# moray offshore renewables ltd

## Environmental Statement

### Technical Appendix 3.4 A - Metocean and Coastal Processes Baseline

**Telford, Stevenson, MacColl Wind Farms and associated Transmission Infrastructure Environmental Statement**

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# Contents

# 1. Introduction

## 1.1 Project Description

ABP Marine Environmental Research Ltd (ABPmer) has undertaken a baseline assessment of physical processes for the proposed Moray Offshore Renewables Ltd (MORL) wind farms and Offshore Transmission Operator (OFTO) cable route. The MORL application site is Zone 1 of The Crown Estate's Round 3 offshore wind development sites in the UK and is located in the Outer Moray Firth, approximately 20 km south-east of the Caithness coast (Figure 1). The zone encompasses an area of 522 km$^2$ but has been divided into two Project Areas, namely the 'Eastern' and 'Western' Development Areas (EDA and WDA respectively). This report considers the physical environmental baseline of the EDA and the transmission infrastructure cable route.

## 1.2 The MORL Wind Farm Application Sites

Three sites, 'Telford', 'Stevenson' and 'MacColl' are separately identified for development within the EDA. A more detailed and complete description of the wind farm site characteristics, including details of all planned infrastructure, is given in the spreadsheets and other spatial data files that comprise the Project Design Statement (PDS) (MORL, 2011a).

The MORL EDA encompasses part of the summit and the eastern flank of Smith Bank, a morphological high point in the Outer Moray Firth measuring, approximately, 35km long from south-west to north-east, 20km wide (295 km$^2$). Water depths across the site range from approximately 35 to 55 m CD (below Chart Datum), with the greatest depths found along the south-eastern margin of the site. Smith Bank, and the MORL Zone, is separated from the Caithness coast by a relatively deep (up to approximately 75 m CD) channel (Figure 1).

The north-western boundary of the MORL EDA is also the boundary to the adjacent Beatrice Offshore Windfarm Ltd (BOWL) proposed wind farm development. The BOWL application site also encompasses part of the summit and the northern flank of Smith Bank.

Figure 1 also illustrates the 'near-field' and 'far-field' boundaries for the present study, also referenced in the associated physical processes scheme impact assessment studies. The near-field boundary includes the array of wind turbines and substructures and its immediate surroundings and is the area in which direct effects to the physical environment are expected to occur during the lifecycle of the development. The far-field boundary broadly delineates the wider area which might also be affected indirectly by the development, e.g. due to the potential disruption of waves, tides or sediment pathways passing through the application site.

## 1.3 The Transmission Infrastructure Cable Route

The baseline metocean conditions along the proposed route of the transmission infrastructure export cable (also shown in Figure 1) are provided in this report in order to inform other related impact assessment studies.

The export cable route corridor extends from the southern edge of the EDA, south-west towards a landfall point at Fraserburgh. In the corridor, water depths are typically 60-80 m in the central part of the Moray Firth, deepening to approximately 150 m to transit the eastern end of the Southern Trench and shoaling then relatively gradually from 50m depth to the landfall. The proposed cable route avoids the deeper parts of the Southern Trench, which has steep slopes and maximum water depths of up to 220 m (Admiralty Chart 115).

The near-field of the export cable route (where direct impacts are most likely to arise) is considered to be limited to a small distance from the actual installed position of the cable (order of metres to tens of metres). The scale of the physical disturbance and therefore the potential for far-field effects is smaller than that posed by the wind farm (order tens to hundreds of metres) and will be contained within the previously published extent of the cable corridor.

# 2. Assessment Methodology

## 2.1 Overview

This assessment of baseline physical processes has been sub-divided into three categories, namely:

- ***Hydrodynamic regime:*** water levels, currents, waves and stratification;
- ***Sediment regime:*** seabed sediment distribution, bedload and suspended load transport; and
- ***Morphodynamic regime:*** form and function of both the coast and offshore, the morphodynamic regime is defined as a response to both the hydrodynamic and sediment regime.

The baseline assessment describes the natural variability of these regimes prior to the construction of the three proposed wind farms and transmission export cable. This provides the reference conditions against which to compare the proposed wind farm enabling, and providing the basis to inform the assessment of the significance of any consequential changes to the baseline.

The baseline environment is not static and will exhibit some degree of natural change with or without the wind farm in place due to naturally occurring cycles and processes. Therefore, when undertaking impact assessments it becomes relevant to place any potential impacts of the MORL EDA in the context of the envelope of change that might occur naturally over the timescale of the development. For example, it is generally anticipated that climate change will result in global scale effects which will be represented at regional scales by the trends in rising mean sea level and increased storminess (Lowe *et al*., 2009).

This baseline assessment of the physical processes has been developed through the analysis and interpretation of data and information from a variety of sources, including a programme of site surveys, pre-existing datasets, available literature sources and output from numerical modelling. These are further detailed in Section 2.7.

The impact assessment of the MORL EDA in relation to physical processes is presented in a separate report (ABPmer, 2012a) but draws upon the conceptual understanding developed here.

## 2.2 Key Guidance Documents

Guidance on the generic requirements, including spatial and temporal scales, for coastal process studies is provided in the following main documents:

- 'Offshore wind farms: guidance note for Environmental Impact Assessment in respect of Food and Environmental Protection Act (FEPA) and Coast Protection Act (CPA) requirements: Version 2' (Department for Environment, Food and Rural Affairs (Defra), Centre for Environment, Fisheries and Aquaculture Science (Cefas) and Department for Transport (DfT), 2004) – in the process of being superseded by;
- 'Guidelines for data acquisition to support marine environmental assessments of offshore renewable energy projects' (Cefas, 2011);
- 'Guidance on Environmental Impact Assessment in Relation to Dredging Applications' (Office of the Deputy Prime Minister, 2001);
- 'Nature Conservation Guidance on Offshore Wind Farm Development' (Defra, 2005);
- 'Marine Renewable Energy and the Natural Heritage: An Overview and Policy Statement' (Scottish Natural Heritage, 2003);
- 'Coastal Process Modelling for Offshore Wind Farm Environmental Impact Assessment' (COWRIE, 2009); and
- 'Consenting, EIA and HRA Guidance for Marine Renewable Energy Deployments in Scotland. Report commissioned for Marine Scotland' (EMEC & Xodus AURORA, 2010).

It is noted that Marine Scotland has commissioned a set of guidance documents to be produced for the marine renewable industry, specifically wave and tidal devices, which include reference to Environmental Impact Assessment (EIA) requirements (EMEC & Xodus AURORA, 2010). It is considered that some elements of the advice offered can be transferred across to the Scottish offshore wind industry, and as such is referenced within this study. ABPmer is currently unaware of any similar guidance from Scottish Environmental Protection Agency (SEPA) and are, therefore, presently assuming that those listed above can be adopted for the present study.

The purpose of the available generic guidance is to provide an overall consistency in approach and methodology to the identification and assessment of potential impacts. Using the recommended approaches, MORL application site specific issues and methodologies have been determined during the EIA scoping and consultation process (Section 2.5).

The interaction of any changes in the tidal, wave and sedimentological regimes may, consequently, result in changes to the morphodynamic regime. It is therefore recommended that the results from these assessments be investigated with regard to the morphological regime, with consideration to, for example, bed form changes.

## 2.3 Spatial Scales

A consideration of the tidal, wave and sedimentological regimes is required over the following spatial scales:

- Near-field (i.e. the area within the immediate vicinity of the turbine grid and along the cable route); and
- Far-field (i.e. the wider coastal environment in which effects of the wind farm could potentially result).

## 2.4 Temporal Scales

There are four main phases of development that require consideration in the physical process part of the EIA. These are:

- Baseline;
- Construction;
- Operation; and
- Decommissioning.

In order to provide the context for the usage of this baseline report, a brief description of each phase is summarised in the following sub-sections. The study of impacts during other phases is the subject of a companion report by ABPmer (2012a).

### 2.4.1 Baseline

The baseline phase considers the ranges and interactions of naturally occurring physical processes both prior to the installation of any wind farm infrastructure and over the lifetime of the development (in the absence of the proposed infrastructure). The baseline study is important as it provides a condition against which the potentially modified physical processes can be compared, throughout the lifecycle of the development. Consideration of any predicted naturally occurring variability in or long-term changes to physical processes within the lifetime of the array due to natural variability (e.g. seasonality, natural cycles or meteorology) and climate change (e.g. sea level rise) will also be included in this phase. Aside from small magnitude / long timescale naturally occurring evolution of the physical environment, the baseline has been/will be present as described on timescales of tens to hundreds of years.

### 2.4.2 Construction

The construction phase will last in the order of 3 to 5 years.

#### Tidal and wave regimes

Impacts upon the hydrodynamic regime, as a consequence of the construction phase, are typically only likely to be associated with the presence of engineering equipment, for example, jack-up barges placed temporarily on site to install, the turbine structures. As such equipment is only likely to be positioned at one specific location at a time for a relatively short duration (of the order of days), the consequential effects upon the hydrodynamic regime is deemed to be small in magnitude and localised in both temporal and spatial extent.

In addition, health and safety regulations are such that it is likely that operations will only be undertaken during relatively benign metocean conditions.

#### Sedimentological regime

It is during the construction phase that the greatest impact upon suspended sediment concentrations and consequential sediment deposition are anticipated. However, this impact is only expected to occur over the short-term (order of days) during the construction period. The effects could be as a consequence of material released during the:

- Installation of the structures; and/or
- Cable laying processes.

### 2.4.3 Operation

The operational phase of the wind farm will be equivalent to the duration of the initial lease period (order 25 years). In total, the Eastern Development Area encompasses an area of 296 $km^2$ within which the wind turbines will be installed. Effects during the operational phase have the potential to be larger in magnitude and in temporal and spatial extent than during other phases.

#### Tidal regime

Potential effects may include changes to the naturally occurring water levels, current speeds and directions.

#### Wave regime

Potential effects may include changes to the naturally occurring wave heights, periods and directions.

#### Sedimentological regime

Effects upon the sediment regime during the operational phase of the modelling may occur due to the effects on the tidal and wave climate as above, potentially manifesting as:

- The alteration of suspended and/or bed load sediment transport pathways within both the near and far-fields;
- Scour around the turbine foundations and/or the cables, with the potential for the eroded material to be transported away from the application site; and
- Changes to longshore transport processes along adjacent coastlines.

### 2.4.4 Decommissioning

Specific details of the decommissioning phase are presently unknown. However, it is expected that at the end of the wind farms lifetime the developer will remove all structures and return the seabed to a usable state, in accordance with Department of Energy and Climate Change decommissioning guidelines (DECC, 2011).

It is assumed that the decommissioning phase will involve the removal and/or burial of any structures related to the wind farm development. Therefore, impacts upon tidal, wave and sedimentological regimes as a consequence of this phase will be comparable to, and no greater than, those identified for the construction phase.

Post-decommissioning, the application site is expected to return to baseline conditions (allowing for some measure of climate change).

## 2.5 Consultation and Scoping of EIA Issues

The EIA Scoping report for the Moray Offshore Wind Farm was first circulated to relevant parties in August 2010; responses were received in late 2010. Following the main wind farm sites scoping exercise, the scope for the assessment of cumulative and in-combination impacts was developed in conjunction with BOWL (Moray Firth Offshore Wind Developers Group, 2011). A separate EIA scoping report was also submitted in relation to the offshore transmission cable (MORL, 2011b). At the end of 2011, MORL released draft Environmental Statement chapters to selected stakeholders for comment.

A number of issues and particular concerns to address in the EIA were raised by in the various scoping responses. Those that are of direct relevance to the assessment of physical processes are presented in Table 1.

**Table 1. Physical process issues and concerns expressed during the EIA consultation and scoping process**

| Physical Process Issue | Consultee | | | |
|---|---|---|---|---|
| | Marine Scotland | SNH/JNCC/RSPB | Historic Scotland | MCA/RYA/Ports and Harbours |
| Tidal (water levels and currents) and wave regime | | Impacts upon the extent, distribution, function or structure of marine and coastal habitats (SACs and SPAs).<br><br>RSPB - especially the East Caithness Cliffs SPA. | | Changes in the set and rate of the tidal stream. Ref MCA guidance MGN371 (MCA, 2008). |

| Physical Process Issue | Consultee | | | |
|---|---|---|---|---|
| | Marine Scotland | SNH/JNCC/RSPB | Historic Scotland | MCA/RYA/Ports and Harbours |
| Sediment dynamics (changes to sediment transport pathways, suspended sediment concentrations and resulting sediment deposition) | | Impacts upon the extent, distribution, function or structure of marine and coastal habitats (SACs and SPAs). | Impacts upon sites of potential archaeological interest | Potential for changes in sediment mobility that might affect navigable water depth. Ref MCA guidance MGN371. |
| Footprint of seabed lost (Footprint of foundations, of scour around foundations and of installation vessels) | | Impacts upon the extent, distribution, function or structure of marine and coastal habitats (SACs and SPAs). | | |
| Cable burial | Concern regarding impacts on local (inc. intertidal mudflat) habitats. However, temporary and localised nature of any effect is acknowledged. | | | MCA - Concerns regarding depth of cable burial. |
| Importance of considering cumulative/in-combination effects | Noted | Noted | | Noted |

Potential concerns regarding the quality of surfing waves on the Moray Firth coastline have also been anticipated, following the guidance provided in a publication by Surfers Against Sewage (2009).

## 2.6 Physical Processes Receptors

Waves and tides are not direct environmental receptors that are inherently sensitive to the presence of the development, but they are both factors that can be affected by the development that control local and regional rates and patterns of sediment erosion, transport and deposition. These rates and patterns directly influence short- and long-term net morphological change on the seabed and at the coast. As such, it is rather the morphological features that are sensitive receptors in the physical processes domain. In this context, Smith Bank (the major morphological feature upon which the proposed development will be located and where any near-field impacts may occur) is considered as the primary near-field physical receptor.

The majority of the physical and ecological receptors identified within the far-field study area are the conservation sites located along the Moray Firth coast (Table 2; Figure 2). An overview of the main characteristics of the Moray Firth coastline is provided in Section 5.4

and summarised in Figure 3. This information has been distilled from more detailed publications on the geomorphology of the Moray Firth coast, in particular *The coastline of Scotland* (Steers, 1973); *The beaches of North East Scotland* (Ritchie *et al*., 1978); *The Beaches of East Sutherland and Easter Ross* (Smith and Mather, 1973) and *The Beaches of Caithness* (Ritchie and Mather, 1970).

The Moray Firth and Caithness areas are noted for the richness of their natural heritage and much of the Caithness coastline is designated under international or national nature conservation orders. Most of the sites are protected on the basis of the habitats they contain; however, several designated areas have been assigned conservation status because of the geological and geomorphological interests they contain, which are maintained by present-day physical processes. Examples include the actively prograding spit at Whiteness Head and the active gravel beach complex at the mouth of the River Spey which are both afforded SSSI (Site of Special Scientific Interest) status. A separately undertaken assessment of impacts of the wind farm will focus upon the potential for significant modification of the naturally occurring processes at these designated sites which could indirectly affect the habitats they support. The further assessment of effects on the biological environment in terms of the faunal and floral populations found within the Firth will be informed by these results (but will be reported elsewhere in the project, separate from the physical processes discussion).

Socio-economic receptors relate primarily to the locations of surf beaches along the Moray Firth coastline. Changes to baseline wave characteristics could potentially be detrimental to the quality or frequency of certain surfing wave conditions. Surf beaches within the Moray Firth region have previously been identified in a report by Surfers Against Sewage (SAS) (2009) and are listed in Table 2.

**Table 2. Physical processes receptors identified within the study area**

| Receptor | Designation | Description |
|---|---|---|
| Smith Bank | (None) | A submerged bathymetric high in the Outer Moray Firth, covered by a veneer of sands and gravels of variable thickness and proportion. |
| Loch of Strathbeg | SPA and Ramsar | Marshes, reedbeds, grassland and dunes |
| Troup, Pennan and Lion's Heads | SPA | Sea-cliffs, occasionally punctuated small sand or shingle beaches |
| The Moray and Nairn Coast | SPA and Ramsar | Intertidal flats, saltmarsh and sand dunes |
| The Inner Moray Firth | SPA and Ramsar | Extensive intertidal flats and smaller areas of saltmarsh. |
| Cromarty Firth | SPA and Ramsar | Extensive intertidal flats and salt marsh |
| The Dornoch Firth | SPA and Ramsar | Large estuary containing extensive sand-flats and mud-flats, backed by saltmarsh and sand dunes |
| The East Caithness Cliffs | SPA | Old Red Sandstone cliffs, generally between 30 to 60 m high, rising to 150 m at Berriedale. |
| The Inner Moray Firth | SAC | (Highly varied) |
| Dornoch Firth | SAC | Extensive areas of mudflats and sandflats. Sub-tidally, the Firth supports rich biogenic reefs |

| Receptor | Designation | Description |
|---|---|---|
| Berriedale and Langwell, Oykel, Morriston and Spey | SACs | (Riverine systems emptying into the Moray Firth) |
| Culbin Bar | SAC | Extensive dunes, vegetated shingle and salt meadows |
| Frontal Systems | (Tidal front) | Vertical stratification front |
| Skirza | (Surf beach) | Sand beach (with particular wave climate). |
| Freswick Bay | (Surf beach) | Sand beach (with particular wave climate). |
| Keiss | (Surf beach) | Sand/ shingle beach (with particular wave climate). |
| Sinclair's Bay | (Surf beach) | Sand/ shingle beach (with particular wave climate). |
| Ackergill | (Surf beach) | Sand/ shingle beach (with particular wave climate). |
| Lossiemouth | (Surf beach) | Sand beach (with particular wave climate). |
| Spey Bay | (Surf beach) | Sand/ shingle beach (with particular wave climate). |
| Cullen | (Surf beach) | Sand/ shingle beach (with particular wave climate). |
| Sunnyside Bay | (Surf beach) | Rocky beach (with particular wave climate). |
| Sandend Bay | (Surf beach) | Sand beach (with particular wave climate). |
| Boyndie Bay | (Surf beach) | Sand/ Shingle beach (with particular wave climate). |
| Banff Beach | (Surf beach) | Sand beach (with particular wave climate). |
| Pennan | (Surf beach) | Rocky beach (with particular wave climate). |
| Widemans | (Surf beach) | Sand/ shingle beach (with particular wave climate). |
| Phingask | (Surf beach) | Sand/ shingle beach (with particular wave climate). |
| West Point | (Surf beach) | Sand/ shingle beach (with particular wave climate). |
| Fraserburgh | (Surf beach) | Sand beach (with particular wave climate). |
| St Combs to Inverallochy | (Surf beach) | Sand beach (with particular wave climate). |

In the accompanying assessment report (ABPmer, 2012a), the above receptors will be addressed specifically when considering the potential impacts of the MORL EDA on the physical environment.

## 2.7 Data Sources

As part of the planning, assessment and development of the proposed MORL EDA, a series of new data collection over the whole Round 3 Zone and offshore transmission cable route and historical data collation exercises have been undertaken. These have yielded a range of comprehensive datasets, including geophysical, benthic and metocean (meteorological and oceanographic) parameters (Table 3 and Table 4). The point-location or spatial coverage of the data collection is shown in Figure 4. Where possible, relevant information and knowledge from these surveys have been incorporated into appropriate sections of this report.

Additional information for the region has also been obtained from other sources to complement that obtained from the geophysical, geotechnical, benthic and metocean surveys described above. This additional data includes:

- British Geological Survey (BGS) 1:250,000 surface sediment maps, used to provide a more regional indication of the seabed material. This has been broadly verified within the application site using the grab samples provided by the benthic survey;
- Modelled data generated by the Met Office European Waters, UK Waters (UKW) and Wave Watch III models providing up to 20 years wind and wave data time-series for the Outer Moray Firth;
- Extreme storm surge predictions from the Proudman Oceanographic laboratory (POL); and
- UKCIP '09 predictions of future changes to the hydrodynamic regime due to climate change.

Further to the additional data sets acquired, a number of key reports have also been used which hold direct relevance to this project. These include, but are not limited to:

- Strategic Environmental Assessment - SEA 2; SEA 5 (Balson *et al*., 2001; Holmes *et al*., 2004);
- JNCC Coastal Directory Series: Regional Report 3 North East Scotland; Cape Wrath to St Cyrus (Barne *et al*., 1996);
- United Kingdom Offshore Regional Reports Series: The Moray Firth (Andrews *et al*., 1990); and
- Sand banks, sand transport and offshore wind farms (Kenyon and Cooper, 2005);

**Table 3. Newly collected data and information sources in the MORL R3 Zone**

| Survey/Study | Date of Survey | Undertaken By | Description |
|---|---|---|---|
| Geophysical Surveys | 1/04/2010 to 21/05/2010 | Osiris | High-resolution swath bathymetric survey<br>Side Scan Sonar survey<br>Sub-bottom seismic profiling survey |
| Benthic Survey | 12-16/10/2010 | Emu | Baseline information on the benthic communities in and adjacent to the proposed wind farm application site has been collected. Approximately 80 grab samples are available from the application site. These samples have been used for particle size analysis (PSA) which provides a good indication of the seabed characteristics throughout the application site. This information has been augmented with grab samples collected from the adjacent (proposed) BOWF as well as available BGS grab sample data |
| | 12-14/10/2011 | CMACS | |
| | 09-10/04/2010 | Partrac | PSA from five additional grab samples within the zone at the locations of the deployed metocean survey equipment. |
| Geotechnical Survey | 2/11/2010 to 14/12/ 2010. | Fugro | 25 geotechnical boreholes including six bumpover boreholes collected from within the MORL EDA |
| Metocean Surveys | 10/02/10 to present (not continuous data) | Partrac | Dataset includes current speed, water levels, wave heights/directions and information on suspended sediment concentrations (OBS data) |

**Table 4. Newly collected data and information sources along the MORL offshore transmission cable route**

| Survey/Study | Date of Survey | Undertaken By | Description |
|---|---|---|---|
| Geophysical Surveys | Mid 2011 | Gardline | High-resolution swath bathymetric survey<br>Side Scan Sonar survey<br>Sub-bottom seismic profiling survey |
| Benthic Survey | August 2011 | Emu | Baseline information on the benthic communities along the cable route has been collected. Seabed sampling was attempted at 20 locations, however, as a result of the presence of hard and /or coarse substrate, only 12 samples were successfully recovered. These samples have been used for particle size analysis (PSA) which provides some indication of the seabed characteristics at specific locations along the cable route. This information has been augmented with available BGS grab sample data |

## 2.8 Modelling

Simulations of the physical process conditions acting across the study area have been undertaken using best practice numerical modelling approaches. More details of the models used, including details of their setup, calibration and validation may be found in ABPmer (2012b). These models have also been used to establish the baseline and will be used to determine the scale of the likely effects of potential development phases (construction; operational; decommissioning) upon the existing physical processes. The numerical modelling domains include both the far and near-field as previously discussed.

The Danish Hydraulics Institute (DHI) MIKE21 suite of numerical models has been used to create a tidal model and a wave model of the Moray Firth and surrounding area for the purposes of this baseline assessment.

The procedure for model calibration/validation is based on the need to demonstrate that each of the models is 'fit-for-purpose' for the range of scenario tests required. For example, the tidal model has been calibrated and validated over a range of tidal conditions, including mean neap and spring ranges. Likewise, the wave model has been calibrated and validated in its ability to reproduce a range of wave event types and intensities. Predicted values from the models are shown to compare closely to the target measured data (i.e. water levels, current speeds and directions, wave heights, periods and directions).

Model performance in representing the baseline conditions is considered to be very good with the model reproducing the correct tidal and wave processes with regards magnitude, direction and phase. The models are therefore considered fit for the purposes of the present study, informing the baseline understanding of physical processes across the study area.

# 3. Hydrodynamic Regime

## 3.1 Overview

The hydrodynamic regime encompasses the range of processes that together describe the physical marine environment in and around the application site, namely:

- Water levels;
- Currents;
- Winds (as a driving force for waves);
- Waves; and
- Stratification.

These parameters are described in more detail in the following sub-sections. This information has subsequently been used to develop a conceptual understanding of the sedimentary and morphological regimes at the application site (see Sections 4 and 5).

## 3.2 Water Levels

Marine water level measurements typically contain both a predictable astronomical tidal signal (that caused by the sun and moon) and a more random non-tidal signal, typically related to meteorological influences and referred to as the 'tidal residual'.

### 3.2.1 Sources of Water Level Data

Multiple sources of water level data are available from within the application site and adjacent region. These datasets are listed in Table 5 and their locations are shown in Figure 4.

**Table 5. Sources of water level data**

| Data Source | Latitude (°N) | Longitude (°E) | Period Analysed | Duration |
|---|---|---|---|---|
| AWACs in the MORL R3 Zone | 58.248 | -2.746 | Jul/10 to Dec/10 | 100 days |
| | 58.140 | -2.695 | Oct/10 to Feb/11 | 106 days |
| | 58.036 | -3.152 | Jul/10 to Jan/11 | 124 days |
| | 58.167 | -2.900 | Jul/10 to Feb/11 | 103 days |
| Wick tide gauge | 58.441 | -3.086 | 1965 to present | ~ 45 years |
| Admiralty Tide Tables (Wick) | 58.441 | -3.086 | N/A | N/A |
| NOC CSM Surge Statistics Location 1 | 58.167 | -3.250 | N/A | N/A |
| NOC CSM Surge Statistics Location 2 | 58.167 | -2.750 | N/A | N/A |
| Published Storm Surge Statistics (Flather, 1987; Dixon and Tawn 1997) | N/A | N/A | N/A | N/A |
| Admiralty tidal co-range chart | Variable | Variable | N/A | N/A |
| Numerical tidal model | Variable | Variable | Variable | Variable |

The astronomical tide is harmonic and periodic, i.e. in this context the tide is repeatable and predictable, as described by the summation of a number of harmonic components of differing amplitude and phase, and exhibits cycles on a variety of timescales including:

- Semi-diurnal - a complete tidal cycle (including one high and one low water) occurs approximately twice every day in the Moray Firth;
- Spring-neap - the semi-diurnal tidal range varies smoothly between a relatively larger (spring) and relatively smaller (neap) range over an approximately 14 day cycle;
- Solstice-equinox - the relative size of spring and neap ranges vary during the year. The largest spring and smallest neap tidal ranges occur in March and October, around the solar equinox, whilst the difference in range between springs and neaps is least in December and June, around the solar solstice;
- Inter-annual - spring-neap and solstice-equinox cycles vary from year to year due to the progressively different relative positions of the sun and the moon in their orbits relative to the earth; and
- Metonic cycle - the relative positions of the sun and the moon (and the above patterns) nearly repeat on an approximately 18.6 year cycle.

## Wick tide gauge

The nearest permanent tide gauge to the application site is located at Wick (Figure 4). Astronomical tidal water level statistics for Wick have been referenced from Admiralty Tide Tables (2011) and are presented in Table 6. On this basis, Wick is characterised as a meso-tidal regime (maximum or typical tidal range between 2 and 4m), with a mean spring tidal range of 2.8 m and a maximum normal tidal range of 4 m.

**Table 6. Astronomical tidal water level statistics**

| Water Level Statistic | | Level (m CD Wick) | | |
|---|---|---|---|---|
| | | Wick Tide Gauge | Fraserburgh Secondary Port | MORL EDA* |
| Highest Astronomical Tide | HAT | 4.0 | - | 4.1 |
| Mean High water of Spring Tides | MHWS | 3.5 | 4.3 | 3.6 |
| Mean High Water of Neap Tides | MHWN | 2.8 | 3.4 | 2.9 |
| Mean Sea Level | MSL | 2.1 | - | 2.2 |
| Mean Low Water of Neap Tides | MLWN | 1.4 | 1.6 | 1.5 |
| Mean Low water of Spring Tides | MLWS | 0.7 | 0.6 | 0.7 |
| Lowest Astronomical Tide | LAT | 0.1 | - | 0.1 |
| Mean Spring Range | MHWS to MLWS | 2.8 (m range) | 3.7 (m range) | 2.9 (m range) |
| Mean Neap Range | MHWN to MLWN | 1.4 (m range) | 1.8 (m range) | 1.5 (m range) |
| * Inferred from the Wick tide gauge statistics on the basis of a + 3.5% observed difference in tidal range between the two locations over the metocean survey period, rounded to 1 decimal place. | | | | |

### MORL AWAC deployments

Approximately three months of water level measurements have also been collected by Partrac (2011) on behalf of MORL at each of four locations within and nearby to the MORL EDA (Figure 4). A subset of these data, including one neap-spring-neap cycle, is compared directly in Figure 5. The Figure shows that there is only a small (~0.1 m) difference in spring tidal range over the length of the application site, with the largest tidal range experienced at the south-western end. This is in agreement with the trend of increasing tidal range into the Moray Firth indicated by Admiralty Tide Table publications and by Admiralty tidal co-range charts.

A comparison between the Wick tide gauge record and the water level data collected at the application site (Figure 5) shows that both tidal ranges are similar, however, the tidal range at any given time at the application site will be slightly (approximately 3.5%) larger than the corresponding tide at Wick but with no meaningful difference in phase. On this basis the key water level statistics at the application site are provided in Table 6.

### Fraserburgh secondary port

Tidal information for the secondary port of Fraserburgh is also presented in Table 6 and provides water level information in the vicinity of the cable landfall. (The next nearest standard port to the cable land fall is Aberdeen, approximately ~50 km further south). At Fraserburgh, the mean spring range is 3.7 m, indicating variation in tidal range across the Outer Moray Firth and therefore along the cable route, with the highest water levels experienced on the southern coastline, at the landward end of the cable route. Data from secondary ports is not as robust as that from primary ports; however, the difference in values is sufficiently large to be confident when interpreting the general trend and magnitude of the difference.

### 3.2.3 Non-Tidal Influences on Water Level

In addition to the astronomical tide, water levels may be influenced by meteorology. For example, higher than average atmospheric pressure causes the water level to be relatively depressed (negative surge) whilst low pressure causes water levels to be relatively elevated (positive surge). Either effect can be enhanced or reduced by the additional effect of winds if sufficiently strong and persistent enough, depending upon the direction, location and timing. Moving low pressure systems and associated strong and persistent wind fields may generate a strong positive surge, often referred to as a 'storm surge'. The difference between the predicted astronomical tidal water level and that actually observed is termed the tidal residual.

In general, even large storm surges are reported to be of relatively small amplitude (approximately 1 to 1.25 m) at the location of the application site in the Moray Firth, becoming smaller with distance into the Firth. This situation in the Moray Firth contrasts with larger values observed elsewhere, e.g. in the southern North Sea where positive storm surges can be between 2 to 3 m (e.g. HSE, 2002). This difference can largely be explained by the configuration and orientation of the two water bodies, including their relative positions within the North Sea basin.

## National Oceanographic Centre modelled surge statistics

A study of tidal surge water levels and currents was undertaken by the National Oceanography Centre (NOC, originally known as the Institute of Ocean Sciences, (IOS), and more recently as the Proudman Oceanographic Laboratory, (POL)). The results of the study have been requested as a bespoke report to ABPmer (NOC, 2010), to provide return period information as required for the present study (Table 7). Estimates of surge water level residuals are derived from differencing the results of two numerical model simulations, one of the astronomical tide alone and another of tide and surge combined over a 40 year period (1955 to 1994). The ten most significant positive surge levels in each year were extracted and statistical extremes analysis was then applied.

**Table 7. Extreme positive surge level estimates hindcast by the POL CSX continental shelf model for the 40-year period 1955 to 1994**

| Return Period (years) | Location 1: 58.167° N; 3.250° W | | Location 2: 58.167° N; 2.750° W | |
|---|---|---|---|---|
| | Positive Surge Height (m) | Surge Height Error (±m) | Positive Surge Height (m) | Surge Height Error (±m) |
| 2 | 0.83 | 0.02 | 0.82 | 0.02 |
| 5 | 0.94 | 0.02 | 0.93 | 0.02 |
| 10 | 1.01 | 0.03 | 1.00 | 0.03 |
| 20 | 1.07 | 0.04 | 1.06 | 0.04 |
| 50 | 1.13 | 0.05 | 1.12 | 0.05 |
| 100 | 1.17 | 0.06 | 1.16 | 0.06 |

## Published storm surge statistics

Estimates for 50-year return period positive storm surge elevations for this region are also available from Flather (1987). For the Outer Moray Firth, these are found to be in the range 1 to 1.25 m (±0.05m), increasing in magnitude from east to west. These values are consistent with the NOC (2010) analyses. The findings of both NOC (2010) and Flather (1987) are also consistent with those of Dixon and Tawn (1997) who undertook a detailed study of tidal gauge data for the purposes of characterising the spatial coherence of surge water levels around the UK.

None of the reports include information regarding the phasing of surges relative to high water periods. Comparison with extreme total still water levels from the same data sources at equivalent return periods indicates that surges do not necessarily coincide with high water periods but it is not known if there is a consistent pattern of tide-surge interaction.

## Future changes to the baseline

Mean sea level at the application site is likely to alter over the initial lease period of the wind farm (which is expected to be 25 years). This change is generally accepted to include contributions from global eustatic changes in mean sea level and also as a result of regionally varying vertical (isostatic) adjustments of the land.

Information on the rate and magnitude of anticipated relative sea level change in the Moray Firth during the 21st Century is available from the UKCIP (United Kingdom Climate Change Impact Programme, http://www.ukcip.org.uk/). Summary predictions of 21st Century changes in relative sea level at the closest reported location to the application site (Bruan, shown in Figure 1) are presented in Table 8. These findings suggest that by 2050, relative sea level in the application site and surrounding area will have risen between 0.22 and 0.35 m above 1990 levels. As shown by the rate of increase in values in the table, the majority of predicted sea level rise occurs during the second half of the 21st Century when the rate of change is predicted to be greatest. It should be noted that such an increase in mean water level is significantly smaller than the tidal and non-tidal water level variations presently experienced at the application site.

**Table 8. Summary statistics of 21st Century sea level rise at Bruan (Caithness Coast), relative to 1990 levels**

| Year | Relative Sea Level Rise Based On Low Emissions Scenario (m) | Relative Sea Level Rise Based On Medium Emissions Scenario (m) | Relative Sea Level Rise Based On High Emissions Scenario (m) |
|---|---|---|---|
| 1990 | 0.00 | 0.00 | 0.00 |
| 2000 | 0.03 | 0.04 | 0.04 |
| 2010 | 0.06 | 0.07 | 0.09 |
| 2020 | 0.09 | 0.12 | 0.15 |
| 2050 | 0.22 | 0.28 | 0.35 |
| 2100 | 0.49 | 0.63 | 0.79 |

The UKCIP also includes projections of changes to storm surge magnitude in the future as a result of climate change (Lowe *et al.*, 2009). For a 'medium emissions' scenario, the 1 in 50-year storm surge event will increase by between 0.08 and 0.36 mm/yr (values apply until 2099), which is approximately equivalent to adding 2 to 9 mm to the values in Table 7 over a nominal 25 year lifetime for the wind farm. The resulting effect is evidently small in comparison to natural variability and would not constitute a measurable change.

