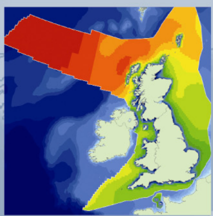
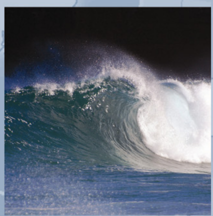
Beatrice Offshore Windfarm Limited

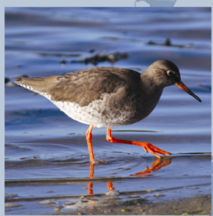
Beatrice Offshore Wind Farm
Physical Processes Baseline Assessment

Report R.1795

January 2012

Creating sustainable solutions for the marine environment



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Quality Manager:	C L Hinton	[signature]	27.01.2012
Project Director:	W S Cooper	[signature]	27.01.2012

ABP Marine Environmental Research Ltd
Suite B, Waterside House
Town Quay
SOUTHAMPTON
Hampshire
SO14 2AQ

Tel: +44(0)23 8071 1840
Fax: +44(0)23 8071 1841
Web: www.abpmer.co.uk
Email: enquiries@abpmer.co.uk

ABPmer is certified by:

Abbreviations

ABPmer	ABP Marine Environmental Research Ltd
AWAC	Acoustic Wave And Current
BERR	The Department for Business, Enterprise and Regulatory Reform
BGS	British Geological Survey
BODC	British Oceanographic Data Centre
BOWL	Beatrice Offshore Windfarm Limited
c.	Circa
CD	Chart Datum
CEFAS	Centre for Environment, Fisheries & Aquaculture Science
COWRIE	Collaborative Offshore Wind Research Into the Environment
CMACS	Centre for Marine and Coastal Studies
CPA	Coast Protection Act
cSAC	Candidate Special Area of Conservation
CSM	Continental Shelf Model
DECC	Department of Energy and Climate Change
Defra	Department for Environment, Food and Rural Affairs
DfT	Department for Transport
DHI	Danish Hydraulic Institute
EIA	Environmental Impact Assessment
EW	European Waters
FEPA	Food and Environmental Protection Act
GCR	Geological Conservation Review
GW	Gigawatt(s)
HAT	Highest Astronomical Tide
H(max)	Maximum wave height
HMSO	Her Majesty's Stationary Office
HRA	Habitats Regulations Appraisal
Hs	Significant Wave Height
HSE	Health and Safety Executive
HW	High Water
IOS	Institute of Ocean Sciences
JNCC	Joint Nature Conservation Committee
km	kilometre(s)
LAT	Lowest Astronomical Tide
m	metre(s)
m/s	metres per second
mg/l	milligrams per litre
MAFF	Ministry for Agriculture Farming and Fisheries
MCA	Maritime and Coastguard Agency
MCCIP	Marine Climate Change Impacts Partnership
MHW	Mean High Water
MHWN	Mean High Water Neap
MHWS	Mean High Water Spring

MLW	Mean Low Water
MLWN	Mean Low Water Neap
MLWS	Mean Low Water Spring
MORL	Moray Offshore Renewables Limited
MSL	Mean Sea Level
MW	Megawatt(s)
NAO	North Atlantic Oscillation
NERC	Natural Environment Research Council
NOC	National Oceanography Centre
N/m^2	Newtons per square metre
OBS	Optical Backscatter Sensor
OREIs	Offshore Renewable Energy Installations
OSPAR	Oslo and Paris Commission (Convention for the Protection of the Marine Environment of the North-East Atlantic)
OWF	Offshore Wind Farm
POL	Proudman Oceanographic Laboratory
PDS	Project Design Statement
PSA	Particle Size Analysis
Ramsar	Ramsar Convention
RSL	Relative Sea Level
RSPB	Royal Society for the Protection of Birds
RYA	Royal Yachting Association
SAC	Special Area of Conservation
SAS	Surfers Against Sewage
SEA	Strategic Environmental Assessment
SEPA	Scottish Environmental Protection Agency
SNH	Scottish Natural Heritage
SPA	Special Protection Area
SSC	Suspended Sediment Concentration
SSSI	Sites of Special Scientific Interest
Tz	Zero crossing wave period
Tp	Peak wave period
UK	United Kingdom
UKCIP	UK Climate Change Impact Programme
UKHO	UK Hydrographic Office
µm	micrometre(s)
UKCS	UK Continental Shelf
UKW	UK Waters (Model)
WW3	Wave Watch III (Model)

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1. Introduction

1.1 Project Description

ABPmer has undertaken a baseline assessment of physical processes for the Beatrice Offshore Wind Farm on behalf of Beatrice Offshore Windfarm Limited (BOWL). The BOWL application site is located in the north of the Outer Moray Firth, approximately 15km south-east of the Caithness coast (Figure 1). The full description of the wind farm's characteristics, including details of all planned infrastructure, is given in the Project Design Statement (PDS) (BOWL, 2011).

1.2 The BOWL Application Site

The application site is located on the north-western flank of the Smith Bank, a morphological high point in the Outer Moray Firth measuring, approximately, 35km long from south-west to north-east, 20km wide. Water depths across the application site range from approximately 35 m below Chart Datum (CD) in the southern margin, close to the crest of the bank, to 50 m CD along the western and northern margins. The greatest water depths in the immediate vicinity outside of the application site are along the western margin where the Smith Bank is separated from the Caithness coast by a relatively deep channel (up to approximately 75 m CD, see Figure 1). The figure also illustrates the 'near-field' and 'far-field' boundaries for the present study, also referenced in 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 disruption of waves, tides or sediment pathways passing through the application site.

2. Assessment Methodology

2.1 Overview

The assessment of baseline physical processes around the application site has been sub-divided into three broad 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 Beatrice Offshore Wind Farm. This provides the reference condition 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 Beatrice Offshore Wind Farm 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 Beatrice Offshore Wind Farm in relation to physical processes is presented in a separate report (ABPmer, in prep. a) 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 five 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) - current at the time of reporting;
- '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 recently commissioned a set of guidance documents to be produced for the marine renewable industry, specifically wave and tidal devices, which included 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 Beatrice Offshore Wind Farm project.

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, BOWL 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 ABPmer (in prep, a).

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.

2.4.2 Construction

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 site 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 Crown Estate Lease area consented covers an area of approximately 131km^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 the littoral drift processes along adjacent coastlines.

2.4.4 Decommissioning

Specific details of the decommissioning phase are presently unknown. However, it is expected that on expiry of the lease 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 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 Beatrice Offshore Wind Farm was first circulated to relevant parties during 2009 and a scoping report was submitted in March 2010 to statutory and non-statutory consultees (BOWL, 2010). A number of issues and particular concerns to address in the EIA were raised by in the 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). 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 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, the 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 impact 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
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).

Receptor	Designation	Description
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, in prep. a), the above receptors will be addressed specifically when considering the potential impacts of the Beatrice Offshore Wind Farm on the physical environment.

2.7 Data Sources

As part of the planning, assessment and development of the proposed Beatrice Offshore Wind Farm, a series of new data collection 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). 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 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); and
- United Kingdom Offshore Regional Reports Series: The Moray Firth (Andrews *et al*., 1990)
- Sand banks, sand transport and offshore wind farms (Kenyon and Cooper, 2005);

Table 3. Data and information sources referred to in the assessment

Survey/Study	Date of Survey	Undertaken By	Description
Geophysical Surveys	1/04/2010 to 21/05/2010	Osiris	High-resolution swath bathymetric survey
Benthic Survey	12-14/10/2011	CMACS	Baseline information on the benthic communities in and adjacent to the proposed wind farm application site has been collected. Approximately 100 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) Moray Offshore Wind Farm as well as available BGS grab sample data
	09-10/04/2010	Partrac	
	12-16/10/2010	Emu	
Geotechnical Survey	2/11/2010 to 14/12/ 2010.	Fugro	25 geotechnical boreholes including six bumpover boreholes collected from the Moray Firth wind farm site
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)

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 (in prep. b). These models have also been used to establish the baseline and will be used to determine the scale of the likely the 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) MIKE 21 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 excellent 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

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

Table 4. Sources of water level data

Data Source	Latitude (°N)	Longitude (°E)	Period Analysed	Duration
Wick tide gauge	58.441	-3.086	1965 to present	~ 45 years
AWAC in the Beatrice OWF	58.179	-2.950	10/2/10 to 04/3/10	23 days
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

3.2.2 Astronomical Tidal Water Levels

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 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 obtained from Admiralty Tide Tables (2011) and are presented in Table 5. 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 5. Astronomical tidal water level statistics

Water Level Statistic		Level (m CD Wick)	
		Wick Tide Gauge	BOWL AWAC*
Highest Astronomical Tide	HAT	4.0	4.1
Mean High water of Spring Tides	MHWS	3.5	3.6
Mean High Water	MHW	~3.15	3.3
Mean High Water of Neap Tides	MHWN	2.8	2.9
Mean Sea Level	MSL	2.1	2.2
Mean Low Water of Neap Tides	MLWN	1.4	1.5
Mean Low Water	MLW	~1.05	1.1
Mean Low water of Spring Tides	MLWS	0.7	0.7
Lowest Astronomical Tide	LAT	0.1	0.1
Mean Spring Range	MHWS to MLWS	2.8 (m range)	2.9 (m range)
Mean Neap Range	MHWN to MLWN	1.4 (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.

BOWL AWAC deployments

Approximately 3 months of water level measurements have also been collected by Partrac (2010) on behalf of BOWL at two locations, one at each end of the application site (Figure 4). A subset of these data, including one spring-neap cycle, is compared directly in Figure 5. The figure shows that there is only a small (~0.2 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, any given tidal range at the application site will be 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 5.

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 6; Figure 4). 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 6. 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.

Future changes to the baseline

Mean sea level at the application site is likely to alter over the lifetime 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 7. 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 7. 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 4 to 18 mm to the values in Table 6 over a nominal 50 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 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 8 and their locations are shown in Figure 4.

Table 8. Sources of current data

Data Source		Latitude (°N)	Longitude (°W)	Period Analysed	Duration
AWACs in the BOWL application site		58.179	2.950	10/02/2011- 10/03/2011	(29 days)
		58.297	2.775		
AWAC in the MORL application site		58.167	-2.900	10/12/2010 to 14/02/2010	(67 days)
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, in prep. b). The model was calibrated using the other 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 application site, peak current speeds are typically between 0.5 to 0.7 m/s on mean spring tides and 0.25 to 0.35 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, enhancing 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 the Smith Bank and especially in the deep water channel to the north-west;
- Within the application site, tidal currents are directed generally to the south-south-west during the flood tide and to the north-north-east during the ebb tide; and
- There is little consistent asymmetry between flood and ebb in tidal current speeds and directions.

Project specific AWAC deployments

Current profile data collected during the metocean survey is summarised in Figure 8, and Figure 9. The data confirm that:

- The highest current speeds are encountered in the north of the application site, reaching a peak depth mean speed of ~ 0.7 m/s during spring tides;
- During spring tides, peak current speeds in the south of the application site are ~ 0.65 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 0.3 and 0.35 m/s; 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-east of the application site where they reach a maximum velocity of ~0.7 m/s (B0014185). The weakest currents are observed to 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 Beatrice AWAC deployments. 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 a large 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. Three 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 9. 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 9. Summary of tidal stream data from Admiralty Chart 115

Hours		Tidal Diamond M			Tidal Diamond N			Tidal Diamond F		
		58.375° N; 2.642° W			58.283° N; 2.625° W			58.167° N; 3.10° W		
		Direction (ºN)	Spring (m/s)	Neaps (m/s)	Direction (ºN)	Spring (m/s)	Neaps (m/s)	Direction (ºN)	Spring (m/s)	Neaps (m/s)
Before HW (Flood)	-6	115	0.21	0.10	094	0.10	0.05	253	0.26	0.15
	-5	148	0.31	0.15	143	0.26	0.10	257	0.26	0.15
	-4	161	0.36	0.21	156	0.46	0.21	253	0.21	0.10
	-3	174	0.41	0.21	165	0.57	0.26	264	0.15	0.05
	-2	185	0.36	0.21	178	0.62	0.31	230	0.05	0.00
	-1	210	0.21	0.10	179	0.26	0.10	118	0.10	0.05
HW	0	298	0.15	0.10	227	0.05	0.00	082	0.21	0.10
After HW (Ebb)	1	342	0.26	0.10	334	0.26	0.10	072	0.21	0.10
	2	347	0.31	0.15	338	0.46	0.21	074	0.21	0.10
	3	345	0.31	0.15	341	0.62	0.31	071	0.21	0.10
	4	343	0.36	0.21	347	0.51	0.26	067	0.10	0.05
	5	353	0.26	0.15	359	0.31	0.15	253	0.15	0.05
	6	090	0.15	0.05	055	0.10	0.05	252	0.26	0.10

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 x 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 wind farm. 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 10 for a series of extreme wave events at two nominal locations and water depths in the application site: at the BOWL wave buoy (the deeper offshore end of the application site); and, at AWAC 3a (the shallower inshore end of the application site). 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 10. 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	8.0	8.9	9.2
Zero Crossing Wave Period Tz (s)	11.0	11.8	12.2	12.4
Orbital Velocity Amplitude (m/s) (Location 1: Beatrice Directional Wave Buoy; 50 m CD)	0.62	0.82	0.96	1.01
Orbital Velocity Amplitude (m/s) (Location 2: Beatrice AWAC 3a; 35 m CD)	0.94	1.19	1.36	1.43

From Table 10 it is apparent that the highest nearbed orbital current amplitudes will be found in the shallower parts of the application site. Here, current velocities are close to 1 m/s for a 1 in 1-year return period storm event and exceed 1.4 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 waves. 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 11 and shown in Figure 4).

Table 11. Sources of wind data in the Moray Firth

Data Source	Latitude (ºN)	Longitude (ºW)	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

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 speed data is available 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 (in prep. c). Although the records are found to be broadly similar, the Wick Airport anemometer consistently reports a lower wind speed than the 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 12.

Table 12. Wind Speeds (m/s) and associated directional sectors for selected return period storm events at the application site

Return Period (years)	Wind Speed* m/s							
	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 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 sea bed within the application site and to stir any sediments present. 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 13. It is important to note that the data sources available are of varying quality and duration. The highest quality datasets are the observational wave records, e.g. those from the metocoean deployments and from the WaveNet Moray Firth wave buoy. However, with the exception of the Moray Firth wave buoy record, the metocoean wave records are only relatively short-term (less than 12 months) duration and so do not reliably reflect the longer term (> c.2 years) 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 13. Wave data available from the Moray Firth

Data Source	Latitude (°N)	Longitude (°W)	Period Analysed	Duration
Directional Wave Buoy in the Beatrice OWF (Partrac, 2010)	58.307	2.810	11/02/10 - 15/11/2010	~9 months
Directional Wave Buoy in the Moray OWF (Partrac, 2010)	58.166	2.634	15/06/2010-15/11/2010	~5 months
Beatrice AWAC 2a	58.296	2.776	11/02/2010-15/06/2010	(Discontinuous)
Beatrice AWAC 3a	58.179	2.950	10/02/2010-15/06/2010	~4 months
WaveNet Moray Firth wave buoy (CEFAS)	57.97	3.33	29/08/08 - 06/01/11	~ 2 years
Jacky Platform	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	
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 BOWL 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 14. 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 application site, the most frequent wave direction is from the north-east with waves originating from this sector between approximately 18 to 40% of the time;
- With the exception of the Jacky Platform record, the most frequent wave heights are 0.5 to 1 m, accounting for between approximately 35 and 45% of all waves;
- The most frequent wave heights in the Jacky Platform record are slightly larger (1 to 1.5 m). However, this is to be expected as the record only covers the (stormier) winter period; and
- The largest significant wave height observed during the metocean survey was encountered in the north of the application site and was approximately 5.5 m. The larger waves observed in this period all approach from either the east-south-east or east-north-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 14. In summary the frequency analysis shows:

- In the majority of records, the most frequent mean wave periods are between 3 and 4 seconds, accounting for between approximately 35 and 45% of the records. These short wave-periods are indicative of wind waves and strongly suggest that the wave regime across the application site is dominated by waves of this type;
- The Jacky Platform record is characterised by slightly longer period (5 to 6 second) waves. This difference can be explained by the winter sampling period; and
- Peak-mean wave-periods exceed 8 seconds. These longer period waves typically approach from the north-north-east and north-east and are characteristic of swell waves.

Table 14. 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	Peak Observed mean Wave Period and Associated Direction Sector
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 seconds (NNE)
MORL Directional Wave Buoy	15/06/2010-15/11/2010	NNE (18%)	0.5-1 (34%)	5.41 m (ESE)	3-4 seconds (36%)	8.8 seconds (ESE)
Beatrice AWAC 2a	11/02/2010-15/06/2010	NE (24%)	0.5-1 (37%)	4.48 m (ESE)	3-4 seconds (42%)	8.4 seconds (NE)
Beatrice AWAC 3a	10/02/2010-15/06/2010	NE (40%)	0.5-1 (45%)	4.18 m (ENE)	3-4 seconds (47%)	8.5 seconds (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 seconds (NE)
Jacky Platform	30/09/2008-10/03/2009	NE (18%)	1-1.5 (45%)	5.2 m (ESE)	5-6 seconds (28%)	12.5 seconds (NNE)
Percentages are rounded to integers						

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

Table 15. 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	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 15 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).

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 14 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 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 modal 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, in prep. b). 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.

Analysis has been undertaken to quantify the baseline wave climate at surfing venues identified in the Moray Firth (Figure 2). Table 16 summarises the occurrence of various surf conditions (in days/year), defined according to Surfers Against Sewage (2009), after Halcrow (2006). The values in Table 16 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.

Table 16. 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			*1.12m 7.2s*	*0.72m 5.9s*	*0.89m 6.4s*	*0.83m 6.3s*	*0.86m 6.3s*	*1.19m 7.3s*	*0.69m 5.9s*	*0.77m 6.0s*	*0.97m 6.5s*	*1.00m 6.6s*	*1.03m 6.7s*	*0.63m 5.3s*	*0.81m 6.3s*	*0.85m 6.3s*	*1.02m 6.8s*	*1.20m 7.1s*	*1.17m 7.3s*	*1.23m 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			*5.09m*	*3.96m*	*5.36m*	*5.09m*	*5.18m*	*4.35m*	*4.40m*	*4.89m*	*6.07m*	*5.27m*	*6.41m*	*3.24m*	*4.89m*	*5.18m*	*5.41m*	*6.77m*	*6.75m*	*6.80m*

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 19th and early 20th century; followed by a decrease up until about 1970. A subsequent rise in the late 20th 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 21st 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.

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 to 2070-2100 will slightly decrease by approximately 0 to 0.5 m.

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 high freshwater influence, owing to the input from large rivers draining into the Firth (Baxter *et al*., 2008).

In practice, stratification can be measured as a vertical gradient in either temperature and/or salinity and may also manifest as gradients in nutrient concentrations and 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 the focus of considerable attention for their potential role as locations of enhanced biomass production (Hill *et al*., 1993). Indeed, the frontal features greatly influence the availability of light and nutrients to plankton driving both primary and secondary productivity which in turn attract fish, birds and cetaceans.

3.6.1 Sources of Stratification and Frontal Data

A series of predictive maps illustrating the seasonal variability in the pelagic environment are also 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:

- 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 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 surface and deeper waters, forming a weak thermocline at 10 to 15 m depth in the application site (Figure 18). The field data collected also indicate no significant fresh-water influence on salinity. The stratification breaks up 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 more at the coast than in the Outer Moray Firth due to more highly variable local river input; local temperature stratification in summer may also be associated with relatively warm river water overlying colder North British Coastal 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 Figure 2 and Figure 3, 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 on-average faster tidal currents. On this basis, the position of the fronts is likely to migrate onshore-offshore 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 tidal and surge 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 certain threshold relevant to the specific material type found at the application site. This can lead to the erosion, transportation or deposition of sediments. Spatial gradients in the properties and availability of sediment and the erosive forcing applied to them, leads to the natural formation of net sediment transport pathways and areas of net erosion ('sources') or deposition ('sinks'). Over longer time-scales, the behavioural changes in the sediment regime will determine the net morphological evolution of the application site.

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 is 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 application site and the wider far-field study area;
- The composition of the sub-strata across the application site 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 17:

Table 17. Sediment and geological data available from the Moray Firth

Data Source	Reference
BOWL application site benthic survey	CMACS (2011)
BOWL application site geophysical survey	Osiris (2011)
MORL application site benthic survey	Emu (2011)
BGS seabed sediment maps	BGS (1984, 1987)
Regional Geology and Geomorphology	Andrews *et al*. (1990); Holmes *et al*. (2004)
BGS Rock/ Hard Substrate Map	Gafeira *et al*. (2010)

4.3 Seabed Sediments: Composition and Distribution

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 grab samples collected during the BOWL site surveys (Partrac, 2010; CMACS, 2010) as well as historical grab sample data held by BGS. This information is presented in Figure 19. Side scan sonar data has also been used to infer the nature of the seabed substrate across the application site and is shown in Figure 20 (Osiris, 2011). All of the grab samples collected during the BOWL 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. (This ensured 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.

