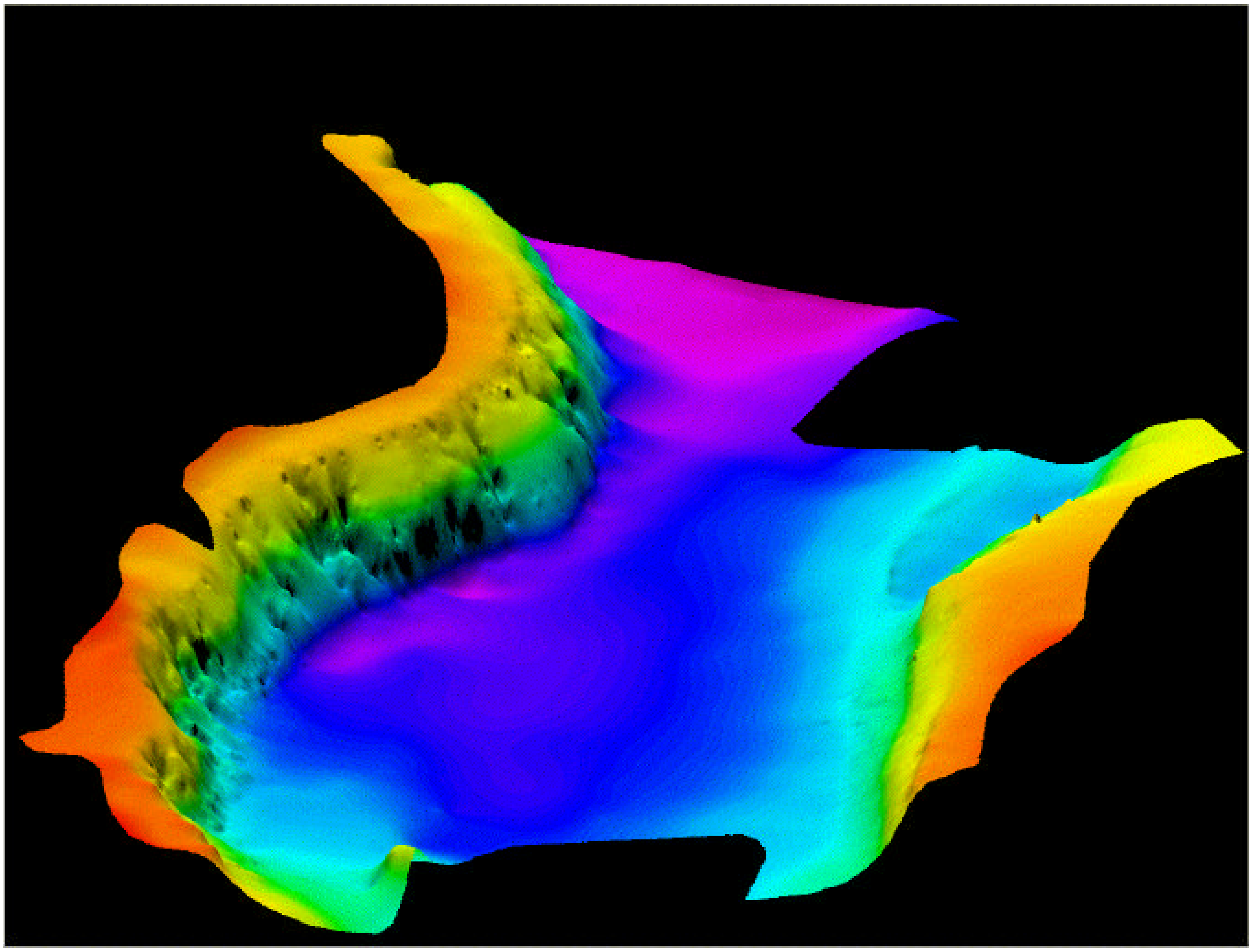
ROCKALL TROUGH SHALLOW STRATIGRAPHY

AND GEOHAZARDS STUDY

Petroleum Infrastructure Programme

Rockall Studies Group

HYDROSEARCH



Bathymetry of the Rockall Trough (viewed from the north)

ROCKALL TROUGH SHALLOW STRATIGRAPHY AND GEOHAZARDS STUDY

RSG PROJECT NO. 98/23

June 2000

Petroleum Infrastructure Programme

Rockall Studies Group

Report No.:	99239 - PIP	Hydrosearch Associates Limited,
		Goldsworth House,
Author:	Bryn Austin	Denton Way, Goldsworth Park
	(Brynterpretation Ltd.)	Woking, Surrey. GU21 3LG
Approved:		Tel: +44 (0) 1483 746500
		Fax: +44 (0) 1483 746505
Date:	August 2000	E-mail: info@hydrosearch.co.uk

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A.3.1 Geophysical Database
A.3.2 Geological Database

EXECUTIVE SUMMARY

The Seabed Technical Subcommittee of the Rockall Studies Group (RSG) commissioned the Study as part of the Irish Petroleum Infrastructure Programme (PIP) sponsored by 16 oil companies under the auspices of the Petroleum Affairs Division, (RSG Project 98/23). All geophysical, geological and geotechnical data available to the RSG – some 12 –15,000 line km of commercial 2D exploration data - was to be integrated during the study and a selected grid of approximately 11,000 km or more was to be utilised during seismic interpretation and mapping.

The aim was to make a breakthrough in our understanding of the sedimentary and other depositional processes that exist within the Irish Sector of the Rockall Basin Area (RBA). Such an understanding is essential to the economic and safe development of hydrocarbons from such an unexplored Frontier region. Primarily these processes are driven by fundamental earth forces including Gravity and Coriolis (through oceanic water mass circulation). These processes strongly affect the morphology and hence seabed geotechnical conditions and character of the RBA. Their influence through time has inflicted quite astonishing differences over the region that covers more than 300,000 square kilometers and includes:-

1) The comparatively moderately benign, shallower Continental Shelf environment, (100 – 500m water depth).
2) The deep to ultra-deep, Continental Slope of the Rockall Trough that is often characterized by a steeply dipping seabed of up to 12 degrees. Major mass wasting activity (landslides and slumps) is complexly interwoven with the effects of strong contourite current activity.
3) The abyssal Basin floor (2500 – 4000m) where again contourite currents and debris flow or turbidity processes are active.

By attempting to regionally map for the first time the shallow geology basin-wide and establish a full regional sequence stratigraphic framework a more thorough understanding of the basin geometry and history would emerge. This knowledge would allow the reports of locally endemic, potentially unstable, hazardous seabed and sub-seabed conditions to be put into a unified perspective thus providing more effective information to engineering and management functions involved with E & P decisions.

An important underlying philosophy of the Study was to seek active involvement and advice from the various academic institutions and experts. These included the British Geological Survey (BGS), University College, Dublin (UCD) and the Dublin Institute for Advanced Studies (DIAS) all of whom have wide experience and knowledge from previous work and study of the RBA. The Study commenced during October 1999 with the following set of objectives:-

1(a) Integrate the geological data from five recently completed deep water Shallow Drilling Sites into the conceptual Late Cenozoic Stratigraphic and tectonic framework as being actively worked on by the BGS. This consists of three major regional unconformity surfaces named C10, C20 and C30 that separate four megasequences RT-a to RT-d.

1(b) By seismic interpretation and correlation make decisions as to the robustness of the assumed model and extend if appropriate to the limits of the Rockall Trough using the PIP commercial 2D seismic database.

2) Identify and map regionally all geohazard features observed during the seismic interpretation. Compare with the results of the TOBI sonar interpretation and mapping project undertaken by UCD/DIAS and use this extra dimension in the interpretation and mapping of fifteen groups of geohazards. These include the results of large scale mass wasting processes such as submarine landslides, rafted sheets and blocks. Also slumps, debris flow material etc. both at seabed and sub-seabed. Similarly carbonate mounds and pinnacle reefs together with outcropping volcanic rocks, basement or faulted/ exposed Mesozoic and older sediments were also to be mapped. As far as possible shallow soils variations, amplitude anomalies, gas vents/chimneys and possible Bottom Simulating / Diagenetic Reflections (BSDR's) were also to be identified and mapped if possible. These features are reported upon specifically in Section 6 of the report.

3) Construct megasequence surface structure and isopachyte (equal thickness) maps in TWT and Depth together with results from the observation of geohazards. These maps to be at scales suitable for display in a concise, graphical report containing many data examples of the interesting features along with digital products as specified by the participating oil companies.

4) Provide recommendations for complementary work or further phases of study to include site specific areas where additional survey data would be useful in order to maximise value from the Study.

The above objectives have been accomplished successfully and the results of the Study are presented here with a minimum of text. Thirty-one Figures and maps are presented in the report as Appendix A1. These show i) the bathymetry and database, ii) geological succession and stratigraphic framework, iii) megasequence occurrence and structure followed by iv) the location of identified geohazards.

For each of the categories above an RBA overview map is followed by three more-detailed local maps at 1:1,500,000 covering the Licensed Acreage in:-

a) the SE Rockall area

b) NE Rockall area

c) NW Rockall area.

Also forming an integral part of the report are the fifty-one fully annotated Data Examples, (DX). They are included as Appendix A2 to illustrate interpreted data from what is a truly phenomenal Frontier province.

In Section 7 (Recommendations), several suggestions are made for further work or additional study to ensure maximum value is obtained from current efforts where the Study has provided a strong hub around which further more detailed investigation or related projects can be centered.

1.0 REGIONAL INTRODUCTION AND BATHYMETRY

This section introduces the Study region and identifies some of the principal physical systems involved in understanding the late Cenozoic geology.

1.1 Structure and Geometry of the Rockall Basin Area (RBA)

The Rockall Basin Area (RBA) refers to the large NE-SW trending, largely Mesozoic basin located in the NE Atlantic Ocean on the passive continental margin offshore Ireland and NW Britain. The Rockall Trough refers to the huge, steep sided and serpentine shaped, bathymetric feature that has an essentially flat bottom lying above the RBA as defined by Naylor et al. (1999).

In the Irish sector it covers an area of greater than 300,000 square kilometers, deemed to stop in the south at the onset of Oceanic Crust, taken as the NW/SE trending Charlie Gibbs Fracture Zone, (51.5 degrees S; 16 degrees W). Ancient crystalline rocks and younger igneous complexes of the Rockall High (that culminates as the Rockall Bank islet) bound the deep subsided Rockall Basin to the west. To the east the RBA is bounded by the protruding Porcupine High in the south and the Erris - Donegal Basin Margin further north. These features are easily picked out by the 500m or 1000m isobath, see **Figures 1** and **2**.

1.2 Bathymetry

At its northeastern extremity in UK waters the basinal Rockall Trough water depths reach 1000m. At the Ireland/UK Median Line, however, they already approach 2500m and increase to almost 4000m off the southern Porcupine High margin. Assuming a conventional 200m cut-off, only the extreme northeast of the area covered by this study would qualify as being termed "Continental Shelf".

A more convincing Shelf Break, however, occurs at close to the 500m isobath that allows vast areas of the Porcupine and Rockall Highs to be deemed "shelfal" or "moderate to deep water" in terms of water column drilling depths. This distinction gives a truer and more useful representation of the seabed and sub-seabed conditions existing there.

The onset of the upper continental slope occurs extremely rapidly as can be seen from the colour contoured bathymetry maps, **Figures 1, 2 - 2c.** The slope continues its steep descent, often with only minimal terracing down to the basinal break of slope, which is similarly usually very sharply defined. Along the steep eastern margin the break of slope ranges in depth from 2600 – 3000m whereas in NW Rockall area the change is shallower at around 2250m. This range reflects not only the relatively asymmetrical nature of the continental slope over the Study area but also the great variety of slope profiles and gradients contained therein. This is perhaps not unexpected over such a geographically large region where gradients range from 0.5 to a staggeringly steep 25 degrees. More will be said about properties of the slope areas in Sections 5 and 6 later in the report. However a glance at the slope profiles presented as **Figures 10 – 13** gives a good overview of the enormous variation down the slopes and also lateral changes along the slope from area to area.

1.3 Sedimentological Processes and Principles

An introduction to the variety of sedimentological processes active during the late Cenozoic to Recent within the Study area is given in the excellent Geological Society Special Publication 129, 1998, (Stoker, M. S., Evans, D & Cramp, A). The effects of the interplay between the major forces of :

1) Gravity driven down-slope mass movement,
2) Coriolis Acceleration and
3) Powerfully influential oceanic water mass circulation systems such as the North Atlantic Drift (NAD) and the Cold Norwegian Sea Deep Water (CNSDW).

It is crucial to understand that ocean current systems operate continuously 24 hours a day, 365 days a year. Because of this fact they tend to be regarded as having fairly constant velocities that can range between 10 – 30cm/sec. It has been discovered, however, that disturbances to an otherwise regular regime do occur where current velocities can dramatically increase and current vectors may alter. During such sporadic "gusts" and helical flow gyres these have been estimated to increase up to70cm/sec. from evidence collected by the Southampton Institute of Oceanography for example. These massive systems, therefore, are capable of producing both depositional and non-depositional, as well as erosional elements that often extend for 100's of km but alternatively can change completely within less than a kilometer laterally.

A good example of such phenomena is that of the evolution of a submarine landslip or landslide. The absolute chaos of deformed material down-slope at the slide or slump snout may pass up-slope into more well layered but still transported slide components. Continuing upslope we pass the fairly obvious (initially) head wall of the slide into unmoved, in-situ bedrock or sediments. If strong seabed currents are active then a proportion of the initial landslide material (that is suspended in the water column at the time of the catastrophic mass movement) will begin to be transported by current forces. This will either be dumped close to or some distance away from the site of the submarine landslip depending upon factors such as sustained and periodic current velocity, slope gradient, sediment grade and local base level, **Data Examples 20, 22, 23** and **25**.