## 3.3 Currents

At the regional scale, the tidal streams present in the Moray Firth are relatively complex and variable in direction (Adams and Martin, 1986). The main tidal wave in the open water of the North Sea approaches from the north and progresses south; essentially only the edge of the tidal wave is diverted into the Moray Firth, leading to the observed complexity. Owing to the less restricted passage of the tidal wave across the Outer Firth, tidal currents are stronger here than inshore, where flows are more topographically constrained (Adams and Martin 1986).

In addition to astronomically driven tidal currents, meteorological forcing may also cause an increase in locally observed current speeds. Of particular note in the Moray Firth are (i) currents associated with storm surges; and (ii) orbital currents associated with the passage of waves, both of which have the potential capacity to stir the seabed.

### 3.3.1 Sources of Current Data

Current (flow) data for the application site and surrounding area are available from several sources. These datasets are listed in approximate order of the confidence afforded to them in Table 9 and their locations are shown in Figure 4.

**Table 9. Sources of current flow data**

| Data Source | | Latitude (°N) | Longitude (°E) | Period Analysed | Duration |
|---|---|---|---|---|---|
| AWACs in the MORL R3 Zone | | 58.248 | -2.746 | Jul/10 to Dec/10 | 100 days |
| | | 58.140 | -2.695 | Oct/10 to Feb/11 | 106 days |
| | | 58.036 | -3.152 | Jul/10 to Jan/11 | 124 days |
| | | 58.167 | -2.900 | Jul/10 to Feb/11 | 103 days |
| AWACs in the BOWL application site | | 58.179 | -2.950 | 10/02/2011-10/03/2011 | (29 days) |
| | | 58.297 | -2.775 | | |
| BODC Data Archive | B0014185 | 58.400 | -2.617 | 04/11/74 to 08/12/74 | (34 days) |
| | B0049799 | 58.25 | -3.00 | 04/07/82 to 13/07/82 | (9 days) |
| | B0020756 | 58.194 | -3.001 | 28/04/81 to 20/06/81 | (53 days) |
| | B0029252 | 58.106 | -3.095 | 27/05/78 to 28/06/78 | (32 days) |
| Numerical tidal model | | Variable | Variable | Variable | Variable |
| NOC CSM Surge Statistics Location 1 | | 58.167 | -3.250 | N/A | N/A |
| NOC CSM Surge Statistics Location 2 | | 58.167 | -2.750 | N/A | N/A |
| TotalTide (UKHO tidal diamonds) | | 58.375 | -2.642 | N/A (Representative spring and neap tidal cycle) | N/A |
| | | 58.283 | -2.625 | | |
| | | 58.167 | -3.100 | | |

### 3.3.2 Astronomical Tidal Currents

#### Numerical tidal model

A numerical tidal model has been created for use in the present study. The design of the model and its inputs, together with a more detailed description of the accuracy and limitations of the model are available in a separate report (ABPmer, 2012b). The model was calibrated using the discrete observed data sets described in the following sub-sections and so model outputs are in close agreement with the measured data (within the levels of confidence established during model validation). As a result, the model provides a coherent and continuous source of quantitative astronomical tidal water level and depth mean current data over a large area, encompassing both the near-field and potential far-field extent of any effects of the wind farm.

Tidal current predictions from the tidal model have been plotted to show both the near-field (Figure 6) and regional (far-field, Figure 7) patterns of peak flood and peak ebb currents during spring and neap tides. The Figures show that;

- In the far-field, the highest current speeds are observed to the north of the application site associated with exchange through the Pentland Firth, and to the south-east of the application site off the Fraserburgh - Peterhead coast;

- Elsewhere in the Outer Moray Firth, peak current speeds are generally less than 0.3 to 0.4 m/s on spring tides and approximately half the corresponding value on neap tides;
- Generally, peak current speeds decrease in magnitude from the Outer to the Inner Moray Firth, except in narrow tidal inlets where flow speed may be locally increased;
- Within the EDA, peak current speeds are typically between 0.5 to 0.6 m/s on mean spring tides and 0.25 to 0.3 m/s on mean neap tides. This is higher than is generally observed in the Moray Firth as the site is located at the edge of the zone of effect of the Pentland Firth which enhances both flood and ebb tidal current speeds;
- Current speeds within and around the application site are relatively higher in the quoted range closer to the Pentland Firth and in deeper water, i.e. to the northern end of the site, in locations off the crest of Smith Bank and especially in the deep water channel further to the north-west;
- Within the application site, tidal currents are directed generally to the south or south-south-west during the flood tide and to the north or north-north-east during the ebb tide;
- There is little consistent asymmetry between flood and ebb in tidal current speeds and directions; and
- Along most of the cable route, mean spring peak current speeds are typically less than ~0.4 m/s. However, current speeds are markedly increased in an area from Kinnairds Head (at the landfall) south east to beyond Rattray Head. Here, peak spring tidal currents speed are more typically 1.0m/s (maximum 1.15 m/s) up to 10km from the coastline due to acceleration around the headland.

### MORL AWAC deployments

Current profile time series data collected during the metocean survey is summarised in Figure 8 and Figure 9. The data are in agreement with the numerical model outputs previously described and in particular confirm that:

- The highest current speeds are encountered in the north of the EDA, reaching a peak depth mean speed of ~ 0.6 m/s during mean spring tides;
- During spring tides, peak current speeds in the south of the EDA are ~ 0.5 m/s;
- During neap tides, peak current speeds at all locations in the application site are typically half of that observed on spring tides, i.e. between 0.25 and 0.3 m/s;
- Flow speeds decrease in magnitude from the Outer to the Inner Moray Firth, with peak depth mean speeds of ~0.35 m/s encountered at the western margin of the WDA during mean spring tides; and
- The expected vertical profile in current speed for open water un-stratified flows is apparent at both AWAC deployment locations, i.e. exhibiting a decrease in current speed towards the bed.

### BODC data archive

A number of additional single point current meter data sets from locations in the Outer Moray Firth are also available from the British Oceanographic Data Centre (BODC) archive. These provide some additional information on tidal flows across the far-field region. The locations of data holdings in proximity to the application site are shown in Figure 4. The information from these observational records has been summarised in a series of (depth-averaged) current roses (Figure 8). These show that the strongest currents are found to the north of the application site where they reach a maximum velocity of ~0.7 m/s (B0014185). The weakest currents are observed in the south-west of the application site where maximum velocities do not exceed ~0.3 m/s (B0029252). This north-south variation is consistent with the findings of the Moray AWAC deployments and the numerical model outputs previously described. The main axes for tidal flow vary across the far-field study area, principally as a result of the way in which the tidal wave interacts with the Moray Firth at the regional scale.

### UKHO tidal data

Tidal stream tables are available on UKHO Chart 115: Moray Firth, including various locations within the Firth for the purposes of assisting navigation. These, and additional similar data sets, can also be accessed using the UKHO 'Total Tide' software package. Because of the relatively simplistic data collection methods traditionally used, such data can only be assumed to provide an indicative rate and direction of surface flow for a representative spring or neap tide. Four tidal diamonds are in relatively close proximity to the application site (Figure 4). The variation of flow at these locations through a tidal cycle is summarised in Table 10. These values are in good general agreement with the current data obtained from the numerical tidal model and that collected during the metocean survey (Figure 8).

**Table 10. Summary of tidal stream data from Admiralty Chart 115**

| Hours | | Tidal Diamond M | | | Tidal Diamond N | | | Tidal Diamond F | | | Tidal Diamond G | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 58°22.50'N, 2°38.50'W | | | 58°17.00'N, 2°37.50'W | | | 58°10.00'N, 3°06.00'W | | | 58°00.20'N, 3°02.00'W | | |
| | | Direction °N | Spring (m/s) | Neaps (m/s) | Direction °N | Spring (m/s) | Neaps (m/s) | Direction °N | Spring (m/s) | Neaps (m/s) | Direction °N | Spring (m/s) | Neaps (m/s) |
| After HW | -6 | 115° | 0.21 | 0.10 | 094° | 0.10 | 0.05 | 253° | 0.26 | 0.15 | 229° | 0.10 | 0.05 |
| | -5 | 148° | 0.31 | 0.15 | 143° | 0.26 | 0.10 | 257° | 0.26 | 0.15 | 215° | 0.15 | 0.10 |
| | -4 | 161° | 0.36 | 0.21 | 156° | 0.46 | 0.21 | 253° | 0.21 | 0.10 | 203° | 0.15 | 0.10 |
| | -3 | 174° | 0.41 | 0.21 | 165° | 0.57 | 0.26 | 264° | 0.15 | 0.05 | 192° | 0.15 | 0.10 |
| | -2 | 185° | 0.36 | 0.21 | 178° | 0.62 | 0.31 | 230° | 0.05 | 0.00 | 185° | 0.10 | 0.05 |
| | -1 | 210° | 0.21 | 0.10 | 179° | 0.26 | 0.10 | 118° | 0.10 | 0.05 | 173° | 0.05 | 0.00 |
| HW | 0 | 298° | 0.15 | 0.10 | 227° | 0.05 | 0.00 | 082° | 0.21 | 0.10 | 042° | 0.10 | 0.05 |
| After HW | 1 | 342° | 0.26 | 0.10 | 334° | 0.26 | 0.10 | 072° | 0.21 | 0.10 | 041° | 0.21 | 0.10 |
| | 2 | 347° | 0.31 | 0.15 | 338° | 0.46 | 0.21 | 074° | 0.21 | 0.10 | 024° | 0.21 | 0.10 |
| | 3 | 345° | 0.31 | 0.15 | 341° | 0.62 | 0.31 | 071° | 0.21 | 0.10 | 013° | 0.15 | 0.05 |
| | 4 | 343° | 0.36 | 0.21 | 347° | 0.51 | 0.26 | 067° | 0.10 | 0.05 | 004° | 0.10 | 0.05 |
| | 5 | 353° | 0.26 | 0.15 | 359° | 0.31 | 0.15 | 253° | 0.15 | 0.05 | 290° | 0.05 | 0.00 |
| | 6 | 090° | 0.15 | 0.05 | 055° | 0.10 | 0.05 | 252° | 0.26 | 0.10 | 235° | 0.10 | 0.05 |
| Maximum | | | 0.41 | 0.21 | | 0.62 | 0.31 | | 0.26 | 0.15 | | 0.21 | 0.1 |

### 3.3.3 Non-tidal Influences

In addition to modifying water levels, storm surges may also modify the locally observed current speed from that expected from astronomical forcing alone. Because they are induced by meteorological forcing, surge currents are not directly related to the modified tidal range or the rate of water level change during the surge event. In addition to storm surges, individual storm waves can generate significant oscillatory currents through the water column and at the seabed.

#### National Oceanographic Centre modelled surge statistics

Directional 50-year return period surge currents were obtained directly from the NOC (2010) study report. Values for each of 24 times 15° directional sectors were obtained for Locations 1 and 2 (Figure 4, Figure 8, Figure 9, Figure 10). Estimates for the maximum depth-mean currents associated with a 50-year return period storm surge are 0.23 m/s and 0.75 m/s for Locations 1 and 2 respectively, i.e. decreasing rapidly with distance into the Moray Firth along the length and axis of the MORL R3 Zone. The large difference between these values over such a short distance does also lead to the conclusion that values may vary greatly within the site and that the accuracy of the predicted surge statistics may be sensitive to uncertainty. At Location 1, the strongest surge-induced currents are to the south-west whilst at Location 2, the strongest currents are to the south. These estimates are in broad agreement with the modelling analyses of Flather (1987) who suggests depth averaged surge currents over 50 years across the application site are approximately 0.60 to 0.90 m/s. Currents of this magnitude exceed the peak astronomical tidal flows commonly observed across the application site (Section 3.3.2), although storm surge currents of this magnitude are experienced only infrequently.

The predicted surge current speeds are markedly reduced with distance into the Moray Firth and the orientation of the peak surge current also varies between offshore and coastally constrained areas; generally, the strongest surge currents are directed into the Firth.

Estimates of 'total' current speed are also available from NOC (2010). These estimates take into account surge currents associated with a 1 in 50-year return period storm surge, combined with the mean spring astronomical tidal current contribution. Estimates of total current speed are 0.39 m/s and 1.17 m/s for Locations 1 and 2 respectively. (This information is considered further in the context of sediment transport at the application site (Section 4.6).

#### Wave induced orbital currents

Individual waves induce circular or elliptical movements through the water column. If this motion extends to the seabed, an oscillatory near-bed current will result. Wave induced currents oscillate at wave-period time-scales (order of seconds), typically with a symmetrical near-sinusoidal pattern unless in particularly shallow water. The amplitude of these oscillatory currents can be estimated as a function of wave height, period and the local water depth (Dean and Dalrymple, 1991) and are estimated in Table 11 for a series of extreme wave events at four nominal locations and water depths in the application site (Table 11; Figure 4. The return period wave conditions were obtained from analysis of a long hindcast data from

UK Met Office meteorological models (see Section 3.5 for further details).

**Table 11. Maximum orbital current velocities (m/s) at the seabed associated with a series of low frequency, high magnitude storm events**

| | Return Period (years) | | | |
|---|---|---|---|---|
| | 1 | 10 | 50 | 100 |
| Significant Wave Height Hs( m) | 6.7 | 8 | 8.9 | 9.2 |
| Zero Crossing Wave Period Tz (s) | 11.0 | 11.8 | 12.2 | 12.4 |
| Orbital Velocity Amplitude (m/s) (MORL AWAC 5c; ~36 m CD) | 0.96 | 1.24 | 1.43 | 1.50 |
| Orbital Velocity Amplitude (m/s) (MORL AWAC 2c; ~39 m CD) | 0.88 | 1.14 | 1.31 | 1.38 |
| Orbital Velocity Amplitude (m/s) (MORL Wave Buoy; ~49m CD) | 0.65 | 0.88 | 1.02 | 1.08 |

From Table 11 it is apparent that the highest nearbed orbital current amplitudes will be found in the shallowest parts of the application site. These are encountered along the western margin of the EDA and shallow to approximately 35 m CD. Here, current velocities are close to 1 m/s for a 1 in 1-year return period storm event and reach 1.5 m/s for a 1 in 100-year event. Orbital current speeds of this magnitude are considerably greater than observed peak spring tidal flow speeds (Section 3.3.2). The implications of these findings for sediment mobility across the application site are discussed further in Section 4.6.

## 3.4 Winds

Although not part of the hydrodynamic regime, the wind regime is relevant to the generation of local wind waves and/or larger swell waves, depending upon the direction and strength of the forcing. The relationship between wave generation and meteorological forcing means that the wind and wave regimes are similarly episodic and exhibit both seasonal and inter-annual variation in proportion with the frequency and magnitude of changes in wind strength and direction.

### 3.4.1 Sources of Wind Data

Several wind datasets are available from different locations within the Moray Firth (Table 12 and shown in Figure 4).

**Table 12. Sources of wind data in the Moray Firth**

| Data Source | Latitude (°N) | Longitude (°W) | Period Analysed | Duration |
|---|---|---|---|---|
| Wick Airport anemometer | 58.46 | 003.09 | Jan 1996 to present | ~ 14 years |
| Lossiemouth anemometer | 57.72 | 003.32 | 1976 to 1988 | ~ 12 years |
| Beatrice Alpha Oil Platform | 58.12 | 003.09 | 02/1990 to 01/1991 | ~ 1 year |
| Met Office UKW Archive | 58.17 | 002.75 | Mar 2000 to Nov 2008 | 8 years, 8 months |
| Met Office WW3 Archive (modelled data) | 58.11 | 002.83 | Nov 2008 to present | ~ 2 years |
| Met Office European Waters Archive (modelled data) | 58.3 | 002.9 | Nov 1988 to Nov 2008 | ~ 20 years |

Measured wind data are typically obtained at around 20 m above ground or sea level. The Met Office winds are reported at the same height.

### Wick Airport record

Wick Airport is located on the Wick Peninsula and has maintained an anemometer as part of an operational weather station since 1983 (Figure 4). A subset of the data including the most recent 14 years was obtained for this investigation and is summarised in Figure 11. Although these data do provide a uniquely long-term measured data set from a location near to the application site, no detailed record of the anemometer mounting position, servicing or other issues potentially affecting the accuracy of the data could be obtained. It is therefore possible that these data may contain some land bias or other anomalies due to sheltering from certain wind directions or diurnal heating/cooling effects on the land.

Frequency analysis of the Wick Airport wind data shows that the most frequent wind directions are from the west (247.5 to 292.5 ˚N), accounting for almost 20% of the record, and from the south (157.5 to 202.5 ˚N) and south-east (112.5 to 157.5 ˚N), together accounting for around 35% of the total record. Over 70% of the record contains wind speeds in the range 2 to 8 m/s and observed wind speeds only infrequently (<1% of time) exceed 16 m/s.

### Lossiemouth record

Babtie Dobbie Ltd (1994) provides a summary of wind data collected at Lossiemouth Airport (see Figure 4) in the period 1976 to 1988. The Lossiemouth wind rose (shown in Figure 12) is broadly similar to that for Wick, with winds coming most frequently from the west, the south and the south-east, and least frequently from northerly through easterly sectors.

### Beatrice Alpha oil platform

Comber (1993) summarises a relatively short measured wind record from the Beatrice Alpha oil platform, which is located near to the application site in the Outer Moray Firth (Figure 4). In the period February 1990 to January 1991, winds are reported to have most frequently come from south-west through westerly sectors (210 to 280 ˚N) and only infrequently from all other directions.

### Met Office modelled data

Modelled wind data were obtained from the Met Office as part of the UK Waters (UKW), European Waters (EW) and Wave Watch III (WW3) wave model data obtained for the present study (Figure 4). A comparison between the Met Office modelled wind data and the Wick Airport wind record has been undertaken by ABPmer (2010). Although the records are found to be broadly similar, the Wick Airport anemometer consistently reports a lower wind speed than the coincident UKW model data. The differences between the measured and modelled data can potentially be explained by the distance between Wick Airport and the application site, the differential exposure of an onshore and offshore location, and the unknown positioning or shielding of the Wick Airport anemometer itself.

A frequency analysis has been undertaken on the Met Office wind data and extreme return period statistics are presented in Table 13.

**Table 13. Extreme return period wind speeds (m/s) and associated directional sectors in the application site**

| | Wind Speed* m/s | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Return Period (years) | North 337.5 to 022.5˚ N | NE 022.5 to 067.5˚ N | E 067.5 to 112.5˚ N | SE 112.5 to 157.5˚ N | S 157.5 to 202.5˚ N | SW 202.5 to 247.5˚ N | W 247.5 to 292.5˚ N | NW 292.5 to 337.5˚ N |
| 1 | 23.51 | 18.68 | 19.01 | 22.67 | 22.38 | 23.36 | 24.03 | 23.17 |
| 10 | 27.31 | 22.10 | 22.47 | 25.70 | 25.50 | 26.39 | 27.60 | 26.60 |
| 50 | 29.70 | 24.24 | 24.65 | 27.59 | 27.45 | 28.28 | 29.83 | 28.73 |
| 100 | 30.68 | 25.11 | 25.53 | 28.36 | 28.24 | 29.05 | 30.74 | 29.60 |
| * | Based on Met Office model data provided with UK Waters & Wave Watch III wave model data. | | | | | | | |

## 3.5 Waves

In an area such as the Moray Firth, which is generally characterised by low tidal current energy, winds and waves are critical energy inputs to the coastal system (Reid and McManus, 1987). The wave regime is defined here as the combination of locally generated wind waves and swell waves:

- Wind waves result from the local transfer of wind energy to the water surface. The amount of wind energy transfer and wind-wave development is a function of the available fetch (distance of open water across which the wind blows), the wind speed, the wind duration and the original state of the sea. The longer the fetch distance, the stronger the wind and the greater the duration of the wind, the greater the potential there is for the wind to interact with the water surface and generate larger waves. In sufficiently shallow water, depth may become a limiting factor on the further growth of waves. Once further wind input ceases, small wind waves will be dissipated without travelling significant distances.

- Swell waves are long-crested, uniformly symmetrical waves, originally wind waves created by a significant storm event outside of the Moray Firth or even outside of the North Sea. Swell waves are different from wind waves as they continue to efficiently propagate over long distances in the absence of any further wind energy input. The longest open fetches over which swell waves can be generated and enter the Moray Firth are approximately 500 to 850 km, from north-north-easterly through south-easterly directions (22 to135° N).

Large waves associated with storms occurring several times per year have the potential to cause water movement at the seabed within the application site. Wave action at the coastline typically has a controlling influence on erosion processes and littoral drift rates at the coast. The rates and directions of these processes are influenced by both the height and direction of the waves reaching the coast. (Sediment transport and littoral drift are considered further in Sections 4.5 and 5.4).

The observed and modelled wave data are presented and discussed in the following sections.

### 3.5.1 Sources of Wave Data

Wave data for the study area are summarised in Table 14. It is important to note that the data sources available are of varying quality and duration. The highest quality datasets are the local observational wave records, e.g. those from the metocean survey deployments and from the WaveNet Moray Firth wave buoy. However, with the exception of the Moray Firth wave buoy record, the metocean survey wave records are only relatively short-term (less than 12 months) duration and so do not reliably reflect the longer term (> 3-5 years return period) wave climate of the region if used alone. The observational records have however been employed to calibrate numerical models that can be used, in conjunction with other long-term hindcast data sources, to extend the measured data sets and to characterise both the near and far-field wave regime.

**Table 14. Wave data available from the Moray Firth**

| Data Source | Latitude (°N) | Longitude (°E) | Period Analysed | Duration |
|---|---|---|---|---|
| Directional Wave Buoy in the MORL EDA | 58.166 | -2.634 | Jun/2010-May/11 | ~11 months |
| AWACs in the MORL R3 Zone | 58.248 | -2.746 | Jul/10 to Dec/10 | 100 days |
| | 58.140 | -2.695 | Oct/10 to Feb/11 | 106 days |
| | 58.036 | -3.152 | Jul/10 to Jan/11 | 124 days |
| | 58.167 | -2.900 | Jul/10 to Feb/11 | 103 days |
| Directional Wave Buoy in the BOWL application site | 58.307 | -2.810 | 11/02/10 - 15/11/2010 | ~9 months |
| WaveNet Moray Firth wave buoy (Cefas) | 57.97 | -3.33 | 29/08/08 - 06/01/11 | ~ 2 years |
| Jacky Platform Wave Buoy | 58.183 | -2.979 | 30/09/2008-10/03/2009 | ~ 6 months |
| Beatrice Alpha Oil Platform (Comber, 1993) | 58.12 | -3.09 | Summer/ winter 1990 | < 1 year |
| Outer Moray Firth Geosat Altimeter (NERC, 1992) | - | - | 1986-1989 | ~ 3 years |
| Met Office UKW Archive (modelled data) | 58.17 | -2.75 | Mar 2000 - Nov 2008 | 8 years, 8 months |
| Met Office WW3 Archive (modelled data) | 58.11 | -2.83 | Nov 2008 - present | ~ 2 years |
| Met Office European Waters Archive (modelled data) | 58.3 | -2.9 | Nov 1988 - present | ~ 22 years |
| Numerical wave model (modelled data) | Variable | Variable | Variable | Variable |

### 3.5.2 Near-Field Wave Regime

#### Observational records

The short-term (less than 1 year) wave data collected during the MORL metocean survey can be used to make an initial assessment of the wave climate at the application site. A frequency analysis of wave heights and direction is presented as a series of wave roses in Figure 13 and summarised in Table 15. It should be noted that not all of the data sets are from the same overlapping periods of time, explaining some of the apparent differences. However, from these sources it is evident that:

- Across the MORL EDA, the most frequent wave direction is from the north-east and north-north-east with waves originating from this sector between approximately 15 to 40% of the time;
- The most frequent wave heights are between 0.5 and 1.5 m, accounting for between approximately 50 to 75% of all waves;
- The largest significant wave height observed during the metocean survey occurred on 18/11/2010 and exceeded 6 m at all three measurement locations within the MORL EDA; and
- The larger waves observed during the analysis period all approach from either the east or east-south-east.

A similar analysis was undertaken to define the relationship between the most frequent mean wave period and significant wave height, these wave statistics are shown in Table 15. In summary the frequency analysis shows:

- At the MORL Directional Wave Buoy site, the most frequent mean wave periods are between 3 and 4 seconds, accounting for approximately 35% of the record. These short wave-periods are indicative of locally generated wind waves;
- At the MORL AWAC 3c site, the most frequent mean wave periods are between 7 and 8 seconds, accounting for approximately 50% of the record. These long wave-periods are indicative of swell waves, created some distance from the MORL EDA by storms out in the North Sea;
- This variation in wave periods can be explained by the different times at which the records were collected. The MORL Directional Wave Buoy site captures almost a year of data whilst at the MORL AWAC 3c, wave data is only available from October to January. Winter months are typically characterised by more stormy conditions thus one would expect a higher incidence of swell-waves; and
- The largest observed mean wave-periods exceed 10 seconds. These longer period swell-waves typically approach from the north-easterly quadrant.

**Table 15. Summary of frequency analysis of observational wave records**

| Buoy/ Deployment | Dates of Deployment | Most Frequent Wave Direction and Percentage of Record | Most Frequent Wave Height and Percentage of Record | Maximum Observed Significant Wave Height and Associated Direction Sector | Most Frequent Mean Wave period and Percentage of Record | Largest Observed mean Wave Period and Associated Direction Sector |
|---|---|---|---|---|---|---|
| MORL Directional Wave Buoy | 15/06/2010-15/11/2010 | NNE (15%) | 0.5-1 (34%) | 6.17 (E) | 3-4 seconds (34%) | 10.3 sec. (E) |
| MORL AWAC 2c | 27/07/2010-13/12/2010 | NE (34%) | 0.5-1 (28%) | 6.61 (ESE) | 4-5 seconds (41%) | 8.16 sec. (NNE) |
| MORL AWAC 3c | 13/10/2010-27/01/2011 | NE (39%) | 1-1.5 (41%) | 6.29 (ESE) | 7-8 seconds (51%) | 10.78 sec. (NE) |
| MORL AWAC 4c | 28/07/2010-27/12/2010 | NE (37%) | 1-1.5 (27%) | 4.69 (E) | 5-6 seconds (34%) | 8.15 sec. (NE) |
| MORL AWAC 5c | 27/07/2010-29/01/2011 | NE (34%) | 0.5-1 (30%) | 5.55 (E) | 4-5 seconds (37%) | 8.35 sec. (NE) |
| BOWL Directional Wave Buoy | 11/02/10 - 15/11/2010 | NE (21%) | 0.5-1 (36%) | 5.53 m (ESE) | 4-5 seconds (34%) | 8.9 sec. (NNE) |

| Buoy/ Deployment | Dates of Deployment | Most Frequent Wave Direction and Percentage of Record | Most Frequent Wave Height and Percentage of Record | Maximum Observed Significant Wave Height and Associated Direction Sector | Most Frequent Mean Wave period and Percentage of Record | Largest Observed mean Wave Period and Associated Direction Sector |
|---|---|---|---|---|---|---|
| BOWL AWAC 2a | 11/02/2010-15/06/2010 | NE (24%) | 0.5-1 (37%) | 4.48 m (ESE) | 3-4 seconds (42%) | 8.4 sec. (NE) |
| BOWL AWAC 3a | 10/02/2010-15/06/2010 | NE (40%) | 0.5-1 (45%) | 4.18 m (ENE) | 3-4 seconds (47%) | 8.5 sec. (NE) |
| WaveNet Moray Firth Buoy record | 29/08/2008-06/01/2011 | NE (27%) | 0.5-1 (40%) | 5.43 m (ENE) | 3-4 seconds (45%) | 10.3 sec. (NE) |
| Jacky Platform Wave Buoy | 30/09/2008-10/03/2009 | NE (18%) | 1-1.5 (45%) | 5.2 m (ESE) | 5-6 seconds (28%) | 12.5 sec. (NNE) |
| Percentages are rounded to the nearest integer | | | | | | |

## Met Office UK modelled data

Modelled wave data from the Met Office UKW and WW3 models have been used to characterise storm events for this region (Figure 4).

Table 16 provides details of a series of key low-frequency events in the vicinity of the application site.

**Table 16. Extreme value analysis used to estimate the significant wave height (Hs, in metres) for given return periods for location 58.25° N 2.86° W**

| Sector | Directional Range (°N) | Return Period - Hs(m) | | | |
|---|---|---|---|---|---|
| | | 1 | 10 | 50 | 100 |
| 1 | 337.5 to 22.5 | 6.3 | 7.2 | 7.6 | 7.9 |
| 2 | 22.5 to 67.5 | 6.7 | 8.0 | 8.9 | 9.2 |
| 3 | 67.5 to 112.5 | 6.7 | 7.5 | 8.0 | 8.2 |
| 4 | 112.5 to 157.5 | 6.3 | 7.1 | 7.6 | 7.9 |
| 5 | 157.5 to 202.5 | 4.6 | 6.0 | 6.7 | 7.0 |
| 6 | 202.5 to 247.5 | 4.9 | 5.8 | 6.4 | 6.6 |
| 7 | 247.5 to 292.5 | 4.7 | 5.6 | 6.2 | 6.4 |
| 8 | 292.5 to 337.5 | 4.1 | 5.0 | 5.5 | 5.6 |
| Maximum Hs (m) | | 6.7 | 8.0 | 8.9 | 9.2 |

From Table 16 it is apparent that the largest significant wave heights occur from the north-east and range in magnitude from 6.7 m (for a 1 in 1-year return period storm event) to 9.2 m (for a 1 in 100-year return period storm event).

Using 20 years of the timeseries of wave heights from the MetOffice, the number of occurrences (3 hourly timesteps) of a given wave height range and per month were counted. The percentage of time in that month and cumulative exceedance (the percentage time that the wave height is in that range OR exceeded).

**Table 17. Probability of wave height occurrence (% by month)**

| From (m) | To (m) | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 0.5 | 0.2 | 1.4 | 2.0 | 2.4 | 6.7 | 8.1 | 10.6 | 8.5 | 2.7 | 1.2 | 0.1 | 2.8 |
| 0.5 | 1 | 6.4 | 11.8 | 13.1 | 21.4 | 28.3 | 33.1 | 39.6 | 37.0 | 24.2 | 8.9 | 5.4 | 8.8 |
| 1 | 1.5 | 22.0 | 18.9 | 26.2 | 34.1 | 36.5 | 33.1 | 30.7 | 32.1 | 32.9 | 22.8 | 22.2 | 20.9 |
| 1.5 | 2 | 21.7 | 23.0 | 21.7 | 21.5 | 13.5 | 15.5 | 13.5 | 12.5 | 20.6 | 23.0 | 25.4 | 23.8 |
| 2 | 2.5 | 19.1 | 16.0 | 15.0 | 9.8 | 8.3 | 6.7 | 3.4 | 6.6 | 10.4 | 17.9 | 16.9 | 17.7 |
| 2.5 | 3 | 13.8 | 11.6 | 9.2 | 5.0 | 4.5 | 1.8 | 1.8 | 2.4 | 5.2 | 11.7 | 11.0 | 10.2 |
| 3 | 3.5 | 7.6 | 6.2 | 5.1 | 2.9 | 1.5 | 1.0 | 0.4 | 0.7 | 2.9 | 6.3 | 7.3 | 6.5 |
| 3.5 | 4 | 4.3 | 4.9 | 3.8 | 1.1 | 0.6 | 0.4 | 0.0 | 0.1 | 0.6 | 3.7 | 4.0 | 3.9 |
| 4 | 4.5 | 2.1 | 2.4 | 2.2 | 0.8 | 0.1 | 0.2 | 0.0 | 0.0 | 0.1 | 2.0 | 2.9 | 2.1 |
| 4.5 | 5 | 1.1 | 1.4 | 0.8 | 0.6 | 0.0 | 0.0 | 0.0 | 0.0 | 0.1 | 1.3 | 2.0 | 1.6 |
| 5 | 5.5 | 0.6 | 1.2 | 0.5 | 0.2 | 0.0 | 0.0 | 0.0 | 0.0 | 0.1 | 0.9 | 1.3 | 1.1 |
| 5.5 | 6 | 0.8 | 0.8 | 0.4 | 0.1 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.2 | 0.9 | 0.5 |
| 6 | 6.5 | 0.3 | 0.3 | 0.1 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.1 | 0.2 | 0.2 |
| 6.5 | 7 | 0.1 | 0.1 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.1 | 0.0 | 0.2 | 0.0 |
| 7 | 7.5 | 0.0 | 0.0 | 0.1 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.1 | 0.0 |
| 7.5 | 8 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| | Total | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% |

**Table 18. Probability of wave height occurrence/exceedance (% by month)**

| From (m) | To (m) | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 0.5 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 |
| 0.5 | 1 | 99.8 | 98.6 | 98.0 | 97.6 | 93.3 | 91.9 | 89.4 | 91.5 | 97.3 | 98.8 | 99.9 | 97.2 |
| 1 | 1.5 | 93.4 | 86.8 | 84.8 | 76.2 | 65.0 | 58.8 | 49.9 | 54.5 | 73.1 | 89.9 | 94.5 | 88.4 |
| 1.5 | 2 | 71.4 | 67.9 | 58.6 | 42.1 | 28.5 | 25.7 | 19.1 | 22.4 | 40.2 | 67.1 | 72.3 | 67.6 |
| 2 | 2.5 | 49.7 | 44.9 | 37.0 | 20.5 | 15.0 | 10.1 | 5.6 | 9.9 | 19.5 | 44.1 | 46.9 | 43.8 |
| 2.5 | 3 | 30.6 | 28.9 | 22.0 | 10.8 | 6.7 | 3.4 | 2.2 | 3.3 | 9.1 | 26.3 | 30.0 | 26.0 |
| 3 | 3.5 | 16.8 | 17.3 | 12.8 | 5.8 | 2.2 | 1.6 | 0.4 | 0.9 | 3.9 | 14.5 | 19.0 | 15.8 |
| 3.5 | 4 | 9.2 | 11.0 | 7.8 | 2.9 | 0.7 | 0.6 | 0.0 | 0.1 | 1.0 | 8.3 | 11.7 | 9.3 |

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 4 | 4.5 | 4.9 | 6.2 | 4.0 | 1.8 | 0.1 | 0.2 | 0.0 | 0.0 | 0.4 | 4.6 | 7.7 | 5.4 |
| 4.5 | 5 | 2.8 | 3.8 | 1.8 | 1.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.3 | 2.6 | 4.8 | 3.4 |
| 5 | 5.5 | 1.7 | 2.4 | 1.0 | 0.4 | 0.0 | 0.0 | 0.0 | 0.0 | 0.2 | 1.2 | 2.8 | 1.8 |
| 5.5 | 6 | 1.2 | 1.2 | 0.6 | 0.1 | 0.0 | 0.0 | 0.0 | 0.0 | 0.1 | 0.3 | 1.5 | 0.7 |
| 6 | 6.5 | 0.3 | 0.4 | 0.2 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.1 | 0.1 | 0.6 | 0.2 |
| 6.5 | 7 | 0.1 | 0.1 | 0.2 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.1 | 0.0 | 0.3 | 0.0 |
| 7 | 7.5 | 0.0 | 0.0 | 0.1 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.1 | 0.0 |
| 7.5 | 8 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |

### 3.5.3 Far- Field Wave Regime

#### Observational records

The longest observational wave record in the Moray Firth is provided by the WaveNet Moray Firth wave buoy. This record was analysed for the period August 2008 to January 2011 and is summarised in Table 15 and Figure 13. The Figure and table show that at the application site, the most frequent wave direction is from the north-east whilst almost 75% of the record is comprised of waves from the north-east and east; this is consistent with the metocean records collected from within the application site, despite the differing length of the records. The largest significant wave height observed by the buoy was approximately 5.5 m and coming from the east-north-east. This finding is broadly consistent with the observational record (from another period of time) from the Jacky Platform wave buoy where the largest recorded significant wave height was 5.2 m. Consideration of the WaveNet Moray Firth buoy time series alongside the MORL and BOWL application site metocean deployments reveals an apparent reduction in maximum observed significant wave heights as they propagate into the Moray Firth.

