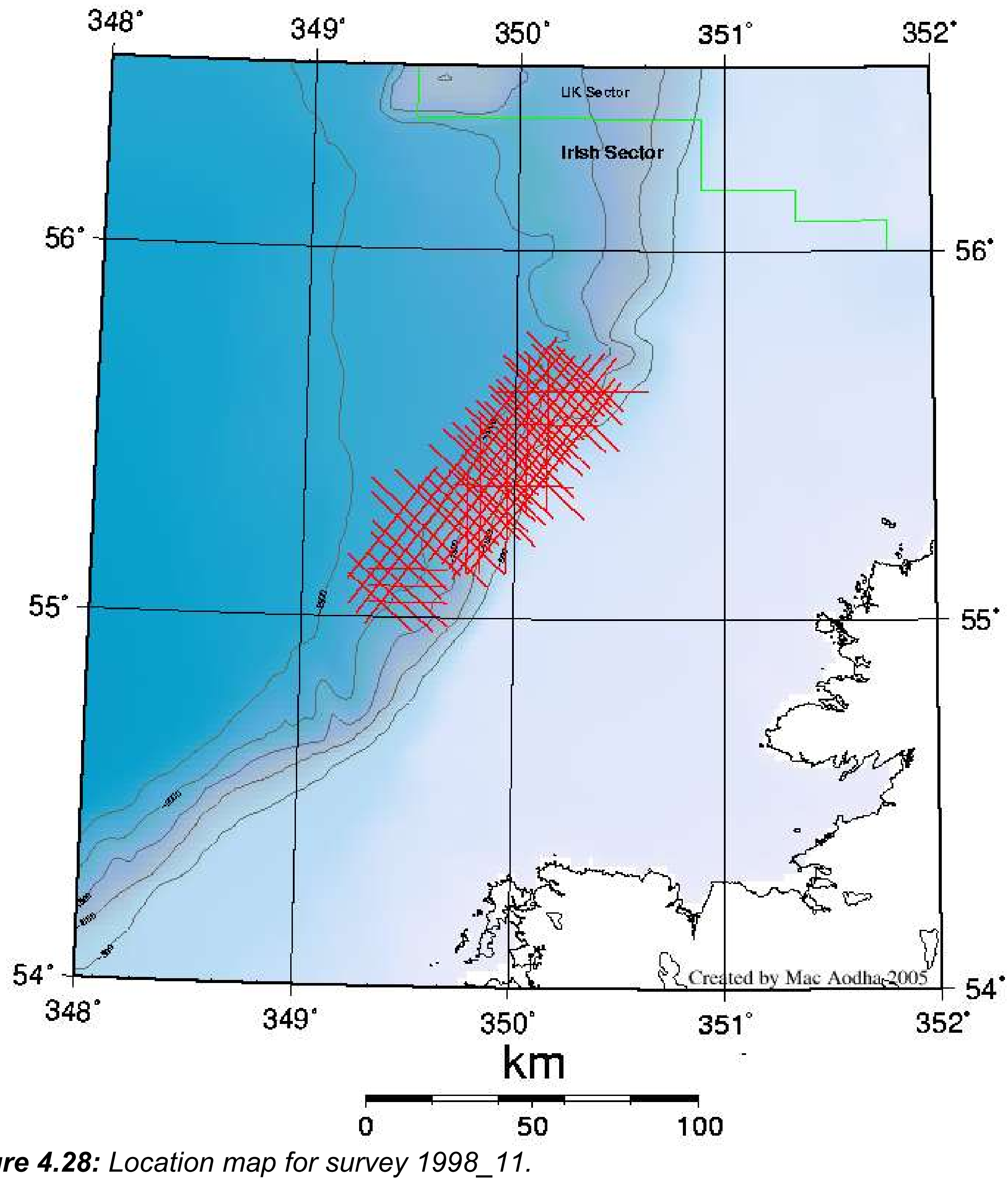


Figure 4.28: *Location map for survey 1998_11.*

The quality of the data is good but there is a general lack of resolution in the upper 200 ms which hampers assessment of the reservoir potential to some degree.

The HSZ scored reasonably well considering the extent to which the survey extends up onto the shelf and 25% of the area covered scored 0.7 or higher. Migration is low as seen previously in this area with values of 0.7 exceeded by only 10% of the data points. Reservoir potential is high with 21% of the data points scoring 0.7% or greater.

The results (Fig. 4.29) for this survey reaffirm the high potential of this area of the Rockall Basin, though the survey does not stretch out very far into the key area.

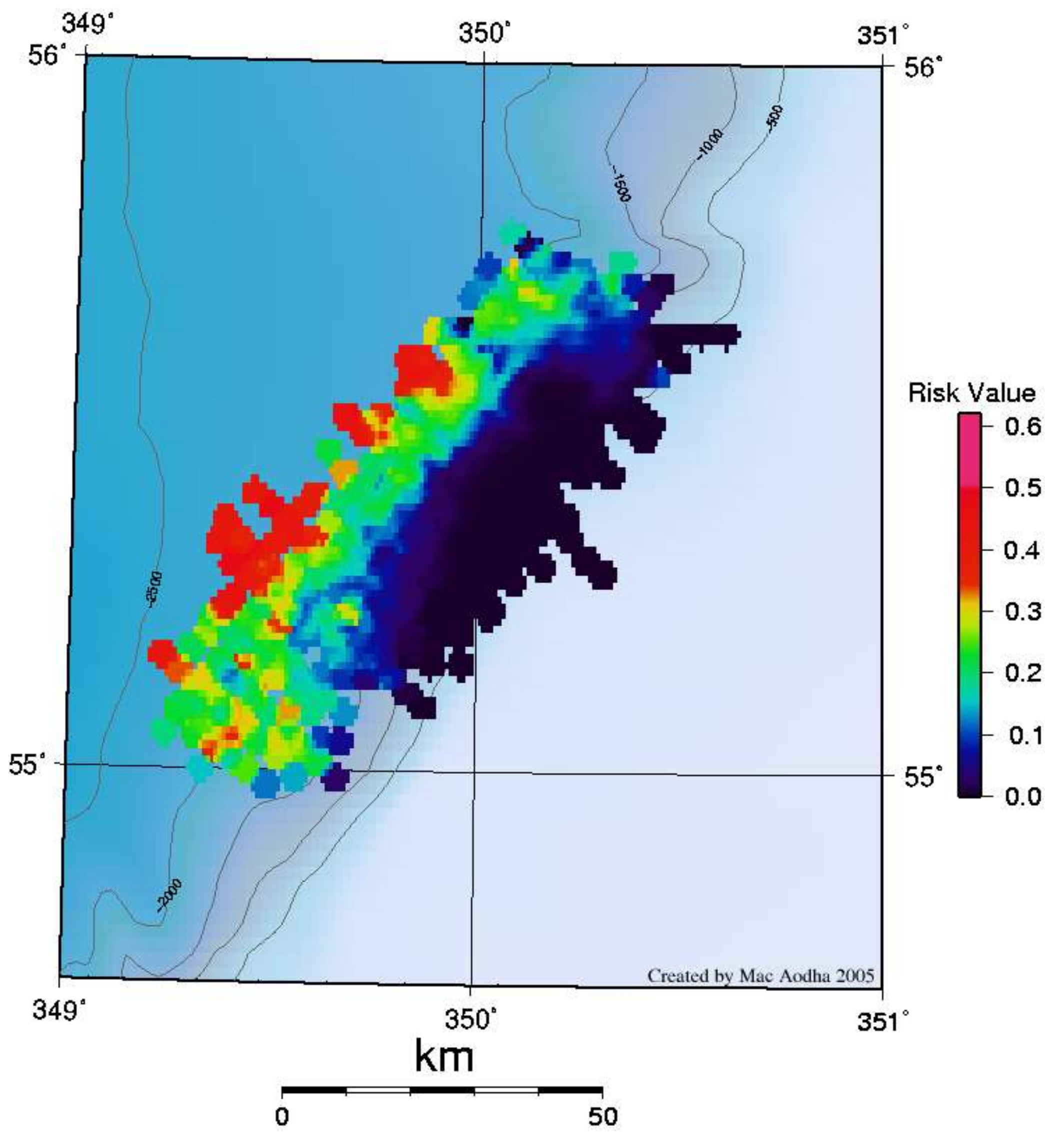


Figure 4.29: *Results of the risk assessment from Survey 1998_11.*

This survey also exhibits the best example of a possible BSR seen in this review. Figure 4.30 show a strong semi-continuous reflection which closely follows the seabed topography. The phase of first arrival of this reflection is negative. Whether it is accepted as a BSR or not will depend on how much interference is interpreted in the seabed reflection. The polarity of the seabed reflection is not as clear and seems to change polarity (Fig. 4.31). If accepted as a valid BSR it has implications for the HSZ calculations as it is about 100 ms shallower than the calculated base of the HSZ for that water depth.

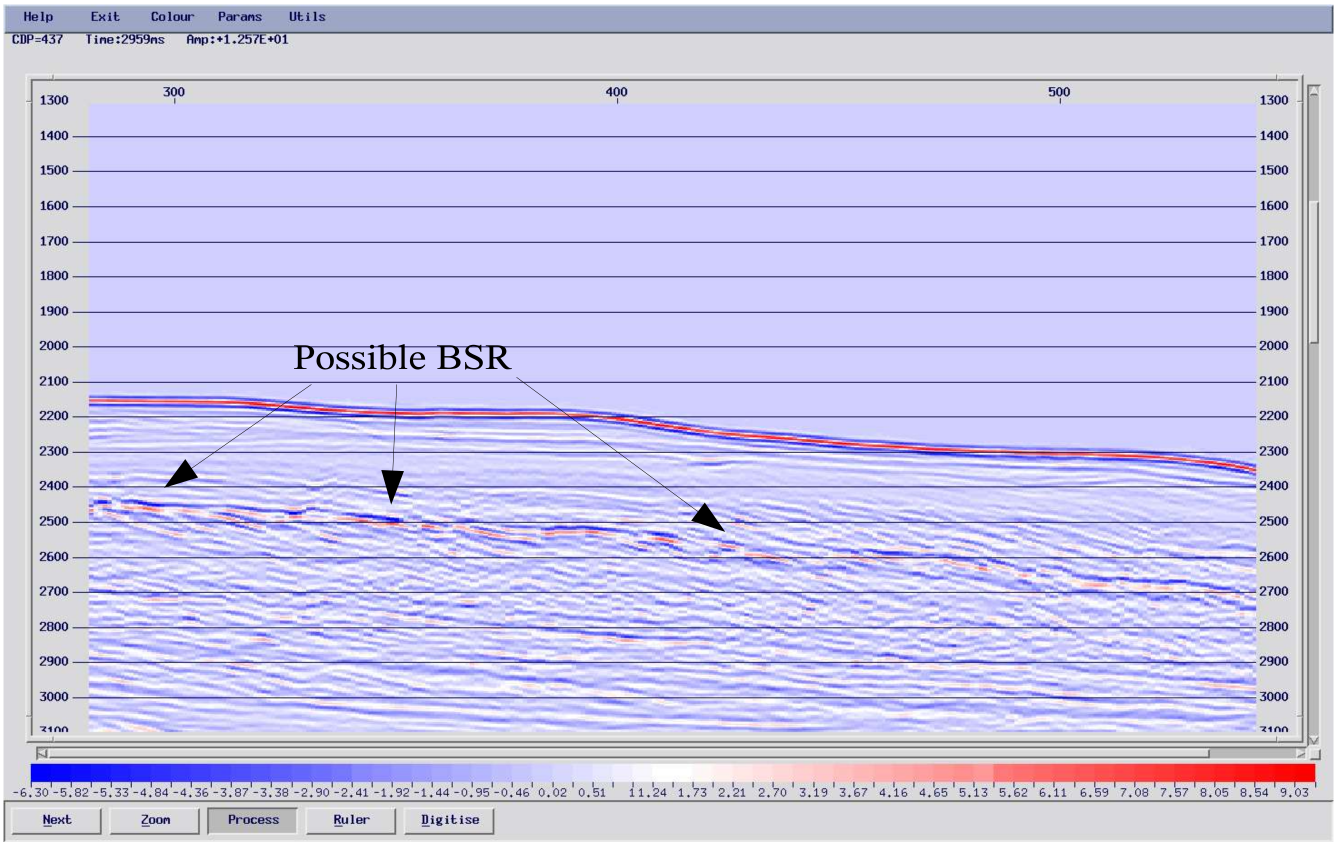


Figure 4.30: *Possible BSR from Survey 1998_11.*

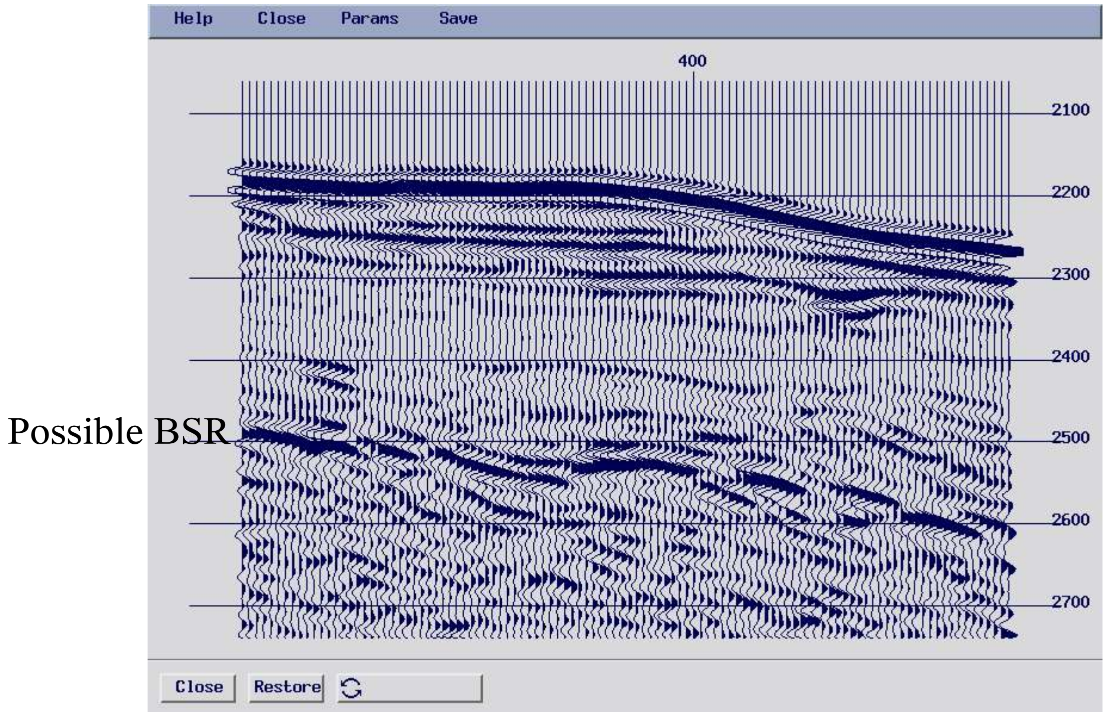


Figure 4.31: *A seismic zoom on the same area as Figure 4.30 showing the ambiguity of the phase of the first arrival.*

4.11 1998_14

This survey was shot by Geo-Prakla for Elf, and covers an area in water depths of 1000-1500 m on the more gradual margin of the Rockall Basin south west of the Hebrides Terrace Seamount Centre (4.32).

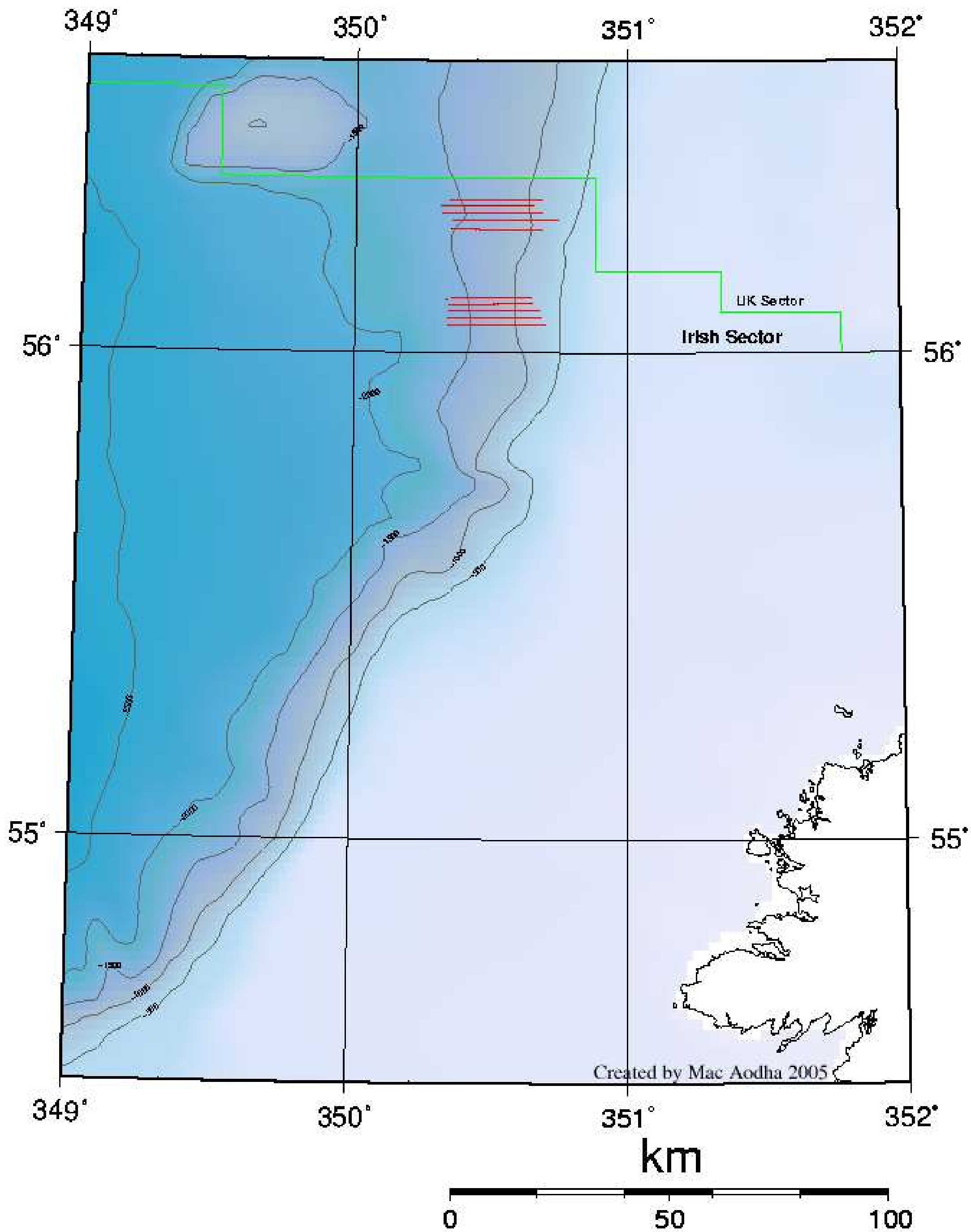


Figure 4.32: *Location map for survey 1995_08.*

The data was of good quality and imaged both shallow section and deeper faults.

