APPENDIX D

Drill Cuttings Modelling (Amec Foster Wheeler 2017)

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Nexen Energy ULC
Flemish Pass Exploration Drilling Program,
Drill Cuttings Dispersion Modelling

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EXECUTIVE SUMMARY

Amec Foster Wheeler Environment & Infrastructure, a Division of Amec Foster Wheeler Americas Limited (Amec Foster Wheeler), has completed a cuttings dispersion modelling study for Nexen Energy ULC (Nexen). Nexen is planning to conduct a program of petroleum exploration drilling and associated activities in the eastern portion of the Canada-Newfoundland and Labrador Offshore Area over the period 2018 to 2028 (hereinafter also referred to as the Project). The objective of this study is to model drill cuttings release and dispersion from exploration well drilling in the Project Area that includes two Exploration Licences (ELs 1144 and 1150) in the Flemish Pass; the results are intended to support the Environmental Assessment of the Project.

Over the course of the anticipated 11 year duration of the Project, it is estimated that up to 10 wells could be drilled, with specific well site locations being selected as planning and design activities progress. Once a well site location has been identified, drill site clearance has been completed and the Mobile Offshore Drilling Unit (MODU) has been positioned the initial top hole drilling commences, which is a large diameter hole that is drilled without a riser in place. The initial sections are drilled using a water-based mud (WBM), where mud and cuttings are returned to the seabed in accordance with the Offshore Waste Treatment Guidelines (OWTG) (NEB et al 2010). When the top conductor and surface section drilling has been completed to the depth where the rock formation strength is sufficient, the structural casing is run and cemented and the wellhead is installed at seabed. Synthetic-based muds (SBM) are used for deeper hole sections. Once the riser has been installed, drilling mud and cuttings are returned to the MODU deck in a closed loop system, where the drilling fluids and cuttings are separated; the cuttings are treated prior to discharge overboard and the drilling fluids are continually reconditioned and reused throughout drilling of the well.

Drill cuttings are the small pieces of rock, ranging in size from medium-sized pebbles and coarse sand to fine silts and clays, created when a drill bit penetrates rock. The material is forced up the annulus (the space between the drill pipe and the outer diameter of the wellbore) as drilling proceeds. The composition of the drill cuttings is dependent on the stratigraphy of the area, the type of drill bit used, the type of drilling mud used and the nature of the cuttings treatment applied with solids control systems (i.e., shale shakers, cuttings dryers, or centrifuges which all have the effect of further reducing the cuttings particle sizes) on the MODU prior to discharge to the ocean. The drill cuttings composition along with water depth and ocean current determine the deposition of the cuttings on the seabed.

A numerical computer model, developed by Amec Foster Wheeler, employs a transport computation to simulate the advection of dispersed drill cuttings materials in three dimensions through the water column, following release into the sea, until the particles come to rest on the sea bottom. Key inputs for the model include cuttings particle characterizations and ocean currents. The primary outputs are predictions of the deposition pattern of released drill cuttings on the seabed (e.g., weight, density, thickness of cuttings).

The drill cuttings dispersion modelling considered two well designs expected to represent the range of wells that could be drilled in the Project Area. These are a Deepwater Jurassic Well Design and a Shallow Water Cretaceous Well Design. With the possibility either well type is selected for drilling in either of the exploration licences EL-1144 and EL-1150 license blocks, two example modelling locations are were considered with one in each EL in order to represent the variations in ocean currents and water depth likely to be encountered. The Deepwater example well design was modelled for EL-1144 and the Shallow Water example well design was modelled for EL-1150. With the potential to drill multiple wells and at any time during the year, four model simulation runs or ‘scenarios’ for March, June, September, December were considered at each location, i.e., a total of eight scenarios were completed.

EL-1144 Deepwater Jurassic Example Well

In all four monthly simulations, all of WBM cuttings released at the wellhead are predicted to settle within 500 m. Given their released close to the seafloor there is little time for these cuttings to be transported large distances by the ambient currents. Over 93 percent settle within 100 m. WBM cuttings are predicted to drift as far as from 210 m in September to 280 m in December. Maximum WBM cuttings thicknesses, allowing for anticipated slumping of the ‘pile’ are estimated to be on the order of 0.7 to 1.4 m. Maximum thickness values fall to about 0.21 to 0.26 m within 100 m. Mean WBM cuttings thicknesses within 100 m are about 19 mm in all months.

The SBM cuttings released from the MODU at the sea surface settle generally within 2 km, with over 90 percent settling within 500 m. The farthest these cuttings settle, within 2 km, ranges from 1.4 km in March to 1.7 km in September. Only 3.5 percent of the total SBM cuttings from one well drift farther away and settle with thicknesses less than 0.1 mm. These small amounts of fine sand and silt-sized SBM cuttings are predicted to drift to the south and south-southwest up to about 25 km in June, 46 km in March and 54 km in September and December. Mean SBM cuttings thicknesses out to 200 m generally range from 1 to 10 mm with the exception in September, that with very light currents, the mean thickness is 37 mm within 10 m of the wellhead. The predicted maximum SBM cuttings thicknesses are all located to the south-southwest and range from 38 mm at 150 m from the wellhead in June, to 48 mm at the wellhead in September.

The predicted areas of total cuttings thickness above the predicted no effect thresholds (PNET) value of 1.5 mm are confined to a patch of about 550 m by 280 m oriented to the south-southwest. The areas are generally offset about 50 to 100 m to the north of the wellhead. The largest area is about 700 m by 260 m in September. The predicted areas of total cuttings thickness above the 6.5 mm threshold are about an average size of 400 m by 150 m in March, June and December; in September the area is smaller, about 180 m by 150 m, and symmetrical about the wellhead in evidence of the light currents.

EL-1150 Shallow Water Cretaceous Example Well

Over 99 percent of the WBM cuttings released at the wellhead are predicted to settle within 200 m, with settling of small amounts predicted to drift as 260 m in March and 240 m during the other months. Maximum WBM cuttings thicknesses, allowing for anticipated material slumping are estimated to be on the order of 0.45 to 0.9 m. Maximum thickness values fall to about 0.18 to 0.21 m within 100 m. Mean WBM cuttings thicknesses within 100 m are 12 to 13 mm in all months.

The SBM cuttings released from the MODU at the sea surface settle generally within 1 km, with over 94 percent settling within 500 m. The farthest these cuttings settle, within 1 km, ranges from 720 m in September to 940 m in March and December. Only 3.6 percent of the total SBM cuttings from one well drift farther away and settle with thicknesses less than 0.1 mm. These small amounts of fine sand and silt-sized SBM cuttings are predicted to drift to the northeast up to about 12 km in September, 15 km in June and 18 km in March and December. Mean SBM cuttings thicknesses out to 100 m generally range from less than 1 mm in March to 43 mm in September (with the very light currents) within 10 m of the wellhead. The predicted maximum SBM cuttings thicknesses are all located to the east in all months (except to the north in December) and range from 84 mm at 50 m from the wellhead in June, to 99 mm at 40 m in September.

The predicted areas of total cuttings thickness above the PNET value of 1.5 mm are confined to an average size, over the four months, of about 320 m by 220 m. These areas are oriented primarily to the east in March and June and to the north in September and northeast in December. The areas are generally offset about 50 to 100 m to the west, or south or southwest. The largest area is about 350 m by 240 m in December. The predicted areas of total cuttings thickness above the 6.5 mm threshold are similar in all months averaging 250 m by 150 m in size; the largest footprint is predicted in December at about 260 m by 180 m.

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1.0 INTRODUCTION

Amec Foster Wheeler Environment & Infrastructure, a Division of Amec Foster Wheeler Americas Limited (Amec Foster Wheeler), has been contracted by Nexen Energy ULC (Nexen) to complete modelling of drill cuttings dispersion from the proposed Flemish Pass Exploration Drilling Program, for use in the Project's Environmental Assessment.

1.1 Background

Nexen is planning to conduct a program of petroleum exploration drilling and associated activities in the eastern portion of the Canada-Newfoundland and Labrador Offshore Area over the period 2018 to 2028 (hereinafter also referred to as the Project). The proposed Project Area includes two Exploration Licences (ELs 1144 and 1150) in the Flemish Pass region for which Nexen is the operator and is currently the sole interest holder, and which have not yet been subject to exploration drilling activity to date pursuant to these licences. The Project will include exploration drilling within these ELs, possible appraisal (delineation) drilling in the event of a hydrocarbon discovery, vertical seismic profiling (VSP), well testing, eventual well abandonment or suspension procedures, and associated supply and service activities.

Over the course of the anticipated 11 year duration of the Project, it is estimated that up to 10 wells could be drilled, with specific well site locations being selected as planning and design activities progress. Once a well site location has been identified, drill site clearance has been completed and the Mobile Offshore Drilling Unit (MODU) has been positioned the initial top hole drilling commences, which is a large diameter hole that is drilled without a riser in place. The initial sections are drilled using a water-based mud (WBM), where mud and cuttings are returned to the seabed in accordance with the Offshore Waste Treatment Guidelines (OWTG) (NEB et al 2010). When the top conductor and surface section drilling has been completed to the depth where the rock formation strength is sufficient, the structural casing is run and cemented and the wellhead is installed at seabed. Synthetic-based muds (SBM) are used for deeper hole sections. Once the riser has been installed, drilling mud and cuttings are returned to the MODU deck in a closed loop system, where the drilling fluids and cuttings are separated; the cuttings are treated prior to discharge overboard and the drilling fluids are continually reconditioned and reused throughout drilling of the well.

Drill cuttings are the small pieces of rock, ranging in size from medium-sized pebbles and coarse sand to fine silts and clays, created when a drill bit penetrates rock. The material is forced up the annulus (the space between the drill pipe and the outer diameter of the wellbore) as drilling proceeds. The composition of the drill cuttings is dependent on the stratigraphy of the area, the type of drill bit used, the type of drilling mud used and the nature of the cuttings treatment applied with solids control systems (i.e., shale shakers, cuttings dryers, or centrifuges which all have the effect of further reducing the cuttings particle sizes) on the MODU prior to discharge to the ocean. The drill cuttings composition along with water depth and ocean current determine the deposition of the cuttings on the seabed.

A numerical computer model, developed by Amec Foster Wheeler, employs a transport computation to simulate the advection of dispersed drill cuttings materials in three dimensions through the water column, following release into the sea, until the particles come to rest on the sea bottom. Key inputs for the model include cuttings particle characterizations and ocean currents. The primary outputs are predictions of the deposition pattern of released drill cuttings on the seabed (e.g., weight, density, thickness of cuttings).

1.2 Objectives

The objective of this study is to model drill cuttings release and dispersion from exploration well drilling in the Project Area with the results intended to support the Environmental Assessment of the Project.

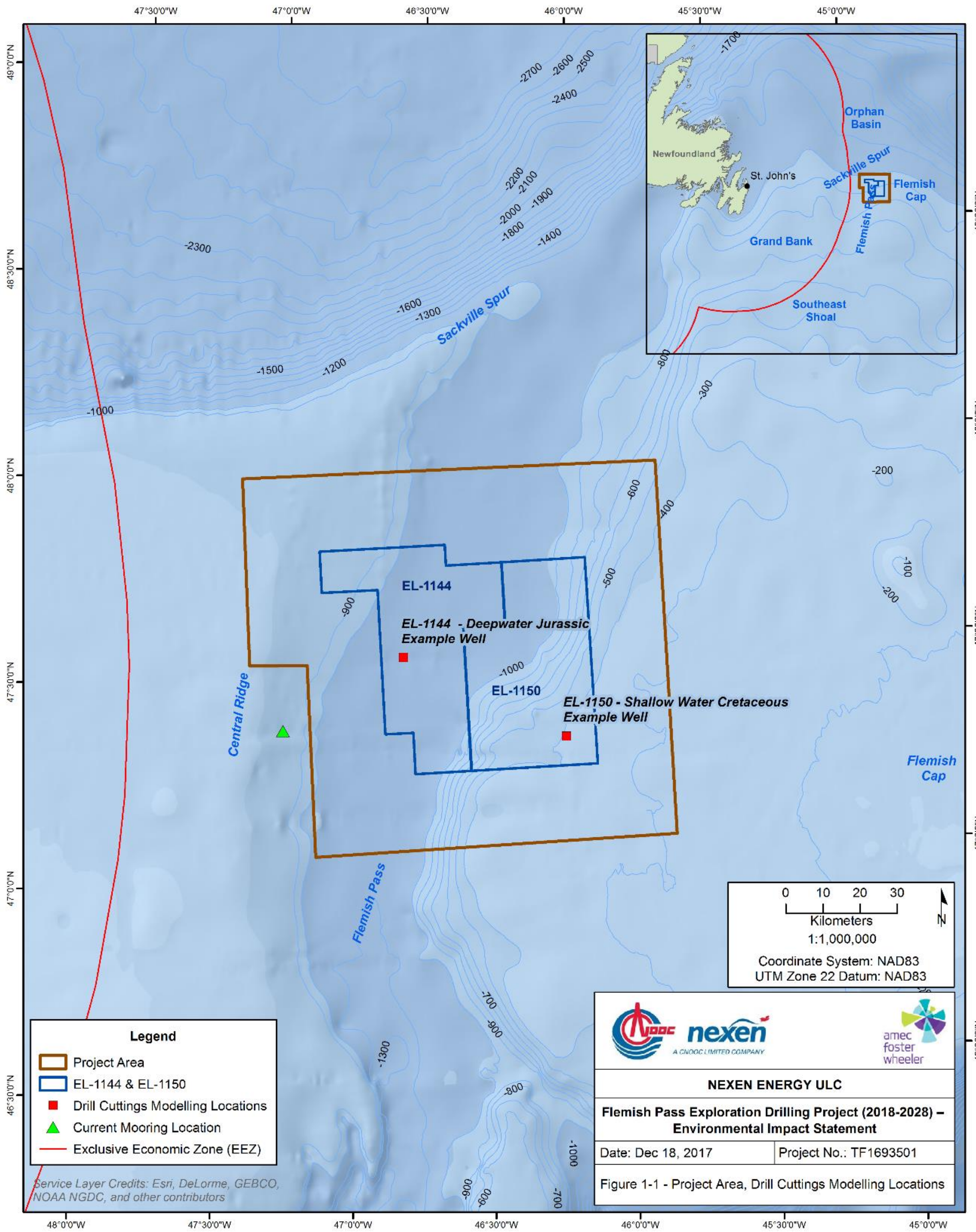
Nexen is considering two well designs which is expected to represent the expected range of wells that could be drilled in the Project Area. These include a Deepwater Jurassic Well Design and a Shallow Water Cretaceous Well Design. There is the possibility either well type is selected for drilling in either of the exploration licences EL-1144 and EL-1150 license blocks. Up to 10 wells may be drilled as part of the Project.

To estimate the potential drill cuttings release in the Project Area, two example modelling locations are considered with one in each EL to represent the variations in ocean currents and water depth between the two ELs. The Deepwater example well design is modelled for EL-1144 and the Shallow Water example well design is modelled for EL-1150 (Figure 1-1).

With the potential to drill multiple wells and at any time during the year, four model simulation runs or ‘scenarios’ for March, June, September, December are considered to capture the associated variation in currents at each example location. Each scenario model run provides a prediction of the cuttings footprints from drilling of a representative (i.e., similar depth and current regime) well design and location for a given time of year. It is emphasized these are example wells and example modelling locations; however, a reasonable assumption is that similar cuttings discharge footprint will result from other wells nearby one of these locations.

This report presents details of the model methods, inputs and results.

Figure 1-1 Project Area, Drill Cuttings Modelling Locations



2.0 DRILLING PROGRAM

This section provides a summary of key elements of the drilling program considered in modelling of the release of drill cuttings to the sea.

The two example modelling locations are shown in Table 2-1 and Figure 1-1, with the Deepwater Example Well Design selected for EL-1144 and the Shallow Water Example Well Design selected for EL-1150.

Note: it is emphasized that either of these two well designs could occur in either EL; however, for simplicity in discussing the modelling inputs and results moving forwards, these two well design – EL location assignments are those carried forwarding for the modelling.

Table 2-1 Drill Cuttings Modelling Example Locations

Example Location	Example Latitude (N)	Example Longitude (W)	Example Water Depth (m)
EL-1144 Deepwater Jurassic Example Well	47° 31' 01.23"	46° 43' 09.20"	1,137
EL-1150 Shallow Water Cretaceous Example Well	47° 18' 13.21"	46° 09' 18.53"	378

Hole sections and drill cuttings volumes (per well) and release locations associated with these two example well types are presented in Table 2-2 and Table 2-3. Well schematics for the Deepwater and Shallow Water example wells are shown for illustration only in Figure 2-1 and Figure 2-2: these will change once a real well is selected. all All of these details are specific to the example wells only and details of the real wells that may be drilled will vary.

Table 2-2 Example Well Hole Sections

Example Well Hole Section (hole size)	Example Section TD (m) [c]	
	Deepwater Jurassic Example Well	Shallow Water Cretaceous Example Well
Nominal Water Depth (m)	1,140 [a]	380 [b]
Conductor (42") Openwater Drilling	1,260	500
Surface (26") Openwater Drilling	2,020	910
Intermediate (17.5") Riser Connected Drilling	3,300	1,650
Production (12.25") Riser Connected Drilling	4,550	2,880

Notes: a) For the Deepwater Jurassic Example Well, the mudline is 1,168 m DFE (MODU floor elevation), MODU elevation=31 m. b) For the Shallow Water Cretaceous Example Well, the mudline is 409 m DFE; c) depths are the bottom of the section relative to DFE, e.g., the conductor casing overall length is 90 m, running from 1,168 m to 1,258 m DFE.

Table 2-3 Example Drill Cuttings Volumes (m^3) and Release Locations

Example Well Hole Section	Release Location	Deepwater Jurassic Example Well [c]	Shallow Water Cretaceous Example Well[c]
Conductor	Seabed [a]	150	150
Surface	Seabed [a]	460	250
Intermediate	Subsea [b]	310	180
Production	Subsea [b]	150	150
Sidetrack	Subsea [b]	150	150
	Total WBM cuttings	610	400
	Total SBM Cuttings	610	480
	Total Cuttings	1,220	880

Notes: a) Both the Deepwater Jurassic Well and the Shallow Water Cretaceous Well are example wells only and actual wells could have different depths with different sections and different associated cuttings volumes; b) WBM cuttings from conductor and surface sections released directly at the seabed: estimate 2 m above seabed allowing for some initial upward momentum as cuttings materials exit the well hole; b) SBM cuttings from intermediate and production and sidetrack released from MODU, estimated 2 m below sea surface. c) cuttings volumes are in situ with bulking and washout, and are reported per well, e.g., one EL-1144 well yields 1,220 m^3 of cuttings, one EL-1150 well yields 880 m^3 of cuttings.