According to grab samples and seabed type maps from BGS (Figure 19) the application site can be expected to be dominated by slightly gravelly sand. However, of the benthic grab samples more recently collected from the application site, gravel was not consistently observed to be present at all locations; approximately 40% (38 out of 88) samples contained no gravel sized material. A small number (5 out of 88) of grabs, mainly from the central eastern section of the application site, could be described as sandy gravel (relatively courser still). Silt and clay sized material did not constitute more than 2% of any of the samples.

The majority of the samples collected from the application site were found to have either a bimodal or trimodal grain size distribution; ~75% of the samples were moderately to well-sorted. Dominant modal particle sizes are variable across the application site, ranging from 27,000 µm (pebble gravel) to 110 µm (very fine sand). However, almost every sample contained a modal peak at approximately 430 µm (medium sand), indicating that this is the most common sediment type in this area, a finding which is in close agreement with that of Holmes *et al*. (2004). The scatter plots of modal grain sizes against water depth indicates that a (weak) relationship exists between grain size and depth in the application site with the larger mean grain sizes found in the shallower water depths (Figure 21), typically around the crest of the Smith Bank. The explanation for this relationship is that sediments in shallower water depths are more frequently and more energetically worked by wave action, leading to net sediment transport out of an area, than sediments in deeper water which rather tend to act as sinks for finer grained sediments.

Numerous small boulders (>300 mm diameter) have been identified across the application site (Osiris, 2011). 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.

Detrital carbonate sediments (comprised mainly of shell fragments) make a significant contribution to the sediment deposits of the Moray Firth and proportional shell content in the benthic grab samples from and nearby to the application site are frequently in excess of 50% (Partrac, 2010; 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 discrete grab sample data collected from the application site were used in conjunction with an interpretation of the side scan sonar evidence, confirming that the application site is dominated by medium to coarse grained sand interspersed with areas of gravel-sized sediment, possibly present as a lag deposit. In the central and northern areas of the application site these sandy-gravel areas are broadly arranged into NNW-SSE trending patches and are often crescentic in form, orientated transverse to the main axis of tidal flow. Gravel is most abundant in central and eastern areas of the application site although is also found in the base of channel-like features identified along the western flank of Smith Bank (Figure 20 and Figure 22). Outcrops of glacial till comprising clay and cobbles are also identified in central-western and north-western areas of the application site and are evidence of thin or absent Holocene sediment cover in these areas.

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 contract was undertaken to help improve the current understanding of where rock 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 the 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).

4.4 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 18 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 18. 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)	Late Pleistocene Sediments
Sandy silty CLAY (chaotic to featureless appearance)	Unit 3b (Mid to Late Pleistocene)	
Isopachyte 2 - Base of Late Pleistocene Sediments		
Very stiff to hard CLAY (Overconsolidated Sediments)	Unit 4 (Early Pleistocene)	Early - to mid Pleistocene Sediments
Isopachyte 3 - Base of Early - to Mid Pleistocene Sediments		
Very hard CLAY	Unit 5a (Early Pleistocene/Lower Cretaceous)	Ice pushed Formations
Isopachyte 4 - Base of Ice Pushed Formations		
Very hard CLAY (intact bedded formations)	Unit 5b (Lower Cretaceous)	(Cretaceous Rocks)

An overview of each of the four main sediment groupings is provided in Osiris (2011) and repeated below.

(i) Marine Sediments

Surface sand/silt unit (Unit 1): Comprised of variable, (possibly locally silty and gravelly) sands. The unit is thickest (up to ~5.0 m) over more elevated parts of the site and is absent in some of the shallow valleys across the Smith Bank plateau area and where the older sediments outcrop at seabed. It is generally absent towards the north west edge of the site. This unit is suggested to have accumulated since the Holocene transgression, in marine conditions similar to the present day, and may be mobile in places, migrating slowly down slopes and in response to wave motion.

Sand unit (Unit 2a): Comprises the bulk of the marine sediments found in the more western and north western parts of the site. This unit ranges from 10.0 to 20.0 m thick over much of the western and north western sections of the site, but this increases to between 25.0 m and 32.0 m within a number of elongate troughs, or channel features. Historical borehole data suggests that this material comprises fine to medium, or fine to coarse sands, with variable shell content. The unit exhibits an internal structure, which suggests progradation away from the more elevated central part of Smith Bank.

Finer grained unit (Unit 2b): interpreted to be a potentially very soft sandy silty clayey mix, lying below the sand unit. This unit is generally between 5.0 m and 8.0 m thick (locally up to 16.0 m) and is present where the underlying older sediments are less elevated.

An east-west division exists in the distribution of marine sediments across the site, with only a thin cover of the recent marine sediments in the east of the site and a much thicker expanse of these sediments across the western side. This uneven distribution is mainly caused by marine sediments of Units 2a and 2b infilling channels and hollows in the undulating surface of older harder units. The marine sediments are up to 34 m thick within a number of channels, which generally traverse the western section of the site (Osiris, 2011).

(ii) Late Pleistocene Sediments

Layered sandy silty clays (Unit3a): there is a clearer discontinuity separating the marine sediments from a more clearly draped unit (Unit 3a) with less onlap, and with bedding that closely follows the underlying surface. This unit is of limited extent and is found down to approximately 40 m below seabed, within relatively shallow troughs or depressions in the older sediments, generally within the southern and central section of the site. These sediments are suggested to form part of the Forth Formation.

These reworked and infill units reach thicknesses of up to 17.0 m in localised troughs or channel features, although average thicknesses lies between 4.0 m and 7.0 m.

Chaotic to featureless sandy silty clays (Unit 3b): found overlying the older Pleistocene and Lower Cretaceous sediments in some areas of the application site. These sediments reach thicknesses of over 35.0 m in localised troughs or channel features, but their average thicknesses is generally between 6.0 m and 8.0 m.

(iii) Early to Mid-Pleistocene Sediments

Very Stiff clay formation (Unit 4): locally up to 7.0 m thick and may represent a lodgement till or moraine, but it is also possible that they are derived locally from the underlying Lower Cretaceous sediments. There are also undulating parallel bedded, probable stiff sandy clay sediments (also Unit 4) that occur primarily in two deep trough features, slightly to the north east and north west of the centre of the site, but also elsewhere to a lesser extent. These bedded sediments achieve thicknesses of up to 50.0 m within these two troughs.

Pleistocene deposits occur close to the seabed in several places and an isolated outcrop is present at 505330m E, 6463135m N, in the far north west of the site.

(iv) Ice Pushed Formations

Very hard clay formation (Unit 5a): generally found across the more southern and central parts of the site. Exhibits extensive faulting and folding, together with zones of a chaotic nature - or an apparent absence of any internal structure, and are thought to have been caused by the pressure and movement of ice sheets or glaciers.

Lower Cretaceous (Unit 5b): depths to bedrock are very difficult to ascertain because of the ice-related deformation. In the northern section of the site, where the deformation appears almost absent, rockhead generally lies within 10 to 15 m below seabed. However, the top to *interpreted 'intact' (non-deformed) bedrock elsewhere across the site is highly variable, with depths of 70 to 130 m below seabed indicated across the central, western and south western areas. In the extreme south of the site, the interpreted 'intact' bedrock surface generally lies between 10 m and 40 m below seabed.*

4.5 Conceptual Understanding of the Sediment Regime

In comparison to other areas of the North Sea, relatively little is known 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 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 along the Caithness coast and into the Inner Moray Firth (Figure 23). Once within the Firth, marine sediments become dispersed along routes parallel to the tidal flow axes. 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.

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) 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 sources:

- Suspended sediment concentrations measurements collected during the metocean survey (Partrac, 2010); 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 with the two AWAC devices as part of the metocean survey. The OBS units were mounted 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 (10/02/10 to 10/03/10) are presented in Figure 24; 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 SSC.

It is shown in Figure 24 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 24 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 associated with 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 of lower peak wave height, the second storm event shown is more sustained, with wave heights persisting for longer, allowing more time for the SSC load to build. At the southern end of the 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 24).

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.

The application site specific observations can be complimented by regional scale information. 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, which is broadly consistent with the findings described above from the application site survey.

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

Table 19. 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 (Wentworth)	Number of Occurrences in 88 Samples	Threshold Bed Shear Stress for Mobility (N/m^2)
27,000	Pebble gravel	2	23.8
3,400	Granule gravel	3	2.42
1700	Very coarse sand	10	0.93
850	Coarse sand	36	0.40
430	Medium sand	83	0.24
215	Fine sand	69	0.18
110	Very fine sand	4	0.15

4.6.1 Potential Mobility Due to Tidal Currents

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 four 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 four locations are the Beatrice AWAC2a and 3a deployment sites, the Beatrice wave buoy and an additional analysis point (‘Beatrice Analysis Point 1’) in the centre of the application site (Figure 4).

The calculated bed shear stress values are plotted in Figure 25 and compared to the threshold values for mobility of the sediment grain sizes listed in Table 19. The figure shows that mobilisation events (when the critical bed shear stress values are exceeded) are generally confined to a brief period 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 20.

Table 20. Estimated potential sediment mobility (due to tidal currents only) at four locations across the application site

Location		Very Fine Sand	Fine Sand	Medium Sand	Coarse Sand	Very Coarse Sand
Beatrice AWAC 2a (46 m CD)	Mobility Summary	Only mobile during highest springs	Only mobile during highest springs	Not mobile	Not mobile	Not mobile
	Mobility % time	8%	4%	0%	0%	0%
Beatrice AWAC 3a (36 m CD)	Mobility Summary	Only mobile during highest springs	Not mobile	Not mobile	Not mobile	Not mobile
	Mobility % time	3%	0%	0%	0%	0%
Beatrice wave buoy (49 m CD)	Mobility Summary	Only mobile during highest springs	Only mobile during highest springs	Not mobile	Not mobile	Not mobile
	Mobility % time	8%	4%	0%	0%	0%
Beatrice Analysis Pt. 1 (44 m CD)	Mobility Summary	Only mobile during highest springs	Only mobile during highest springs	Not mobile	Not mobile	Not mobile
	Mobility % time	7%	4%	0%	0%	0%
Analysis based on an assumed bed type of sand/ gravel characterised by a d50 bed value of 500 µm						

It is apparent from Table 20 that there is only very limited potential for sediment mobilisation by tidal currents in the application site, typically only on large spring tides and only then for the finer sand fractions (215 µm and smaller). 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 high 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 flat at the scale of a few meters (i.e. without very small bedforms).

Although Figure 25 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 BOWL AWAC deployments. Spatial variation in residual flow and residual sediment displacement patterns over a 30-day period for a very fine sand are shown in Figure 26; residual sediment displacement (the net advective pathways) 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 26); 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 west across the application site. This means that finer material held in suspension will generally be transported to the west, towards the Caithness coast and into the Moray Firth.

There is a south-westerly trend in predicted sediment displacement which is entirely consistent with published information on the direction of net sediment transport in this region (e.g. Figure 23). This pattern can be readily explained as a result of the relatively higher peak flood current speeds, which lead to a longer net duration of currents (in a south-westerly direction) that (just) exceed the threshold of sediment mobility for finer grain sizes.

4.6.2 Potential Mobility Due to Waves

The regional wave climate has been discussed in more detail in Section 3.5. Significant wave heights in excess of 5 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 for a 1 in 50-year 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 24 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 21.

Table 21. 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)
Beatrice AWAC 2a (46 m CD)	0 (current only)	Not mobile	Not mobile	Not mobile	Not 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	Not mobile	Mobile	Mobile	Mobile
	4	Not mobile	Mobile	Mobile	Mobile	Mobile	Mobile
	5-8	Mobile	Mobile	Mobile	Mobile	Mobile	Mobile
Beatrice AWAC 3a (36 m CD)	0 (current only)	Not mobile	Not mobile	Not mobile	Not mobile	Not mobile	Mobile
	1	Not mobile	Not mobile	Not mobile	Not 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
	5-8	Mobile	Mobile	Mobile	Mobile	Mobile	Mobile
Analysis Point 1 (44 m CD)	0 (current only)	Not mobile	Not mobile	Not mobile	Not 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
	5-8	Mobile	Mobile	Mobile	Mobile	Mobile	Mobile
Analysis Point 2 (53 m CD)	0 (current only)	Not mobile	Not mobile	Not mobile	Not mobile	Mobile	Mobile
	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	Not mobile	Mobile	Mobile	Mobile
	4	Not mobile	Not mobile	Mobile	Mobile	Mobile	Mobile
	5	Not mobile	Mobile	Mobile	Mobile	Mobile	Mobile
	6-8	Mobile	Mobile	Mobile	Mobile	Mobile	Mobile

From Table 21 it is apparent that when taking into consideration the combined influence of tidal currents and wave-induced orbital currents, significantly larger sediment particles become mobile. It should be noted though that there is an inverse relationship between water depth and orbital current velocity at the bed (Table 10). However, within the application site, the shallowest water depths coincide with the slowest peak tidal currents. As such, a relatively complex spatial pattern of differing bed shear stress exists across the application site.

At all locations, a 3 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 application site (Section 4.3). Waves of this size (or greater) are relatively common within the application site 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 application site is ‘active’ to some degree.

In the north-east and centre of the application site, 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-east of the application site (Beatrice AWAC 2a) and moderate depth in the centre of the application site (Beatrice Analysis Point 1) means these areas of the application site are likely to be most mobile.

Gravel-sized material is only likely to be mobile during very large (> 5 m) storm events. Such waves are present in the observational wave records from the application site (Table 14) but are only likely to occur a few times each year.

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 17.

5.3 Seabed Morphology

The bathymetry of the application site has previously been described within the geophysical survey report (Osiris, 2011) and this description is repeated here:

> *Seabed levels range from 35.1 m below LAT, close to the south western corner of the development area, to 68.1 m below LAT at the extreme north west corner.*
>
> *A marked escarpment is present along the western edge of the area, where the seabed dips towards the west north west. Seabed levels along the escarpment fall*

from ~38 m below LAT to ~52 m below LAT in the south (maximum gradient 2.6°), from ~42 m below LAT to ~56 m below LAT in the central section (maximum gradient 1.6°), and from ~50 m below LAT to ~68 m below LAT (maximum gradient 1.1°) in the north.

Away from the western escarpment, the seabed is gently undulating. No obvious bed forms (sand waves or megaripples) are seen on the bathymetry data, but a number of raised ridges and associated narrow troughs are present, with the ridge features standing between 0.5 m and 1.2 m above the surrounding seabed (see Figure 22*). The ridges appear to be comprised of mainly finer grained sediments, are up to 500 m wide and are orientated generally west - east or west north west - east south east. Maximum gradients of approximately 1.0° can be found around the edges of some of these features.*

A broad south south west - north north east orientated channel is evident (see Figure 22*, below), running from approximately the central western section of the application site (where it is ~500 m wide), to the northern section of the development area, where its width has increased to between 2500 m and 2800 m.*

Although Osiris (2011) note that there are no 'obvious' (large sand wave) bedforms in evidence at the application site, it is noted within the geophysical survey report that the finer grained (sandy) materials do exhibit some shallow relief across the coarser grained (more gravelly) sediments, with the sandy gravels present within the intervening troughs. These features occur with a very regular spacing (typically 50 m to 70 m) in the north eastern part of the area, resembling low-lying sand waves with crest heights of approximately 0.5-1.5 m. However, it is noted that they possess a different profile to 'classic' sand waves with broad ridges separated by relatively narrow troughs (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 27).

The DTI 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) NNW-SSE, 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.

The high-resolution geophysical survey of the application site also reveals the presence of linear channel features. These are most well developed along the western and north-western margins of the application site and are broadly orientated in a north-west to south-east direction, perpendicular to the contours of Smith Bank, i.e. in a down slope direction.

Across the far-field region, numerous ridges and channels have previously been mapped from echo sounder records compiled by Olex (www.olex.no) (Figure 27). 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 Characteristics of the Moray Firth

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.

5.5 Conceptual Understanding of Seabed Morphology

As previously described, the application site is situated on the north-west flank of the 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 the 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 the 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 application site survey and previously, during the DTI SEA surveys reveal the presence of sediment waves and sharp edged sand patches on Smith Bank (Holmes *et al*., 2004; Osiris, 2011) (Figure 20 and Figure 22). Holmes *et al*. (2004) note that the sediment waves 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). This observation that the sediment waves found in the north of the application site are mobile is in agreement with the sediment mobility analyses presented in Table 20 as well as published evidence concerning the relationship between the distribution of bedforms and current speed. Indeed, in the north of the application site 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 20) and form mega-ripples/ small sand waves (Belderson *et al*., 1982) (Figure 28). However, current speeds of less than ~0.55 m/s are of insufficient velocity to form transverse bedforms and this accounts for their absence across the southern half of the application site.

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 directional currents (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 21 and as previously stated, it is probable that medium-sized sand (the most commonly occurring sediment in the area) is regularly mobilised in all but the deepest areas of the application site.

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 channel features identified on the western flank of Smith Bank are orientated downslope and could be relict bedforms which developed at a time when sea level was considerably lower and Smith Bank was sub-aerially exposed. However, this interpretation is at odds with model simulations of postglacial relative sea level change for this region which suggest that at no point over the past 20,000 years were water depths shallower than ~ -10 m across the crest of Smith bank (Bradley *et al*., in press).

The ridges shown in Figure 27 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 Beatrice 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

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;

- 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; and

- 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.

Currents:

- Information available on the strength of tidal currents in this region shows that recorded (depth-averaged) peak spring current speeds are around 0.55-0.6 m/s, with the fastest speeds recorded in the north of the application site;

- 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; and

- 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.

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;

- Even though water depths across the application site are no less than 35 m, storm waves sufficiently large to stir the seabed are not uncommon; and

- 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.

Stratification and Fronts:

- The Outer Moray Firth may experience some seasonal 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.

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 430 µm (medium sand) was consistently found across almost all samples. Other modal peak grain sizes were also variably observed across the application site, ranging from 27,000 µm (pebble gravel) to 110 µm (very 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).

- Across much of the application site, surficial 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 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 central and north-eastern areas of the application site are most active in this way; and

- 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 west and 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.

Morphology:

- The application site spans the crest and north-west flank of the Smith Bank and is characterised by water depths in the range 35 to 68 m below LAT. The shallowest depths are found in the south of the application site whilst the greatest depths are found at the north;

- 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 present in the north of the application site whilst sharp-edged sand patches are found in the shallower water depths of central and south-eastern areas;

- 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;

- Linear, down-slope channels have been identified along the western margin of the application site and these may also be of glacial origin; and

- 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 the Smith Bank over the lifetime of the proposed development.