Some material may even be transported back *up-slope* since many deep ocean current flow systems are influenced by bottom topography as well as by water mass mixing and eddy generation. It is often the case that the freshly formed slide scar or headwall, which is originally readily identifiable, can be relatively quickly covered up. This depositional or erosional modification occurs since by its very creation the feature will attract "attention" from the systems that just thrive on steady state/ equilibrium principles but can react strongly to even subtle changes in flow parameters and external geometry.

Fundamentally, the principles are that gravity driven sedimentary processes act generally by transportation downslope, whereas contouritic processes can act both down and significantly alongslope under certain circumstances. This state of affairs can normally be relied upon except that it is known that debris flows and slide deposits also overcome sometimes significant relief on the seafloor especially at the margins of the slide or slump (just like a terrestrial avalanche can) until the transporting energy is lost. Therefore this introduces the counter-intuitive complication that mass movement deposits may also travel upslope.

The most important and arguably most poorly understood caveat to predicting and interpreting rates at which the above systems work is that of the influences of (global) climatic change. Recent evidence suggests that mechanisms like the "oceanic conveyor system" are markedly affected by climate that can oscillate or change rapidly. "These sub-Milankovitch variations have not been explained in terms of known astronomical causes, but appear to be semi-cyclic in nature with major changes occurring over timescales of between 500 and 2000 years," (Rothwell, 2000). Confirming this, Kroon et al, (2000) state that major shifts in terrigenous sediment supply were extremely rapid over the past 15ka. Evidence from ice cores to radiochemical tracers shows that shifts in terrigenous supply have occurred over time spans of less than a century.

One further important factor in the discussion of the sedimentological processes active over the Study area must be the lack of essential data as to the rate at which the various influences act between and upon one another. This is more especially the case given the fundamental links between ocean circulation systems and phenomenal climatic changes of the kind deduced to have occurred during (at least) Pliocene and Pleistocene times.

Given the above it is not surprising that there is an inherent risk in ascribing the correct nature of the sedimentary processes involved when attempting to describe a particular sequence. With insufficient calibration control from wells or borings the situation is only partially improved by careful interpretation of internal and external seismic reflection geometries and onlap/truncation relationships etc., since sequences are often composed of fundamentally non-layer-cake successions, as observed during interpretation of the seismic database. Attempting to obtain a correct predictive assessment of the stability of a particular slope for engineering reasons without sufficient data and knowledge is of course particularly difficult.

2.0 OBJECTIVES AND SCOPE OF STUDY

The Rockall Trough Shallow Stratigraphy and Geohazards Study was commissioned by the Seabed Technical Subcommittee of the Rockall Studies Group (RSG) as part of the Irish Petroleum Infrastructure Programme (PIP) sponsored by the 16 oil company members under the auspices of the Petroleum Affairs Division. The RSG Project 98/23 Contract No: 99.16.11 was awarded to Hydrosearch Associates Limited on the basis of technical experience and economic considerations with set-up and kick-off meetings held during October/November 1999.

Of some importance to the success of the Study was the active participation and involvement of key academic expertise. Notably this knowledge and experience came from the British Geological Survey (BGS), University College Dublin (UCD), Dublin Institute for Advanced Studies (DIAS), Nederlands Institute of the Sea (NIOZ), and the Renard Centre of Marine Geology, University of Ghent (RCMG).

The stated task of the Study was to perform seismic interpretation of geophysical and geological/geotechnical data comprising the PIP dataset from the RBA. The interpretation should focus on the seabed and selected seismic units in the upper 0.500 seconds TWT of the sediments. The aims of the Study, however, were to make a positive breakthrough in the understanding of the history of sedimentary and other depositional processes that exist within the Irish Sector of the Rockall Basin Area (RBA). Such an understanding is essential to the economic and safe development of hydrocarbons from such a vast and under-explored frontier region. It is also intended for the Study to form the central hub upon which other follow-up or related projects and research can input to or receive feedback from.

2.1 Study Objectives

Following the active discussions of the kick-off meetings the Study was set to be undertaken in two consecutive phases, Phase 1 having the following objectives:

2.1.1 Examine the validity of the existing late Cenozoic Stratigraphic Framework model as proposed by M. Stoker of BGS for the basinal RBA. This consists of at least three major megasequences based upon identification of three major flooding surfaces/unconformity surfaces defined as C10, C20 and C30.

2.1.2 Integrate the PIP database with geological and geotechnical data from the five PIP Shallow Drilling Sites and as many useful well-seismic ties as can be supplied (e.g. 132/15-1, 12/13-1a. 19/15-1).

2.1.3 Extend the newly calibrated Stratigraphic Framework model to the limits of the PIP database over the Rockall Trough using a subset of the seismic database of minimum 8000 line km.

2.1.4 Advise the Seabed Technical Committee as soon as possible should the initial Stratigraphic Framework model be invalid over the Study region.

Phase II objectives of the Study were specified as follows: -

2.1.5 Construct TWT Structure maps of megasequences and sequence units at 1: 500,000 (working) and 1:1,500,000 (reporting) scales.

2.1.6 Construct megasequence interval TWT “thickness” maps for selected sequence units if useful for the general interpretation of the area.

2.1.7 Undertake regional T/D Conversion to construct maps in depth as per 2.1.5 and 2.1.6 above.

2.1.8 Identify and map regionally all geohazard features observed during the study. Specifically integrate the PIP commercial exploration seismic dataset with the results from the Intermediate report of the RSG TOBI Rockall Irish Margins (TRIM) Project No: 97/14a, in order to establish relative ages of slides and other mass movement processes over the Rockall Trough region. Areas showing significant geohazards which require a lot of detailed mapping are to be “ring fenced” for further study in a later phase.

As a minimum, the following potential features shall be mapped:-

- Slides/slumps, slide scars and slide sediments both on surface and sub-surface.
- Debris flows and turbidites
- Creep/compressional features
- Diapirism
- Carbonate mounds
- Shallow faults. Main faults to be interpreted
- Lava intrusions/basalt flows (depth, extent, thickness, continuity etc.).
- Contourite sediments
- Glacial till and boulders (if possible)
- Shallow soils variations
- Gas indications
- Gas blanking/wipe-out
- Amplitude anomalies
- Gas vents/chimneys
- BSDR’s or other possible gas hydrate indications

2.1.9 Provide recommendations for additional work including areas where additional survey data would be useful.

2.2 Scope of Work

Not long after commencement of the Study it was realised by all parties how difficult it would be to carry the existing stratigraphic concepts across the basin and up the eastern margin slopes onto the shelf. This had already been partially envisaged since the BGS Stratigraphic Framework model had been more dominantly derived from a different set of seismic data, (see Section 4.1) that covers the northern UK Rockall and the western Irish Rockall. The complex shallow geology in the eastern slopes together with lack of adequate strikeline control necessitated lots of jump correlation and hence increased the possibilities for aliasing.

Unfortunately these imaging and interpretation difficulties continued, especially in the Erris (NE Rockall) region, even when interpreting every available line from the PIP commercial 2D seismic database. However, given that some 250km separate this region from the three southerly Shallow Drilling control locations it was agreed to risk possible flaws in the model and press on with the extremely useful seismic sequence stratigraphy.

Given the above problems, the adequacy of the original database became an important issue which was partially overcome by the addition of several thousand line kilometers of additional seismic supplied by Shell and Phillips in order to infill several large gaps. These consisted mainly of cross-basin lines and a few slope-dip parallel lines that allowed a correlation route to be explored where previously none existed and the stratigraphic concept could not otherwise have been developed.

3.0 DATABASE

The Study database consisted of a wide variety of datasets and reported information supplied by the RSG or the academic institutions in hard copy, digital and multimedia formats

In common with the Geodetic conventions used in the TOBI Rockall Irish Margins (TRIM) and other RSG projects, the following were used in the present Study and in the production of the resulting maps:-

Projection:	Universal Transverse Mercator
Zone:	28 North
Spheroid:	International, 1924
Central Meridian:	15.0 deg. 0.0 min 0.0 sec. West
Map Sheet Datum:	European Datum 1950, Common Offshore

3.1 Geophysical and Geological Database

The full extent of the geophysical database used in the Study is listed as **Table 1** and shown in **Figure 1**. It is described in more detail as Appendix 3 at the end of this report. By far the largest item in the database consisted of the PIP commercial exploration 2D seismic database. This comprises approximately 12,000-line km of conventional, commercial 2D speculative exploration seismic acquired and processed by the following Industry Contractor companies:-

Veritas DGC
CGG
Fugro Geoteam A/S,
Schlumberger Geco-Prakla
Baker Hughes Western Geophysical

The NERC vessel Challenger was utilised by the BGS to acquire some limited slightly higher resolution (Single Air Gun {SAG} and deep towed sparker) data over small grids at and between the sites selected by the RSG for potential and actual Shallow Drilling. These data are extremely useful to cover the 'no-data-zone' beneath the seabed where no interpretation is possible on the conventional seismic data. However these tight grid data are obviously extremely sparse and short and therefore cannot be shown on **Figure 1**.

Various levels of higher resolution are available from the acquisition by the R/V Professor Logachev during the TTR-7 academic cruise in 1997. SAG, pinger as well as deep-towed sonar data are available in the vicinity of the two study areas (of chemosynthetic communities) on the eastern and western Rockall margins as shown on **Figure 1.**

The TOBI Rockall Irish Margins (TRIM) dataset does have 3.5KHz pinger data associated with the central track of the deep-towed fish. These data were not provided to the Study in a readily available format until very late on into the Study and have been accessed only to confirm the interpretation, (or otherwise), in specific places. Much of the anticipated regional integration and detailed work is still to be completed, see Recommendations Section 7.

Very few geologically age dated samples exist over the study area apart from those cores taken from wells (on the eastern shelf) and the ODP/DSDP wells 610 and 981. As is the case elsewhere, however, most exploration wells do not sample the upper 1000 feet or so below mudline. The BGS, on the other hand, have collected a good range of borehole samples from several Shallow Drilling campaigns in the UK Rockall Trough. These were complemented by the five 1999 PIP Shallow Drilling Locations shown on all the map figures. They represent the first samples recovered by this technique in the Irish Rockall region, (BGS 1999). The shallow drilling locations are **shown on all maps** and referred to in more detail in **Section 5.2** below.

Rather more gravity core samples and surficial grab samples have been recovered over the Study region as shown on **Figures 1 and 2**. The limited penetration, however, and scattered locations makes their importance to this phase of study only of limited value. Some have been put to good use, particularly those specifically targeted to sample the bioherms and carbonate reefs that are so prevalent in certain parts of the Study region, (**Figures 28 – 30**). Continued use during an integrated and detailed interpretation phase of study is recommended, see **Section 7.1.14.**

Table 1 PIP Database

P.I.P. ROCKALL TROUGH SHALLOW STRATIGRAPHIC FRAMEWORK INTERPRETATION - DATABASE					
DATA TYPE	**FORMAT**		**INITIALISED**	**IN - HOUSE**	
	Digital	Paper Copy		Digital	Paper
P.I.P. 2D LMK Seismic dataset # I	D		Early Oct.	Early Oct.	
Base Maps	D	P	Early Oct.	Early Oct.	
P.I.P. 2D LMK Seismic dataset # II	D		Early Oct.	End Dec.	
Base Maps		P	Early Oct.	Early Oct.	
P.I.P. 2D LMK Seismic extra lines	D		Mid Dec.	End Dec.	
Phillips Regional 2D Seismic		P	Mid Oct.	Mid Oct.	
Shell Regional 2D Seismic	D	P	Mid Oct.	End Dec.	Early Dec.
NIOZ SAG 2D Seismic data		?only P	Early October/Week 50	NOT HAVE	
Base Maps		?only P	Early October/Week 50	NOT HAVE	p (A4)
PIP/RSG Hi Res 2D Seismic data (BGS)		p (PAD)	Early October		End Dec.
PIP/RSG SEG-Y 2D Seismic (BGS)			Mid October	NOT HAVE	
Base Maps		P	Early October	End Dec.	
Navigation data	D		Early October	Mid Dec.	
PIP Shallow Drilling Sites Report		P	Early October	Early Oct.	
Coordinates and Logs	D	P	Early October	Early Oct.	
PIP/RSG Gravity Cores (BGS)		P	Early October	Early Oct.	
Coordinates and Logs	D	P	Early October	Early Oct.	
TOBI Initial Interpretation Report		P	Early October	Early October	
TOBI Intermediate Interp. Report		P	Early October	End Oct	
TOBI Int. Int. Report Figures and Maps	D	P	Early October	February	End Dec.
TOBI Navigation	D		Early October	End Oct	
Logachev 1997 Cruise Report	D			Early October	
RSG Struct. Nomenclature Report	D	P	Early October	End Oct	
Phillips Structural Elements Map		P		End Oct	
Mid - Late Cenozoic Tectonostratigraphic Framework for the Rockall Trough		P	Early October	Early October	
Cold Water Carbonate Mounds & Sediment Transport on the NE Atlantic Margin		P	Early October	Early October	
12/13 - 1A Well - Seismic tie info	d	p	End November		

Table 1. P.I.P. GEOPHYSICAL AND GEOLOGICAL DATABASE

PIPDATABASE_010300.xls

3.2 Limitations of the Database

Much of the data was provided at the commencement of the Study, whereas other important information such as alternative regional lines, infill lines or the maps from the TRIM interpretation were not transferred until quite late into the Study.