Wave data has also been collected at the Beatrice Alpha oil platform and has been published in Comber (1993) (see Figure 4 and Figure 14). During the winter months, the most commonly occurring significant wave height was 1.5 m and the largest recorded maximum wave height ($H_{max}$) was 8 m. In the summer months, a smaller range in wave heights was recorded: the modal wave height was 1 m whilst the largest recorded value of $H_{max}$ was 3 m. The winter months were also characterised by longer period waves (approximately 5 seconds). Comber (1993) notes that the combination of higher, longer period waves experienced during the winter months results in a strong seasonal divide in wave energy reaching the Moray Firth coast with the highest incident energy experienced in the late winter months.

Derived monthly mean significant wave heights for the Outer Moray Firth are also available from Geosat altimeter data (NERC, 1992). However, although broadly in agreement with the other data sources quoted, this data is regarded as being of lower quality than the direct observational records described above and as such, the Geosat altimeter data is not discussed further here

#### Numerical wave model

A numerical wave model, covering both the near and far-field, has been created for use in the present study. The design of and inputs to the model, together with a more detailed description of the accuracy and limitations of the model are available in a separate report (ABPmer, 2012b). The model has been calibrated using the other discrete observed data sets described in the preceding sub-sections and so model outputs are in close agreement with the measured data (within the levels of confidence established during model validation). As a result, the model provides a coherent and continuous source of quantitative tidal data over a large area encompassing the potential far-field extent of any effects of the wind farm.

**Table 19. Summary of occurrence of surf conditions (days/year) at various locations around Moray Firth**

| SAS (2009) Description | Hs (m) | Tp (s) | Fraserburgh | Lossiemouth | Banff Beach | Sandend | Boyndie Bay | Inverallochy | Ackergill | Sinclairs Bay | Keiss | Freswick Bay | Skirza | Spey Bay | Cullen Bay | Sunnyside Bay | Pennan | Wisemans | Phingask | West Point |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Small waves | 1 | 7 | 47.7 | 31.0 | 36.9 | 36.9 | 36.1 | 36.1 | 29.3 | 29.3 | 39.0 | 43.6 | 41.2 | 36.1 | 60.4 | 29.3 | 39.0 | 43.6 | 41.2 | 40.6 |
| *Annual mean wave* | | | *1.12 m 7.2s* | *0.72 m 5.9s* | *0.89 m 6.4s* | *0.83 m 6.3s* | *0.86 m 6.3s* | *1.19 m 7.3s* | *0.69 m 5.9s* | *0.77 m 6.0s* | *0.97 m 6.5s* | *1.00 m 6.6s* | *1.03 m 6.7s* | *0.63 m 5.3s* | *0.81 m 6.3s* | *0.85 m 6.3s* | *1.02 m 6.8s* | *1.20 m 7.1s* | *1.17 m 7.3s* | *1.23 m 7.3s* |
| | 2 | 10 | 15.2 | 6.6 | 14.3 | 14.3 | 12.9 | 12.9 | 6.4 | 6.4 | 8.1 | 8.6 | 7.6 | 12.9 | 12.3 | 6.4 | 8.1 | 8.6 | 7.6 | 8.4 |
| | 3 | 12 | 5.2 | 2.3 | 6.2 | 6.2 | 3.1 | 3.1 | 2.6 | 2.6 | 1.4 | 1.6 | 1.3 | 3.1 | 0.7 | 2.6 | 1.4 | 1.6 | 1.3 | 1.9 |
| | 4 | 14 | 0.4 | 0.2 | 0.1 | 0.1 | 0.0 | 0.0 | 0.2 | 0.2 | 0.2 | 0.1 | 0.0 | 0.0 | 0.2 | 0.2 | 0.2 | 0.1 | 0.0 | 0.2 |
| Large "classic" wave | 4 | 16 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| *1:1 extreme wave height* | | | *5.09 m* | *3.96 m* | *5.36 m* | *5.09 m* | *5.18 m* | *4.35 m* | *4.40 m* | *4.89 m* | *6.07 m* | *5.27 m* | *6.41 m* | *3.24 m* | *4.89 m* | *5.18 m* | *5.41 m* | *6.77 m* | *6.75 m* | *6.80 m* |

Consideration of Figure 15 and Figure 16 reveals that across the far-field region, the largest significant wave heights are likely to be experienced due to winds/waves from between north and east. The OFTO transmission cable route is likely to be exposed to waves of equal or possibly larger size than the wind farm itself from exposed offshore sectors; the size of waves from other fetch limited sectors will vary along the route depending upon the wind direction and corresponding fetch. The variable and on average greater water depths along the route mean that the ability of a given wave condition to penetrate to the seabed may also be variable.

Analysis has been undertaken to quantify the baseline wave climate at surfing venues identified in the Moray Firth (Figure 2). Table 19 above summarises the occurrence of various surf conditions (in days/year), defined according to Surfers Against Sewage (2009), after Halcrow (2006). The values in Table 19 are based upon 2 years of modelled wave climate (2007-2008) extracted at locations 500m offshore of each of the identified surf venues. The 1 in 1 year return period extreme wave has been determined by ranking the wave heights in the data record at each location and assigning a return probability.

These two years of data suggests that large "classic" surfing waves do not occur at any of the Moray Firth surfing venues. Similarly large wave height events do occur, however, they are not typically of a sufficiently long wave period to meet the "classic" criteria; this is likely due to the relatively restricted fetch length in comparison to other UK venues exposed directly to the Atlantic.

### 3.5.4 Future Changes to the Baseline

There is now strong evidence to suggest that longer-term changes in storminess have taken place across this region (e.g. Alexandersson *et al*., 2000). These changes may be related to long-term changes in the strength of the North Atlantic Oscillation (NAO), a hemispheric meridional oscillation in atmospheric mass with centres of action near Iceland and over the subtropical Atlantic (Visbeck *et al*., 2001). Longer-term trends in storminess across north and north-western Europe are summarised in Figure 17. Storminess in this region was relatively high during the late 19$^{th}$ and early 20$^{th}$ century; followed by a decrease up until about 1970. A subsequent rise in the late 20$^{th}$ century can be clearly identified although most recent years have seen a decline in storminess (Matulla *et al*., 2007). These findings are broadly consistent with published investigations into 21$^{st}$ century wave climate changes in the North Sea (e.g. Bacon and Carter, 1991; Leggett *et al*., 1996; Weiss and Stawarz, 2005). For example, Leggett *et al*., (1996) analysed wave climate data between 1973 and 1995 and found that in the open northern North Sea:

- Mean significant wave heights increased by approximately 0.2 to 0.3 m (5 to 10%) between 1973 and 1995;
- Peak $H_s$ values between 1988 and 1995 were generally higher than those from the period 1973 to 1987. (Peak $H_s$ values recorded before 1987 were around 11-12 m compared with values of between 12.5-14 m in the period 1988 to 1995); and
- From the early 1980's up until the end of the record, wave conditions became calmer in autumn and more severe in winter.

Climate change modelling as part of UKCIP (Lowe *et al.*, 2009) currently gives the most up-to-date projection of the likely future wave climate. Changes in climate over the 21st century may include changes in mean wind speed and direction which will in turn affect the wave regime. Despite many effects of climate change being associated with an increase in values, UKCIP09 indicates that in the Moray Firth, mean annual maxima of significant wave heights between 1960-1990 and 2070-2100 may decrease slightly (by approximately 0 to 0.5 m). The effect of climate change on wave height over the relatively shorter lifetime of the MORL development is therefore likely to be negligible in comparison to typical inter-annual or inter-decadal variability.

## 3.6 Stratification and Frontal Systems

In a large body of water such as the sea, the water column may become vertically stratified where a more buoyant surface layer develops as a result of local solar heating or fresh water input, and where the strength of local mixing forces are not sufficient to mix it with the underlying less buoyant layer.

In the UK shelf seas, vertical stratification of the water column is typically controlled by tidally driven mixing from the bottom (spatially varying - higher under stronger tidal currents and in shallower water) and wind or wave driven mixing from the top (temporally varying - seasonal) balanced by the stratifying influence of solar heating or freshwater input at the surface (also temporally varying - seasonal) (Dye, 2006). In coastal waters the direct input of freshwater from land run-off and rivers dominates changes in salinity. The inner parts of the Moray Firth are considered to be areas of freshwater influence, owing to the input from large rivers draining into the Firth (Baxter *et al*., 2008).

In practice, stratification can be caused by vertical gradients in either temperature and/or salinity and as a result may also be associated with gradients in nutrient concentration and any resulting biological activity. Away from regions of particularly strong fresh water influence (e.g. at the mouth of a river entering an estuary), stratification does not measurably affect the physical action of currents or waves or any related sediment transport processes

Vertical fronts in shelf seas are the transitional boundary between bodies of more vertically mixed and more stratified water. They are also often associated with sharp horizontal gradients in salinity, temperature and bio-chemical quantities and tend to be most pronounced in the summer months when solar heating is strongest. Such fronts typically develop at generally predictable locations where the water depth and tidal current speeds are consistently just sufficient to overcome the typical input of heat or fresh water to a given area.

Since their discovery, tidal fronts have been a focus of attention for their potential role as locations of enhanced biomass production (Hill *et al*., 1993). Indeed, frontal features can also influence the availability of light and nutrients to plankton, enhancing both primary and secondary productivity.

### 3.6.1 Sources of Stratification and Frontal Data

A series of predictive maps providing a synoptic illustration of the seasonal variability of stratification features in the pelagic environment are available from UKSeaMap (Connor *et al*., 2006). These maps are based upon hydrographic datasets obtained from the Proudman Oceanographic Laboratory and provide information on (*inter alia*) salinity, temperature, seasonal variation in the probability of fronts forming and seasonal variation in the degree of water column stratification. A relatively small number of measured temperature and salinity profiles from the previously described metocean survey campaigns are available from both the Beatrice and Moray Firth Offshore Wind Farm application areas. These data provide examples of seasonal variation in the degree of stratification found in the area.

The locations of frontal systems in the study area (also indicating the general states of stratification) have been documented in a number of publications and reports including:

- Temperature and salinity data collected during the MORL and BOWL metocean surveys;
- The OSPAR Quality Status Report 2000, Region II - Greater North Sea (OSPAR, 2000);
- The JNCC Coastal directory series (Barne *et al*. (1996); and
- The DTI SEA 5 Environmental Report (Holmes *et al*., 2004).

However, although the biological aspects of fronts in this region have been considered in some detail, less information is available regarding the physical processes that support them.

### 3.6.2 Seasonal Stratification in the Study Area

Within the Moray Firth, solar heating causes the water temperature to vary unevenly with depth and season (e.g. Adams and Martin, 1986; Connor *et al*., 2006). In the summer, the water becomes seasonally stratified due to temperature-related density differences between warmer surface waters and cooler deeper waters, typically forming a weak thermocline at 10 to 15 m depth in the application site (Figure 18). The field data collected indicate that there is no significant fresh-water / salinity contribution to the observed stratification. The stratification breaks down at the end of summer and the water column remains well mixed during the winter months due to the increased frequency and severity of storms and a reduced rate of heat input. Temperature and salinity may fluctuate to a greater extent at the coast and in the Inner Moray Firth, due to more highly variable local river input; local temperature stratification in summer may also be associated with relatively warm, fresh river water overlying colder, more saline sea water (Adams and Martin, 1986).

### 3.6.3 Frontal Systems in the Study Area

Weak thermal fronts are also present in the Moray Firth and their locations have been deduced from infrared satellite images (OSPAR, 2000) (Figure 2 and Figure 3). Based on the information provided in these Figures, the fronts represents the boundary between deeper, weakly seasonally stratified water offshore and an area of more intense mixing inshore due to a combination of shallower water depths and relatively stronger tidal currents. On this basis, the position of the fronts are likely to migrate in an onshore-offshore direction in response to the spring-neap cycle and its measurable signal may become weak or absent altogether in proportion to the strength of local (offshore) seasonal stratification.

### 3.6.4 Future Changes to the Baseline

Although temperature and salinity are standard oceanographic parameters, few studies or time-series observations have been undertaken of long-term changes to stratification in the shelf seas around the UK. Thus although the dynamics of stratification in shelf seas are fairly well understood, confidence in understanding long-term change in shelf stratification is regarded as low (Dye, 2006).

The present understanding of climate change predicts variability in many of the parameters affecting stratification, but all with a high degree of uncertainty and with unknown net result, it is assumed that the future baseline situation within the lifetime of the wind farm will be broadly similar to the present.

# 4. Sediment Regime

## 4.1 Overview

The surficial seabed sediments present on the UK Continental Shelf vary spatially in character (e.g. grain size distribution) and thickness. The potential for the transport of these sediments is locally controlled by the net action of currents and waves in variable proportions; the relative contribution and dominance of these different driving factors is both spatially and temporally variable (e.g. Kenyon and Cooper, 2005). Mobilisation of sediments will occur when the shear stress imposed on the seabed by these hydrodynamic forces exceeds a critical threshold relevant to the specific material. Once mobilised, sediment will be eroded, transported and eventually redeposited at rates proportional to the shear stress applied in excess of the critical value.. Spatial gradients in the properties and availability of sediment and the erosive forcing normally applied to them leads to the natural formation of areas of net erosion ('sources') or deposition ('sinks'), connected by sediment transport pathways. Over longer time-scales, changes to these components of the sediment regime will determine the net morphological evolution of an area.

Within the Outer Moray Firth, previous surveys have revealed that the seabed is typically devoid of contemporary large scale bedform features, indicating that in terms of sediment transport this is a low energy region in most locations for most of the time. This is further confirmed by models of maximum bed-stresses presented in UKSeaMap which are typically very low (Conner *et al*., 2006). Net sediment transport pathways are directed into the Firth in the north and due to the relatively benign tidal regime it is suggested that transport is limited in frequency and related to low-frequency, high-energy events. This assertion is supported by the observed trend of decreasing sediment grain size with increasing water depth within the Firth, reflecting the relative importance of wave energy to sediment transport processes (Reid and McManus, 1987). Supplies of new sedimentary material from the land into the Firth are very limited (Barne *et al*., 1996).

The sediment regime in and around the application site has been considered in the following sections:

- The composition and distribution of seabed sediments across the EDA and the wider far-field study area;
- The composition of the sediment sub-strata across the EDA and the wider far-field study area;
- Sediment transport pathways in the vicinity of the application site in the form of a conceptual understanding of the sediment regime; and
- The key process controls on sediment mobility and thresholds of sediment motion.

## 4.2 Sources of Sediment and Geological Data

Key sediment and geological data for the application site is available from several sources which are summarised in Table 20.

**Table 20. Sediment and geological data available from the Moray Firth**

| Data Source | Reference |
|---|---|
| MORL application site benthic survey | Emu (2011) |
| MORL export cable route benthic survey | Emu (2011) |
| MORL application site geophysical survey | Osiris (2011) |
| MORL OFTO transmission cable route geophysical survey | Osiris (In preparation) |
| BGS seabed sediment maps | BGS (1984, 1987) |
| Regional Geology and Geomorphology | Andrews *et al*. (1990); Holmes *et al*. (2004) |
| MORL AWAC deployments (OBS turbidity sensors) | Partrac (2011) |
| BOWL AWAC deployments (OBS turbidity sensors) | Partrac (2010) |
| BGS Rock/ Hard Substrate Map | Gafeira *et al*. (2010) |

## 4.3 Seabed Sediments: Composition and Distribution

### 4.3.1 MORL EDA

The present day seabed surficial sediments were laid down within the last 10,000 years during the Holocene Epoch and are largely derived from the re-working of glacial material. Seabed sediment data for the region is available from benthic samples collected during the site surveys (Emu, 2011) as well as grab samples held by the BGS. The distribution of sediments across the MORL site and surrounding area is shown in Figure 19, Figure 20 and Figure 21. All of the grab samples collected during the site survey campaign were analysed using the GRADISTAT grain size distribution and statistics package (Blott and Pye, 2001) and classified using the Folk (1954) sediment classification scheme (for consistency with pre-existing broad-scale mapping such as that offered by the BGS). Sample locations have been plotted overlying the BGS Moray-Buchan and Caithness seabed sediment maps BGS (1984; 1987). The benthic samples share the same colour scheme as that employed in the BGS seabed sediment map in order to facilitate comparison between the two datasets.

Figure 19 shows that, according to the locally collected grab samples and regional BGS data, the proposed development site is dominated by gravelly and slightly gravelly sands with mud almost entirely absent from the samples. However, sands are found towards the centre of the site, on the crest of Smith Bank, whilst sandy gravels are found in deeper water along the sites eastern and south-eastern margin. Comparison of the BGS seabed sediments maps and the grab sample data available from the EMU (2011) survey reveal only partially agreement. Although the grab samples are also dominated by gravelly and slightly gravelly sands, all of the samples contain gravel sized material and the area of sand over the crest of Smith Bank cannot be identified from the EMU survey data. Instead, the MORL EDA side scan sonar evidence presented in Figure 20 suggests that the crest of Smith Bank is characterised by the presence of gravel patches, a finding which is in agreement with the earlier work of Hartley and Bishop (1986). It is also the case that the extensive tracts of gravelly sediments identified in the BGS maps along the eastern margin of the MORL EDA cannot be clearly discerned in either the MORL EDA side scan survey records or the MORL grab sample data. These variations are likely to relate to the differences in sampling density between the surveys and it should be noted that the BGS sediments maps are compiled from a relatively low density of samples in this area.

Most (78%) of the benthic samples were also found to have a unimodal distribution, with the remaining samples possessing either a bimodal (12%), trimodal (6%) or polymodal (4%) distribution. Over half of the samples are either poorly or very poorly sorted. Poor sorting of material is indicative of low seabed sediment mobility and lends some credence to the suggestion that much of the seabed at the proposed wind farm development site is a lag gravel deposit. Modal particle sizes are found to be variable across the site, ranging in size from 24000μm (pebble gravel) to 150μm (fine sand). However, over half the samples contained a modal value of 185μm (fine sand).

Numerous small boulders (>300 mm diameter) have been identified across the application site (Osiris, 2011) (Figure 20). These are thought to have been winnowed out of the underlying glacial till unit although the larger boulder sized clasts (>1.0m) may also represent glacial erratics, deposited during the last glacial period.

The BGS data reveals that for the most part, the MORL EDA is immediately surrounded by sandy sediments accompanied by varying amounts of gravel. However muddy sediments are encountered in the deeper water to the south of the proposed development site.

Carbonate sediments (comprised mainly of shell fragments) make a significant contribution to the sediment deposits of the Moray Firth and the proportion of shell content in the benthic grab samples from and nearby to the application site are frequently in excess of 50% (Emu, 2011; BGS, 1987). The proportion of carbonate material in seabed sediments decreases with distance from the source (in this case thought to be the Shetland and Orkney Islands)

The BGS was recently commissioned by Defra to produce a digital data layer (map) of the distribution of hard substrate at, or near (~ <0.5 m), the seabed surface across all areas of the United Kingdom Continental Shelf (UKCS) (Gafeira *et al*., 2010). This study was undertaken to help improve the current understanding of where rock or hard ground outcrops occur in the marine environment. The data layer was compiled using a variety of published and unpublished survey data and indicates that the southern half of the application site is characterised by a hard seabed substrate. Across this area, surficial sediments are generally thin (<0.5 m) with the underlying glacial till of Smith Bank very close to the surface. However, BGS core sampling (unpublished) also indicate that seabed and superficial sediments on the crest of the bank can be greater than 2 m thick in places (Holmes *et al*., 2004).

### 4.3.2 Transmission Cable Route

Seabed sampling was attempted at 20 locations along the export cable route. However, as a result of the presence of hard and /or coarse substrate in places, only 12 samples were successfully recovered. The data are in broad agreement with the general distribution of seabed sediments shown in BGS seabed sediment maps.

Near to the wind farm site, in intermediate water depths, the cable route will transit areas of mixed sands and gravels, with a initially small and variable fines content. Seabed sediments become progressively finer in deeper water along the route, becoming relatively muddy in the deepest parts, at the eastern end of the Southern Trench. The sediment character and distribution in these offshore sections is the result of the relatively benign tidal regime and the spatially variable effect of wave action at the seabed, depending upon the local water depth.

In the shallower waters approaching the landfall, the generally faster tidal current speeds become the dominant factor in controlling sediment transport. Seabed sediments become progressively more mixed and coarse. The grab samples and seabed imagery indicate coarse mixed sediments, including cobbles, boulders and exposed bedrock in the near shore area of the landfall (Emu, 2011).

## 4.4 Sediment Sub-Strata: Composition and Distribution

The offshore surface geology in the Outer Firth is comprised predominantly of Cretaceous rocks whilst both Jurassic and Permo-Triassic rocks are encountered along the southern/inner margins of the Firth. An extensive blanket of Quaternary deposits is present across almost the entire Firth with sediment thicknesses of around 70 m commonly observed (Chesher & Lawson, 1983). Chesher & Lawson (1983) have classified the Quaternary deposits within the Moray Firth and have defined a series of sedimentary units based upon the thickness of the deposits. The units in the north of the Firth are generally thinner whilst the southern units were found to be much thicker. Stratigraphic details of the sediments of the Moray Firth are presented in Chesher & Lawson (1983) whilst a more comprehensive account of the geology of the Moray Firth is given by Andrews *et al*., 1990.

A summary of the sedimentary units encountered at the application site is given in Table 21 and has been compiled from the geophysical survey undertaken by Osiris (2011). These individual units have been arranged into larger sediment groupings separated by 'isopachytes' (lines connecting points on the seabed with an equal depth of sediment).

**Table 21. Summary of sedimentary units at the application site, from Osiris (2011)**

| Description and Sections | Designation | Sediment Grouping |
|---|---|---|
| SAND/SILT (Surface Unit) | Unit 1 (Holocene) | Marine Sediments |
| SAND | Unit 2a (Holocene/Late Pleistocene) | |
| Fine SAND/SILT/CLAY | Unit 2b (Holocene/Late Pleistocene) | |
| Isopachyte 1 - Base of Marine Sediments | | |
| Layered sandy silty CLAY | Unit 3a (Mid to Late Pleistocene) | Mid to Late Pleistocene Sediments |
| Sandy silty CLAY (chaotic to featureless appearance) | Unit 3b (Mid to Late Pleistocene) | |
| Very stiff to hard CLAY/dense SAND generally poorly ordered | Unit 4a (Mid to Late Pleistocene) | |
| Very stiff to hard CLAY/dense SAND parallel bedded | Unit 4b (Mid to Late Pleistocene) | |
| Very stiff to hard CLAY/dense SAND generally massive/chaotically bedded | Unit 4c (Mid to Late Pleistocene) | |
| Isopachyte 2 – Top of ice pushed sediments | | |
| Very hard CLAY/ dense sand | Unit 5a (Early Pleistocene/Lower Cretaceous) | Ice pushed Formations |
| Isopachyte 3 – Top of unaltered Lower Cretaceous | | |
| Very hard CLAY (intact bedded formations) | Unit 5b (Lower Cretaceous) | (Cretaceous Rocks) |

Total sediment thicknesses are highly variable across the MORL EDA, ranging from ~5 m to over 150 m, in places (Osiris, 2011). An overview of each of the four main sediment groupings is provided in Cathie Associates (2011) and repeated below.

### (i) Unit 1 – Surficial Marine Sediments

The surface sediments were generally shown to comprise very loose to medium dense sand, occasionally dense to very dense and soft to firm slightly sandy clay. The unit was encountered across the site as thin deposits at seabed level and is suggested to have accumulated since the Holocene transgression, in marine conditions similar to the present day. In places, these sediments may be mobile, migrating slowly down slopes and in response to wave motion.

### (ii) Unit 2 – Marine Sediments

This unit generally occurs a thin deposits across the Phase 1 area, however is locally thicker infilling channels and/or depressions towards the centre and south-west. Here, the marine sediments reach a maximum of 48 m within a localised channel feature (Osiris, 2011). The sediments are typically medium dense to very dense sometimes silty sand with some gravel and shell fragments, typically becoming looser/more cohesive with depth. Clay beds, up to 2.4 m thick bands of very soft to very stiff sandy clay were noted in places. Unit 2 is thought to represent Holocene to Upper Pleistocene (Possible Forth Formation) aged marine sediments.

#### (iii) Unit 3 – Chaotic/Lag Till

Likely to be part of the Forth Formation and found as a notably variable lag/chaotic till unit. The unit, as presented on geotechnical boreholes logs comprises very soft to occasionally very stiff sandy clay. A smaller fraction of loose to very dense sometimes silty sand, occasionally with some shell fragments and gravel is also noted.

#### (iv) Unit 4 – Over-consolidated Till

Likely to be part of the Coal Pit or other older formations and generally comprises interbedded medium dense to very dense silty Sand with shell fragments and gravel or pockets of clay, or stiff to very hard sandy Clay with laminae/beds of silty fine sand and occasional gravel and cobbles. Occasional black or organic material is noted. The unaltered (non ice pushed) Pleistocene deposits are thickest towards the eastern side of the MORL EDA, where thicknesses reach over 100 m within a deep basin-like feature (roughly 5.0 km x 8.0 km), although average thicknesses lie between 40 and 60 m (Osiris, 2011).

#### (v) Unit 5 – Lower Cretaceous Sediments

Determined through palynolgical testing to be from the Lower Cretaceous era and is described as dense (occasionally medium dense) to very dense silty SAND with thin to thick beds or pockets of clay, and very stiff to very hard sandy CLAY with thin laminae to medium beds of silty sand. The soil descriptions indicate little difference between unit 5a and 5b. A significant buried channel feature through the Lower Cretaceous sediments is located over the centre of the Phase 1 area trending northwest-southeast, infilled with thick successions of glacial till.

The boundary between the ice pushed sediments and the overlying Pleistocene sediments is complex, and occasionally the older ice pushed sediments are encountered over the Pleistocene sediments suggesting multiple ice movement/ glaciation events.

## 4.5 Conceptual Understanding of the Sediment Regime

In comparison to other areas of the North Sea, relatively little has been previously published about the dynamics of sediment transport in the Moray Firth. By far the most comprehensive account of sediment exchange within the Moray Firth has been provided by Reid and McManus (1987). Some discussion is also provided by Holmes *et al*. (2004). Findings from these investigations are summarised in the following sub-sections

There are two primary mechanisms of sediment transport:

- **Bed-load transport.** This mechanism refers to all sedimentary grains that move, roll or bounce (saltation) along the seabed as they are transported by currents. This mode of transport is principally related to coarser material (sands and gravels); and
- **Suspended-load transport.** This mechanism refers to particles of sediment that are carried above the seabed by currents and are supported in the water without recourse to saltation.

These two mechanisms of transport can be variably controlled or dominated by different processes (e.g. currents, waves or some combination of the two) and hence require separate consideration.

### 4.5.1 Bed Load Transport

Although there is a general scarcity of well defined bedforms characteristic of frequent bedload transport in the Moray Firth, a limited number of observations have been made outside of the EDA in previously collected geophysical data. Sand ribbons and sand waves have been identified in the vicinity of the Caithness coastline and longitudinal and transverse sand patches have been observed as the dominant bedform in the centre of the Outer Moray Firth. Using information contained in references such as Stride (1982) to interpret the likely net transport associated with these bedforms, Reid and McManus (1987) inferred a number of sediment transport paths within the Moray Firth. They suggest that material is circulating through the Firth, entering from the north, moving then either along the Caithness coast and into the Inner Moray Firth (Figure 23). Once within the Firth, marine sediments become dispersed along routes broadly parallel to the tidal flow axis. Sediment is also exiting the Firth in the south-east, with eastward transport noted along the southern coast, particularly to the east of the River Spey; in the Outer Firth, to the south of the EDA, some sediment transport pathways also branch in a southerly direction, bypassing the Moray Firth altogether.

Modelling analysis presented in Holmes *et al*. (2004) has provided an insight into the relationship between tidal state, storminess and sediment movement in the Moray Firth. For example, during fair weather mean peak spring tide near-bed current speeds and directions were not found to closely follow observed sediment transport directions in the Moray Firth; however, stormy conditions in conjunction with the same tidal scenario was found to more closely correlate with the observed net sediment transport directions. This analysis indicates that tidal currents modified by stormy conditions and storm surge (typically directed into the Firth along the Caithness coast – see Section 3.3.3) are the major influence on the net movement of seabed sediments in the Moray Firth.

### 4.5.2 Suspended Load Transport

Information on the naturally occurring range of suspended sediment concentrations is available from several reference sources:

- Suspended sediment concentrations measurements collected during the MORL EDA and BOWL metocean surveys (Partrac, 2010; 2011);
- Satellite-based observations of suspended particulate matter in surface waters (Dolphin *et al*., 2011); and
- An ecosystem model of suspended sediment concentrations (Baxter *et al*., 2008).

Suspended sediment concentration (SSC) has been inferred from Optical Backscatter Sensors (OBS) deployed together with the each AWAC device as part of the metocean surveys undertaken at the MORL and BOWL applications sites The OBS units were mounted approximately 0.75 m above the seabed on the AWAC frame and recorded water turbidity by measuring the backscatter intensity from a pulse of light emitted into the adjacent water. The raw units of turbidity measurement were calibrated to a suspended sediment concentration in a laboratory using artificial suspensions of the locally present sediments. A subset of measurements (14/10/10 to 27/01/11) from the MORL application site are presented in Figure 24 whilst a subset of measurements (10/02/10 to 10/03/10) from the BOWL application site are shown in Figure 25. Hydrodynamic data collected during the same time interval are also shown to demonstrate the relationship between the forces potentially driving sediment resuspension and the resulting levels of SSC.

Inspection of the SSC data available from the MORL application site reveals that SSC's are typically in the range 0 to 10 mg/l, interspersed with short periods of very high (> ~100 mg/l) concentrations. On the basis of the findings presented in Table 11 (which show the relationship between wave height, water depth and orbital current speeds at the bed), one might expect there to be some correlation between SSC's and storm events, especially at the shallower site. However, consideration of the sequential graphs reveals little correlation between waves and SSC at either site. Neither is there a clear relationship between SSC's and any of the other hydrodynamic variables presented in Figure 24.

A similar set of graphs has been presented for the SSC data available from the adjacent BOWL application site (Figure 25). It is shown in the Figure that during periods of calm weather nearbed SSC remains generally low across the application site. Values are typically less than 5 mg/l and rarely exceed 10 mg/l. This is because (i) there is little fine sediment available in the surficial seabed sediments (see Section 4.3); (ii) tidal currents are generally of insufficient strength to mobilise the majority of the surficial sediments - (this is explored further in Section 4.6); and additionally (iii) there are no known significant fluvial sources of SSC in the Outer Moray Firth. It is also apparent from the full measured data set that there is no consistent significant increase in SSC associated with faster spring tide currents over neap tidal conditions.

It is also shown in Figure 25 that SSC is significantly increased during periods of increased wave activity. The time-series shown in the Figure includes two storm events: the first occurs on the 17 February 2010, with significant wave heights of up to 4.5 m, resulting in a significant increase in near-bed SSC to 30 to 50 mg/l; the second event peaks around 28 February 2010, with significant wave heights of up to 3.5 to 4 m, resulting in an also significant but smaller increase in near-bed SSC to 15 to 20 mg/l. Following the peak of the storm event, SSC gradually decreases (as the sediment settles out of suspension) to the baseline condition which is controlled by the ambient regional tidal regime.

Although peaking at a lower significant wave height, the second storm event shown is more sustained, with wave heights persisting for longer, allowing more time for SSC levels to build. At the southern end of the BOWL application site (at the location of Beatrice AWAC 3a), the period of elevated SSC is greater as a result of the shallower water depth, making waves more likely to have greater interaction with the bed for longer during a given storm event (Figure 25).

Despite the proximity of the MORL and BOWL sites (which are characterised by similar hydrodynamic and sedimentary environments), the separate records reveal contrasting relationships between SSC's and hydrodynamic conditions. This cannot readily be explained by differences in water depth between the sites and/or the magnitude of storm events during the two analysis periods. Given the very strong correlation between storm events and SSC in the BOWL application site it seems likely that across Smith Bank, large waves do stir the bed causing short term increases in SSC. Differences in the BOWL and MORL records may be explained by known problems encountered when calibrating the OBS sensors, which are sensitive to both variations in the colour and size of the sediment grains in suspension and to the presence of material other than sediment in suspension (e.g. biofouling of the sensor or free-floating detritus or marine growth).