Figure 2-1 EL-1144 Deepwater Jurassic Example Well Schematic

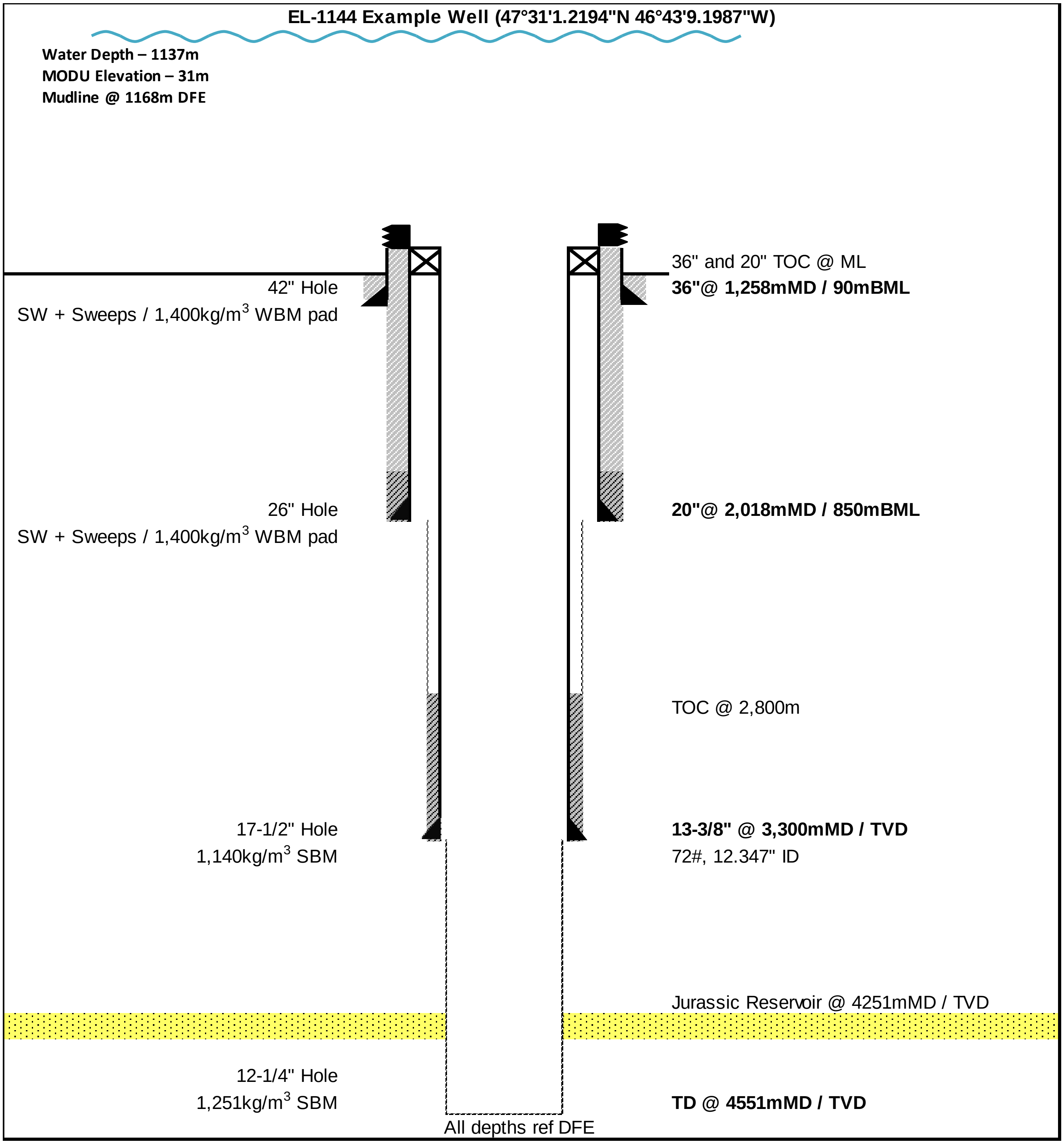
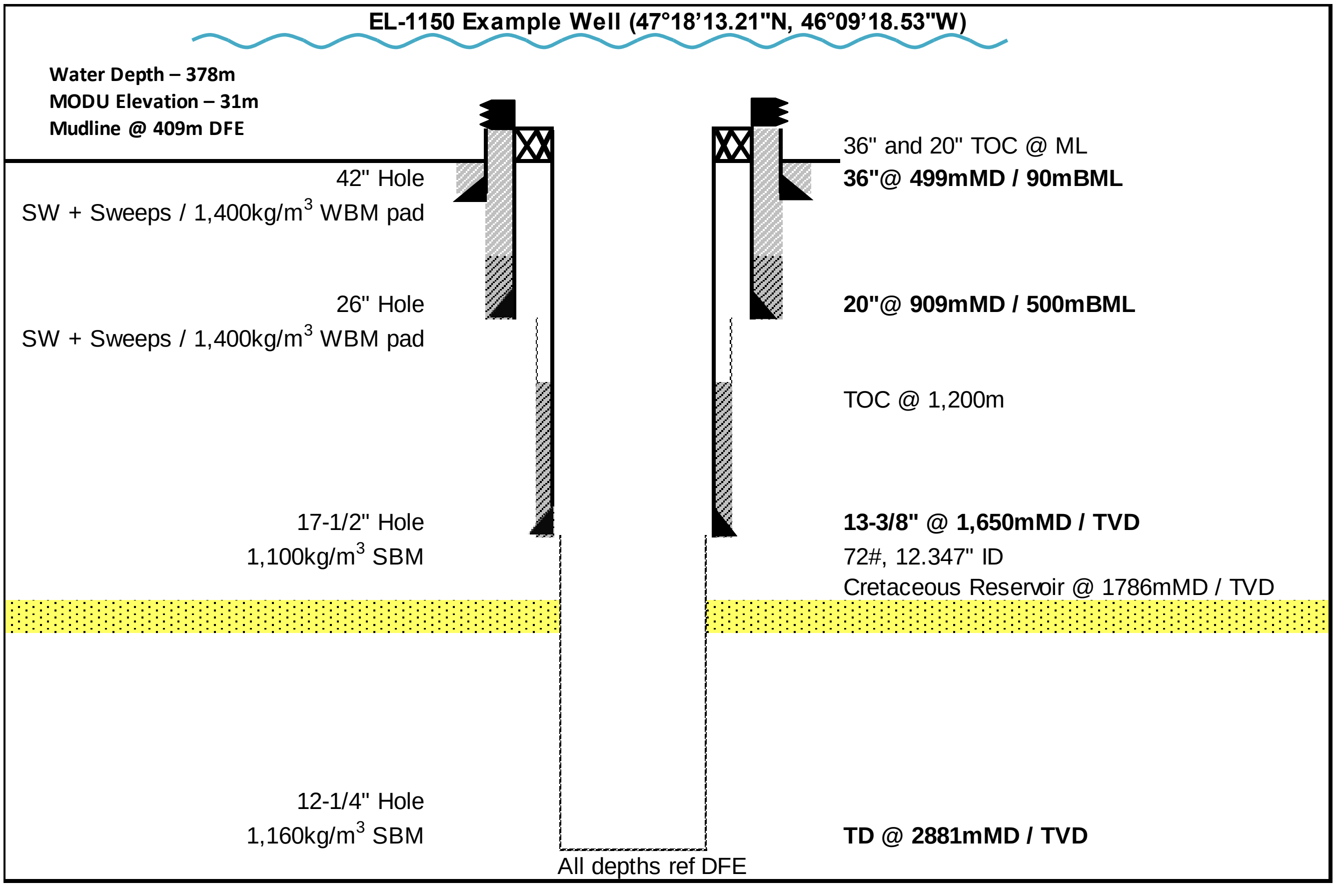


Figure 2-2 EL-1150 Shallow Water Cretaceous Example Well Schematic



3.0 DRILL CUTTINGS DEPOSITION

The drill cuttings model considers drilling of well hole sections and the associated cuttings discharges. The subsequent path of the discharged cuttings (with advection as a result of the ambient ocean current) to their ultimate fate on the seabed is predicted with a three-dimensional sedimentation numerical model.

3.1 Methods

3.1.1 Advection Dispersion Model Description

The analysis of the drill cuttings discharges was accomplished by using a numerical computer model developed by AMEC[1] to determine cuttings depositions at the time of drilling operations. The AMEC Advection Dispersion Model (ADM) software is written in Visual Fortran and developed based on previous corporate experience and modelling algorithms including those from the Hibernia (Hodgins 1993) and White Rose (Hodgins and Hodgins 2000) fate and effects modelling studies. The ADM model has also been used as part of the Hebron Project environmental assessment (AMEC 2010) and the White Rose Extension Project environmental assessment (AMEC 2012, Amec Foster Wheeler 2016a)

In the model, a transport computation is employed to simulate the advection of the dispersed drill cuttings materials in three dimensions through the water column, following release into the sea, until the particles come to rest on the sea bottom. For the purposes of predicting their physical deposition on the seabed, the cuttings are considered as a composition of particle types or sizes; typically larger cuttings pieces, pebbles, coarse sand, medium sand and fines. These particle sizes are assumed to be generally representative of the materials likely to be encountered in the area and generated using WBM or SBM.

At any given time, a particle is assumed to be subject to independent displacing forces due to the ocean current and to a fall velocity that is constant for a given particle type. A displacement term to model turbulent diffusion is added to the equations. Over the time step of the available ocean current data, the displacements are calculated and added to yield a new particle position. Vector additions are computed over each successive time step until the simulation terminates with deposition on the sea bottom (which may be some time after well drilling has terminated).

A model grid is selected to encompass the drilling area and possible domain for the deposition of the cuttings (model domain is further discussed at the end of Section 3.2.4). The model tracks the fate and deposition of the particles. In addition to each particle’s path, the weight of material is tracked. This is the primary particle attribute. After completion of a model run, when all particles have settled, or have reached the model grid boundaries (in which case, they are taken to have drifted outside the domain and are tabulated as ‘lost’), each particle is binned in one of the model grid cells and the total weight, W, is calculated. In addition, the following other parameters are calculated for each grid cell:

[1] AMEC Environment & Infrastructure legally changed its name to Amec Foster Wheeler Environment & Infrastructure in January 2015. Any reference to AMEC herein can be understood to mean Amec Foster Wheeler, and vice versa.

$$C = W \times 1000 / A \tag{1}$$

$$T = C / \gamma \tag{2}$$

$$OC = OC_{initial} \times W / \left(A \times h \times (1 - n) \times \gamma_s \right) \tag{3}$$

Where

W = cuttings weight (kg)
C = cuttings density (g/m^2)
T = cuttings thickness (mm)
OC = oil concentration on cuttings (mg/kg)
A = area of one grid cell (m^2)
γ = in situ bulk density (1,850 kg/m^3)
$OC_{initial}$ = initial oil concentration
h = sediment mixing depth (0.08 m)
n = seabed porosity (0.4)
γ_s = specific weight of cuttings (2,300 kg/m^3)

The specific weight of cuttings is taken as the weighted sum of the specific weights estimated for each of the well hole sections. The approach for calculating T and OC follows that employed by Hodgins and Hodgins (2000). The oil concentration on cuttings (OC), is the weight of material times its initial concentration, divided by the volume of an assumed thin benthic layer in which the cuttings are assumed to settle and mix with the seabed sediments. Oil concentration is only applicable where SBM are discharged during MODU drilling. All cuttings are assumed to be adequately treated to reclaim oil as required by present regulations. Oil content on cuttings produced during drilling with SBM, $OC_{initial}$, was set to 7.4 g / 100 g, equal to 6.9 g / 100 g oil on wet solids, as per the OWTG (NEB et al. 2010).

3.2 Model Input

3.2.1 Scenarios, Well Sequences, Well Types

While full details of the drilling schedules have not been finalized, well durations are estimated at about 63 days for the EL-1144 Deepwater Jurassic Example Well and 53 days for the EL-1150 Shallow Water Cretaceous Example Well. These are estimates only: actual wells to be drilled may have longer or shorter drill times. The schedule includes a sidetrack following completion of the production hole as well as wireline logging, plugging and abandoning of the well and demobilization. While it is uncertain whether sidetracks will be part of the well plan or not, it is possible and a worst case in terms of amount of cuttings material per well. Therefore, to be conservative, sidetrack drilling and the associated cuttings discharge are included in the drilling activity and discharge plan.

The estimated timing for completing each well hole section is presented in Table 3-1. It is assumed the drilling and associated cuttings release would be during the initial days of the section. For example, the five well hole section discharges at the EL-1144 Deepwater Jurassic Example Well are simulated to take place at days 2, 6, 15, 30 and 49 and last 1, 2, 3, 5 and 5 days respectively. The discharge start and end days are rounded to the nearest day. It is noted again these are example wells and estimated drilling schedules for the modelling: the actual wells to be drilled could have additional sections or durations once sites and depth are selected.

Table 3-1 Drilling and Cuttings Discharge Activity Schedule, EL-1144 Deepwater Jurassic Example Well

Activity	Section Start Day	Section End Day	Drilling Duration (d)	Cuttings Discharge Start Day	Cuttings Discharge End Day
Prespud Preparations	0	1.5	0.0	-	-
Drill Conductor Hole	1.5	5.0	0.5	2	2
Drill Surface Hole / BOPs	6.0	14.0	2.2	6	7
Drill Intermediate Hole	15.0	29.0	3.0	15	17
Drill Production Hole	30.0	39.0	5.0	30	34
Wireline / Plug back to Sidetrack	39.0	49.0	0.0	-	-
Drill Sidetrack	49.0	58.0	5.0	49	53
Wireline / P&A / Demob	59.0	63.0	0.0	-	-

Table 3-2 Cuttings Discharge Schedule, EL-1150 Shallow Water Cretaceous Example Well

Activity	Section Start Day	Section End Day	Drilling Duration (d)	Cuttings Discharge Start Day	Cuttings Discharge End Day
Prespud Preparations	0	1.5	0.0	-	-
Drill Conductor Hole	1.5	5.0	0.5	2	2
Drill Surface Hole / BOPs	6.0	11.5	1.2	6	6
Drill Intermediate Hole	12.5	23.0	2.0	12	13
Drill Production Hole	24.0	33.0	5.0	24	28
Wireline / Plug back to Sidetrack	33.0	43.0	0.0	-	-
Drill Sidetrack	43.0	52.0	5.0	43	47
Wireline / P&A / Demob	53.0	57.0	0.0	-	-

Since drilling of the wells could happen during any month of the year, four seasonal scenarios are considered, for both locations, to simulate ocean current conditions most likely to be encountered. Accordingly, well start dates as follows are assumed:

- 1 March (“winter”)
- 1 June (“spring”)
- 1 September (“summer”
- 1 December (“fall”)

A unique well type, used for cuttings release in the model, is defined for both locations. The well type defines, for each of the four well hole sections of a given well, the volume of cuttings (WBM for conductor and surface sections; SBM for intermediate and production sections) and release locations as per Table 2-3 and cuttings particle compositions (Section 3.2.2).

3.2.2 Cuttings Particle Characterization

Characterization of drill cuttings is used in the dispersion model to predict the fall or settling of the cuttings particles in the ocean until they settle on the seabed (or drift outside the model geographical domain).

Given no exploration wells have been drilled previously in the Project Area, there are no cuttings particle size distributions that specifically quantify the composition of the different mineral materials as a function of well depth. The actual compositions will depend on rate of penetration, rotary table speed, hydraulics, bit selection and the geology of the well and, for SBM cuttings, how the cuttings are processed through solids control systems onboard the MODU, e.g., shale shakers, cuttings dryers, or centrifuges. In the absence of this information, analogs from a review of well history reports for wells in the region were estimated. For the purposes of these example well scenarios, the assumed cuttings particle size characterizations and compositions are presented in Table 3-3.

Table 3-3 Cuttings Particle Size Composition

Cuttings Type, Well Section	Measured Weight Percent Material					
	Fine Pebbles	V. Fine Pebbles	V. Coarse Sand`	Medium Sand	V. Fine Sand	Medium Silt
WBM, conductor and surface	0	10	20	25	20	25
SBM, intermediate	52	28	13	4	1	2
SBM, production, sidetrack	8	30	38	20	2	2

Notes: a) for WBM cuttings, formation sample descriptions from Petro-Canada et al Tuckamore B-27, 10 km to the southwest, were considered. The conductor and surface section composition is estimated as sandy, silty, with fine to coarse grains; b) for SBM cuttings, drill cuttings samples from Esso Parax et al Baccalieu I-78, 67 km to the northeast, were considered. The intermediate section composition is the average of the 3,000 and 3,500 m samples; the production section and sidetrack composition is the average of the 11 sample depths of 3,750 to 5,100 m.

It is assumed that the cuttings enter the sea in a relatively disaggregated form. The model considers that the pebble and sand materials will remain disaggregated in their fall to the seabed. Any fines are assumed to aggregate into flocs of size of approximately 0.1 mm and settle with a constant speed.

In addition to the percent compositions shown in Table 3-3, the associated particle fall velocities are also essential for the deposition modelling. Table 3-4 lists, for each particle type, its diameter and associated fall velocity, estimated from particle diameter with Sleath (2014).

Particle fall velocities, w, were estimated from the particle diameter using the following relationships, from Sleath (1984):

$$w = 4.2\sqrt{D}, D > 0.0001m \quad (4)$$

$$w = 12x10^4 D^2, D \leq 0.0001m \quad (5)$$

where w is the fall velocity in m/s and D is the diameter in m.

For the six particle types considered, this yields the values reported in Table 3-4.

Table 3-4 Cuttings Particle Size Characterizations

Cuttings Material	Particle Parameter					
	Fine Pebbles	**V. Fine Pebbles**	**V. Coarse Sand`**	**Medium Sand**	**V. Fine Sand**	**Medium Silt**
Sieve	#4	#8	#16	#50	#200	-
Particle diameter (mm)	4.76	2.36	1.18	0.300	0.074	0.01
Particle fall velocity (m/s)	0.290	0.204	0.144	0.073	0.001	0.001

Based on equation (5), the settling velocities for the very fine sand and medium silt smallest particles are 0.0007 and 1.2×10^{-5} m/s respectively; however, these are not likely scenarios given the components of WBMs and SBMs are likely to flocculate. In the sensitivity analysis discussion for particle settling velocities in the 2012 AMEC report (Section 3.4) the work of Tedford et al. (2003) was referenced. The approximations there considered a fast settling (of flocs) of 0.005 m/s assumed for early stages of discharge, followed by a slowing to 0.0001 m/s (for floc breakup when the bottom stress exceeds a threshold), and finally a larger settling of 0.001 m/s (when the bottom stress falls back below that threshold).

A 'base case' of 0.001 m/s values for the two smallest particle types as reported in Table 3-4, were deemed the most reasonable and selected for the model runs. These values, somewhat smaller than a faster 0.005 m/s settling, provide a somewhat more conservative estimate in terms of how far horizontally the cuttings may disperse.

3.2.3 Ocean Currents

Together with particle settling velocities, horizontal current is the other key factor in determining how far cuttings may disperse, so it is important to employ a good characterization of the local current behaviour as a driving force for the model. Since the cuttings will settle through the water column, a characterization of the currents as a function of depth is required.

No existing current measurements have been found for the Project Area. This includes a query of the Bedford Institute of Oceanography (BIO) Ocean Data Inventory (ODI) database (Gregory 2004, DFO 2017). The nearest current measurements located about 37 km to the southwest of the EL-1144 Deepwater Jurassic Example Well in a water depth of about 750 m (Figure 1-1). The data from two deployments include near-surface (67 m), mid-depth (334 m, 346 m) and near-bottom (589 m, 592 m) currents measured from 22 April through 31 October 1986. A brief summary of monthly mean and maximum current speeds is shown in Table 3-5.

Table 3-5 Monthly Current Statistics, ODI Database Location 47.3542°N, 47.1618°W

		Apr	May	Jun	Jul	Aug	Sep	Oct
	Instrument Depth (m)				67	67	67	67
Near-Surface	Mean (cm/s)				19	21	31	40
	Max (cm/s)				34	41	53	64
	Mean Direction (to)				S	S	S	S
	Instrument Depth (m)	346	346	346	346, 334	334	334	334
Mid-Depth	Mean (cm/s)	6	4	11	12	4	11	11
	Max (cm/s)	28	22	28	32	22	29	43
	Mean Direction (to)	N	SE	S	S	S	S	S
	Instrument Depth (m)	589	589	589	589, 592	592	592	592
Near-Bottom	Mean (cm/s)	3	7	9	10	8	12	18
	Max (cm/s)	34	30	28	33	21	28	41
	Mean Direction (to)	N	S	S	S	S	S	S

1986, ODI Event IDs MCM 86907, 86914

While instructive, these measurements are unlikely to be the most representative source of currents to use for the two modelled locations in the Project Area. Therefore, currents for input to the drill cuttings model were derived from seasonal average currents at near-surface, mid-depth and near-bottom depths through the water column using the WebDrogue CECOM (Canadian East Coast Ocean Model) model (DFO 2015a), and tidal predictions for a full year derived from the WebTide model (DFO 2015b).

Wu et al. (2012) conducted an extensive comparison of the CECOM model results and 11 years of observational data, including both qualitative visual comparisons, and quantitative methods based on statistical analysis. Their comparisons indicated that the main circulation features from the observations were successfully reproduced by the model. Furthermore, the comparison indicated particularly good levels of agreement between model and observations in the regions of the Labrador Shelf, Newfoundland Shelf, and the Flemish Pass, with a mean correlation coefficient in the of 0.91 (ideal value is 1) across all seasons and depths within the Flemish Pass, and an average ratio of kinetic energy difference to the observations of 0.12 (where a lower value is better, and the value of 0.5 indicates "a fair agreement").

The models yield currents at five depth levels: surface, 100 m, 500 m, 1,000 m and bottom. The depth levels selected for the two locations are as noted below.

- EL-1144 Deepwater Jurassic Example Well Location (1,137 m)
- Near-surface: modelled depth level=100 m
- Mid-depth: modelled depth level=500 m
- Near-bottom: modelled depth level=1,000 m

- EL-1150 Shallow Water Cretaceous Example Well Location (378 m)
- Near-surface: modelled depth level=surface
- Mid-depth: modelled depth level=100 m
- Near-bottom: modelled depth level=bottom

In the model algorithm, as each calendar day of drilling and possible discharge is followed, the corresponding day of current data is input from the representative year time series file and is used to advect the particles. It is assumed that the currents are representative of the two locations and are uniform over the deposition grids (domain) modelled.

Further illustration of these currents used as model input is presented in Appendix A-1. This includes time series plots of current speed and direction for near-surface, mid-depth and near-bottom depths for March, June, September and December together with monthly current roses for all three depths.

Ocean currents in the Project Area are low. Near-surface mean current speeds range from 2.6 cm/s in summer to 9.5 cm/s in winter, with maximum values ranging from 4 cm/s in summer to 11.5 cm/s in winter. At greater depths, current speeds are about one half of near-surface values. Annual mean current speeds for mid-depth are about 2.5 cm/s with maximum values of 6 cm/s. Near-bottom mean current speeds range from about 1 cm/s in summer to 3 cm/s in winter, with maximum values ranging from about 3 cm/s in summer to 4.5 cm/s in winter.

Table 3-6 and Table 3-7 present WebDrogue/WebTide monthly near-surface, mid-depth and near-bottom current statistics for the two locations, one location in EL-1144 on the northwestern slopes of the Flemish Pass at a water depth of 1,137 m, the other in EL-1150 on the western slopes of the Flemish Pass at a water depth of 387 m. On the western side of the Flemish Pass at the modelled EL-1144 location, near-surface (at the surface) mean current speeds range from about 2 cm/s in summer to 9 cm/s in fall, with maximum values ranging from 5 cm/s in summer to 12 cm/s in fall. At greater depths (500 m for mid-depth, 1,000 m for near-bottom), current speeds are about one half to one quarter the near-surface values. For near-bottom, mean currents range from 1 to 3 cm/s year-round with maximum speeds of 3 to 5 cm/s, the largest values again being in the fall.