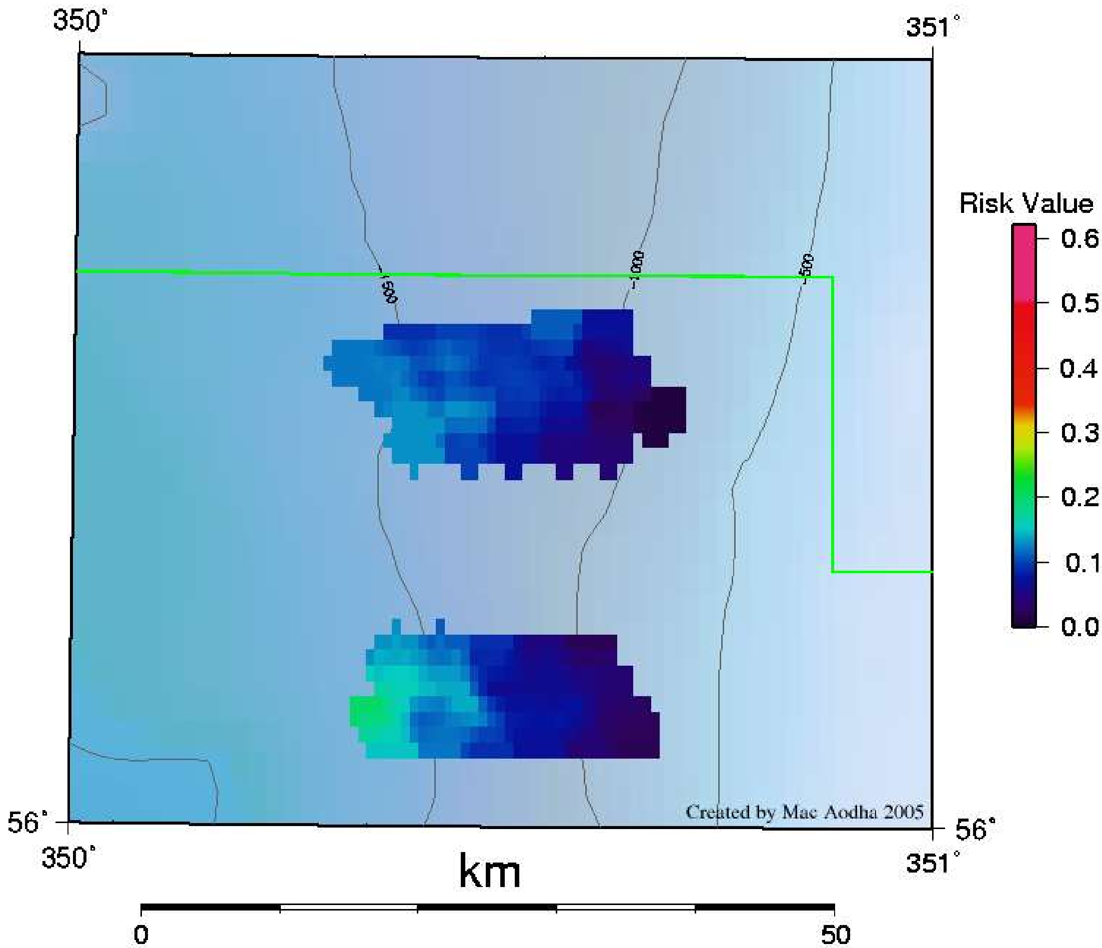


Figure 4.33: *Results of the risk assessment from Survey 1995_08-E95IE07.*

The area was too shallow to expect any highly prospective areas given the current search parameters and only a subset of the survey lines were fully analysed. The results are shown in Figure 4.33; no areas score 0.7 or higher for HSZ. Migration is strong however with 22% scoring 0.7 or better. Reservoir potential again fairs poorly with only one area reaching 0.7 (3/55 scored 0.65). This area is not considered to have any significant potential.

4.12 Porcupine Basin

A quick initial review of the data conducted with Art Johnson showed that the Porcupine Basin had considerably less potential than the Rockall Basin. Figure 4.34 shows a section typical section of data from the basin. As a result of this, full assessment of the lines was not practical in the short time available for this desk study. Instead the only locations within the basin where there was the possibility of sediments with reservoir potential were assessed. There are a number of areas of higher energy deposition within the basin often associated with channel systems, both currently active and buried. The lower geothermal gradient calculated from well data in this basin results in a thicker HSZ (e.g., the HSZ is calculated at 600 m thick for a water depth of 2250 m, compared with 500 m in the Rockall Basin.).

The basin was mainly assessed with data from Survey 1997_06 as other surveys available are in two shallow water or lacked navigation data.

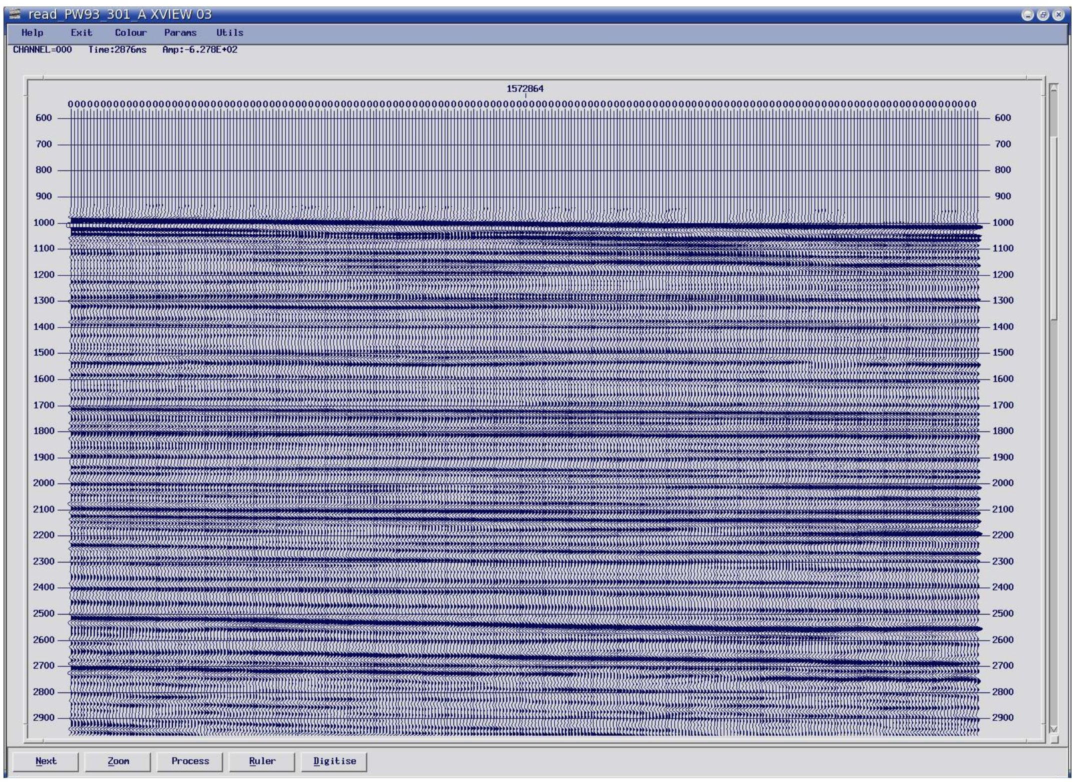


Figure 4.34: *Typical data from the Porcupine Basin. The section shows no discernible reservoir potential and no evidence of faulting.*

The survey, shown in Figure 4.35, mainly focuses on the eastern and southern margins of the basin but with one or two lines crossing the basin.

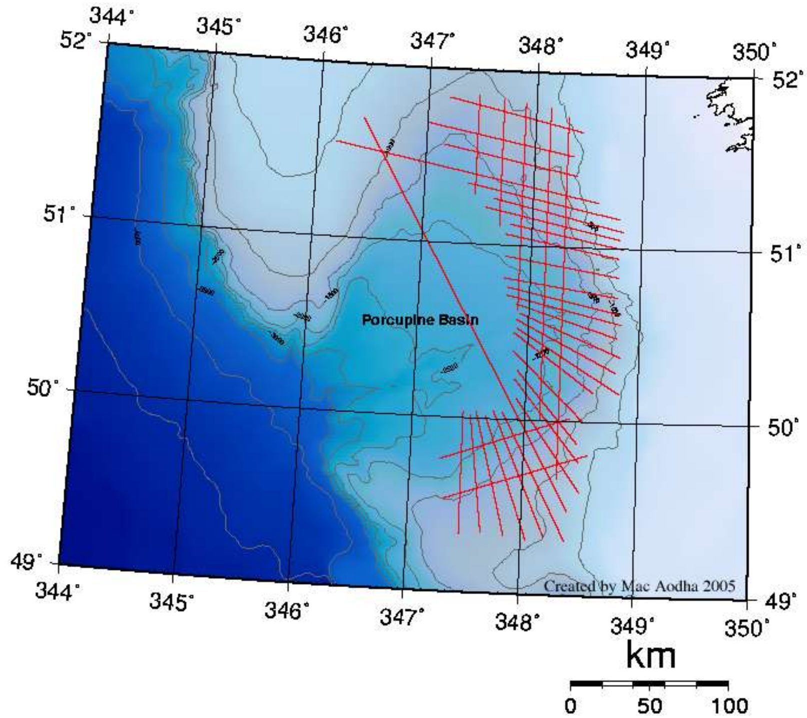


Figure 4.35: *Location of Survey 1997_06.*

The results (Fig. 4.36) showed that while the basin in generally unprospective there are two locations where there has been sufficient influx of sediment under higher energy conditions to create some reservoir potential.

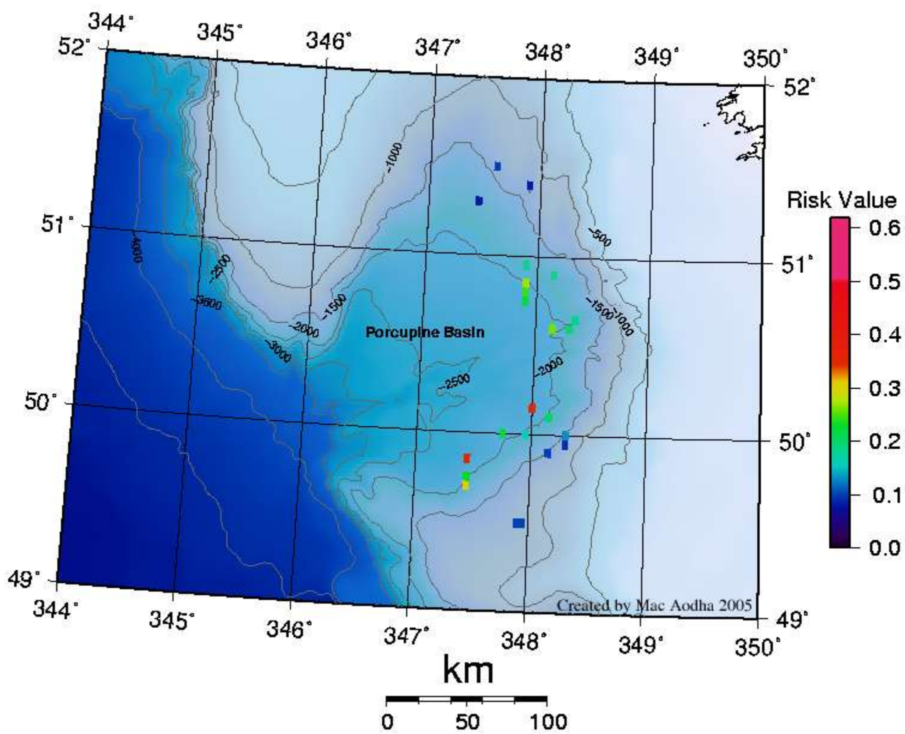


Figure 4.36: *Results of the risk assessment from Survey 1997_06.*

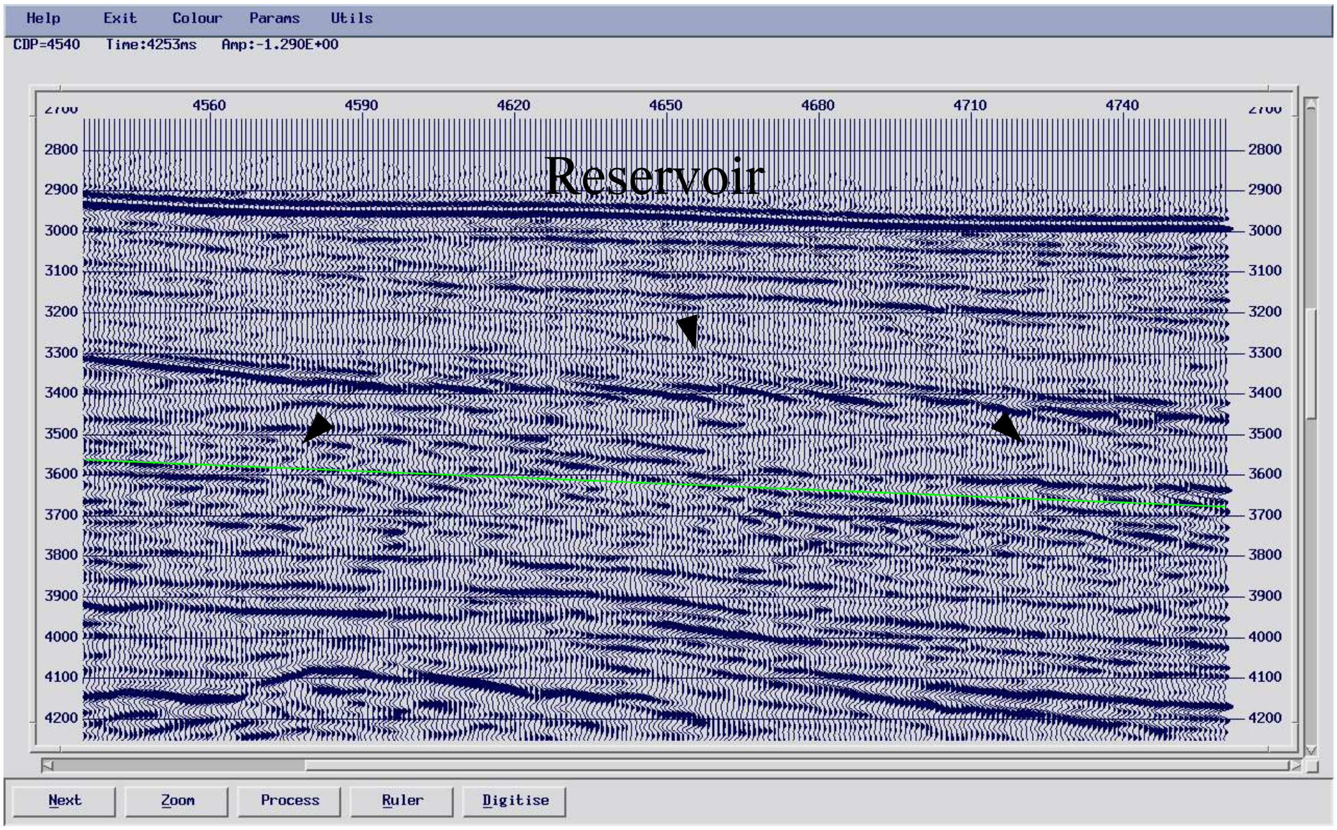


Figure 4.37: *Image from Survey 1997_06 showing an area with a good reservoir potential.*

Figure 4.37 shows part of the survey on the northern flank of the Goban Spur. A series of dipping beds can be seen in the centre left of the image at a depth of 3200-3400 ms. This is well within the HSZ which is calculated at 670 ms thick at this location. Borowski *et al.*, (1999) cite a shallow sulphate-methane interface and a rapid downhole increase in sulphate concentrations as evidence for the presence of hydrate on the Goban Spur. This evidence is from one of the DSDP wells on the spur, although the authors did not indicate which one.

5 Discussion

In this section the methods used in this assessment are critically reviewed. The results presented in the previous section and their implications will be discussed. The key areas found to be most prospective will be outlined. Suggestions for further work will be made.

5.1 Method

In this section some points on the effectiveness of the method, which should be taken into account when reviewing the results, will be made. In general the risk assessment method used was found to be effective in quantifying the potential of the area to act as a host for commercial concentrations of hydrates. There are however a couple of drawbacks.

Firstly, as the data are broken up into panels or sections for analysis the results will reflect the entire section and local highs may be averaged downwards. This is particularly the case in areas with a steep slope as shown in Figure 5.1.

Figure 5.1 shows an analysis section from the eastern margin of the Rockall Basin. As an overall panel it will score as follows 0.48 for HSZ, 0.6 for migration and 0.65 for reservoir potential giving an overall value of 0.19. However, if the left and right sections were analysed separately (divided by the green line) the left would score 0.54 for HSZ, 0.6 for migration and 0.8 for reservoir potential giving a total risk assessment value of 0.26. The right would score 0.46 for HSZ, 0.5 for migration and 0.4 for reservoir potential giving a total value of 0.09. While neither of these values cross the 0.34 cut off point set, the exercise shows that there is a marked contrast between the prospectivity of either side of the section which is glossed over with an intermediate score of 0.19 with the method used.

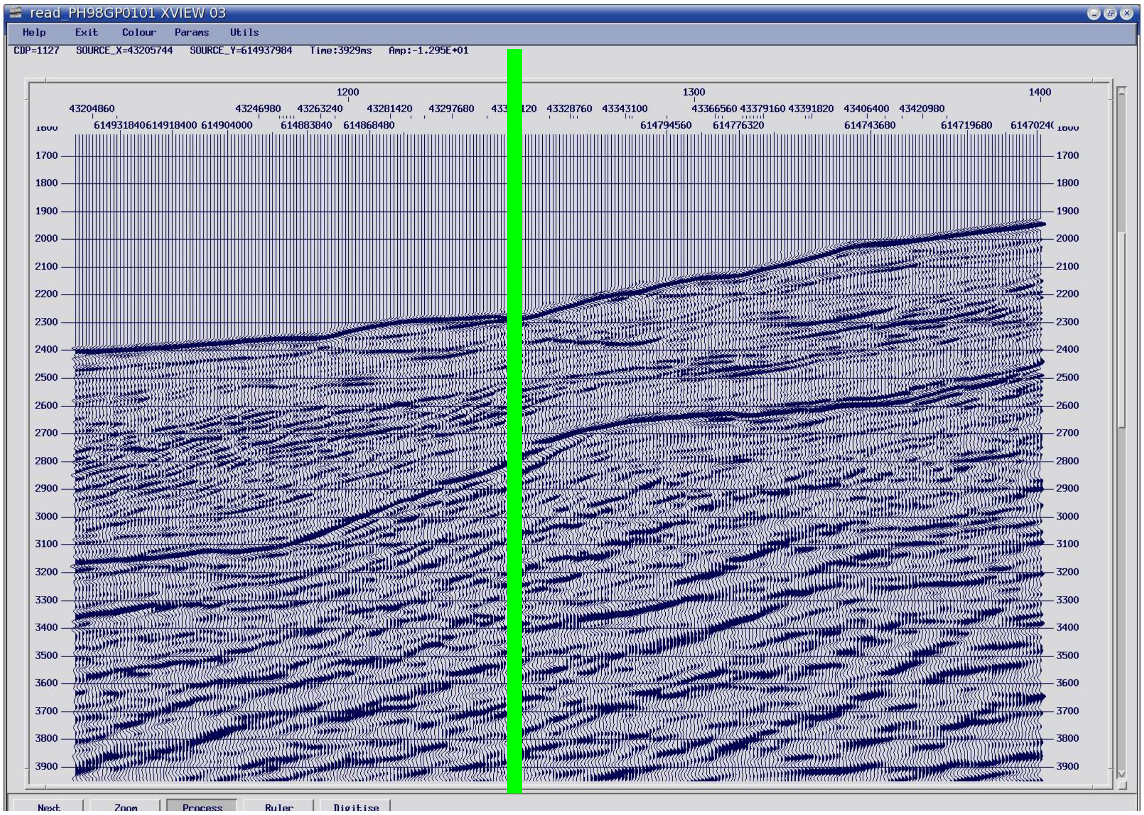


Figure 5.1: *Sample analysis section from the study. This will score a value reflecting its overall prospectivity but not individual highs.*

This is not considered a serious problem in a regional scale review such as this. The problem is alleviated somewhat but the tendency of the interpreter to look for the best features in the section and thus reduce the risk of a prospective area been overlooked. On a more detailed site specific review, however, it is more of a problem and an approach where the line is broken up into sections based on its prospectivity may be more appropriate.