The PIP commercial 2D exploration seismic database was transferred from the providing companies (Phillips and Shell) as two separate Landmark projects on Exabyte tapes. These were screened and re-loaded at HAL as the stand alone *new_rock* LMK project on the GLOBAL 2 disc requiring some 6Gbytes of discspace.

The several recent conventional seismic vintages were acquired mostly between 1993 and 1996 and shot with conventional exploration objectives and specifications. Thus streamer depths of 12 - 15 m or more and CMP interval of 33 - 25m provide vertical interpretation resolution varying between 15-20 and 30+ meters. Given the poor sea surface environment the 12,000-line km of data are of generally very good to moderate quality but the effects of poor weather conditions are often detrimental especially with regard to the streamer induced ghost that so often parallels the seabed.

An even more fundamental constraint, however, is that the vast majority of the spec data are shot parallel to the slope of the margins of the Rockall Trough (for obvious structural and acquisition reflection geometry reasons). A glance at the widely spaced data grid shows dip-orientated lines that vary from 5 – 15 through to 35 km apart. Strikeline control - which is essential in confidently unraveling seismic sequence patterns and boundaries – is, however, extremely limited and localised.

Since the Rockall Basin Area is an under-explored Frontier province this situation was not unexpected but the effects on the integrity of the interpretation and hence Study concepts and ultimately the results are important. For example as is the case along the western margins of the Rockall Trough, what singular strike control that does exist regretfully bears virtually no relevance to the interesting sedimentary successions existing just a few kilometers downslope. This is due to fundamental structural control (faults), complicated sedimentary facies (truncated progradational wedge presumed interdigitating with bathyal sediments) and stratigraphic changes (see **Figure 4** or **Figure 9 or DX 10**). These features can all be observed in dip lines that are spaced 10km apart meaning jump correlation can be inaccurate given the scale as well as the subtlety of the sequence boundaries and unconformity surfaces we are attempting to map. As with most 2D seismic interpretation the more time that can be spent investigating and testing alternative loop correlation the better the final results. During the Study, however, there was often only aliased regional loops available and time was, as ever, at a premium.

3.3 Controls on Project Scope, Methodology and Study Progress

Despite the direct involvement and participation of the various academic institutions there was a great deal of independent and therefore objective interpretation carried out to meet the Study Objectives. For example the transfer of expertise from the BGS as a starting point to develop the late Cenozoic Stratigraphic Framework model relied upon good discussion of the Stoker et al.2000 in-press paper but specifically on only four or five (paper section to paper section) correlations of the key events. This was due to proprietary database issues. The very important TOBI Rockall Irish Margins (TRIM) dataset Intermediate Report maps showing the interpreted features at 1: 300,000 scale, (Readman et al.1999) did not become available to the Study until end January 2000. This meant that identification, interpretation and mapping of geohazards were done independently of the interpreted TOBI data which itself was a fully independent PIP-funded Project carried out by UCD and DIAS (RSG Project 97/14). It was only during the last part of the Study that the anticipated powerful integration techniques could be applied satisfactorily to the myriad of geohazard features interpreted to be present within the RBA.

The Study started with the preconception that only the late Cenozoic geological successions would need to be unraveled since they were thought to occur everywhere throughout the Study region within the upper 0.500 sec TWT beneath the seabed. It was soon discovered, however, in the light of the results from the significant 1999 Shallow Drilling campaign that this was definitely not the case.

The presence of Upper Mesozoic (at least Cretaceous) in the post-rift sequence was unexpectedly proved causing major reinterpretation of the position of the Base Tertiary Unconformity and younger successions. The Study has now shown that older Mesozoic as well as Palaeozoic rock exists well within the uppermost 500 milliseconds below seabed. Seismic interpretation suggests these undoubtedly subcrop as scarps and highs in places along the margins of the Rockall Basin as does interpreted pre-Paleozoic basement, (that is possibly as old as Grenvillian - 1.7 billion years old) as encountered on Rockall Bank, (Daly et al 1995).

The megasequence boundaries C1, C20 and C30 of Stoker et al. are defined dominantly within the relatively tectonically simple Rockall Basin. Their straightforward correlation upslope and along the margins was severely compromised and complicated by the interplay of significant and persistent development of the following:

a) Canyon gully and valley development on the slope
b) Slumping and mass wasting
c) Terrigenous input
d) Alongslope current activity.

Figure 3 provides a guide to the Stratigraphic Framework developed as a result of the Study area that is described in more detail in **Section 5**.

Because of the greater range and complexity of the shallow geology more seismic data needed to be interpreted than was originally conceived but within the same time schedule. In all an estimated 11 – 12,000 line km of 2D has been interpreted, more or less fully, out of a total of approximately 15,000 km. Those areas where data require a more complete evaluation are in the SW Rockall (Conall Basin) and the extreme SE Rockall (Brona Basin) and other areas annotated as requiring further study.

Given the above problems the interpretation progressed as rapidly as possible from the starting points along the western flanks using the key WRM96 Lines –103, -119 and -129; and GSR96 – 116.

Using the 2D Exploration seismic line WRM96 – 103 to move eastwards across the basin, lines in the NE Rockall were interpreted and the megasequence boundaries C10, C20 and C30 were correlated as far as was possible up slope towards the shelf break, (**Data Example 51**). It was observed that the shelf itself often appears to be markedly progradational in terms of external and internal reflection geometry, (**Data Example 50**). WRM96 – 103 is a unique seismic line in that it does show what is fundamentally a basinal seismic stratigraphy as defined by Stoker et al. 2000 to extend a long way up the eastern basin margin. Few other dip lines along the margin show this phenomena and it was soon found that no straightforward correlation route existed towards any of the four Shallow Drilling locations from this fundamental input point. Furthermore insufficient data existed at that time to move southwards through the basinal facies and then upslope to tie into the Shallow Drilling sites. Fundamental and unconstrained interpretation therefore was the option that remained and the decision was made to move northeastwards (through arguably the most complex portion of the whole Study region), towards the 11/20-sb01 Shallow Drilling Location and ultimately the published Well 12/13-1a.

The Stratigraphic Framework and Geohazard objectives were always under consideration as slow progress was made through the massively slumped margin. When the local calibration points were eventually reached they were found to be lacking in much useful Cenozoic age information but the reliable biostrat age picks in the muddy outer shelf/upper slope Paleogene sequences at the 12/13-1a well location inferred tremendous basin margin subsidence and faulting. This left the stratigraphic framework model more or less as unconstrained as before except that several thousand kilometers of data had been interpreted and several seismic stratigraphic ideas and concepts were beginning to flourish. These were examined carefully and expanded as the interpretation moved southwestward towards the Fursa Basin along the eastern flank of the Rockall Trough through the Corrib Field area up onto the eastern shelf.

Significant gaps in the database became critical in this area which is heavily eroded by steep sided submarine canyons and valleys adding to the problems of acquisition and processing as well as correlation. Whilst extra data was being arranged work continued to tie the four southerly Shallow Drilling Locations into the PIP commercial 2D seismic database. This was only partially successful again due to Shallow Drilling Location 83/20 being 4km from the nearest available line as well as the big differences in geology compared to the NE Rockall region.

Work then progressed trying to integrate and correlate the late Cenozoic information from the five Shallow Drilling Locations themselves, then to work outwards and away to cover the SE Rockall region, generally working back northwards across the Padraig and Macdara Basins towards the 16/28 Shallow Drilling Location.

Confidence that the evolving model resulting from the seismic stratigraphic interpretation appeared to be working continued to grow. Particular emphasis was placed upon a faulted and deformed seismically transparent “marker” sequence considered to exist generally below the C30 unconformity surface. It often rests upon the Base Tertiary Unconformity (BTU) and appears to be of a pre-late Eocene, RT-d age – see **Section 4.5 or Figures 3, 6, or Data Example 48**. It was also noticed that although being somewhat contradictory, the initial 16/28 Shallow Drilling Location results, (in the vicinity of a partially filled canyon system), did not appear to tie into the Stratigraphic Framework model under development.

Work then shifted westwards across the basin to the Ronan Basin and Ladra High areas and then the western margin in general – still with the same evolving seismic stratigraphic model. When more cross-basinal data arrived the interpretation concentrated first on the western margin thence back to the SE Rockall and lastly NE Rockall areas again to attempt to unify the late Cenozoic stratigraphic framework. It was during the latest (i.e. only the second) pass that one or two leg differences at the 16/28 Shallow Drilling Location became apparent concurrent with the results of more detailed age dating work in late March. These showed that the RT-c and RT-b megasequences were apparently not present over large portions of the SE and Central/S.E. Rockall (EC), regions, (**DX 15)**. The corollary was therefore that the C10 unconformity was rather a more important event than previously envisaged unless the stratigraphic cut-out was locally due to faulting or downslope mass movement.

A concerted further effort was then made to more fully evaluate and correlate the shallow drilling location results that has resulted in the present stratigraphic proposed framework. Not surprisingly large areas are noted on the various structure maps as still requiring further detailed interpretation and work. The recommendations in **Section 7** suggest ways of testing the framework and tectono-stratigraphic concepts resulting from the Study.

3.4 Map grids and Time to Depth Conversion

The sizes of the RBA and the seismic dataset have meant that the generation of grids and construction of useful contoured map information (within an A3 max format) has been a challenge. The regional bathymetry maps **Figures 1 and 2** have been constructed using a grid cell size of 1000 x 1000 metres initially. This was necessary to allow the deeper parts and basal portions of the slope to be mapped. The local area maps, however, **Figures 2a, 2b and 2c** have been made using a much closer 100 x 100 meter cell size to ensure the optimal surface is generated to depict the geohazards like fault scarps and canyon/valley systems. Each local map took some 4 hours of computer time to generate the desired grid.

Given the requirement for maps at 1: 1,500,000 scale the megasequence boundary maps C10, C20 etc. must be by definition a sampled surface. It was therefore decided to use a grid cell size of 500 x 500 metres as the best compromise between speed and regional detail. This has been used for the Regional maps as well as the three local area maps of SW, NE and NW Rockall.

Well data in the Rockall Basin Area does not input into the shallow section due to the "no returns to seabed" law that has been standard industry practice for the shallow section. The PIP Shallow Drilling Locations have been tied into the 2D Exploration and Hi Resolution data set to provide some very limited velocity information that, from experience, shows little variation from any other region of the NE Atlantic. This is based upon years of experience correlating geotechnical and other soils boring data with Hi Resolution seismic specifically acquired for that purpose (or other seismic). There is very little published data available on which to base velocity functions, e.g. Praeg et al. 2000, or Green et a1. 1980. For that reason the mapping T/D Conversion has been done in the most simplistic fashion with the following single average velocities (underlined) being used to generate the maps in a straightforward downward layercake sequence commencing with the seabed:-

MSL – Seabed……………………….1500 m/second
Seabed – C10……………………….1600 - 1650
C10 – C20…..……………………….1650 - 1700

C20 – C30…………………………..1700 - 1750
C30 – BTU………………………….1750 – 1900 (1800)

4.0 ROCKALL TROUGH SEISMIC SEQUENCE STRATIGRAPHY

4.1 Introduction and Regional Considerations

The Rockall Trough contains one of the largest under-explored continental margin basins in the world. Partially due to its exceptionally severe surface and water column environmental conditions it still remains the focus of ongoing geological research. As is understandably the case in frontier exploration, research tends to focus primarily on structural analysis and hydrocarbon source and reservoir objective zones. This has been the case along much of the N.E. Atlantic margin. The overburden section (usually the last 50 million-year period broadly spanning the Eocene to Recent) has therefore been largely neglected.

During this time period however, the circum-N. Atlantic region has undergone considerable changes in landmass and ocean circulation in addition to the severe global climatic changes that occurred through the Pliocene and Pleistocene. Factors generating the changes include the following:-

a) Mid-Atlantic Ridge Spreading Center activity and associated N.E. Atlantic Passive Margin re-adjustments.

b) Orogenic movements related to the generation of the Alps.

c) The Tertiary Igneous Province/Iceland Plume.