As illustrated by the current roses in Appendix A-1, the modelled currents are predominantly to the south and southwest in fall and winter at all depths. In spring, the currents near-surface flow predominantly to the south; at mid-depth and near-bottom directions are more evenly distributed to all directions (albeit at the very low current speeds). At near-bottom there is a slight preference to the west. In summer, near-surface currents flow predominantly to the southeast, with conditions mid-depth and near-bottom similar to those in spring.

On the eastern side of the Flemish Pass at the modelled EL-1150 location, predicted near-surface (surface) mean current speeds range from about 5 cm/s in summer to 11 cm/s in winter, with maximum values ranging from 10 cm/s in summer to 15 cm/s in winter. At greater depths (100 m for mid-depth and the bottom depth level to characterize near-bottom), current speeds are generally one half to one third the near-surface values. Mid-depth and near-bottom mean currents are 2 to 3 cm/s in all months with maximum speeds ranging from 5 to 7 cm/s, the largest values again being in the winter. The modelled currents near-surface are predominantly to the northeast in fall and winter. In spring the flow near-surface is to the east and northeast, while in summer it is mostly to the east. The generally light (about 2-3 cm/s on average) currents at mid-depth and near-bottom flow primarily to the northeast quadrant (occasionally also to the northwest) in all months.

Table 3-6 EL-1144 Deepwater Jurassic Example Well Location, Monthly Current Statistics

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Near-Surface	Min (cm/s)	6	6	6	5	5	5	1	1	1	8	8	7
	Mean (cm/s)	8	8	8	7	7	7	2	2	2	9	9	9
	Max (cm/s)	10	10	10	9	9	9	5	5	5	12	12	12
	Most Frequent Direction (to)	S	S	S	S	S	S	SE	SE	SE	S	S	S
Mid-Depth	Min (cm/s)	1	1	1	0.1	0.1	0.03	0.1	0.1	0.1	2	2	2
	Mean (cm/s)	3	3	3	1	1	1	1	1	1	4	4	4
	Max (cm/s)	6	6	6	3	3	3	3	3	3	6	6	7
	Most Frequent Direction (to)	SW	SW	SW	S	S	S	N	N	N	SW	SW	SW
Near-Bottom	Min (cm/s)	0.1	0.1	0.1	0.1	0.02	0.1	0.1	0.1	0.01	1	1	1
	Mean (cm/s)	2	2	2	1	1	1	1	1	1	3	3	3
	Max (cm/s)	4	4	4	3	3	3	3	3	3	5	5	5
	Most Frequent Direction (to)	S	S	S	SW	SW	W	W	W	NW	S	S	S

Table 3-7 EL-1150 Shallow Water Cretaceous Example Well Location, Monthly Current Statistics

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Near-Surface	Min (cm/s)	8	8	8	5	5	6	1	1	1	5	5	5
	Mean (cm/s)	11	11	11	9	9	9	5	5	5	8	8	8
	Max (cm/s)	15	15	15	13	13	13	10	10	10	12	12	12
	Most Frequent Direction (to)	NE	NE	NE	E	E	E	E	E	E	NE	NE	NE
Mid-Depth	Min (cm/s)	0.3	1	1	0.3	0.1	0.2	0.1	0.1	0.1	0.1	0.1	0.2
	Mean (cm/s)	3	3	3	3	3	3	2	2	2	3	3	3
	Max (cm/s)	7	7	7	7	7	7	6	6	6	6	6	6
	Most Frequent Direction (to)	NE	NE	NE	E	E	E	E	E	E	E	E	E
Near-Bottom	Min (cm/s)	0.1	0.3	0.1	0.1	0.04	0.1	0.01	0.02	0.1	0.3	0.1	0.1
	Mean (cm/s)	3	3	3	2	2	2	2	2	2	2	2	2
	Max (cm/s)	7	7	7	6	5	6	6	6	6	5	5	5
	Most Frequent Direction (to)	N	N	N	E	E	E	E	E	E	NW	NW	NW

A regional illustration of the modelled surface and bottom currents is also shown in Figure 3-1 to Figure 3-8. These figures provide a good illustration of the variation in magnitude and direction of currents over the Project Area including the southerly flow through the Flemish Pass near the EL-1144 Deepwater Jurassic Example Well location and the northeasterly flow along the Flemish Cap slopes near the EL-1150 Shallow Water Cretaceous Example Well location.

Comparison of the currents shown in these figures near the ODI database site reported in Table 3-5, over the range of seasons and depths, shows a generally good agreement with the limited measurement data set.

Figure 3-1 Winter, Surface Currents

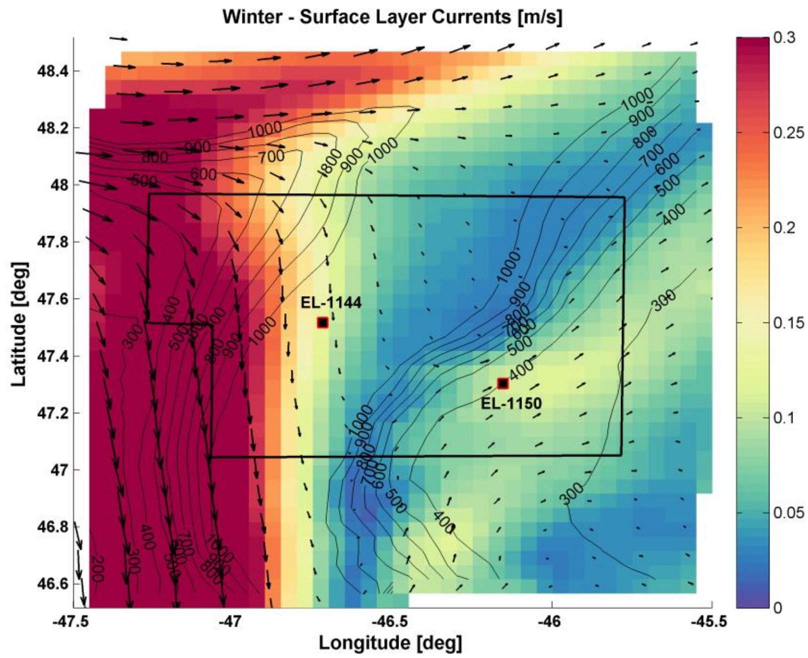


Figure 3-2 Winter, Bottom Currents

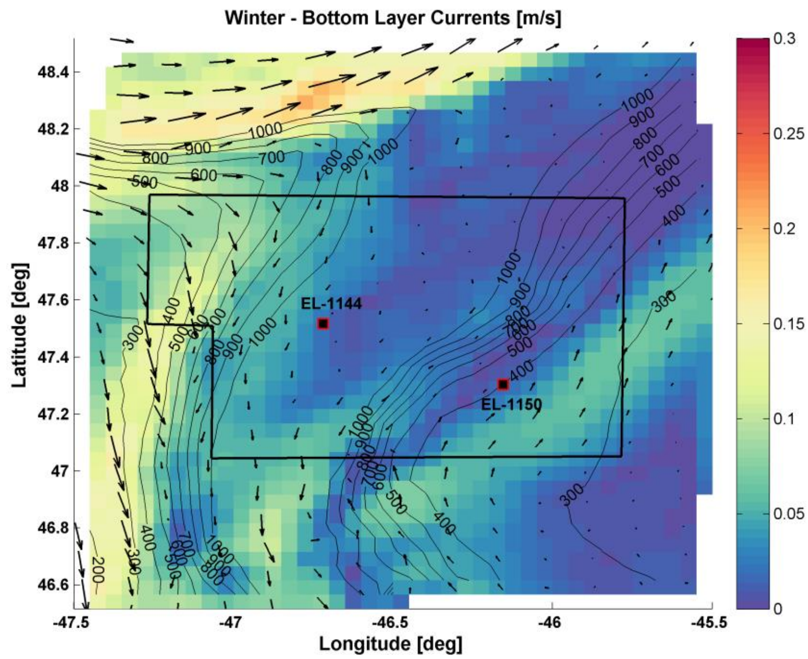


Figure 3-3 Spring, Surface Currents

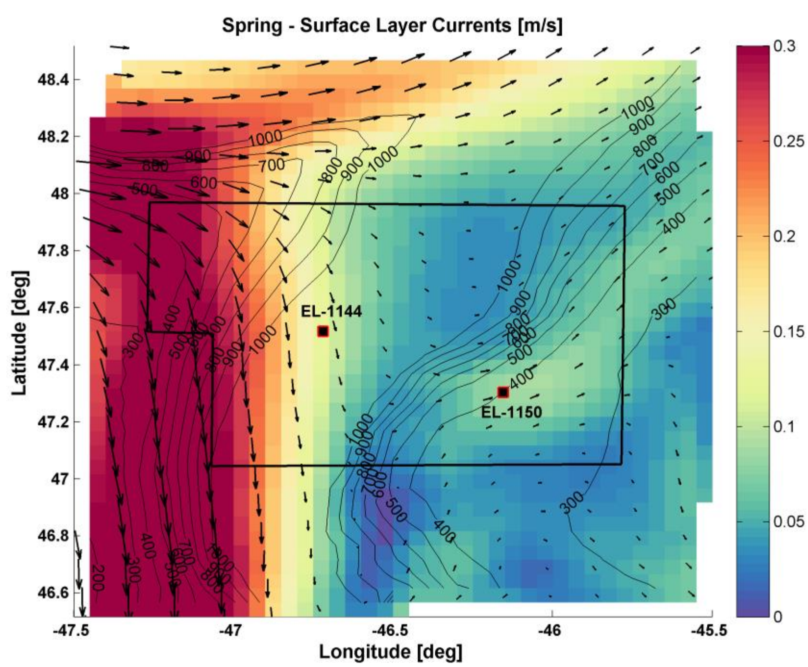


Figure 3-4 Spring, Bottom Currents

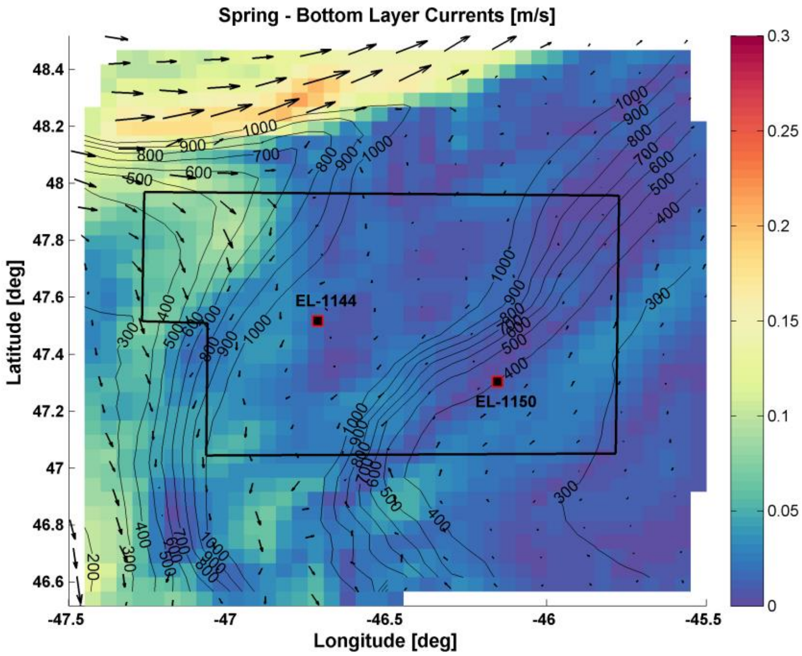


Figure 3-5 Summer, Surface Currents

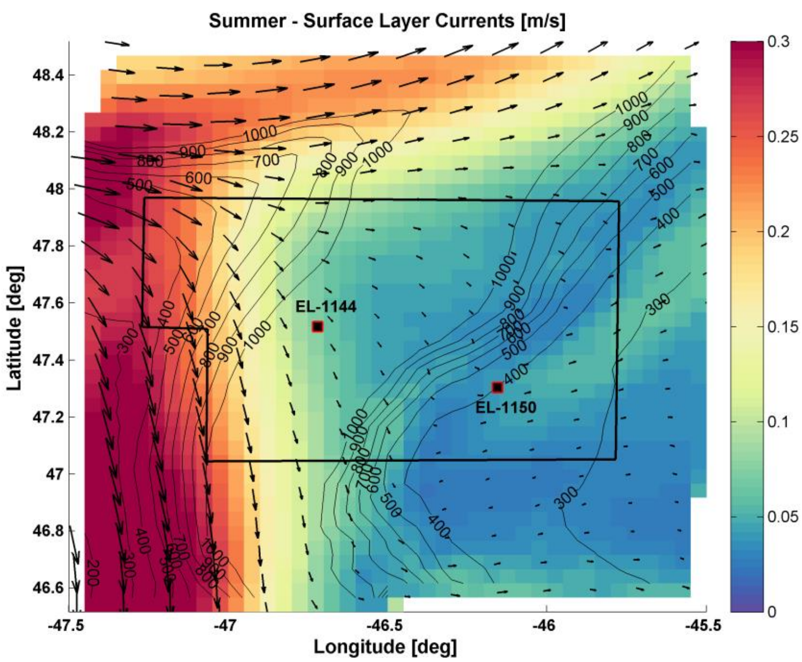


Figure 3-6 Summer, Bottom Currents

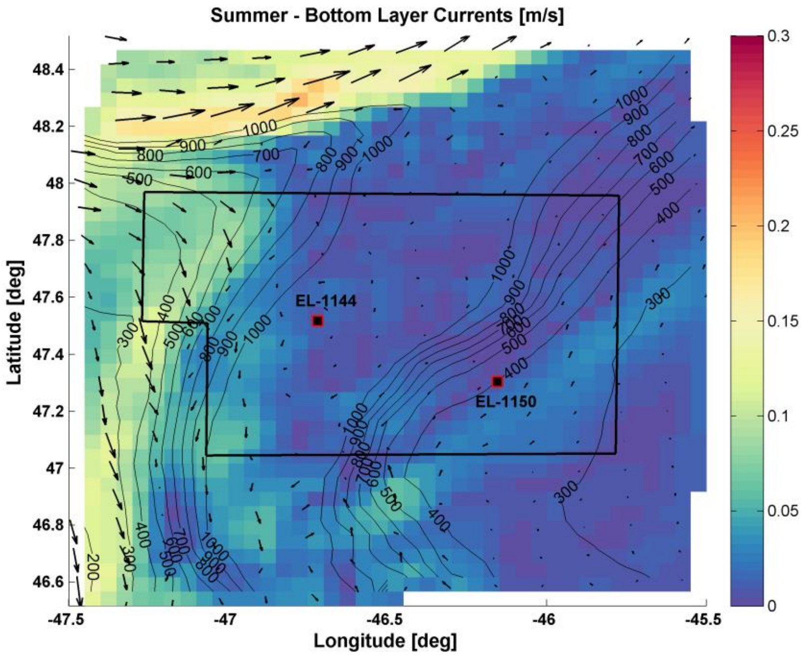


Figure 3-7 Fall, Surface Currents

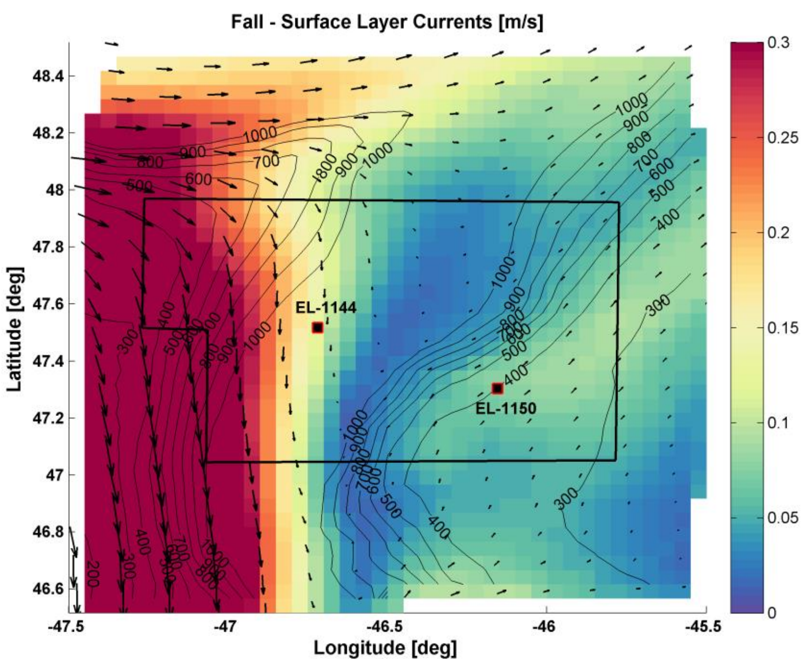
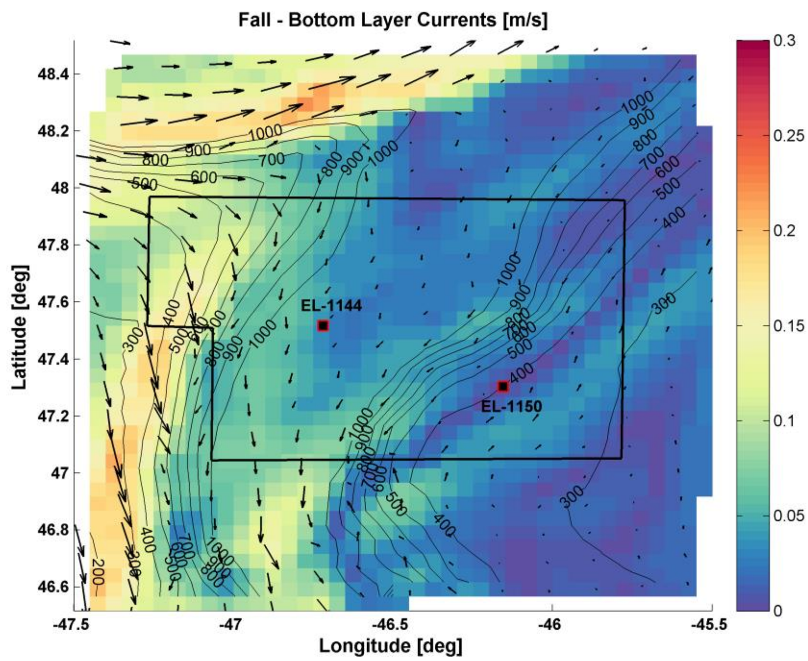


Figure 3-8 Fall, Bottom Currents



3.2.4 Model Geometry

The transport (and spatial extent) and fate of the cuttings are modelled as a function of time. A given well sequence as a number of days drilling is employed. For each day, and for each different size class of material (i.e., the two pebble, three sand and one silt sizes in Table 3-4), a collection of particles are discharged. Particles are assigned a weight apportioned on the number of days drilling (Table 3-1) and the volume of cuttings associated with the particular well section. A time step is assigned appropriate for the geographic scale and model grid of the study area and the ambient current conditions. It is also necessary to choose time steps appropriate for each of the different particle types which exhibit a range of fall velocities. At each time step in the model, a new location for a given particle is calculated. Selection of too large a time step may yield inaccurate results. Too small a time step makes for overly intensive computations in the model. The time steps employed are listed in Table 3-8.

Table 3-8 Model Time Steps for Cuttings Particle

Particle Parameter	Cuttings Material					
	Fine Pebbles	**V. Fine Pebbles**	**V. Coarse Sand`**	**Medium Sand**	**V. Fine Sand**	**Medium Silt**
Time Step, Δt (s)	20	20	60	120	3600	3600
# Particles per Δt	1	1	3	6	180	180
# Steps per day	4,320	4,320	1,440	24	24	24

It is instructive to consider these time steps together with the particle settling velocities presented in Section 3.2.2. Their application in the model has a direct bearing on the deposition predictions. For the WBM cuttings discharge 2 m above the seafloor, the particles will quickly settle to the seabed. The pebble- and sand-sized particles will settle in less than one minute, while the very fine sand- and silt-sized particles will take about one hour to settle. For SBM cuttings released near the sea surface (2 m depth assumed) the water depth will clearly be a defining parameter in how quickly materials settle. At the EL-1144 location modelled, at 1,137 m, the fine pebble-sized particles (fall velocity of 0.29 m/s) will be modelled to settle to the seabed in about one hour; the medium sand-sized particles will take about four hours; while the very fine sand- and silt-sized particles (fall velocity of 0.001 m/s) will take over 13 days. At the EL-1150 location modelled, at 378 m water depth, the settling times will be about one third of those at the deeper location. This illustrates the key roles of the location water depth and the large influence of the particle size composition and settling velocity assumptions.

A grid of the seabed is used in the model to track the spatial extent of depositions. The model grid is a Cartesian grid of size 2000x2000 centred at the drill cuttings scenario location (i.e., at the wellhead) and extending out a finite distance both in X (or East-West) and Y (or North-South) directions. Two grid cell sizes were used. A 64 m cell provides coverage out to 64 km and was used to first assess the extent of the cuttings drift. A smaller 4 m cell size is used for greater resolution about the wellhead, particularly for the WBM cuttings released near the seabed.