The second issue is the consistency of results between surveys and lines within surveys. For example in the results for Survey 1996_15, the angle at which a seismic line cuts a sedimentary structure will effect the how the structure looks. As the reservoir quality assessment was based on sedimentary structure, the results for this parameter will be affected by the orientation of the seismic line analysed with respect the the sedimentary structure. There is no way round this without analysis of amplitude changes versus offset (AVO). The risk of this factor resulting in missing a prospective area can be reduced when gridding the results by using the highest value at a point, where there is more than one value, instead of averaging them.

Achieving consistency between surveys is slightly more complicated. The quality of a survey affects the ability to assess the prospectivity of the area. In this study this was especially true of migration pathways where poor imaging of the deeper section makes it impossible to fully assess the degree of faulting. Figure 5.2 shows a comparison between the results from Surveys 1996_15 and 1997_07.

The two surveys shown in Figure 5.2 do not cover exactly the same area but they do overlap sufficiently to allow comparison. All of the prospective areas highlighted on the 1996_15 survey (left) have also been picked up on the 1997_07 results. Their spatial extent and scores are, however, higher. There are three separate hotspots in the bottom left quadrant (labelled 1-3) that were not picked up by 1996_15 survey. Hotspot 1 location did score in the 0.22-0.27 range in survey 1996_15. Hotspots 2 and 3 are however, much more worrying as both those areas score under 0.1 for survey 1996_15.

The differences pointed out are attributed to the difference in data quality between the two surveys, particularly the ability to recognise migration pathways on 1996_15. It is not possible to eliminate this problem (reprocessing may help to some degree) and so attention must be paid to the notes made about the quality of the data for each of the surveys.

The final point to make is that the value given to the reservoir potential took no account of the position of the reservoir within the HSZ. There is increasing evidence from hydrate drilling programs around the world that the concentration of gas hydrate increases towards the base of the HSZ. This has not been fully explained though this author believes it is due to the hydrate deposit acting as a natural barrier to the flux of methane to the upper parts of the HSZ by reducing the pore space of the sediment. This has implications for the resource potential of a hydrate deposit. From a commercial point of view the aim is to find high concentrations of hydrates and this is more likely to occur in a reservoir which is located at the base of the HSZ. It is hoped to take this factor into account in future work in the area. Consideration was given to this factor in recommending locations for further study (section 5.2).

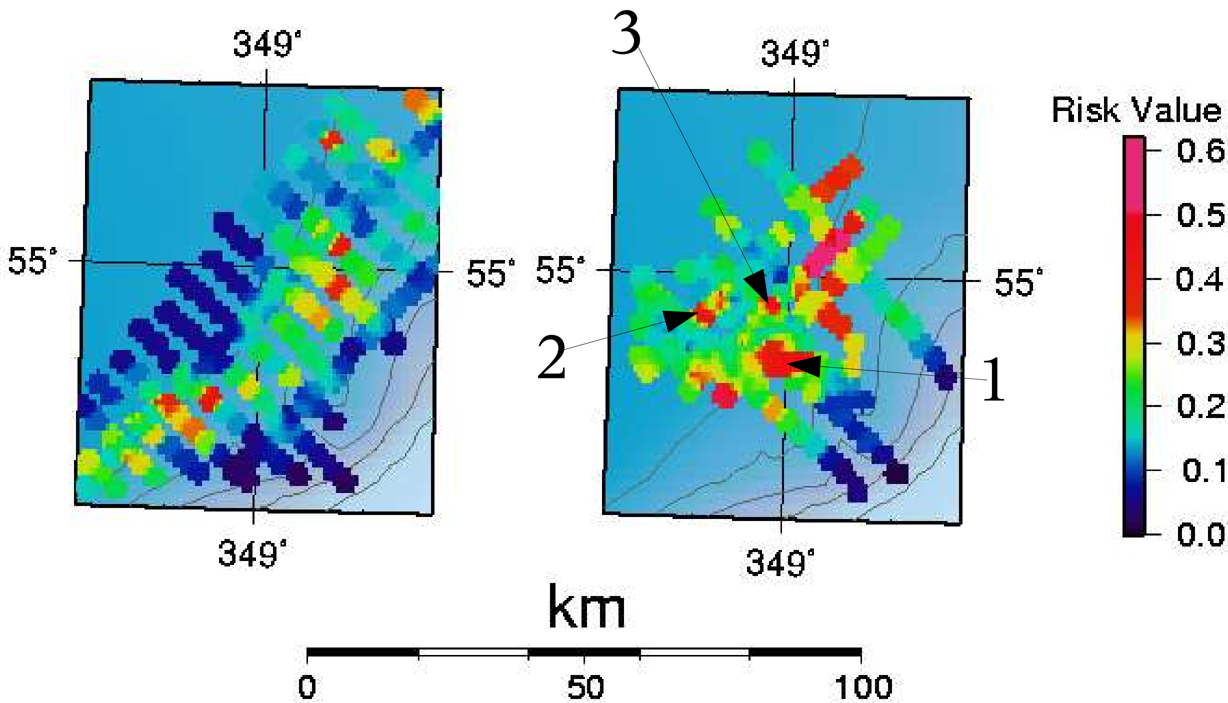


Figure 5.2: *Comparison between the results from 1996_15 (left) and 1997_07 (right). The figure illustrates the effect of data quality on the results.*

Despite these factors the methods used are considered to have been effective in this initial review. Areas of high potential have been identified. The data have been recorded in such a way that new factors, e.g., a change in the HSZ in light of new geothermal data, can be taken into account without fully reviewing the data.

5.2 Results

The results of this review have been presented already on a survey by survey basin so discussion here will limit itself to the overall prospectivity of the region. The regional variations in the parameters governing prospectivity will also be covered.

Figure 5.3 shows the regional variation in migration pathways in the study area. The colour palette used here is slightly different than that used to display the overall results as the data here ranges from 0-1 rather than from 0-0.6; any offshore area shown in yellow or red has scored over 0.7.

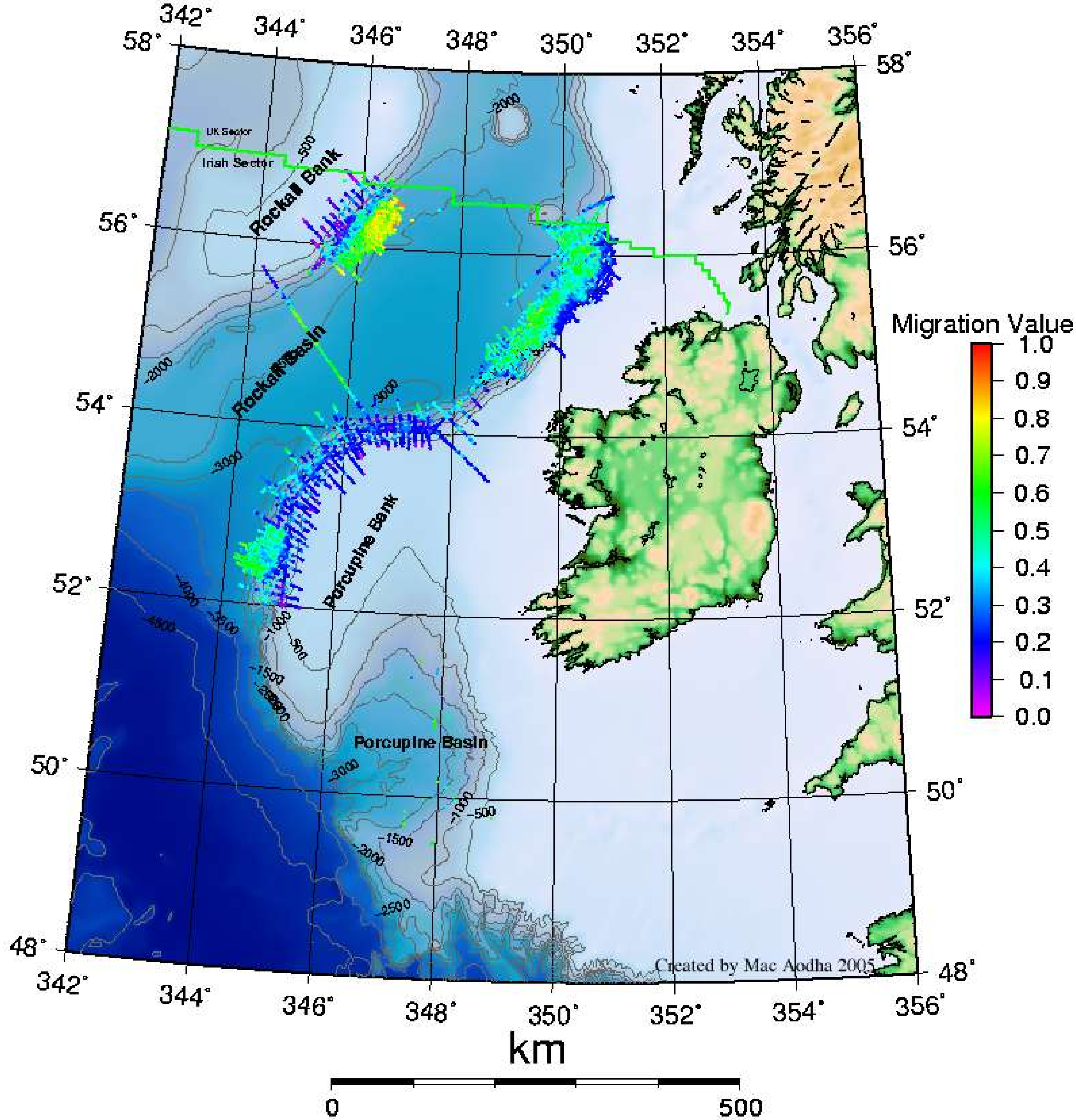


Figure 5.3: *Migration potential in the study region. Offshore areas marked yellow or red have scored over 0.7 and have very good migration potential. Plotted in UTM zone 29.*

The figure shows that the north west Rockall Basin has clearly the best migration potential in the region. The eastern margin of the basin does not show the same potential. Most of this area is denoted by blue to blue-green i.e., scores in the 0.3-0.6. In the northern eastern part of the Irish sector of the Rockall Basin reservoir potential is very good (see Fig. 5.4) and the availability of migration pathways will be the controlling factor in the prospectivity of the area. The line which crossed the centre of the basin shows that migration potential is reasonably good in this area. It improves as we move to the western side of the basin which is in keeping with the general results from either margin. It is interesting to note a general improvement in the results from the western margin of the Porcupine Bank, as the radial lines of the ISROCK survey move out into the basin.

It is hard to draw any conclusions for the data points in the Porcupine Basin but from the review of the survey it was clear that faulting is much more prevalent than potential reservoirs.

Figure 5.4 shows the regional variation in the reservoir potential of the study area. The colour palette used here ranges from 0-1; any offshore area shown in yellow or red has scored over 0.7. The north east of the Rockall Basin just west of Donegal shows the best potential, with extensive areas just west of the margin scoring very highly. Areas further south on the eastern margin of the Rockall Basin do not score as high in general. Where the results are good they are in smaller localised bodies. This area is more distal to the onshore Ireland source provenience and, in some areas, separated from it by the Porcupine Basin. As a result the sedimentary starved area did not form major fan complexes. What reservoir potential is present is the result of canyons on the steep margin reworking material into the basin.

The north western corner of the basin does show reasonable potential though not as good as the north eastern corner. Given the high quality of the migration pathways in this area, it is considered that the reservoir quality will be the controlling factor in this region.

The general pattern is not as clear in the Porcupine Basin as a full coverage survey was not attempted. However, the locations that were assessed are those with the best reservoir potential so the areas marked can be considered the highlights of the basin. In general there are number of isolated areas showing some potential, scores of 0.5-0.7. The best results came from the northern slope of the Goban Spur.

Figure 5.5 taken from Weaver *et al.* (2000) shows the extent of recent depositional activity in the study area. Both the north east and west of the Irish sector contains extensive debris flow/turbidite fan deposits. The evolution of the sediment transportation pathways that feed these systems since the late Cretaceous will be the controlling factor for the presence of large scale reservoirs in the HSZ.

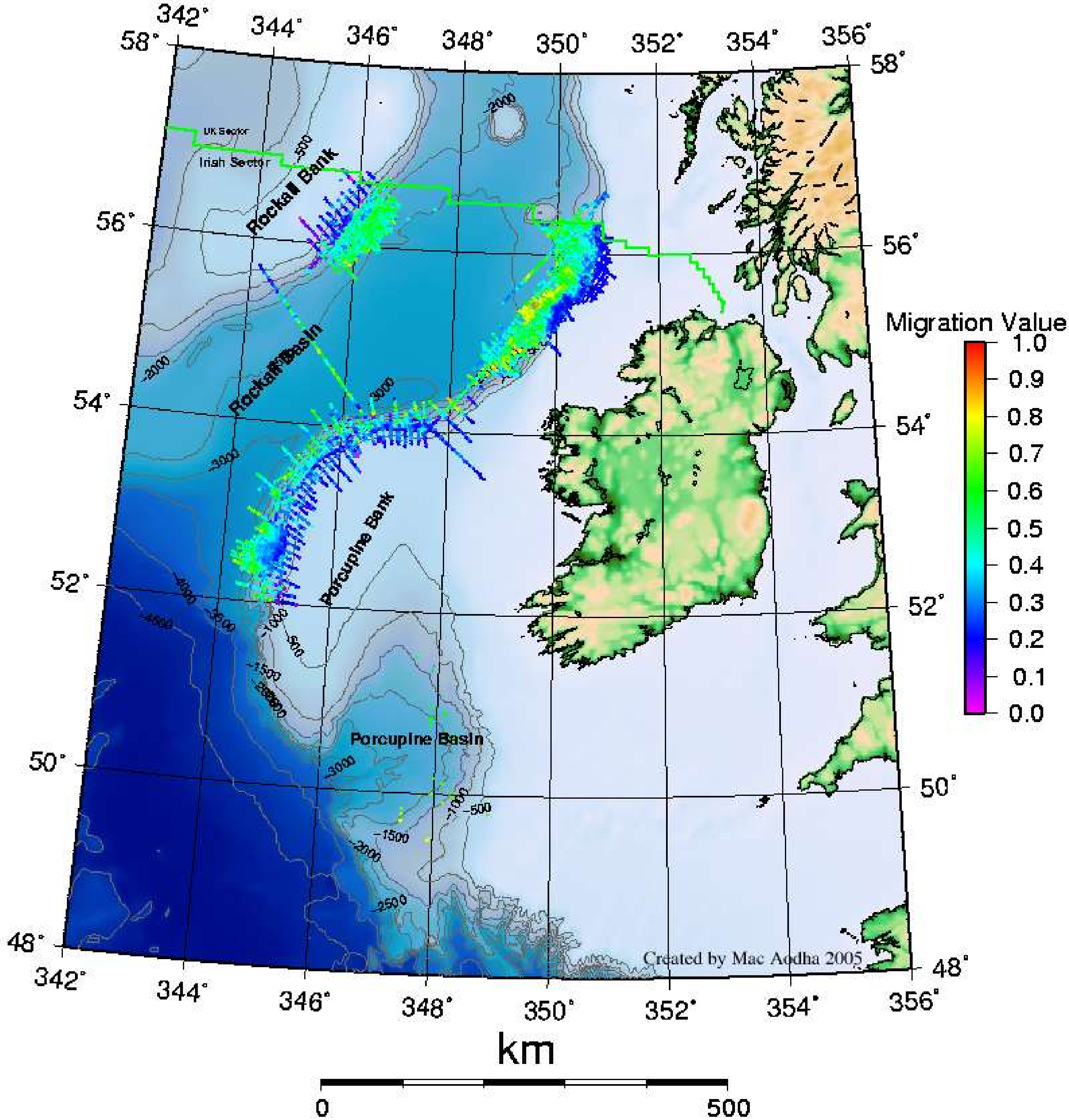


Figure 5.4: *Reservoir potential in the study region. Areas marked yellow or red have scored over 0.7 and have very good potential. Plotted in UTM zone 29.*

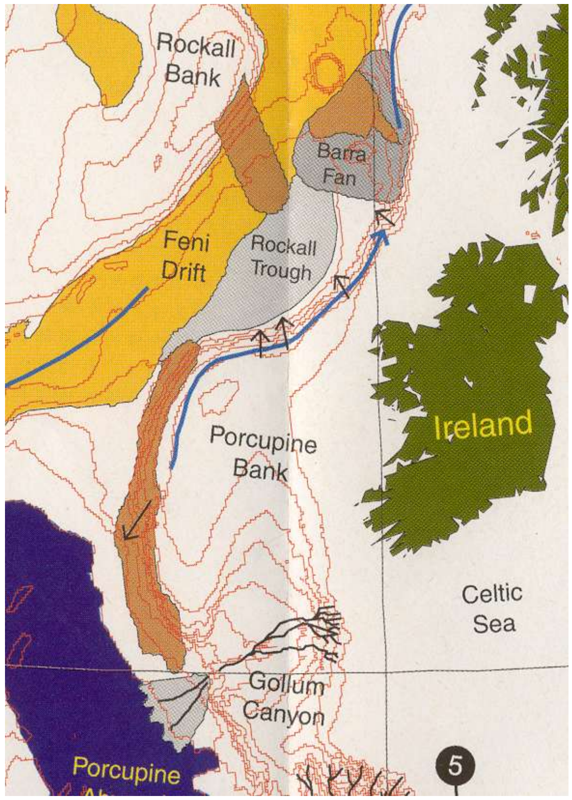


Figure 5.5: *Sedimentary features west of Ireland. Reproduced from Weaver et. al., (2000). Areas marked in grey denote fan system; brown are slump features, yellow represents deposition due to bottom currents. The arrows denote direction of sediment movement from canyons on the margin.*

5.3 Key Areas

Figure 5.6 shows all the results over the survey area. While every location shown in red is considered to be prospective five areas circled in white have been chosen as areas of particular interest.