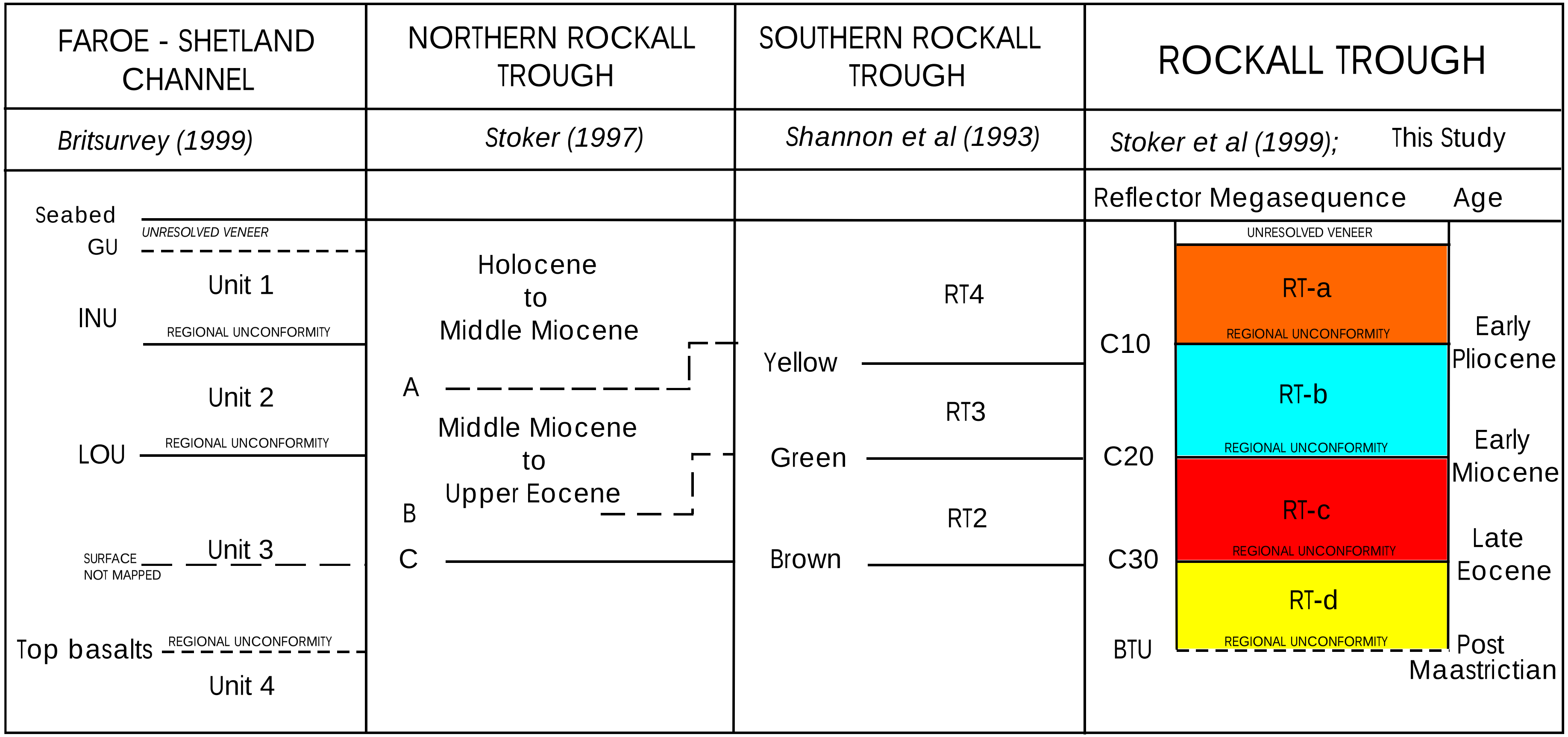
d) Development of new and vigorous oceanic water circulating systems due to the newly established links to the Boreal Ocean beginning in late Eocene times.

Study of the influence of the above changes is made more difficult since there is little significant preserved terrestrial outcrop of the mid- to late Cenozoic existing in the British Isles and Ireland.

Only relatively recently did workers concentrate some effort into understanding the more recent geological past in the RBA. Initiatives from Industry, such as the Seabed Project covering the Norwegian and N. North Seas, the Faroes GEM Regional Geohazard Study (Britsurvey 1999) and the BGS/Oil company Neogene stratigraphic nomenclature project, West of Shetland (Stoker 1999) have helped to start to redress the balance. Fundamentally of course the West of Shetlands Paleocene turbidite discoveries (Schiehallion & Foinaven) and a more general study of Petroleum Systems and long distance migration have been the driving forces. These efforts have brought confirmation of the broadening realization that much of the N.E. Atlantic has undergone significant depositional, erosional and structural history during the past 50 million years. This has been of sufficient intensity to have a striking impact upon some of the historically accepted risks to hydrocarbon habitat and accumulation in the circum North Atlantic (Dore 1999), of which the RBA forms an integral part. Much more work still remains to be done, however, and the stratigraphy offshore has still to be defined over large regions.

A number of academic institutions have helped to show the usefulness of taking a broader, truly regional view as a means to understanding the evolution of the N.E. Atlantic margin. Although still far from complete, the tectono-stratigraphic episodes emerging from such regional projects do show quite significant correlation, (**Table 2)**. However, the ability to

Table_2



GU = Glacial Unconformity
INU = Intra Neogene Unconformity
LOU = Latest Oligocene/Earliest Miocene Unconformity

} Terms from Stoker et al (1999)

Table 2 Comparison of previous and adjacent megasequence stratigraphies with key reflectors on basis of the current stratigraphic framework used in this report recover sufficiently good, (albeit very widely spaced), samples to allow accurate age dating is still often problematic. Also the apparent lack of significant Holocene – Recent sediments gives rise to the possibility that exhumed or relict seabed topographic surfaces exist. This possibility presents an important geotechnical challenge. The Rockall Trough Shallow Stratigraphy and Geohazards Study is huge in its extent and introduces a further piece into the tectono-stratigraphic framework jigsaw. It is hoped that the Study will form the basis for future industry and academic studies of direct use to seabottom engineers, drilling managers and explorationists.

4.2 Selection of Stratigraphic Framework Scheme

This Study has followed a stratigraphic scheme that concentrates upon recognition and dating of megasequence and sequence boundaries as regional unconformity surfaces that bound the intervening geological sequences. This was achieved through detailed and iterative interpretation of seismic data, preferably using a digital workstation, according to the concepts and techniques of seismic sequence stratigraphy and seismic facies analysis (Emery & Myers 1996; Vail 1987).

Since the mid- seventies a variety of workers have published alternative, though similar stratigraphic schemes covering the RBA. **Table 2** compares the more recent schemes. These suffer to a greater or lesser extent from ambiguities caused by: -

1) insufficient seismic coverage or database gaps,
2) application of "best guess" interpreted ages based on very long range jump correlation,
3) lack of sufficient, well dated in-situ core data with which to tie the interpreted seismic events.

Given the shortcomings of the earlier frameworks this Study focused on testing and developing the most recent stratigraphic scheme as shown below.

A culmination of work by Martyn Stoker of BGS has attempted to overcome many of the aforementioned difficulties and organise a unified stratigraphic scheme based upon seismic sequence stratigraphic principals. It is applicable to the entire Rockall Trough and is consistent with the recent developments in stratigraphical understanding mentioned above in 4.1 along the whole N.E. Atlantic Margin, (Stoker et al. 2000 *in press*).

This stratigraphical scheme, see **Figure 3**, proposes a three-numbered notation where numbering increases in descending stratigraphic order. The scheme allows for further subdivision as necessary with important regional unconformity surfaces numbered C10, C20 and C30, the prefix "C" standing for Cenozoic. From the stratigraphic framework shown in **Figure 3** it will be seen that the Late Cenozoic megasequences, bounded by regional unconformity surfaces, are recognised simply as (Rockall Trough) RT-a, RT-b, RT-c and RT-d. Whilst admitting this to be geologically unconventional, it is quite in keeping with most engineering based schemes that conventionally require straightforward referral to the seabed and beneath by the drilling bit.

Fundamental interpreted seismic profile data used to define the framework described in the Stoker et al. paper comes from the Regional BGS Offshore Mapping Program. It is strongly biased towards the UK portion of the Rockall Trough. This is a positive factor since it satisfies the desired requirement for continuity with the Faroes and Hebridean regions and others further to the northeast to be incorporated in the scheme. The BGS data is complemented to the south near the median line by the important WRM96- vintage commercial seismic data from Fugro-Geoteam. As mentioned in **Appendix 3** this vintage fortunately *does* form part of the PIP commercial exploration 2D seismic database. These seismic data are dominantly dip orientated and stretch down to the southwest where they tie with the useful, higher resolution ENAM seismic data acquired by the NIOZ along the western flank of the Irish Rockall Basin (NW and SW Rockall Regions). The location of both the latter seismic vintages are shown on **Figures 1 and 2**.

It should be noted that the PIP Rockall Trough Shallow Stratigraphic and Geohazard Study could not access the higher resolution ENAM seismic data for the first phase. The dominant control for the stratigraphic framework in the Study area is heavily centered along the western margin, as there is very little data available to the BGS over the eastern Rockall margin apart from seismic Lines WRM96-103 and GSR96-116, (**Figure 4**). Accordingly, as discussed below in **Section 5.2**, the five-location RSG shallow drilling campaign took place during 1999. Prior to this there was no fundamental age-dating control for the stratigraphic framework scheme along the eastern Rockall Trough margin south of the Hebrides Terrace Seamount see **Figure 1**. Therefore as referred to in Section 2.1 (2.1.4), the Study objectives and scope were highly ambitious and the constraints above were identified at the commencement of the study. Upon evaluation they were viewed as just part of the evaluation risk that had to be accepted during a Study of this magnitude into under-explored territory.

4.3 Stratigraphic Framework

The late Cenozoic stratigraphic framework proposed by Stoker et al. (2000) has been developed successfully and extended to cover the entire RBA as covered by the PIP dataset. There is an enormous time range covered by the rocks existing at or just beneath the seabed and this is described further in Section 5.0 below. Therefore, in keeping with the Study objectives, only a framework for the Cenozoic is covered here in detail, (**Figure 3)**.

The regional geoseismic profiles and sections, **Figures 4 – 13,** show the wide variety of geology across the basin and especially its strongly faulted margins. The strong angular unconformities of the BTU and BCU are clearly visible defining the structure with the younger C30 to C10 unconformities reflecting (?starved) post rift sedimentation. Significant onlap and truncation is observed together with concomitant thickening or non-occurrence of individual megasequences RT-d to RT-a due to differential uplift.

Figure 14 runs down the eastern RBA margin shelf and slope tying the Shallow Drilling Locations and the only available Well 12/13-1A. It is an attempt to show as much of the available biostratigraphically dated evidence as possible on one geoseismic strike section and, although wildly vertically exaggerated, it shows the complicated nature of the seabed and the underlying influence of geological structural control. This is a key to the understanding of the basin stratigraphy since there is much evidence of the composite nature of unconformity surfaces and the complicated configuration of the Cenozoic strata along the basin margins. The annotated structural maps **Figures 15 – 26** show how the stratigraphic framework has been constructively developed but also that there are still several fundamental unanswered questions. Examples of these are:

1) the relationship of the undated carbonate build-ups and reefs to the progradational shelf system of RT-a or RT-b age

2) the importance and composite age of slope and shelf break canyon/valley systems
3) the influence of the Donegal Fan and slides in NE Rockall
4) apparent Miocene –Early Pliocene age for the voluminous Erris/Gullwing toe-of–slope fan.

These and other issues are referred to later in the **Recommendations of Section 7**.

4.4 The C10 Unconformity at base of Megasequence RT-a.

Stoker et al. define the seismic expression of the regional unconformity C10 as a strong and regionally correlatable event with internal reflections in the overlying Megasequence RT-a showing definite onlap onto it. Often there is truncation of underlying RT-b reflections as units subcrop beneath the unconformity. These features are often difficult to identify due to the low resolution of the PIP dataset compared to the NIOZ and further north, the BGS data used by Stoker et al.. The interpreted occurrence and structure of the C10 surface over the RBA is shown in TWT and estimated depth as **Figures 15 – 16c**. The surface generally mimics the present day bathymetry and shows little structure apart from the steeply dipping eastern and western margins which are often faulted.

The maps show that the occurrence of C10 is dominantly basinal and it onlaps older megasequences at the foot of the slope on both eastern and western margins of the Rockall Trough. Since the megasequence overlying C10 includes Holocene to Recent aged sediments its presence is also assumed to exist on the eastern margin shelf as well as on Rockall Bank. It is worth pointing out here that in the UK Sector C10 also forms the base of the major prograding wedges that are the Barra Fan and Sula Sgeir fan. Hence, in the UK Sector, C10 can be confidently traced into the slope apron and shelf-margin succession. In both settings it may, however, be locally extremely thin (centimetres) and exist beneath only a seabed veneer essentially paralleling the present day seabed. This situation and the fact that in areas of extensive seabed erosion C10 is a composite erosion surface, cannot be resolved on the current PIP 2D commercial exploration seismic database.

Above C10, the overlying Megasequence RT-a shows many internal reflections within what is dominantly a blanket volume exhibiting parallel to sub-parallel internal reflection geometry. Some internal events can probably be carried over considerable distances but no attempt has been made to do this at this stage of the Study. Regional differences are noticeable from SW to NE since in the latter areas there are many signs of (active) sediment transport via channel-levee systems some of which are incised whilst elsewhere the systems provide a gentle positive seabed relief. This is expressed for example on the subtle seabed expressions shown on lines NA-15, WRM96-103 or LINE 3 in **Figure 4**.

Towards both edges of the basin there is some evidence to suggest truncation of internal reflection packages within RT-a. These occur in a complex pattern over the region, (**Figure 4)**, which remains poorly resolved and understood but is likely to be related to contour current erosion.

In an opposite manner **Figure 4** also shows that in some areas of the RBA Megasequence RT-a is ponded and trapped, e.g. to the west of the main Feni Ridge in SW Rockall area and also to the NE of the Porcupine Bank e.g. Line GSR96-116 and NA-01. The **Data Examples 4, 5, 6** and **10** also show these depositional phenomena.

Further evidence of recent deposition, albeit of a different nature, is shown by the positive seabed relief at the crestal ridge of the Feni Drift which migrates into the lower slope of the RBA western margin at around the latitude of the **DSDP Well #981**, (55deg 30'N). The regional correlation of C10 shows RT-a existing at seabed further south along the ridge with a younger RT-a unit trapped in the western flank of the Feni Drift, which can just be made out on **Line NA-01**, and in **DX 10**. The resolution and seismic line spacing leave much room for ambiguities in the sequence stratigraphic interpretation of the Megasequence RT-a. The upper western RT-a boundary appears, however, to become truncated as the ridge crest nestles into the lower slope as seen on **Line NA-01**. The lateral extent and boundaries of the C10 surface and overlying Megasequence RT-a could be defined more confidently by integrating all the available data available i.e. the NIOZ ENAM lines not included in this Study.