The model assumes uniform depth, with values set equal to the water depth at each modelling location (Table 2-1): EL-1144 at 1,137 m, EL-1150 at 378 m. The assumption of a flat bathymetry is borne out as a reasonable approximation given the distances and directions that the cuttings drift, e.g., at EL-1144, the drift is to the south in the deep waters of the Flemish Pass. At EL-1150, the drift is to the northeast along the western slope of the Flemish Cap. Bathymetry is illustrated both in the Project Area Figure 1-1 and the seasonal current maps, e.g., Figure 3-2.

3.2.5 Model Algorithm

The path of each particle released is tracked by calculating at each new time step, n+1, its position (x,y,z) based on its position at the previous time step, n, as given by equations (6) to (8):

$$x_{n+1} = x_n + u \times \Delta t + x' \times R_x \tag{6}$$

$$y_{n+1} = y_n + v \times \Delta t + y' \times R_y \qquad (7)$$

$$z_{n+1} = z_n + w \times \Delta t + z' \times R_z \qquad (8)$$

Where

- x = the particle position in the east-west horizontal distance (m)
- y = the particle position in the north-south horizontal distance (m)
- z = the particle position, or depth, in the vertical distance (m) (depth positive downwards)
- u = east-west component of the ocean current (m/s)
- v = north-south component of the ocean current (m/s)
- Δt = time step for the given particle type (s)
- w = fall velocity for the given particle type (m/s)
- Rx, Ry, Rz= random numbers in the range (-1,1)

and where the x’×Rx terms, and similarly for y and z, are included to simulate an element of turbulence in the current drift of the particles.

3.3 Model Output

Following each well run, an output file is generated containing an x,y grid of the model domain with the following variables calculated for each grid cell:

- x, y, origin of cell (km), relative to discharge (x,y,z) origin
- range (km) and bearing (°T) from origin
- for each of WBM cuttings, SBM cuttings, and total (WBM+SBM) cuttings:
  - total weight of cuttings (kg)
  - cuttings density (g/m^2)
  - cuttings thickness(mm)
- number of particles of each of six types (coarse, medium, fine and very fine sand, coarse and medium silt, fine silts and clays)

A run log file is also generated that echoes key model inputs and reports the total weight of cuttings (WBM and SBM) deposited on the seabed and the amount of any cuttings which drift outside the model grid.

4.0 RESULTS

The cuttings model tracks and outputs separately, the WBM, SBM and total (WBM plus SBM) deposition results. Model results are presented in Section 4.1 and 4.2 for the two locations EL-1144 Deepwater Jurassic Example Well and EL-1150 Shallow Water Cretaceous Example Well. For each location, each results section presents a summary of cuttings material that settles on the seabed and associated thicknesses by distance from the well site origin together with plan-view maps of the cuttings deposition footprints.

Cuttings from drilling the upper two well sections with WBM will all be released as per the Offshore Waste Treatment Guidelines (OWTG) (National Energy Board (NEB) et al. 2010) close to the seafloor. Therefore, there is little time for the cuttings to be transported large distances by the ambient currents. SBM cuttings will be treated in accordance with the OWTG and released near the sea surface (2 m assumed, see Table 2-3). The larger pebble and sand sized particles will drift and settle within about 2 km of the well site, while the finer sands and silts may drift for many kilometres before settling.

The settling of the SBM drill cuttings characterized by pebbles and very coarse and medium sand (Table 3-3) are predicted to take about 1 to 4 hours to reach the seabed at a water depth of 1,137 m (EL-1144 Deepwater Jurassic Example Well location), whereas the very fine sand and medium silt clay cuttings flocs is predicted to require about 13 days. For the shallower, 387 m, EL-1150 Shallow Water Cretaceous Example Well location, these times are predicted to be about 30 minutes to 2 hour for the pebbles and sand-sized cuttings and about 4 hours for the finest-sized particles.

To assist in the EIS's assessment of potential biological effects of drill cuttings deposition, predicted no effect thresholds (PNET) for cuttings thicknesses are used. Previous studies indicate that sedimentation and burial effects from drill muds and cuttings on benthic invertebrates have mainly been localized to the vicinity of a drill cuttings pile area (Neff et al 2000; Holdway 2002; Schaanning et al 2008; Trannum et al 2010; Gates and Jones 2012; Larsson et al 2013; Cordes et al 2016; Tait et al 2016). Average burial depths of 6.5 mm are considered to be the predicted no effect threshold (PNET) for non-toxic sedimentation based on benthic invertebrate species tolerances to burial, oxygen depletion and change in sediment grain size (Kjeilen-Eilertsen et al 2004; Smit et al 2006; 2008). However, as some species may be more susceptible to shallower burial depths, an average PNET burial depth of 1.5 mm is suggested to be a more conservative approach to assessing drilling discharges (Kjeilen-Eilertsen et al 2004; Smit et al 2006, 2008). This level coincides with assessments on more sensitive coral species where injury from sedimentation was observed with sedimentation of less than 6.3 mm (Larsson et al 2011, 2013).

In the results section for each location, the amounts of WBM and SBM cuttings material modelled to settle for selected distances out to 2 km from the well site (origin) are presented in a table. All four seasonal (monthly) scenarios are reported. In a second, similar, table a summary of mean and maximum cuttings thicknesses is presented. Mean thicknesses are calculated over those sea bottom cells with cuttings deposition (i.e., cells with no cuttings deposits are not considered). Thickness and percent material settled are reported for the 4 m x 4 m finer resolution grid. The mean thickness is the average over all model grid cells with cuttings deposit. The maximum thicknesses are the one largest thickness observed in each 'distance from well site' bin. For example, in the EL-1144 Deepwater Jurassic Example Well cuttings thickness Table 4-2, for March, the largest WBM cuttings thickness predicted in the range of 10 to 100 m from the well site is 257 mm (at a location 30 m to the southwest).

A set of five cuttings deposition map figures are also presented for each of the four seasonal scenarios at each location. This includes footprints of the modelled thicknesses for i) total cuttings – two scales of view, ii) WBM cuttings, iii) SBM cuttings and iv) total cuttings above PNET values of 1.5 mm and 6.5 mm.

Different distance scales are set to best illustrate the spatial extent and show detailed resolution in the footprint maps. A Project Area view is used to show the full extent of cuttings drift for the total cuttings thicknesses, although, in all cases, the majority of material settles within about 500 m of the wellhead origin. A 1.5 km scale is used to again show the predicted total and SBM cuttings thicknesses near the wellhead; a 250 m scale is used for WBM cuttings. The figures include radii drawn at 200 m and 1 km on the 1.5 km view plots and at 100 m and 200 m on the 250 m view plots. The 1.5 km scale is again used for the PNET plots.

4.1 EL-1144 Deepwater Jurassic Example Well

This section presents results of cuttings modelling for the EL-1144 location. Four seasonal scenarios are presented with drilling of wells commencing in March, June, September and December.

For all months, all WBM cuttings released at the wellhead are predicted to settle within 500 m (Table 4-1). In March and June, over 98 percent of the WBM cuttings settle within 100 m; the corresponding values are 97 percent in September and 93 percent in December. The greatest distance the WBM cuttings are predicted to drift ranges from 210 m in September to 280 m in December.

The SBM cuttings released from the MODU at the sea surface settle generally within 2 km, with over 90 percent settling within 500 m. The farthest these cuttings settle, within 2 km, ranges from 1.4 km in March to 1.7 km in September. Only 3.5 percent of the total SBM cuttings from one well drift farther away with all of these settling with thicknesses less than 0.1 mm. These small amounts of fine sand and silt-sized SBM cuttings are predicted to drift to the south and south-southwest: up to about 46 km in March (Figure 4-1), 25 km in June (Figure 4-6) and 54 km in September (Figure 4-11) and December (Figure 4-16). All cuttings settle therefore within the 64 km model domain.

Table 4-1 Cuttings Material Settled by Distance, EL-1144 Deepwater Jurassic Example Well

EL-1144 Deepwater		Distance from Well Site						
		0-10m	10-100m	100-200m	200-500m	500m-1km	1-2km	
Month	Cuttings Type	% Material Settled						% Material Unsettled
Mar	WBM	31.7	66.7	1.52	<0.1	-	-	-
	SBM	<0.1	4.9	41.1	43.3	6.9	0.2	3.5
Jun	WBM	35.1	63.7	1.2	<0.1	-	-	-
	SBM	0.4	22.5	37.3	32.0	4.0	0.3	3.5
Sep	WBM	31.5	65.9	2.6	<0.1	-	-	-
	SBM	1.6	47.8	8.1	28.9	8.7	1.4	3.5
Dec	WBM	30.5	62.1	7.4	<0.1	-	-	-
	SBM	<0.1	1.1	25.7	61.5	7.7	0.5	3.5

Note: due to rounding some row percentage totals may not exactly equal 100.

Mean and maximum WBM and SBM cuttings thicknesses are reported in Table 4-2. Maximum WBM cuttings thicknesses range from about 2.7 to 2.8 m all located directly at the well site origin. These maximum thicknesses or heights do not account for slumping of the cuttings 'pile'. Assuming a likely angle of repose of approximately 30°, one might estimate a maximum height more likely on the order of 0.7 to 1.4 m. Maximum thickness values fall to about 0.21 to 0.26 m within 100 m. Mean WBM cuttings thicknesses within 100 m are about 19 mm in all months. Mean SBM cuttings thicknesses out to 200 m generally range from 1 to 10 mm with the exception in September, that with very light currents, the mean thickness is 37 mm within 10 m of the wellhead. The predicted maximum SBM cuttings thicknesses are all located to the south-southwest: a) March, 47 mm at 130 m from the wellhead; b) June, 38 mm at 150 m; c) September, 48 mm at the wellhead; d) December, 42 mm at 210 m.

At the EL-1144 Deepwater Jurassic Example Well location, the predicted areas of total cuttings thickness above the 1.5 mm threshold are confined to an average size, over the four months, of about 550 m by 280 m oriented to the south-southwest. The areas are generally offset about 50 to 100 m to the north of the wellhead. The largest area is about 700 m by 260 m in September. The predicted areas of total cuttings thickness above the 6.5 mm threshold are about an average size of 400 m by 150 m in March, June and December; in September the area is smaller, about 180 m by 150 m, and symmetrical about the wellhead in evidence of the light currents.

Table 4-2 Cuttings Thickness by Distance, EL-1144 Deepwater Jurassic Example Well

EL-1144 Deepwater		Distance from Well Site					
		0-10m	10-100m	100-200m	200-500m	500m-1km	1-2km
Cuttings Type		Cuttings Thickness (mm)					
	March						
WBM	Mean	716	19	1	1	-	-
	Maximum	2,760	257	7	1	-	-
SBM	Mean	0.4	2	8	2	0.2	0.1
	Maximum	1	24	47	31	1	0.2
	June						
WBM	Mean	793	18	1	1	-	-
	Maximum	2,874	210	5	1	-	-
SBM	Mean	10	6	3	1	0.1	0.1
	Maximum	12	21	38	22	1	0.4
	September						
WBM	Mean	712	19	2	1	-	-
	Maximum	2,742	244	19	1	-	-
SBM	Mean	37	12	1	1	0.2	0.1
	Maximum	48	47	7	9	7	0.5
	December						
WBM	Mean	688	19	4	1	-	-
	Maximum	2,709	255	41	1	-	-
SBM	Mean	0.1	1	6	3	0.2	0.1
	Maximum	0.2	6	42	42	1	0.3

March

Figure 4-1 Total Drill Cuttings Deposition, EL-1144 Deepwater Jurassic Example Well, March, Project Area View

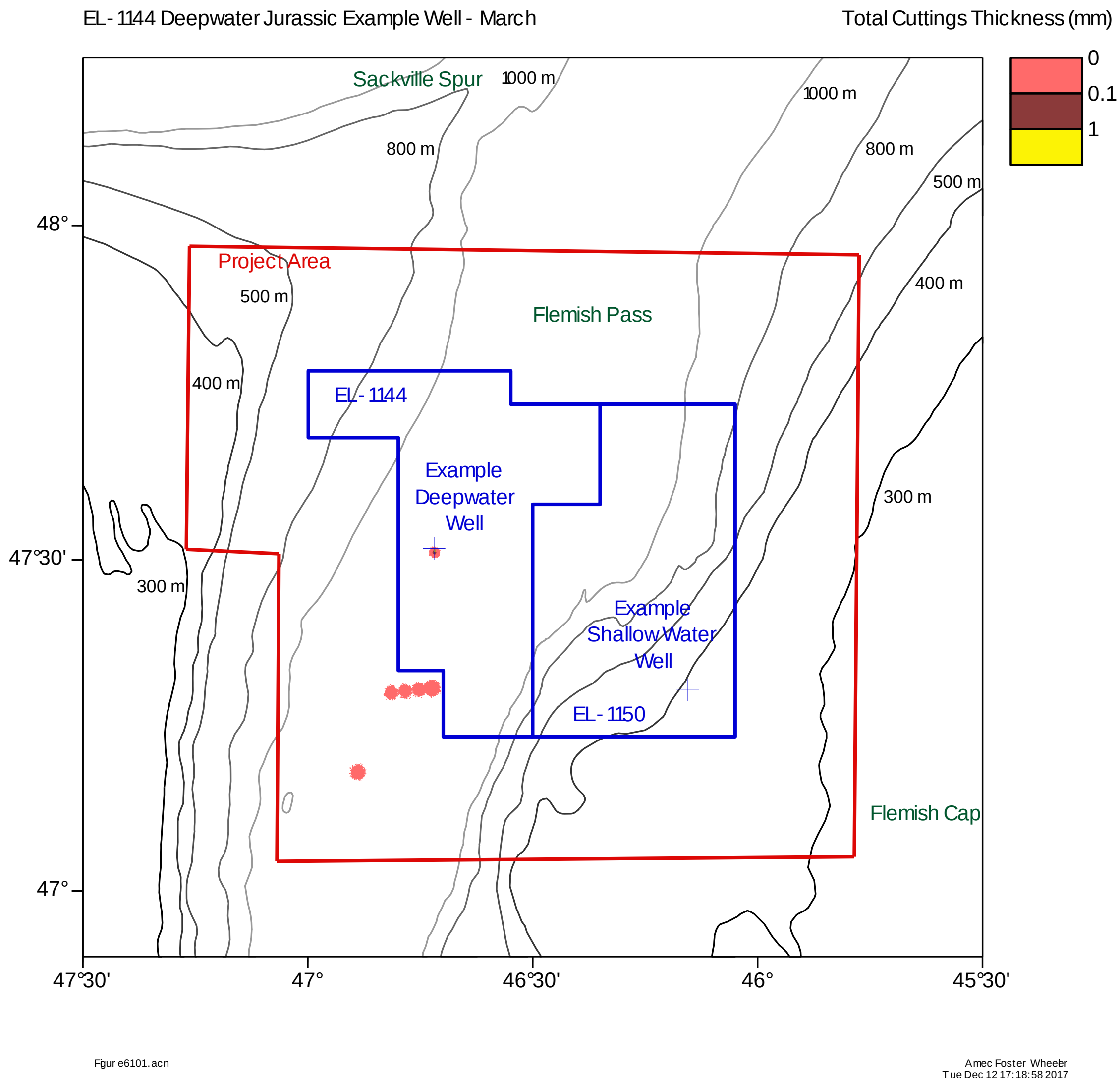


Figure 4-2 Total Drill Cuttings Deposition, EL-1144 Deepwater Jurassic Example Well, March, 1.5-km View

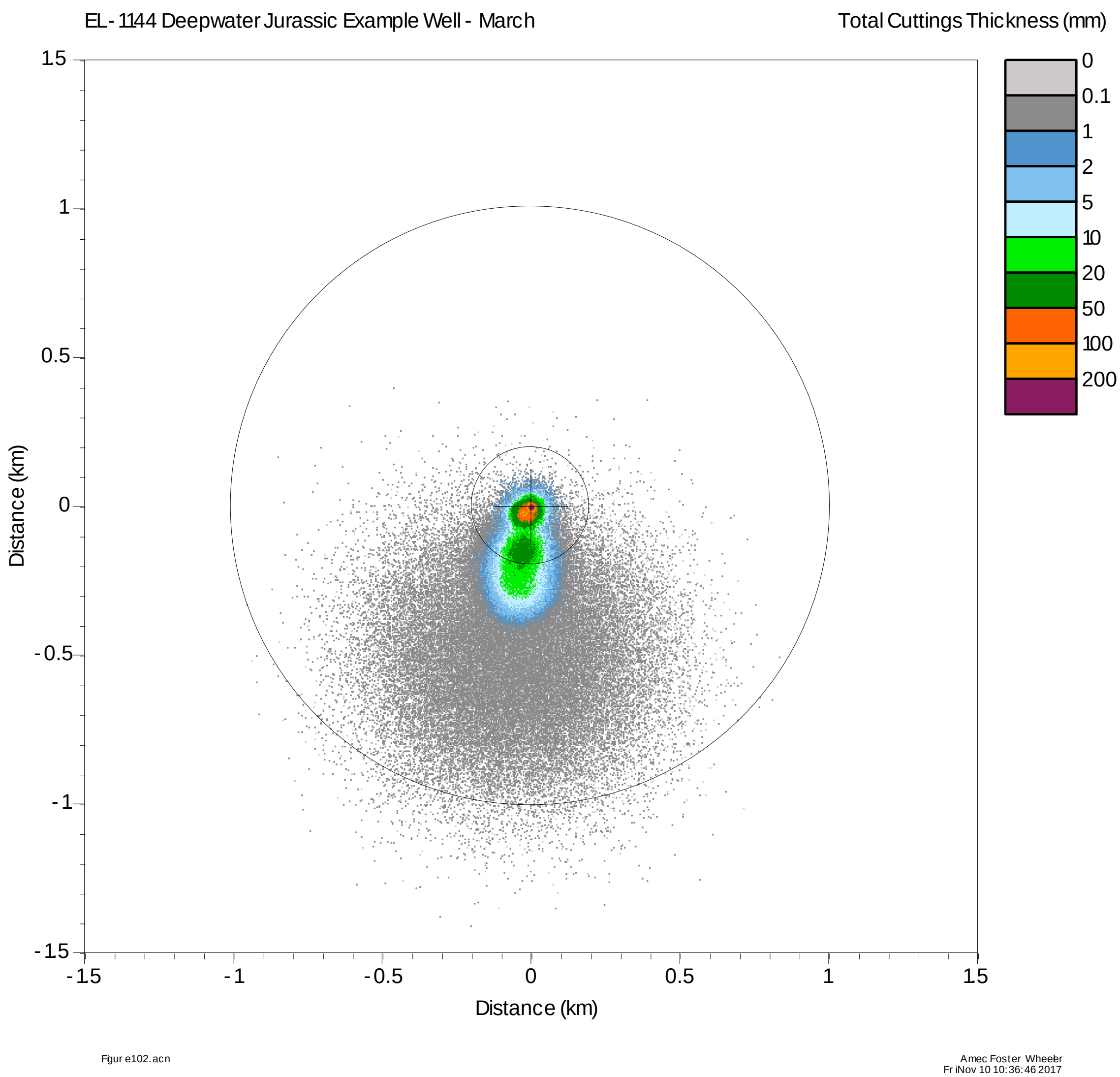


Figure 4-3 WBM Drill Cuttings Deposition, EL-1144 Deepwater Jurassic Example Well, March, 250-m View

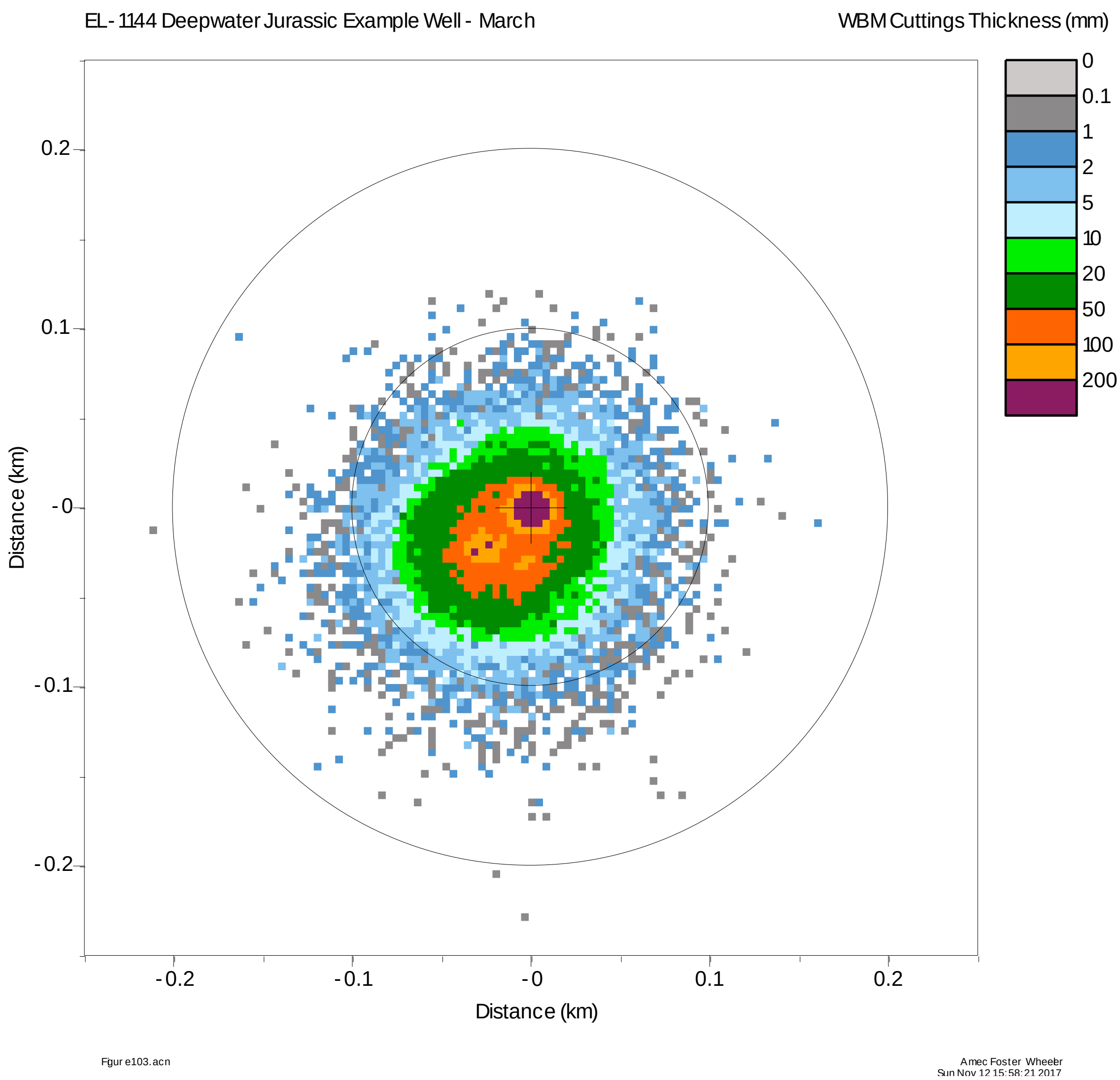


Figure 4-4 SBM Drill Cuttings Deposition, EL-1144 Deepwater Jurassic Example Well, March, 1.5-km View