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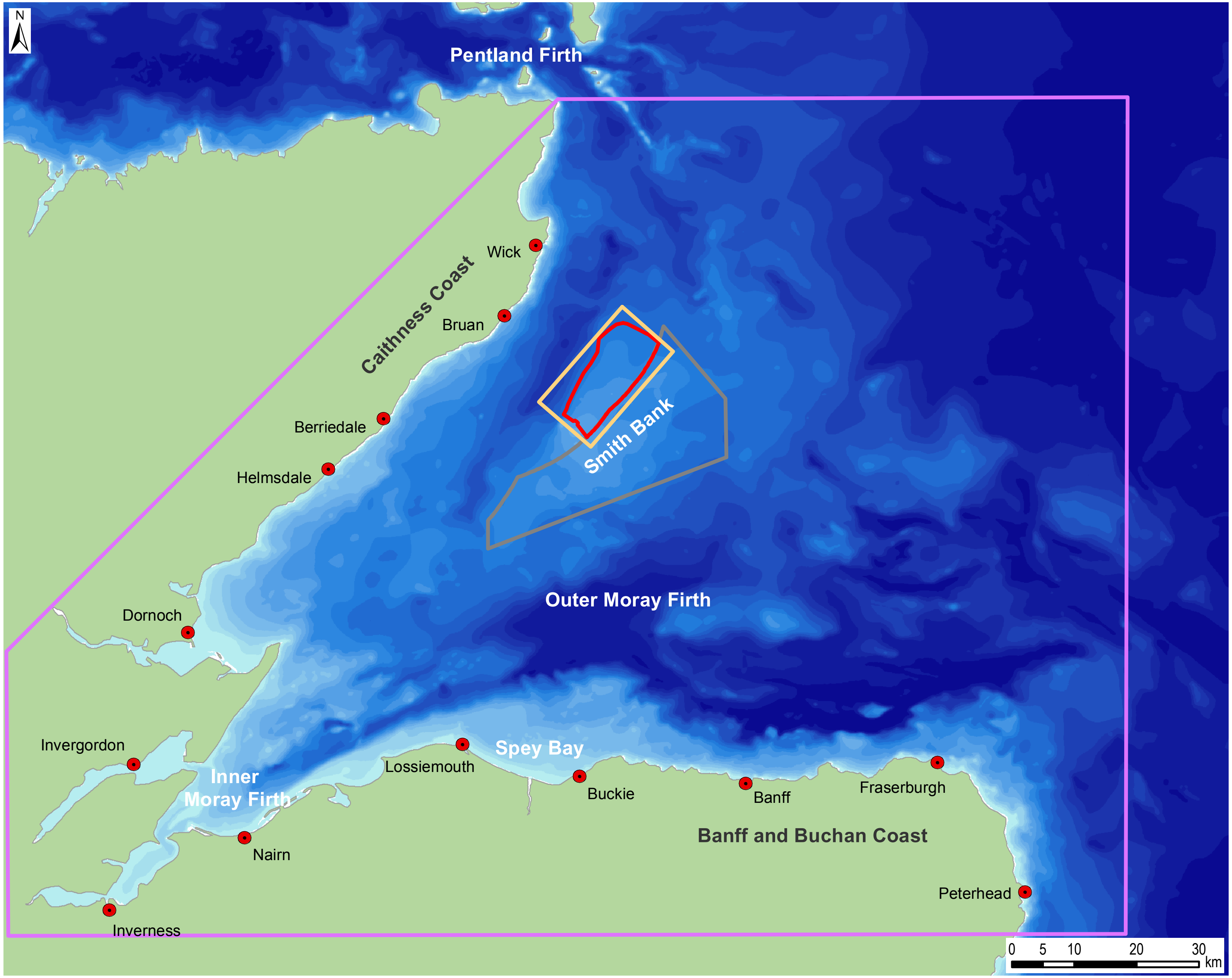
Figures



Application site boundary
Moray Firth OWF site boundary
Far-Field study boundary
Near-Field study boundary
Place names

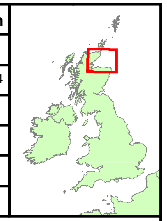
Bathymetry (m MSL)

- -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

Date	By	Size	Version
Apr 11	NKD	A4	2
Projection		UTM30N WGS84	
Scale		1:900,000	
QA		NJG	

3888_010_Fig1_Study_area.mxd

Produced by ABPmer Ltd



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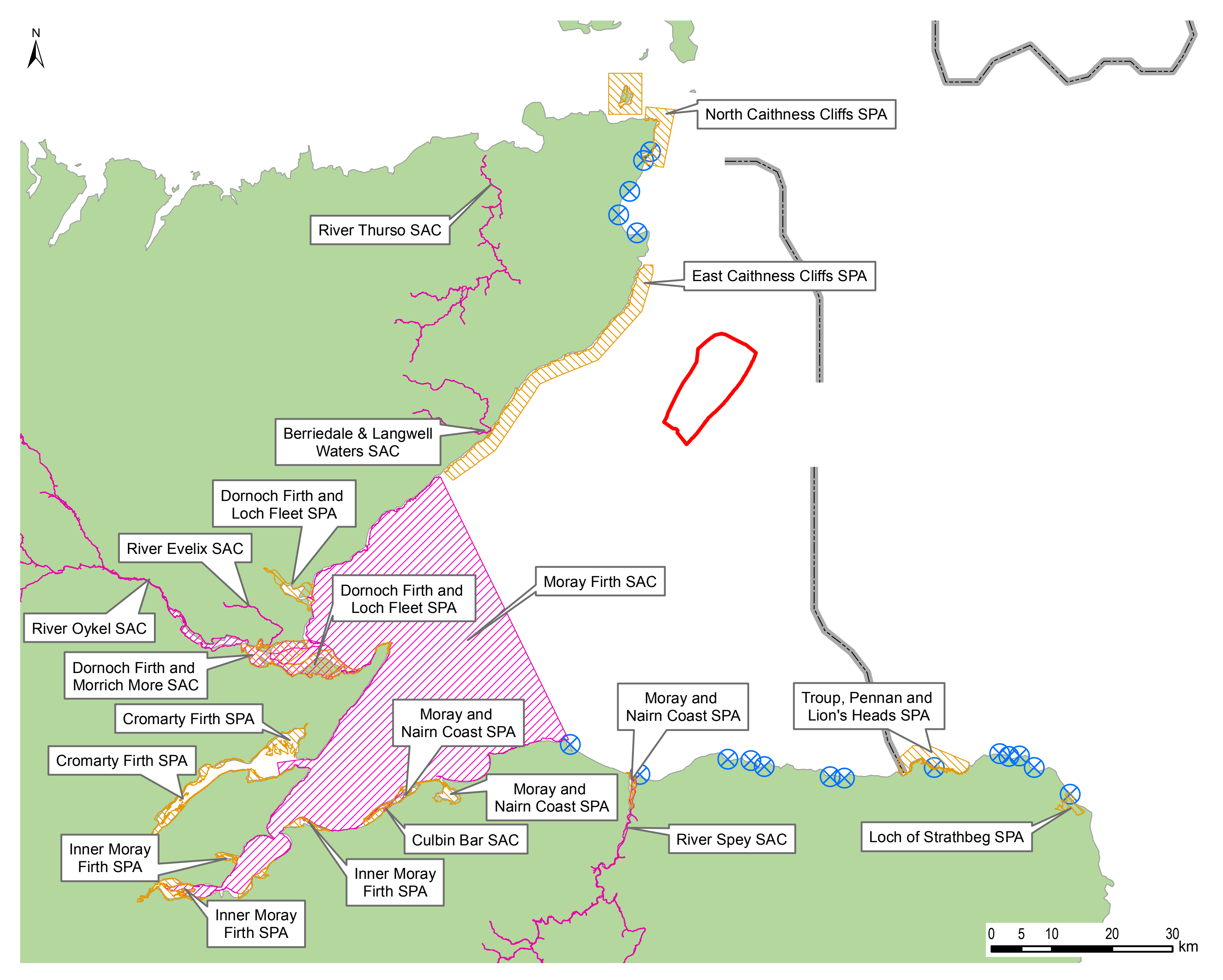
The Study Area

Figure 1



Application site boundary
SPA sites
SAC sites
Surfing locations
Fronts

Data sources: JNCC/ Scottish Natural Heritage (2010); Barne et al (1996); SAS (2009)

Date	By	Size	Version
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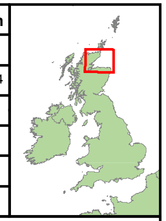

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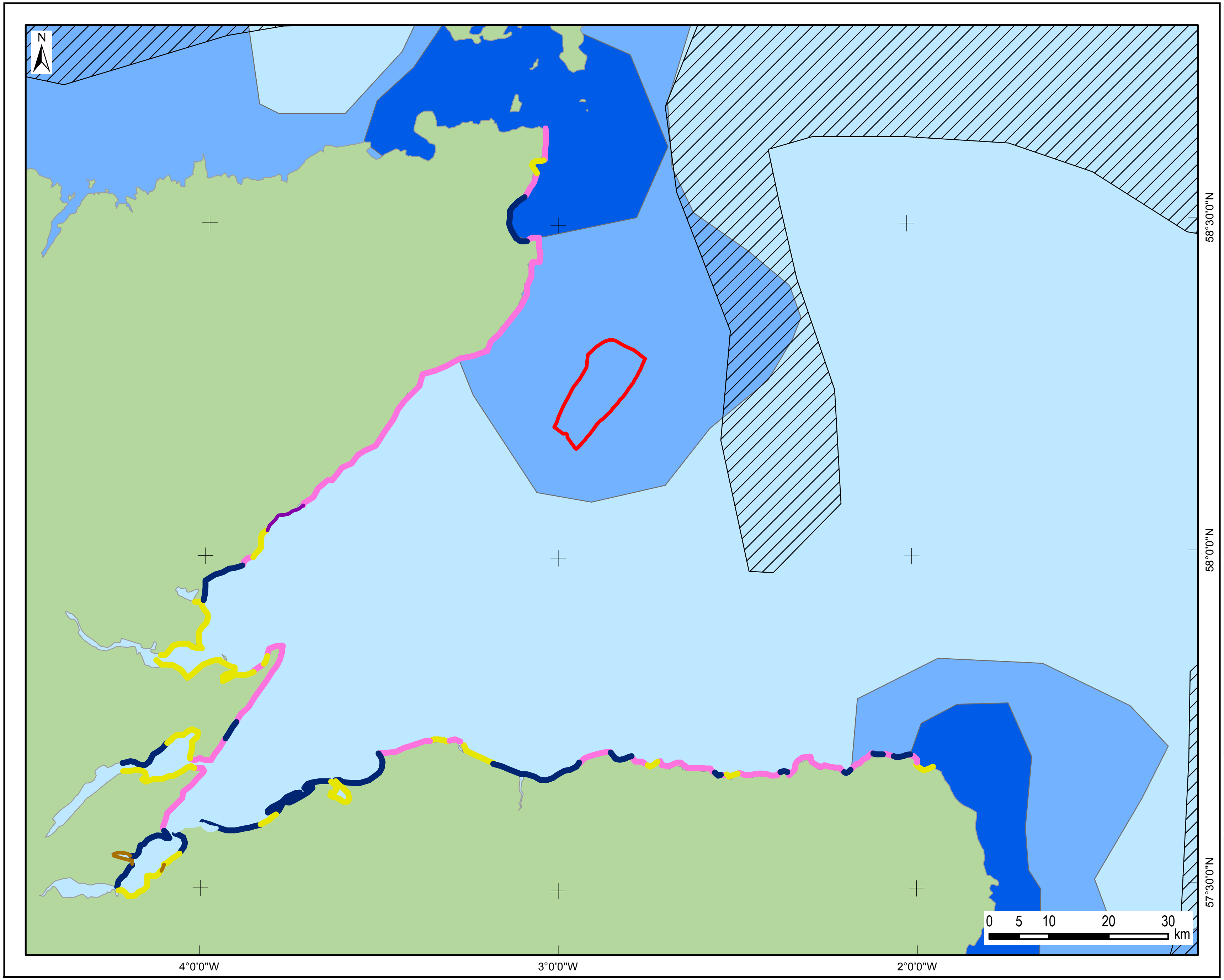
Designated Sites and Identified Receptors in the Moray Firth

Figure 2



Application site boundary
Dominantly bedrock
Dominantly sand
Links, raised beach and land <5m elevation
Marsh
Sand / bedrock
Sand / shingle
Fronts
Mixed water
Transition zone
Stratified water

Date	By	Size	Version
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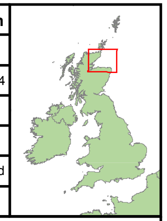

Ramsay & Brampton, 2000; OSPAR 2000 (after: Becker, 1990)

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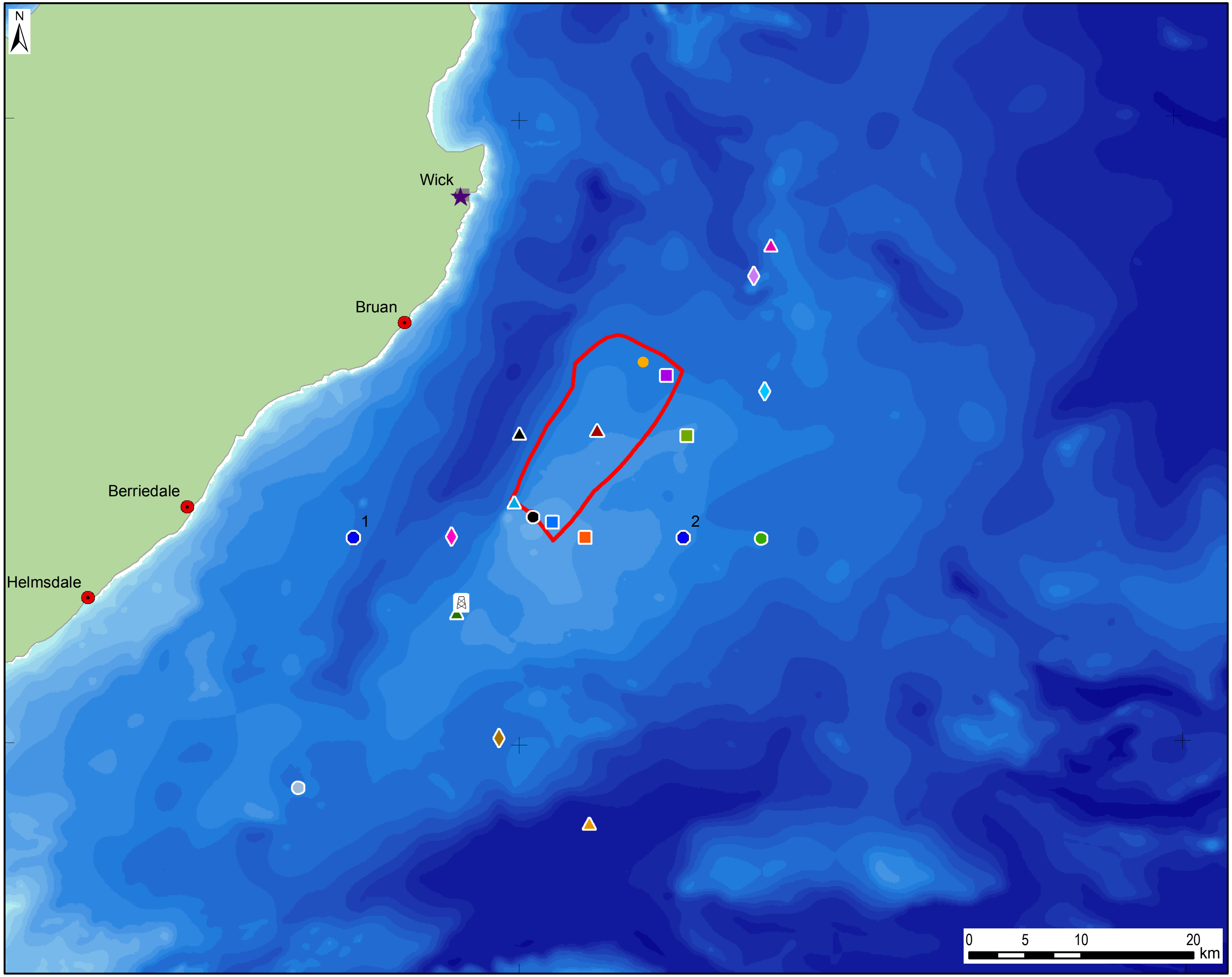
Coastal Characteristics of the Moray Firth

Figure 3



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
Application site boundary
Place names

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

Date	By	Size	Version
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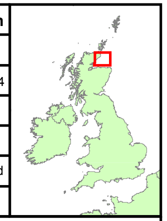

Bathymetry; Tcarta, 2011
NOT TO BE USED FOR NAVIGATION

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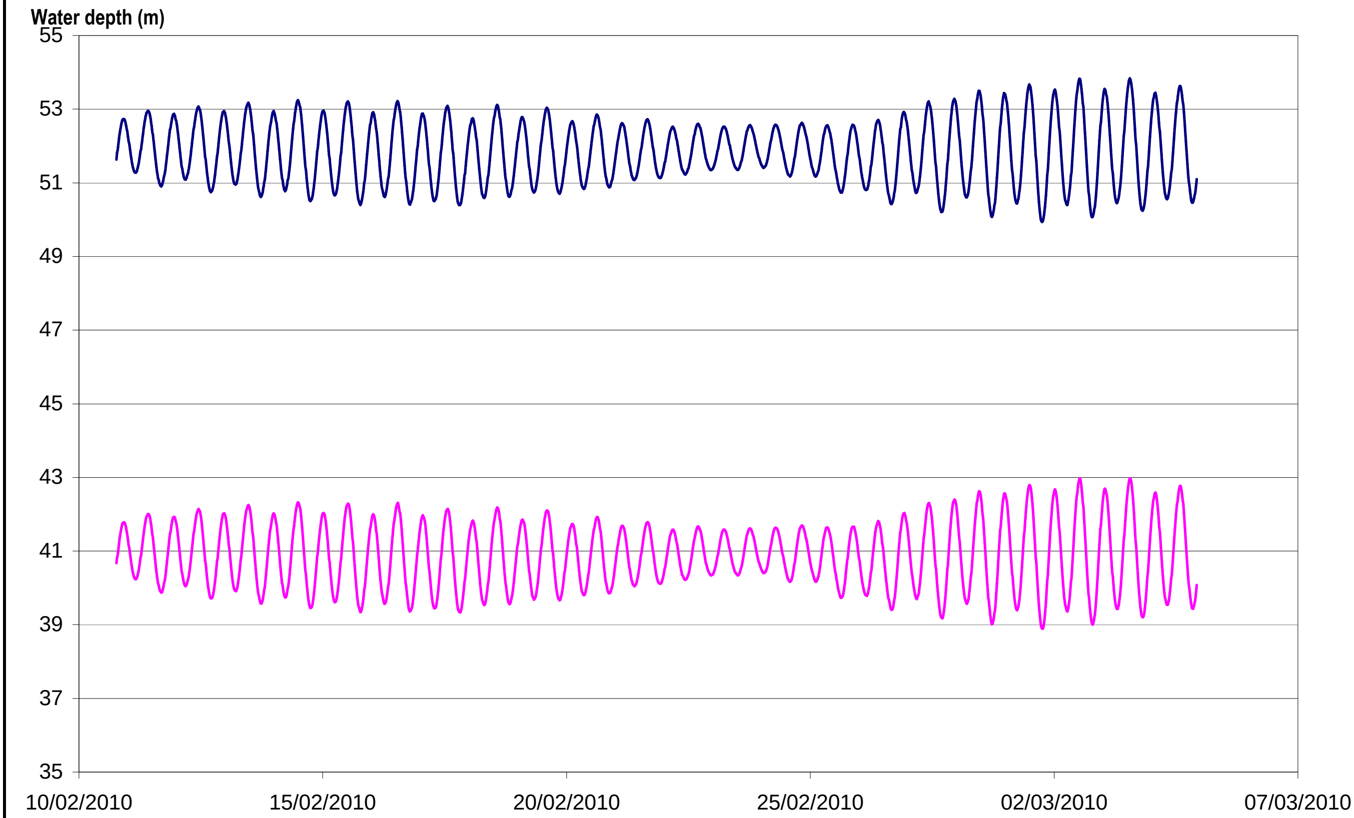
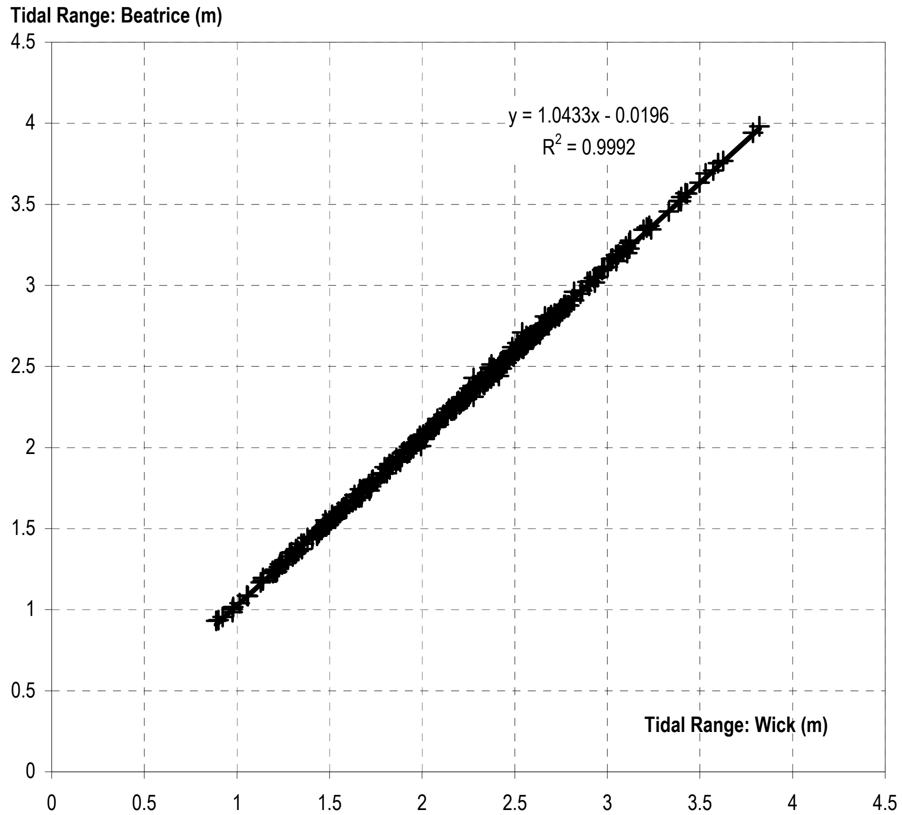
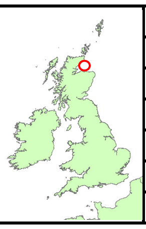
Data and Deployment Locations in the Moray Firth

Figure 4







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Scale		n/a	
QA		NKD	
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Produced by ABPmer Ltd.			