5.3.1 Area 1

This area is located on the north eastern margin of the Rockall Basin circled as 1 on Figure 5.6. The area has the best reservoir potential encountered during the survey; Figure 5.7 shows an example of one off those reservoirs. The area encircled is approximately 70 km long with a HSZ which increases from 250 to 500 m, east to west. Well 12/2-1z to the north east had gas condensate shows indicating an active hydrocarbon system in the area. The quality and extent of the migration pathways is the biggest unknown and establishing this will be the key to setting targets within this area.

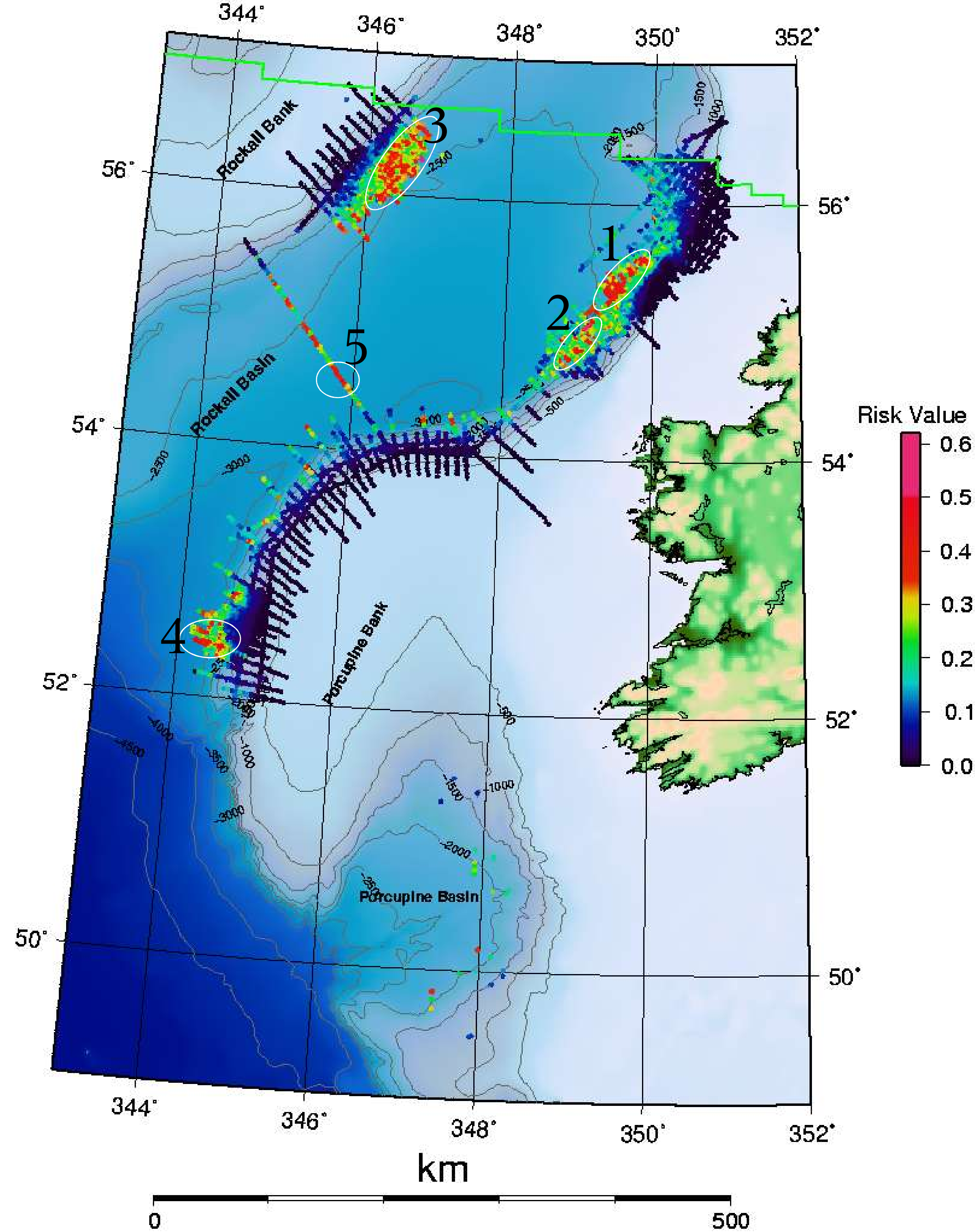


Figure 5.6: *Overall results of the risk assessment of the study region. Areas marked red have scored over 0.34 and have very good potential. Plotted in UTM zone 29.*

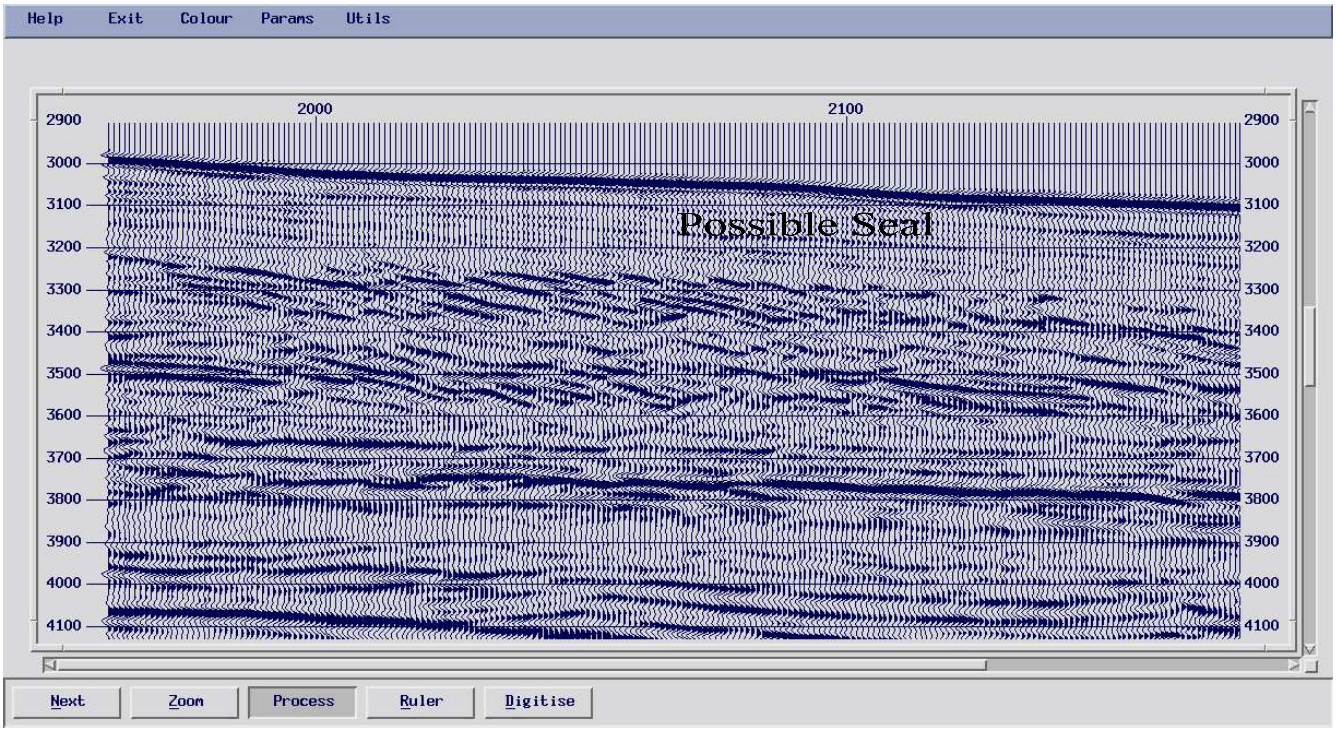


Figure 5.7: *example of a reservoir from Area 1. An AGC of 300 ms has been applied.*

One of the areas in which a hydrate deposit differs from a conventional oil/gas accumulation is that there is no need for a seal on the reservoir as hydrate acts as it own seal. However, in dissociating the hydrate in order to extract the trapped gas the seal is also destroyed. So one of the benefits of this area (Fig. 5.7) is the presence of a layer, sometimes up to 300 ms thick, of finer horizontally bedded sediment overlying the reservoir. This layer has the potential to act as a seal, or at least a barrier, which will prevent dissociated gas escaping from the system before it can be pumped out. Its effectiveness will depend on the geotechnical properties of the overlying layer.

Other benefits of this location include its proximity to the Irish coast in comparison to Areas 3-5 and the existence of gas pipelines to north Mayo and Derry.

5.3.2 Area 2

This area lies to the south of Area 1 on the eastern margin of the Rockall Basin (Fig. 5.6). Like Area 1 it also has excellent reservoir potential, though the reservoirs are more localised.

Figure 5.8 shows an example of one of the reservoirs from the area. It does not have the overlying layer of finer material discussed above but this is present elsewhere in the area. The area has the advantage of having better migration pathways than Area 1. The better scores for this parameter may, however, be more closely linked with the quality of the data than the actual level of faulting. The HSZ for this area increases from 300 m in the east to 500 m in the west. Evidence for an active hydrocarbon system is still based on well 12/2-1z to the north. The area is closer to the Corrib field than this well but lies in a structurally separated basin. One advantage of this proximity is the possibility to leverage infrastructure which will be associated with this field.

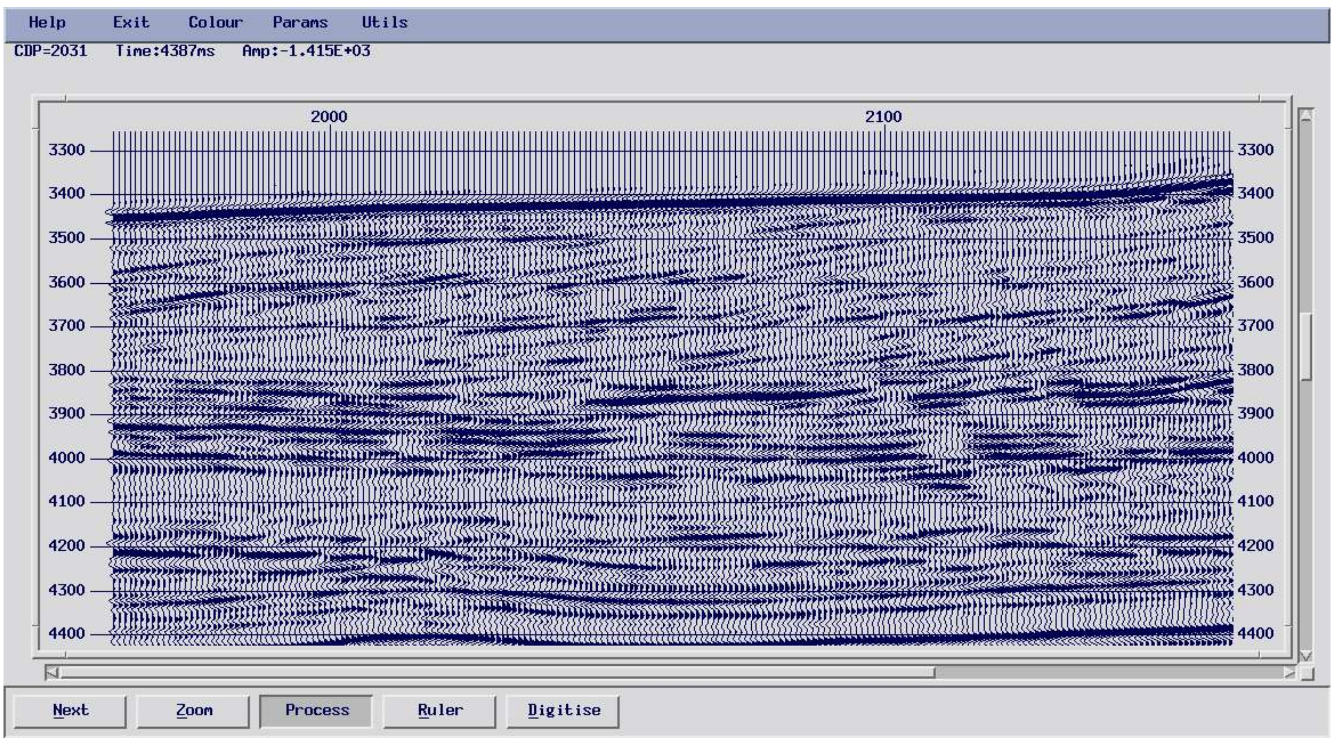


Figure 5.8: *Example of reservoir from Area 2. An AGC of 300 ms has been applied.*

5.3.3 Area 3

This area lies on the north western margin of the Rockall Basin (Fig. 5.6). The area has the best migration pathways of the study area with faults running through the system from the basement or deep sedimentary section to the HSZ. The reservoir quality is not as good as Areas 1 or 2 but as can be seen from Figure 5.9 there is potential. The HSZ in the area varies between 400 and 500 m, increasing west to east. The presence of an active hydrocarbon system is implied from the presence of a gas chimney on one of the seismic sections from Survey 1997_10 (Fig. 4.23). There have been no commercial wells in the area but ODP well 982 lies just to the north on the boundary between the Irish and UK sectors of the basin. Hydrates were not recovered from this site (1145 m water depth). This is to be expected as pressure cores were not used. Jansen *et al*., (1995) did cite dissociated hydrate as a possible explanation for the observed downhole increases in dissolved chloride.

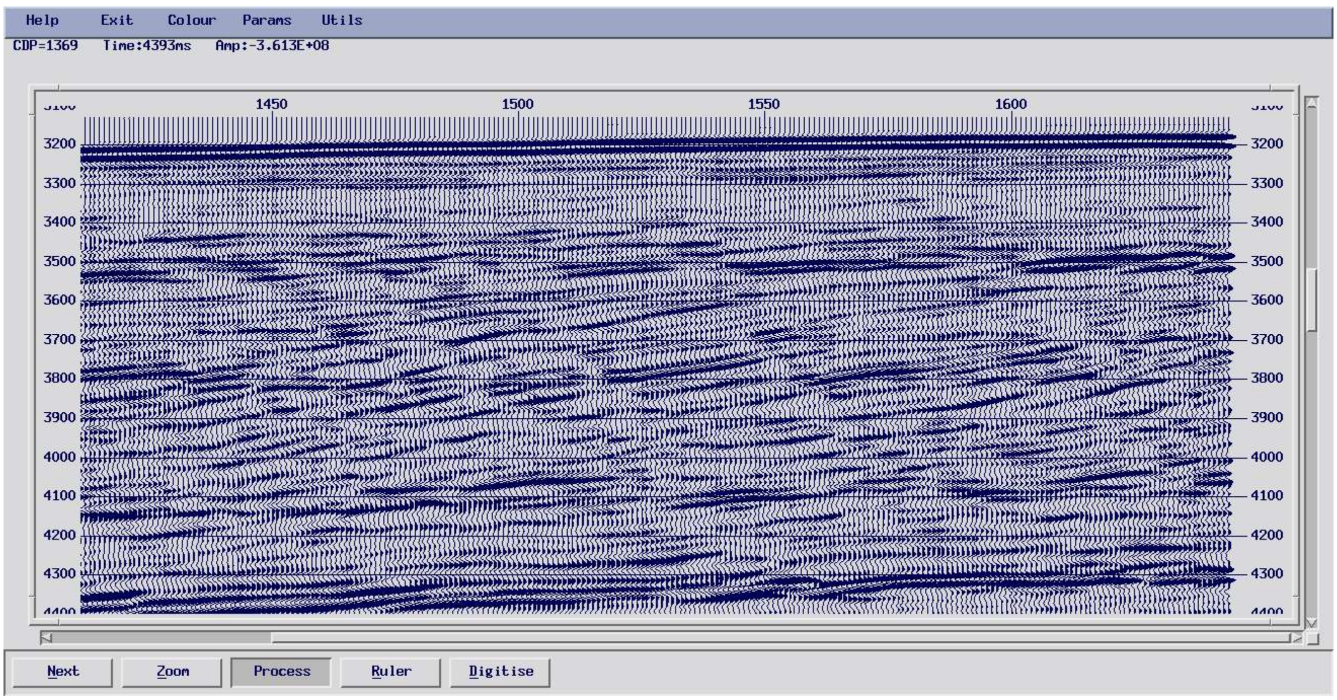


Figure 5.9: *Example of potential reservoir from Area 3. An AGC of 300 ms has been applied.*

5.3.4 Area 4

This area is situated on the south eastern margin of the Rockall Basin on the western flank of the Porcupine High (Fig. 5.6). This region of the basin is generally less prospective than either of the northern margins. The high scoring areas here are linked to localised sediment input which may be associated with the numerous canyons which cut the edge of the Porcupine High. The example shown in Figure 5.10 is typical of the area. The reservoirs are smaller in thickness and lateral extent. This area shows better migration pathways than the region in general, though data quality may be masking migration pathways elsewhere. The margin is very steep here and the area is deeper than those further north. Depths range from 3000-3500m This gives a HSZ thickness between 570 and 600 m. Its hydrocarbon system is unproven though one is expected given that the area has a similar geological history to the northern part of the Rockall Basin (Naylor *et al*., 1999).

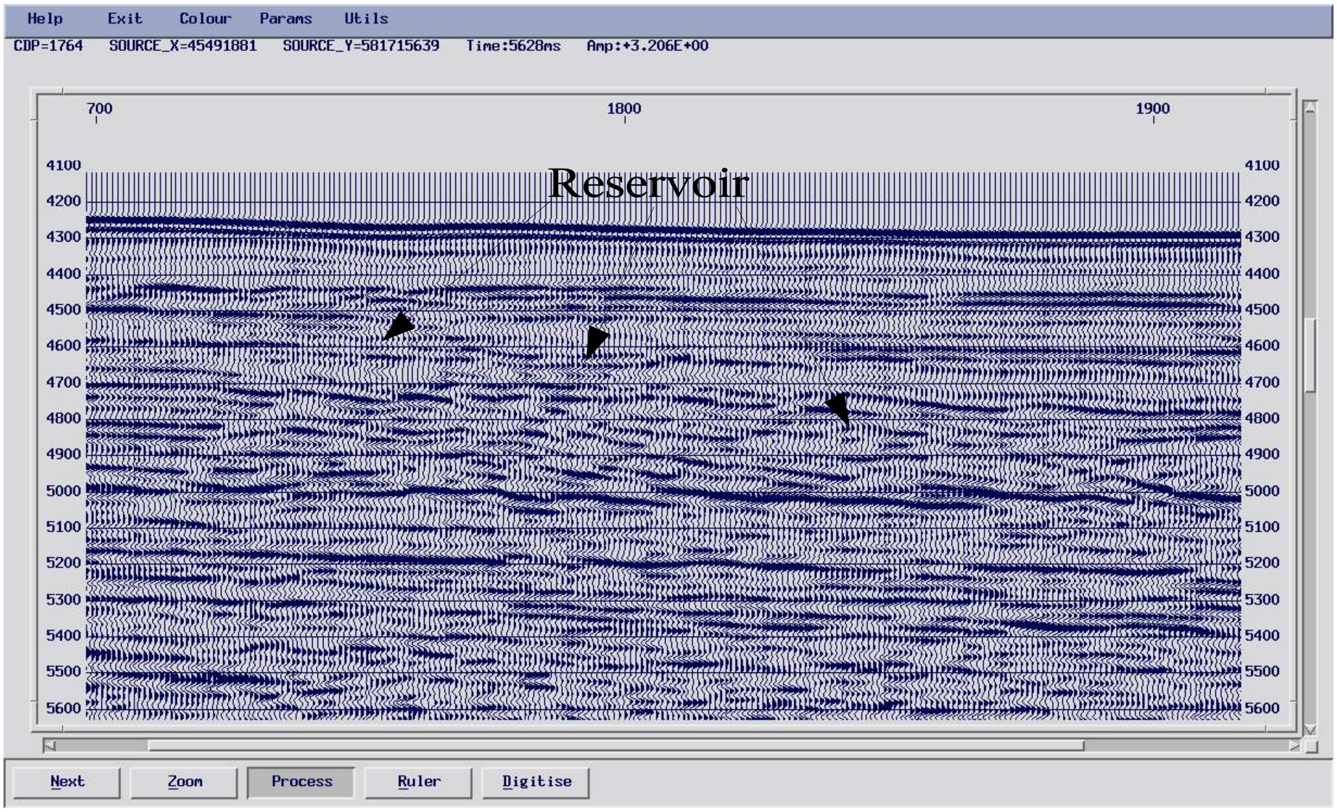


Figure 5.10: *Example of potential reservoir from Area 4. An AGC of 300 ms has been applied.*

Area 5

This area is situated just east of the centre of the Rockall Basin between 54^{o} and 55^{o} N (Fig. 5.6). It is in deep water; close to 3000 m and unlike the other areas a considerable distance from the margin. Despite this distance it has a thin but continuous layer within the HSZ which shows reservoir potential (Fig. 5.11). Migration pathways are good with regular faulting through most of the sedimentary section over the area. The HSZ is calculated at 500 m thick and the target reservoir is usually shallower than this. Like Area 4 the hydrocarbon system is unproven but the shared history of the basin would point to one being present. Exploration at this location is not recommended while commercial exploitation of hydrate is still in its infancy. However, further work at this location with a more academic climate change focus is a possibility. If the conditions here can be shown to be representative of areas where hydrate can occur in high concentrations over large areas of the Rockall Basin floor, a better understanding of the volume involved will provide insights into the role of methane hydrate as a carbon sink.