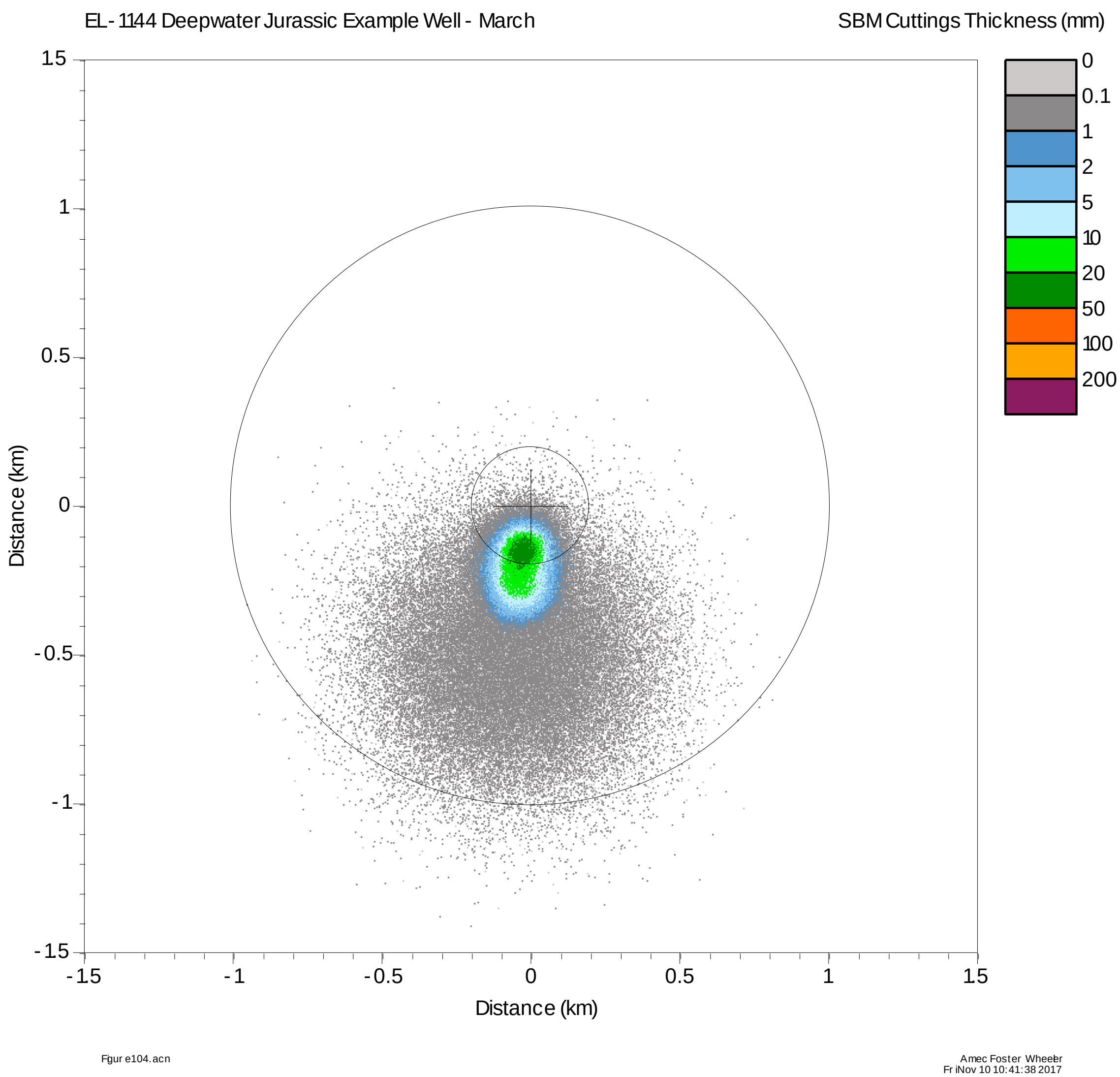
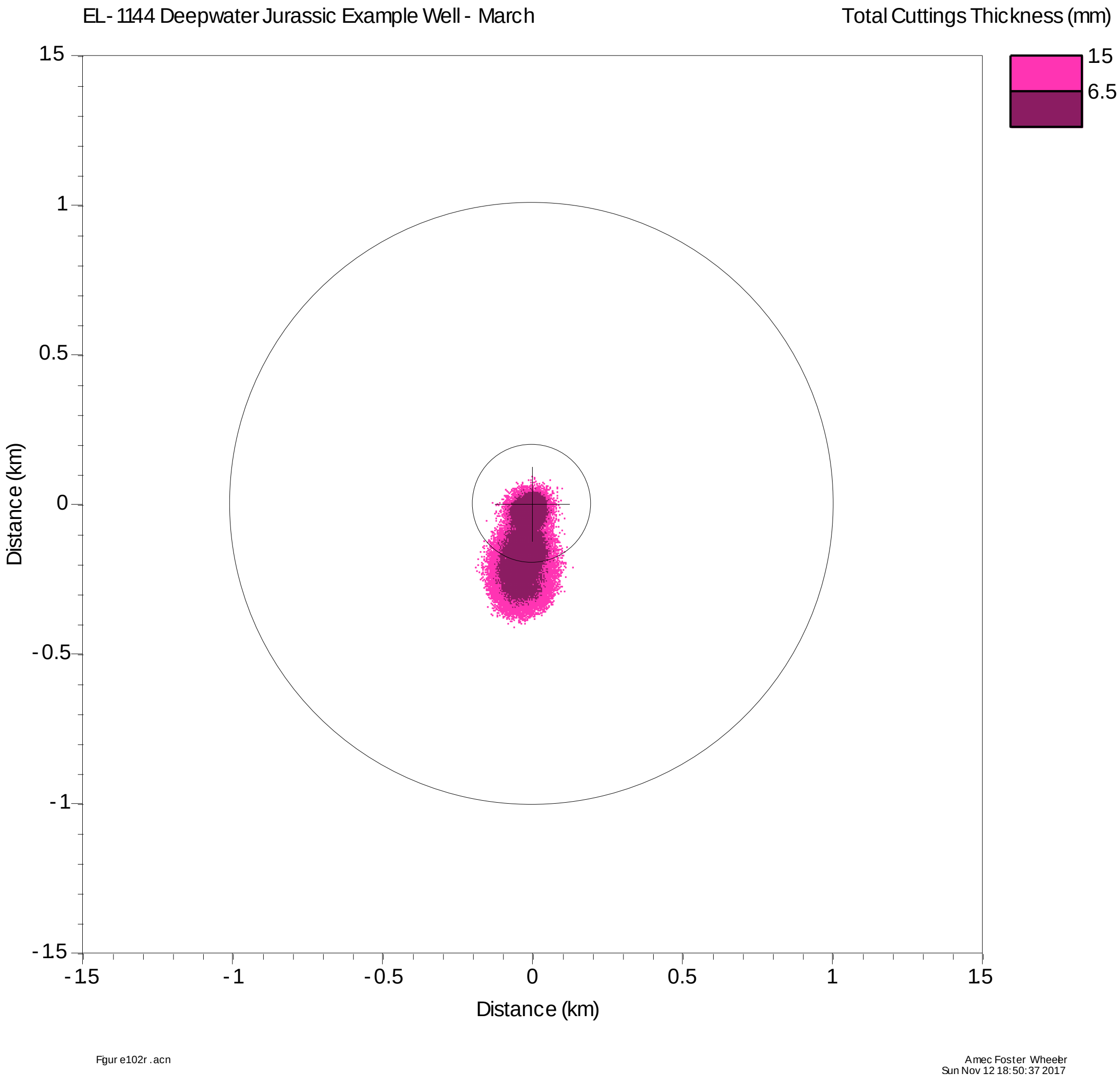


Figure 4-5 Total Drill Cuttings Deposition, PNET Limits, EL-1144 Deepwater Jurassic Example Well, March, 1.5-km View



June

Figure 4-6 Total Drill Cuttings Deposition, EL-1144 Deepwater Jurassic Example Well, June, Project Area View

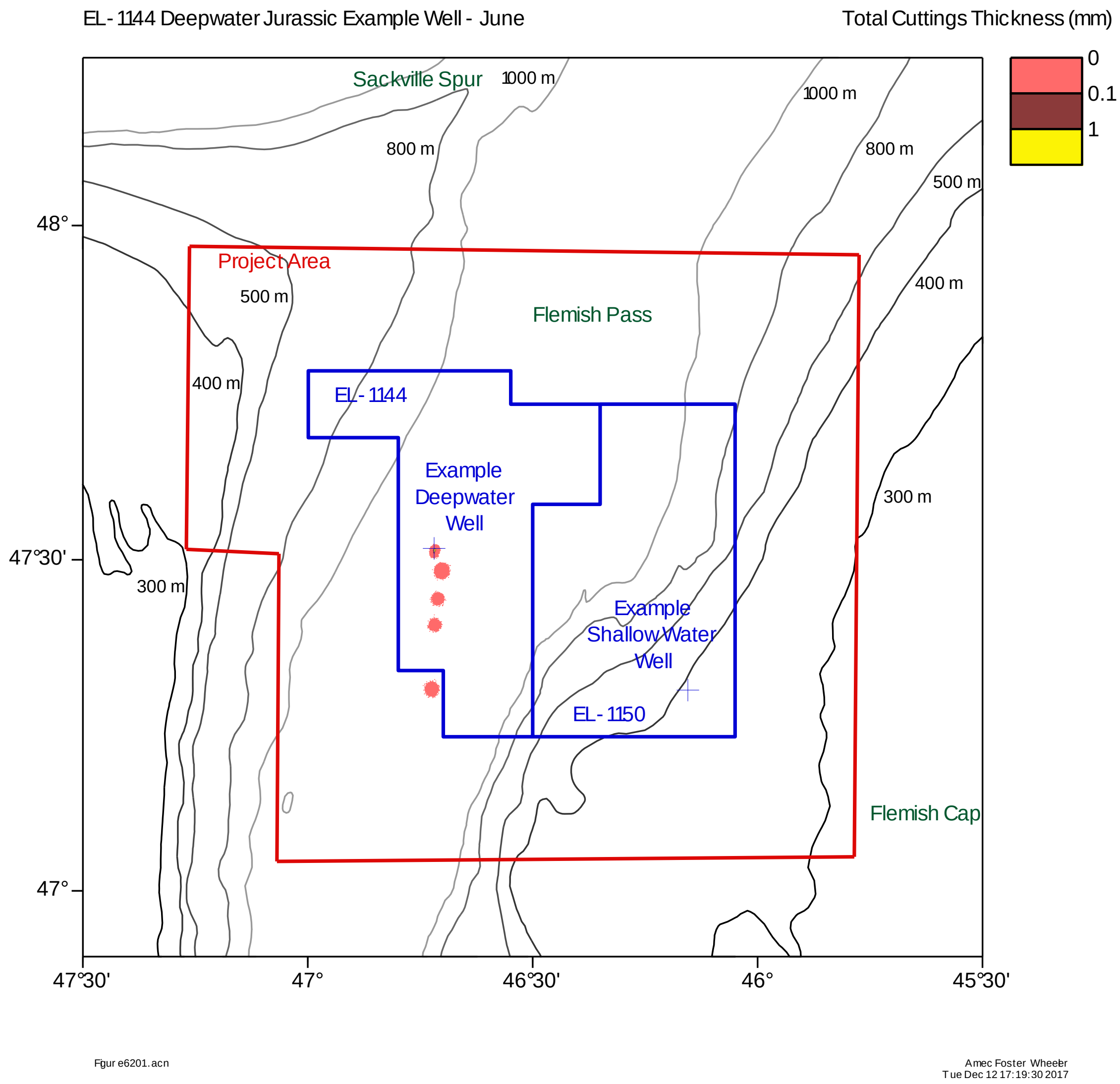


Figure 4-7 Total Drill Cuttings Deposition, EL-1144 Deepwater Jurassic Example Well, June, 1.5-km View

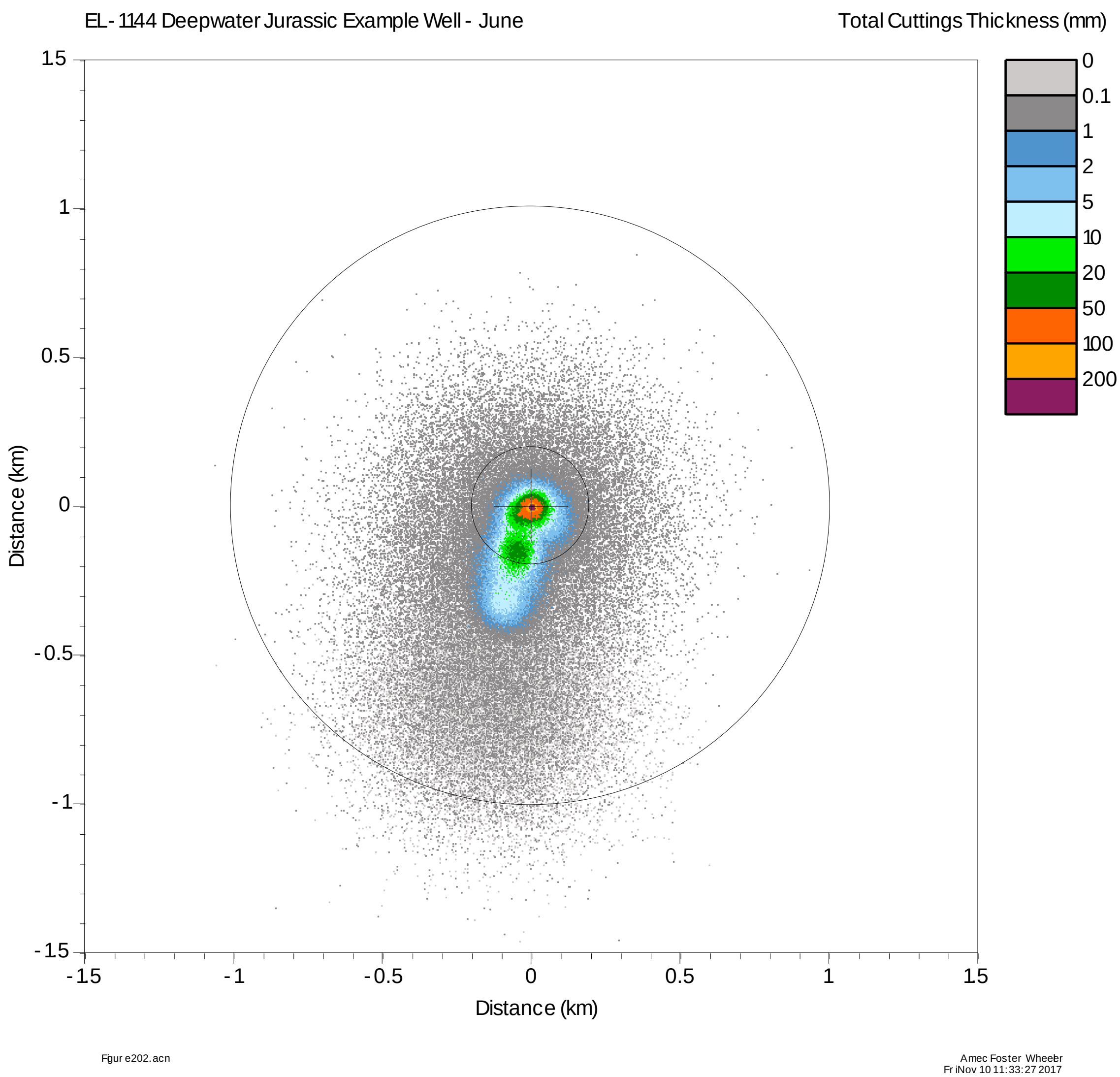


Figure 4-8 WBM Drill Cuttings Deposition, EL-1144 Deepwater Jurassic Example Well, June, 250-m View

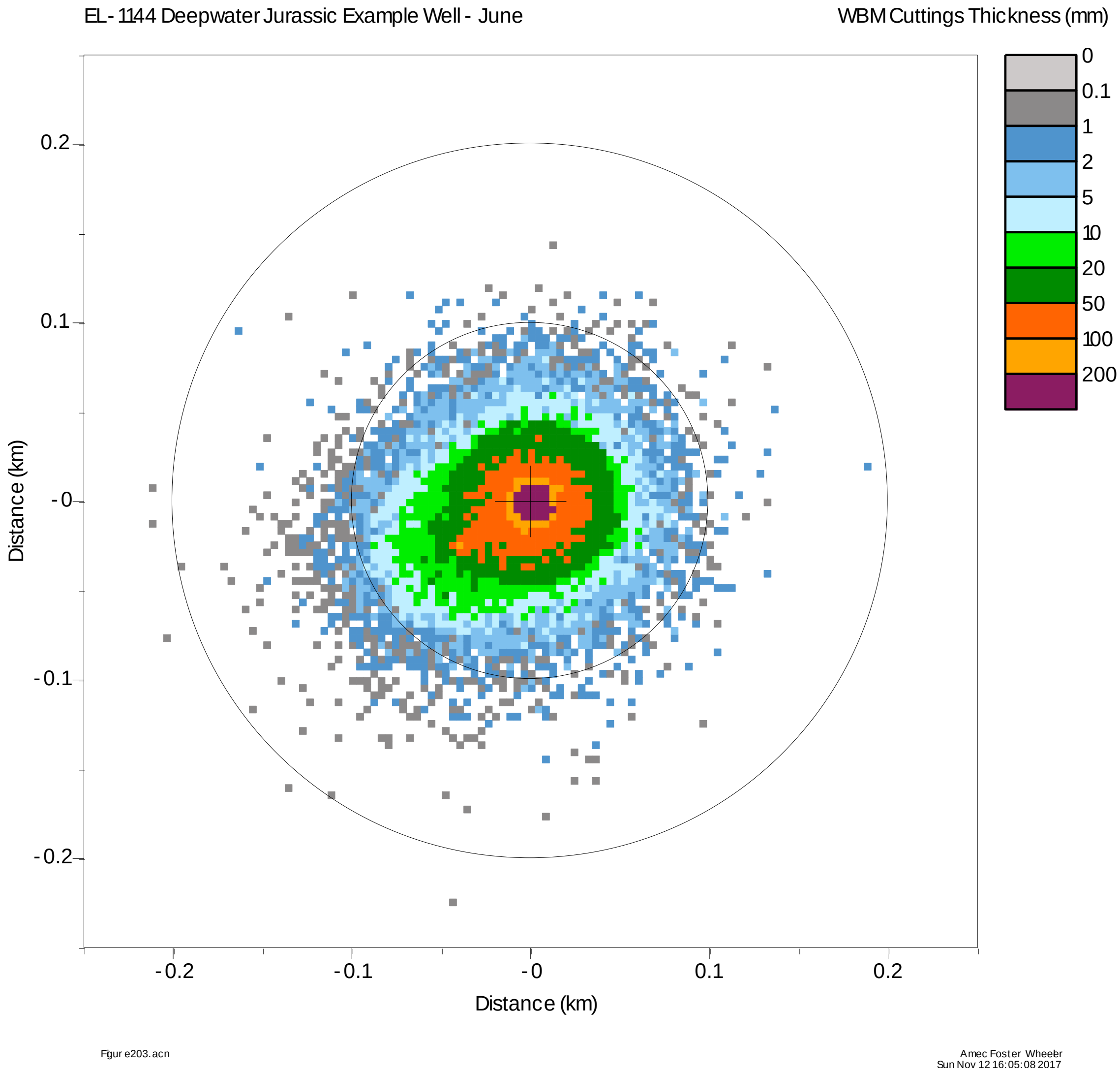


Figure 4-9 SBM Drill Cuttings Deposition, EL-1144 Deepwater Jurassic Example Well, June, 1.5-km View