Due to the seasonal nature of the frequency and intensity of storm events, levels of SSC will likely follow a broadly seasonal pattern with higher values observed more frequently during late spring, winter and early autumn months. It is also possible that seasonal blooms of marine plankton may also contribute to apparent seasonality in measurements of total turbidity, but this is not directly associated with the resuspension of (inorganic) sediments.

A series of monthly/ seasonal regional scale turbidity maps are also available from Dolphin *et al*. (2011), including the MORL EDA and OFTO transmission cable route (Figure 26). These maps were compiled from several sources including research cruise databases, a numerical model and the Moderate Resolution Imaging Spectroradiometer (MODIS) satellite database. Of the sources used in the Dolphin *et al*. investigation, the MODIS observations provide the most comprehensive data due to their high spatial and temporal resolution. On the basis of the MODIS satellite data, it is found that:

- Winter (surface) SSC values are in the range 0 to 10 mg/l; and
- Summer (surface) SSC values are generally between 0 and 5 mg/l.

For both summer and winter, SSCs are found to increase with greater proximity to the coast. Accordingly, the highest SSC values are expected to occur in the vicinity of the cable landfall. These satellite derived maps provide a very useful overview of spatial and temporal trends in suspended sediment concentrations at the regional scale. However, sources of uncertainty exist in the relationship between satellite-derived reflectance and ground-based SSC or turbidity data. These result from differences in sediment colour, grain size, and mineralogy within a study region reducing accuracy and hence applicability at the local scale.

Finally, Baxter *et al*., (2008) used a numerical ecosystem model to produce a map of typical SSC in the North Sea including the Moray Firth. The reported range of depth mean SSC in the Firth was approximately <5-10 mg/l. This value is broadly consistent with the findings described above from the MORL and BOWL application site surveys and from the satellite-derived SSC values presented in Dolphin *et al*., (2011).

## 4.6 Process Controls on Sediment Mobility

An assessment has been made of sediment mobility within (and nearby to) the application site by identifying the modal sizes of available sediments (from the grab sample data) and calculating the bed shear stresses required to initiate transport (using standard methods described in Soulsby, 1997).

Table 22 provides a summary of the most commonly occurring modal grain size classes, their frequency of occurrence and critical shear stress values for transport.

**Table 22. Summary of the main sediment types within (and nearby to) the application site including associated theoretical bed shear stress thresholds for mobility**

| Common Modal Size (μm) | Size Class | Bed Shear Stress Threshold (N/m$^2$) | Number of Occurrences in 81 Samples |
|---|---|---|---|
| 150 | Fine sand | 0.160 | 4 |
| 185 | Fine sand | 0.170 | 45 |
| 215 | Fine sand | 0.179 | 11 |
| 375 | Medium sand | 0.221 | 9 |
| 750 | Coarse sand | 0.354 | 3 |
| 1500 | Very coarse sand | 0.779 | 6 |
| 3000 | Granule gravel | 2.02 | 4 |
| 24000 | Pebble gravel | 20.95 | 7 |

### 4.6.1 Potential Mobility Due to Tidal Currents Alone

The regional tidal current regime has been described in more detail in Section 3.3. Here, tidal current time series have been extracted from the tidal model at three locations in the application site. These have been used to calculate an equivalent bed shear stress time-series (due to currents only) for a 30-day period (encompassing two spring-neap cycles). The three locations are the Moray AWAC 2c and 5c deployment locations and the WaveNet Moray Firth wave buoy (Figure 4).

The predicted bed shear stress values are plotted in Figure 27 and compared to the threshold values for mobility of the sediment grain sizes listed in Table 22. The Figure shows that mobilisation events (when the critical bed shear stress values are exceeded) are generally confined to brief periods around peak current flow on spring tides. The proportion of the time series during which each sediment fraction is potentially mobilised is summarised in Table 23.

**Table 23. Estimated potential sediment mobility (due to tidal currents only) at three locations across the application site**

| Location | | Fine Sand (150 μm) | Fine Sand (185 μm) | Fine Sand (215 μm) | Medium Sand (375 μm) | Coarse Sand (750 μm) |
|---|---|---|---|---|---|---|
| Moray AWAC 2c (39 m CD) | Mobility Summary | Not mobile during lowest neaps | Only mobile during springs | Only mobile during springs | Only mobile during highest springs | Not mobile |
| | Mobility % time | 15% | 13% | 11% | 5% | 0% |

| | | | | | | |
|---|---|---|---|---|---|---|
| Moray AWAC 5c (36 m CD) | Mobility Summary | Only mobile during highest springs | Only mobile during highest springs | Not mobile | Not mobile | Not mobile |
| | Mobility % time | 3% | 2% | 2% | 0% | 0% |
| Moray wave buoy (49 m CD) | Mobility Summary | Only mobile during highest springs | Only mobile during highest springs | Only mobile during highest springs | Not mobile | Not mobile |
| | Mobility % time | 2% | 1% | 1% | 0% | 0% |

It is apparent from Table 23 that the greatest potential for sediment mobilisation exists in the north of the application site. However, even here there is only limited potential for sediment mobilisation by tidal currents and the largest sized material that is mobile is medium sand. In the south and west of the application site, only the finer sand fractions (215 µm and smaller) are predicted to be mobile. These predictions of spatial and temporal variations in sediment mobility are considered further in Section 5.5 and have been used to enhance the conceptual understanding of the seabed morphology across the application site.

It is important to note that the calculated bed shear stress is sensitive to the 'roughness' of the seabed with coarser grained and/or more rippled surfaces inducing greater flow turbulence and hence bed shear stress than a fine grained and/or flat surface for the same flow speed. In terms of both grain size and the potential for the development of ripple bedforms, there is known to be variability within the application site (see Section 4.3, Figure 19 and Figure 20). This variation might result in a degree of spatial variability in the inferred bed shear stress across the application site. For the purposes of the present study, where the sediment is typically immobile, the seabed is assumed to be largely featureless at the scale of a few meters (i.e. without very small bedforms).

Although Figure 27 provides information on the duration of exceedance of various mobilisation thresholds, it is important to note that these episodes of exceedance may not be of equal duration on both the ebb and flood tide. Indeed, any asymmetry in the tide (both in terms of the duration of the ebb and flood and the magnitude of peak flows) will result in variations in the direction of sediment transport for different sized sediment particles.

To investigate the effect of asymmetry further, progressive vector analyses have been undertaken using current data obtained from the two MORL AWAC deployments located within the EDA (AWAC 2c and AWAC 3c). Spatial variation in residual flow and residual sediment displacement patterns over a 30-day period for a very fine sand are shown in Figure 28; residual sediment displacement (the net advective pathway) is calculated as the net displacement of water only when current speeds are above the threshold for sediment mobility. The absolute magnitude of residual sediment displacement calculated in this way is not quantitatively meaningful and is anyway very small in these cases as the threshold for mobility is not typically exceeded (as shown in Figure 28); however, the net direction can be used together with the relative magnitude to draw a qualitative comparison between the different sites.

Residual tidal flow is broadly towards the south-west across the application site. This means that finer material held in suspension will generally be transported to the south-west, towards the Inner Moray Firth. However, whilst there is clear residual flow to the south-west, minimal sediment displacement is predicted to occur over the analysis period.

### 4.6.2 Potential Mobility Due to Waves and Wave-Current Interaction

The regional wave climate has been discussed in more detail in Section 3.5. Significant wave heights in excess of 6 m have been observed in the vicinity of the application site during the approximately 12 month metocean survey period and are expected to be as high as 9 m during a 1 in 50-year return period extreme storm event. In comparison to tidal currents, the near bed orbital current velocities associated with such waves in the water depths found at the application site can result in significantly higher bed shear stresses and therefore sediment mobility. As tidal currents (perhaps modified by storm surge) are also present during storm events, the combined influence of both waves and currents was also investigated. (This point is further emphasised through reference to Section 3.3.3 and Figure 25 which clearly shows that larger waves have the capacity to stir the bed, resulting in the increased mobility or suspension of finer sediment). Spatial variations in sediment mobility (due to both currents and waves) across the application site are summarised in Table 24. Once mobilised, resuspended sediments are transported at a rate and direction dependant upon the ambient currents.

**Table 24. Spatial variation in sediment mobility (due to peak mean spring currents and waves of varying height) at four locations across the application site**

| Location (Depth) | Mean Spring Current + Significant wave height (m) | Sediment Fraction | | | | | |
|---|---|---|---|---|---|---|---|
| | | Granule Gravel (3,400 µm) | Very Coarse Sand (1700 µm) | Coarse Sand (850 µm) | Medium Sand (430 µm) | Fine sand (215 µm) | Very fine sand (110 µm) |
| MORL AWAC 2c (39 m CD, mean spring current speed 0.5m/s) | 0 (current only) | Not Mobile | Not Mobile | Not Mobile | Mobile | Mobile | Mobile |
| | 1 | Not Mobile | Not Mobile | Not Mobile | Mobile | Mobile | Mobile |
| | 2 | Not Mobile | Not Mobile | Not Mobile | Mobile | Mobile | Mobile |
| | 3 | Not Mobile | Not Mobile | Mobile | Mobile | Mobile | Mobile |
| | 4 | Not Mobile | Mobile | Mobile | Mobile | Mobile | Mobile |
| | >5 | Mobile | Mobile | Mobile | Mobile | Mobile | Mobile |
| MORL AWAC 3c (49 m CD, mean spring current speed 0.45m/s) | 0 (current only) | Not Mobile | Not Mobile | Not Mobile | Not Mobile | Not Mobile | Mobile |
| | 1 | Not Mobile | Not Mobile | Not Mobile | Not Mobile | Not Mobile | Mobile |
| | 2 | Not Mobile | Not Mobile | Not Mobile | Not Mobile | Not Mobile | Mobile |
| | 3 | Not Mobile | Not Mobile | Not Mobile | Mobile | Mobile | Mobile |
| | 4 | Not Mobile | Not Mobile | Mobile | Mobile | Mobile | Mobile |
| | 5 | Not Mobile | Mobile | Mobile | Mobile | Mobile | Mobile |
| | >6 | Mobile | Mobile | Mobile | Mobile | Mobile | Mobile |
| MORL AWAC 4c (44 m CD, mean spring current speed 0.3m/s) | 0 (current only) | Not Mobile | Not Mobile | Not Mobile | Not Mobile | Not Mobile | Not Mobile |
| | 1 | Not Mobile | Not Mobile | Not Mobile | Not Mobile | Not Mobile | Not Mobile |
| | 2 | Not Mobile | Not Mobile | Not Mobile | Not Mobile | Not Mobile | Not Mobile |
| | 3 | Not Mobile | Not Mobile | Not Mobile | Not Mobile | Mobile | Mobile |
| | 4 | Not Mobile | Mobile | Mobile | Mobile | Mobile | Mobile |
| | >5 | Mobile | Mobile | Mobile | Mobile | Mobile | Mobile |
| MORL AWAC 5c (37 m CD, | 0 (current only) | Not Mobile | Not Mobile | Not Mobile | Not Mobile | Mobile | Mobile |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| mean spring current speed 0.45m/s) | 1 | Not Mobile | Not Mobile | Not Mobile | Not Mobile | Mobile | Mobile |
| | 2 | Not Mobile | Not Mobile | Not Mobile | Not Mobile | Mobile | Mobile |
| | 3 | Not Mobile | Not Mobile | Mobile | Mobile | Mobile | Mobile |
| | >4 | Mobile | Mobile | Mobile | Mobile | Mobile | Mobile |

From Table 24 it is apparent that when taking into consideration the combined influence of tidal currents and wave-induced orbital currents, significantly larger sediment size fractions can become mobile than under tidal currents alone. Spatial variation in both peak current speeds and water depths (affecting the strength of wave penetration to the seabed) within the EDA results in the variability described in the table. In general, wave action is shown to dominate the magnitude and frequency of sediment mobility, and sediment is therefore generally considered to be more mobile in shallower water within the study area.

At all locations, a 4 m high wave in conjunction with a spring tide is sufficient to mobilize medium-sized sand which is found in almost all sediment samples collected from the EDA (Section 4.3). Waves of this size (or greater) are relatively common within the EDA and account for c. 3 to 5% of each of the five observed wave records shown in Figure 13. It is therefore probable that the entire seabed across the EDA is 'active' to some degree. Finer sediments will be generally more (or more frequently) mobilised than coarser sediments.

In the north-east and centre of the EDA, a 1 m high wave in conjunction with a spring tide is sufficient to mobilize medium-sized sand. Waves of 1 m (or greater) account for approximately 50% of the observational wave records and thus medium-sized (or finer) sands are likely to be mobilized relatively frequently. Indeed, the combination of stronger tidal currents in the north of the EDA (MORL AWAC 2c) and moderate depth in the centre of the EDA (MORL AWAC 3c) means these areas of the EDA are likely to be most mobile.

Gravel-sized material may potentially become temporarily mobile during very large (Hs > 5 m) storm events. Such waves are present in the observational wave records from the EDA (Table 15) but are only likely to occur a few times each year at most. Gravel may be moved *in-situ* but is unlikely to be significantly displaced during such episodes.

# 5. Morphodynamic Regime

## 5.1 Overview

The contemporary morphology of the application site as well as the coastal characteristics of the Moray Firth is described in this section. Seabed morphology is considered alongside knowledge of regional sediment transport to develop a conceptual understanding of the seabed morphology in the Moray Firth and to assess the degree to which areas of the seabed may be active and changing in form or level in a net sense over time.

Across the Moray Firth, seabed topography and sediment substrate are variably influenced by the structure and composition of underlying bedrock, the configurations and composition of features originating at former terrestrial and submarine ice-sheet margins, carbonate biological sedimentary input and by the interactions of all these with near bed tidal and wave induced currents (Holmes *et al*., 2004).

During the late Devensian glaciation, ice spread into the Moray Firth and diverged northwards towards Caithness and the Orkney Isles as well as eastwards approximately parallel to the present day Grampian coast (Barne *et al*., 1996). This ice sheet was at its maximum extent approximately 25,000 years ago and covered this region up until around 15,000 years ago. Since the last glacial maximum, the position of sea level has varied considerably in response to both glacio-isostatic rebound of the land and rising glacio-eustatic sea level. However, model simulations of past sea level change suggest that at no point over the past 20,000 years has the application site become sub-aerially exposed (Bradley *et al*., 2011).

## 5.2 Sources of Morphological Data

Information regarding the morphological regime for the application site and surrounding area is available from those sources previously identified in Table 20.

## 5.3 Seabed Morphology

The detailed bathymetry of the EDA is most clearly described by the swath bathymetry data collected during the geophysical survey (Figure 22). Across the MORL EDA, seabed levels range from ~37 m below LAT along the western margin of the application site, approaching the crest of Smith Bank, to ~57 m below LAT along its eastern margin. A broad, irregular, north-north-west to south-south-east trending channel feature is present towards the central/western section of the MORL EDA. This feature is between 300 m and 2600 m wide and its sides are relatively gently sloping. The deepest section of the channel lies at approximately 48.0 m below LAT and maximum seabed gradients of approximately 1 in 75 (<1.0°) are seen on the sides of this feature (Osiris, 2011). The regional morphology surrounding the EDA is also shown in Figure 1.

When examined in more detail, the geophysical survey data also reveals a large number of raised sand ridges and associated shallow troughs over the edges of Smith Bank. Individual ridges stand between 0.3m to 1.2m above surrounding seabed and generally trend north-north-west to south-south-east or west to east. Maximum gradients of approximately 0.7° can be found around the edges of some of the ridges (Osiris, 2011). The multibeam swath backscatter data previously collected during the DTI SEA surveys also reveals the presence of these same sediment (likely gravel) wave features found only on the northern flanks of Smith Bank (Holmes *et al*., 2004) (Figure 29).

The DTI SEA survey report also makes reference to the presence of sharp edged sand patches on Smith Bank. These are elongate features commonly 500 m long and around 2 m thick in their centre and are especially prevalent across the southern half of the application site (Holmes *et al*., 2004). The orientation of their long axis is typically (but not exclusively) north-north-west to south-south-east, i.e. not orientated to the tidal axis but approximately to the direction of approach for large waves. This was found to consistent with the published literature concerning the genesis of these features, i.e. indicating a wave dominated, relatively tidally benign environment.

Across the far-field region, numerous ridges and channels have previously been mapped from echo sounder records compiled by Olex (www.olex.no) (Figure 29). Ridges range in length from 500 m to 20km and are typically ~500 m wide and <10 m high. They are mainly found a short distance to the north-east and east of the application site although one such ridge has been identified within the application site boundary. Channels are mainly found to the south and south-east of the application site and trend broadly west to east. Most of the channels exceed 10km in length, are often several 10's of metres deep and frequently possess branching, sinuous courses (Bradwell *et al*., 2008).

## 5.4 Coastal Morphology

Coastal morphology as well as the nature of longshore sediment transport will strongly influence the susceptibility of the coast to any changes in the baseline wave and current regime.

The coastal characteristics of this region have previously been described by Barne *et al*. (1996) and are summarised in Figure 3. The overview provided by Barne *et al*., is also presented below.

The coastline of the Moray Firth can be described according to its solid geology and its degree of exposure to climatic and tidal influences. There are three distinctive zones:

(i) *The hard Old Red Sandstone rocks of Caithness, together with the predominantly cliffed coastline from Portknockie to Fraserburgh on the north Grampian coast.* These areas are exposed to the full force of winter storms. These conditions allow few opportunities for accretionary habitats such as sand dunes to develop, except in the shelter of kyles (narrow straits) and bays;

(ii) *West from Portknockie*. Here, the Outer Moray Firth is less exposed, though there are still tidal and storm effects, which have moved shingle and sandy sediments to create the extensive sand and shingle formations on either side of the Firth; and

(iii) *The sheltered inlets of the firths (Dornoch, Cromarty and the Inner Moray Firth and Beauly Firth)*. These environments have a much lower energy environment, in which wave attack is reduced and intertidal mudflats and saltmarshes can develop.

The land shelves steeply into the sea off the coasts of Caithness, Banff and Buchan. Along much of the coast, currents have swept the bedrock clean and this is particularly apparent along the Caithness and north Grampian coasts.

Longshore sediment transport along the Moray Firth coastline has previously been described by Ramsey and Brampton (2000). Findings from this investigation have been summarised in Figure 23. The Figure shows that beaches with sediment available for longshore transport are generally confined to the inner parts of the Moray Firth. Where beaches are present (instead of rocky cliff coastline morphology), the beach material generally fines with distance into the Moray Firth, i.e. moving from east to west along the Caithness coastline, beaches are initially boulders and pebbles, becoming gravelly, then progressively sandy and finer into the Inner Firth, where muddy salt marshes dominate the more protected inner estuaries.

## 5.5 Conceptual Understanding of Seabed Morphology

As previously described, the application site is situated on the north-eastern flank of Smith Bank. Overall, Smith Bank is approximately 35km long from south-west to north-east, around 20km wide, rising from a base level of between 50 and 60 m below sea level to less than 35 m. The position, elevation and orientation of the bank is closely associated with the underlying Smith Bank Fault block and the geophysical survey undertaken by Osiris (2011) reveals that Cretaceous sediments are relatively close (<10 m) to the seabed across much of the crest of the bank. The main body of Smith Bank is underpinned by solid bedrock, with variable thickness layers of stable overlying sedimentary deposits and a more mobile sediment veneer. The position and form of Smith Bank is therefore controlled by the underlying geology and so is not sensitive as a whole to minor changes in sediment transport onto, over or off the Bank.

Side scan sonar and multibeam swath backscatter data collected during the site geophysical survey reveals a number of raised sand ridges and associated shallow troughs over the edges of Smith Bank (Cathy Associates, 2011). Across the site, these ridges generally trend north-north-west to south-south-east or west to east although in the north of the site, these bedforms are more typically aligned west-north-west to east-south-east (Figure 20 and Figure 22). The more detailed metocean and other sediment transport information presented in this report were not available to Cathie Associates at the time their analysis was undertaken, including: (i) the direction of tidal current flow across the MORL EDA (Section 3.3.2); (ii) the sediment mobility analyses presented in Table 23; and (iii) published evidence concerning the relationship between the distribution of bedforms and current speed. Taking further account of the combined sets of information suggests the ridges in the north of the MORL EDA may be a mobile bedforms formed by tidal currents. This interpretation is consistent with the earlier findings of Holmes *et al*. (2004) who note that the sediment waves on the north of Smith Bank appear to be migrating to the south and west in a direction that is consistent with the axis of peak tidal currents in this area (Figure 8). Indeed, in the north of the MORL EDA peak flow speeds during mean spring tides are approximately 0.6 m/s. Currents of this magnitude are (just) of sufficient strength to mobilise medium/ coarse sized sand (Table 23) and to form mega-ripples/ small sand waves (Belderson *et al*., 1982) (Figure 30). However, current speeds of less than ~0.55 m/s are not normally sufficient to form transverse bedforms and so, on this basis, it is unlikely that the ridges identified elsewhere across the MORL EDA are sediment waves being actively maintained by tidal currents. Further south, the ridges are also not (generally) aligned perpendicular to the main axis of tidal flow and so, on this basis, are unlikely to be mega-ripples/ small sand waves but might be either relic features from periods of lower later level and other tidal patterns, or contemporary but infrequently mobile features that are the result of the particular wave-current regime in these areas.

In addition to the presence of sediment waves on the north of Smith Bank, the DTI SEA surveys also revealed the presence of sharp edged sand patches over the crest of Smith Bank (Holmes *et al*., 2004; Osiris, 2011) (Figure 20 and Figure 22). Similar features to the sharp edged sand patches identified on Smith Bank have also been mapped elsewhere in the central North Sea (e.g. in the western Dogger Bank region) and are found to be one of the most widespread of all shelf bedforms (Kenyon and Cooper, 2005). They have previously been found in areas where the currents present (tidal and surge induced) are too weak on their own to move sediment as bedload, except on rare occasions. (The modelled extreme, depth averaged, surge currents over 50 years are about 0.6 to 0.9 m/s at the application site - Section 3.3.3). Instead, such a bedform typically becomes mobile when long-period storm waves enhance sediment erosion whilst subsequent transport is controlled by other tidal and non-tidal currents. This observation is consistent with the findings presented in Table 24. On the basis of the above discussion taking further account the available hydrodynamic data, it seems more likely that the north-north-west to south-south-east or west to east trending sand ridges identified across much of the MORL EDA by Cathy Associates (2011) are sharp edged sand patches. These ridges are not orientated to the main tidal axis but instead, approximately to the direction of approach for large waves (Section 3.5.3).

The mechanism by which the patches maintain a fairly constant 2 m height and thickness, together with steep sides, is not fully understood (Holmes *et al*., 2004). However, Belderson *et al*. (1982) note that it might be because storm-wave currents sweep sand from the gravel areas into the patches and that 2m is the typical maximum height to which the storm waves can carry the sand into suspension.

The ridges shown in Figure 29 which are present across much of the far-field region have been interpreted as relict glacial moraines. Similarly, the channels found mainly to the south and south-east of the application site are also suggested to be relict features, formed by the pressurised flow of glacial meltwater beneath the British Ice Sheet (Bradwell *et al*., 2008).

## 6. Summary

This report provides a baseline assessment of physical processes in the MORL EDA Offshore Wind Farm application site and surrounding area. This has primarily been achieved on the basis of data collected during targeted metocean and geophysical survey campaigns, data created using numerical models, and data and information from previously published studies. Overall the findings of the baseline can be summarised as follows:

### 6.1 Hydrodynamic Regime

#### 6.1.1 Water Levels

- The application site is situated within a meso-tidal setting and is characterised by a mean spring tidal range of just under 3 m and a maximum astronomic range (HAT to LAT) of approximately 4 m.

- There is some variation in tidal range along the OFTO transmission cable route, with the highest water levels experienced at the landward end. At Fraserburgh, (near the cable landfall), the mean spring range is 3.7 m.

- Storm surges may cause short term modification to predicted water levels and under an extreme (1 in 50-year return period) storm surge, water levels may be up to 1.25 m above predicted levels.
- It is probable that relative sea levels will rise in this region during the course of the 21st Century and by 2100 is likely to be approximately 0.5 to 0.8 m higher across the application site.
- Climate change may be expected to slightly increase the mean water level over the lifetime of the proposed development; however, the tidal range about the new mean level will likely remain not measurably affected.

### 6.1.2 Currents

- Information available on the strength of tidal currents in this region shows that recorded (depth-averaged) peak spring current speeds are around 0.45-0.5 m/s, with the fastest speeds recorded in the north of the EDA.
- Current speed decrease with distance into the Moray Firth. Peak mean spring current speeds in the western end of the WDA are around 0.3 m/s.
- Along most of the cable route, peak current speeds are typically less than 0.4 m/s. However, they increase markedly at and south east of Kinnairds Head, in a region extending approximately 10km offshore of the cable landfall. Here, peak spring tidal currents speed are more typically 1.0m/s (maximum 1.15 m/s) due to acceleration around the headland.
- Both storm waves and storm surges may cause short term modification of astronomically-driven tidal currents. During a 1:1 year storm event, orbital currents are likely to approach 1 m/s in the south of the application site, in the relatively shallow water over the crest of Smith Bank. Currents of this magnitude are considerably greater than that observed during peak spring tidal flows. Similarly, under an extreme (1 in 50-year return period) storm surge, current speeds may be more than twice that encountered under normal peak spring tide conditions.
- Residual tidal currents (over a period of days to weeks) are directed into the Moray Firth.
- Climate change is not expected to have any effect on the local tidal current regime (currents are largely controlled by the corresponding tidal range) over the lifetime of the proposed development.

### 6.1.3 Waves

- The wave regime in the Outer Moray Firth includes both swell waves generated elsewhere in the North Sea and locally generated wind waves. The wave regime in the Outer Moray Firth is typically characterised by wind waves although longer period swell waves can be identified within the observational wave records collected from within and nearby to the application site.

- The OFTO transmission cable route is likely to be exposed to waves of equal or possibly larger size than the wind farm itself from exposed offshore sectors; the size of waves from other fetch limited sectors will vary along the route depending upon the wind direction and corresponding fetch. The variable and on average greater water depths along the route mean that the ability of a given wave condition to penetrate to the seabed may also be variable.

- Even though water depths across the application site are no less than 35 m, storm waves sufficiently large to cause water motion at the seabed are not uncommon.

- Along the coastlines of the mid and Inner Moray Firth, waves have a critical role to play in driving sediment transport through the process of longshore drift.

- Climate change is predicted to cause variability in the inter-annual wave climate over the lifetime of the proposed development; however, historical trends have shown that this variability may include both increases and decreases in mean storminess on decadal timescales.

### 6.1.4 Stratification and Fronts

- The Outer Moray Firth may experience some seasonal thermal stratification.

- Applying general oceanographic theory, it is likely that the strength and natural position of both fronts is governed by the magnitude of tidal current flows in the adjacent inshore areas and of seasonal stratification in adjacent offshore areas.

- Climate change is not expected to have any effect on the range of natural variability in the location or strength of stratification and fronts over the lifetime of the proposed development.

## 6.2 Sedimentary and Morphodynamic Regimes

### 6.2.1 Sediments

- Seabed sediments across the application site generally consist of Holocene gravelly sand and sand; fine (silt and clay sized) particles are largely absent. A modal peak grain size at 185 µm (fine sand) was found in over half of the grab samples collected from the MORL EDA. Other modal peak grain sizes were also variably observed across the application site, ranging from 24,000 µm (pebble gravel) to 150 µm (fine sand). The proportion of shell in sediment samples from and nearby to the application site are frequently in excess of 50% (Partrac, 2010; BGS, 1987).

- Seabed sampling was attempted at 20 locations along the export cable route. Near to the wind farm site, in intermediate water depths, the cable route will transit areas of mixed sands and gravels, with a initially small and variable fines content. Seabed sediments become progressively finer in deeper water along the route, becoming relatively muddy in the deepest parts, at the eastern end of the Southern Trench. The sediment character and distribution in these offshore sections is the result of the relatively benign tidal regime and the spatially variable effect of wave action at the seabed, depending upon the local water depth.

- Across much of the EDA, surficial marine sediments are generally thin (~0.5 m) with the underlying glacial till very close to the surface.

- An extensive blanket of Quaternary deposits are present across almost the entire Moray Firth with sediment thicknesses in excess of 100 m commonly observed. Within the application site the Quaternary units are of variable thickness, ranging from <10 m to c. 150 m. These sediments are underlain by a thick unit of firm to very hard Lower Cretaceous clay.

- The available evidence suggests that (bedload) material is travelling into the Firth from the north, passing along the Caithness coast and towards the Inner Moray Firth. Tidal currents are largely incapable of mobilising anything larger than fine sand-sized material within the application site and as a result, there is only limited net bedload transport of sediment due to tidal currents alone.

- However, the combination of tidal and non-tidal currents and wave induced currents during storms results in considerably higher current speeds at the bed. As a result, it is likely that the commonly present medium-sized sand is regularly mobilised across the application site during storms. Owing to the combination of higher tidal current speeds and moderate water depths, it is likely that the northern areas of the EDA are most active in this way.

- Across the application site, suspended sediment concentrations are typically very low (approximately < 5 mg/l). However, during storm events, near bed current speeds can be significantly increased due to the influence of waves stirring of the seabed, causing a short-term increase in suspended sediment concentration. Coarser sediments may be transported a short distance in the direction of ambient flow or down-slope under gravity before being redeposited. Finer material that persists in suspension will eventually be transported in the direction of net tidal residual flow, i.e. to the south-west, into the Firth.

- Climate change is not expected to have any effect on the type or distribution of sediments within the extent of and over the lifetime of the proposed development.

### 6.2.2 Morphology

- The application site spans the crest and north-east flank of Smith Bank and is characterised by water depths in the range 37 to 57 m below LAT. The shallowest depths are found in the west of the application site whilst the greatest depths are found in the east.

- Bedforms identified within the application site have been considered alongside the findings from the sediment mobility analysis as well as published literature from this region to develop a conceptual understanding of the morphological regime. Particular attention has been focused on ascertaining those mapped bedforms which are likely to be active and those that are relict.

- Active seabed bedforms are controlled by the combination tidal flows and wave-induced orbital currents. Low sediment waves orientated transverse to the main axis of tidal flow are suggested to be present in the north of the application site whilst sharp-edged sand patches are suggested to be present across much of the MORL EDA.

- Relict seabed bedforms exist as a result of past processes (mainly glacial) and therefore are not maintained by contemporary physical processes. Of particular note are a series of tunnel valleys cut by pressurised flow beneath the former British Ice Sheet, along with glacial moraine ridges deposited between approximately 15,000 to 20,000 years ago.

- The coastal characteristics of the Moray Firth coastline are highly variable, ranging from the predominantly hard rock Caithness and Buchan coastline to the soft coastlines of the Inner Firth.

- Climate change is not expected to have any effect on the form or function of Smith Bank over the lifetime of the proposed development.