Beatrice AWAC2a
Beatrice AWAC3a

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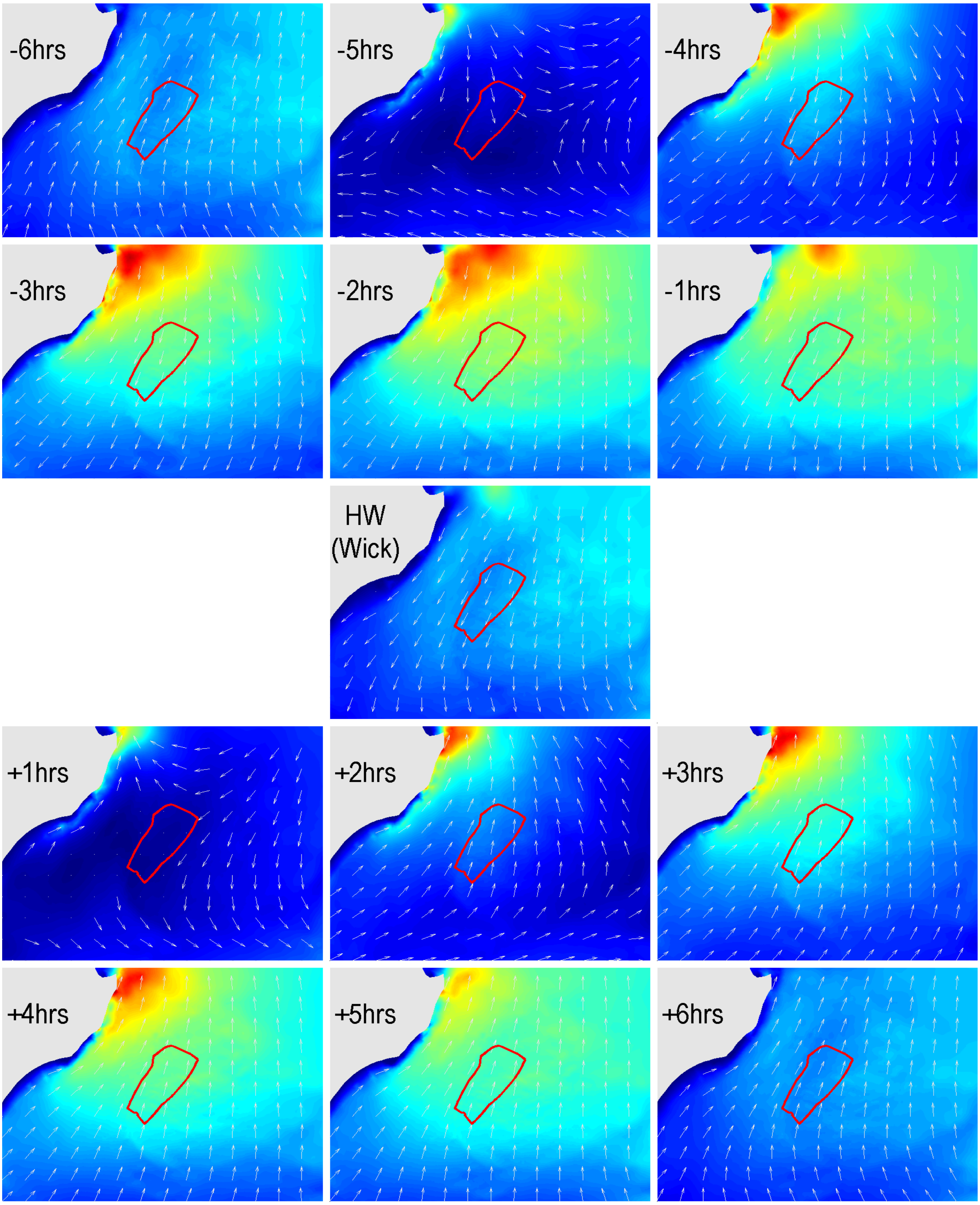
A: Water Level Data from the Application Site AWACs; B: Correlation between Tidal Ranges Measured at Wick Tide Gauge and at the Beatrice AWAC 3a

Figure 5



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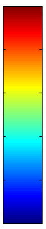

Current speed (m/s)
(Arrows indicate current direction for speeds >0.05m/s)

Application Site

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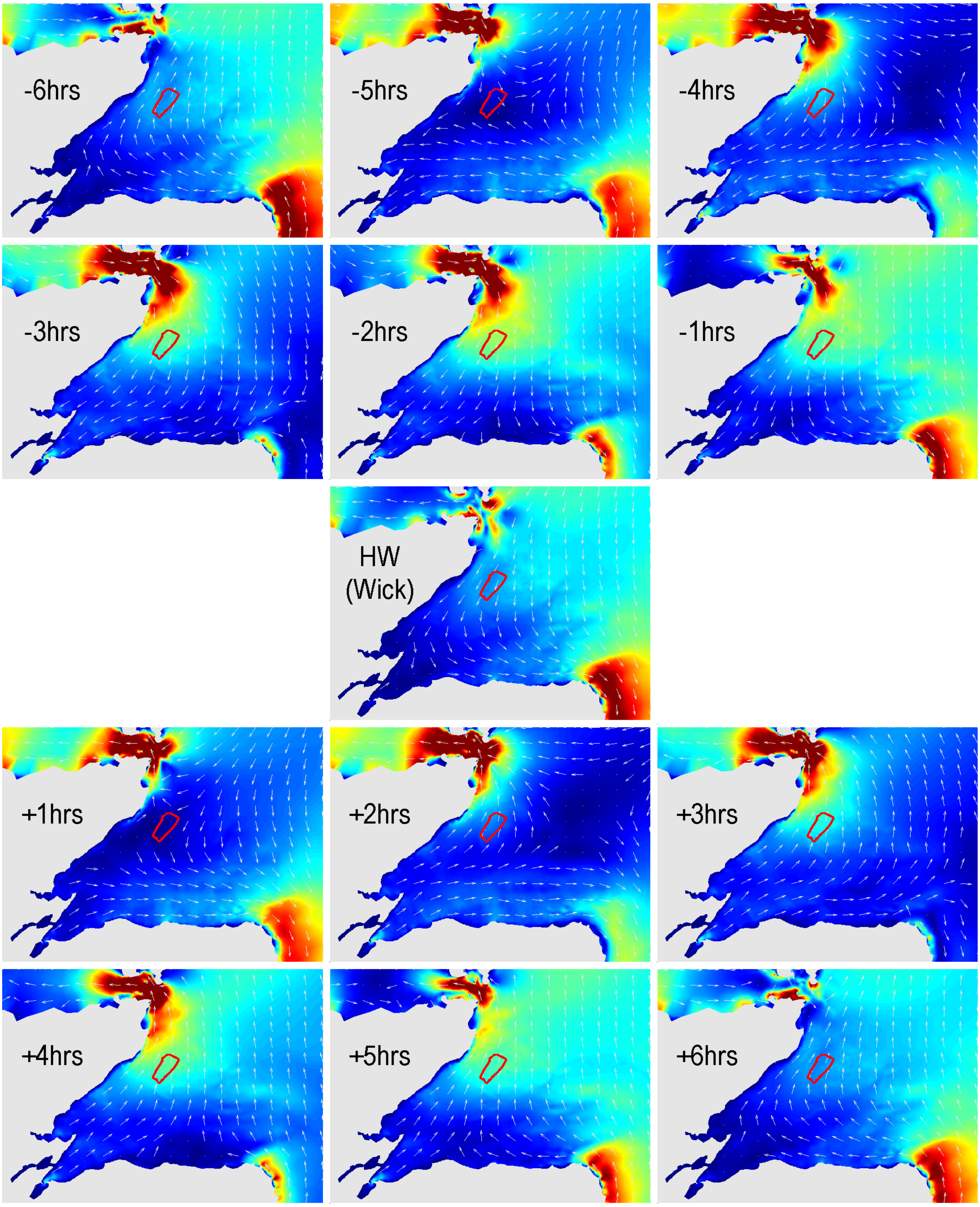
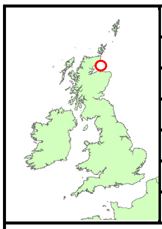
Modelled Near-Field Spring Tidal Flow Patterns

Figure 6





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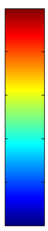

Current speed (m/s)
(Arrows indicate current direction for speeds >0.05m/s)

Application Site

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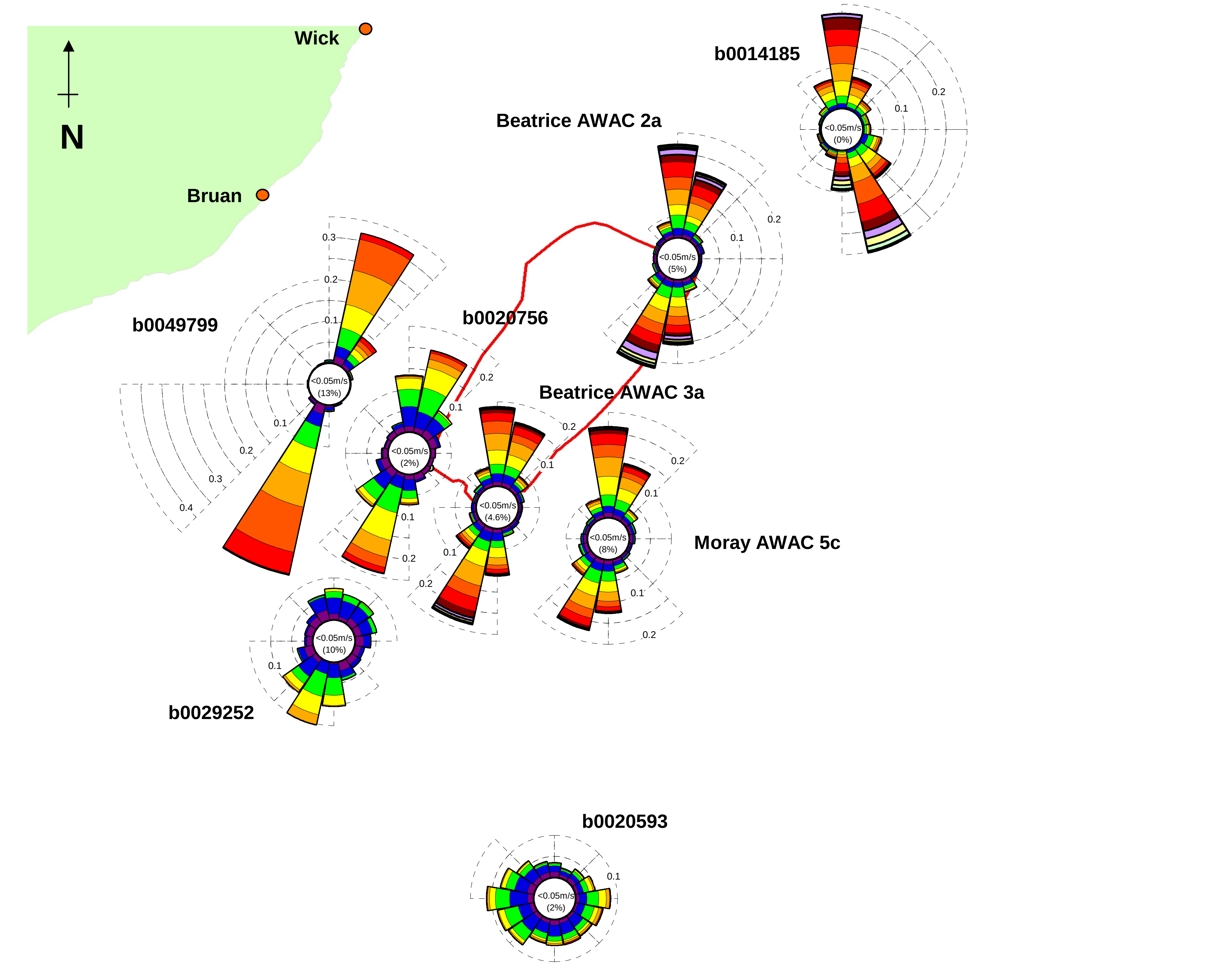
Modelled Far-Field Spring Tidal Flow Patterns

Figure 7



Current Speed (m/s)

- <0.70m/s
- <0.65m/s
- <0.60m/s
- <0.55m/s
- <0.50m/s
- <0.45m/s
- <0.40m/s
- <0.35m/s
- <0.30m/s
- <0.25m/s
- <0.20m/s
- <0.15m/s
- <0.10m/s

Application Site

Date	By	Size	Version
June '11	NW	A4	2

Projection	n/a
Scale	n/a
QA	NKD
3888-Figure-control_oneclick.xls	
Produced by ABPmer Ltd.	

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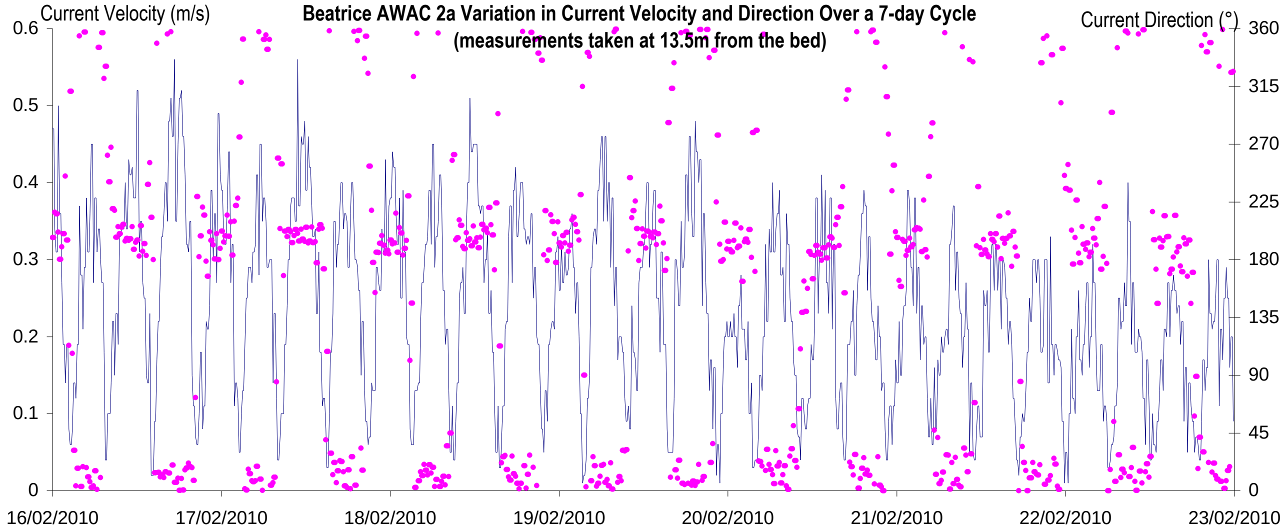
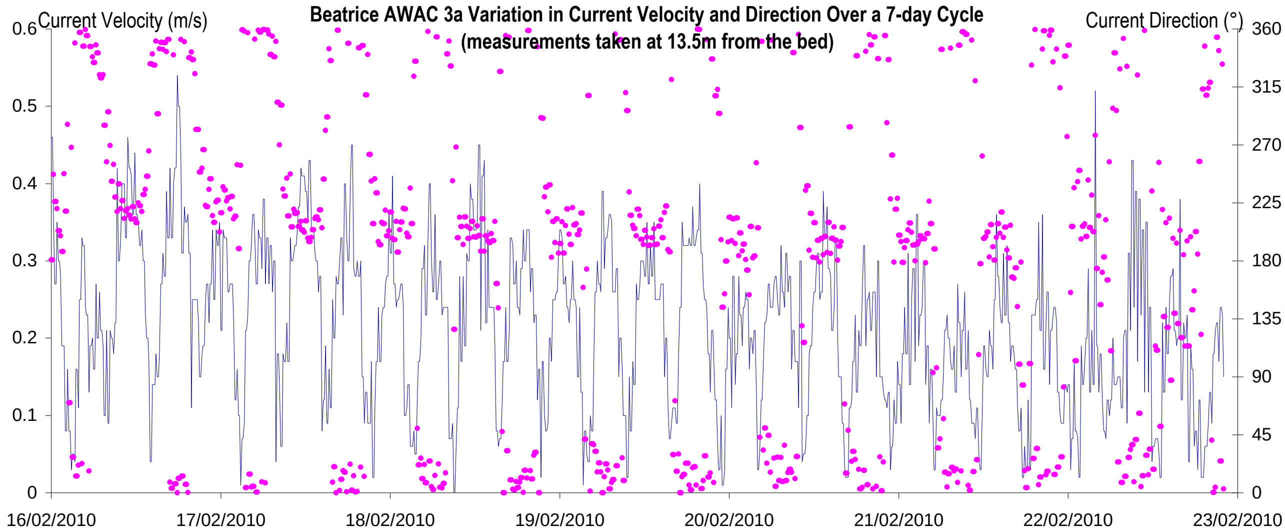
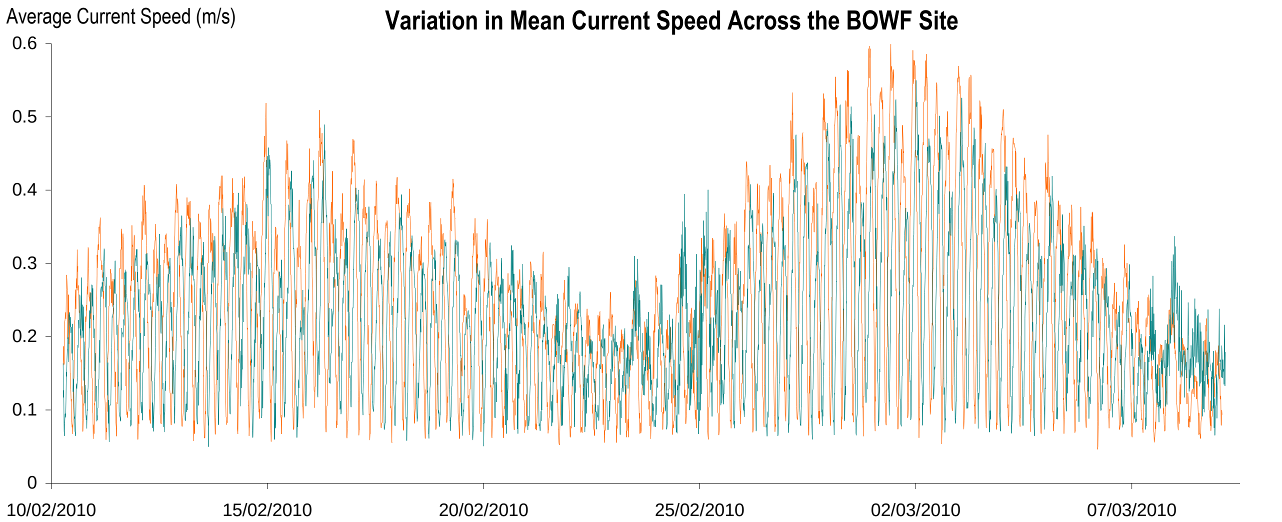
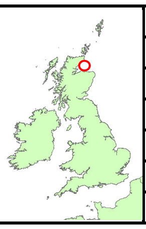
Observational Current Records from within and nearby to the Application Site

Figure 8









Date	By	Size	Version
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Produced by ABPmer Ltd.			