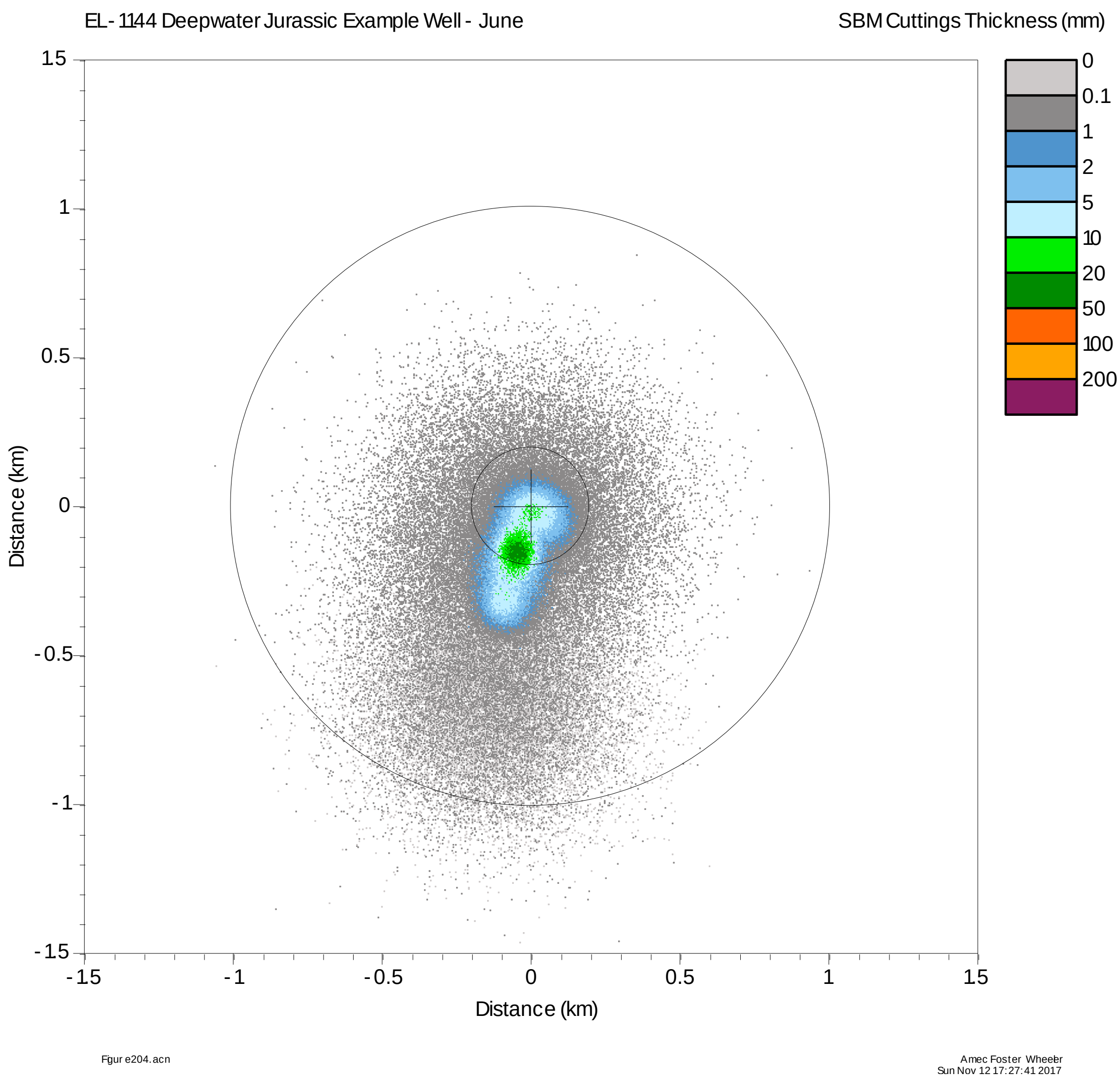
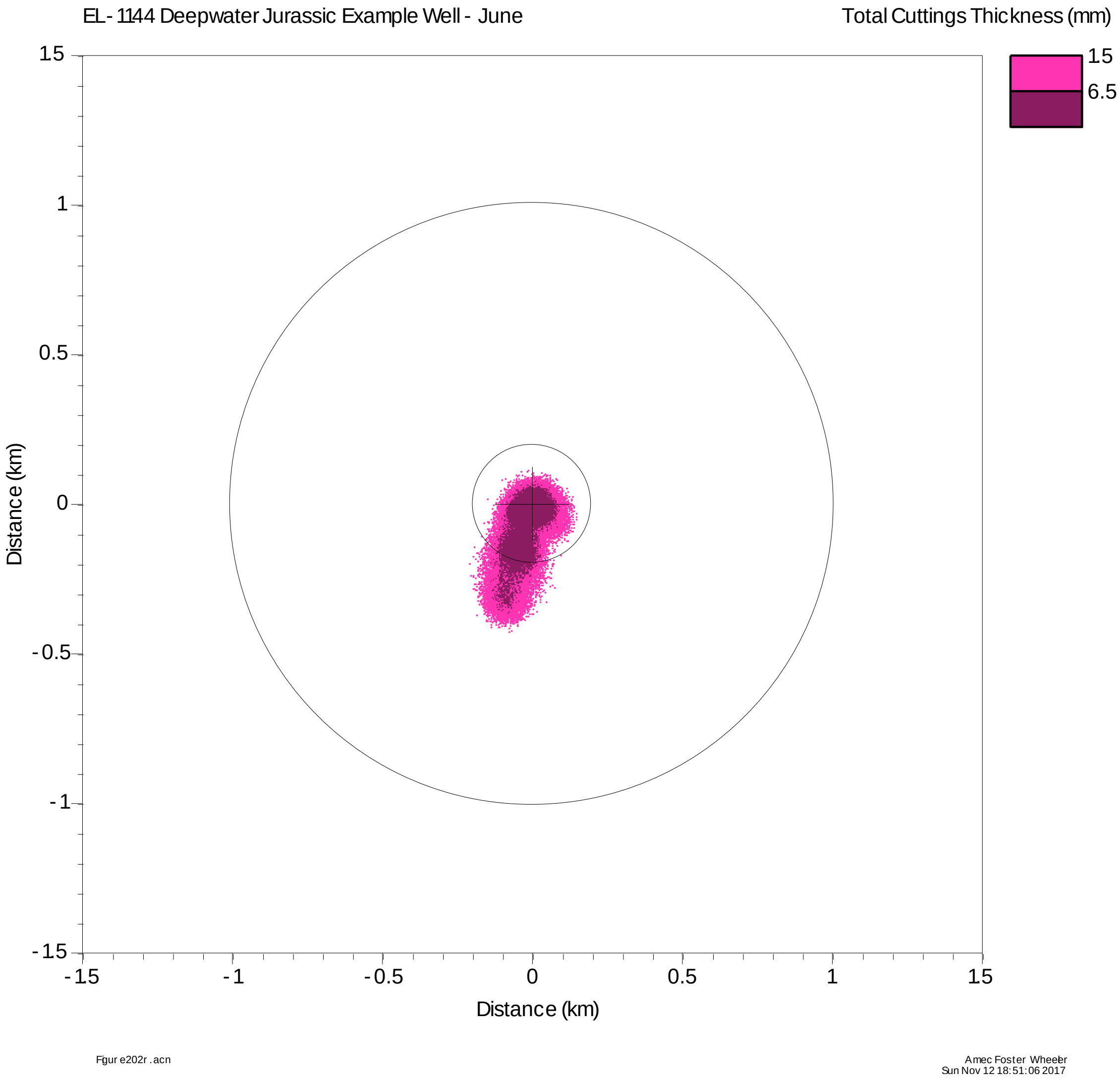


Figure 4-10 Total Drill Cuttings Deposition, PNET Limits, EL-1144 Deepwater Jurassic Example Well, June, 1.5-km View



September

Figure 4-11 Total Drill Cuttings Deposition, EL-1144 Deepwater Jurassic Example Well, September, Project Area View

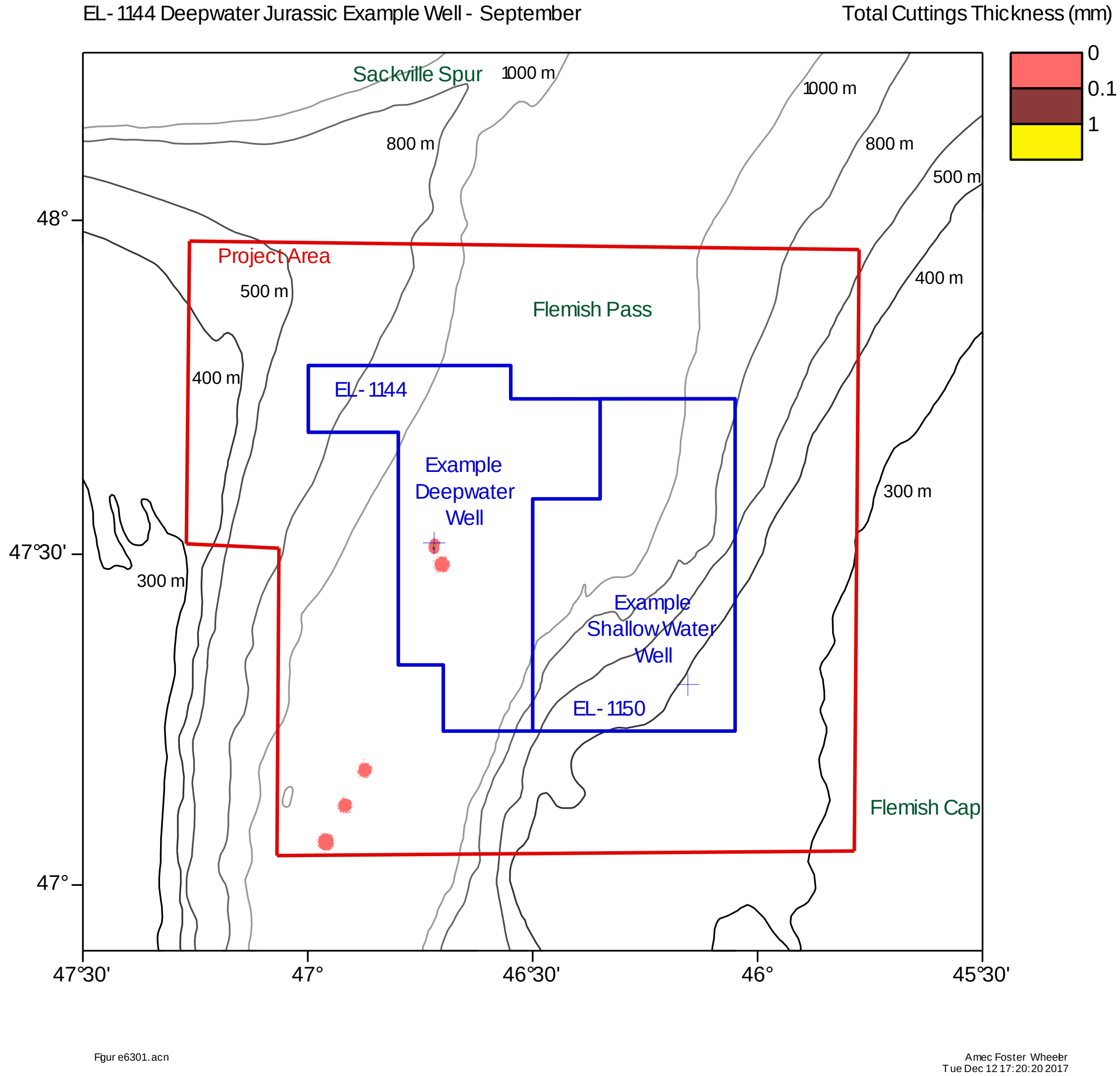


Figure 4-12 Total Drill Cuttings Deposition, EL-1144 Deepwater Jurassic Example Well, September, 1.5-km View

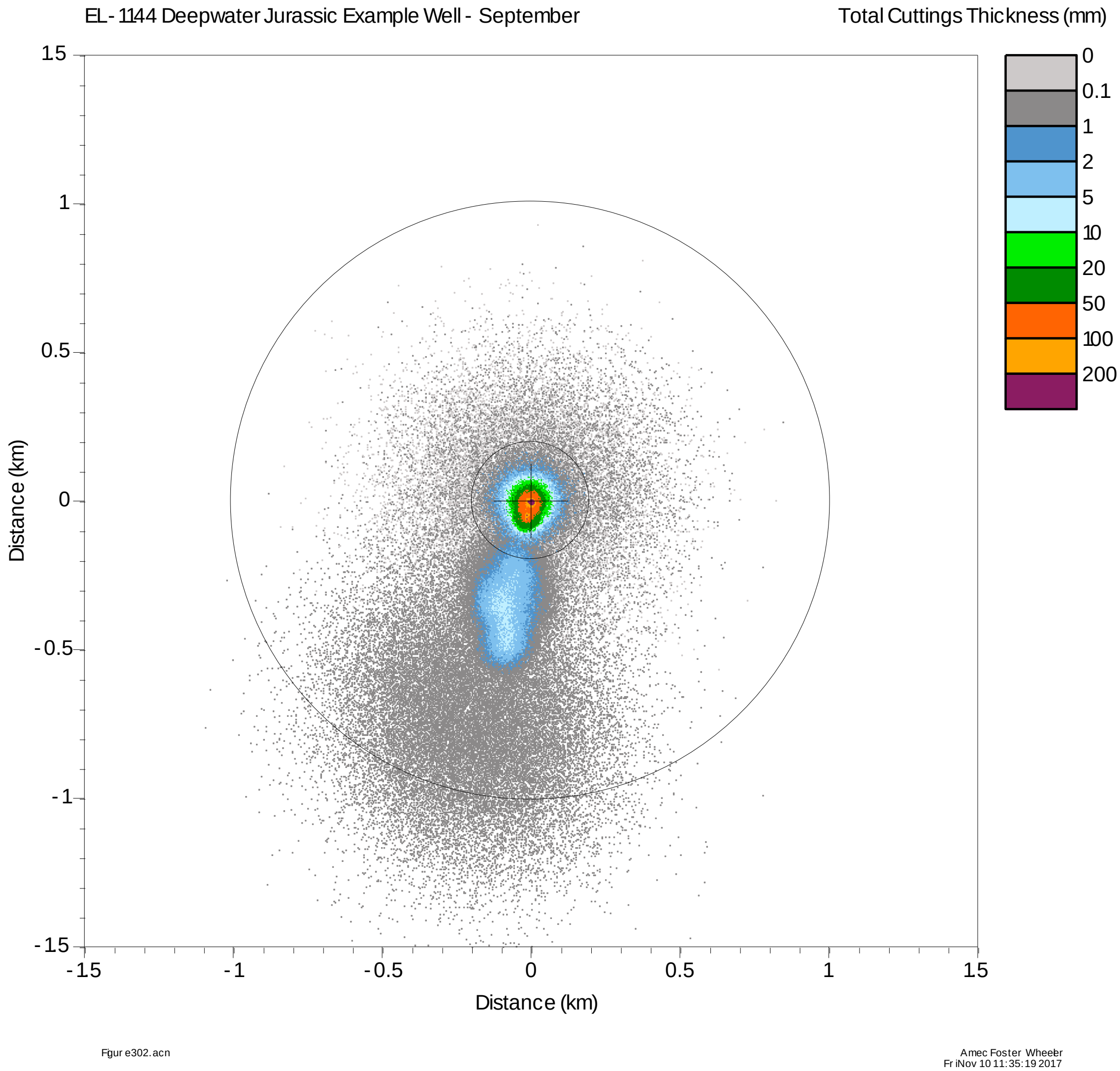


Figure 4-13 WBM Drill Cuttings Deposition, EL-1144 Deepwater Jurassic Example Well, September, 250-m View

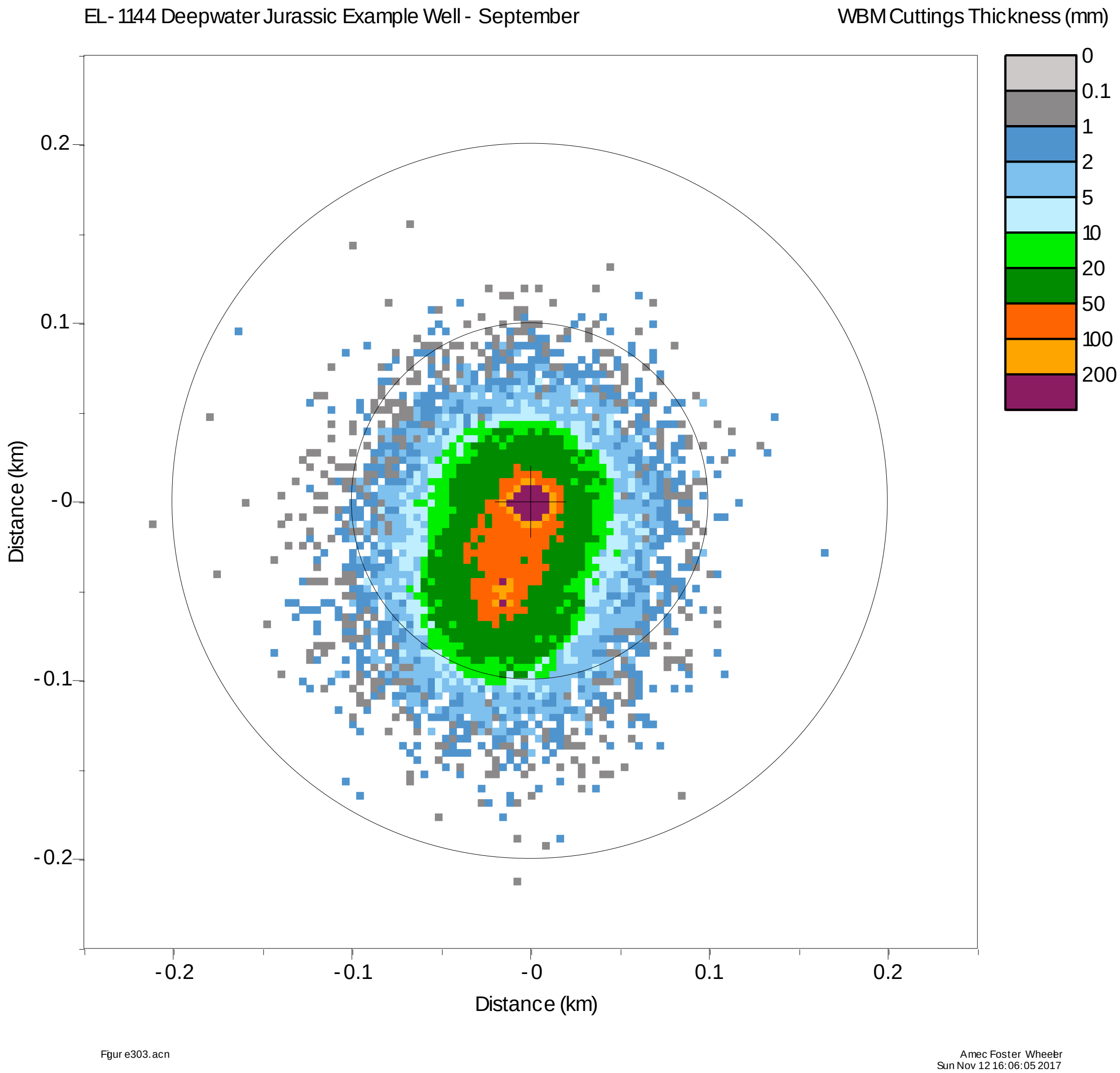


Figure 4-14 SBM Drill Cuttings Deposition, EL-1144 Deepwater Jurassic Example Well, September, 1.5-km View