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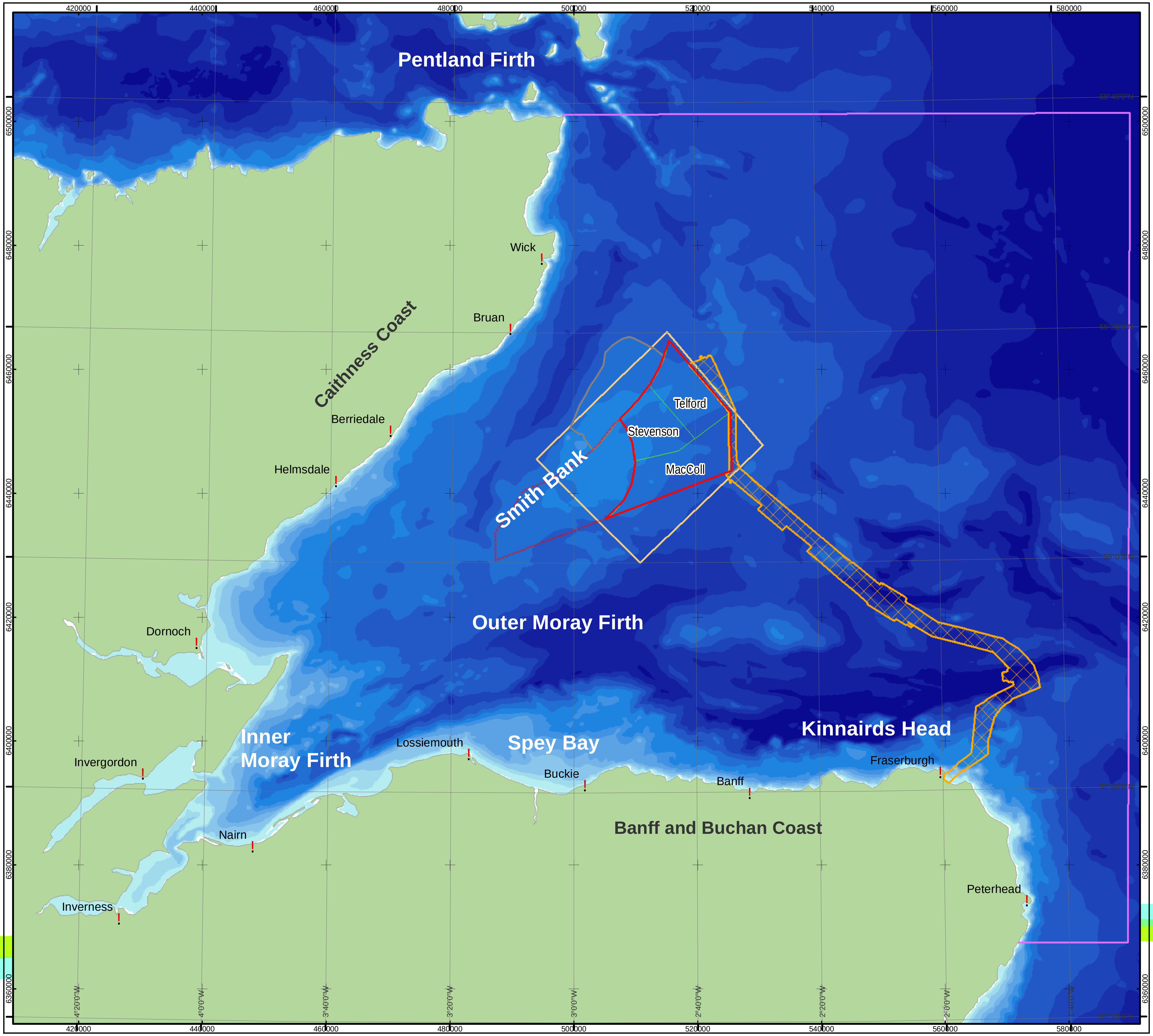


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REPSOL

**Moray Offshore Renewables Ltd**

KEY

- MORL EDA
- MORL WDA
- Beatrice Offshore Wind Farm
- OFTO Transmission Cable
- Site Boundaries
- Far-Field Study Boundary
- Near-Field Study Boundary

m MSL

- < -100
- -99 - -80
- -79 - -70
- -69 - -60
- -59 - -50
- -49 - -40
- -39 - -30
- -29 - -25
- -24 - -20
- -19 - -16
- -15 - -10
- -9 - -6
- -5 - 0

Horizontal Scale: 1:585,000 A3 Chart

0 15,000 30,000 Metres

Geodetic Parameters: WGS84 UTM Zone 30N

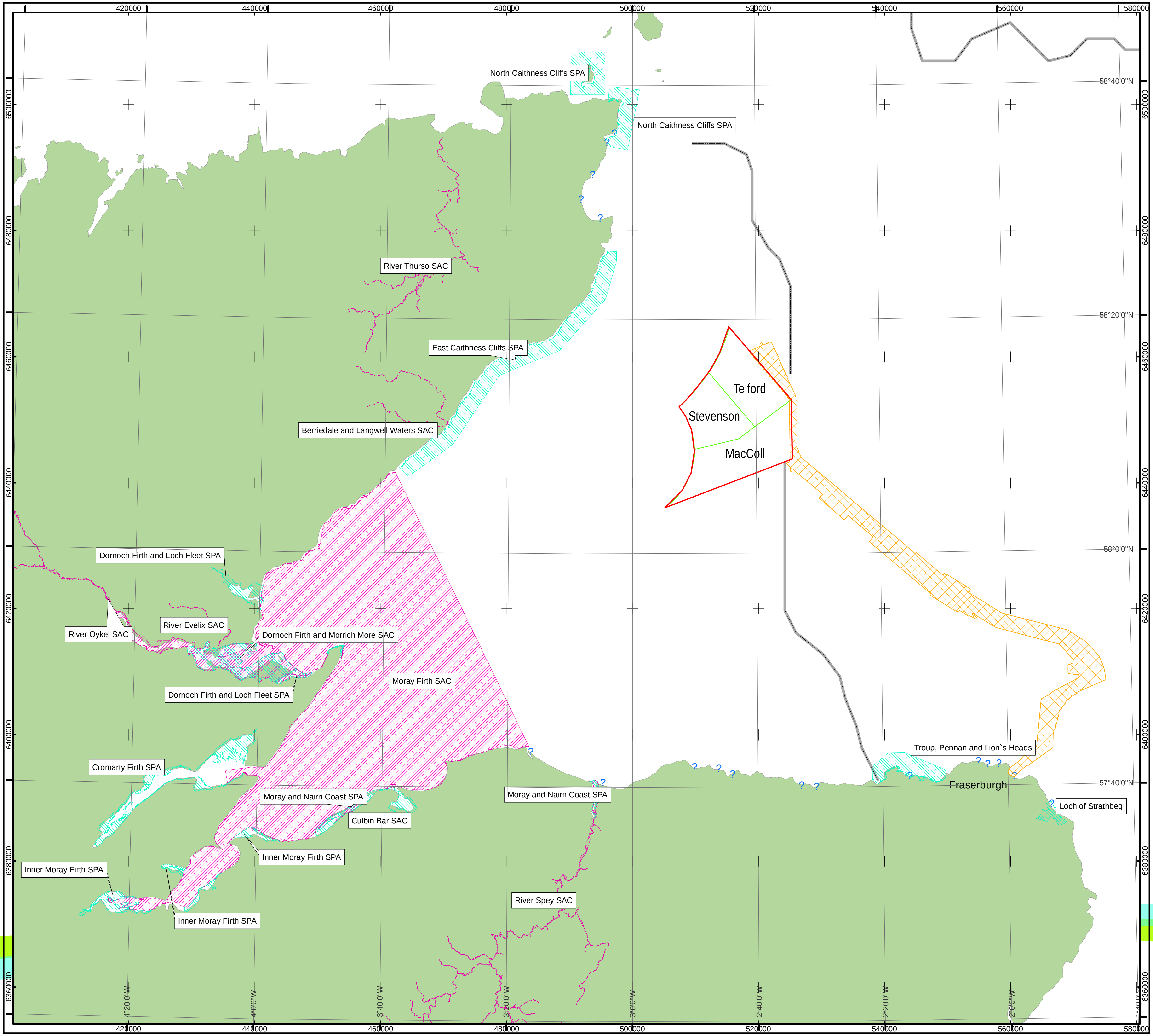
Produced: MCE
Reviewed: NMW
Approved: PH

Date: 04/05/2012 Revision: A

REF: 8460001-PPW0201-ABP-MAP-001

# Fig 1 - Study Area

Moray Offshore Renewables Ltd



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REPSOL

**Moray Offshore Renewables Ltd**

KEY

- MORL EDA
- OFTO Transmission Cable Corridor
- Site Boundaries
- SPA Sites
- SAC Sites
- Surfing Locations
- Fronts

Horizontal Scale: 1:575,000 A3 Chart

0 15,000 30,000 Metres

Geodetic Parameters: WGS84 UTM Zone 30N

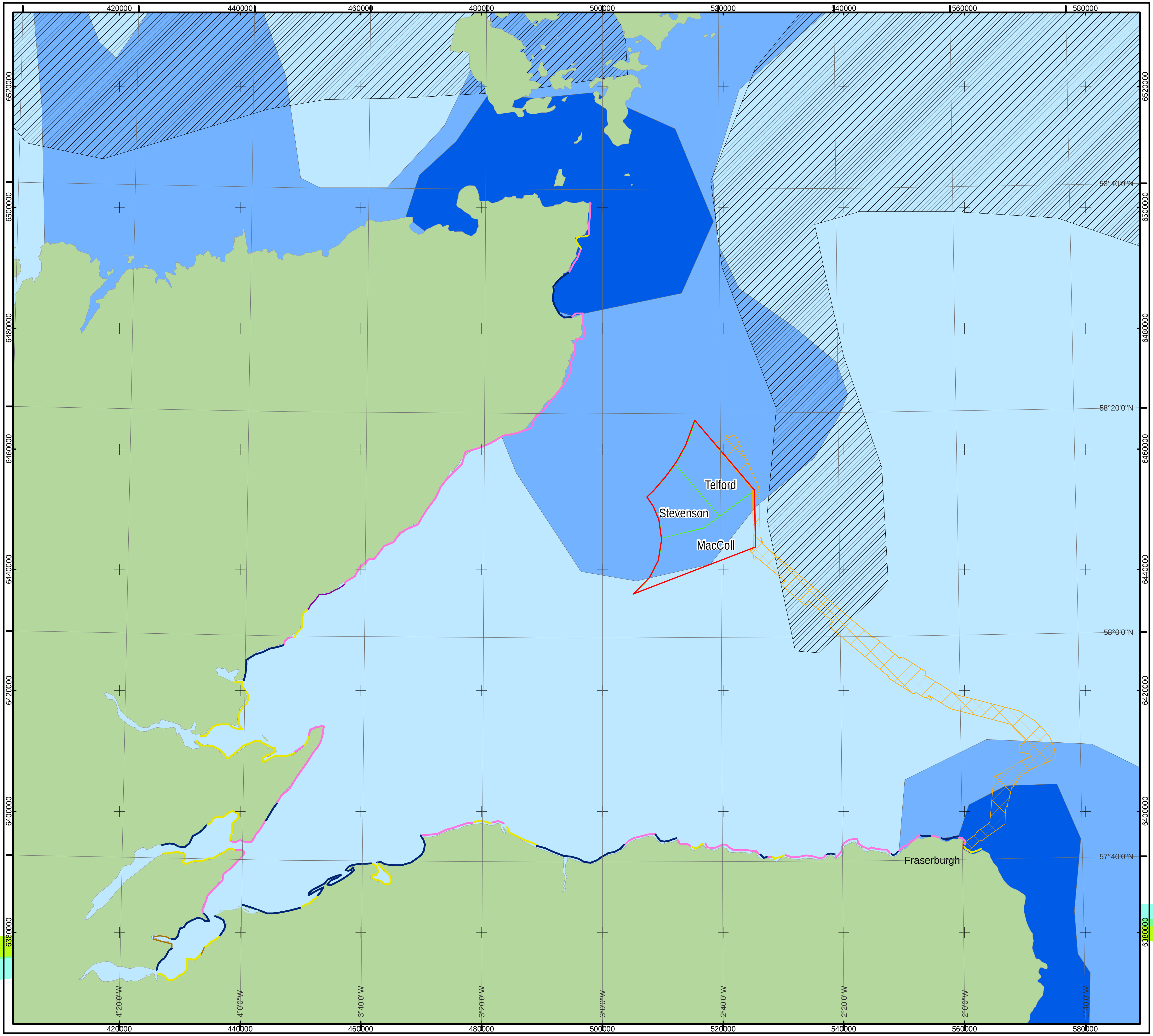
Produced: MCE
Reviewed: NMW
Approved: PH

Date: 04/05/2012 | Revision: A

REF: 8460001-PPW0201-ABP-MAP-002

Fig 2 - Designated Sites and Identified Receptors in the Moray Firth

Moray Offshore Renewables Ltd

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REPSOL

**Moray Offshore Renewables Ltd**

KEY

- MORL EDA
- OFTO Transmission Cable Corridor
- Site Boundaries

Coastal type

- Dominantly Bedrock
- Dominantly Sand
- Links, Raised Beach and Land <5m elevation
- Marsh
- Sand / Bedrock
- Sand / Shingle
- Fronts
- Mixed Water
- Transition Zone
- Stratified Water

Horizontal Scale: 1:600,000 A3 Chart

0 15,000 30,000 Metres

Geodetic Parameters: WGS84 UTM Zone 30N

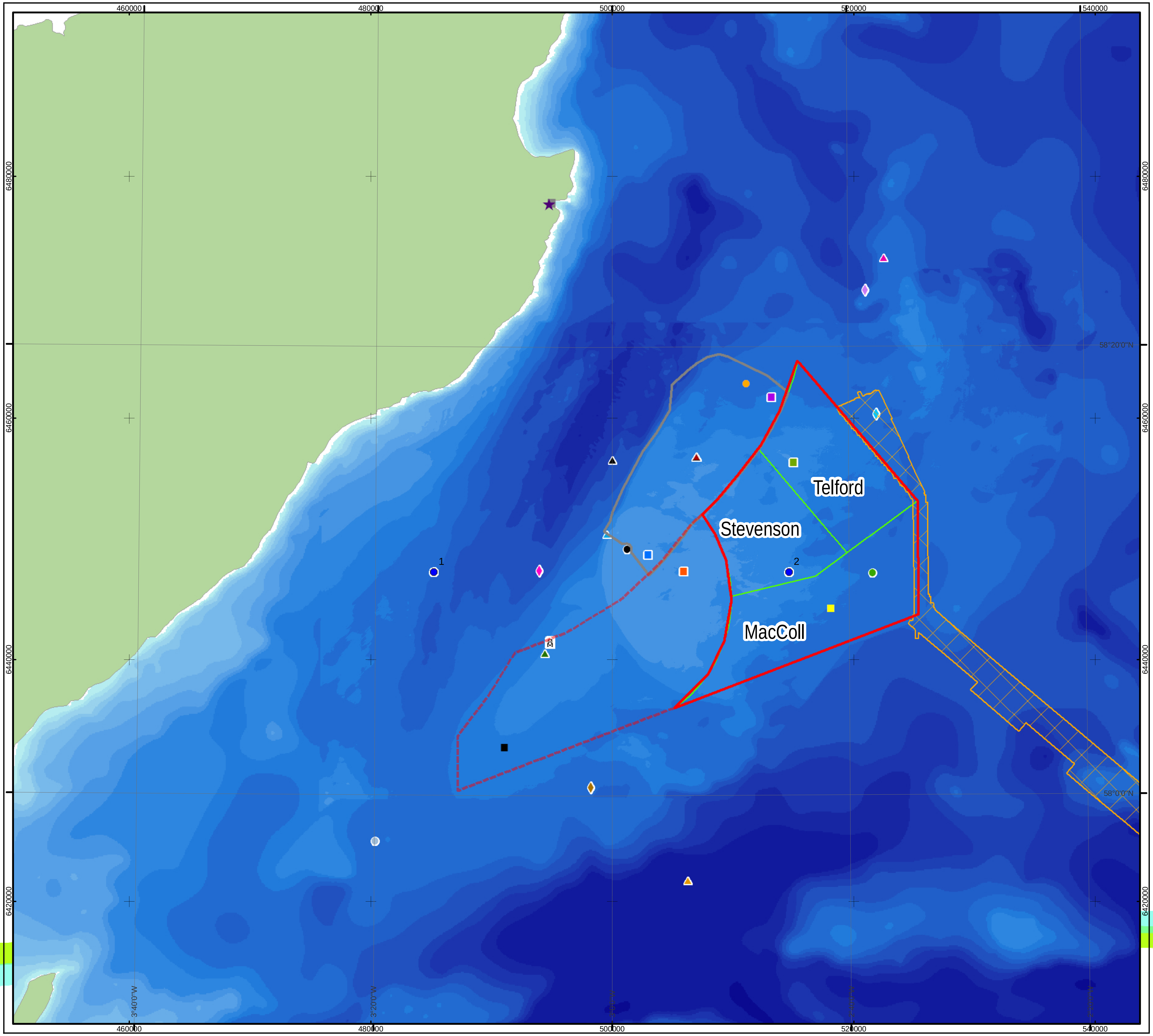
Produced: MCE
Reviewed: NMW
Approved: PH

Date: 12/01/2012 Revision: A

REF: 8460001-PPW0201-ABP-MAP-003

Fig 3 - Coastal Characteristics of the Moray Firth

Moray Offshore Renewables Ltd

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REPSOL

**Moray Offshore Renewables Ltd**

- MORL EDA
- MORL WDA
- Beatrice Offshore Wind Farm
- OFTO Transmission Cable Corridor
- Site Boundaries
- Beatrice Wave Buoy
- Analysis Point
- Moray AWAC 3c
- Moray AWAC 4c
- Analysis Point 1
- Beatrice AWAC 2a
- Beatrice AWAC 3a
- Beatrice Wave Buoy
- Moray Wave Buoy
- Jacky Platform Wave Buoy
- Beatrice Alpha Oil Platform
- Moray AWAC 2c
- Moray AWAC 5c
- WaveNet Moray Firth Wave Buoy
- Tidal Diamond F
- Tidal Diamond G
- Tidal Diamond M
- Tidal Diamond N
- Wick Airport Weather Station
- Wick Tide Gauge
- NOC Surge Predictions (Centroid)

BODC Data Locations

- b0014185
- b0020756
- b0020953
- b0029252
- b0049799

Horizontal Scale: 1:300,000 A3 Chart

0 7,750 15,500 Metres

Geodetic Parameters: WGS84 UTM Zone 30N

Produced: MCE
Reviewed: NMW
Approved: PH

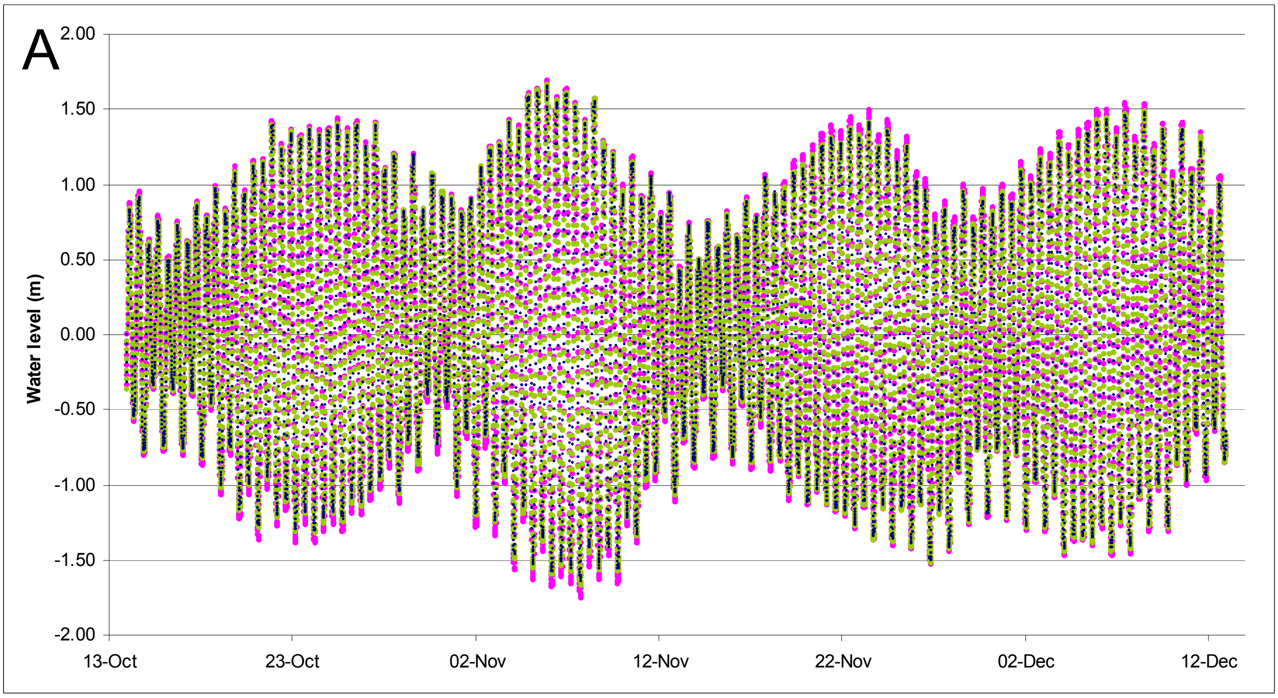
Date: 04/05/2012 | Revision: A

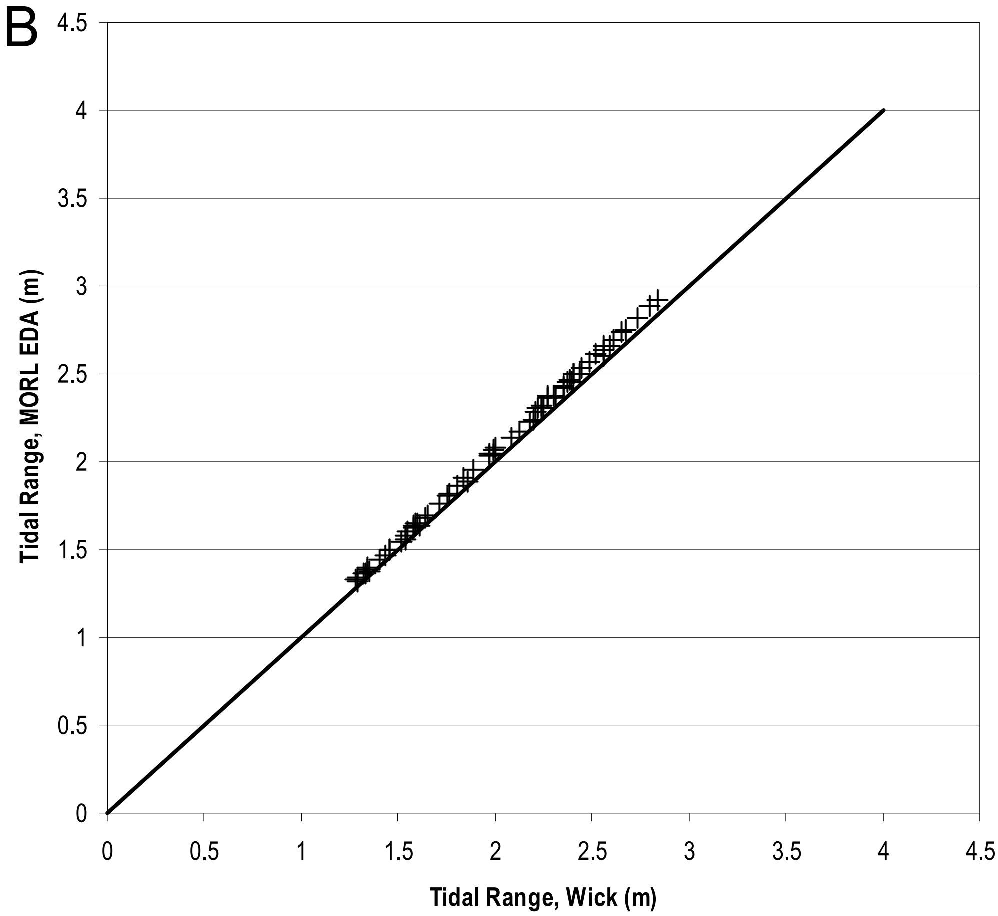
REF: 8460001-PPW0201-ABP-MAP-004

## Fig 4 - Data and Deployment Locations in the Moray Firth

Moray Offshore Renewables Ltd

NOTE: For bathymetry legend see Figure 1.






- Moray AWAC 5c
- Moray AWAC 3c
- Moray AWAC 2c

**A**: Water Level Data from the MORL EDA AWACs; **B**: Correlation between Tidal Ranges Measured at Wick Tide Gauge and at the MORL EDA

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Produced: DOL
Reviewed: CLH
Approved: WSC

A4 Chart

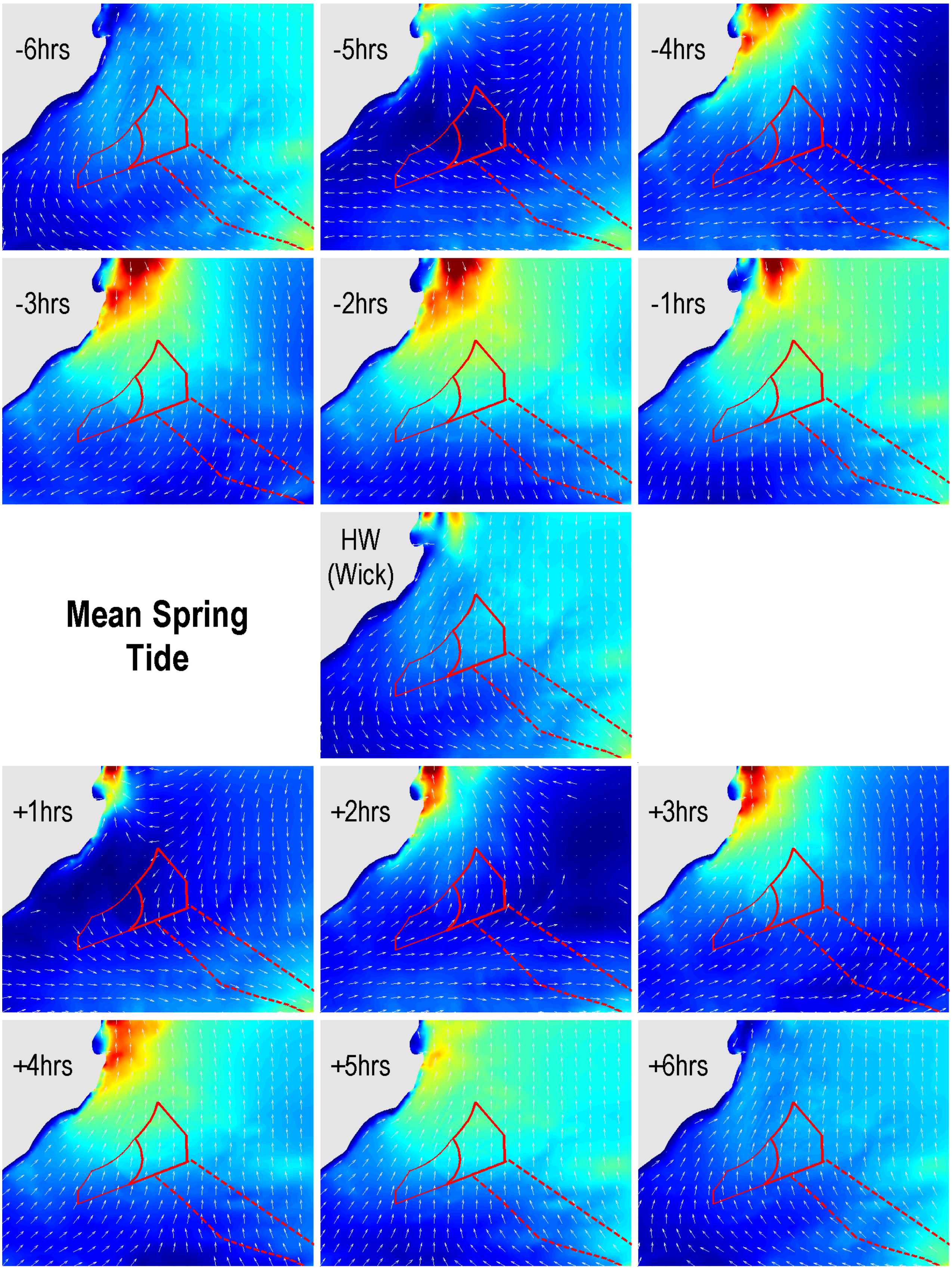
Revision:

Date: 01/06/12

REF: 8460001-PPW0201-ABP-MAP-005

Figure 5. Water Levels in the Project Site

Moray Offshore Renewables Ltd




>1.0
0.8
0.6
0.4
0.2
0.0

Current speed (m/s)
*(Arrows indicate current direction for speeds >0.05m/s)*

MORL EDA

MORL WDA

MORL WDA

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Moray Offshore Renewables Ltd

Produced: DOL
Reviewed: CLH
Approved: WSC

A4
Chart

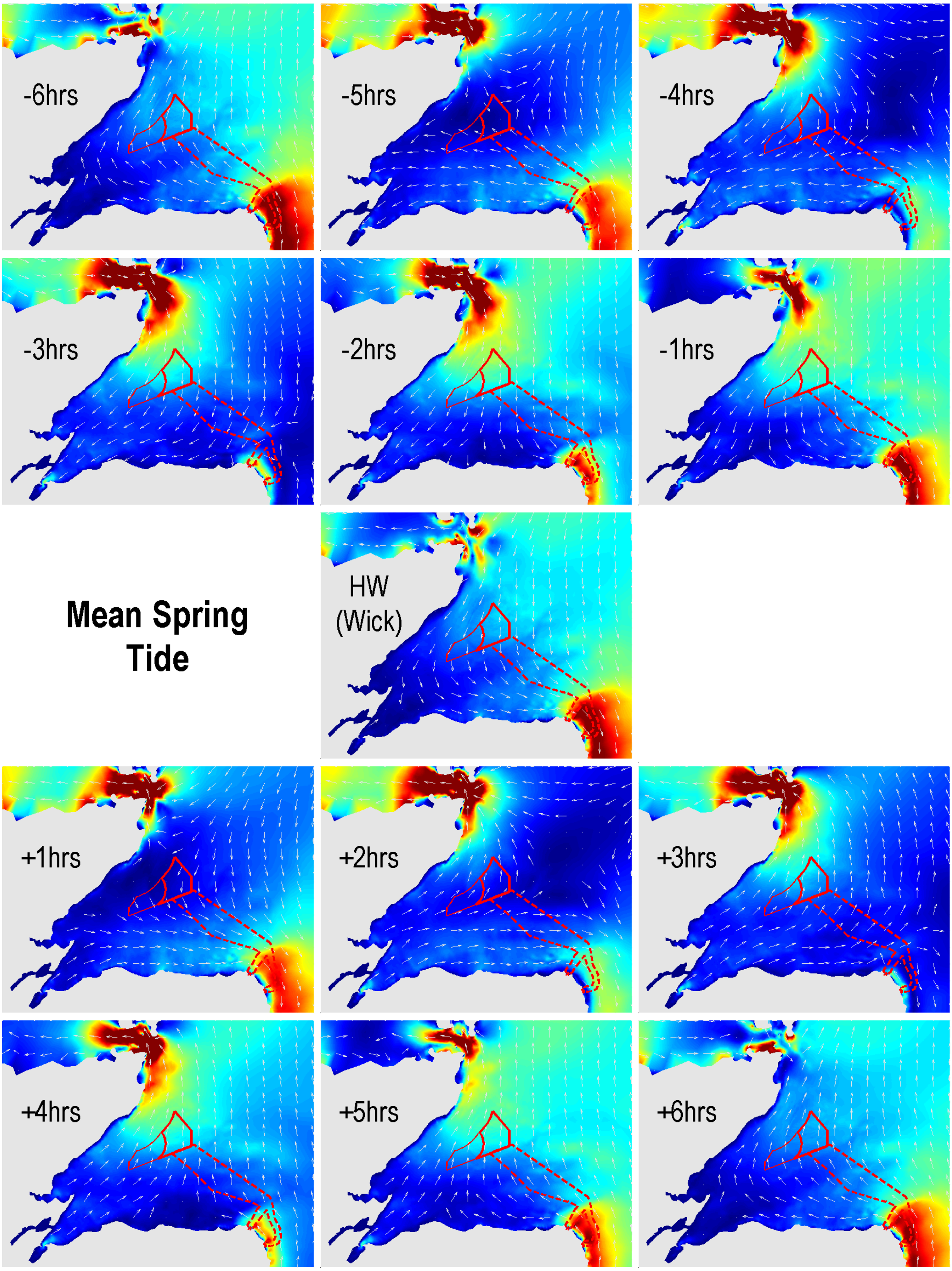
Revision:

Date: 01/06/12

REF: 8460001-PPW0201-ABP-MAP-006

Figure 6. Modelled Near-Field Spring Tidal Flow Patterns

Moray Offshore Renewables Ltd




>1.0
0.8
0.6
0.4
0.2
0.0

Current speed (m/s)
*(Arrows indicate current direction for speeds >0.05m/s)*

MORL EDA

MORL WDA

MORL WDA

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**Moray Offshore Renewables Ltd**

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Approved: WSC

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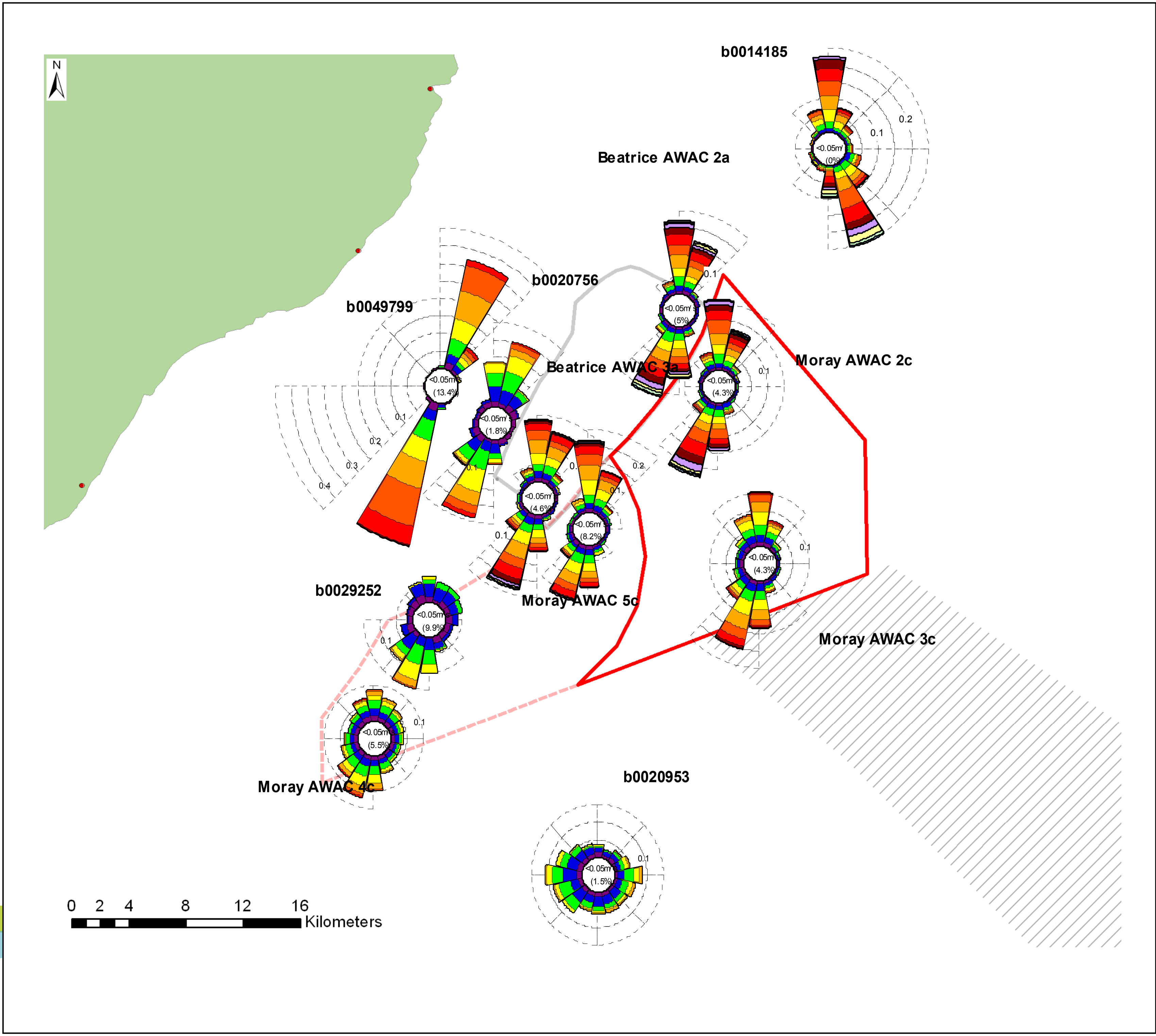
Date: 01/06/12

REF: 8460001-PPW0201-ABP-MAP-007

Figure 7. Modelled Far-Field Spring Tidal Flow Patterns

Moray Offshore Renewables Ltd

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A4 Chart

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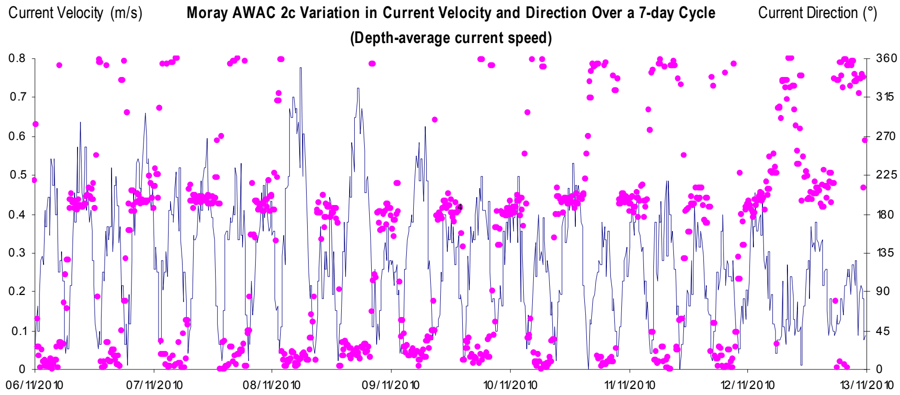
Reviewed: CLH
Approved: WSC