Along the eastern margin of the RBA there is usually just as much difficulty defining the limits of the C10 surface. Just as observed in NW Rockall, in the northeast there is regional scale evidence of truncation at the present day seabed. At a local level, however, it is often not possible to be confident since dips are rather gentle and the truncation occurs within the 'no data zone' inherent to the PIP seismic dataset. Furthermore areas of interpreted contourite sedimentation that may be of RT-a age are observed. By their nature these deposits, which inter-finger up and down the lower slope could initially be interpreted as being the result of large scale slope failure processes. It is interpreted here, however, that they are contourite deposits being driven by oceanic current activity to climb or plaster the slope to greater or less extent. **Data Example 22** provides a classic interpretation example of this process and the lateral extent of the sediment body is shown for example on **Figures 15,16 and 16b.**

The effect of the 'no data zone' and obscuring multiples on the PIP 2D seismic database can be seen on **DX 21** and **22**. The stratigraphical relationship between the basinal facies of RT-a and the climbing contourite sediments (that have a cuspate and diffractive internal reflection geometry) is not clear enough to convincingly decide whether these type of sediments are of younger RT-a age. Rather than being recent sediment bodies they may in fact be relict features sitting astride the underlying Gullwing/Erris base-of-slope wedge.

For these reasons mapping the limits of Megasequence RT-a requires considerably more seismic control and further interpretation to work out the correct sedimentary relationships and therefore it's proper place within the stratigraphic framework. This is referred to in the Recommendations Section 7 below.

Further south along the eastern margin as can be seen on **Lines GSR96-116 and LINE 1** (**Figure 4**) the relationship of C10 changes and the unconformable surface downlaps onto underlying older Megasequence RT-c thus causing truncation and pinchout of megasequence RT-b at the steeply dipping bulge of the Porcupine Bank. Even further south, (**Line WI-32**) the C10 event is probably beginning to climb the lower slope again. **Data Example 17** shows how Megasequence RT-a (sampled at the 83/24-sb01 Shallow Drilling Location) forms a 0.050 – 0.075 sec TWT contourite drape, whilst just some 25 km further north at the 83/20 location the RT- a the contourite facies has thinned to just 2-3 meters in thickness. **DX 16** shows that such a thickness is within the 'no data zone' of the seismic. Looking further down slope, however, the megasequence is interpreted to thicken before becoming truncated at the eroded foot wall of the major fault that defines the lower slope of the western margin of the N. Brona Basin. The inset on **DX 16** shows a similar faulted relationship of the contourite facies of megasequence RT-a to the more parallel layered basinal facies which is here quite thin compared to other places being only 0.110 sec TWT thick.

There is a good deal of interesting evidence from interpretation of these types of depositional patterns and tectonic relationships as to the timing and indications of frequency of movement. It is suggested that a previously greater areal extent of not only RT-a but also of other megasquences occurred in some areas that has subsequently been modified by considerable faulting and erosion of both hanging and foot walls presumably by bottom current activity. If this is true then some of the tectonics must have continued to occur during the past 5 million years. It is this kind of tectonism that may be responsible for the concentration of slope mass-wasting geohazards that are to be found within the Study region and it is feasible that the situation is still ongoing at present. The Recommendations in Section 7.1 are written with this kind of concept in mind, e.g. 7.1.2 and 7.1.9.

4.5 The C20 Unconformity at the base of Megasequence RT-b.

The seismic pick of the regional unconformity C20 is mentioned by Stoker et al. (2000), who used paper hard copy seismic for his correlations, as being rather ambiguous in many places. The picked reflection selected as the C20 surface certainly shows definite evidence of regional onlap by the overlying Megasequence RT-b in some areas, e.g. **Data Example 5.** Elsewhere it becomes weak and the picked event is often interfered with by multiples and ringing from more sub-parallel reflective packages above. It becomes more difficult to pick because of similar reflection patterns beneath it that also have comparable reflection strength. Occasionally there appears to be evidence of truncation of internal reflections beneath the surface. The C20 surface becomes a composite unconformity surface with the pre-existing C30 unconformity along parts of the margins of both sides of the basin. Here the overlying RT-b sediments show distinct onlap onto the C20/C30, (**DX 10** or **49**) with the older underlying Megasequence RT-c, or more often RT-d since especially along the western margin there is considerable overlap of the underlying Megasequence RT-c by RT-b.

As shown in **DX 10** this situation has much to do with the major Feni Drift contourite system. Part of the areal footprint of this major sediment accumulation that exists over SW Rockall is shown on **Figures 15-18,** where interesting internal and external reflection geometries are observed on the seismic data. Virtually identical downlaps, infilled erosional moats and conventional onlaps are interpreted on the seismic to be present not only within the RT-b but also are exhibited within overlying Megasequence RT-a.

Using the PIP dataset on the workstation the expression of C20 can be successfully correlated regionally over wide distances. Naturally there still remains the ambiguity in detail given the often only slightly disconformable reflective packages above and below.

Mapping of the surface interpreted here as C20 is presented as **Figures 17 – 18c**. The unconformable surface again mimics the present day basinal configuration of the Rockall Trough and the deepest part is in the central eastern portion of the basin. C20 is strongly faulted against the Porcupine Bank ancient crystalline massif along much of the eastern margin i.e. from just north of Line NA-01 southwards as shown in **Figure 4**.

In the west, however, the situation is different in that the unconformity oversteps the underlying megasequence RT-c and becomes a composite surface with the C30 unconformity (**DX 10**). Such a situation is not an unusual occurrence. It is seen along the margins of several basins in the NE Atlantic, for example the Faroes-Shetland Basin or Faroe Bank Basin where the C20 Equivalent, the Late Oligocene/Early Miocene Unconformity (LOEMU), runs into the major unconformity at the top of older Paleogene Unit 3, (**Table 2**).

Megasequence RT-b lies unconformably above the C20 unconformity surface and shows an overall lensoid external form with considerable changes in thickness over the region. For example RT-b contains the major portion of Feni Drift down in the southwest where sediment thicknesses estimated as up to 750 meters thick exist, see **DX 38 or DX10**. Both the eastern and western Rockall margins show considerable changes from the parallel to sub-parallel internal and external reflection geometries exhibited in the more basinal environments. As shown on **Figure 4** the RT-b abuts the western margin in a faulted or strongly eroded configuration in the northwest but further south can be seen to very definitely downlap onto the underlying megasequence RT-d sediments (Line 3 southwards). As stated above, the southeast margin shows RT-b faulted against basement on **Line 1** but by **line GSR96-116** RT-b has been thinned by either erosion or non-depositional processes and pinches out before the faulted margin is reached.

Further to the northeast the lower Miocene to lower Pliocene sediments ride up onto the lower slope before pinching out (or become lost within the ‘no-data-zone’), e.g. **Line WRM96-103** or **DX 20 – 23**. The most northerly regional line used in the Study (**NA-15, Figure 4**) shows how much RT-b is thinned along both basin margins as well as from above by the presence of the overlying marine erosion processes associated with the C10 (or younger) unconformity.

As shown on many of the Data Examples and mentioned above in Section 3.1 the eastern margin of the RBA is often only moderately well imaged on the PIP 2D commercial dataset. Even using interpretation software on a Unix workstation the final mapping of the C20 surface in this area is quite difficult and has led to an important difference in the unraveling of the stratigraphy compared to the ideas originally proposed in Stoker et al’s fundamental work. Further investigation is imperative regarding the difference in interpretation opinion since it affects not only the age and stratigraphic integrity of the framework along and up the eastern margin but it also has important implications towards a much younger Neogene age for important tectonic events than has previously been considered.

The differences relate to the interpreted RT-b age of a very large body of sediments (**Data Example 51**) that extends parallel to the eastern margin from Block 4/29 in the north down to approximately Block 17/27 in the south, e.g. **Figure 17**. Seismic interpretation of the upper convex-concave (lower) lens shaped external configuration with chaotic to slumped to sub-parallel internal reflection geometry describes a massive wedge shaped body. This huge mass wasting feature is some 265km in length. The base-of-slope position of the wedge aligns strongly to a hanging wall location on the major Erris fault system. The sedimentary body whilst narrow and apparently sharp edged in the south has a classic gullwing shaped external geometry further north where it extends out into the basinal environment for 100km. The structural form and thickness of what is here termed the ‘Gullwing/Erris base-of-slope wedge’ is shown in map form as **Figures 23 – 26**.

Distinction of the very gently downlapping reflections along this extended feather edge are often difficult to discern but the interpretation here suggests the wedge formed by large scale collapse of the upper slope (?and outer shelf) due to probable extended shelfal progradation and late Miocene if not early Pliocene movements along the Erris fault system. Evidence for the above interpretation is shown on **Data examples 6, 7, 20 – 23, 27, 35, 36.**

Much more needs to be understood about this very large volume of sediments and the processes that caused its occurrence and how they are related to those studied as occurring at the present day. Some data, e.g. **DX 22, or 35** shows chaotic internal reflectivity and a highly irregular top to the deposit. The impression is that the Gullwing/Erris base-of-slope-fan may be composed of multiple debris flows whilst elsewhere, above or below the chaotic character, a more parallel to sub-parallel internal reflection geometry is seen. Especially in the south, where the feature is narrowest, incision into underlying sediments is observed, e.g. line **ISROCK-96-18 SP 220-350**. Furthermore there is the suggestion that the body rides up the slope (as is observed further north e.g. **Line WRM96 - 103).** The lateral extent of the body is never well constrained up-slope but in the south due to the increased dissection of the slope by canyon/valley systems the wedge may be wider than indicated on the maps. Further analysis is desirable of the up-slope and down-slope extents of the feature, (where a degree of sedimentary inter-fingering is suspected), especially if the work could also be tied into age dating and is recommended in **Section 7.1.9.**

The existence of the C20 unconformity on the slope in SE Rockall is complicated and not yet fully understood. At the 83/24 Shallow Drilling Location there is both important biostratigraphical and sedimentological evidence. This shows, together with semi-regional seismic evidence, that the C20 unconformity continued up what is currently the dissected slope and possibly even much further **(Figures 5, 6 and 11 or DX 1, 16, 17 or 18)**. This is the case at least over parts of the SE Rockall region that, as shown in **DX 19**, projects as an up-thrown massif of basement and older Palaeozoic and Mesozoic rocks. This high area has been "capped" by progressively younger aged rocks and sediments following the major unconformity near the base of the Cretaceous (BCU). The C20 unconformity progressively cuts out the underlying RT-c and much of the RT-d sediments to locally cut into the Upper Cretaceous and even the older Greenstone and Brownstone facies of the Lower Cretaceous, (**Figure 6**).

The occurrence of RT-b sediments in SE Rockall contrasts entirely with the situation on the western RBA margin. Here they appear to be entirely absent in SW Rockall (due to pinch out) and interpreted to be only locally present west of the major basin bounding fault zone in the NW Rockall region due to erosional truncation, (**Figure 8**). The presence of Megasequence RT-b and the correlation of the important C10 surface are not well understood in large areas of east central (EC) and NE Rockall, (**Figure 5**). This region requires further study to allow confident interpretation and extrapolation to allow the detailed tectonic history to be unraveled. As shown in the cartoon, (**Figure 7**), uplift and truncation along the middle to upper portions of the slope by C10 appears to have occurred.

It is also not known whether any RT-b aged sediment exist beneath the shallower waters of the outer shelf in these areas. (**Data Example 43**), for example, shows the interpretation that suggests the upper slope reef build-ups in the vicinity of the shelf break may be ponding an eroded prograding shelfal prism of sediments of which the lower two-thirds portion may be the equivalent of Megasequence RT-b in age.

4.6 The C30 Unconformity at the base of Megasequence RT-c.

C30 is defined by Stoker et al. (2000) as a major basin margin unconformity surface that can be correlated regionally with a fair degree of confidence as a strong positive reflection or parallel series of reflections. It sits above the noticeable slope wedge seen in the NW Rockall and is strongly onlapped by C20 and C10. In the basinal regions dips are often very shallow but the surface shows shallow truncation of underlying megasequence reflections and occasional onlap onto lensoid basin floor thicks within the upper part of RT-d, (**DX-7**).

Mapping of the C30 surface is presented as **Figures 19 – 20c**. As shown in **Figure 3** the unconformity surface and overlying megasequence RT-c have been tied to the seismic data sets in shallow BGS Borehole sites 94/1 in the NW Rockall and the RGS 83/24-sb01 Shallow Drilling Location in SE Rockall. Furthermore several other sites, especially 16/28-sb01 have demonstrated how unpredictable and complicated the accurate definition of the stratigraphic framework is (**Data Example 15**). At the 16/28 location, for example, the sequence stratigraphic model derived from the regional seismic interpretation strongly suggested the presence of RT-c above a composite C30 and BTU erosion surface. What the borehole encountered, however, was the presence of a relatively thick older Megasequence RT-d resting directly upon the BTU. These Paleocene to mid Eocene rocks are apparently unconformably overlain by just 14.47 metres of Upper Pliocene-Pleistocene (RT-a) sediments. This result proves that both Megasequences RT-c and RT-b are missing around the RSG 16/28-sb-01 location. Incidentally this provides further strong evidence for the erosive nature of the C10 unconformity here so long as the missing section cannot be due to a possible alternative suggestion. This would need to invoke the presence of shallow dipping faults associated with much persistent down-slope mass wasting to cut out the RT-b section. Similarly for Megasequence RT-c, assuming that it was deposited in the first place. In the direct vicinity there does not appear to be the same evidence (such as the Gullwing/Erris base-of-slope wedge in Megasequence RT-b) supporting long term, large scale mass wasting in this case. Further investigation utilising all available data, however, would seem highly appropriate here.