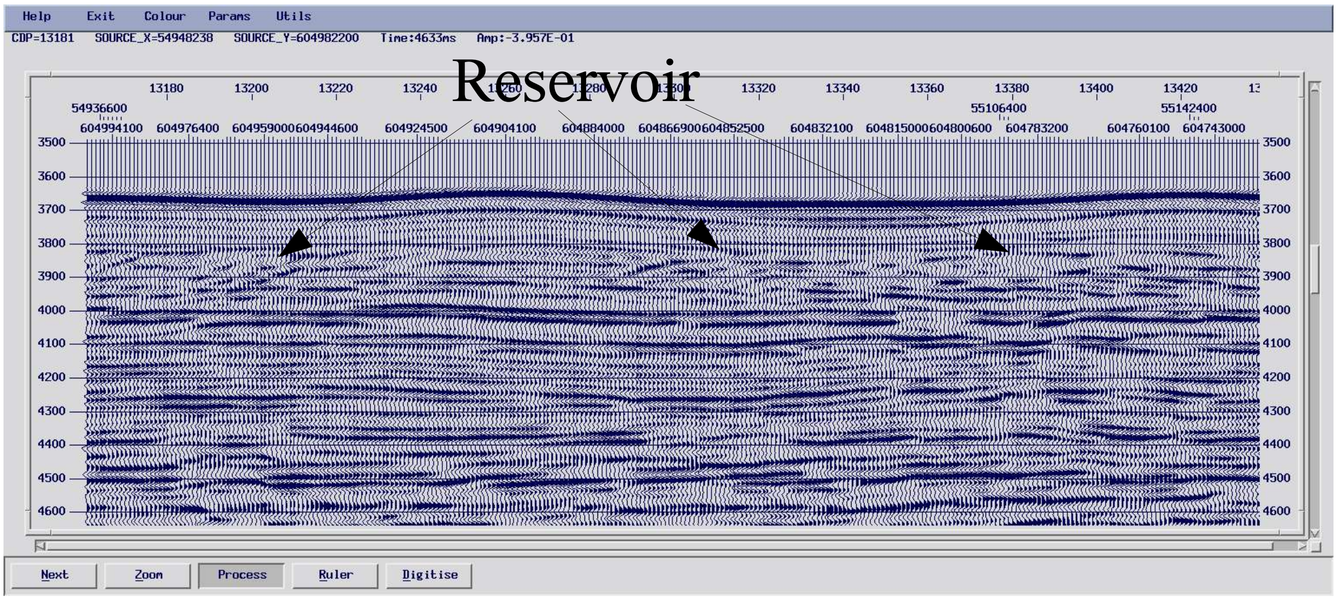


Figure 5.11: *Example of potential reservoir from Area 5. An AGC of 300 ms has been applied.*

Further Work

This project is a first assessment of the methane hydrate resource potential in the Irish Designated Area. Several areas with high resource potential have been identified with the data available. Some of the values used in this study have been estimated from poorly constrained or poor quality data. In order to better constrain these values and to address some of the questions that have arisen from this project, the following future work is recommended:

1) Geological investigation of reservoirs: one of the key features identified in this work is the presence of potential hydrate reservoirs in the HSZ. The geological history, source, grain type, transportation pathways, deposition history and burial history will all provide insights to the quality of these reservoirs. It is recommended that what information already available on these sediments be brought together to build a fuller picture of their nature and allow for specific reservoir modelling. Tied with this would be the use of seismic stratigraphy to delineate the extent of the reservoirs.

2) Reprocessing existing seismic reflection data: two issues arose with the seismic data analysed which affected the assessment; poor imaging of the faulting in the lower section and poor resolution of the sedimentary structures in the upper section. A processing schedule more focused for hydrate exploration could improve the usefulness of these data.

3) Acquisition of new seismic data: acquisition of high frequency seismic data would allow a much better analysis of the HSZ and the nature of the sediments contained within. This would also be of great benefit in for the delineation of reservoirs mentioned above.

4) Shallow coring: a program of shallow coring would confirm the geology of the reservoir sediments, the geotechnical properties of the reservoirs, and allow geochemical analysis of the nature of any gas/hydrate encountered to establish whether it is thermogenic of biogenic in origin. It would also provide an opportunity to undertake recommendations 5-7 below. While the HSZ is up to 600 m thick in some of the key locations, in most cases the reservoirs involved are much closer to the surface or stratigraphically extend to the surface bringing them into the range of a shallow coring program.

5) Constrain the geothermal gradient: as has been previously stated by Unnithan *et al.*, (2004) the geothermal gradient in the Rockall Basin is one of the biggest unknowns. The extremely sparse well data and the large area of the basin mean that the values used are, at best, a regional average. To improve our model of the HSZ the resolution of our geothermal gradient data needs to be improved with direct heat flow measurements.

6) Constrain seabed temperatures: While the INSS gives good coverage of seabed temperatures in shallower areas (<500 m) the readings do not extend all the way to the sea floor in deeper water, often stopping up to 500 m from the bottom. Other data sourced

for this project did provide coverage right to the floor of the Rockall Basin, but this was spatially limited to an area just west of the Porcupine Bank. Given the size of the Basin and the strong current movement through it, a more extensive network of readings is important. These data are easier to acquire than geothermal gradient data, e.g., a considerable amount was recently (July 2005) acquired on a Celtic Explorer cruise investigating carbonate mud mounds on the Porcupine Bank. It is recommended that a database of this data be established and efforts made to have readings taken where possible during all work in waters over 500 m.

7) Sulphate reduction zone: the thickness of the sulphate reduction zone and the depth of the SMI is one of the key indicators of the flux of methane through the HSZ. Hydrate will only form in the HSZ where the water is saturated with respect to methane; therefore the flux needs to be sufficient to achieve this. It is recommended that pore water geochemistry is analysed using piston cores in order to establish the thickness of the sulphate reduction zone.

8) Controlled Source Electromagnetics (CSEM): gas hydrate increases the resistivity of a sedimentary layer (Schwalenberg *et al*., 2005). This can be used to evaluate the presence of hydrate and can be modelled to give some estimation of the concentration.

9) Towed magnetics: recent work by researchers in Canada has shown that the presence of hydrate reduces the magnetic susceptibility of the sediment in which it is found. The reduction was found to have a direct correlation to the concentration of hydrate present. High resolution towed magnetic surveys over identified reservoirs could establish both the presence or absence of hydrates and the concentrations involved.

The work outlined is quite detailed and should be focused on a specific area. In this authors opinion it should be carried out on either Area 1 or 2 (Fig. 5.6). Recommendations 1-3 are suitable for a larger area and are seen as a precursor to the other recommendations, with the exception of no. 6.

6 Conclusions

1) Modelling of the HSZ showed large areas of Ireland's deep water basins lie within the stability zone and can accumulate commercial concentrations of hydrate given a sufficient methane flux.

2) Three key parameters, HSZ thickness, migration pathways and reservoir potential, for a commercial accumulation of hydrate were identified and the study area assessed based on these parameters.

3) The calculated HSZ increases in thickness from 0 m at about 700 m water depth, to 650 m in the Rockall Basin and to 720 m in the Porcupine Basin. These figures are based on poorly constrained hydrothermal and geothermal data; local variations can be expected.

4) The migration pathway analysis shows the best results on the north western margin of the Rockall Basin. Other areas of the Rockall Basin are not as well faulted but, locally, are sufficiently faulted to allow migration of methane into the HSZ. The Porcupine Basin shows sufficient faulting to allow migration in to the HSZ.

5) The reservoir quality analysis shows the best results on the north eastern margin of the Rockall Basin. Other areas of the Rockall Basin do not have the same reservoir potential but do have sufficient potential, usually localised, to allow them to be considered prospective. The Porcupine Basin shows very little reservoir potential. Only some very small areas associated with present and buried channel systems show sufficient reservoir potential for the area to be considered prospective.

6) The method used in the work is efficient for an initial assessment considering the data available and short time scale. The method is affected by the quality of the data which affects the consistency of results between surveys.

7) Several areas score sufficiently well in the risk assessment to be considered prospective for commercial accumulations of methane hydrate. Five areas of particular interest were selected as showing the most potential. Of these it is recommended that initial further work concentrate on the two areas (Areas 1 and 2) on the north eastern margin of the Rockall Basin.

Acknowledgements

We would like to thank Providence Resources Plc. and Sosina Exploration Ltd. for funding this work and for their donation of computing equipment to the EOS which made this project possible. We particularly thank Fergus Roe and John O'Sullivan for their support and enthusiasm. PMA thanks Art Johnson for his instruction in the early stages of the project and acknowledges that the work presented here has benefited greatly from his input. The Petroleum Affairs Division of the Department of the Marine and Natural Resources provided the seismic data used in this work. We would particularly like to mention Peter Croker, Noel Murphy, and Barbara Murray who provided access to this data and paper sections reviewed in the PAD offices at short notice. The data from the INSS was made available to this project by the Marine Geology Division of the Geological Survey of Ireland. We thank Eibhlin Doyle for her help in making this possible. Data and invaluable advice on seabed temperatures and ocean currents were provided by Christian Mohn we thank him for his willing help.

References

Bonatti, E (1985) Punctiform initiation of seafloor spreading in the Red Sea during transition from a continental to oceanic rift, *Nature*, **316**, 33-37.

Borowski, W.S., Paull C.K. and Ussler, W. III (1999) Global and local variations of interstitial sulfate gradients in deep-water, continental margin sediments: Sensitivity to underlying methane and gas hydrates, *Marine Geology*, **159**, 131-154.

Cole, J, and Peachey, J (1999) Evidence for pre-Cretaceous rifting in the Rockall Trough: an analysis using quantitative plate tectonic modelling, *Petroleum Geology of Northwest Europe: Proceedings of the fifth conference*, Fleet, A J and Boldy, S A R, eds, The Geological Society, London 359-370.

Corfield, S, Murphy, N and Parker, S (1999) The structural and stratigraphic framework of the Irish Rockall Trough, in, *Petroleum Geology of Northwest Europe: Proceedings of the fifth conference*, Fleet, A J and Boldy, S A R, eds, The Geological Society, London, 407-420.

Corry, D. and Brown C. (1998) Temperature and heat flow in the Celtic Sea basins, *Petrol. Geosci.*, **4**, 317-326

Croker, P.F. and Shannon, P.M. (1995) *The Petroleum Geology of Ireland's Offshore Basins*, Geological Society, London, Special Publication No.93, 504pp.

Croker, P, and Shannon, P (1987) The evolution of the hydrocarbon prospectivity of the Porcupine Basin, offshore Ireland, *Petroleum Geology of North West Europe*, Graham and Trotman, eds, 633-642.

Daly, E (2002) *Multi-Resolution Coherence and Techniques to Understand Tectonics and Rheology of the Irish Atlantic Margin*, Ph.D. thesis, Applied Geophysics Unit, National University of Ireland, Galway.

Dore, A G, Lundin, E, Jensen, L N, Birkeland, O, Eliassen, P E, and Fichler, C (1999)

Principle tectonic events in the evolution of the Northwest European Atlantic Margin, *Petroleum Geology of Northwest Europe, Proceedings of the 5th conference*, The Geological Society of London, 41-61.

Einsele, G (1985) Basaltic sill-sediment complexes in young spreading centres: genesis and significance, *Geology*, **13**, 249-252.

England, R, and Hobbs, R (1997) The structure of the Rockall Trough imaged by deep seismic reflection profiling, *J. Geol. Soc. London*, **154**, 497-502.

Englezos, P., Bishnoi, P.R. (1988) Prediction of gas hydrate formation conditions in aqueous electrolyte solutions, *American Institute for Chemical Engineering Journal*, **34** 1718-1721.

Hauser, F, O'Reilly, B, Jacob, B, Shannon, P, Markris, J, and Vogt, U (1995) The crustal structure of the Rockall Trough: Differential stretching without underplating, *J. Geophys. Res.*, **100**(B3), 4097-4116.

Jansen E., Rayma, M. and Blum, P. (1995) *Ocean Drilling Program, Leg 162, Preliminary Report, North Atlantic Arctic Gateways II*, Preliminary Report 62, ODP, Texas A&M University.

Joppen, M, and White, R (1990) The structure and subsidence of Rockall Trough from two-ship seismic experiments, *J. Geophys. Res.*, **95**(B12), 19821-19837.

Knott, S D, Burchell, M T, Jolley, E J and Fraser, A J (1993) Mesozoic to Cenozoic plate reconstructions of the North Atlantic and hydrocarbon plays of the Atlantic margins, *Petroleum Geology of Northwest Europe: Proceedings of the fourth conference*, Parker, R J, ed, The Geological Society, London, 953-974.

Kvenvolden, K.A. (2000) Natural gas hydrate; introduction and history of discovery, in Max, M.D. ed, *Natural Gas Hydrate in Oceanic and Permafrost Environments*, Kluwer Academic Publishers, Dordrecht.

Long, D., Jackson, P.D., Lovell, M.A., Rochelle, C.A., Francis, T.J.G. and Schulthesis, P.J. 2005. Methane hydrates: problems in unlocking their potential, in Dore, A.G. and Vining, B.A. (eds) *Petroleum Geology: North-West Europe and Global Perspectives Proceedings of the 6th Petroleum Geology Conference*, Petroleum Geology Conferences Ltd. Published by the Geological Society, London, 723 730.

Mac Aodha, P., Johnson, A. and Brown, C. (2005) *Knowledge Transfer between Hydrate Energy International and the Department of Earth and Ocean Sciences, NUI, Galway*, Technical Report to the Irish Petroleum Infrastructure Program.

Mac Aodha, P. (2004) *Statistical Characterisation of Deep Seismic Reflectivity Patterns, with Application to the Rockall Basin*, Ph.D. thesis, Department of Earth and Ocean Sciences, National University of Ireland, Galway.

Makris, J., Egloff, R., Jacob, A.W.B., Mohr, P., Murphy, T., and Ryan, P. (1988) Continental crust under the South Porcupine Seabight west of Ireland, *Earth Planet. Sci. Lett.*, **89**, 287-397.

Masson, D, and Miles, P (1986) Structural development of the Porcupine Seabight sedimentary basin, offshore Southwest Ireland, *Am. Ass. of Petrol. Geol. Bull.*, **70**, 567-548.

Max, D.M. (2000) *Natural Gas Hydrate in Oceanic and Permafrost Environments*, Kluwer Academic Publishers, Dordrecht.

McCann, T., Shannon, P.M., Moore J.G. (1995) Fault styles in the Porcupine Basin, offshore Ireland: tectonic and sedimentary controls, in Croker, P. and Shannon P.M., eds, *The Petroleum Geology of Ireland's Offshore Basins*, Geol. Soc. Lon. Spec. Publ., **93**, Geological Society of London.

Miles, P.R., (1995) Potential distribution of methane hydrates beneath the European continental margins, *Geophysical Research Letters*, **22**(23), 3179-3182.

Morton, B., (1988) Partnerships in the sea, Hong Kong University Press, Hong Kong.

Musgrove, F W, and Mitchener, B (1996) Analysis of pre-Tertiary rifting history of the Rockall Trough, *Petroleum Geoscience*, **2**, 353-360.

Naylor, D, Shannon, P, and Murphy, N (1999) *Irish Rockall Region - a standard nomenclature system*, Petroleum Affairs Division, Special Publication 1/99, 42pp.

O'Reilly B.M.; Hauser F.; Jacob A.W.B.; Shannon P.M.; Makris J.; Vogt U. (1995) The transition between the Erris and the Rockall basins: new evidence from wide-angle seismic data, *Tectonophysics*, Volume 241(1), 143-163.

O'Reilly, B, Hauser, F, Jacob, A, and Shannon, P (1996) The lithosphere below the Rockall Trough: wide-angle seismic evidence for extensive serpentinisation, *Tectonophysics*, **255**, 1-23.

Pérez-Gussinyé, M., Reston, T.J., (2001) Rheological evolution during extension at nonvolcanic rifted margins: Onset of serpentinization and development of detachments leading to continental breakup, *J. Geophy. Res.*, **106**(B3), 3961-3976

Rao, Y.H. (1999) C-program for the calculation of gas HSZ thickness, *Computers and Geosciences*, **25**, 705-707.

Robeson, D., Burnett, R.D., and Clayton, G. (1988) The upper Palaeozoic geology of the Porcupine, Erris and Donegal Basins, offshore Ireland, *Irish J. Earth Sci.*, **9**, 153-175

Schwalenberg, K., Willoughby, E., Mir, R., Edwads, N.R. (2005) Marine gas hydrate electromagnetic signatures in Cascadia and their correlation with seismic blank zones, *First Break*, **23**, 57-63.

Scrutton R.A., Stacey, A. and Gray, F. (1971) Evidence for the mode of formation of the

Porcupine Seabight, Earth Planet. Sci. Lett., **11**, 140-146

Shannon, P, Jacob, A, Makris, J, O'Reilly, B, Hauser, F, and Vogt, U (1995) Basin development and petroleum prospectivity of the Rockall and Hatton Region, *The Petroleum Geology of Ireland's offshore basins*, The Geological Society, London, **93** 435-447.

Srivastava, S P, and Tapscott, C R (1986) Plate kinematics of the North Atlantic, in, *The Geology of North America*, *Vol. M, The Western North Atlantic Region*: Vogt, P R, and Tucholke, B E, eds, Geological Society of America, Washington, DC, 379-404.