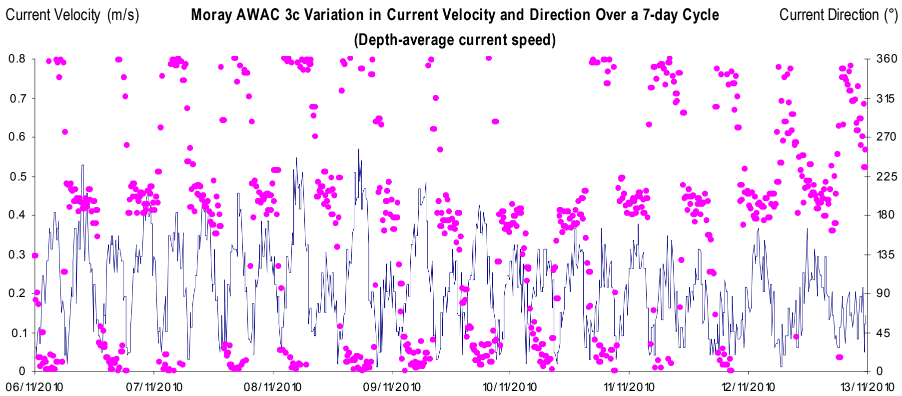
Date: 1/6/12 | Revision: B

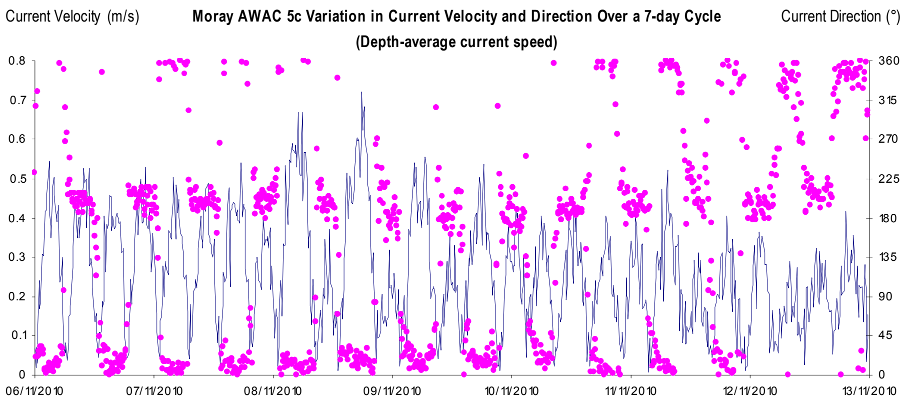
REF: 8460001-PPW0201-ABP-MAP-008

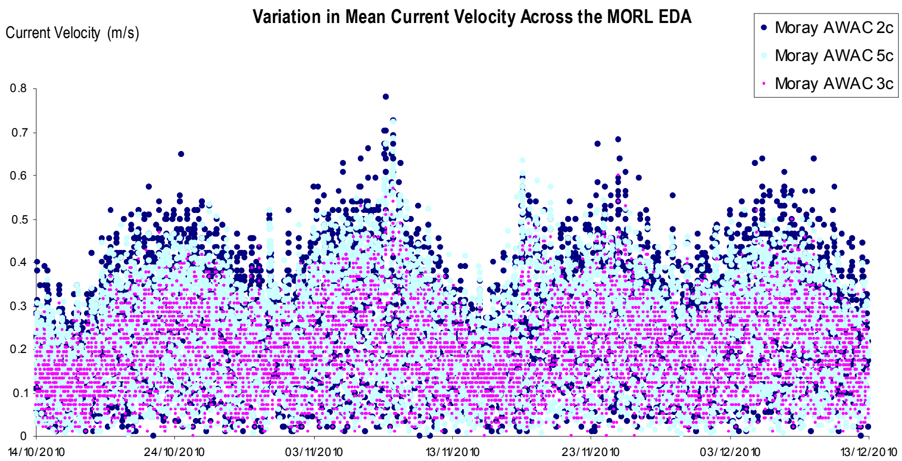
Figure 8. Observational Current Records from within and near to the Project

Moray Offshore Renewables Ltd




Current speed (m/s)
Current direction (°N)

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Moray Offshore Renewables Ltd

Produced: DOL
Reviewed: CLH
Approved: WSC

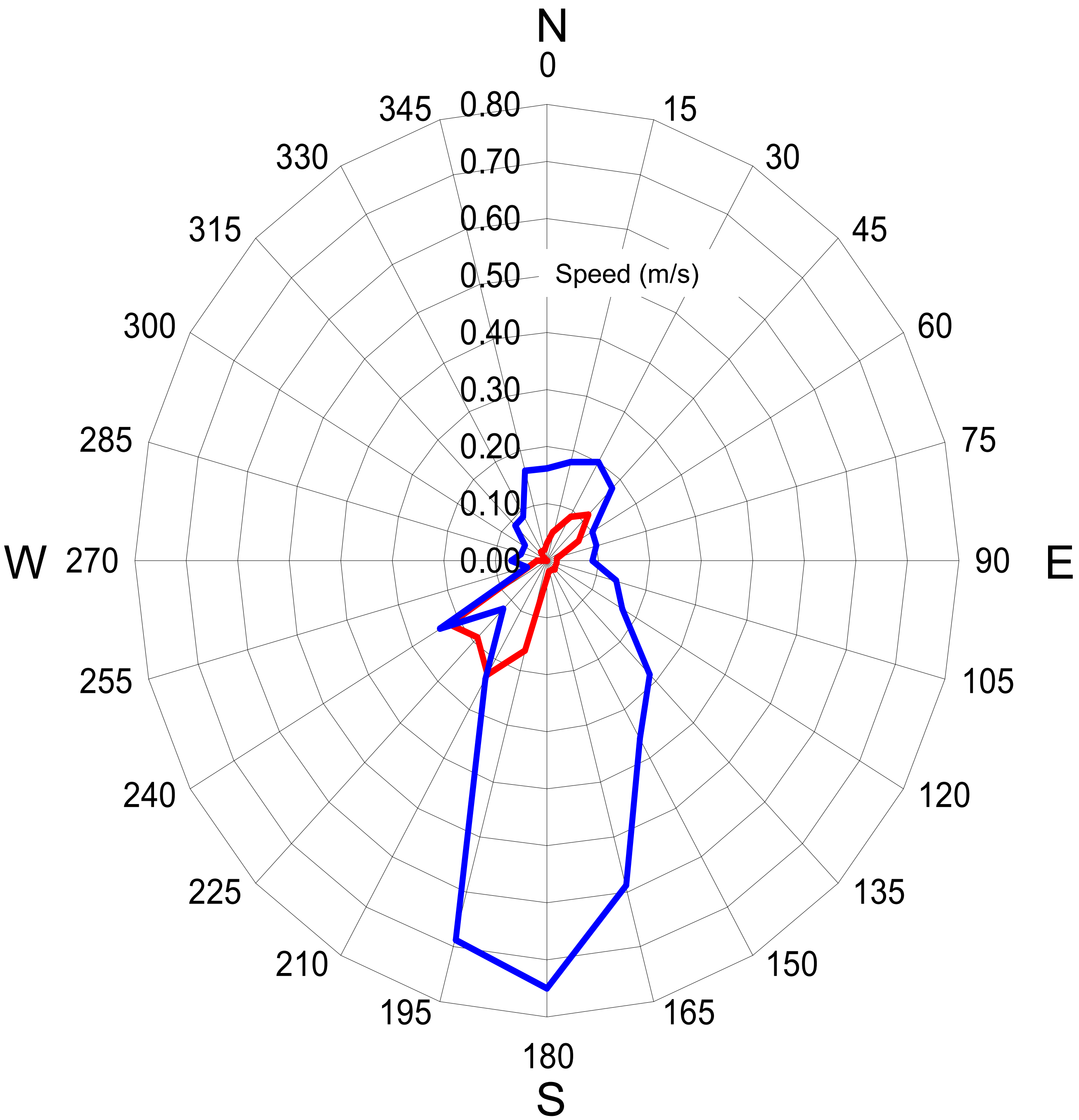
A4
Chart

Revision:
Date: 01/06/12

REF: 8460001-PPW0201-ABP-MAP-009

Figure 9. Variation in Current Speed Across the Project Area

Moray Offshore Renewables Ltd




Location 1 (west of site)
Location 2 (east of site)

See Figure 4 for locations

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Reviewed: CLH
Approved: WSC

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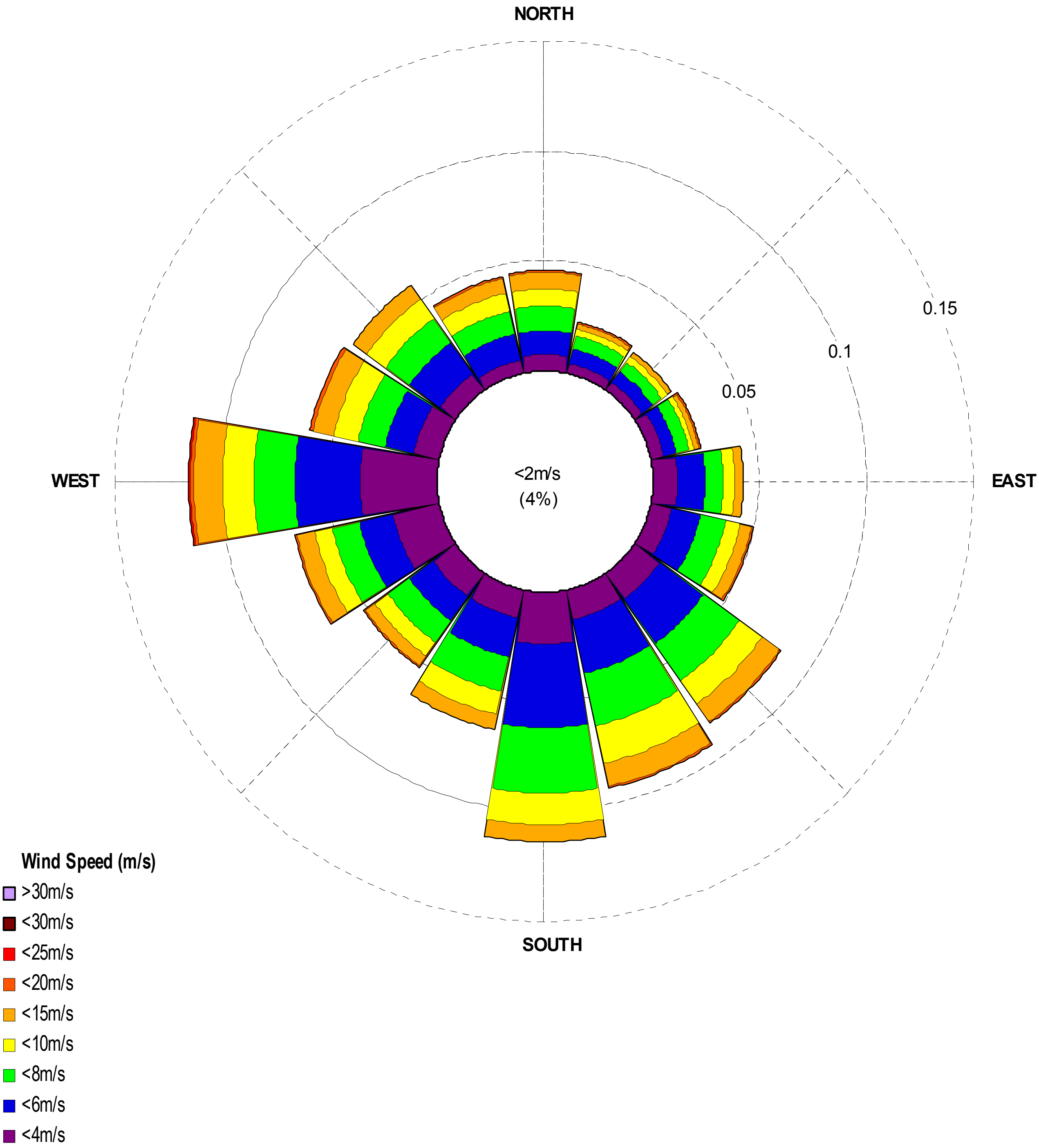
Figure 10. The Directional Distribution of 50-year Return Period Surge Currents.

Moray Offshore Renewables Ltd



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Reviewed: CLH
Approved: WSC

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Chart

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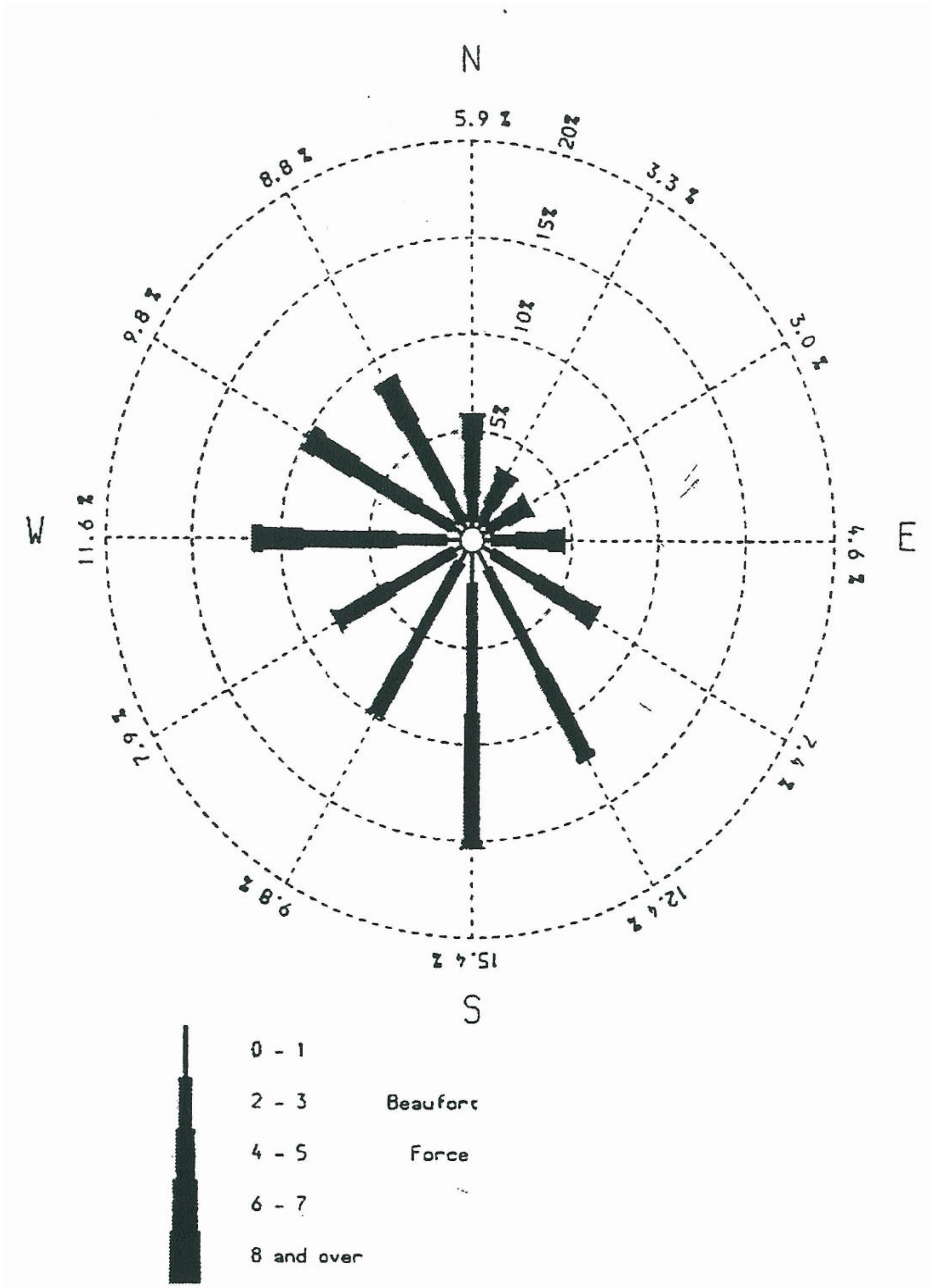
Date: 01/06/12

REF: 8460001-PPW0201-ABP-MAP-011

Figure 11. Wind Rose for Wick Airport (January 1996 - January 2011)

Moray Offshore Renewables Ltd




Data source: Babtie Dobbie Ltd, 1994.
See Figure 1 for location of Lossiemouth.

Moray Offshore Renewables Ltd

Produced: DOL
Reviewed: CLH
Approved: WSC

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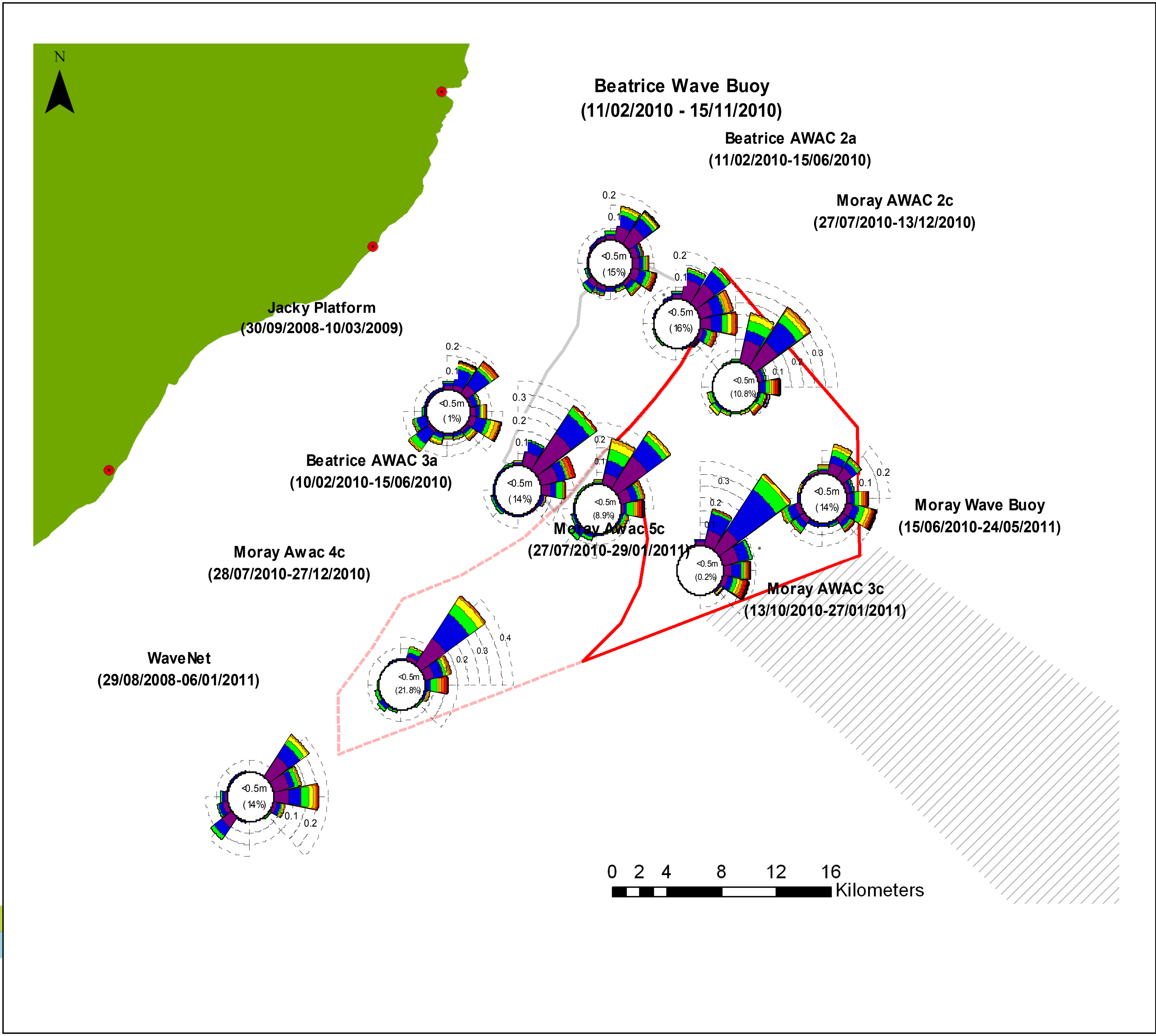
Chart

Revision:
Date: 01/06/12

REF: 8460001-PPW0201-ABP-MAP-012

Figure 12. Wind Rose for 1976-88 from Lossiemouth

Moray Offshore Renewables Ltd

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A4 Chart

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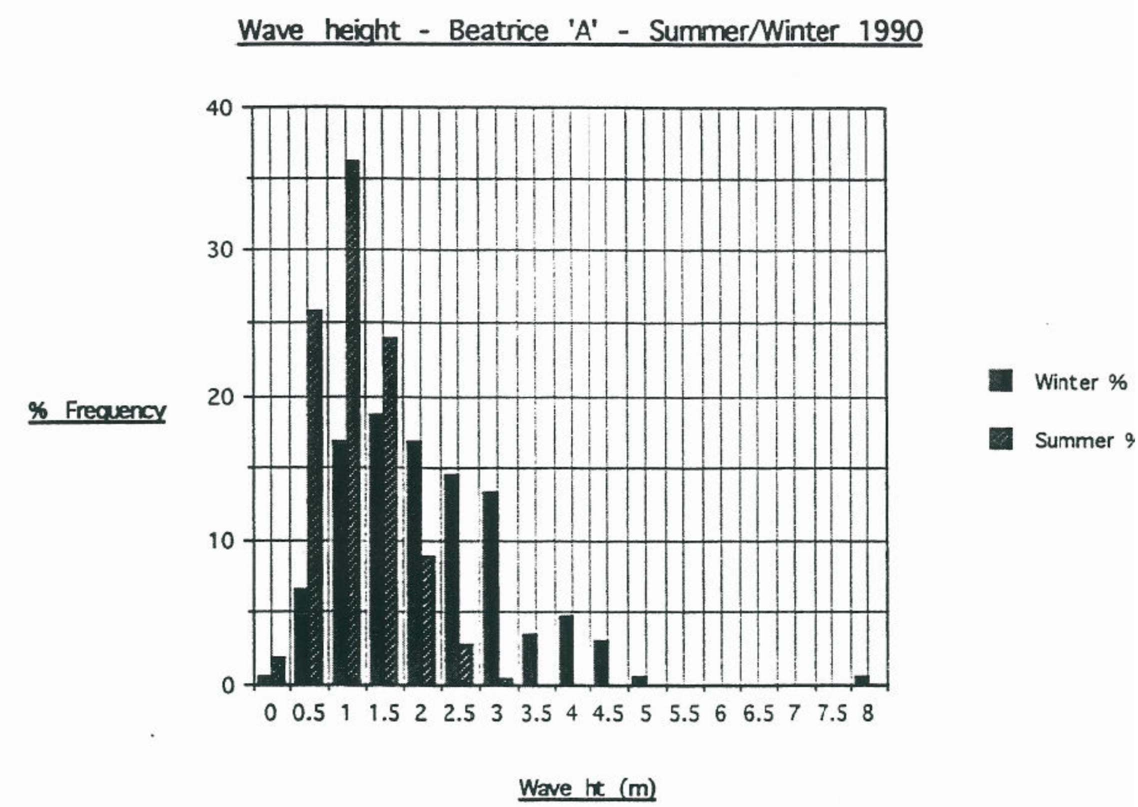
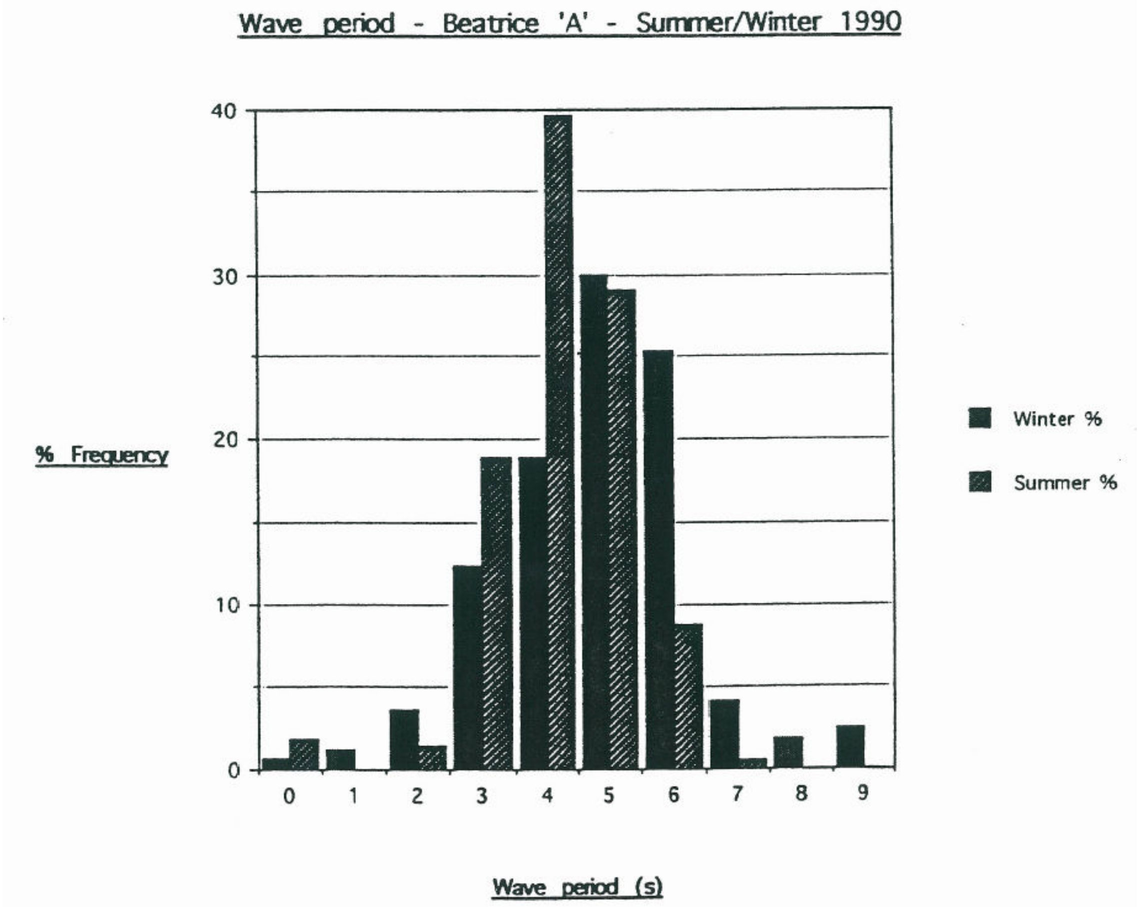
Date: 1/6/12 | Revision: B

REF: 8460001-PPW0201-ABP-MAP-013

Figure 13. Observational Wave Records from within and near to the Project Area

Moray Offshore Renewables Ltd



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Moray Offshore Renewables Ltd

Produced: DOL
Reviewed: CLH
Approved: WSC

A4
Chart

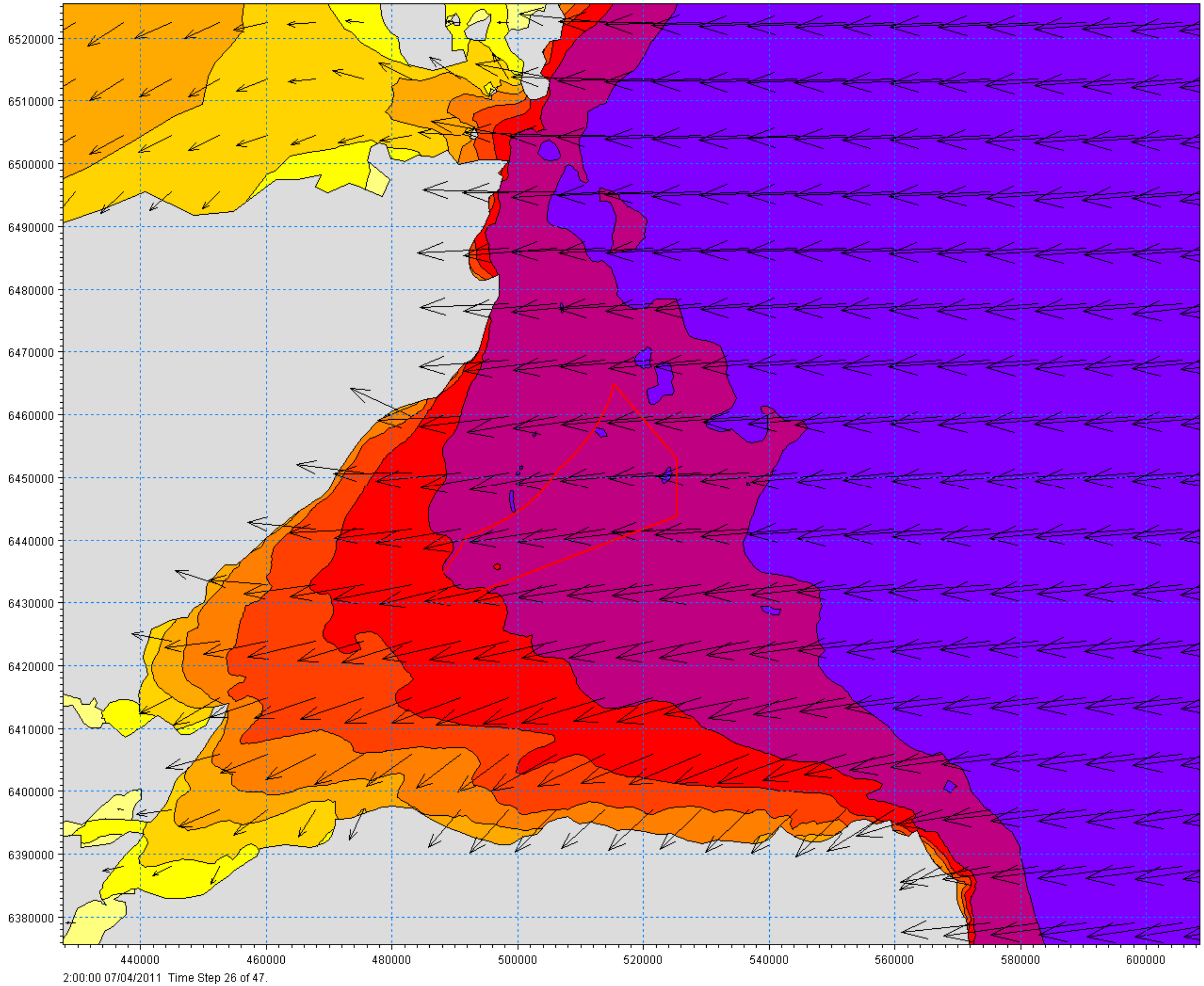
Revision:

Date: 01/06/12

REF: 8460001-PPW0201-ABP-MAP-014

Figure 14. Wave Height and Period for Beatrice A Oil Platform, Summer/Winter 1990

Moray Offshore Renewables Ltd




Moray Offshore Renewables Ltd

| | |
|---|---|
| | >11 |
| | <11 |
| | <10 |
| | <9 |
| | <8 |
| | <7 |
| | <6 |
| | <5 |
| | <4 |
| | <3 |
| | <2 |
| | <1 |
| | <0.15 |

MORL Zone Boundary

A4 Chart

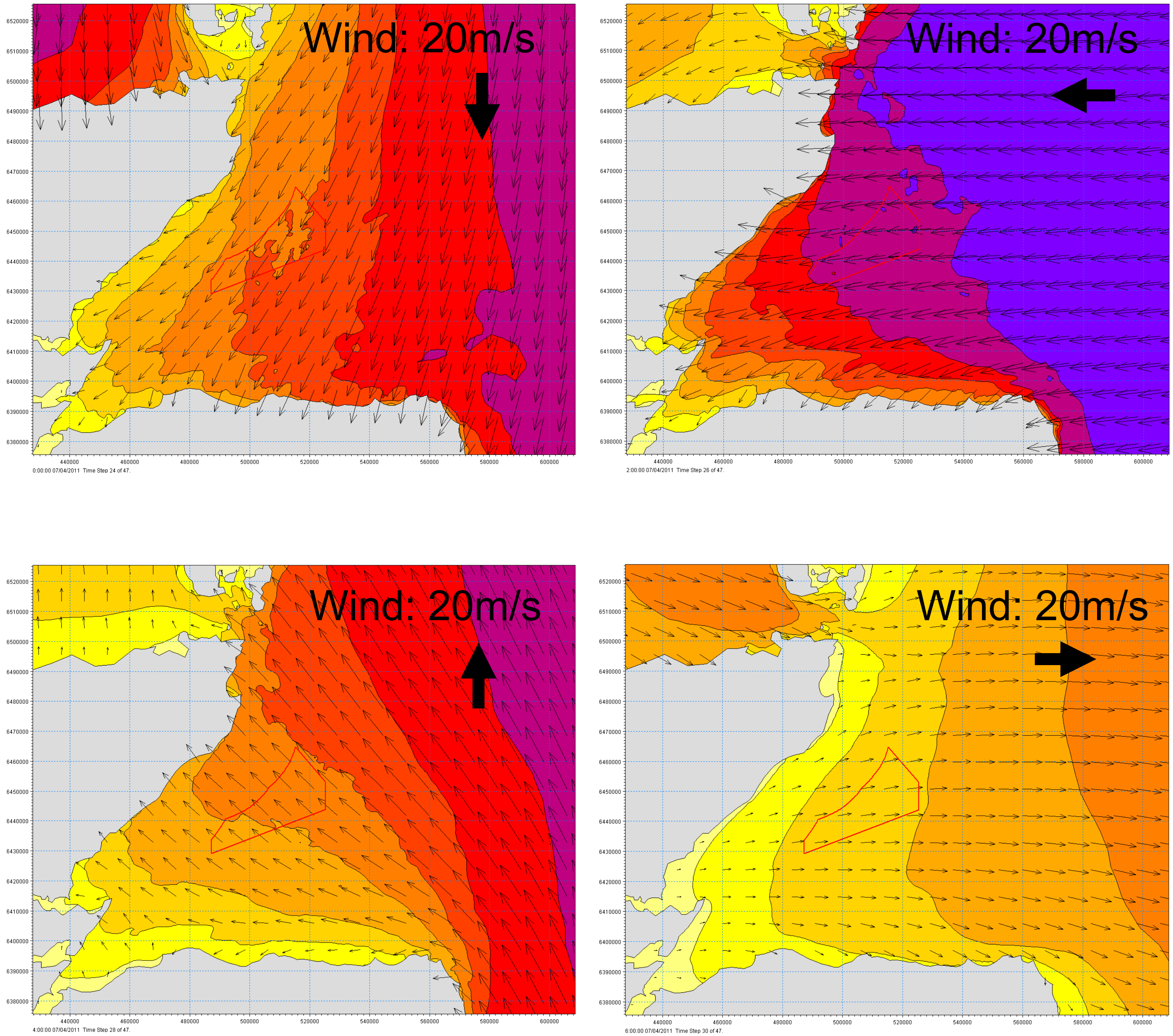
Produced: DOL
Reviewed: CLH
Approved: WSC