Current velocity (m/s)
Current direction (°N)
Beatrice AWAC 2a
Beatrice AWAC 3a

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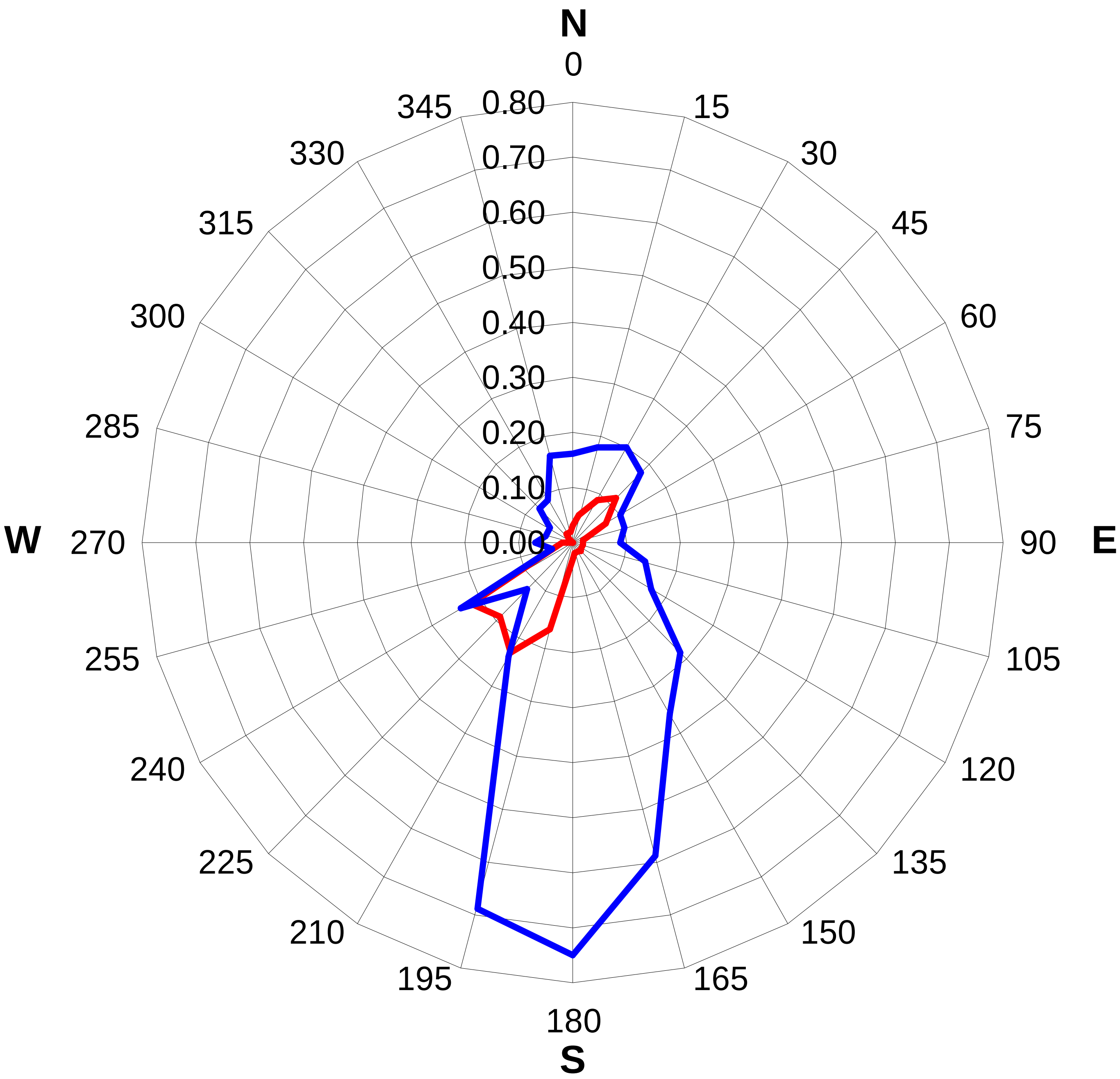
Variation in Current Velocity Across the Application Site

Figure 9



NOC Surge Locations

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

(see Figure 4 for location)

Date	By	Size	Version
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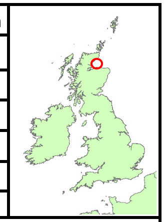

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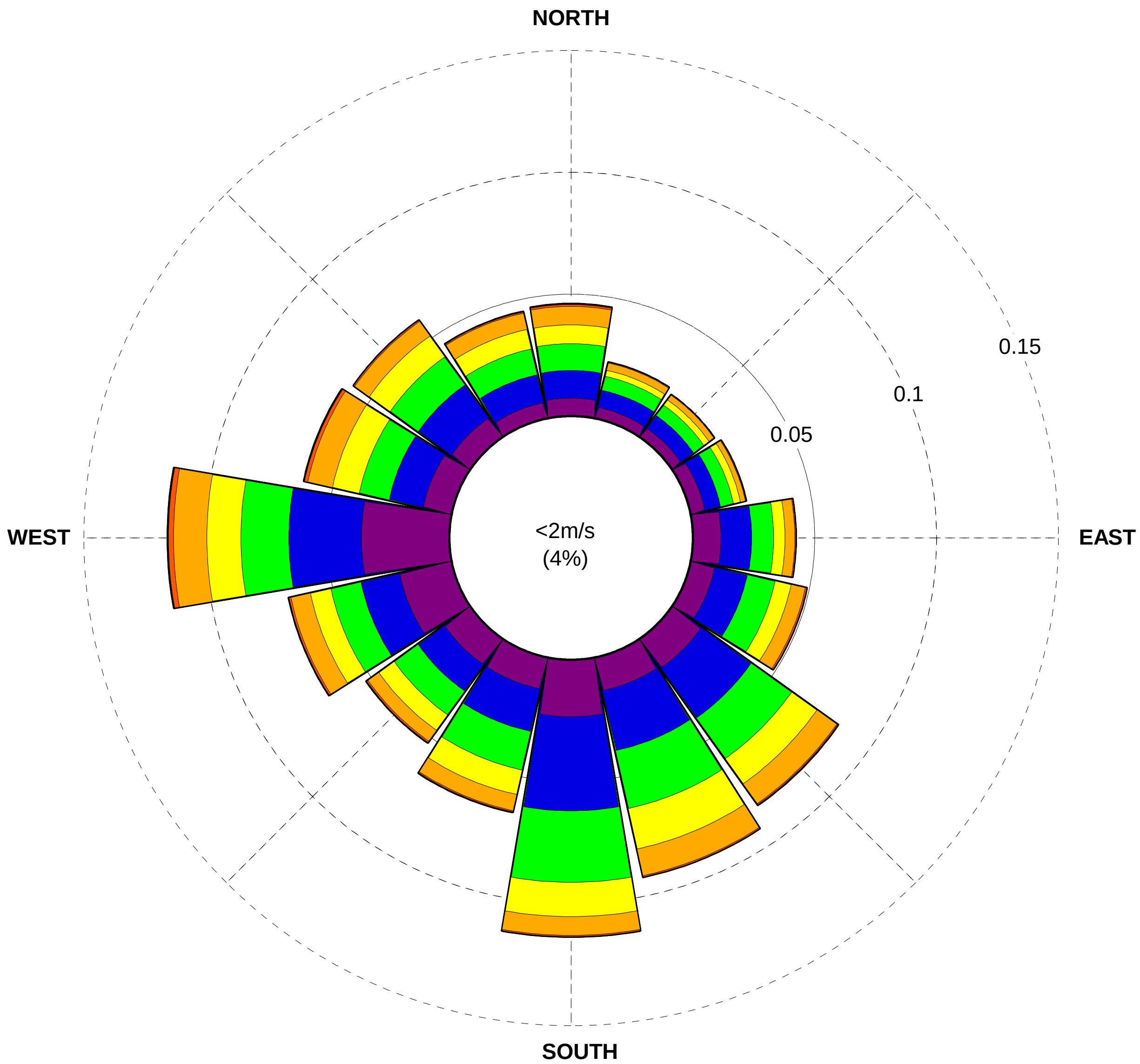
The directional Distribution of 50-year Return Period Surge Currents

Figure 10

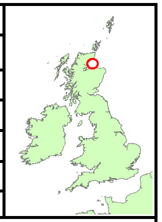


Wind Speed (m/s)

- >30m/s
- <30m/s
- <25m/s
- <20m/s
- <15m/s
- <10m/s
- <8m/s
- <6m/s
- <4m/s

(see Figure 4 for location)

Date	By	Size	Version
June '11	NW	A4	2
Projection	n/a		
Scale	n/a		
QA	NKD		
3888-Figure-control_oneclick.xls			
Produced by ABPmer Ltd.			



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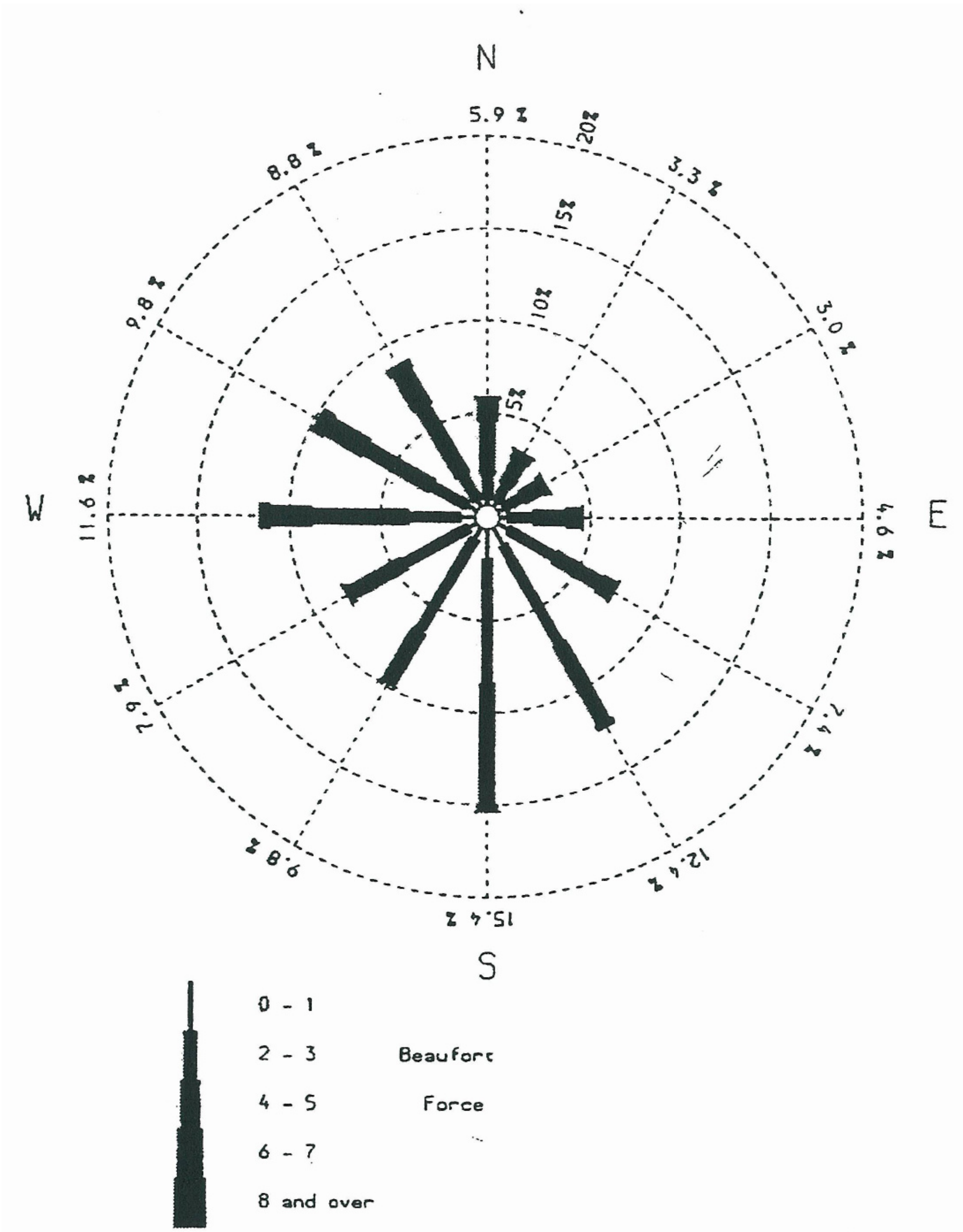
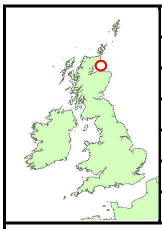
Wind Rose for Wick Airport (January 1996 - January 2011)

Figure 11





Date	By	Size	Version
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Projection		n/a	
Scale		n/a	
QA		NKD	
3888-Figure-control_oneclick.xls			
Produced by ABPmer Ltd.			

Data source: Babtie Dobbie Ltd, 1994.

(see Figure 1 for location)

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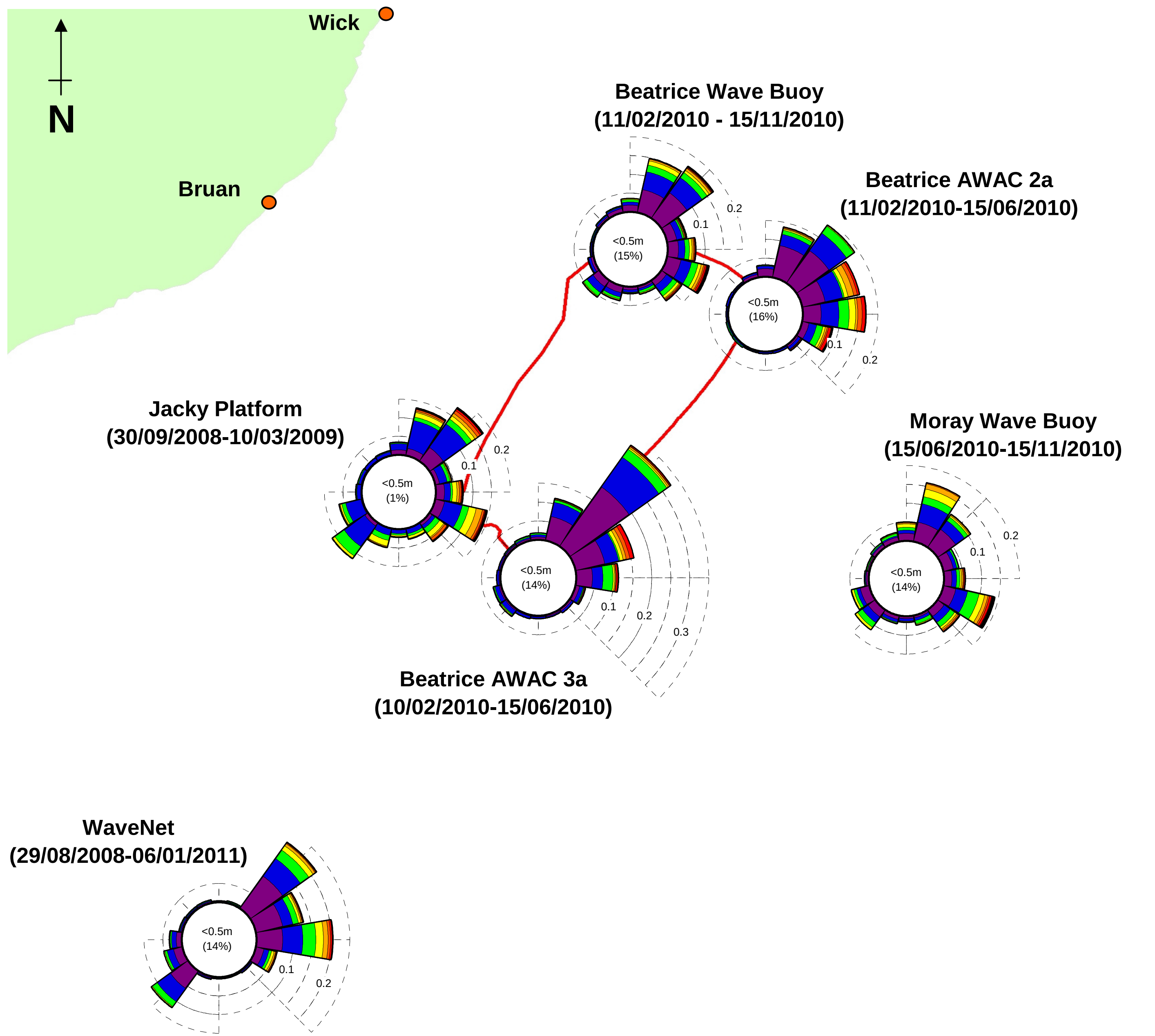
Wind Rose for 1976-88 from Lossiemouth **Figure 12**

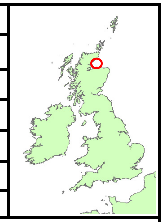


Hs (m)

- <5.0m
- <4.5m
- <4.0m
- <3.5m
- <3.0m
- <2.5m
- <2.0m
- <1.5m
- <1.0m

Application Site

Date	By	Size	Version
June '11	NW	A4	2
Projection		n/a	
Scale		n/a	
QA		NKD	
3888-Figure-control_oneclick.xls			
Produced by ABPmer Ltd.			



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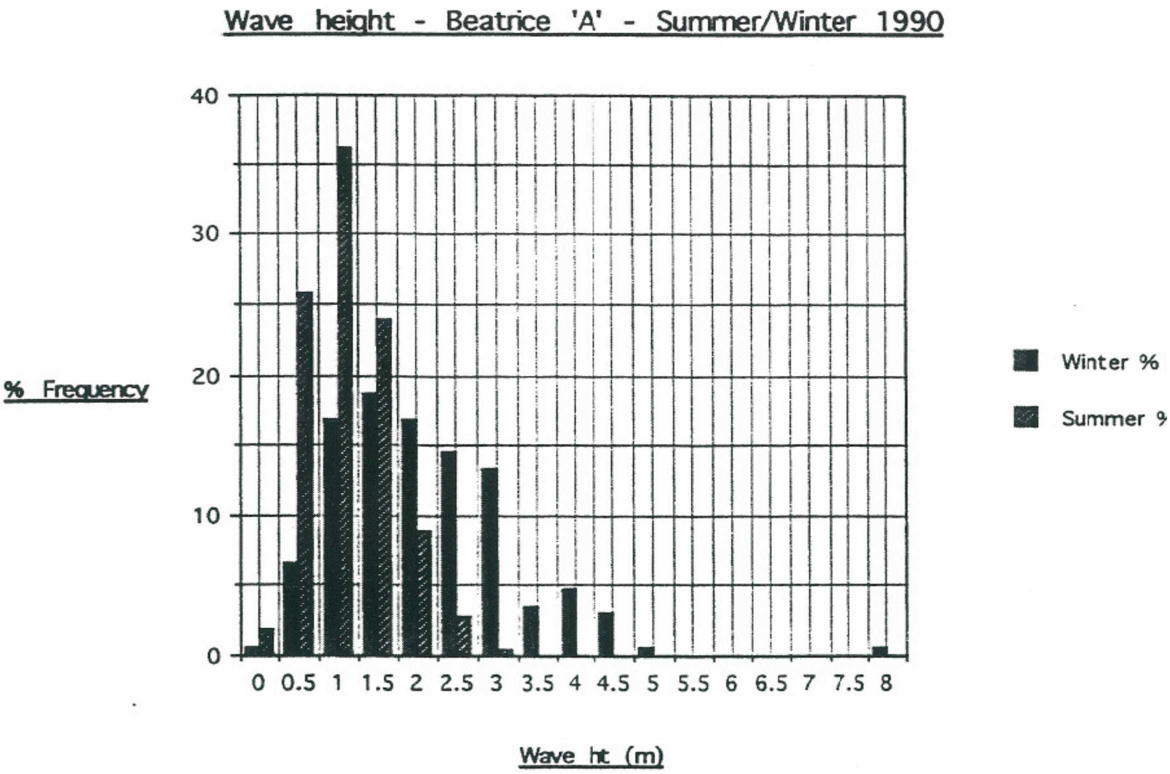
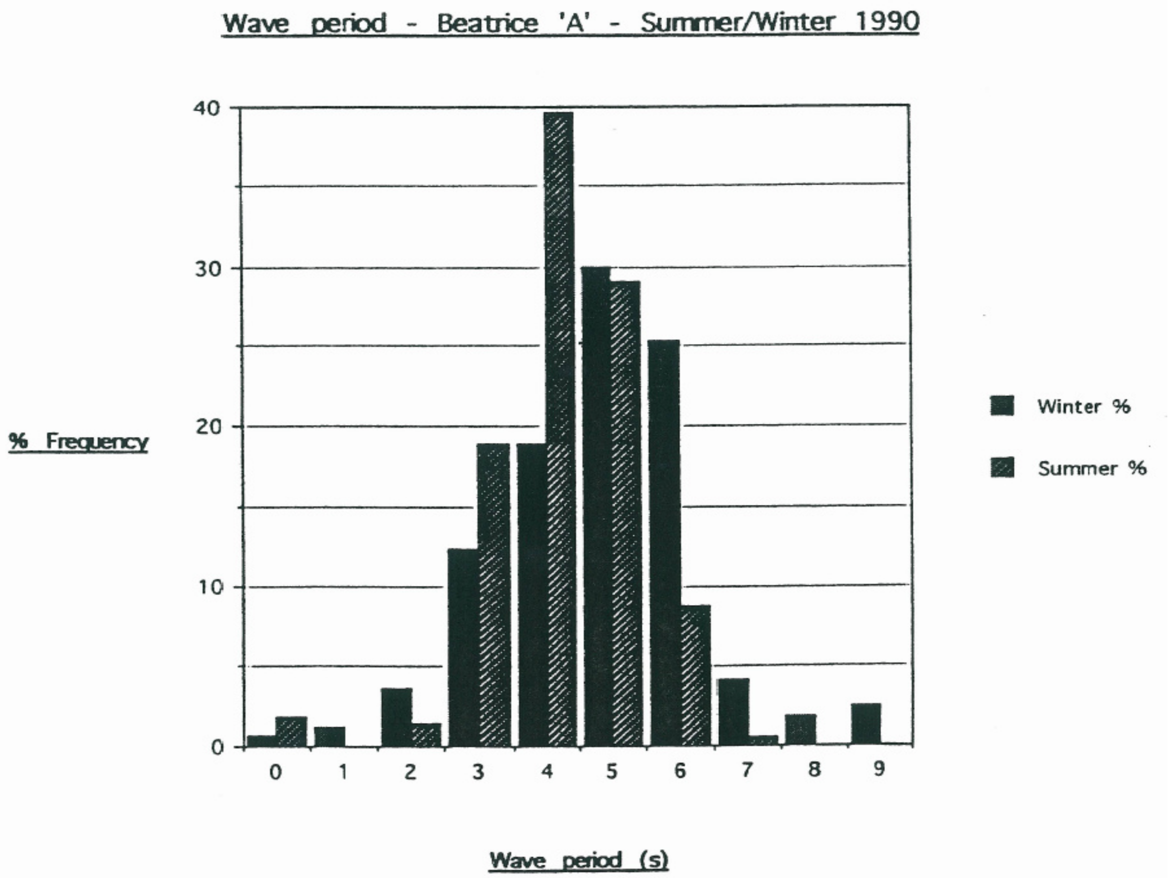
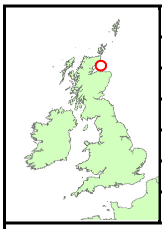
Observational Wave Records from within and nearby to the Application Site

Figure 13







Date	By	Size	Version
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Projection		n/a	
Scale		n/a	
QA		NKD	
3888-Figure-control_oneclick.xls			
Produced by ABPmer Ltd.			