Unnithan, V., Praeg, D., Shannon, P., O'Neill, N. (2004) *Gas Hydrate Stability and Fluid-Escape Features in Deep Water Environments West of Ireland*, Technical Report for the Geological Survey of Ireland under the auspices of the Irish National Seabed Survey.

Vogt, P R, and Tucholke, B E (1989) North Atlantic Ocean Basin: aspects of geologic structure and evolution, in, *The Geology of North America – an overview*, Bally, A W, and Palmer, A R, eds, Geological Society of America, Washington, DC, 53-79.

Walsh, A., Knag, G., Morris, M., Quinquis, H., Tricker, P., Bird, C. and Bower, S. (1999) Petroleum Geology of the Irish Rockall Trough – a frontier challenge, *Petroleum Geology of Northwest Europe: Proceedings of the 5th Conference*, The Geological Society of London, 433-444.

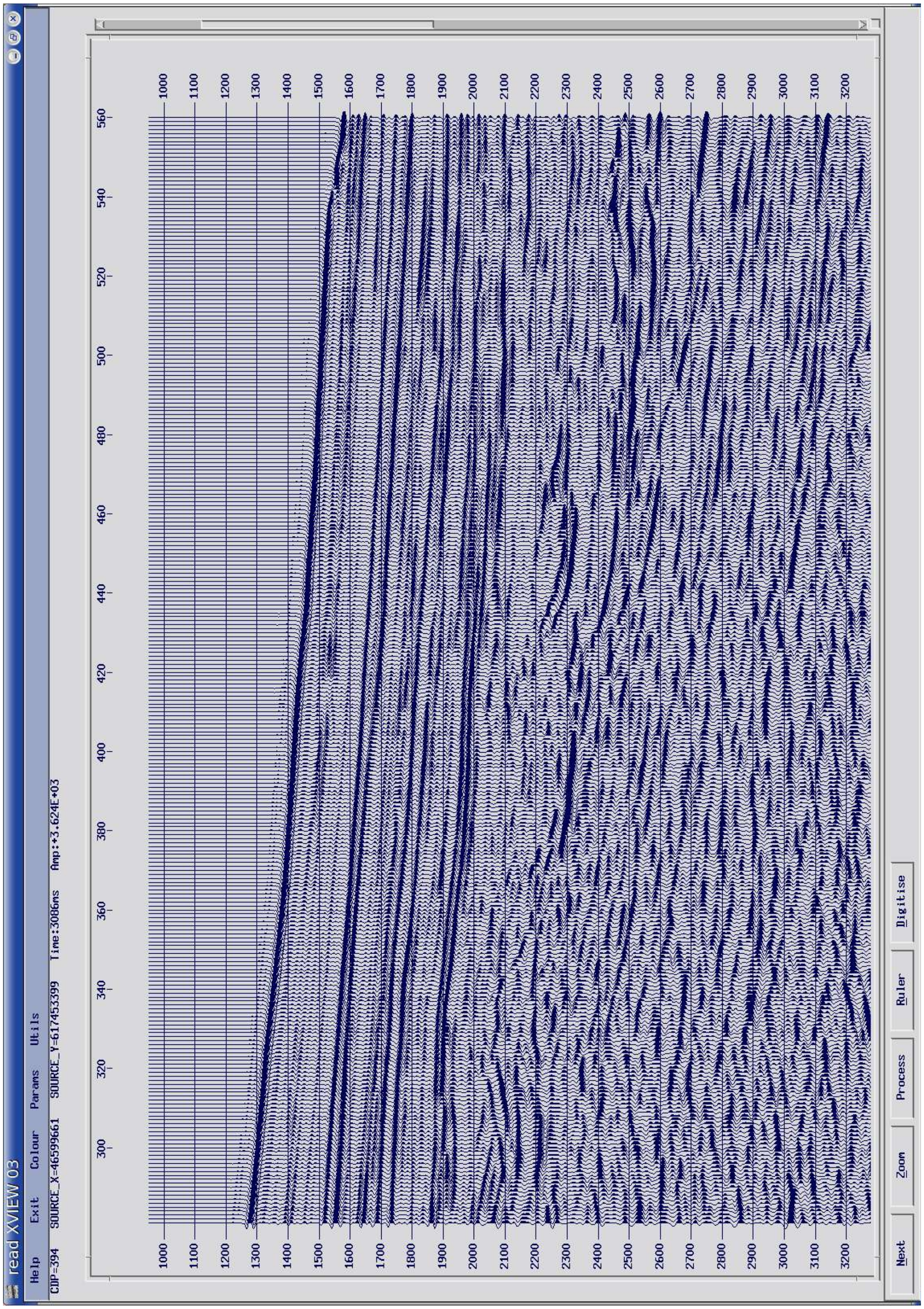
Weaver, P.P.E., Wynn, R.B., Kenyon, N.H., Evans, J. (2000) Continental margin sedimentation, with special reference to the north-east Atlantic margin, *Sedimentology,* **47** (s1) 239-254.

Wessel, P., and W. H. F. Smith, 1998, New, improved version of the Generic Mapping Tools Released, *EOS Trans. AGU, 79*, 579.

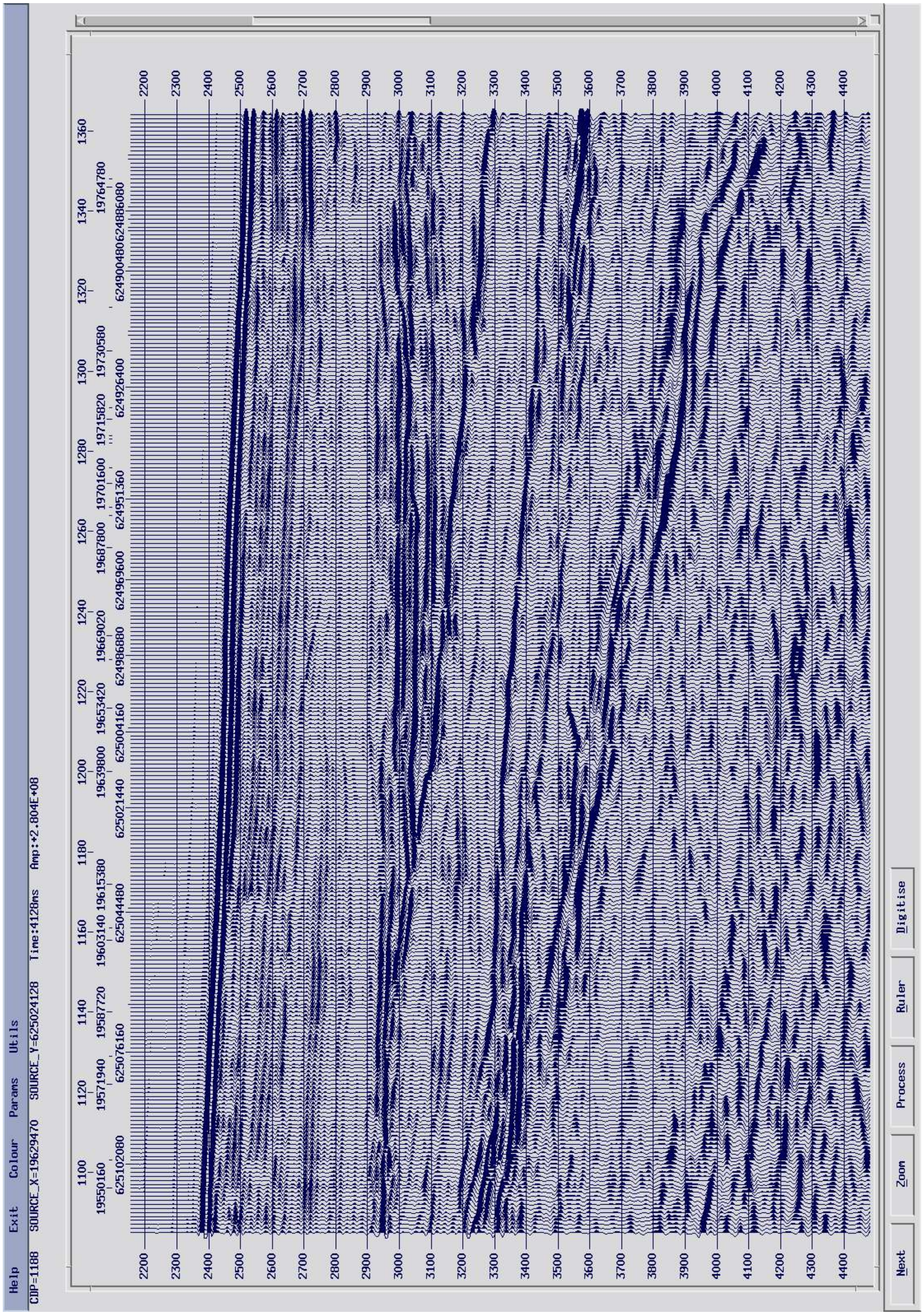
Wilson, M (1997) Thermal evolution of the Central Atlantic passive margins: continental break-up above a Mesozoic super-plume, *J. Geol. Soc., Lon.*, **154**, 491-496.

Appendix 1

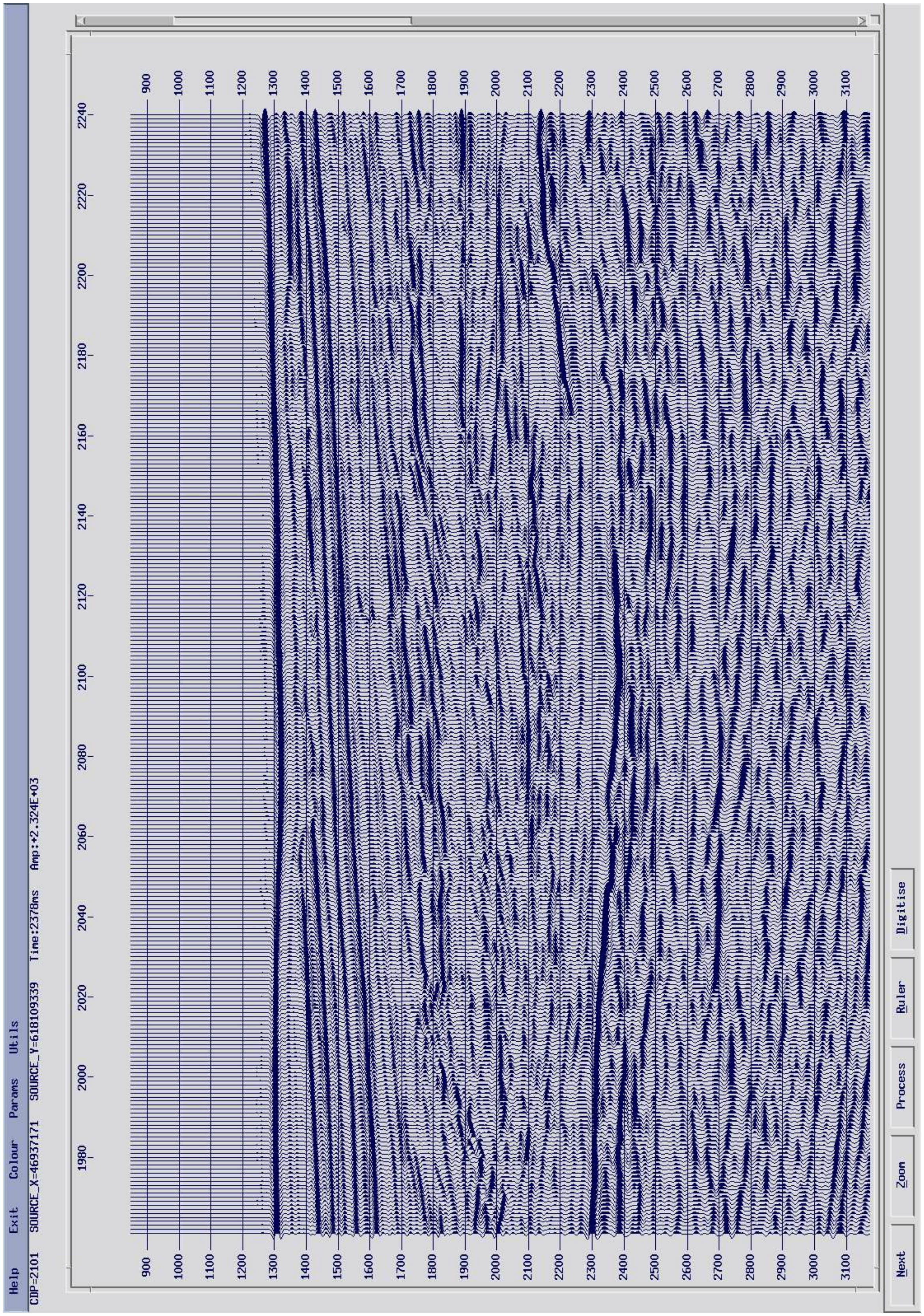
This appendix shows a series of sample sections from the study and the migration pathways score associated with them.



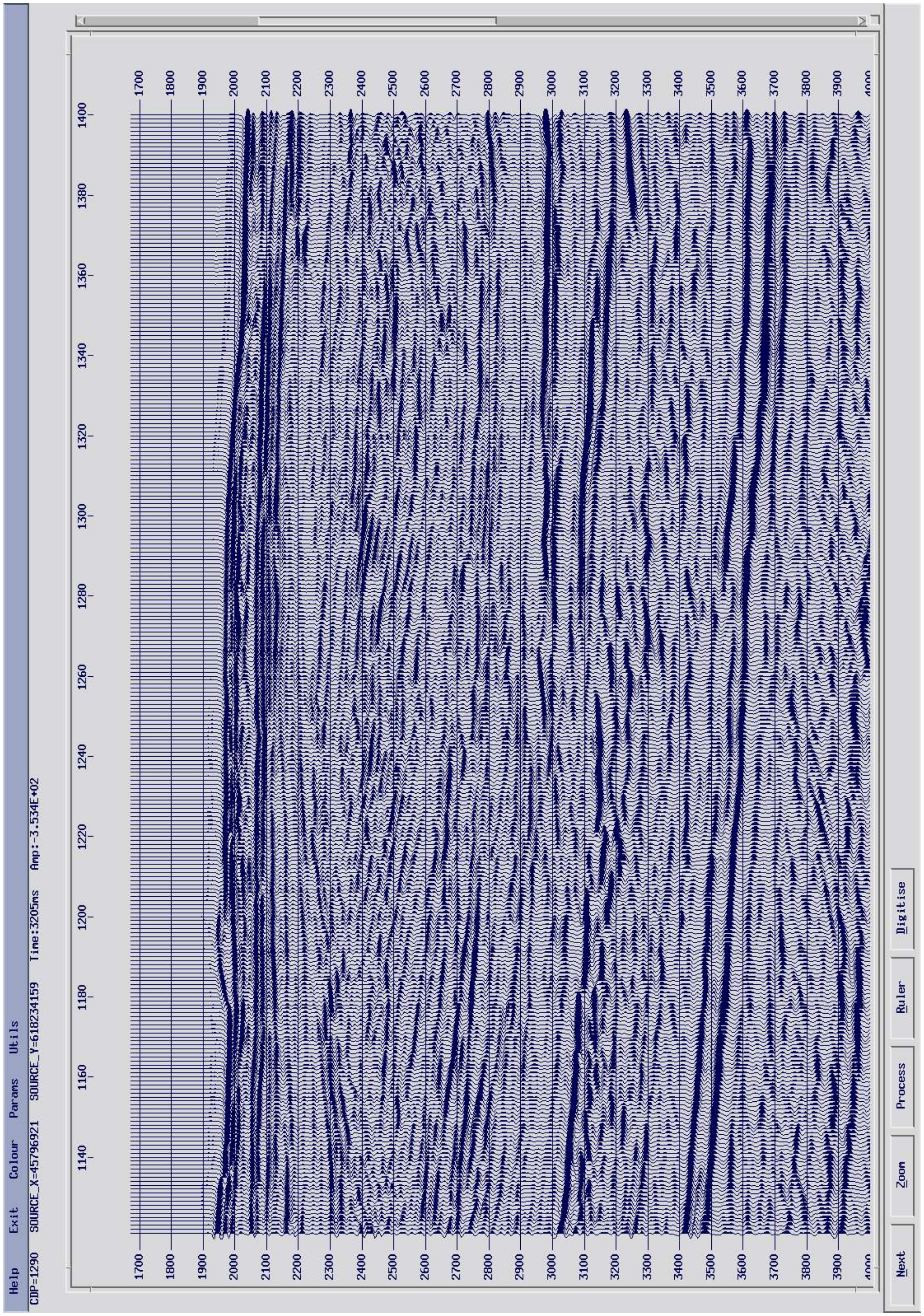
Score: 0.2


Help
Exit
Colour
Params
Utils
CDP=1188
SOURCE_X=19629470
SOURCE_Y=625024128
Time:4128ms
Amp:+2.804E+08
Next
Zoom
Process
Ruler
Digitise

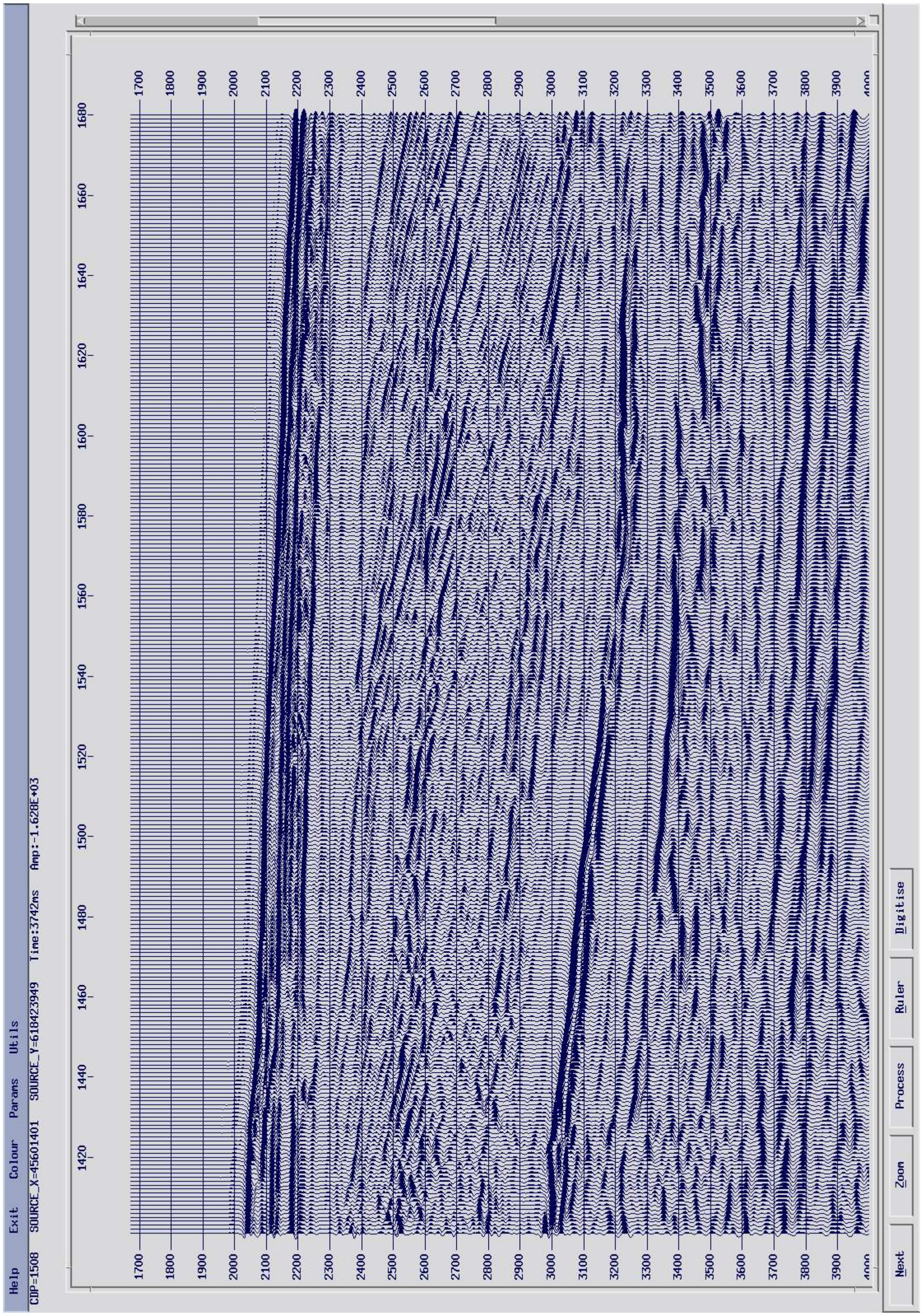
Score: 0.3


Help
Exit
Colour
Params
Utils
CDP=2101
SOURCE_X=46937171
SOURCE_Y=618109339
Time:2378ms
Amp:+2.324E+03
Next
Zoom
Process
Ruler
Digitise