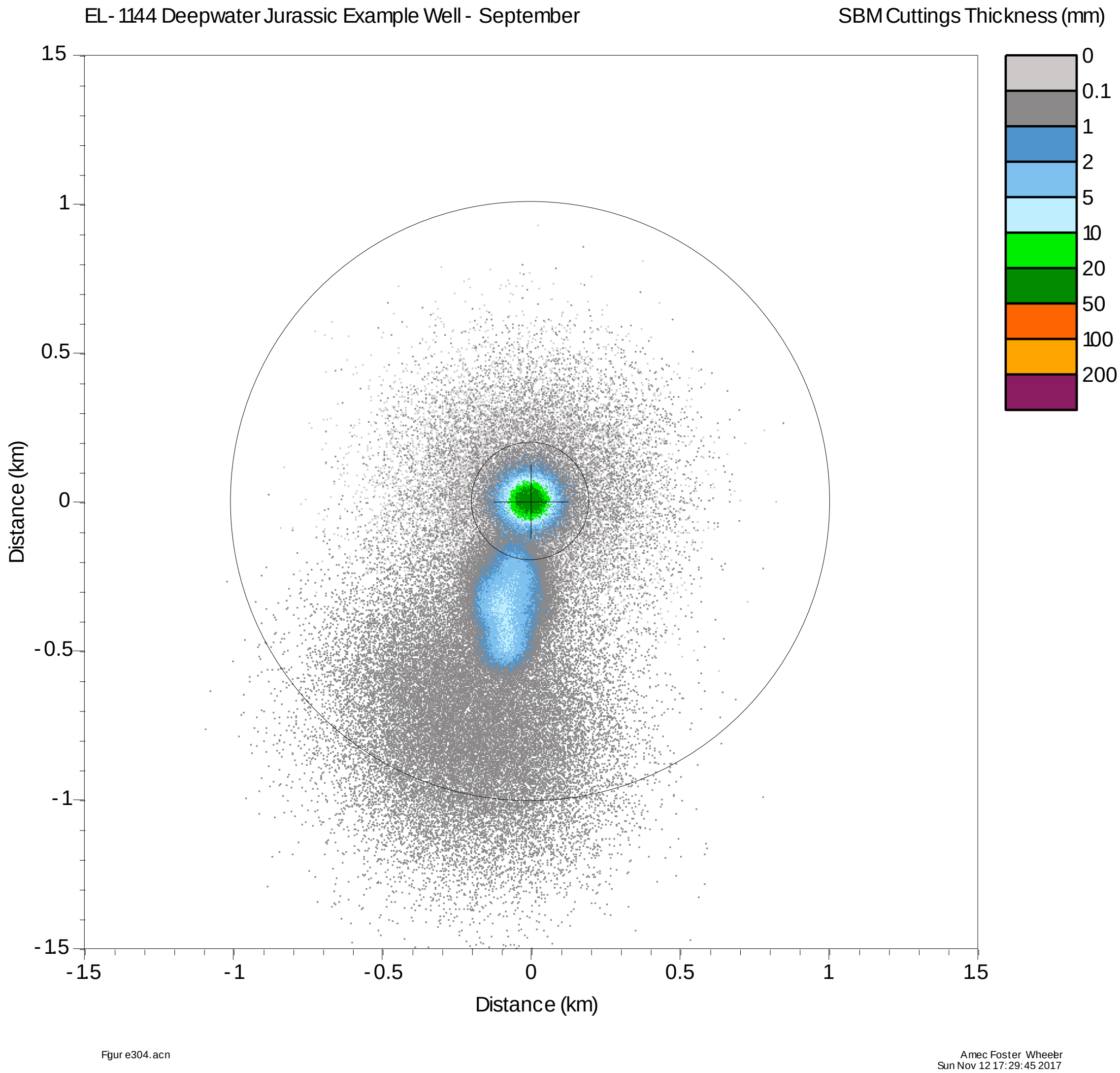
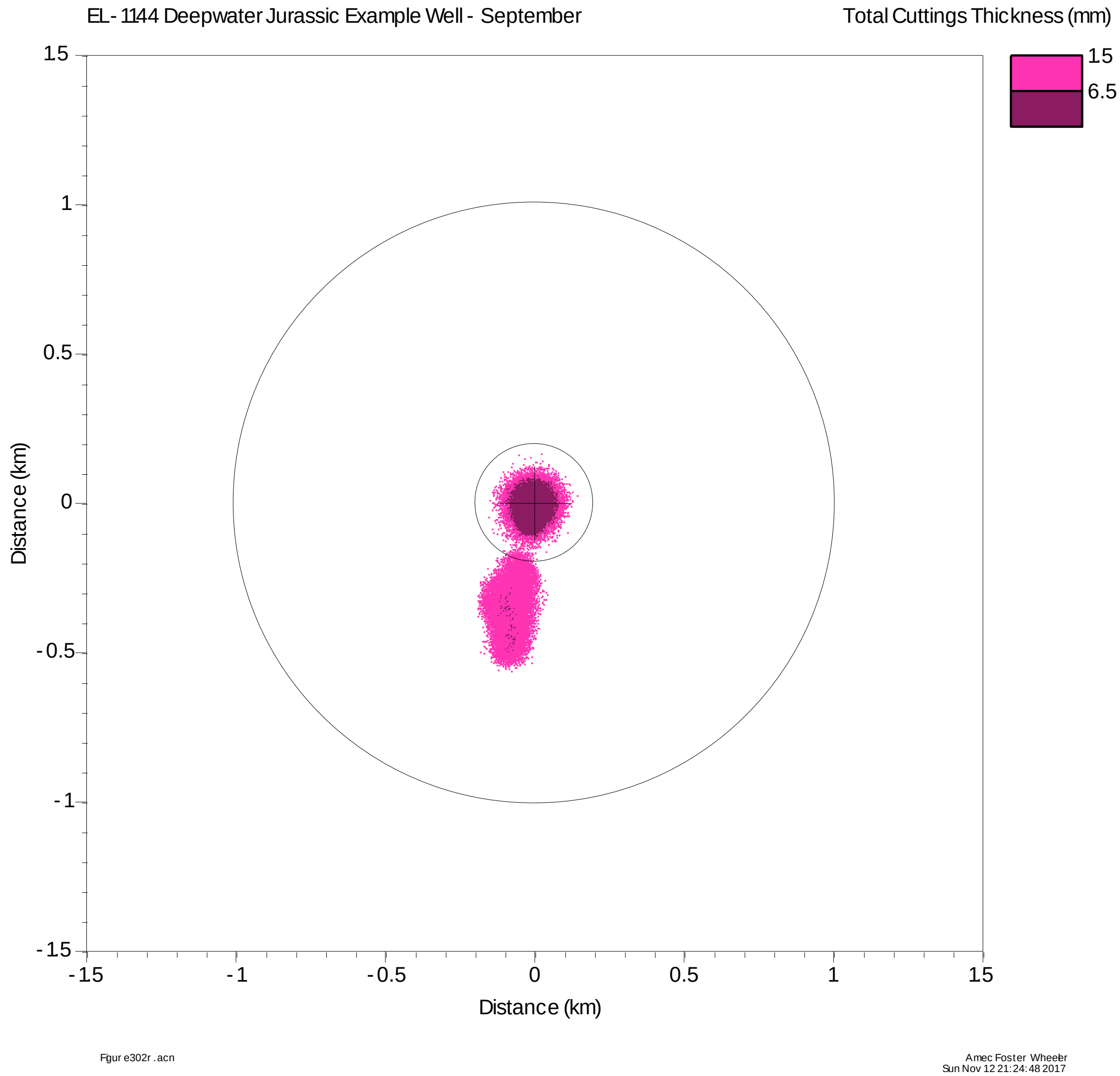


Figure 4-15 Total Drill Cuttings Deposition, PNET Limits, EL-1144 Deepwater Jurassic Example Well, September, 1.5-km View



December

Figure 4-16 Total Drill Cuttings Deposition, EL-1144 Deepwater Jurassic Example Well, December, Project Area View

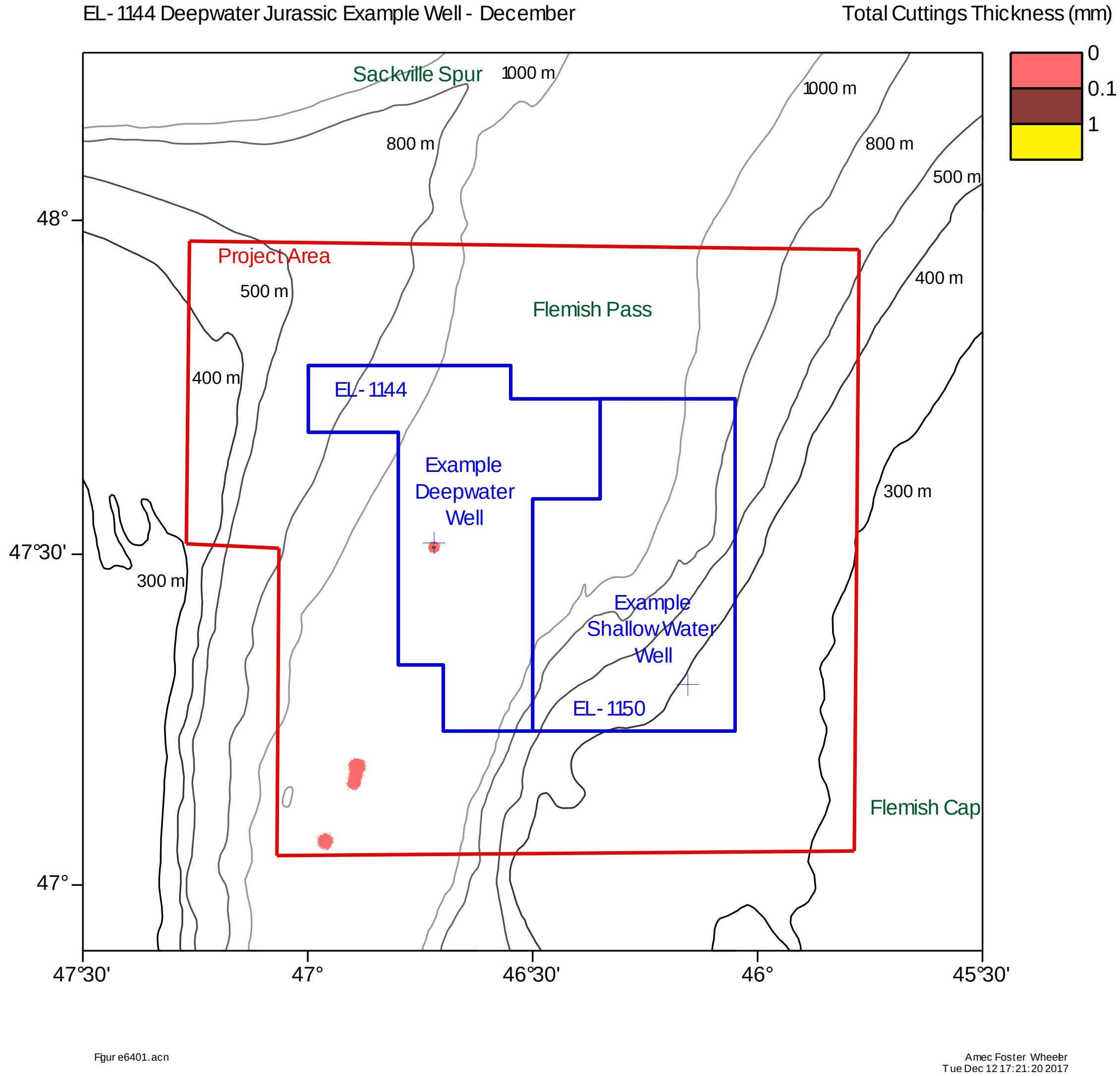


Figure 4-17 Total Drill Cuttings Deposition, EL-1144 Deepwater Jurassic Example Well, December, 1.5-km View

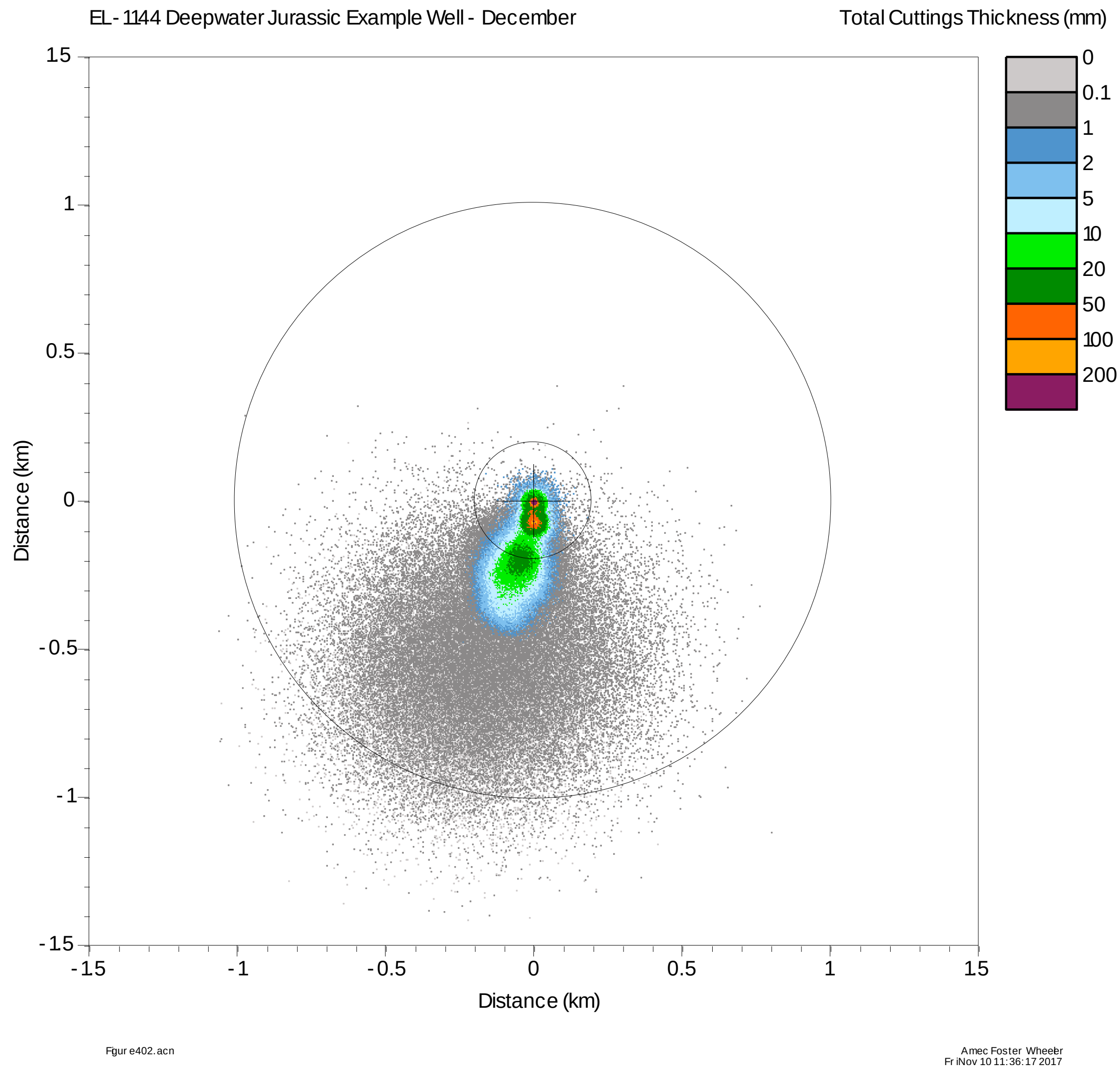


Figure 4-18 WBM Drill Cuttings Deposition, EL-1144 Deepwater Jurassic Example Well, December, 250-m View

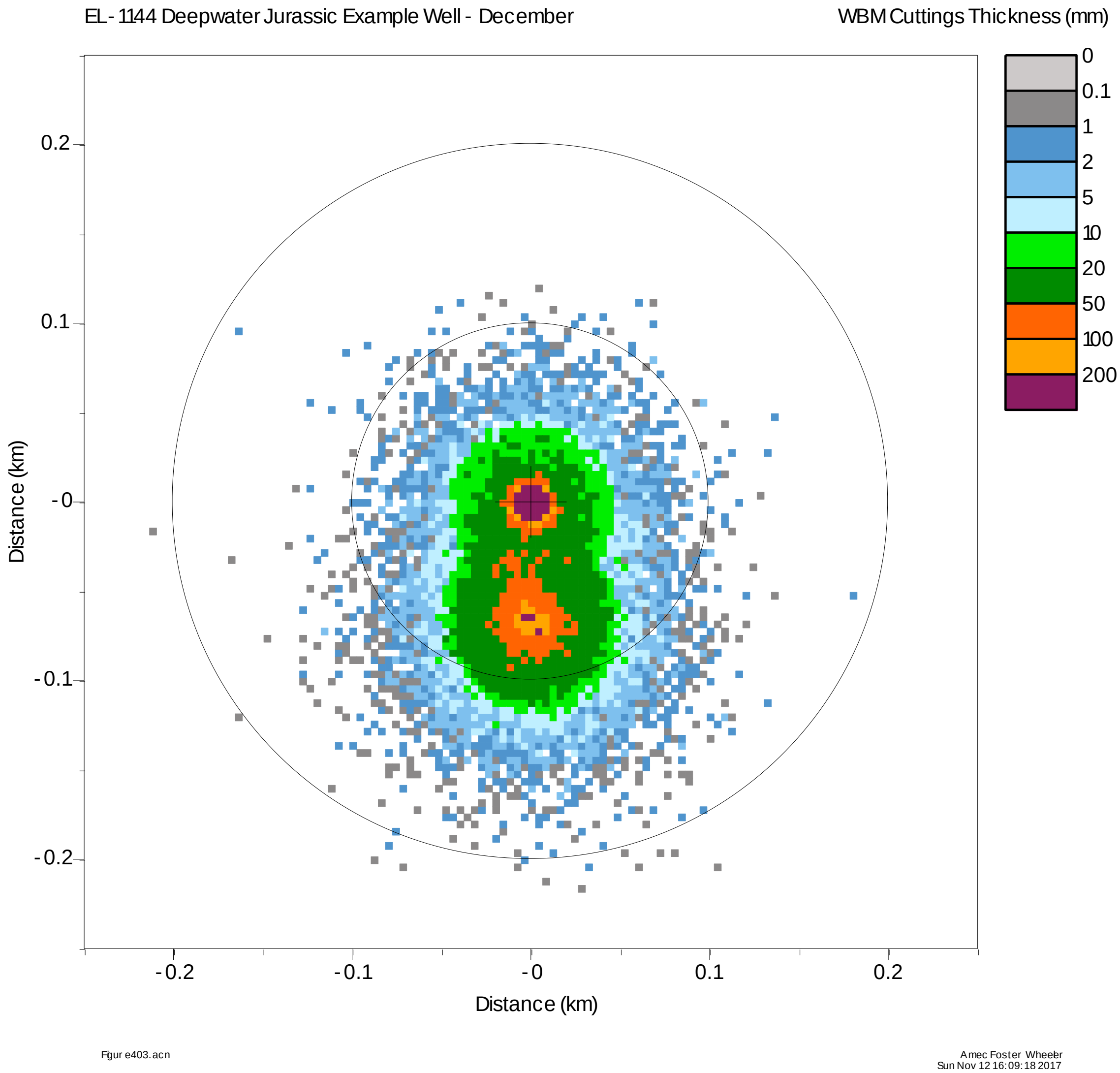


Figure 4-19 SBM Drill Cuttings Deposition, EL-1144 Deepwater Jurassic Example Well, December, 1.5-km View