Data source: Comber, 1993.

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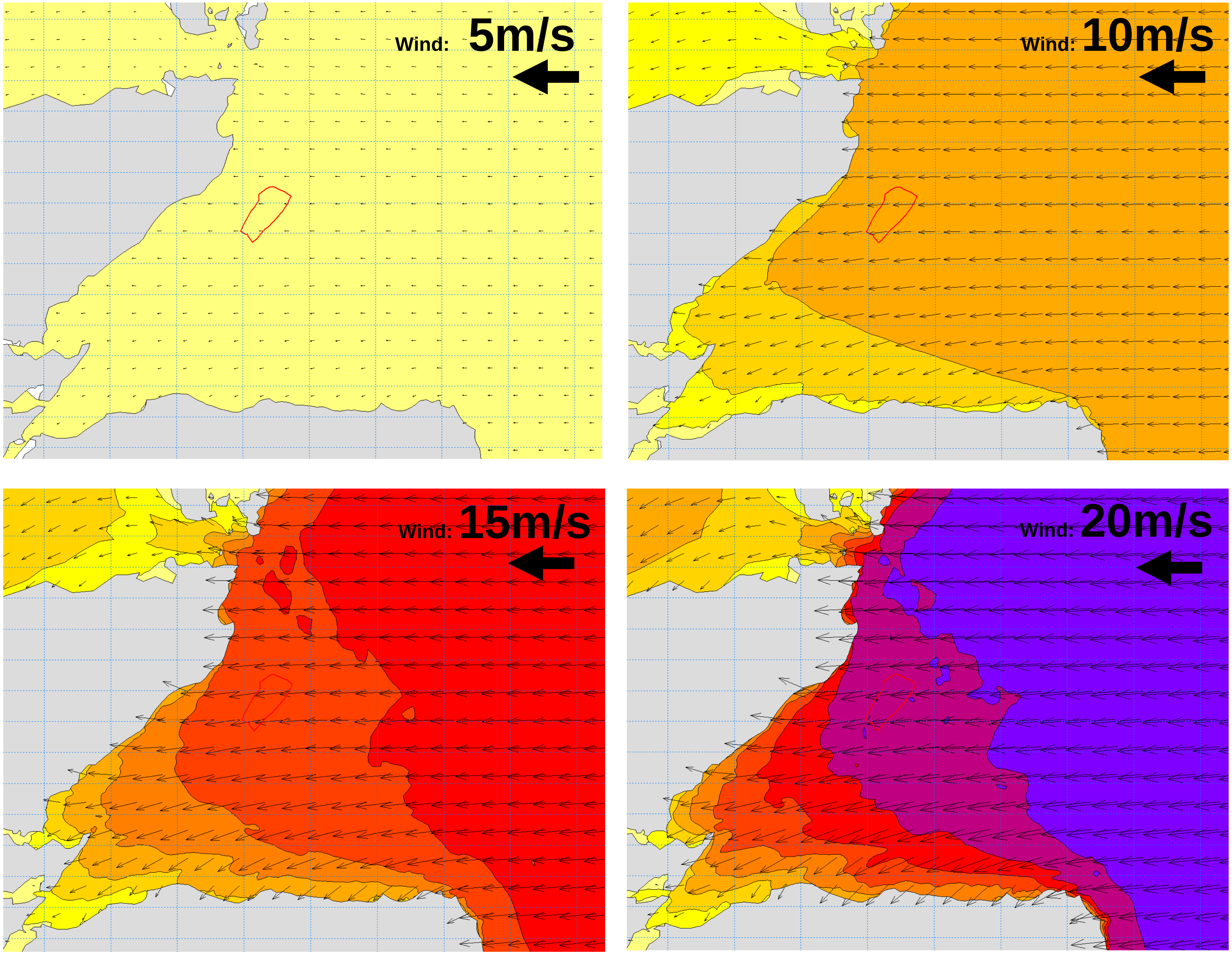
Wave Height and Period for Beatrice A Oil Platform, Summer/Winter 1990

Figure 14

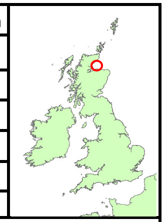


Significant Wave Height (m)

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

Application Site

Date	By	Size	Version
June '11	NW	A4	1
Projection		n/a	
Scale		n/a	
QA		NKD	
3888-Figure-control_oneclick.xls			
Produced by ABPmer Ltd.			



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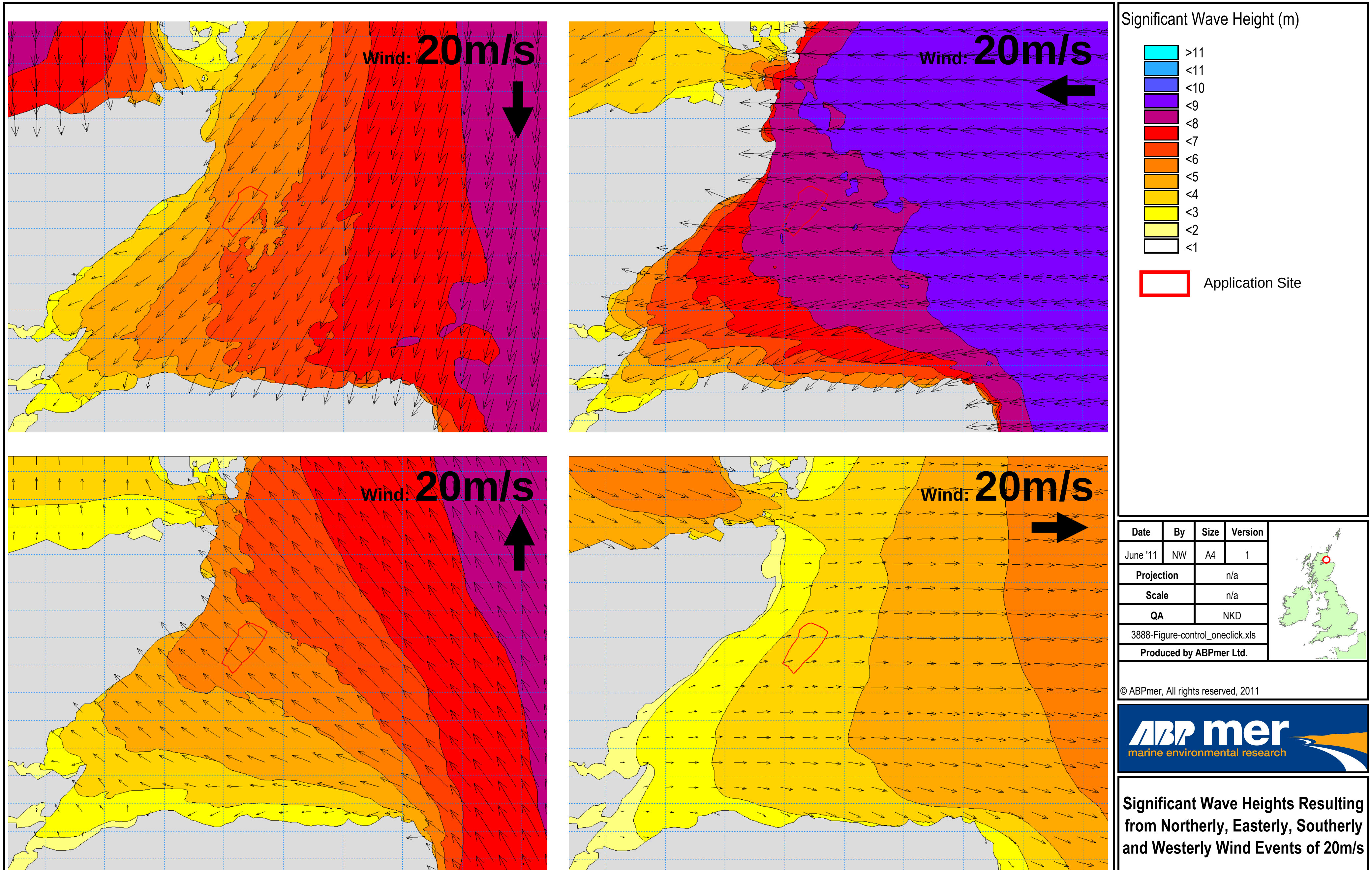
Significant Wave Heights Resulting from Characteristic Easterly Wind Events

Figure 15



Date	By	Size	Version
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Projection		n/a	
Scale		n/a	
QA		NKD	
3888-Figure-control_oneclick.xls			
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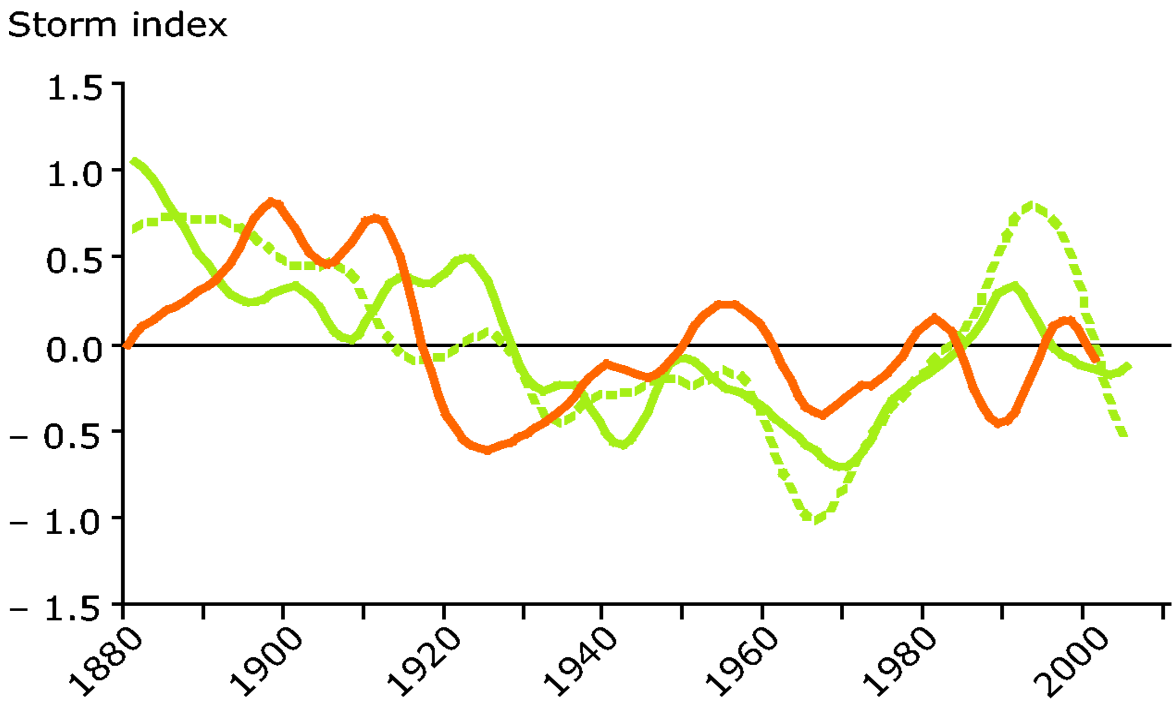
Significant Wave Heights Resulting from Northerly, Easterly, Southerly and Westerly Wind Events of 20m/s

Figure 16



Date	By	Size	Version
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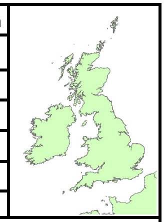
Scale		n/a	
QA		NKD	
3888-Figure-control_oneclick.xls			
Produced by ABPmer Ltd.			



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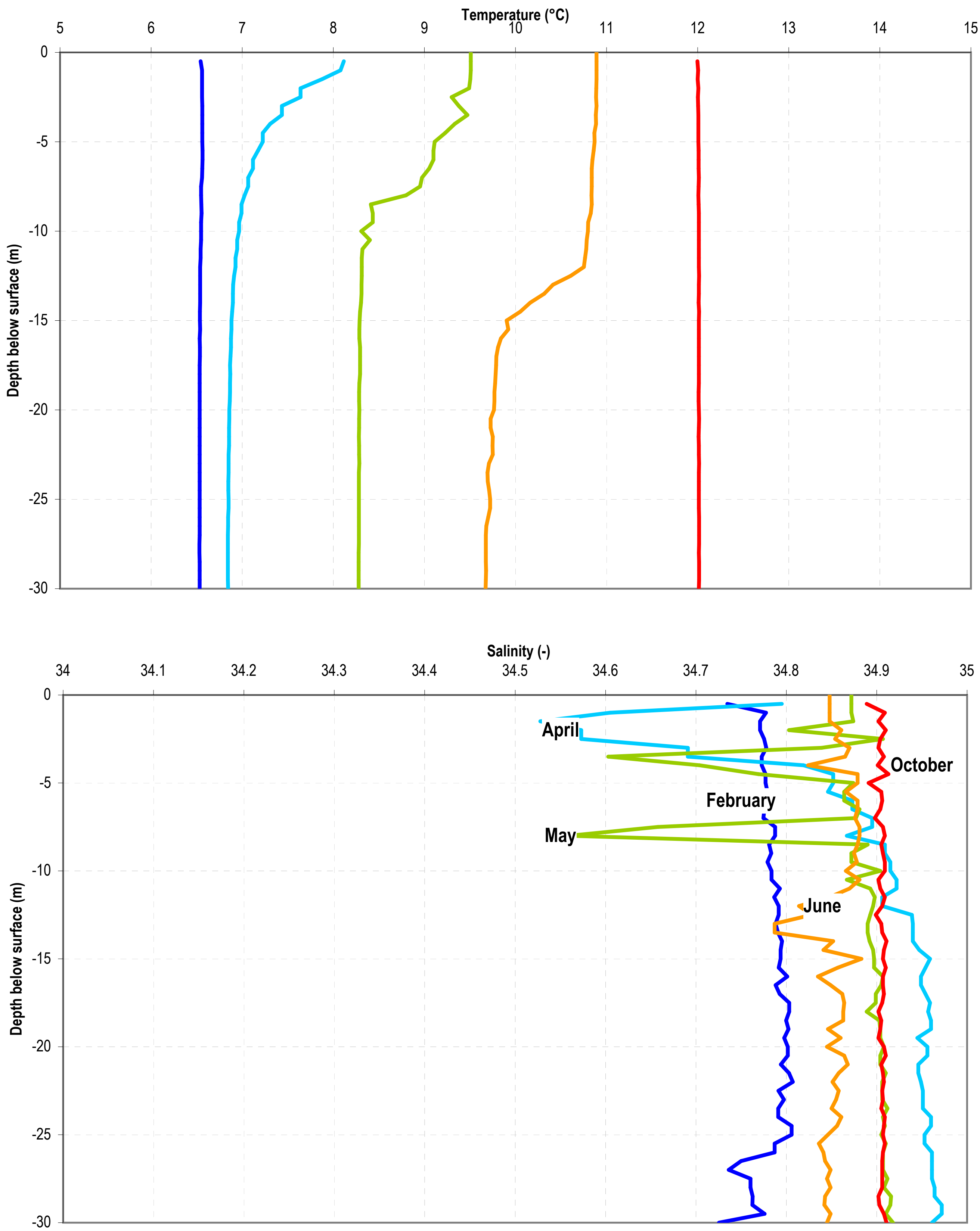
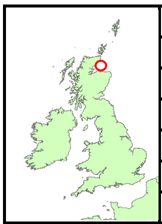
Storm Index for Various Parts of Europe 1881 - 2005

Figure 17





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June '11	NW	A4	1
Projection		n/a	
Scale		n/a	
QA		NKD	
3888-Figure-control_oneclick.xls			
Produced by ABPmer Ltd.			

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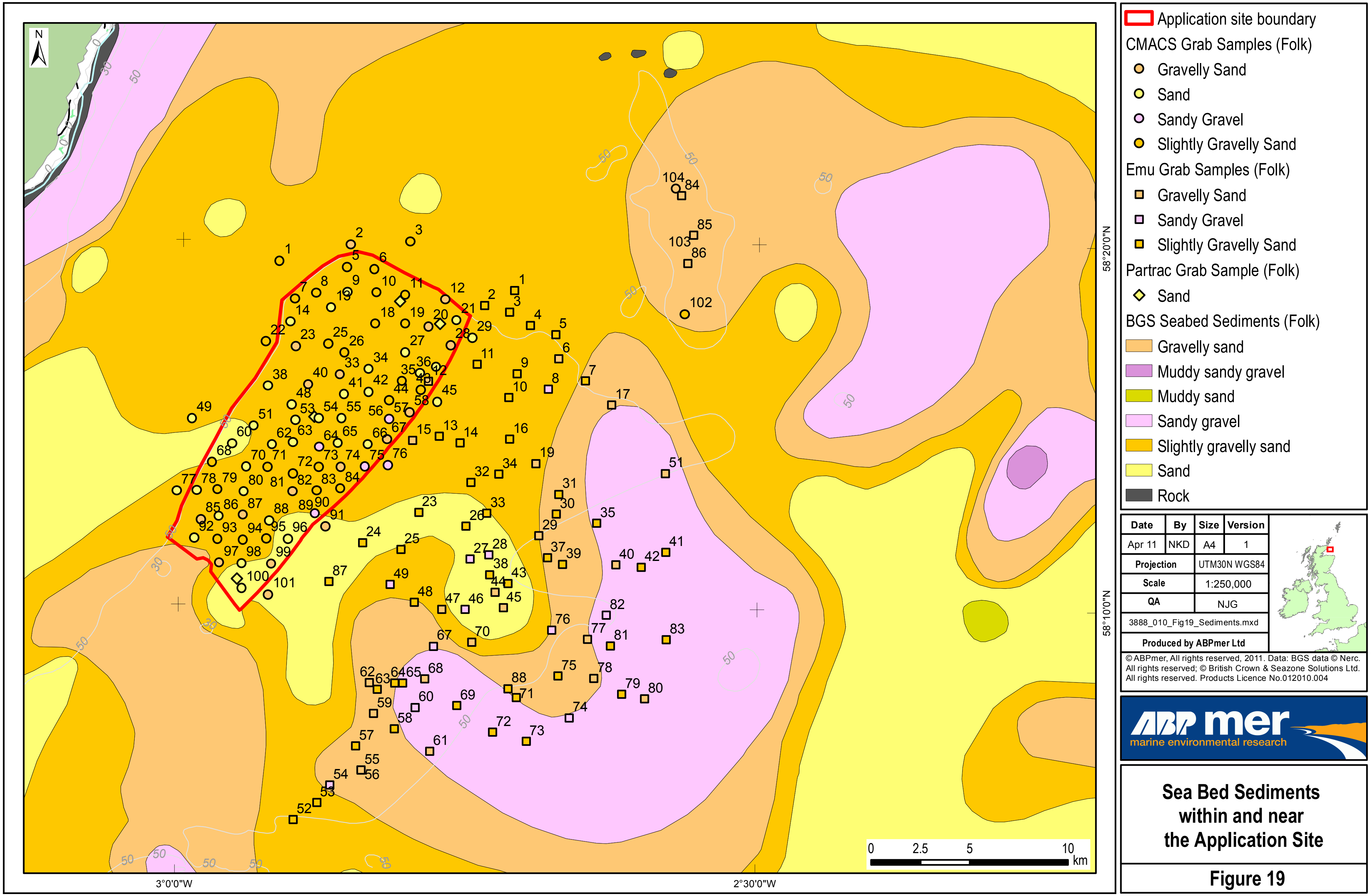
Measured Seasonal Vertical Stratification Within and Near To the Application Site