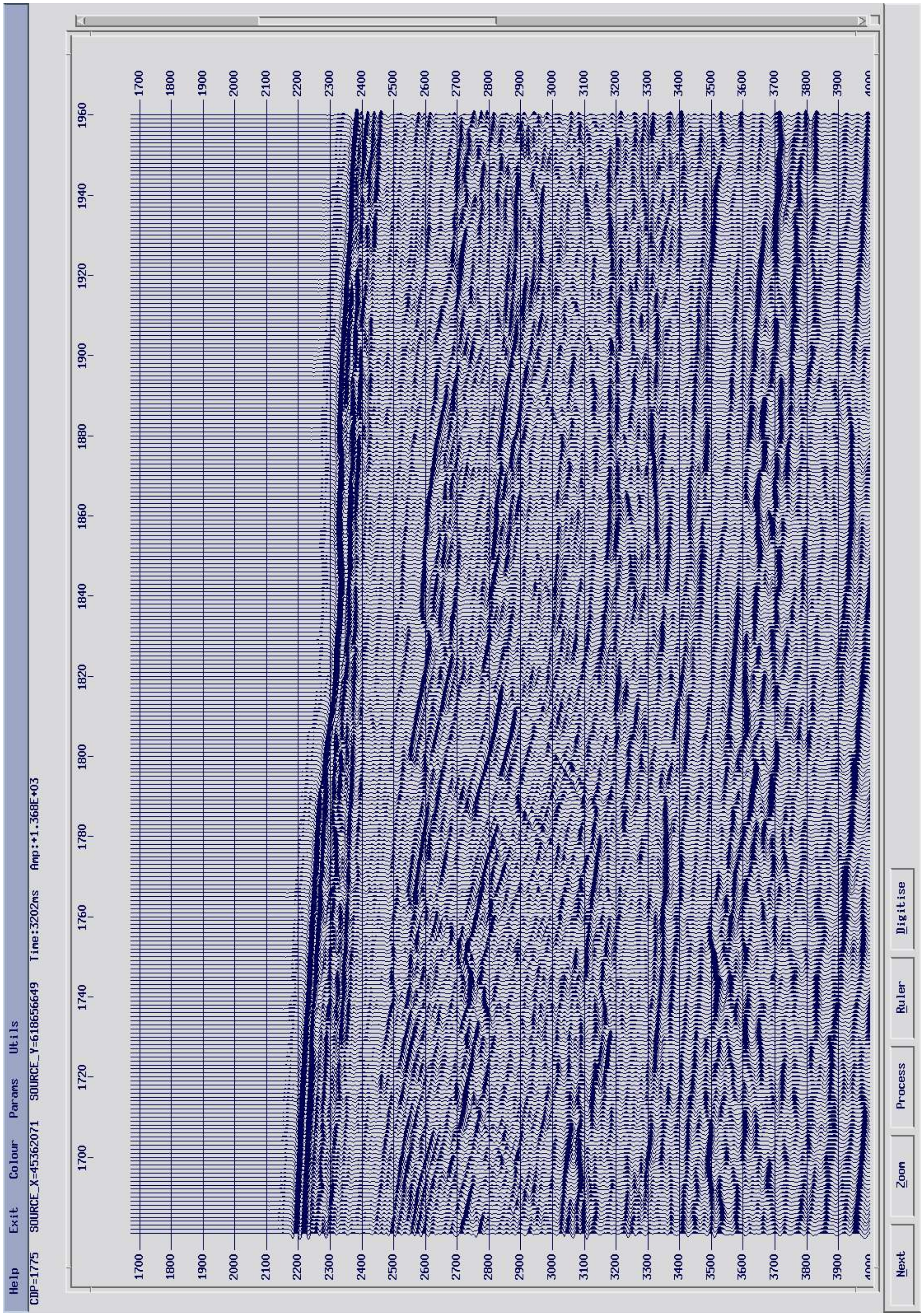
Score: 0.45


Help
Exit
Colour
Params
Utils
CDP=1290 SOURCE_X=45796921 SOURCE_Y=618234159 Time:3205ms Amp:-3.534E+02
Next
Zoom
Process
Ruler
Digitise

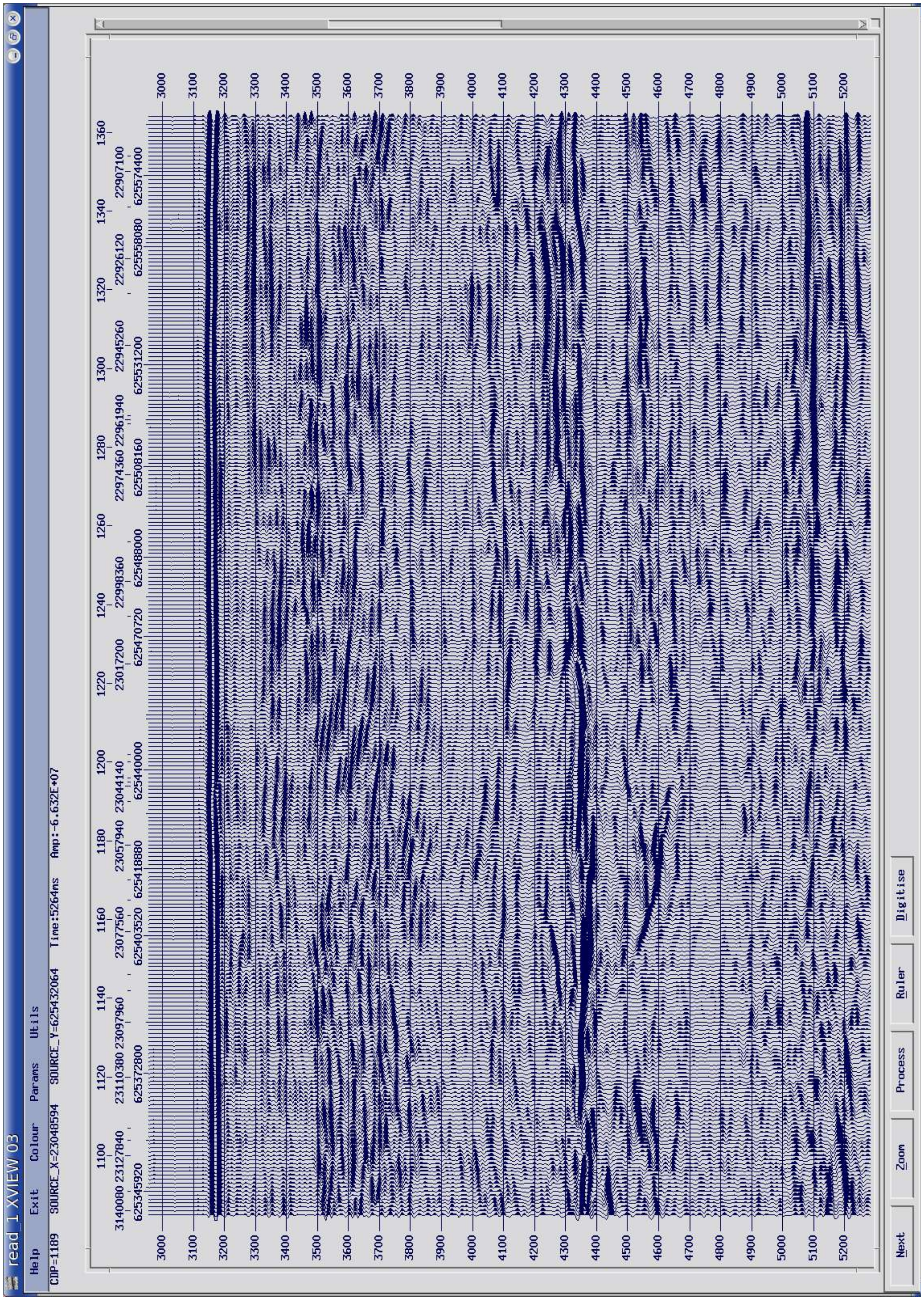
Score: 0.5


Help Exit Colour Params Utils
CDP=1508 SOURCE_X=45601401 SOURCE_Y=618423949 Time:3742ms Amp:-1.628E+03
Next
Zoom
Process
Ruler
Digitise

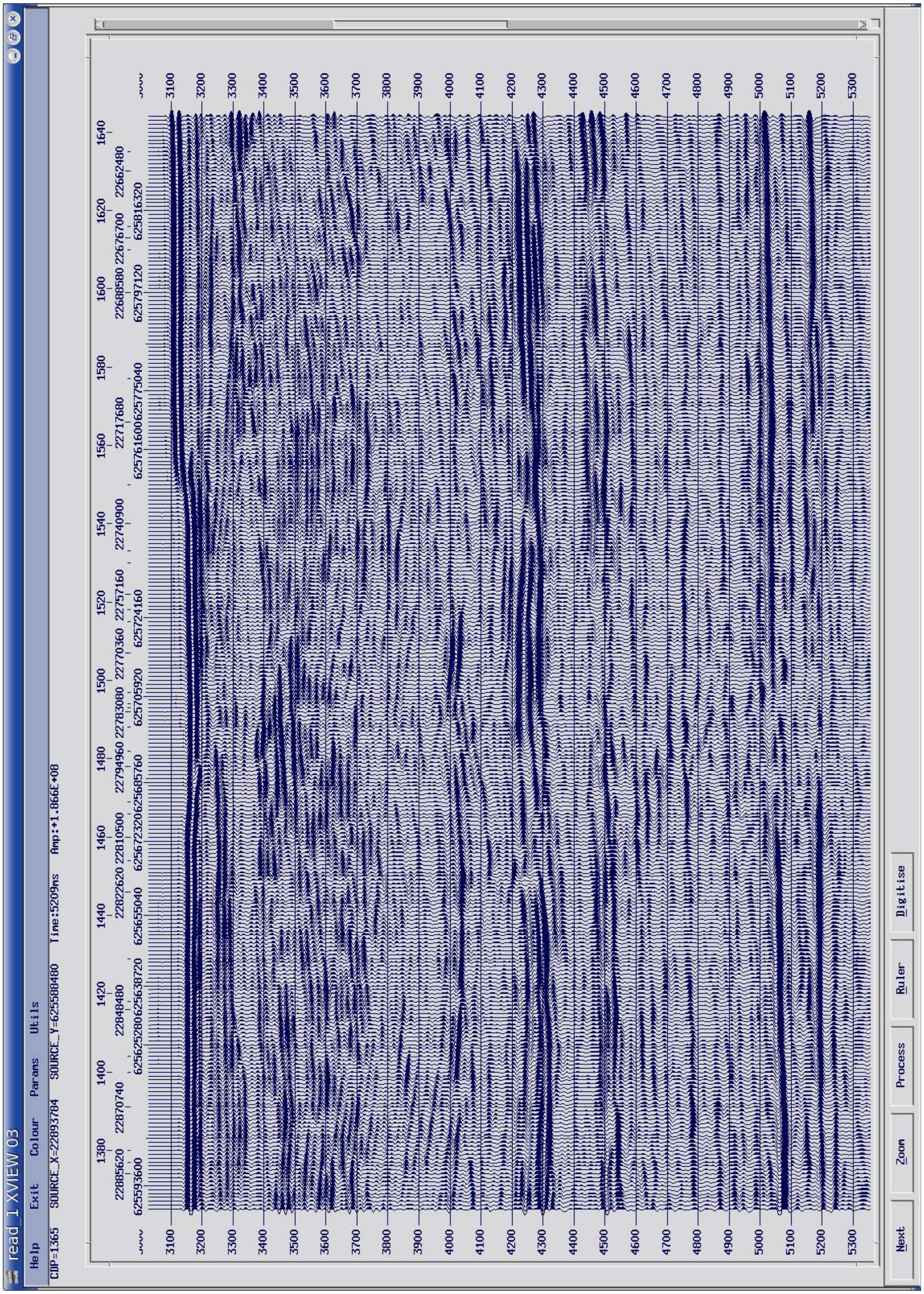
Score: 0.65


Help Exit Colour Params Utils
CDP=1775 SOURCE_X=45362071 SOURCE_Y=618656649 Time:3202ms Amp:+1.368E+03
Next
Zoom
Process
Ruler
Digitise

Score: 0.7


read_1 XVIEW 03
Help
Exit
Colour
Params
Utils
CDP=1189 SOURCE_X=23048594 SOURCE_Y=625432064 Time:5264ns Amp:-6.632E+07
Next
Zoom
Process
Ruler
Digitise

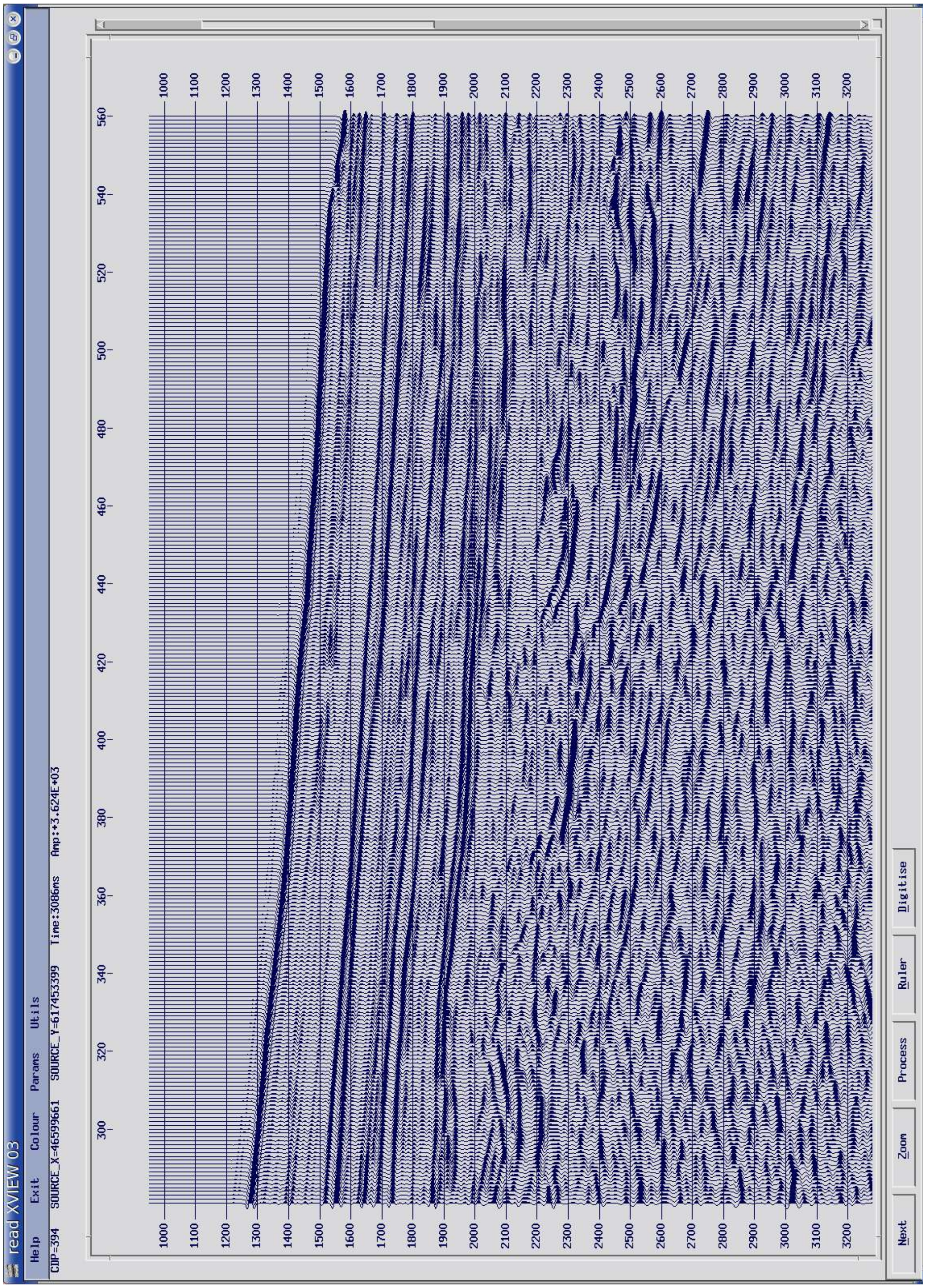
Score: 0.8


read_1 XVIEW 03
Help Exit Colour Params Utils
CDP=1365 SOURCE_X=22893784 SOURCE_Y=625588480 Time:5209ms Amp:+1.866E+08
Next
Zoom
Process
Ruler
Digitise