Date: 1/6/12 Revision: B

REF: 8460001-PPW0201-ABP-MAP-015

Figure 15. Significant Wave Heights Resulting from Characteristic Easterly Wind Events

Moray Offshore Renewables Ltd




Moray Offshore Renewables Ltd

| | |
|---|---|
| >11 | |
| <11 | |
| <10 | |
| <9 | |
| <8 | |
| <7 | |
| <6 | |
| <5 | |
| <4 | |
| <3 | |
| <2 | |
| <1 | |
| <0.15 | |

MORL Zone Boundary

A4 Chart

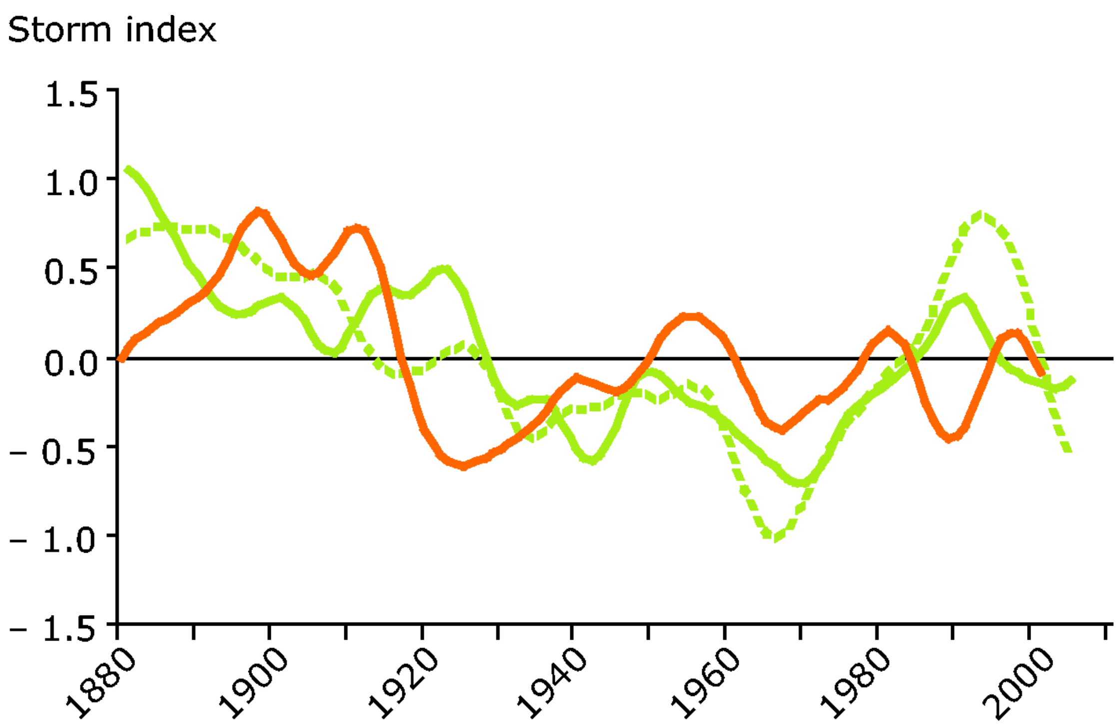
Produced: DOL
Reviewed: CLH
Approved: WSC

Date: 1/6/12 Revision: B

REF: 8460001-PPW0201-ABP-MAP-016

Figure 16. Significant Wave Heights Resulting from Winds of 20m/s

Moray Offshore Renewables Ltd




Moray Offshore Renewables Ltd

North-western Europe
North Europe
Central Europe

A4 Chart

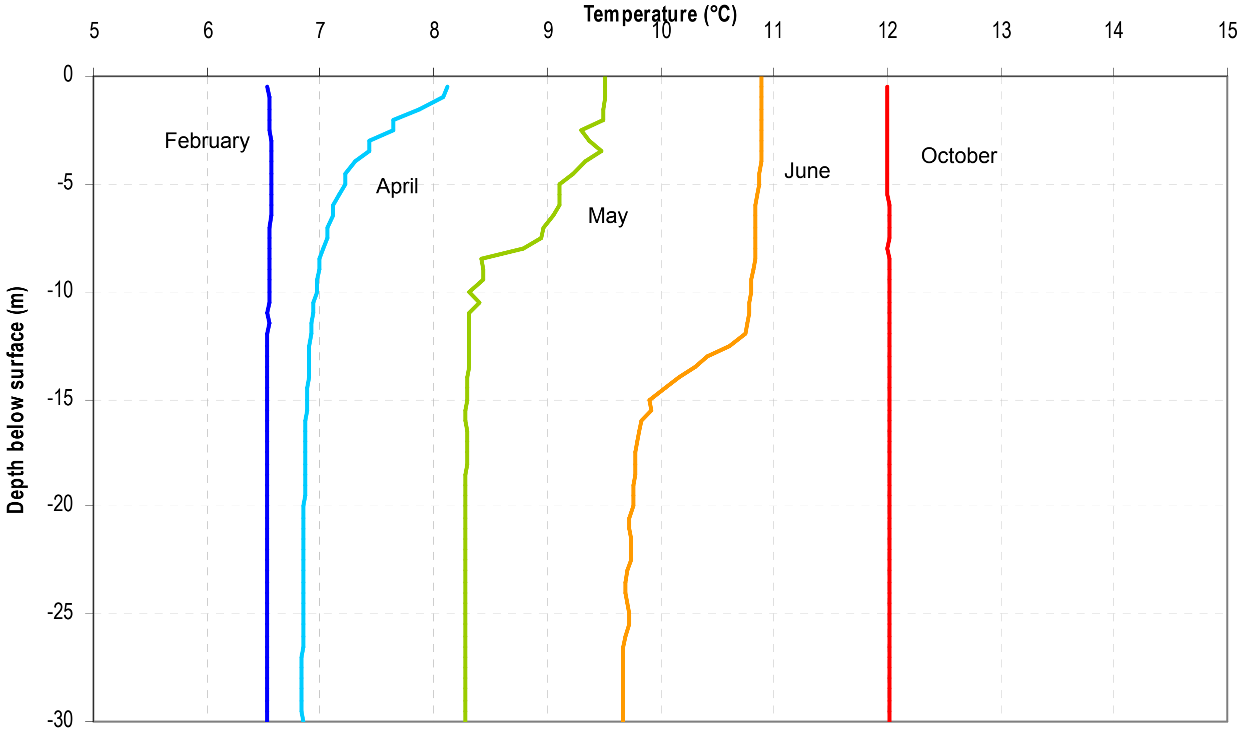
Produced: DOL
Reviewed: CLH
Approved: WSC

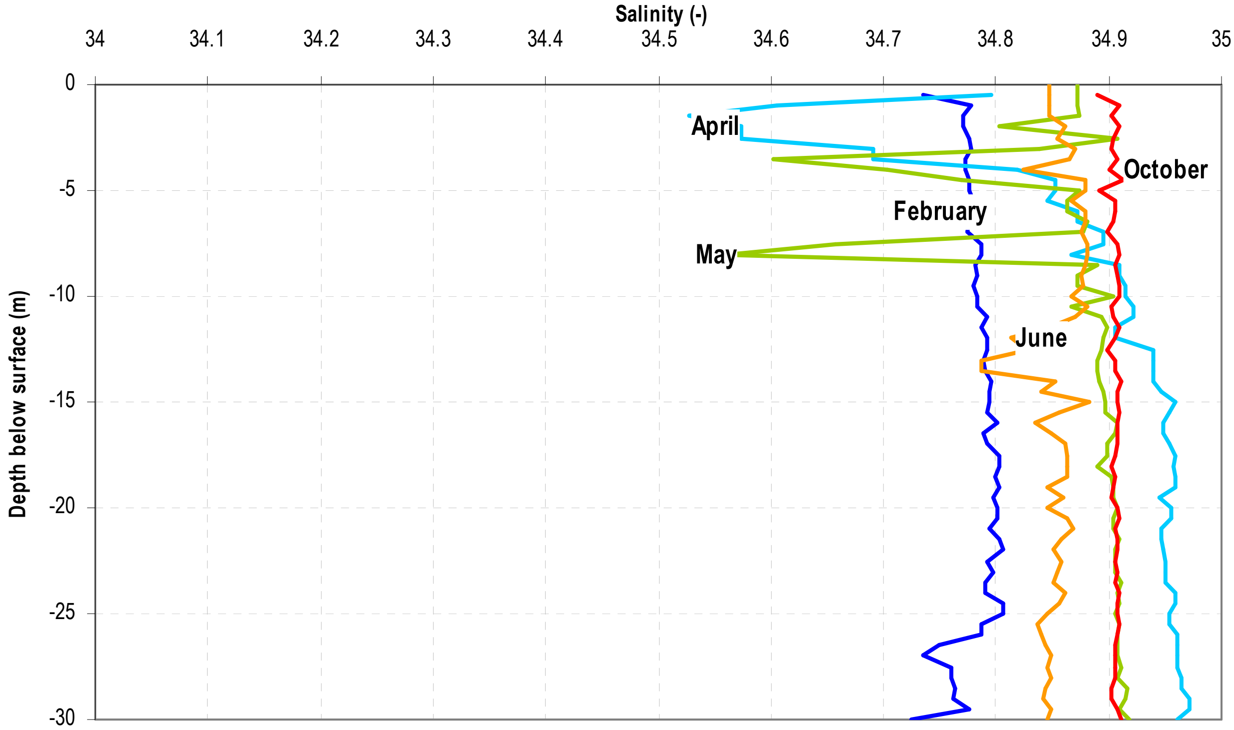
Date: 1/6/12
Revision: B

REF: 8460001-PPW0201-ABP-MAP-017

Figure 17. Storm Index for Various Parts of Europe 1881 - 2005

Moray Offshore Renewables Ltd






renewables REPSOL

Moray Offshore Renewables Ltd

Produced: DOL
Reviewed: CLH
Approved: WSC

A4
Chart

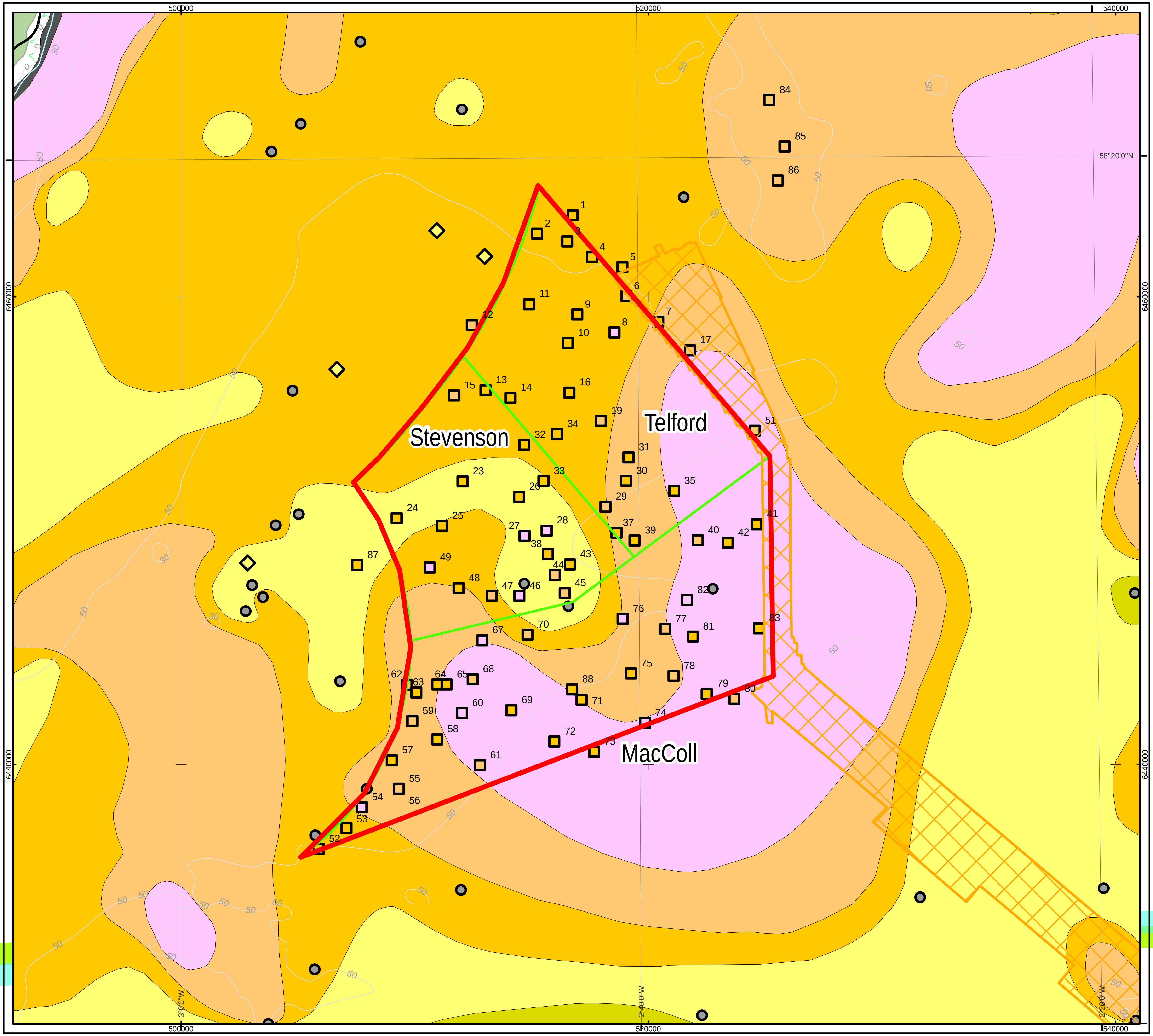
Revision:

Date: 01/06/12

REF: 8460001-PPW0201-ABP-MAP-018

Figure 18. Measured Seasonal Vertical Stratification near to the MORL Development Zone

Moray Offshore Renewables Ltd




**Moray Offshore Renewables Ltd**

KEY

- MORL EDA
- OFTO Transmission Cable
- Site Boundaries
- BGS Grab Samples

Emu Grab Samples (Folk)

- Gravelly Sand
- Sandy Gravel
- Slightly Gravelly Sand

Partrac Grab Sample (Folk)

- Sand
- Gravelly Sand
- Muddy Sandy Gravel
- Muddy Sand
- Sandy Gravel
- Slightly Gravelly Sand
- Sand
- Rock

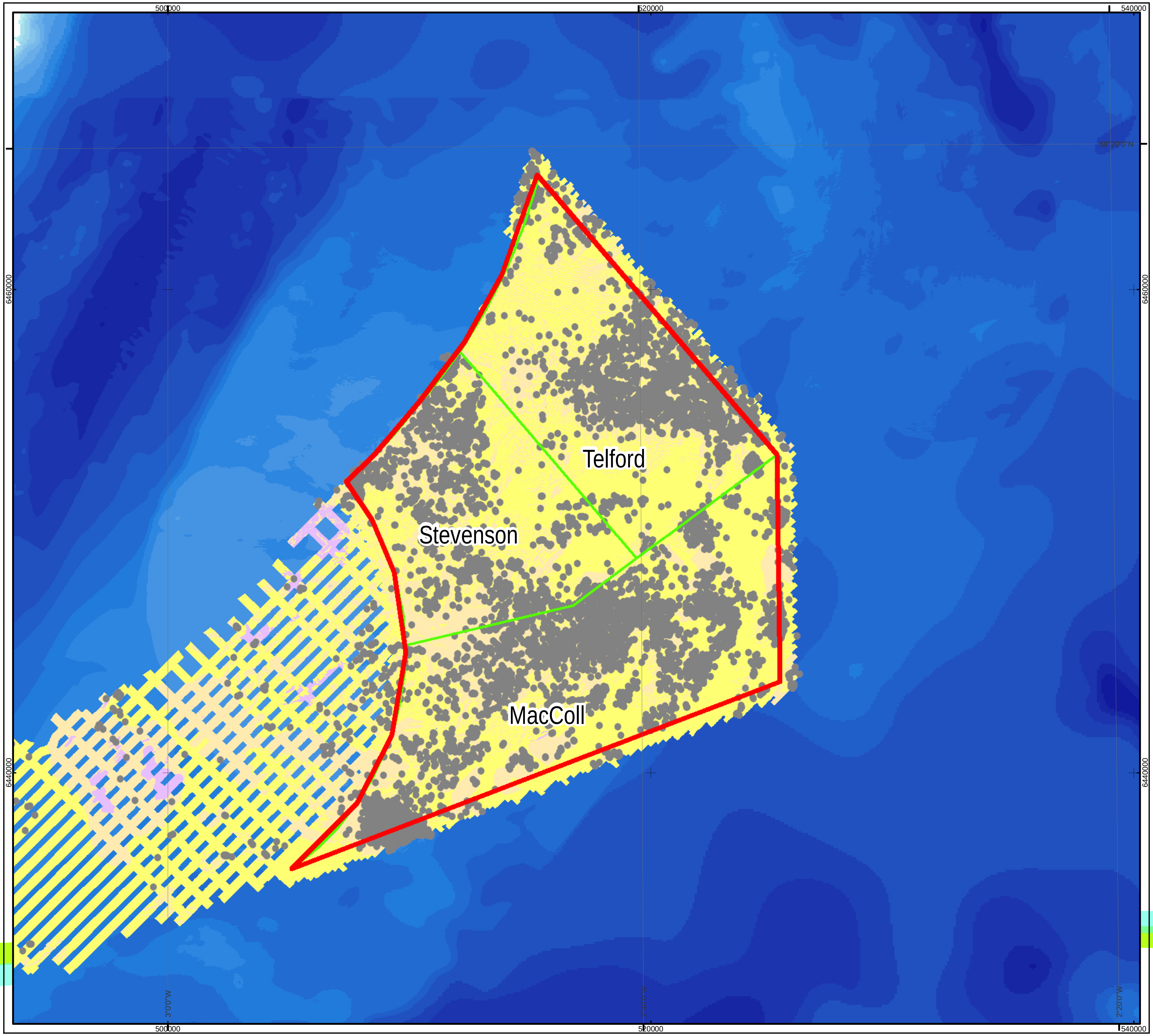
Horizontal Scale: 1:155,000 A3 Chart

0 4,100 8,200 Metres

| | |
|---|---|
| Geodetic Parameters: | WGS84 UTM Zone 30N |
| Produced: MCE<br>Reviewed: NMW<br>Approved: PH | |
| Date: 04/05/2012 | Revision: A |
| REF: 8460001-PPW0201-ABP-MAP-019 | |

## Fig 19 - Seabed Sediments within and Near the MORL EDA

Moray Offshore Renewables Ltd




**Moray Offshore Renewables Ltd**

KEY

- MORL EDA
- Site Boundaries
- Small Boulders
- Sand
- Sand and Gravel
- Gravel

Bathymetry (m MSL)

- -5 - 0
- -9 - -6
- -15 - -10
- -19 - -16
- -24 - -20
- -29 - -25
- -34 - -30
- -39 - -35
- -45 - -40
- -49 - -46
- -55 - -50
- -59 - -56
- -65 - -60
- -69 - -66
- -74 - -70
- -79 - -75
- -99 - -80
- < -100

Horizontal Scale: 1:150,000 A3 Chart

0 4,000 8,000 Metres

Geodetic Parameters: WGS84 UTM Zone 30N

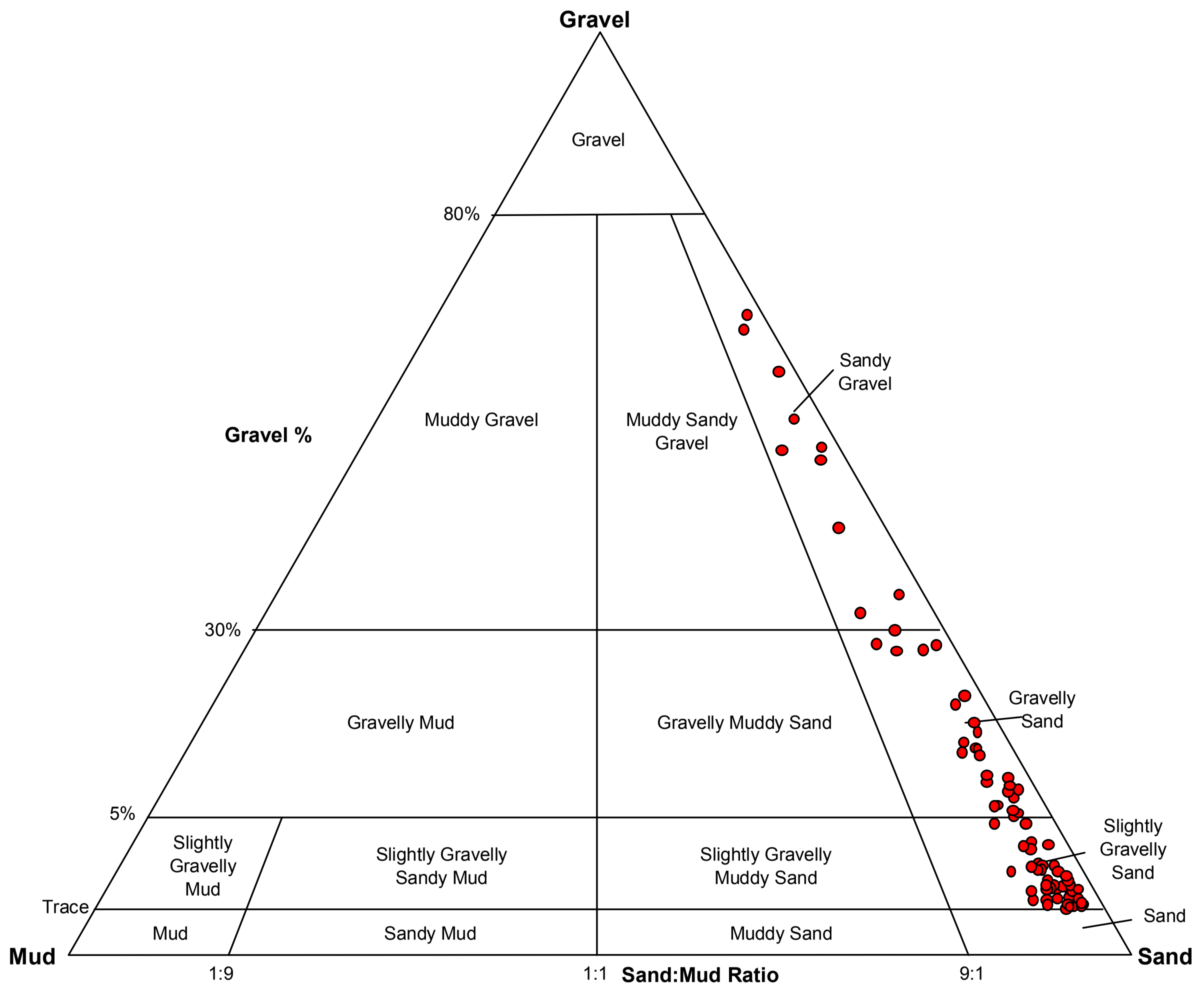
Produced: MCE
Reviewed: NMW
Approved: PH

Date: 04/05/2012 Revision: A

REF: 8460001-PPW0201-ABP-MAP-020

Fig 20 - Seabed Characteristics Interpreted from Sidescan Sonar Mosaic Collected from the Project Area

Moray Offshore Renewables Ltd




Moray Offshore Renewables Ltd

A4 Chart

Produced: DOL
Reviewed: CLH
Approved: WSC

Date: 1/6/12 | Revision: B

REF: 8460001-PPW0201-ABP-MAP-021

Figure 21. Sediment Samples from the Project Area in Relation to the Folk (1954) Sediment Triangle

Moray Offshore Renewables Ltd

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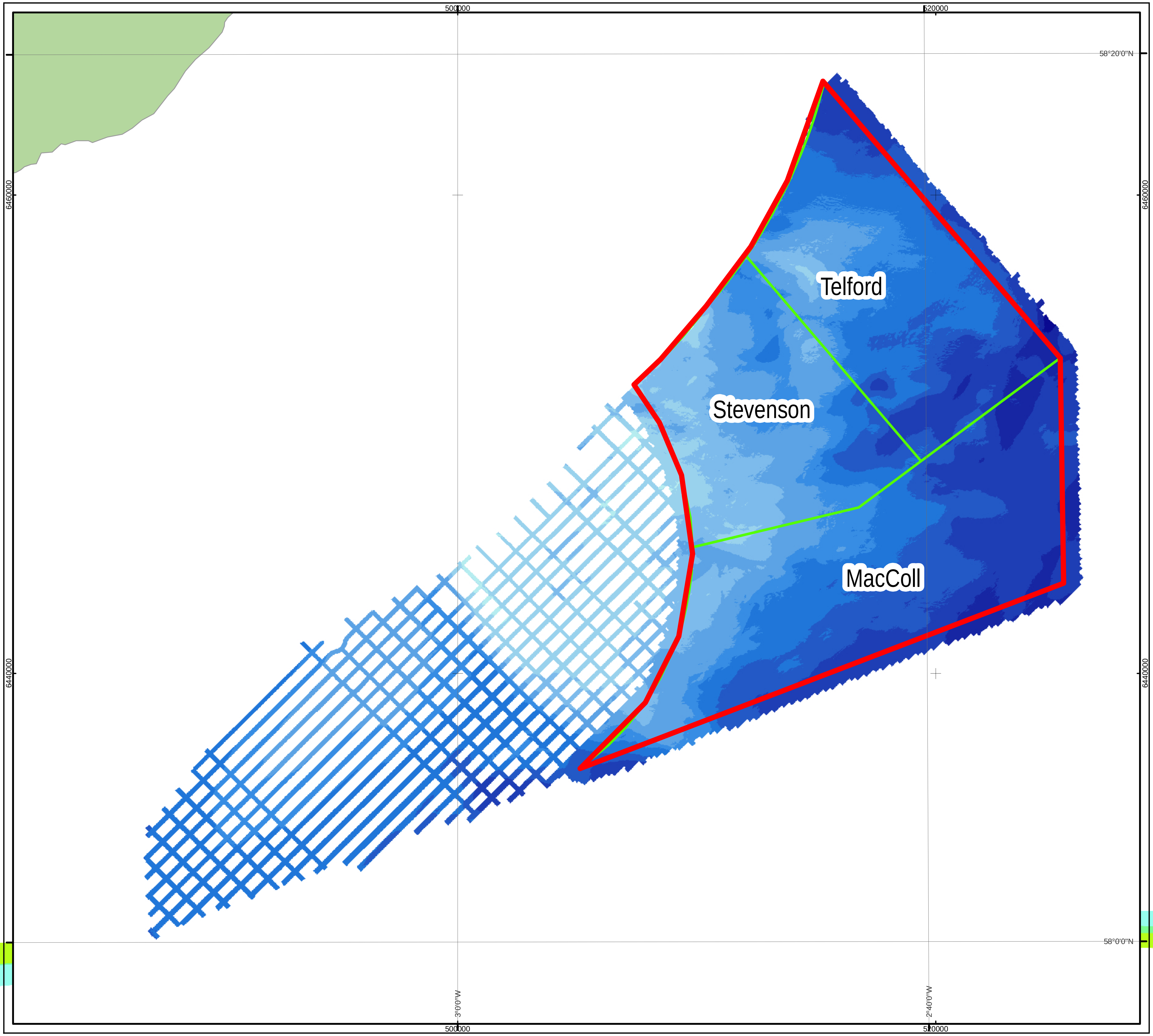



edp renewables

REPSOL

**Moray Offshore Renewables Ltd**

KEY

- MORL EDA
- Site Boundaries

Bathymetry

m LAT

- -60 - -57
- -56.9 - -55
- -54.9 - -52
- -51.9 - -50
- -49.9 - -47
- -46.9 - -45
- -44.9 - -42
- -41.9 - -40
- -39.9 - -37
- -36.9 - -35

Horizontal Scale: 1:151,502 A3 Chart

0 4,000 8,000 Metres

Geodetic Parameters: WGS84 UTM Zone 30N

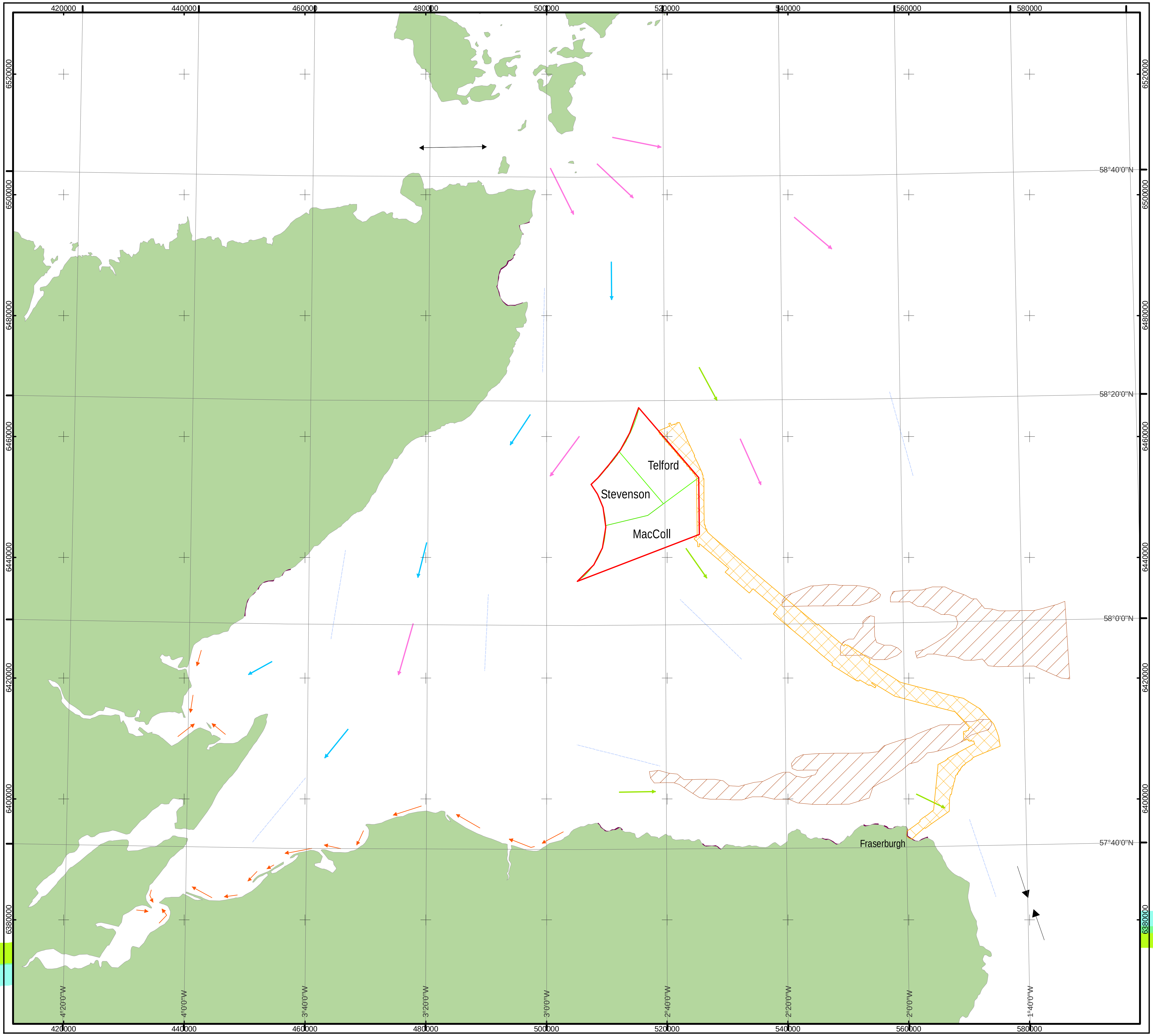
Produced: MCE
Reviewed: NMW
Approved: PH

Date: 04/05/2012 | Revision: A

REF: 8460001-PPW0201-ABP-MAP-022

## Fig 22 - Swath Bathymetry of the MORL EDA

Moray Offshore Renewables Ltd

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KEY

- MORL EDA
- OFTO Transmission Cable Corridor
- Site Boundaries
- Offshore Sediment Sink

Sediment Transport Summary

- Bedload Convergence
- Bedload Parting
- Net Longshore Drift
- Sediment Transport Path
- Sediment Transport Path (probable)
- Semi-independent Beach Unit
- Shelly Carbonate Path
- Tidal Current Ggeneral Orientation