Figure 18


N
Application site boundary
CMACS Grab Samples (Folk)
Gravelly Sand
Sand
Sandy Gravel
Slightly Gravelly Sand
Emu Grab Samples (Folk)
Gravelly Sand
Sandy Gravel
Slightly Gravelly Sand
Partrac Grab Sample (Folk)
Sand
BGS Seabed Sediments (Folk)
Gravelly sand
Muddy sandy gravel
Muddy sand
Sandy gravel
Slightly gravelly sand
Sand
Rock
Date | By | Size | Version
Apr 11 | NKD | A4 | 1
Projection | UTM30N WGS84
Scale | 1:250,000
QA | NJG
3888_010_Fig19_Sediments.mxd
Produced by ABPmer Ltd
©ABPmer, All rights reserved, 2011. Data: BGS data © Nerc. All rights reserved; © British Crown & Seazone Solutions Ltd. All rights reserved. Products Licence No.012010.004
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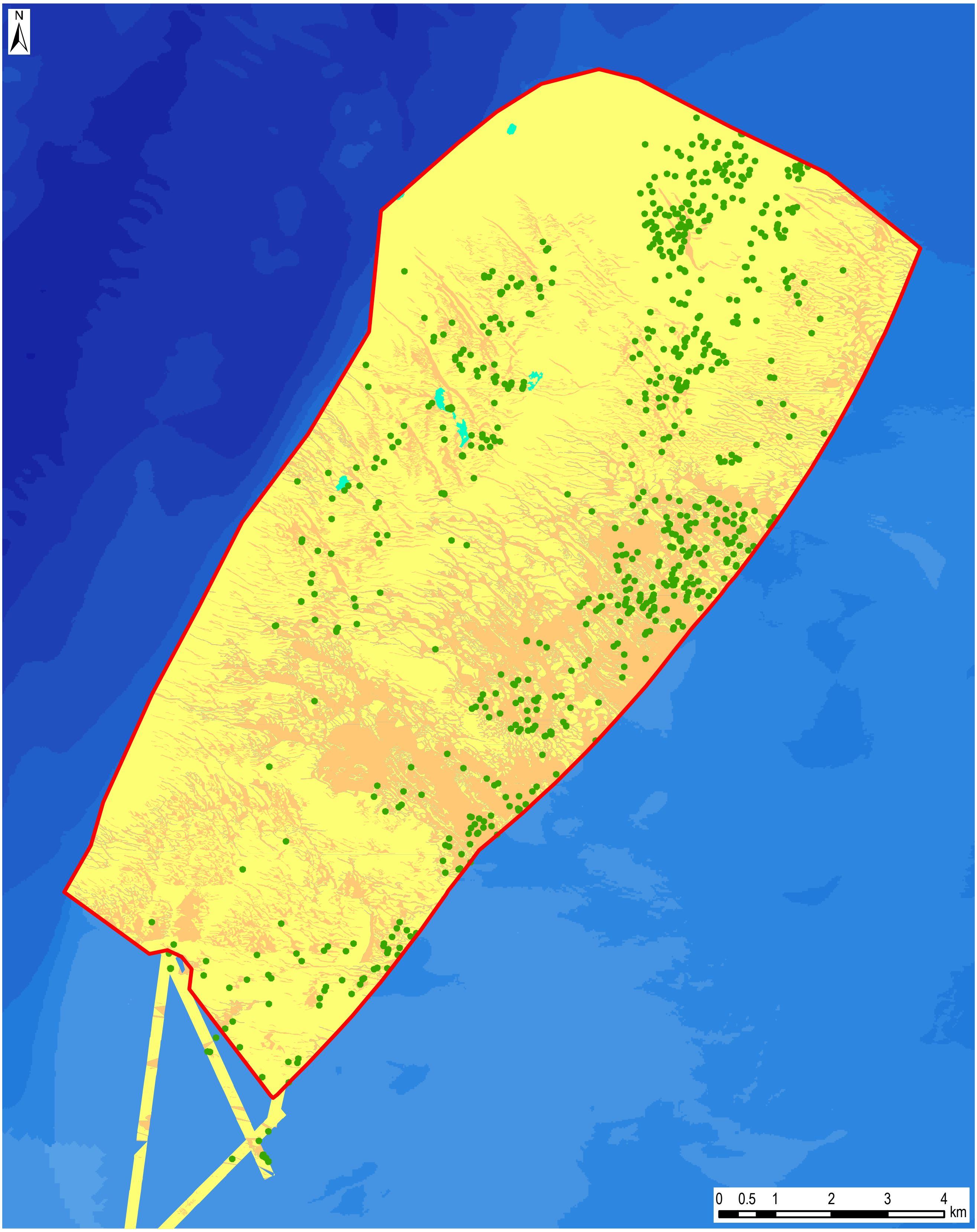
Sea Bed Sediments within and near the Application Site
Figure 19
0 2.5 5 10 km
3°0'0"W
2°30'0"W
58°20'0"N
58°10'0"N



Date	By	Size	Version
Apr 11	NKD	A4	1
Projection		UTM30N WGS84	
Scale		1:100,000	
QA		NJG	
3888_010_Fig20_Sed_Sidescan.mxd			
Produced by ABPmer Ltd			

Application site boundary
Small boulders
Till - Gravelly CLAY with cobbles and boulders
Medium to coarse SAND
Medium to coarse SAND and GRAVEL

Bathymetry (m LAT)
-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

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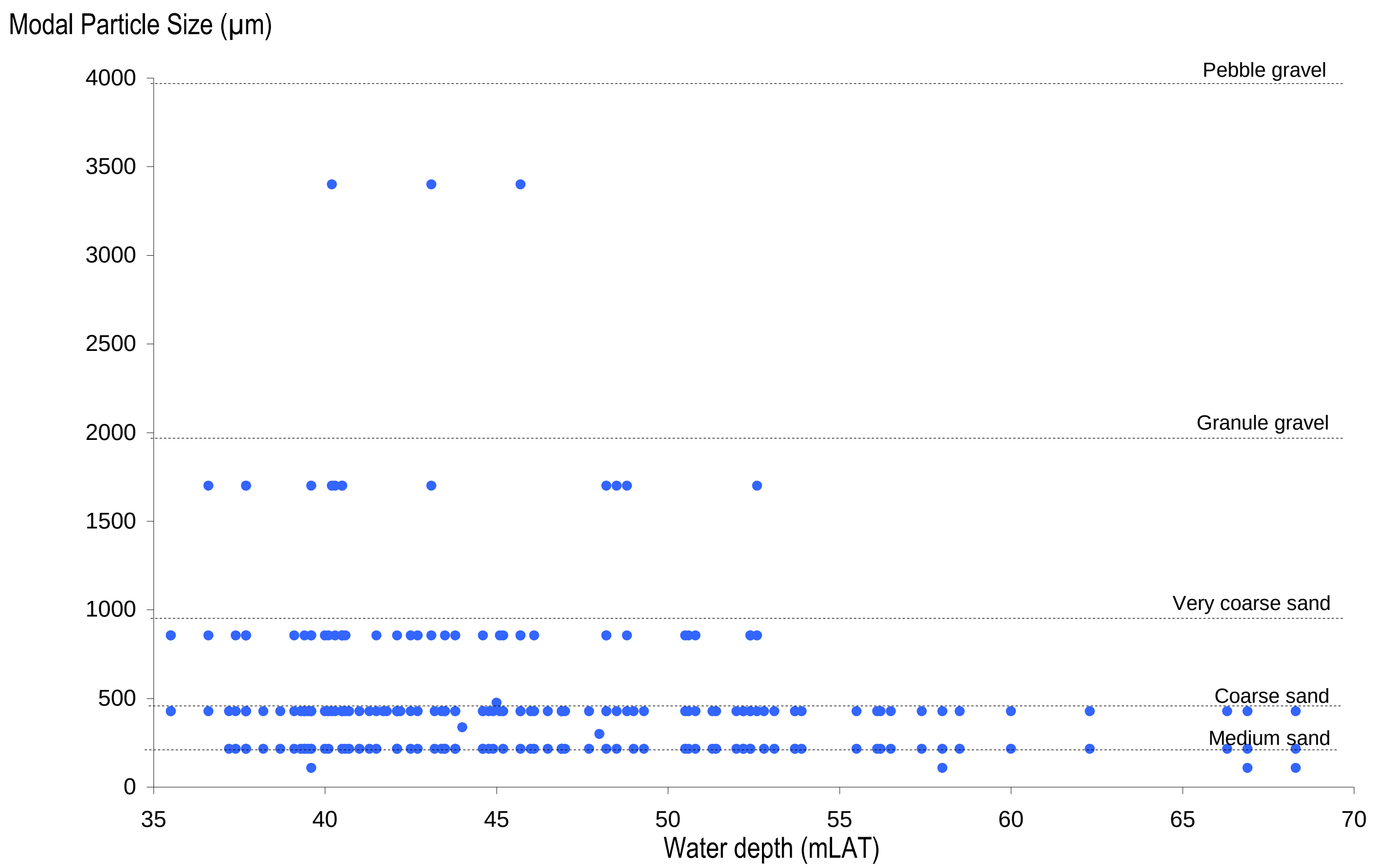
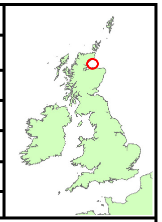
Sea Bed Characteristics Interpreted from Sidescan Sonar Mosaic

Figure 20



Date	By	Size	Version
Apr '11	AJB	A4	1
Projection	n/a		
Scale	n/a		
QA	NKD		
3888-Figure-control_oneclick.xls			
Produced by ABPmer Ltd.			



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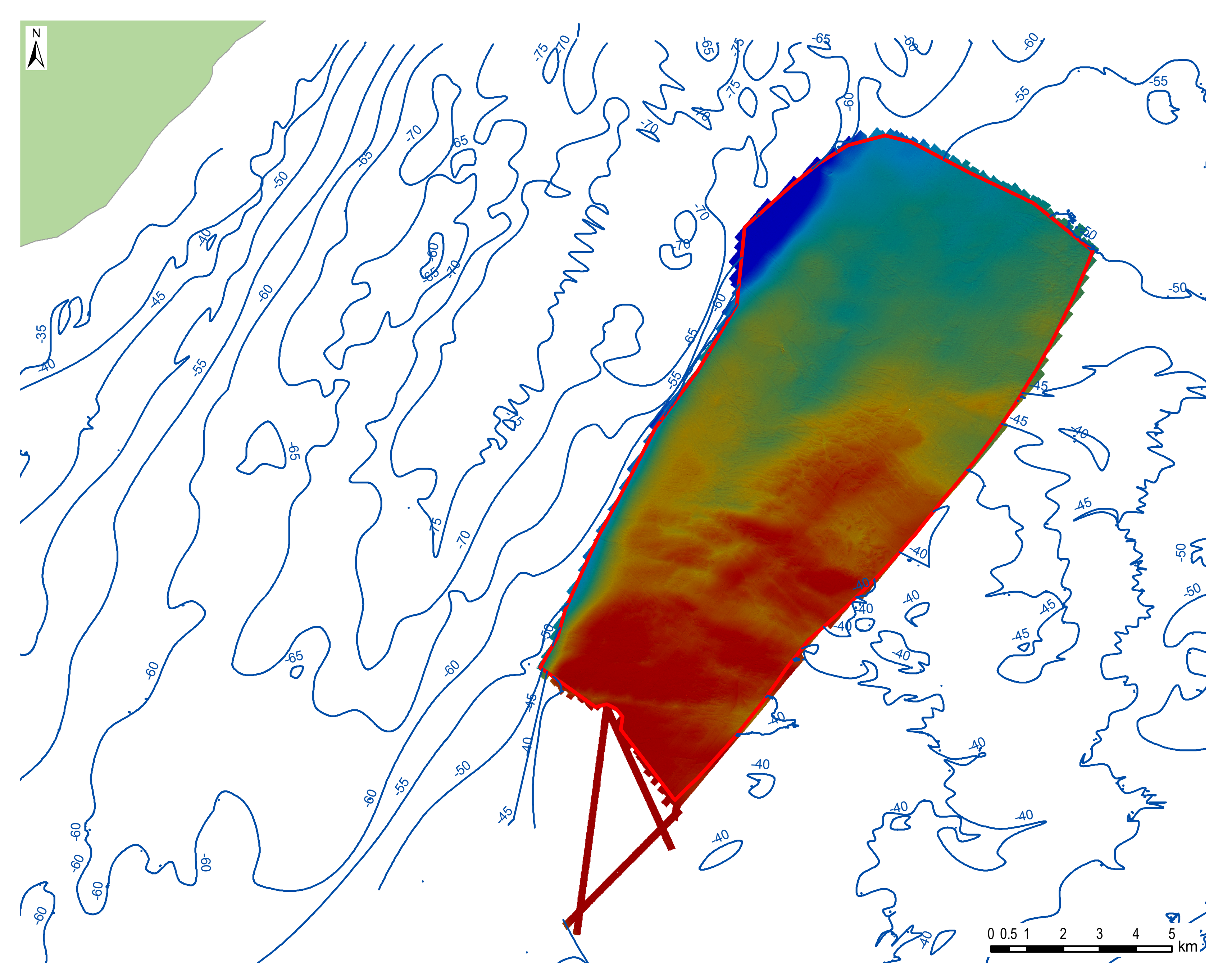
Scatter Plot Showing the Relationship between Modal Grain Size and Water Depth across the Application Site

Figure 21



Application site boundary

Swath Bathymetry (m LAT)

35 m

69 m

Bathymetry contour (m LAT)

Date	By	Size	Version
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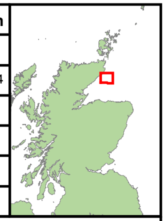
Projection		UTM30N WGS84	
Scale		1:150,000	
QA		NJG	
3888_010_Fig22_Swath.mxd			
Produced by ABPmer Ltd			



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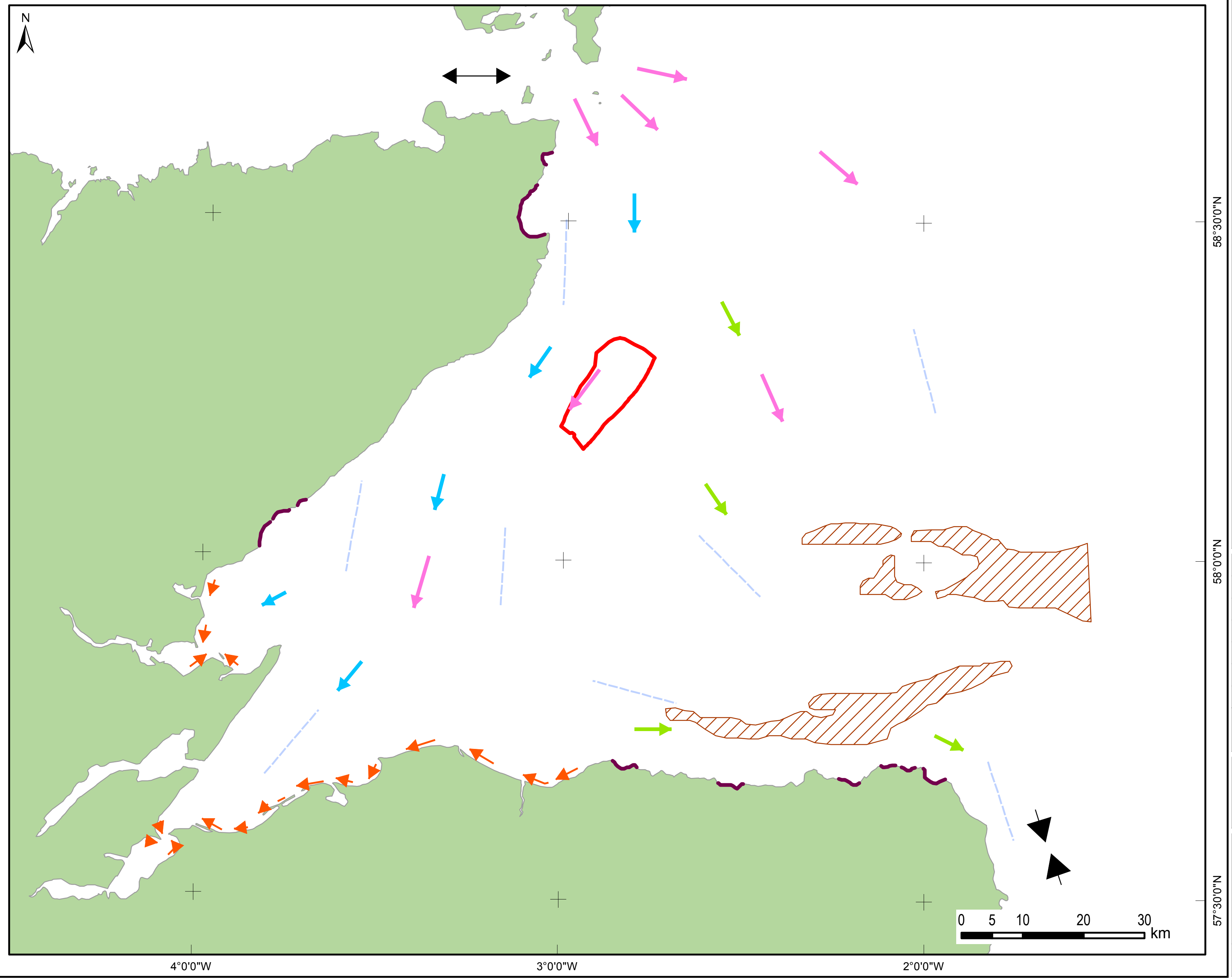
Swath Bathymetry of the Application Site

Figure 22



Application site boundary
Offshore sediment sink
Bedload convergence
Bedload parting
Net Longshore Drift
Sediment transport path
Sediment transport path (probable)
Semi-independent beach unit
Shelly carbonate path
Tidal current general orientation

Date	By	Size	Version
Apr 11	AJB	A4	2
Projection		UTM30N WGS84	
Scale		1:900,000	
QA		NJG	
3888_010_Fig23_Sed_transport.mxd			
Produced by ABPmer Ltd			

Data source:Reid and McManus (1987); Ramsey and Brampton (2000)

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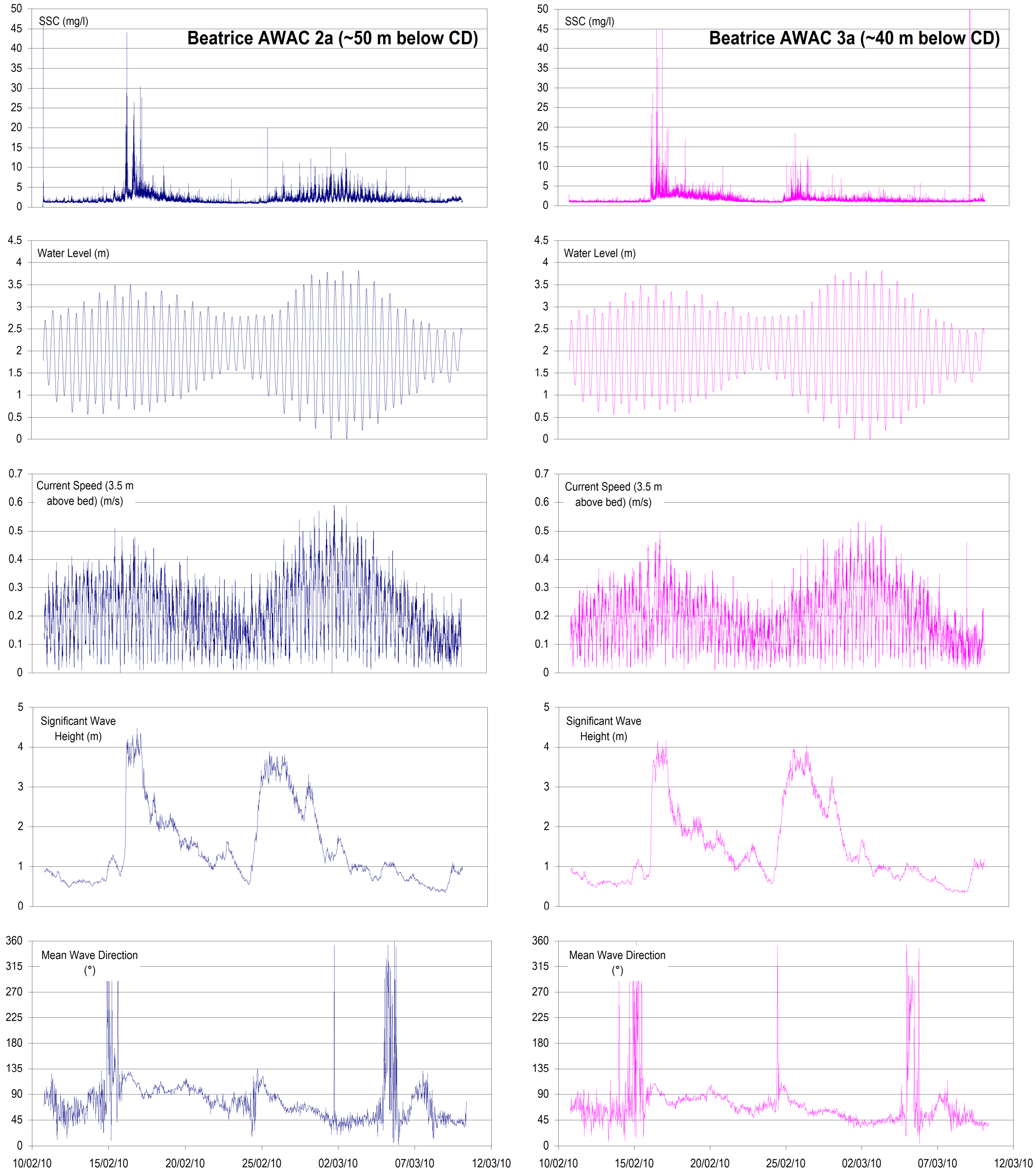
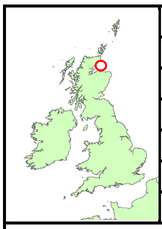
Bedload and Longshore Sediment Transport in the Moray Firth