Regional appraisal of the seismic interpretation shows that Megasequence RT-c can in fact be shown to be regionally eroded (or possibly non-deposited) over large portions of the SE Rockall area. This infers significant uplift and erosion during or after RT-c times and also, around the 16/28 area, during or post RT-b times as well. Because of the seismic resolution, line spacing and the effects of canyon/valley systems further investigation is required to map the full extent of the RT-c along the eastern margin, as indicated in **Figures 19 –20**.

As with the younger megasequences RT-c is difficult to correlate and map up-dip of the lower slopes in NE Rockall. **Data Examples 8, 20** and **26** show the strong effects of faulting and erosional truncation by C10 as well as the masking effects of more recent downslope mass wasting processes. **Data Examples 27, 28 or 35** of strike line **DGER96-52** along the lower slope in NE Rockall shows the variation in reflector continuity moving towards the NE portion of the RBA which requires further study to convincingly define the stratigraphic framework.

At present the model for three megasequences as presented here will work successfully but does require movement during post RT-d times along the Erris fault system in the order of 1.5 second TWT**, (Data Example 48)**. It seems likely that most of the movement could have occurred during RT-b or even RT-a times. Given the evidence for the evolution of the Rockall Trough (that is perhaps more dynamic in the Cenozoic than previously expected), this appears to be an entirely plausible concept. It comfortably ties in the current age dating of Megasequence RT-d aged sediments that are encountered in the 12/13-1A well, see **Recommendations Section 7.1.6**.

Working away from the Well 12/13-1A area Megasequence RT-c is often characteristically seismically transparent with a few internal reflections that are sub-parallel to gently prograding. Near its base reflectivity increases with a noticeable separate parallel to subparallel basal reflection package. This would appear to correlate with an early RT-d aged facies (widespread Paleocene ?deepwater carbonate facies dated as Danian in the well). This presumed Maureen Equivalent in the North Sea is apparently widespread in the Porcupine Basin Area. **Data Examples 14 or 8** show this basal unit overlain by the distinct transparent unit, which can be identified over large areas and is often seen truncated up dip by a clearly angular unconformity. This important erosional surface cannot be mapped in detail on the current dataset since it often occurs just at or off the end of the seismic lines. As interpreted in **Data Example 50** it must surely be the C10 or C20 unconformity lying at the base of Megasequences RT-a (or RT-b). These appear to be the likely candidates to form the progradational shelf units of Erris and northern Porcupine Bank, but again further investigation is required.

The overlying transparent unit within Megasequence RT-c is thought to consist of early to middle Eocene aged muddy sediments from an upper slope to outer shelf environment which is quite different from that existing in the early Paleocene. Lines around **DGER96-37**, (**DX 7**), in NE Rockall suggest that RT-c is shale prone since it is subjected to considerable deformation and faulting but appears seismically to have deformed in a more plastic manner than found elsewhere. Also of interest is that often the truncation and dip of the erosive surface that cuts into RT-c (**DX 50)** tends to mimic the seabed gradients found in present day upper slope and shelf break environments, (for example see **DX 8**).

Moving now to the western margin of the RBA the regional lines of **Figure 4** show how RT-c occurs as a slope front or hanging wall wedge. It is also present in a shelf setting (where large-scale progrades are observed on some seismic lines). In some places there appears to be conflicting evidence to support a totally progradational environment along the western margin during RT-c times. This is based upon observation of buried moats and strongly downlapping packages (against the fault zone). These features give the impression of having a similar depositional environment as those observed to be of younger age that are interpreted as being deposited under the influence of contouritic sedimentation processes during RT-b and RT-a times. It is believed that the geometry and extent of the basin during RT-d times, together with the likely water depths, were not conducive, however, to the formation of contourite deposits. It is thought that the onset of contourite deposits coincides with the major oceanographic (and tectonic) changes of Miocene times (Shannon, personal comm..). Megasequence RT-c does appear to be eroded but has apparently not undergone the same rotation and faulting as in NE Rockall to produce such a sharply defined angular unconformity.

Data Example 10 shows the major unconformity that is C30 by definition. The surface west of SP 2650 is observed on the seismic line to be truncated by the present day seabed and ocean current regime. It is also strongly onlapped by the three Megasequences RT-a, -b and –c. Obviously the ponding influence of the assumed underlying volcanic complex, (possibly with attached buried carbonates), plus the dramatic change in seismic facies observed on this line all need to be explained to derive a correct tectono-stratigraphic history. Line **WRM96-119** is a classic example of the complicated stratigraphy of the RBA that the Study has attempted to put into a regional framework. Further interpretation work is recommended see Section **7.1.7** to firm-up the concepts and framework since no strike control presently exists on the PIP 2D commercial seismic database, **Figure 1**.

4.7 The Base Tertiary Unconformity at the base of Megasequence RT-d.

The Base Tertiary Unconformity (BTU) is observed as a very noticeable and often strong reflection acting as a clearly angular unconformity in many parts of the RBA. This can be seen on the regional profiles or cartoon sections, **Figures 4 to 13**. As is the case along much of the NE Atlantic margin this major unconformity is often preferentially intruded by sills that can seismically enhance the reflectivity along the unconformity whilst at the same time inhibiting deeper seismic penetration. The location of Shallow Drilling Location **16/28-sb01** for example is one such place where drilling was curtailed by the presence of basalt, see **DX 15**.

In many places in the SE Rockall area the BTU lies parallel to and above the thin Cretaceous successions that themselves unconformably overly the major unconformity at or near the base of the Cretaceous (BCU). Elsewhere, however, the BTU cuts down through the BCU into progressively older Mesozoic or Paleozoic rocks. The structure of the BTU is shown as Figures 22 – 22c and any further description of such indications of widespread differential movement along the margins of the Rockall Basin Area, however, lies outside the scope of this Study.

Within the basinal region of the Study area Megasequence RT-d sediments always unconformably overly the BTU. Their internal reflection geometry ranges from transparent to acoustically chaotic with disrupted layering through to sub-parallel on the flanks with occasional strong internal reflections. They are probably at their thickest in the central parts although there are obvious exceptions where volcanic or other igneous centres occur, e.g. the central portion of **Line NA-15** on **Figure 4**. Elsewhere Megasequence RT-d sedimentary thickness is variable or unknown/non existent as is thought to be the case in parts of the EC and NE Rockall areas. As shown on **DX 16,17** and **18** the SE Rockall region has been uplifted and the RT-d presence is often quite thin (just 50m or less). **DX 17** shows RT-d sediments parallel to sub-parallel in the basinal region. Because of the lack of tight biostratigraphic control it is not possible to be particularly precise about the timing of the uplift in the SE Rockall; it could have been a one stage or a multistage series of events as an extension of movements dating back into the Cretaceous. In places it is noticeable that the C20 unconformity has cut down to such an extent that RT-b aged sediments directly overlie the BTU, e.g. at the **83/20-sb01** location. It has yet to be proven that RT-c sediments were never deposited in the area. This would suggest a late Eocene to early Miocene aged extended period of uplift. Alternatively it could also be that either uplift was rapid near the end of the early Miocene or as well as during RT-c times All three concepts could account for the erosion into the Cretaceous strata capping the SE Rockall area.

On the western margin of the Rockall Basin the relationship of BTU and BCU is unclear and in many places Megasequence RT-d may directly overlie crystalline basement or rocks forming a large igneous complex. What is clear is the widespread occurrence of Megasequence RT-d throughout the western margin where it occurs as a hanging-wall wedge and/or strongly progradational package that has subsequently been eroded such that it now subcrops at seabed over large regions, (**Figures 4 – 13** or **DX 10**). Interpretation of mounded internal reflectivity patterns and features on some seismic lines, however, could suggest that the hanging wall wedge is partially composed of climbing contourite sediments that apparently must inter-finger with the otherwise shelf derived progradational depositional sets. Alternatively these features may be the result of slumping or other mass flow processes since established thinking does not support a NE Atlantic Oceanic configuration sufficiently ‘open’ enough to allow the occurrence and circulation of such large water masses.

Little is known of the lithology of these sediments although a larger sand component would appear to be likely. As shown in Figure 5 of Stoker et al.’s paper, (In Press, 2000) the BGS borehole 94/1 penetrated RT-d sediments encountering early late Eocene black silty mudstones and pebbly sandstones in the upper few tens of milliseconds of the stratigraphic unit. Confident correlation away from that sample point is not straightforward on the present PIP dataset. Furthermore significant erosion of the RT-d sediments along the western margin by (at least the present day or Holocene – Recent) ocean current regime is interpreted from the seismic dataset. Further complication regarding the identification of RT-d lithologies is interpreted for example on **DX 10**. Here, as the RT-d noticeably thins over the deeper buried volcanic or slumped carbonate complex between Shot Points 2000 – 2350, is a good example of a considerable change in seismic facies. The slope wedge shows good sub-parallel to hummocky internal reflectivity compared to the chaotic and discontinuous facies of the more basinal part of RT-d. There may also be the added complication of internal deformation and faulting due to compaction and expulsion.

Lithologically, younger RT-d sediments consist of interbedded mudstones and siltstones of slope or bathyal environment; older beds (of assumed Paleocene age) appear to be of a distinctly more shelfal nature and can be moderately well cemented as in 16/28-sb-01. At 83/24-sb-01,02 the early to mid Eocene sediments consist of a micritic limestone /calcareous mudstone facies deposited in an upper slope setting. This is a similar environment to the NE Rockall Shallow Drilling Location 11/20-sb01 where the interesting submarine basaltic flows are intimately associated with undifferentiated RT-d carbonates infilling cooling fractures and joints, **Figures 13, 14, 15** and **17**.

5.0 SHALLOW GEOLOGY

The original remit of the Study was that the uppermost 0.500 seconds TWT should be investigated since conventional wisdom suggested that only late Cenozoic strata would be encountered. Since this was not the case in reality the interpretation needed to be taken much deeper in order to begin to understand the influences of structure and the underlying bedrock that strongly effect the seabed in many places over the Study region. The stratigraphic range of rocks occurring at or close to the seabed over the Rockall Trough does in fact stretch from the Precambrian through to the Recent, see **Figures 1** or **6**.

5.1 Stratigraphic Range and Structural History

At first sight it does appear to be the case that a Holocene – Recent veneer or cover of sediments does exist at the seabed over large regions of the RBA. The veneer (that occurs within the no data zone of the PIP 2D commercial exploration seismic dataset) consists of a wide variety of lithologies and is of variable thickness. The veneer varies from probably just a few centimetres in areas scoured by current activity to several metres or even possibly tens of meters in the case of the younger Feni Drift or other contourites. This uppermost veneer however, not a continuous cover and it is the areas where it is of minimal thickness that are of considerable interest to the drilling or foundation engineer; for example the emplacement and extraction of anchors. These areas are almost always influenced or directly related to underlying geological structure that is often quite complicated. Examples are fault scarps, slide head and sidewalls, current scoured moats or the bottoms of canyon/valley systems together with irregular highs of outcropping bedrock, igneous material, or of course, carbonates.

5.2 Integration of PIP Shallow Drilling Results

Rockall Bank and most likely Porcupine Bank are ancient crystalline massifs consisting of basement the dating of which suggests a Grenvillian age of 1.7 billion years. Likewise tightly folded assumed Palaeozoic rocks are also observed as faulted highs close to or at seabed. Shallow Drilling Location 83/24-sb02 encountered the oldest sedimentary rocks - red stained silt/mudstone as the deepest cored sample. It is interpreted here as an indicator of possible Triassic aged rock existing directly beneath since seismically the location is located on the limb of a thick syncline ramped up against an obviously older upstanding block, (**see Data Example 17**). A bold interpretation would suggest that a further unconformity exists, (subparallel to the BCU above) between the lowest cored sample and the overlying Late Jurassic-dated samples which are also stained red. This would explain the poorly imaged sub parallel reflection observed above the synclinal fold.

Such an interpretation is backed up by the independent assessment of Mike Norton in a recent assessment of the tectonic development of the Rockall Basin, (Norton, M.G. pers. comm.). Alternatively the fold limb must otherwise be composed of a massively thick U. Jurassic sequence.

Further evidence for lower Mesozoic rocks is lacking from the five (though essentially four) drilled locations but core confirming a late Jurassic (late Kimmeridgian) age was also recovered at the 83/20-sb01 location, **Data Example 16**.

The results of the Shallow Drilling campaign are tremendously valuable for the exploration of the basin, (BGS 1999). Since the geology is complicated, careful detailed interpretation is required and unfortunately space and time do not allow justice to be done to the results in this phase of the Study. This is also the case regarding the detailed results of the Shallow Drilling. The reader is referred to the BGS Stratigraphic Summary report mentioned in Section 8.0. This concise document is full of essential lithological and biostatigraphical age information from the recovered core material together with the fundamental borehole to seismic correlations. These have been carefully analyzed and further developed as a basis of the current interpretation. Progress on sedimentological studies and biostratigraphical studies is continuing to be made and it appears that the initial ages estimated onboard are being confirmed thus providing strong evidence for the Stratigraphic Framework presented in this Study.

The Shallow Drilling Results have also been used as the independent starting point for detailed interpretation of the spatially separated 30 sq. km site survey areas covered by Hi Res seismic, (acquired by the BGS over the Shallow Drilling Location sites – BGS Challenger Acquisition Report, 1999). The results of this detailed work appear to agree with the regional interpretation although they have not been referred directly to the Stratigraphic Framework presented here, (Praeg and Shannon 2000), see Recommendations Section 7.1.4.