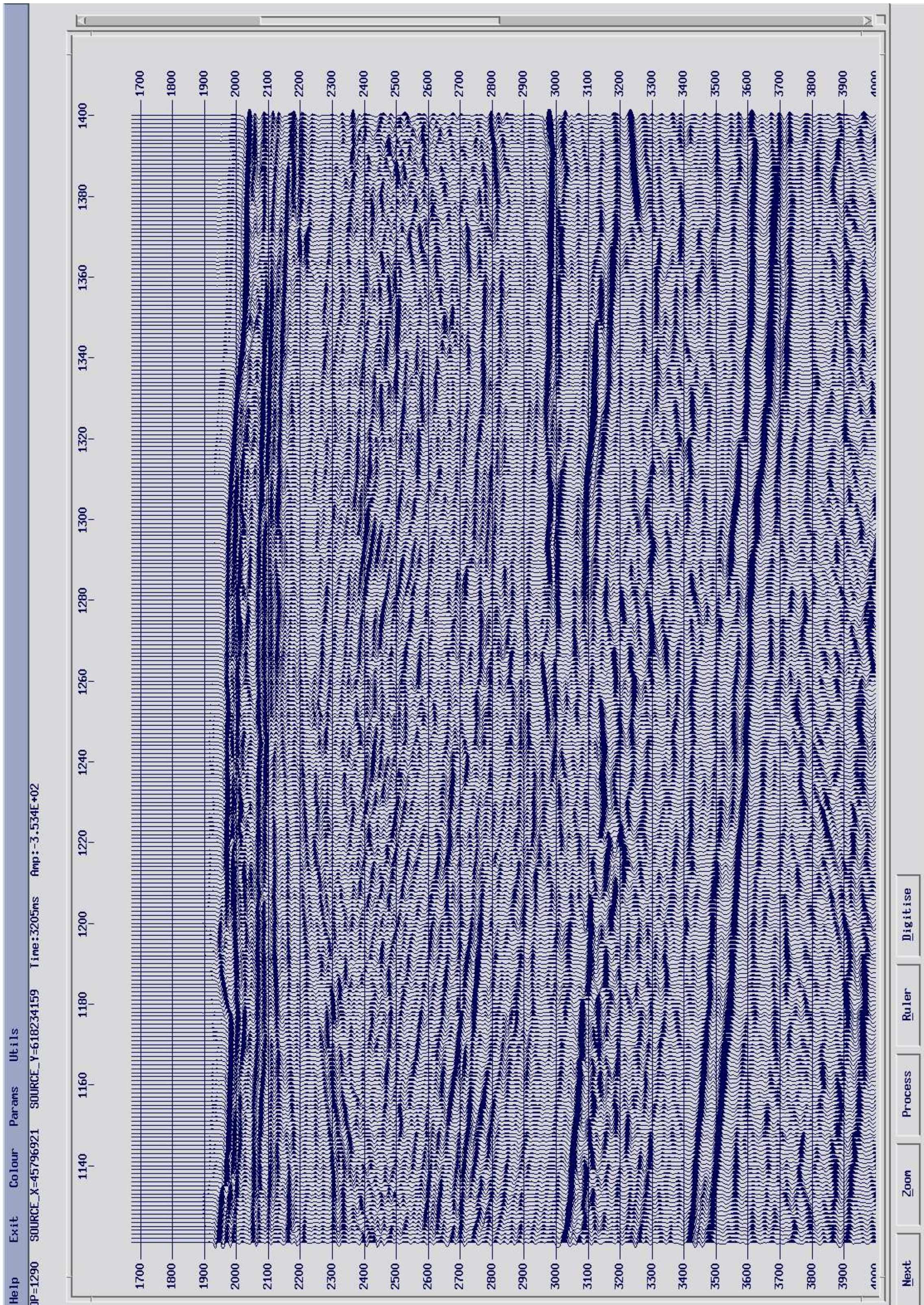
Score: 0.9

Appendix 2

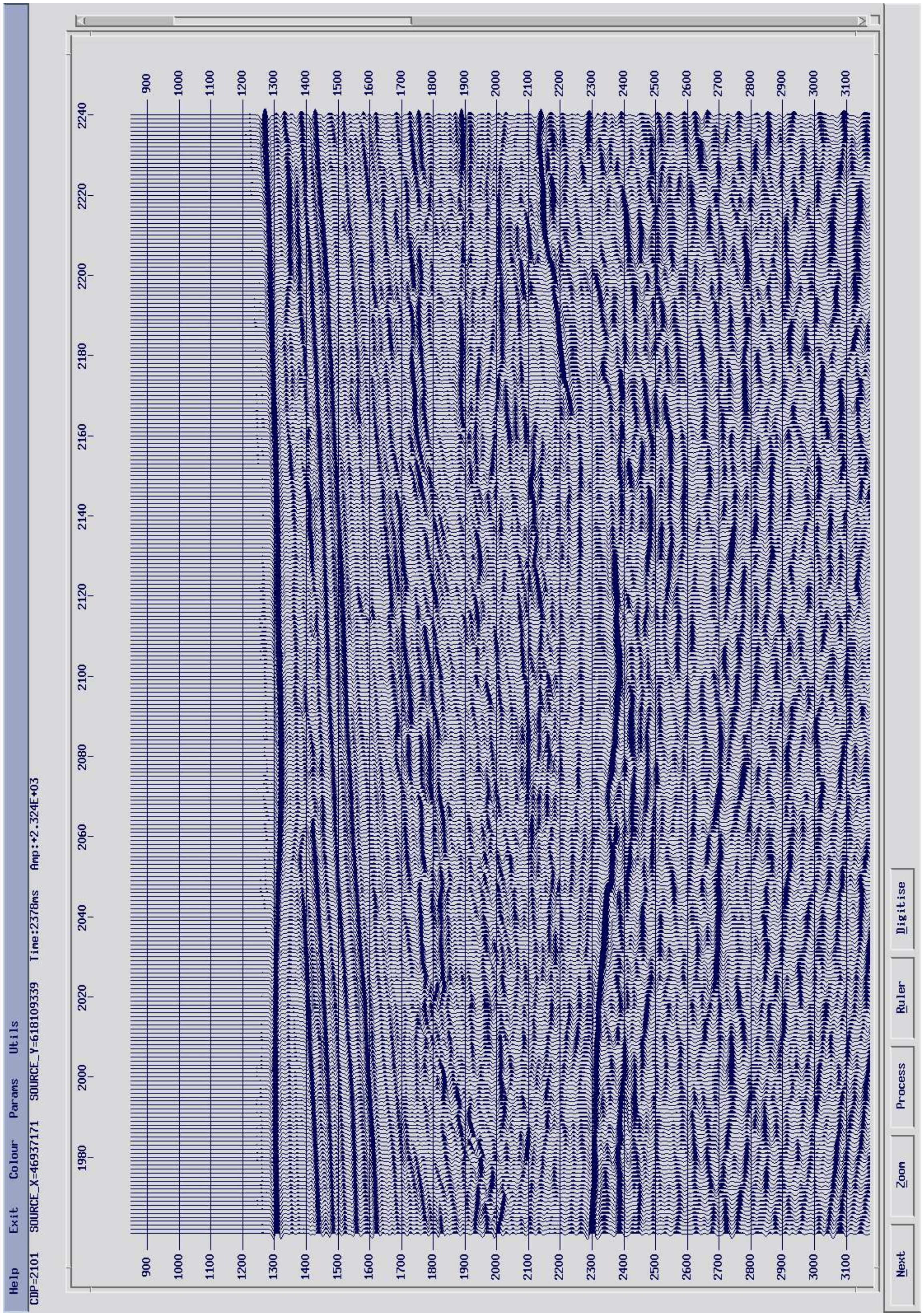
This appendix shows a series of sample sections from the study and the reservoir potential score associated with them.



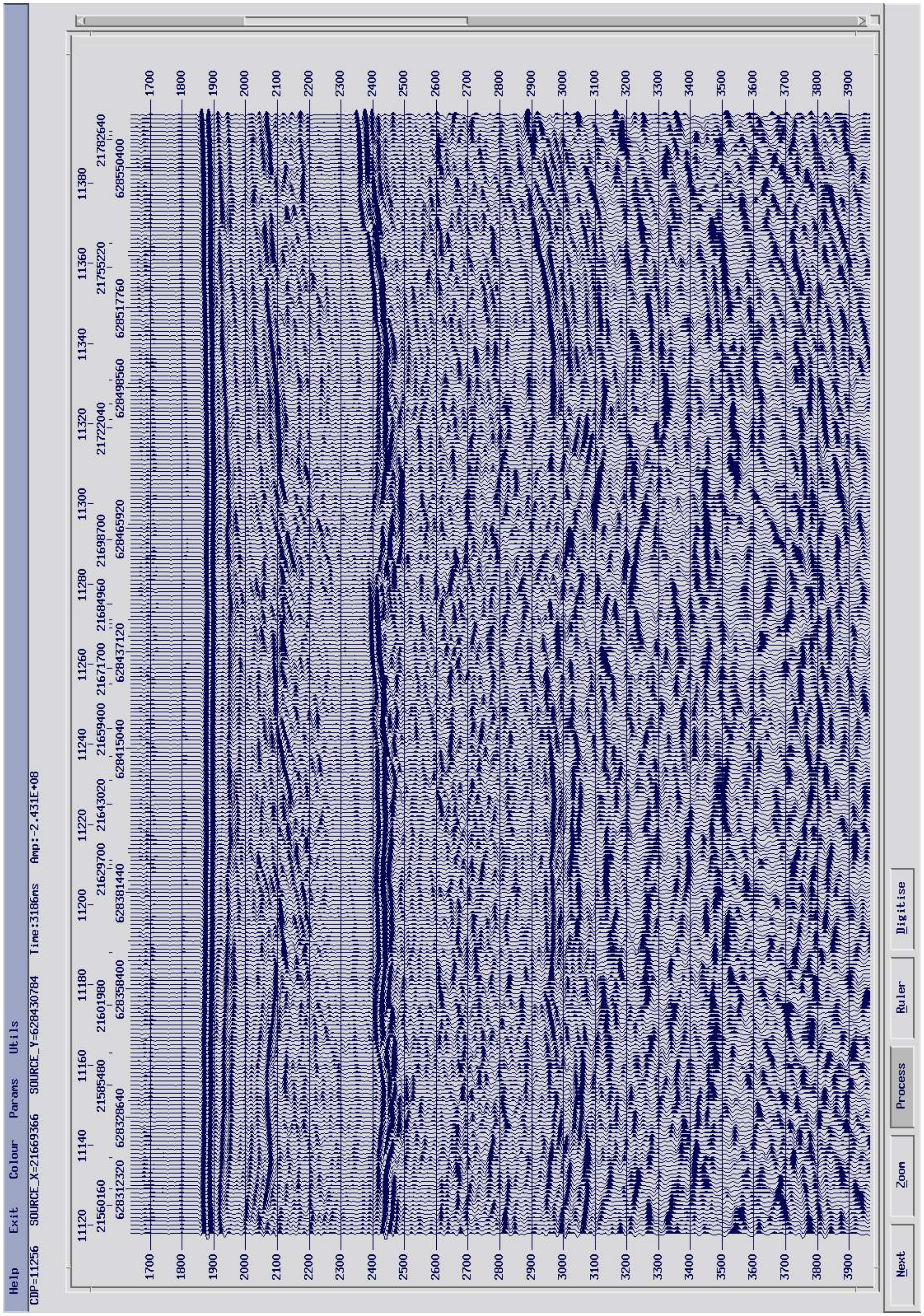
Score 0.3


Help
Exit
Colour
Params
Utils
CDP=1290 SOURCE_X=45796921 SOURCE_Y=618234159 Time:3205ms Amp:-3.534E+02
Next
Zoom
Process
Ruler
Digitise

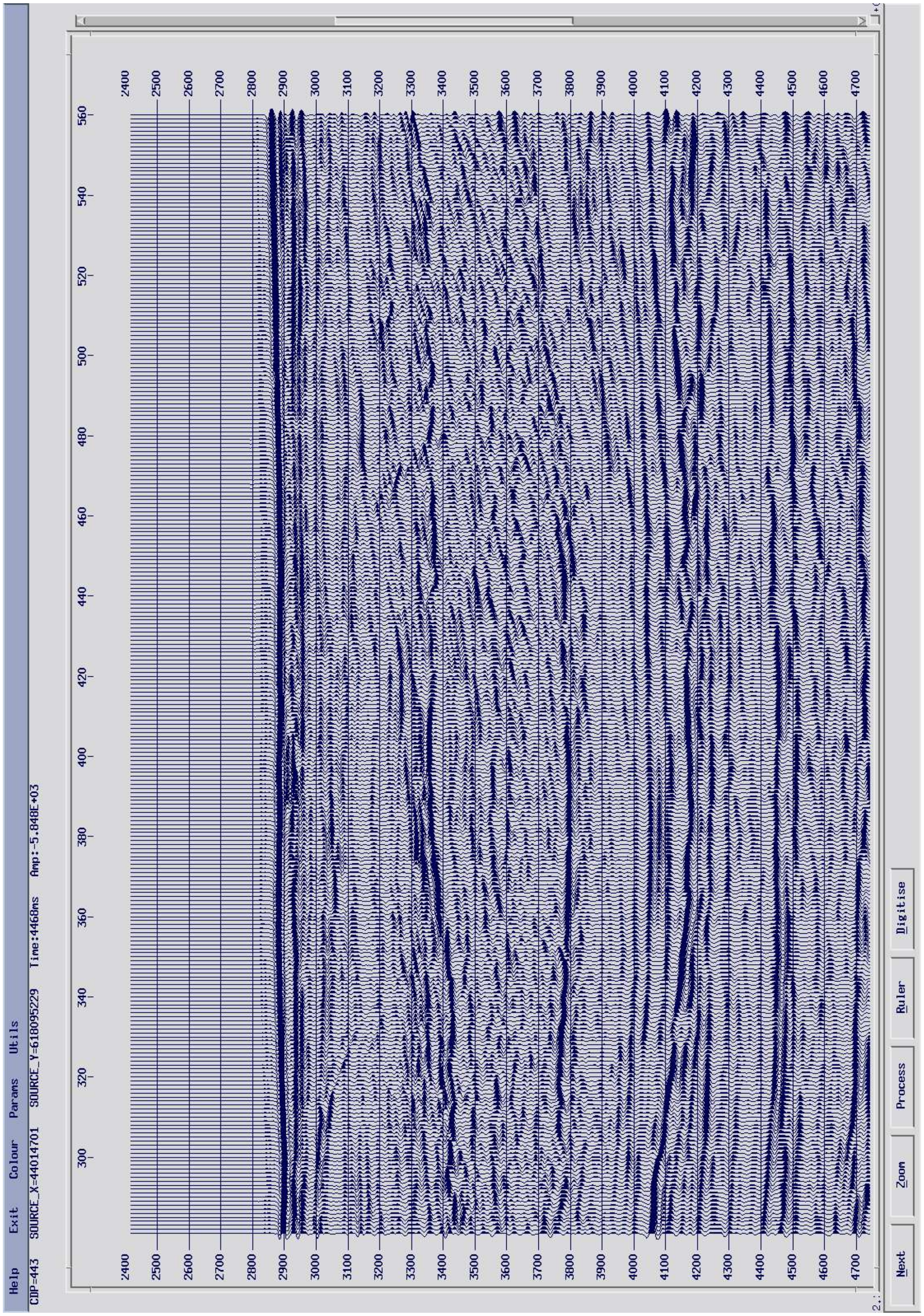
Score: 0.4


Help Exit Colour Params Utils
CDP-2101 SOURCE_X=46937171 SOURCE_Y=618109339 Time:2378ms Amp:+2.324E+03
Next
Zoom
Process
Ruler
Digitise

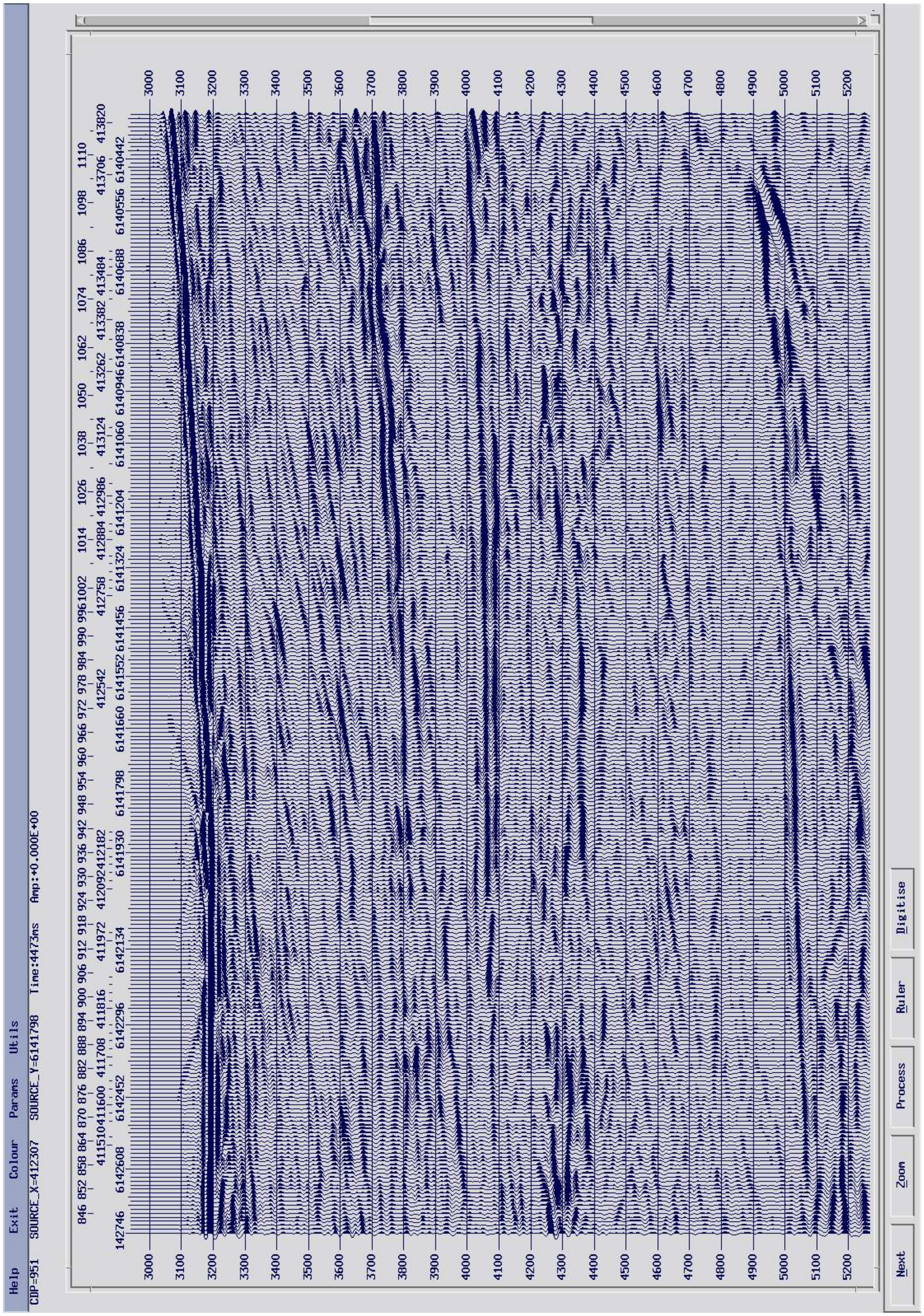
Score: 0.55


Help Exit Colour Params Utils
CDP=11256 SOURCE_X=21669366 SOURCE_Y=628430784 Time:3186ms Amp:-2.431E+08
Next Zoom Process Ruler Digitise

Score: 0.65


Help
Exit
Colour
Params
Utils
CDP=443 SOURCE_X=44014701 SOURCE_Y=618095229 Time:4468ms Amp:-5.848E+03
Next
Zoom
Process
Ruler
Digitise

Score: 0.7


Help
Exit
Colour
Params
Utils
CDP=951
SOURCE_X=412307
SOURCE_Y=6141798
Time:4473ms
Amp:+0.000E+00
Next
Zoom
Process
Ruler
Digitise
3000
3100
3200
3300
3400
3500
3600
3700
3800
3900
4000
4100
4200
4300
4400
4500
4600
4700
4800
4900
5000
5100
5200

Score: 0.8