Figure 23





Date	By	Size	Version
June '11	NW	A4	2
Projection		n/a	
Scale		n/a	
QA		NKD	
3888-Figure-control_oneclick.xls			
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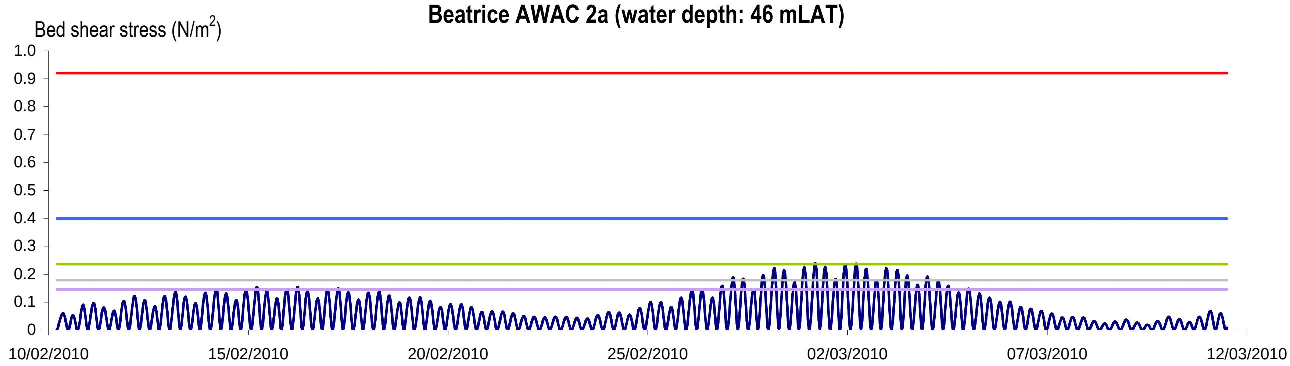
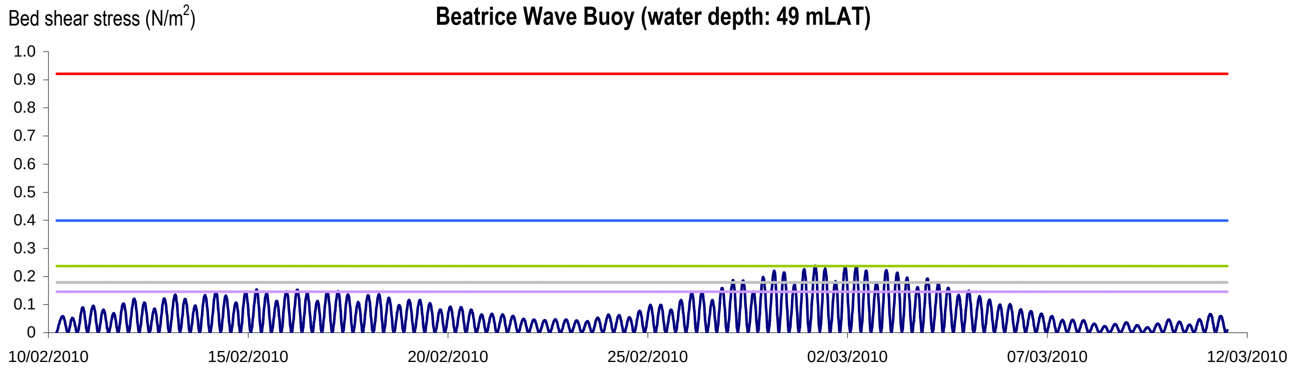
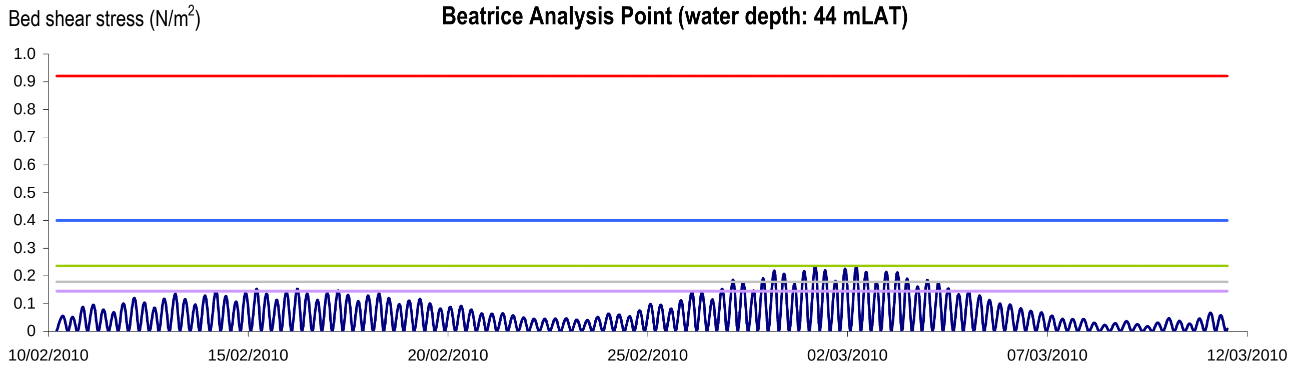
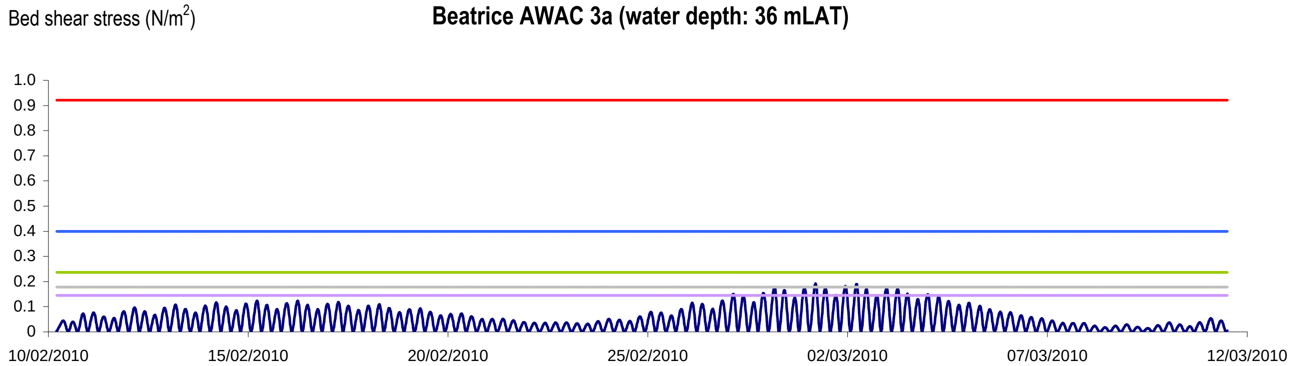
The Relationship Between Suspended Sediment Concentrations and Selected Hydrodynamic Variables

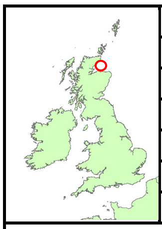
Figure 24











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June '11	NW	A4	2
Projection		n/a	
Scale		n/a	
QA		NKD	
3888-Figure-control_oneclick.xls			
Produced by ABPmer Ltd.			

Bed shear stress (Tau) Analysis Point
Very Fine Sand (110 µm)
Fine Sand (215 µm)
Medium Sand (430 µm)
Coarse Sand (850 µm)
Very Course Sand (1700 µm)

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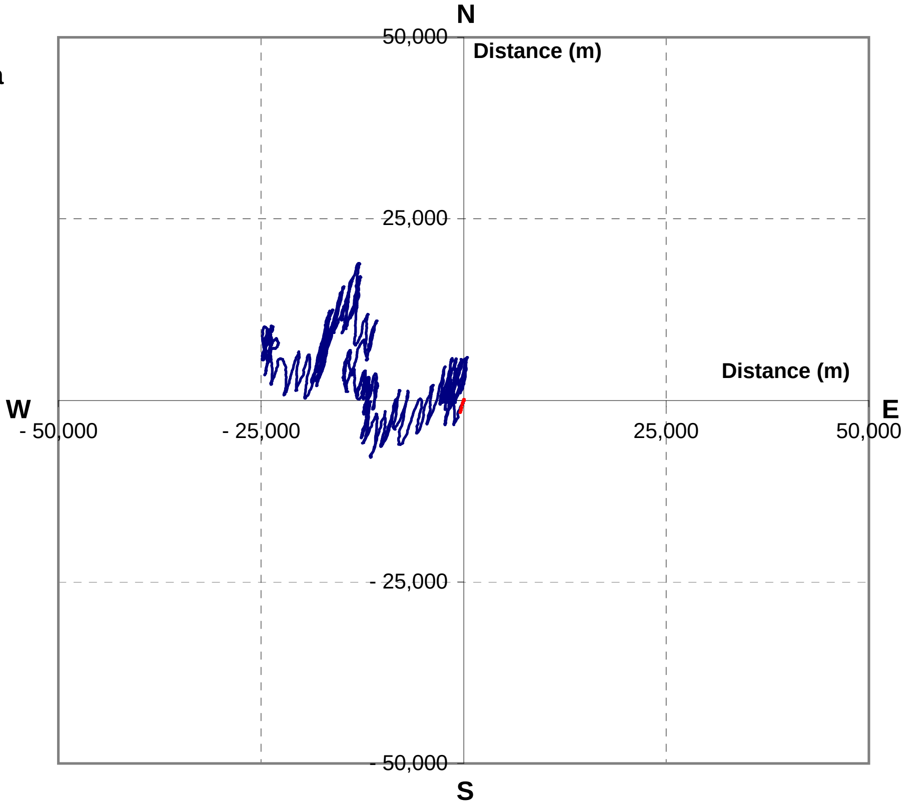
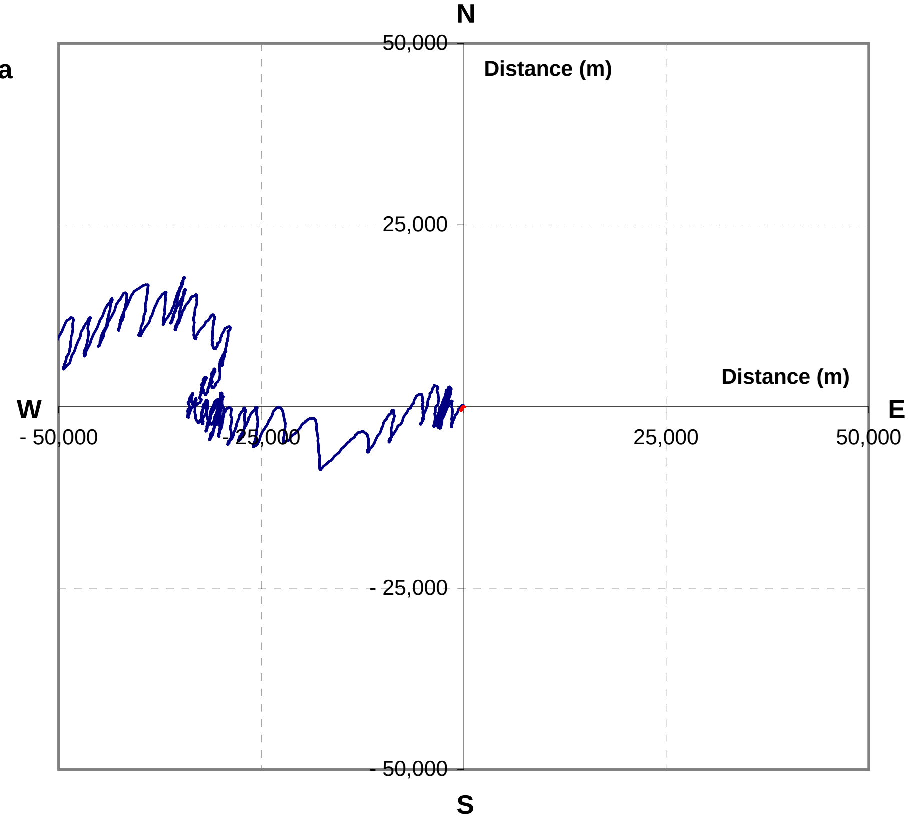
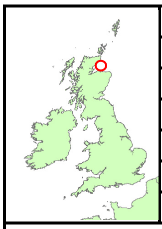
Tidally-Induced Bed Shear Stress and Mobility Thresholds for Selected Locations across the Application Site

Figure 25







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June '11	NW	A4	2
Projection		n/a	
Scale		n/a	
QA		NKD	
3888-Figure-control_oneclick.xls			
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Net Potential Advection
Fine Sediment Displacement

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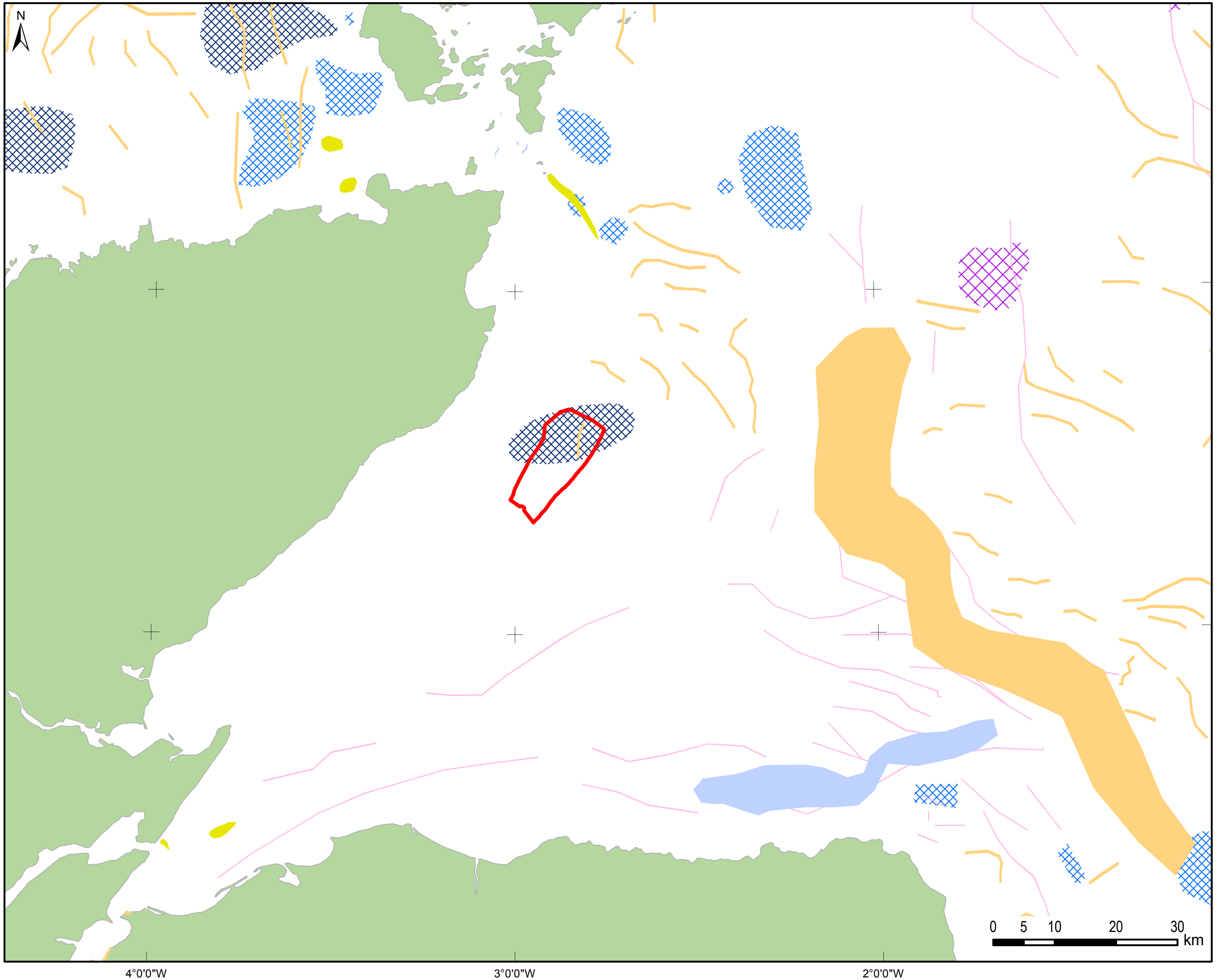
Progressive Vector Analysis Demonstrating Net Advective Pathway and Projected Displacement of Fine Sediment after 30-Days

Figure 26



Date	By	Size	Version
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Projection		UTM30N WGS84	
Scale		1:900,000	
QA		NJG	
3888_010_Fig27_Bedforms.mxd			
Produced by ABPmer Ltd			

NOT TO BE USED FOR NAVIGATION

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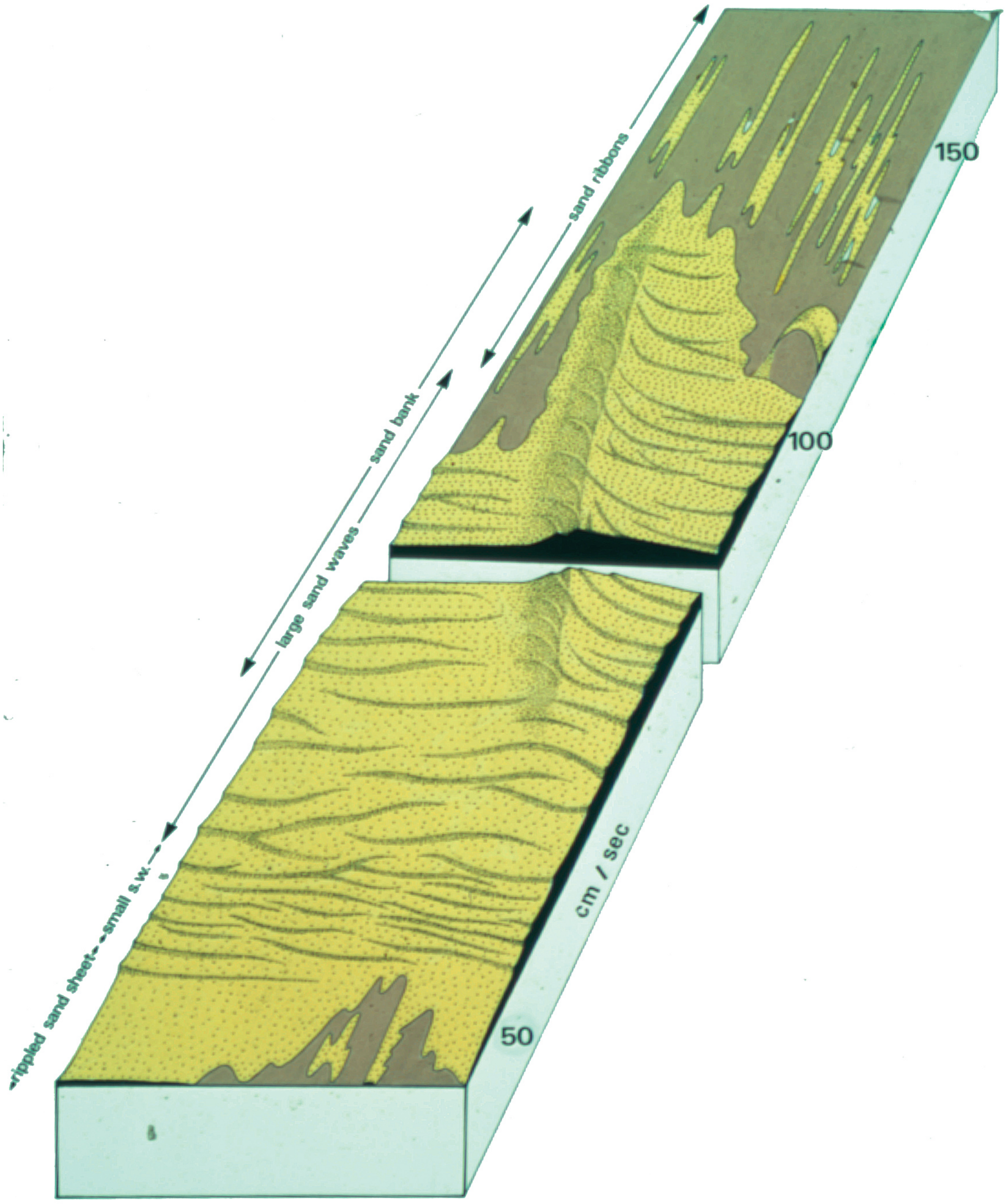
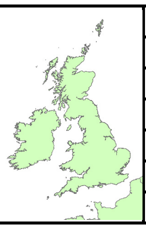
Bedforms Identified (pre application site survey) within the Moray Firth

Figure 27





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Apr '11	AJB	A4	1
Projection	n/a		
Scale	n/a		
QA	NKD		
3888-Figure-control_oneclick.xls			
Produced by ABPmer 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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Scheme of Bedform Zones from a Tidal Sea

Figure 28

ABP Marine Environmental Research Ltd (ABPmer)
Suite B, Waterside House, Town Quay, Southampton, Hampshire SO14 2AQ

T +44 (0)23 8071 1840
F +44 (0)23 8071 1841
E enquiries@abpmer.co.uk

www.abpmer.co.uk

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