5.2.1 Upper Cretaceous Presence

Naylor et al. (1999) have illustrated the structure of the RBA. It is noticeable that the southeastern margin has been uplifted preferentially during (and post) the main rifting phases. Although vertically exaggerated, **Figure 14** and **Data Examples 3 – 7** or **12** show that for a great deal of the outer Porcupine Bank the pre-Cretaceous sediments above the BCU surface form a capping to the (?pre major-rifted) rocks. The thickness varies e.g. on the up dip, eastern portion of **Data Example 1** the total Cretaceous section is 300 meters thick or more. Elsewhere, however, as shown nicely on **Data Examples 15 – 18** a thickness of considerably less than 100 meters is very common. It is quite noticeable that the “capping” is not always just atop the plateau-like area but is also systematically plastered on the flanks, see **Data Examples 19** or **4**.

5.2.2 Marls, Greenstones and Brownstones

All three facies as penetrated and defined at the Shallow Drilling Locations 83/20 and 83/24 can be interpreted and correlated outwards away from the control points. The Maastrichtian and Upper Campanian marls, however, cannot be correlated very far since they appear to have been eroded by the BTU and also locally by the C10 unconformity. Both the remaining units often show strongly reflective and parallel to sub-parallel internal reflection geometries. It is therefore sometimes difficult to tell the underlying Mid Cretaceous iron-rich Brownstones and at least the lower part of the Upper Cretaceous glauconitic sandstones from each other. This is especially the case when jump correlating the many faults on the current line spacing and further work is recommended to map the Cretaceous occurrence in more detail.

Further complicating the correlation and mapping of the stratigraphic units identified at the Shallow Drilling Locations are the presence of numerous steep-sided canyons and valleys. Their interference can be clearly seen on **Figure 14.**

5.2.3 Presence of Upper Jurassic Veneer and Unconformities in General

The presence of late Jurassic aged shale at the 83/24-sb02 location is encountered lying immediately beneath the BCU, the lower of the two more strongly identifiable regional unconformity surfaces interpreted from the seismic. Often in the uplifted SE Rockall region the BCU lies parallel to the overlying BTU but whereas elsewhere this situation is not seen and the two surfaces diverge dramatically.

Generally the BCU is observed beneath a Cenozoic or Upper Cenozoic overburden but at fault scarps on the lower slope in SE Rockall where the complete section is eroded it may be possible to confirm the occurrence by coring. Also there appears to be a high area in the east-southeastern part of the Padraig Basin where the Cretaceous strata are at or close to the seabed.

This area is also apparently associated with some large carbonate reefs that may be preferentially sited because of the subcrop.

This type of occurrence is also recognizable further south where faulted basement subcrops, (**Data Example 45** or **43**). On the latter example it is interpreted that a considerable amount of erosion of bedrock has occurred. This has possibly occurred due to strong current activity at depths around 1000m. Erosion processes are considered to have played an active role in the development of the western Rockall margin throughout its upper Mesozoic and Cenozoic history. It can be seen that on several of the data examples the impression is that large volumes of strata have been removed from the upper and middle slope, (**Data Examples 1, 3 or 5**). The present day situation could, therefore, be strongly influenced by the quite distant past. This important suggestion would help to explain the composite nature of the C10 to BTU unconformity surfaces as interpreted on the enclosed Data Examples. It would also help account for the difficulties in mapping the megasequence boundaries on the current dataset over the present slope environment.

6.0 GEOHAZARDS

6.1 Introduction

Figures 10 – 13 describe seabed profiles from selected seismic lines over both the eastern and western slopes of the Rockall Trough. There was no geological reason for the selection of any particular line, thus they provide an objective view commencing in the north and running towards the south. The profiles cover the majority of the Study region and show the quite considerable variation in slope profile - both regionally and locally. The line spacing varies from 10 to 50km. Furthermore, in many places every line seems to display considerable differences from its neighbour. Some slopes are gently curved and blanketed (with contourite sediments) whilst others appear to steepen downwards or are extremely faulted, and some appear jagged and apparently current scoured.

The gradient derivative of the bathymetry from the PIP database, **Figure 28,** shows that these marine slopes regularly exceed 5 degrees. Often area – wide maxima approaching 15 degrees or more are to be encountered. These slopes are undoubtedly unstable to any changes in equilibrium since it is well established that some marine soils become unstable at very low gradients of only ~ 0.5 degree, (Stoker et al. 1999).

As an overall initial assessment it would appear that possibly only some 10 –20% of the (mainly-lower) slope region could be classified as "benign" with regard to risk of fundamental gravity induced mass-wasting processes let alone those observable geohazards listed below. Interpretation of the TOBI data add weight to this assessment as can be seen in **Figures 27a, - 27c.** The remainder of the region is considered to suffer from one (or more) of the following identified geohazards.

6.2 Identified Geohazards

6.2.1 Slides/slumps, slide scars and slide sediments occur both on surface and sub-surface where they may have been rapidly buried and poorly dewatered / remain slightly overpressured. Size and frequency estimates are required for any assessment of risk to stability hence more detailed interpretation and work is required – see Recommendations in Section 7 below. Numerous examples of rotational slides and collapse where sediment has been transported downslope virtually as a complete and probably only slightly deformed units are to be found. The TRIM Intermediate Interpretation maps shown as overlays to the detailed Geohazard Maps, **Figures 27 – 27C** show various varieties and sizes. This is particularly the case in NW Rockall where the slides tend to be frequent but relatively smaller whereas in NE Rockall individual slides can be found to affect the majority of the middle and lower slope (**Figure 29).**

Slump features are similarly common but tend to be smaller in size (but probably more frequent in occurrence) and are less easy to interpret directly from the PIP 2D commercial seismic dataset. Such features are interpreted to be found more commonly but not exclusively on the middle to lower slopes where, as shown on the TRIM data interpretations, their elongate fan-like shapes occur, sometime showing lineations attributable to downslope flow (**Data Examples 25,26, 35 and 36**).

The areal footprint of the buried Gullwing/Erris base-of-slope wedge is shown on **Figures 27 – 27c**. It is another but more massive example of a gravity driven submarine slide or more likely a rapid series of slides and associated debris flows, (**Data Examples 7,** or **20 – 23** and **Figures 23 – 26**). The origin of the wedge may be responsible for particularly complex geotechnical conditions due to internal deformation, only partial dewatering and other phenomena. Similar variations in soil properties are of course to be found in the more recent slump and slide deposits, which is why it is so important that they be confidently mapped in detail

6.2.2 Canyon and valley systems that are transport pathways for channeled debris flows and turbidites. Such systems are observed to often show a dendritic pattern in map view and also be composite i.e. made up of differently aged sediment units. This suggests that the features, (that are often related to faulting), may date back for considerable periods. **Data Examples 29 –34** refer specifically to canyon and valley systems. These important facts require further detailed study to allow useful prediction to be contemplated.

6.2.3 Creep/compressional features. Apart from suspected bulging areas of seabed and sub-seabed in basinal depths, e.g. Line ISROCK-96-44, shown as **Figure 27a** and mapped on **Figure 28a**, creep features cannot be resolved on the PIP 2D seismic database. Interpretation of the limited higher resolution BGS Challenger data has shown that where steep slopes and scarps occur there is evidence for considerable hummocky downslope movement, (Praeg & Shannon, Section 8). Given the seabed gradients, (**Figure 28**), and apparent intensity of downslope processes that is suspected from the TRIM dataset, such processes and features are likely to be encountered frequently and more detailed interpretation is required.

6.2.4 Diapirism – not interpreted to be particularly extensive on the current seismic dataset. **Data Examples 27 and 28** show a feature that has some of the characteristics of a diapiric or igneous disturbance. More detailed data, e.g. potential field would help relieve the ambiguity.

6.2.5 Carbonate build-up mounds, screes and fully-fledged reefs and pinnacle reefs. These competent features occur with relatively high frequency along the margins of the RBA, see Geohazard Map **Figure 27a, 27c** or **30** and **Data Examples 43 – 46** for example**.** They have been studied briefly in just two areas by the Logachev surveys and the reader is strongly advised to view the UNESCO 1999 reports, especially the interesting figures. Work in the adjacent Porcupine Trough by the Renard Centre of Marine Geology (RCMG), (Henriet 1999), also makes absorbing reading. Further integrated work, especially assessing the strong suspected links to faulting and expulsion phenomena is strongly recommended, see **Section 7.1.5.** It is expected that the GEOMOUND, ECOMOUND and ACES (EU-funded fifth Framework research programmes) will push forward with answers to these important questions, see the European STRATAGEM Project web site at http://www.stratagem-europe.org for further details.

6.2.6 Shallow faulting likely to lead to seafloor collapse or rotation. Many faults are interpreted to cut to seabed whereas others apparently do not. Further study is necessary to understand timings and aid stability risk assessment.

6.2.7 Igneous intrusions and lava extrusions. These have not been mapped in any great detail but are known to exist. They range from the rugged seabed topography associated with the "witches hats" exposure of the Drol igneous centre e.g. Line ISROCK96-38. An example of the many suspected sills occurs at the 16/28-sb01 Shallow Drilling Location. Here a sill has been penetrated by the bit injecting preferentially along the BTU surface, see **Data Example 15.**, This is a common occurrence (e.g. **DX 37**) and the extend of such features that need to be known about *prior* to drilling operations could be interpreted and mapped out in detail.

A further example would be the igneous rock associated with the early Tertiary volcanic cones that outcrop at seabed adjacent to the 11/20 – sb01 drilling location in NE Rockall. Detailed sedimentology from the recovered material is ongoing and suggests volcanic flows deposited in a moderately shallow marine environment. This would appear to be consistent with the seismic interpretation, (**Data Examples 13 and 14**).

6.2.8 Contourite sediments. These occur widely and can be areas of rapid sedimentation, bottom scour or otherwise unstable foundation. They are found in many places over the region but a very major occurrence can be seen along the eastern margin. Here the presumably RT-a aged unit runs along the lower slope but in many places can be seen to attempt to climb upwards towards the middle slope, (**Data Example 22 and 23**). The lateral extent of these deposits can be mapped for several hundred kilometers and is presented on the Geohazard maps, **Figures 27 – 27c.**

In the SE Rockall area similar contourite deposits are interpreted and mapped. For example, such a deposit has been observed climbing up the very steep faulted slope onto the Padraig Basin, (**Figure 27b** and **DX 3**). At shallow Drilling Site 83/20-sb01 and 83/24-sb01 an RT-a aged contourite was encountered that is interpreted as blanketing large portions of the SE Rockall Porcupine plateau region, (**Data Examples 1, 16, 17 or 19**).

Mention must also be made of the massive Feni Drift contourite system that occurs in the SW Rockall region. The present day axial ridge (or more likely rather a series of *en echelon* ridge crests) is shown on **Figures 1, 9 and Figures 16c** for example and **Data Examples 10 and 38**.

6.2.9 Shallow gas accumulation indications, blanking or expulsion phenomena. The NW Rockall province in particular shows much regional seismic evidence to suggest most of the slope in that area is prone to gas hazard. Elsewhere there are several places noted on **Figures 27 – 27c** where shallow gas needs to be investigated further.
Data examples 40 and 41 show what is interpreted as an expulsion phenomenon (seep). The feature has been correlated on seismic and an adjacent TOBI pinger crossing and is considered worthy of further investigation.

6.2.10 Amplitude anomalies and phase changes due to lithology and geotechnical characteristics. Time has not allowed distinction to be made in this Study phase between category 6.2.9 above and this category of geohazard. **Data Examples 38 – 41** refer to areas where interpretation definitely suggests a gas presence within the subsurface.

6.2.11 Hard bedrock and basement at or near seabed. This is exposed at slope fault scarps and possibly in some canyon/valley system bottoms. The large areas on the Porcupine Bank shelf where apparent basement rocks are exposed in east-central Rockall could require more specialist anchor considerations, although because of the no data zone there may or may not be a veneer of recent sediments above the extremely competent bedrock. The limits of these seabed conditions are shown on **Figures 28 and 28a**. There is less likelihood of exposed bedrock on the Rockall Bank shelf, where although relatively close to seabed a thicker sediment cover is observed in most places – except where hard carbonates are observed of course.

In the southern parts of SE Rockall the pattern of basement or bedrock outcrop is especially widespread. This can be mapped by detailed interpretation of the kind specified in Section 7.

6.2.12 Bottom Simulating (or Diagenetic) Reflections (BSDR's) or other possible gas hydrate or silica diagenetic indications. It is well known that the RBA fits into the theoretical envelope for gas hydrate occurrence as well as those criteria that define present as well as palaeo-silica diagenetic boundaries. There are very many seabed parallel or sub-parallel bright events observed within the region. More study, however, is required to investigate their character and definition although nowhere during this regional Study has yet been convincingly interpreted as showing the existence of either phenomenon.

6.3 Slopes, Scarps and Seabed Gradients

The previous statements in 6.2 above suggest that up to 85% of the slope region must be defined as areas showing significant geohazards which require much more detailed interpretation and mapping. These areas lie between the increase in gradient at the outer shelf break down to the foot of the slope at basinal depths. Both these breaks in slope gradient are shown as the blue arrow-headed symbol on all the relevant **Figures, e.g. 27 – 27c**. All the other geohazard features identified during the seismic interpretation are also shown on these maps including identifiable and major scarps.

Figure 28 is based upon the 100 x 100m bathymetry grid generated from the seabed horizon pick of the PIP seismic dataset. It shows that seabed slopes along the margins of the Rockall Trough can be up to 15 degrees. Whilst every effort has gone into producing maps that are as accurate as possible it is necessary that more detailed mapping of the slopes and geohazards will be necessary to satisfy the H&S requirements associated with engineering and drilling activities.