Horizontal Scale: 1:600,000 A3 Chart

0 16,000 32,000 Metres

Geodetic Parameters: WGS84 UTM Zone 30N

Produced: MCE
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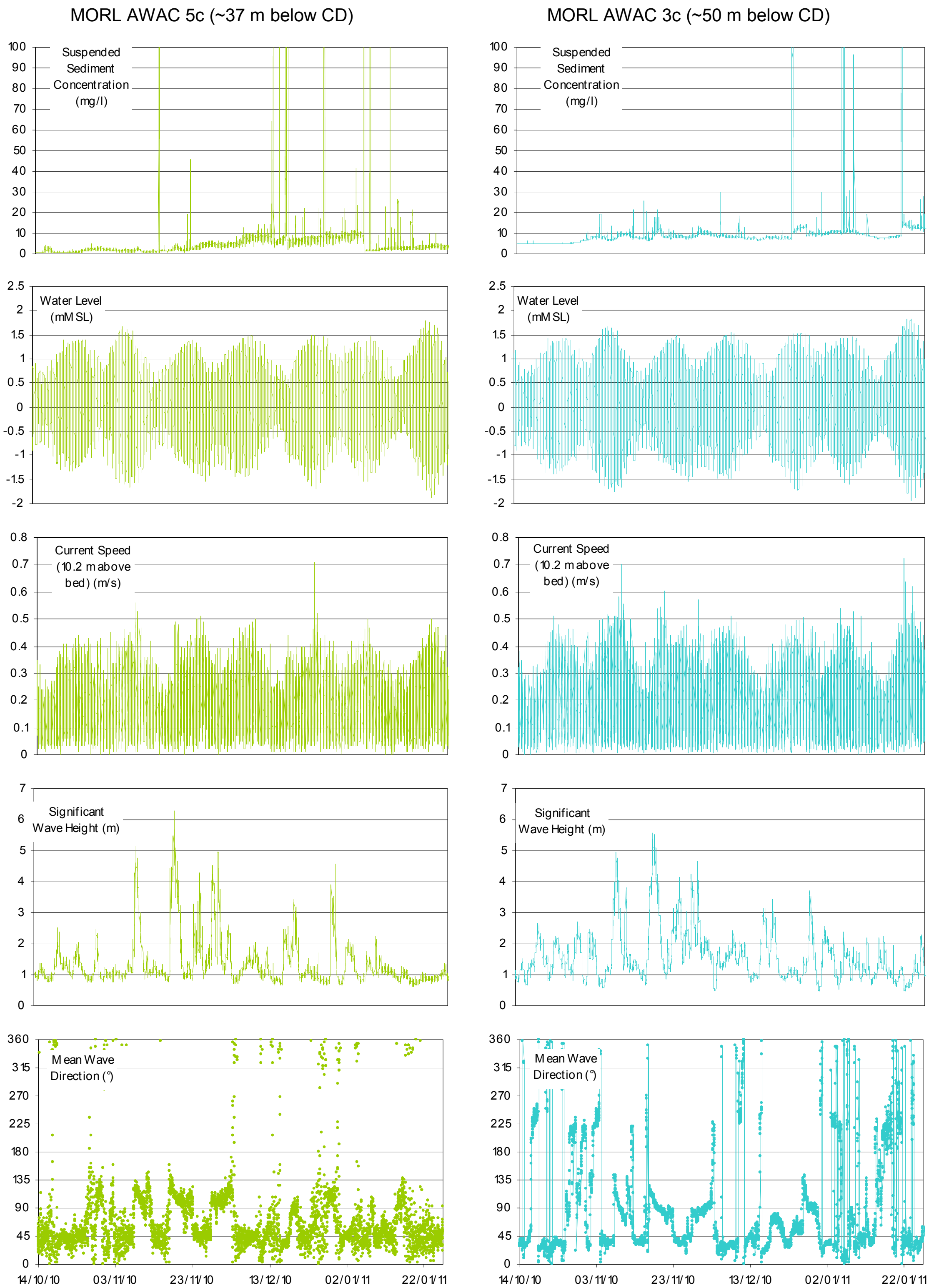
Approved: PH

Date: 04/05/2012 Revision: A

REF: 8460001-PPW0201-ABP-MAP-023

# Fig 23 - Bedload and Longshore Sediment Transport in the Moray Firth

Moray Offshore Renewables Ltd

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Produced: DOL
Reviewed: CLH
Approved: WSC

A4
Chart

Revision:

Date: 01/06/12

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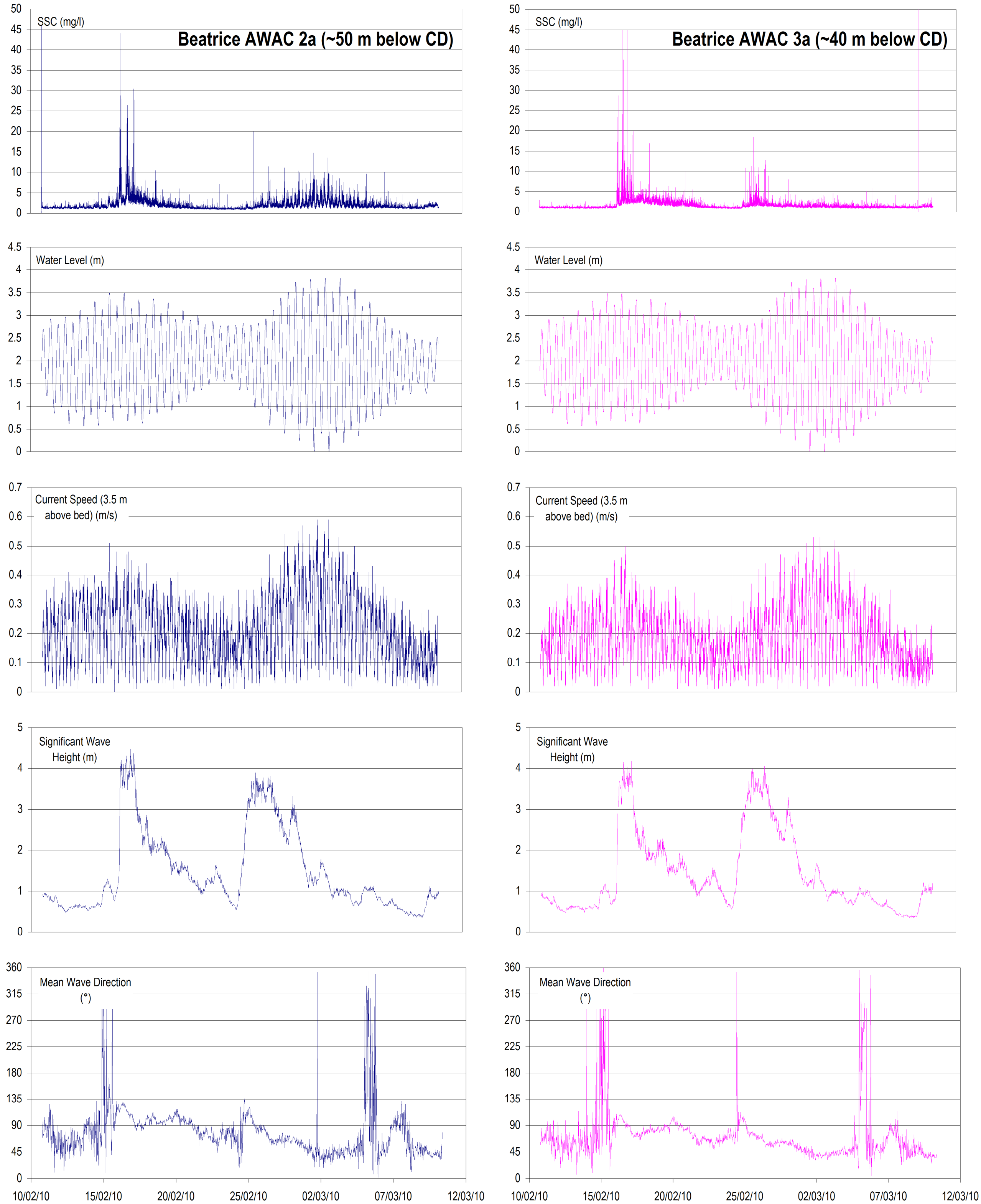
Figure 24. Suspended Sediment Concentrations in the Project Area

Moray Offshore Renewables Ltd





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A4
Chart

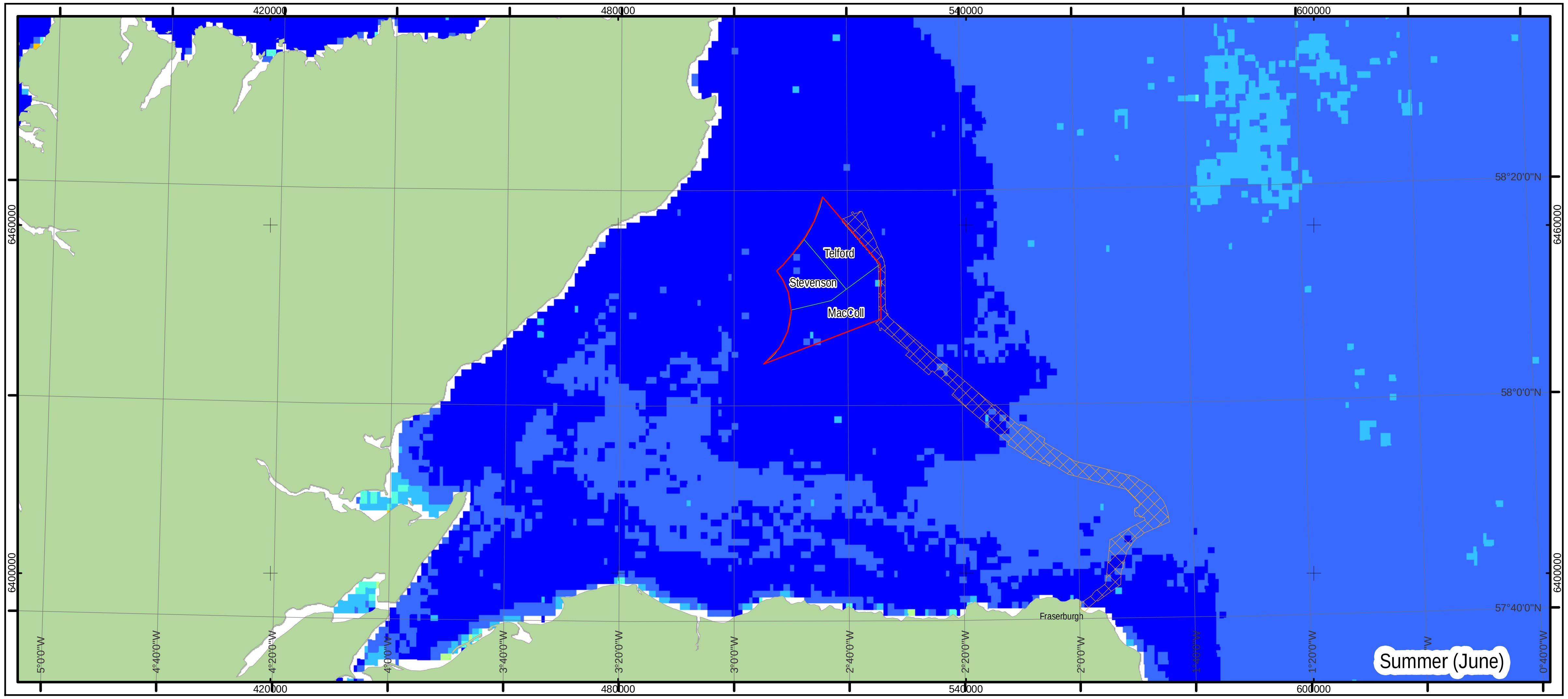
Revision:

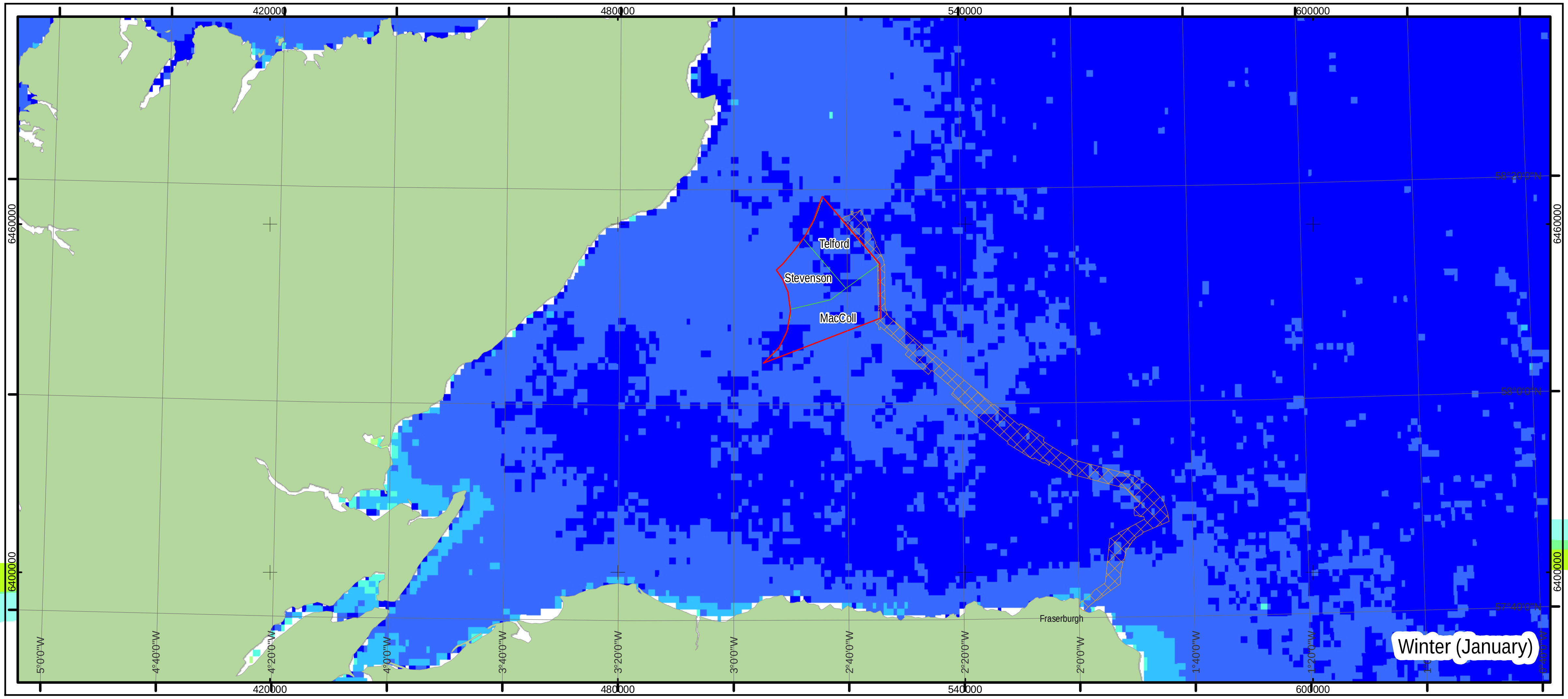
Date: 01/06/12

REF: 8460001-PPW0201-ABP-MAP-025

Figure 25. Suspended Sediment Concentrations in the BOWL Application Site

Moray Offshore Renewables Ltd

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**Moray Offshore Renewables Ltd**

KEY

- MORL EDA
- OFTO Transmission Cable Corridor
- Site Boundaries

Mean SPM (mg / l) (Dolphin et al. 2011)

- 0.05 - 1
- 1 - 2
- 2 - 4
- 4 - 8
- 8 - 16
- 16 - 32
- 32 - 48
- 48 - 64
- 64 - 80

Horizontal Scale: 1:850,000 A3 Chart

0 22,500 45,000 Metres

Geodetic Parameters: WGS84 UTM Zone 30N

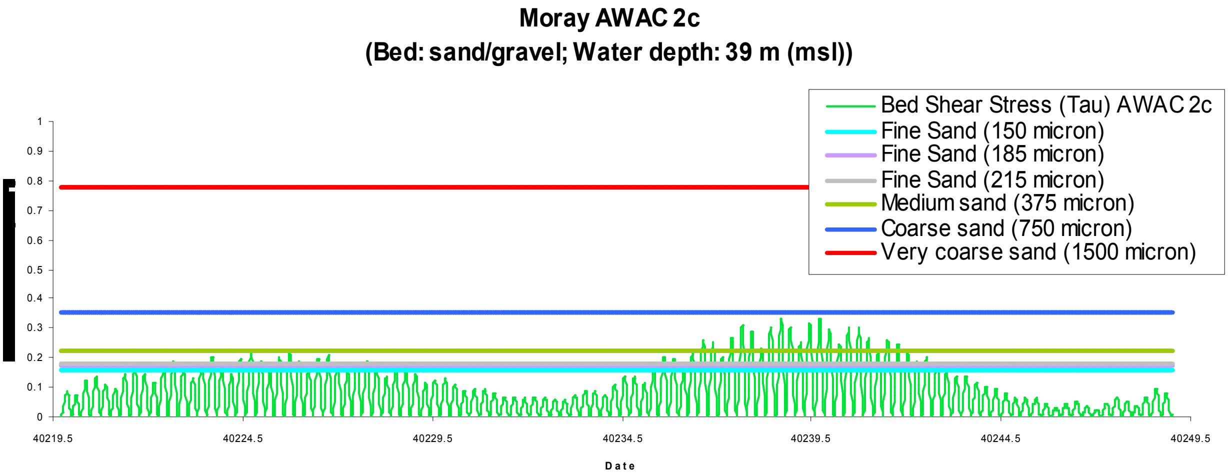
Produced: MCE
Reviewed: NMW
Approved: PH

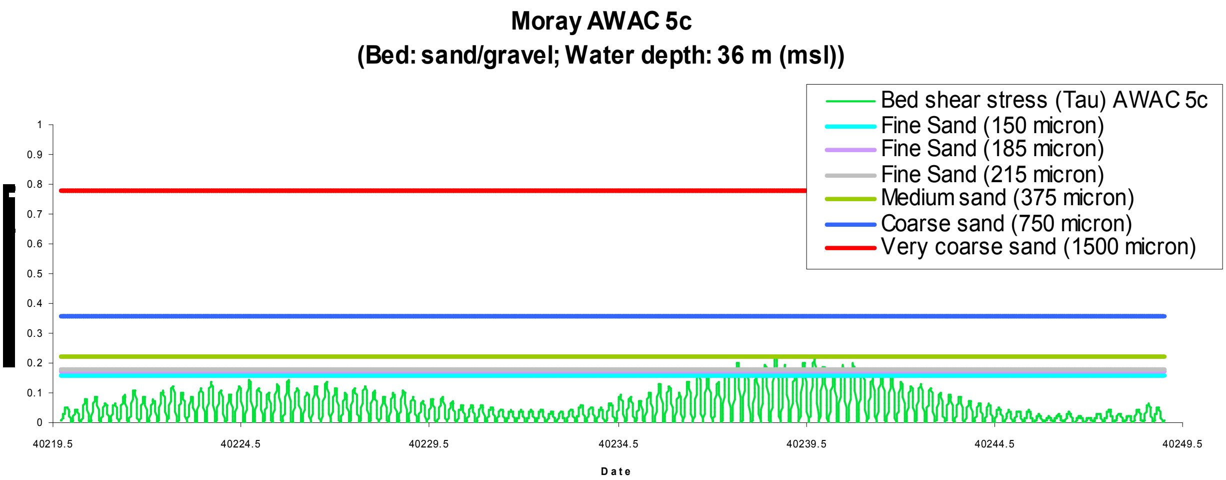
Date: 04/05/2012 Revision: A

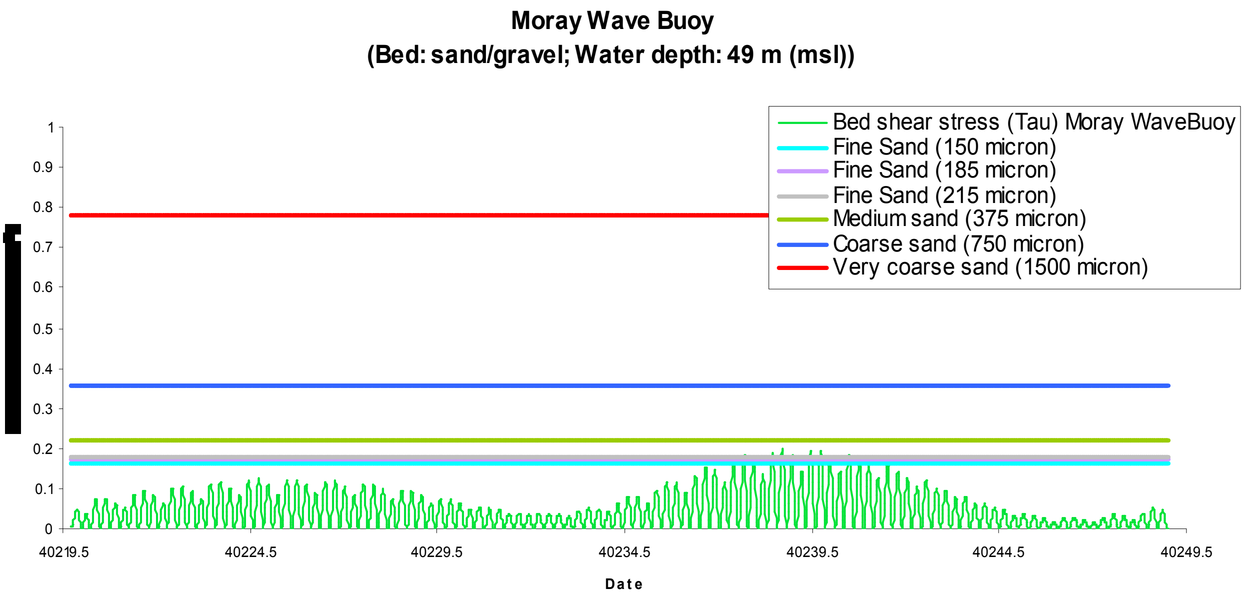
REF: 8460001-PPW0201-ABP-MAP-026

Fig 26 - Suspended Particulate Matter Concentrations in the Moray Firth (Summer & Winter)

Moray Offshore Renewables Ltd

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Produced: DOL
Reviewed: CLH
Approved: WSC

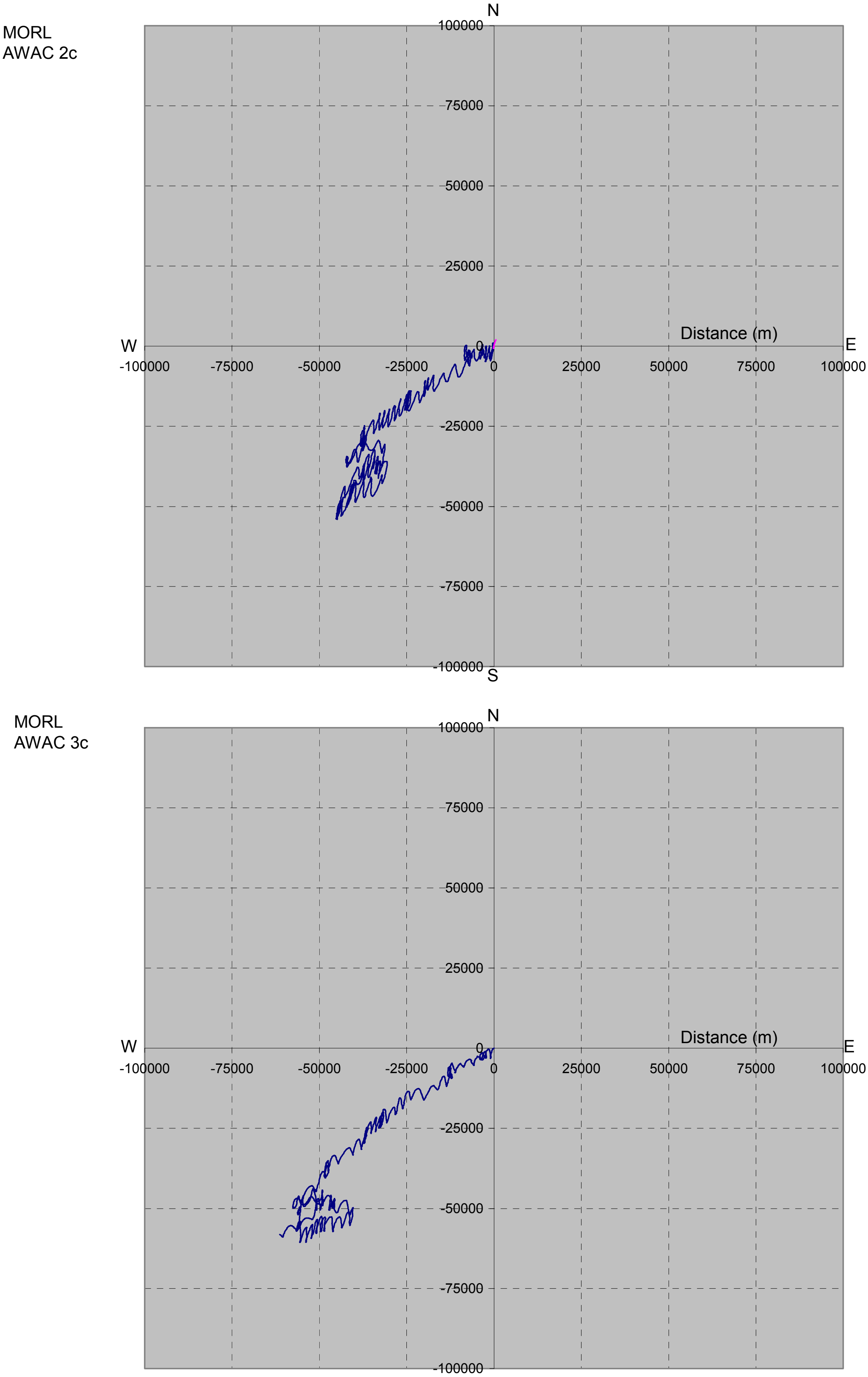
A4
Chart

Revision:
Date: 01/06/12

REF: 8460001-PPW0201-ABP-MAP-027

Figure 27. Tidally-Induced Bed Shear Stress and Mobility Thresholds in the Project Area

Moray Offshore Renewables Ltd




Net Potential Advection
Fine Sediment Displacement

Moray Offshore Renewables Ltd

Produced: DOL
Reviewed: CLH
Approved: WSC

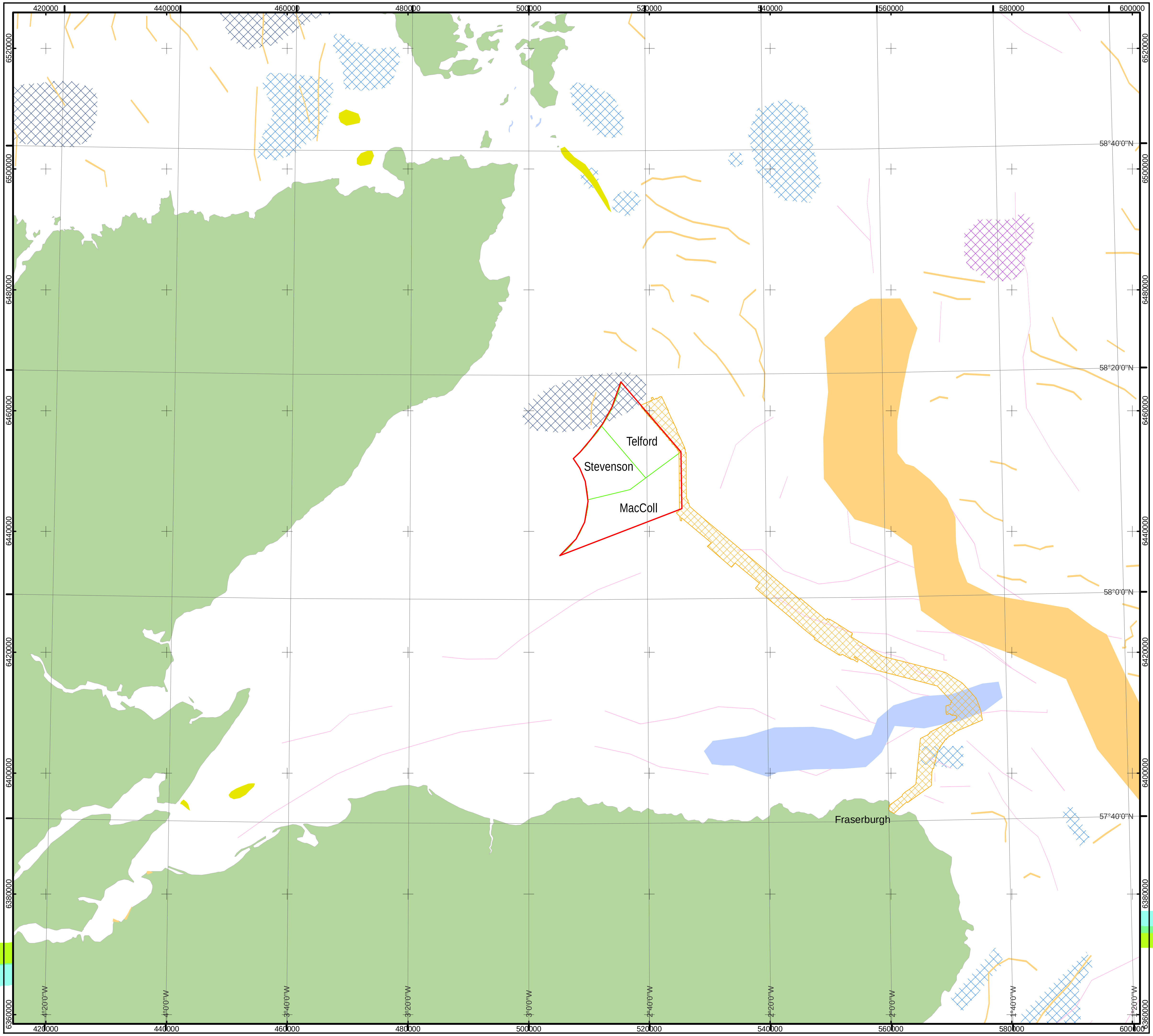
A4
Chart

Revision:
Date: 01/06/12

REF: 8460001-PPW0201-ABP-MAP-028

Figure 28. Residual Flow and Projected Displacement of Fine Sediment after 30-Days

Moray Offshore Renewables Ltd

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**Moray Offshore Renewables Ltd**

KEY

- MORL EDA
- OFTO Transmission Cable Corridor
- Site Boundaries
- Glaciated Channel/Trough
- Moraines
- Tunnel Valley
- Sand Bank
- Sand Wave Field
- Sediment Wave Field
- Pockmarks

Horizontal Scale: 1:600,000 A3 Chart

0 16,000 32,000 Metres

Geodetic Parameters: WGS84 UTM Zone 30N

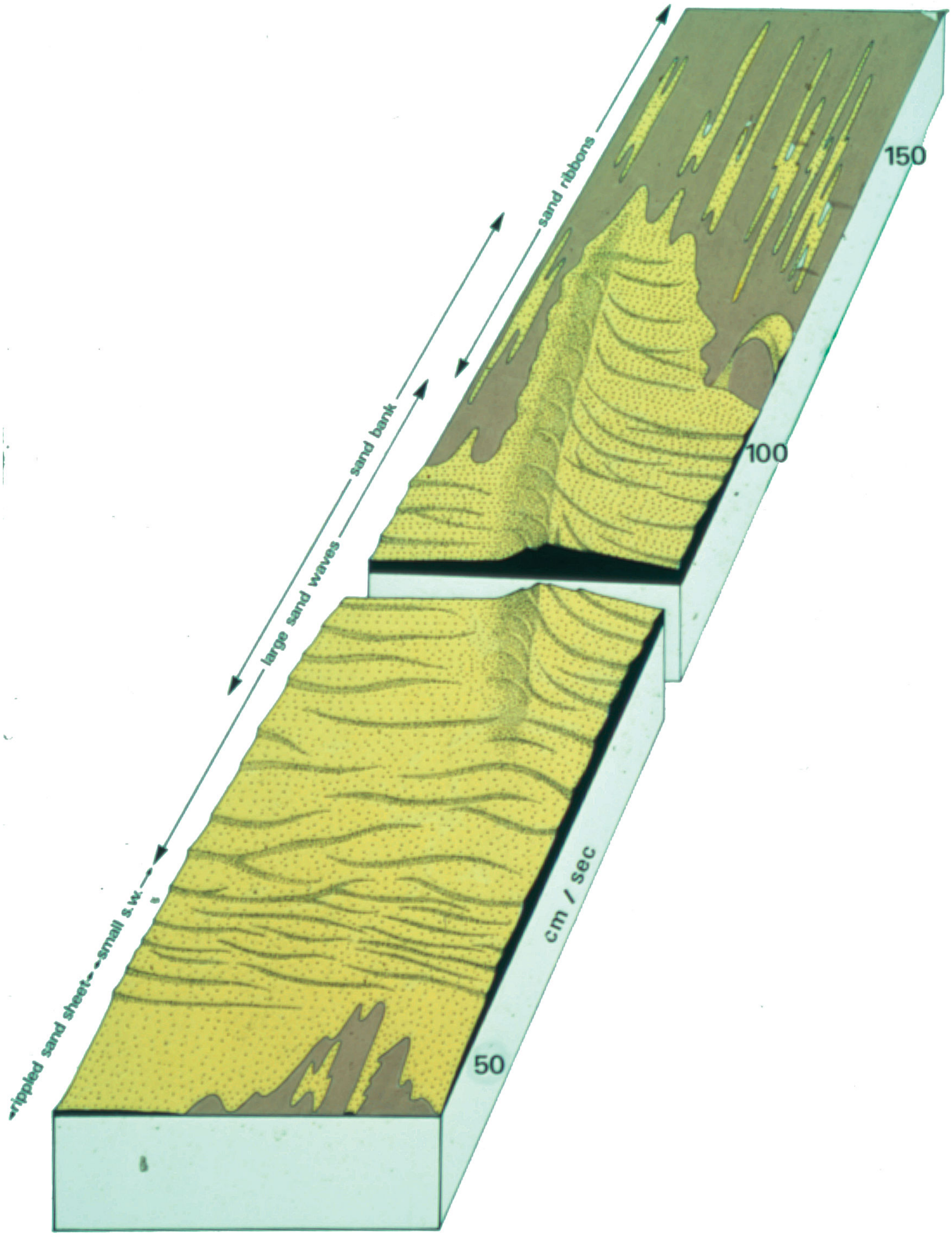
Produced: MCE
Reviewed: NMW
Approved: PH

Date: 10/01/2012 Revision: A

REF: 8460001-PPW0201-ABP-MAP-029

## Fig 29 - Bedforms Identified (Pre Application Site Survey) within the Moray Firth

Moray Offshore Renewables Ltd




Note: for a tidal sea where sand is abundant, with corresponding mean spring peak near surface tidal currents in cm/sec.

Data source: Belderson et al., 1982



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Produced: DOL
Reviewed: CLH
Approved: WSC

A4
Chart

Revision:

Date: 01/06/12

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Figure 30. Scheme of Bedform Zones from a Tidal Sea

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