6.4 Usefulness of TRIM Interpretation and Mapping

Significant integration of the seismic interpretation presented here with the interpretation of the TOBI Rockall Irish Margin (TRIM) sidescan sonar dataset has been made regionally to assess the relative navigation accuracy, degree of resolution, integrity of interpretation and mapping etc.. The TRIM interpretation is an ongoing joint UCD/DIAS project started in 1998 and the reader is referred to the three RSG reports by Readman et al. Although there are differences in the interpretation, the integration of the TOBI sonar data with seismic data has naturally been incredibly useful and has allowed a comparison of the two datasets as well as powerful synergy and enhancement of the overall interpretation to better define the seabed conditions.

Two examples of how carefully argued and integrated interpretation and mapping has enhanced the knowledge of geohazards are shown as **Figures 29** and **30**. The recommendation is that such integrated mapping should be carried out over the remainder of the region to maximise the value of the investment in acquisition and processing of the data since the results of such integrated work are clearly extremely useful and predictive.

7.0 RECOMMENDATIONS

7.1 Highly Recommended

It is important when preparing recommendations to recognize the scale of the task that still lies ahead given the successful results of the present phase of the Study. There is undoubtedly a need to cover the RBA in a regional sense in order to confirm and develop the stratigraphic framework model. Synchronous with this there is also the need for more detailed interpretation and integration for definition and understanding of the mass wasting sedimentary processes and other geohazard features.

In this respect the recommendations detailed below can be applied to both:

i) the full Rockall Basin Area (RBA) or
ii) four or five specific proposed "case study areas" (see **DX 47**) or
iii) otherwise selected areas of interest.

A dozen or so tasks and sets of objectives are considered here that would constitute a further phase of the Study and could provide timely and seamless integration along the lines of sound industry practice.

7.1.1 To carefully integrate the PIP commercial seismic database with the following sets of data is seen as one of the most important and cost effective ways of furthering the Study and maximising the value for the partner companies:

a) The TOBI mosaics and the TRIM interpretations as well as the GLORIA regional sonar data.
The benefits of integrating these datasets are obviously to add the structural dimension of the z axis to the powerful x,y vision that is TOBI. Careful integrated interpretation of not only the backscatter characteristics but also of the 3.5KHz pinger information has already added tremendous value e.g. by locating positive acoustic evidence for (fluid and ?gas) expulsion in SE Rockall. A further example is the ability to link and understand the rotational slide and other evidence of mass movement to deeper-seated structure or sedimentary features that are of prime importance.

b) Higher resolution seismic data e.g. the NIOZ datasets or higher resolution seismic data acquired during the year 2000 season.

The existence of a data gap within approximately the upper 15 – 35 m is the well-known compromise to be paid for exploration seismic data that seeks deep penetration. The data gap can be and has been bridged in those areas where higher resolution seismic then high resolution seismic and finally acoustic and sonar data have been carefully acquired to the necessary high specifications in terms of pulse length, S/N, sampling, tow geometries etc. Specialist correlation where these differing datasets overlap can often provide a very useful insight. Naturally this is something like a fleeting glimpse of an express train 30 meters away viewed from the inside of a letter box – enough to know the orientation of the track, the direction of travel, an estimate of the speed etc. This can be essential information if before one did not even know the existence of, or thought the rail link to be dismantled.

Similarly at these very special crossover places of seismic, high resolution and acoustic data together with core, grab or other sampled information (including video) a better picture of that specific portion of the ocean bottom can be built up. If there are enough, (and obviously the more the better), one's interpretation confidence can under conducive circumstances begin to increase and extrapolative correlations can be attempted to other areas of similar condition or interest. Although this methodology is far from satisfactory and can be dangerously abused it is always worth the effort and again really justifies the value of the expensively acquired datasets.

Part of the NIOZ higher resolution single airgun data acquired as part of ENAM is shown on **Figures 2 – 2c.** This data would be useful to apply the above procedures along with any newly acquired truly high-resolution data.

c) Gravity Core and seabed sampling data.
The BGS Challenger cores require integration into the Study. Concurrently the acoustic, sonar and sampling data acquired during the Logachev surveys of both the western and eastern Rockall margins should also be carefully looked into and expanded upon in the light of the results of this Study.

d) Additional proprietary, BGS or PAD exploration seismic data.
As mentioned in Section 3.0 the study has had access to a vast amount of geophysical data but further investigation into the complete geophysical database including remote sensing could provide more detail to help in areas of poor coverage. Furthermore closer spaced data grids are required in many places to avoid aliasing of structural features and geohazards.

e) Any accessible 3D seismic volume or segment.
A large 3D data volume exists covering the northern part of the NE Rockall slope and upper/?middle slope. A tremendous increase in knowledge of the nature of the seabed, subseabed and geohazards that are known to exist there could be attained by interpretation (and integration with other datasets) of the uppermost few hundred milliseconds of data and enhancing the seabed returns depending upon the data quality. This technique has been used very successfully for example in the Faroese sector to understand quite complex seabed and subseabed conditions with great confidence.

7.1.2 Initiate an age dating campaign (or utilise any existing data) in order to accurately analyze and assess the relationships of the Holocene – Recent seabed with evidence of relict or exhumed seabed surfaces or other erosion/non depositional surfaces. This to be economically targeted on those locations recommended following further detailed interpretation of at least the PIP 2D commercial seismic dataset integrated with at least area-specific TOBI data interpretation i.e. 1) above.

7.1.3 Increase the accuracy of the bathymetry by grid manipulation and merging techniques of seismic TWT picks and or higher frequency data. It is envisaged that industry partner groups and academic institutions supply data or seabed horizon picks to complement the PIP 2D commercial seismic database.

7.1.4 Utilise and build upon the information contained in the UCD high-resolution seismic/shallow drilling site correlations by applying it into the regional stratigraphic framework. This task is essential in order to maximise the value and understanding of this separate piece of work. The timely expert correlation and confident extrapolation of concepts and ideas from the integration of high resolution datasets is fundamental to making progress in the study of the RBA to meet industry needs.

7.1.5 It is particularly important that detailed interpretation and analysis of all or particular geohazards occurs since the region is particularly prone to and so little is known about them. This applies especially to those areas mapped as “poorly understood and requiring further investigation” during this initial Study phase.

Specifically the above applies to the following geohazards:-

a) Slope Canyon and valley systems to derive information pertaining to their development through time and (?cyclic) patterns of fill and scour.
b) Seabed faults, rotational slides and massive slope collapse plus other features associated with mass wasting such as slumps and debris flows.
c) Turbidite and channel levee complexes.
d) Contourite deposits especially their leading/feather edges and significance of solitary or linked patterns of sediment waves including those found in the axes of slope canyons and valleys.
e) Upper slope parallel troughs considered possibly linked to faulting and development of carbonate deposits.
f) Areas of active expulsion of migrating fluids or gas along with less well-defined shallow gas geohazards e.g. those associated with polygonal and linked fault systems.
g) Possible occurrences of gas hydrate accumulations.
h) Carbonate build-ups, reef and pinnacle reef development. Study of apparently similar or related features (in the Porcupine Trough) forms part of the OMARC (Ocean Margins Deepwater Research Consortium) cluster of the EU 5th framework projects, (GEOMOUND and ECOMOUND). The following important questions could be answered fairly soon by more specifically targeted work in one or more of the case study areas. What are the extent of and geotechnical characteristics of the carbonate rocks and sediments? What are the engineering and environmental implications for anchoring and can we define the extents of such deposits more accurately?

7.1.6 More detailed investigation of the regional seismic stratigraphic framework to allow definition of the NE Rockall margin.

The region is an area of concern for the model framework due to the complex nature of the area, (see Data **Example 48)** and possibly strong post Eocene or younger faulting. Because of this it is possible that those that have been mapped may be one, two or even three megasequences out. The region has thus been recognized as an area requiring more investigation on many of the Study maps. Added to this the younger sedimentary units are also complex and poorly understood lying as they do at the southern end of the thick RT-a aged Barra and Donegal Fan systems as mapped in the UK by the BGS. A two pronged approach is envisaged correlating from both the north and the south of the Median line together with the use of older seismic vintage data of which the current database only contains a selection.

7.1.7 Detailed interpretation to assess the geotechnical significance and confirm the age of megasequences along the central and southern parts of the western Rockall margin.

These form the *fundamental* basis of the existing RBA stratigraphic framework, **Data Example 49**, as it now stands but become more problematic south of approximately WRM96-114. The problems may be due to the lack of definition and resolution of the PIP commercial 2D seismic database and the complicated nature of the hanging wall wedge itself.

Here, different phases of erosion as well as potential for facies changes at the lower palaeo break of slope complicate the picture more so than further north. The influence of proto-Feni Ridge as well tends to obscure the picture and direct calibration into the loosely tied well DSDP – 581 would help. The use of the NIOZ seismic data is essential for this test of the basinal stratigraphic framework model from which the whole basin model has been derived.

Incidental to the above, recommendation 7.1.7. would also allow the further important study and investigation of contourite current depositional and erosional features.

7.1.8 Detailed interpretation to assess the geotechnical significance and age of the presumed RT-c / RT-d aged megasequences that are severely truncated by shelfal prograding sequences.

The latter are of unknown age (?RT-b and RT- a) and themselves show strong evidence of rotation and downslope movement, especially at the shelf break, **Data Example 50**. Furthermore their relationship with the shallower carbonate build-ups along the upper slope is unresolved but it would appear that sometimes the carbonates pond the shelfal progrades. This suggestion of relative stratigraphic age relationships is an important observation and the concept needs to be built into the framework to test integrity of the tectono-stratigraphic model.

7.1.9 Detailed interpretation to assess the timing of major slope failure in the past and hence the significance of such activity in terms of the present day stability of the outer shelf and continental slope.

Interfingering with basinal sediments and/or contourites along the downslope and upslope edges of the massive Gullwing/Erris base-of-slope wedge would be good candidates for detailed study, **Data Example 51.** Naturally such interpretation would be even more beneficial if interaction with recommendations **7.1.5b – 5e, 7.1.6, 7.1.7** or **7.1.8** above was ongoing.

7.1.10 Detailed interpretation and application of expertise to provide the navigational detail to allow the best selection of proposed tracks or locations for any further (higher resolution) seismic data, gravity cores, rock drilling, shallow borings or other direct sampling or data acquisition.

It is obviously recommended to acquire further data of various kinds in the future. In order to maximise the benefits of such data collection many of the above recommendations could be seen to be necessary prior to acquisition.

Given the limited season, however, it is essential and good practice to have a good lead-in period of work to allow selected features to be targeted and coordinated effectively. This will ensure such that as far as possible all the questions and objectives requiring to be met and answered by the particular acquisition can be accomplished.

7.1.11 Study the important geological, geotechnical and environmental interactions and implications of the dynamic oceanic current regime as it affects the RBA.

The existence and location of the extensive (and composite through time) slope canyon and valley system has been shown to form a complicated but mappable pattern. It is non-existent, however, in some places and thought to be associated with faulting in others. The system shows evidence of older infill, younger deposition and scour *all* within the same valley group. **Data Example 33** shows exposed bedrock on one line and current formed sediment waves (or possibly sidewall slumps) are seen on an adjacent line. A classic example of a surficial channel levee system has also been identified but we need to understand more to enable to predict with confidence once the processes are understood. There are many, many aspects to be taken into account not least the possibility of density or other current activity running down (or ?up) the canyon …..

7.1.12 Understand the present day ocean current regime through ongoing and detailed discussion with the Metocean Committee.

Fit the locations of current meter strings into the regional Study. Are any located adjacent to scarps, or canyon / valley systems for example? What is known about the Feni Drift now and what made it produce such a thick sediment pile in RT-b times whilst actively eroding elsewhere. What are the constraints that forced the changes – are they related strongly to the regional geology?

7.1.13 Re-evaluate the results of the Geotechnical testing of the samples analyzed under Project 98/?

7.1.14. Confirm the existing geological and stratigraphical framework by site specifically located core campaign and drilling programme.

7.2 Recommended

7.2.1 Evaluate biostratigraphy in 12/13-1A well and confirm the correlation across major fault to assess timing and implications of 1.5 seconds of likely Neogene heave.

7.2.2 Analyze magnetic and other remote sensing data to attempt differentiation of interpreted carbonate build-ups versus regular igneous or basement outcrops. From the results of the Study this can now be done with more confidence and patterns of exposure and growth could be documented as long as the available dataset allows distinction between build-up on sediment substrate as opposed to underlying (protruding) hard rock substrate.

7.3.3 Conduct coring and or shallow drilling programme at carefully selected locations to confirm or sample the geology as interpreted by the Study.

Several areas have been noted for their partial exposure beneath especially thin surficial veneer that make good candidates for calibration. Some areas are steeply dipping fault scarps whilst others lie in the eroded bases of slope canyon/valley systems.

7.3.4 Palinspastic reconstructions of regional lines from the Study to identify the timing of significant tectonic events during the past 10 million years.

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APPENDIX 3 PIP Database used for the Study

A.3 Geophysical Database

A.3.1 2D Seismic Data supplied by Phillips
A.3.2 2D Seismic Data supplied by Shell
A.3.3 PIP/RSG Challenger higher resolution data (BGS)
A.3. TRIM Sonar Data and Interpretations (UCD/DIAS)
A.3.5 GLORIA Sonar Data and Interpretations (part)
A.3.6 Academic Seismic, Acoustic and Sonar Data (Report and CD-ROM)
A.3.7 Gravity and Magnetic Data (part).

A.4 Geological Database

A.4.1 PIP/RSG Shallow Drilling Site Cores (BGS)
A.4.2 BGS Shallow Drilling Cores (part)
A.4.3 Commercial Well 12/13-1A (part)
A.4.4 DSDP Wells (part)
A.4.6 PIP/RSG Seabed Sampling and Cores (BGS)
A.4.7 Academic Sampling and Cores (Report)