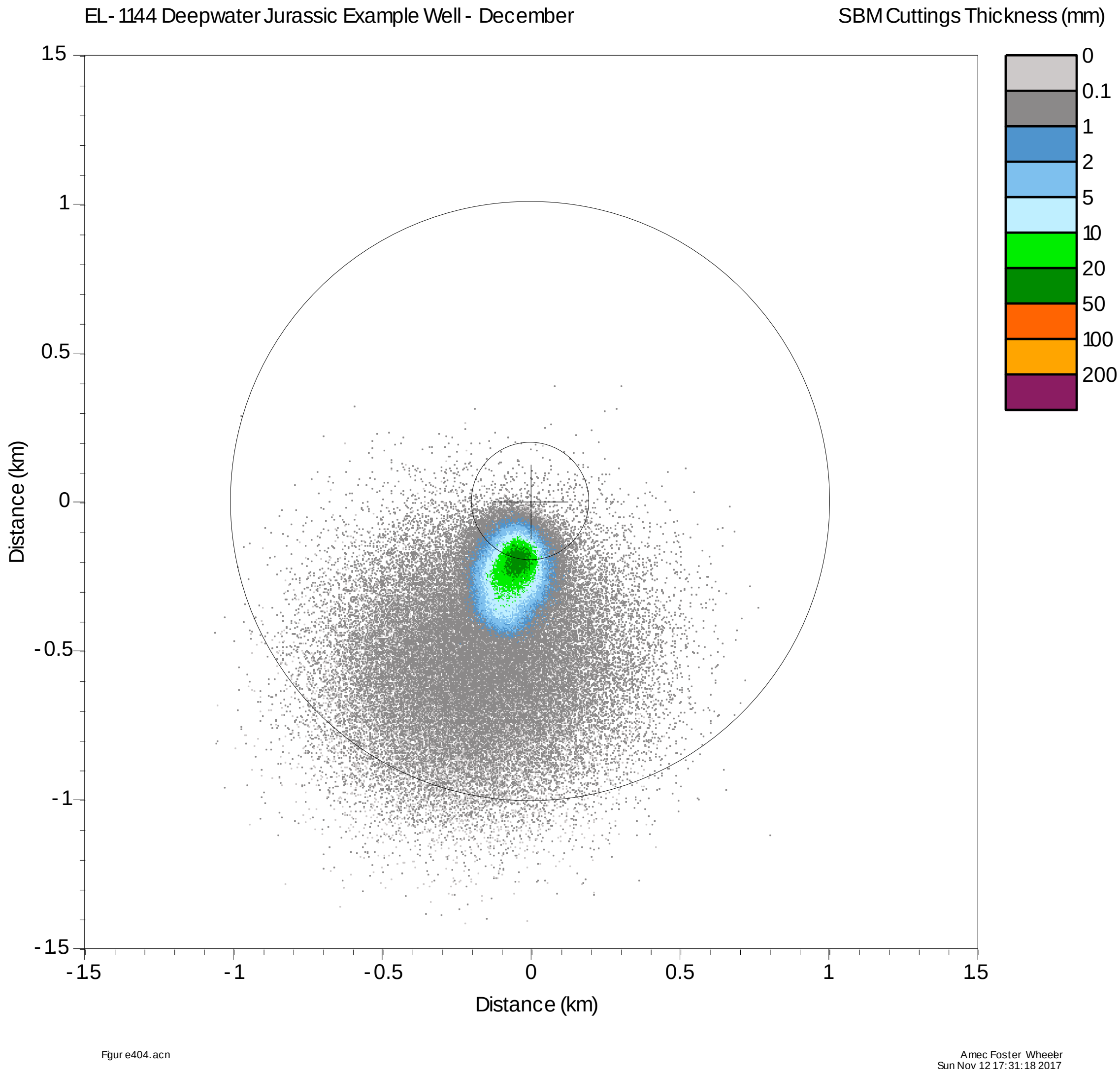
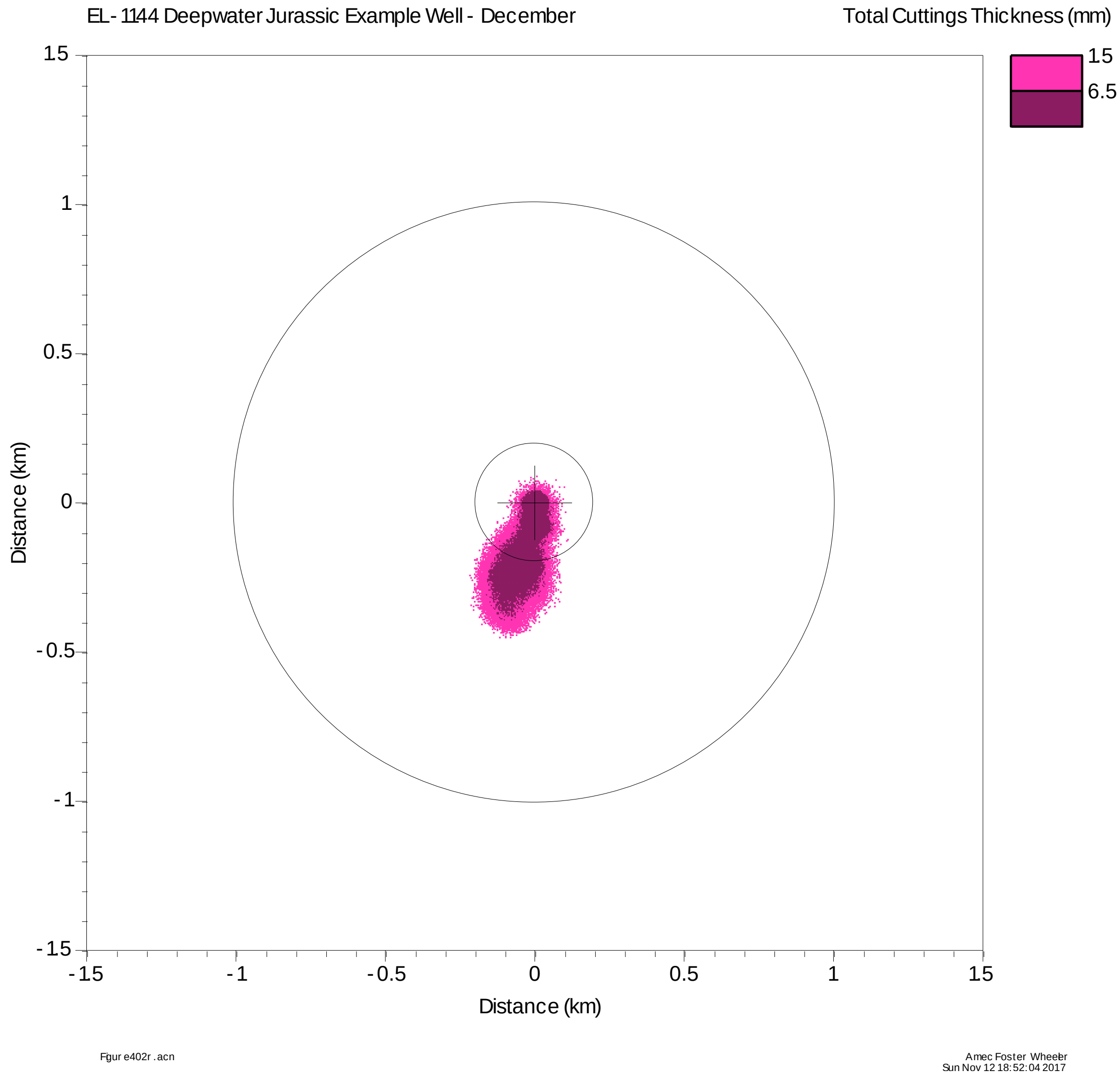


Figure 4-20 Total Drill Cuttings Deposition, PNET Limits, EL-1144 Deepwater Jurassic Example Well, December, 1.5-km View



4.2 EL-1150 Shallow Water Cretaceous Example Well

This section presents results of cuttings modelling for the EL-1150 location. Four seasonal scenarios are presented with drilling of wells commencing in March, June, September and December.

For all months over 99 percent of all WBM cuttings released at the wellhead are predicted to settle within 200 m (Table 4-3). The WBM cuttings are predicted to drift as far as 260 m in March and 240 m during the other months.

The SBM cuttings released from the MODU at the sea surface settle generally within 1 km, with over 94 percent settling within 500 m. The farthest these cuttings settle, within 1 km ranges from 720 m in September to 940 m in March and December. Only 3.6 percent of the total SBM cuttings from one well drift farther away, and with all of these settling with thicknesses less than 0.1 mm. These small amounts of fine sand and silt-sized SBM cuttings are predicted to drift to the northeast: up to about 18 km in March (Figure 4-21), 15 km in June (Figure 4-26), 12 km in September (Figure 4-31) and 18 km in December (Figure 4-36). All cuttings settle therefore within the 64 km model domain.

Table 4-3 Cuttings Material Settled by Distance, EL-1150 Shallow Water Cretaceous Example Well

EL-1150 Shallow Water		Distance from Well Site						
		0-10m	10-100m	100-200m	200-500m	500m-1km	1-2km	
Month	Cuttings Type	% Material Settled						% Material Unsettled
Mar	WBM	30.6	58.4	11.0	0.1	-	-	-
	SBM	<0.1	14.6	56.3	23.1	2.3	-	3.6
Jun	WBM	30.9	65.5	3.5	<0.1	-	-	-
	SBM	1.4	62.4	24.1	8.2	0.4	-	3.6
Sep	WBM	31.6	66.7	1.6	<0.1	-	-	-
	SBM	2.4	76.0	11.6	6.4	0.1	-	3.6
Dec	WBM	30.7	58.8	10.4	<0.1	-	-	-
	SBM	0.7	45.3	28.5	19.3	2.6	-	3.6

Note: due to rounding some row percentage totals may not exactly equal 100.

Mean and maximum WBM and SBM cuttings thicknesses are reported in Table 4-4. Maximum WBM cuttings thicknesses are about 1.8 m, all located directly at the well site origin. These maximum thicknesses or heights do not account for slumping of the cuttings 'pile'. Assuming a likely angle of repose of approximately 30°, one might estimate a maximum height more likely on the order of 0.45 to 0.9 m. Maximum thickness values fall to about 0.18 to 0.21 m within 100 m. Mean WBM cuttings thicknesses within 100 m are 12 to 13 mm in all months.

Mean SBM cuttings thicknesses out to 100 m range from less than 1 mm in March to 43 mm in September (with the very light currents). The predicted maximum SBM cuttings thicknesses are located to the east in all months (except to the north in December): a) March, 87 mm at 120 m from the wellhead; b) June, 84 mm at 50 m; c) September, 99 mm at 40 m; d) December, 72 mm at 50 m.

At the EL-1150 Shallow Water Cretaceous Example Well location, the predicted areas of total cuttings thickness above the 1.5 mm threshold are confined to an average size, over the four months, of about 320 m by 220 m. These areas are oriented primarily to the east in March and June and to the north in September and northeast in December. The areas are generally offset about 50 to 100 m to the west, or south or southwest. The largest area is about 350 m by 240 m in December. The predicted areas of total cuttings thickness above the 6.5 mm threshold are similar in all months averaging 250 m by 150 m in size; the largest footprint is predicted in December at about 260 m by 180 m.

Table 4-4 Cuttings Thickness by Distance, EL-1150 Shallow Water Cretaceous Example Well

EL-1150 Shallow Water		**Distance from Well Site**					
		0-10m	**10-100m**	**100-200m**	**200-500m**	**500m-1km**	**1-2km**
Cuttings Type		**Cuttings Thickness (mm)**					
	March						
WBM	Mean	453	12	3	1	-	-
	Maximum	1,756	179	40	1	-	-
SBM	Mean	0.5	5	9	1	0.2	-
	Maximum	0.9	65	87	29	1	-
	June						
WBM	Mean	458	12	2	1	-	-
	Maximum	1,794	174	15	1		
SBM	Mean	25	12	2	0.3	0.1	-
	Maximum	35	84	37	7	0.5	-
	September						
WBM	Mean	468	13	1	1	-	
	Maximum	1,798	208	5	1	-	
SBM	Mean	43	15	1	0.2	0.1	-
	Maximum	62	99	19	1	0.2	-
	December						
WBM	Mean	454	12	4	1	-	
	Maximum	1,781	175	37	2	-	
SBM	Mean	13	11	3	0.6	0.2	-
	Maximum	26	72	28	13	1	-

March

Figure 4-21 Total Drill Cuttings Deposition, EL-1150 Shallow Water Cretaceous Example Well, March, Project Area View

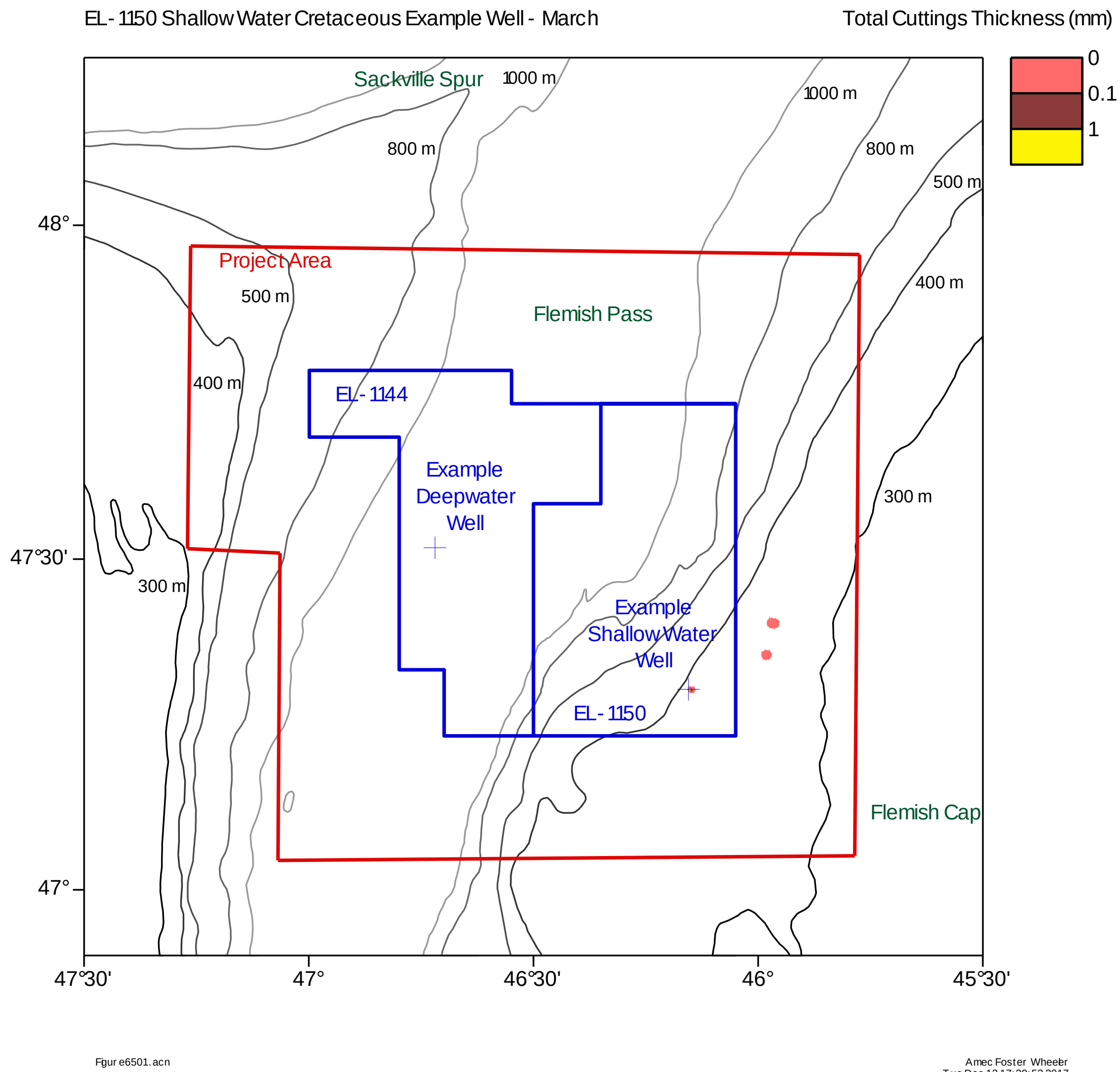


Figure 4-22 Total Drill Cuttings Deposition, EL-1150 Shallow Water Cretaceous Example Well, March, 1.5-km View

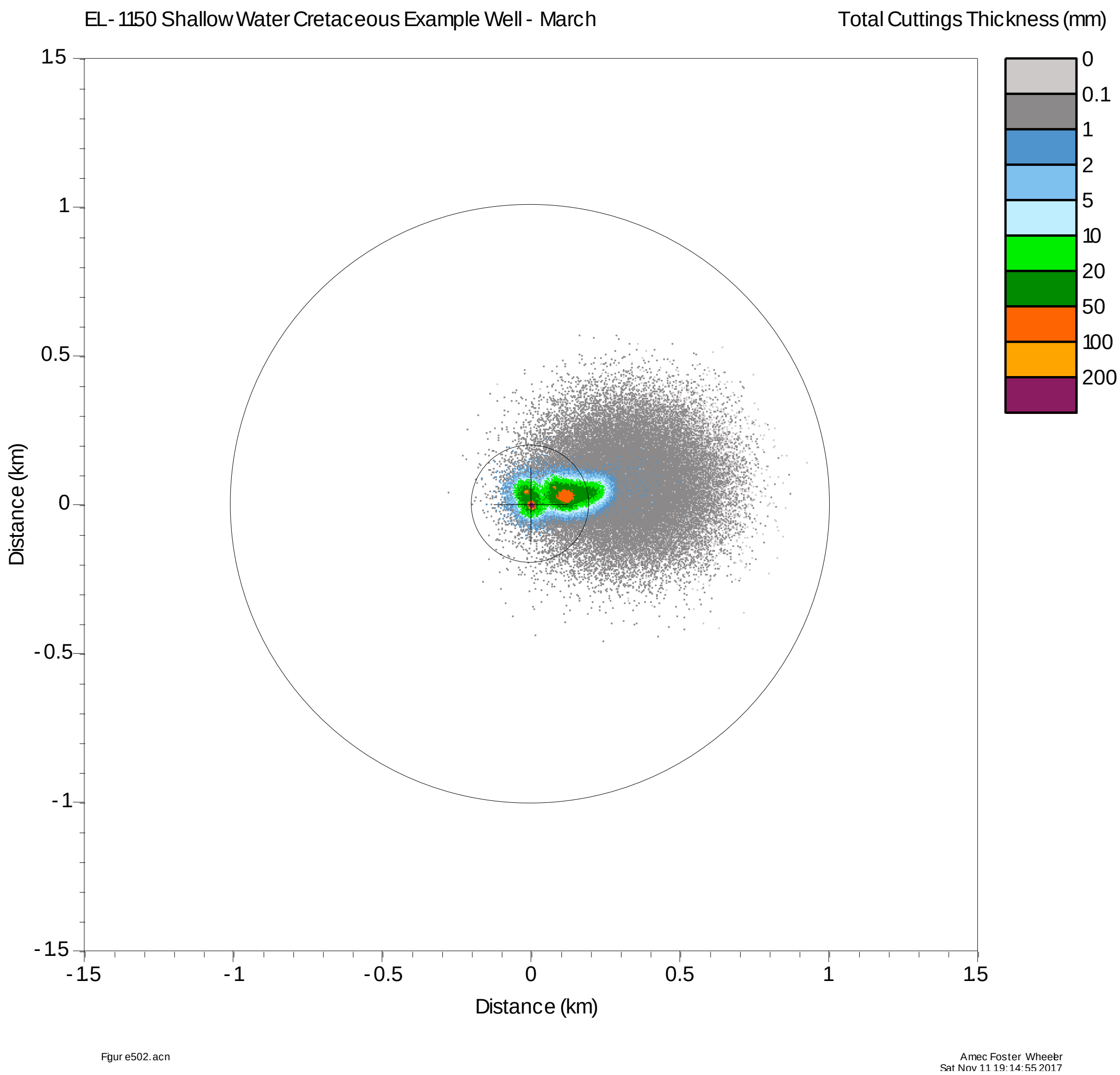


Figure 4-23 WBM Drill Cuttings Deposition, EL-1150 Shallow Water Cretaceous Example Well, March, 250-m View

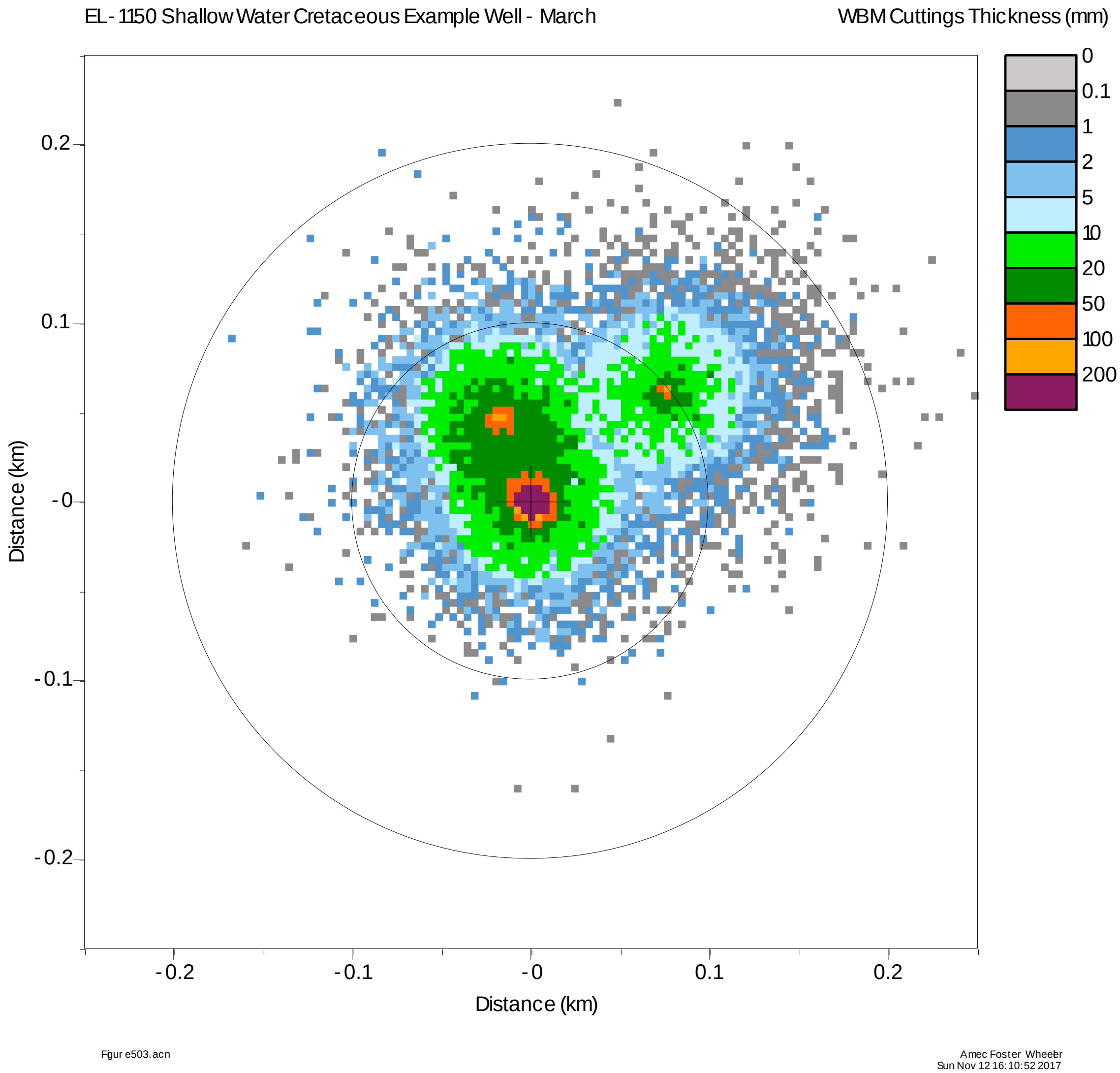


Figure 4-24 SBM Drill Cuttings Deposition, EL-1150 Shallow Water Cretaceous Example Well, March, 1.5-km View

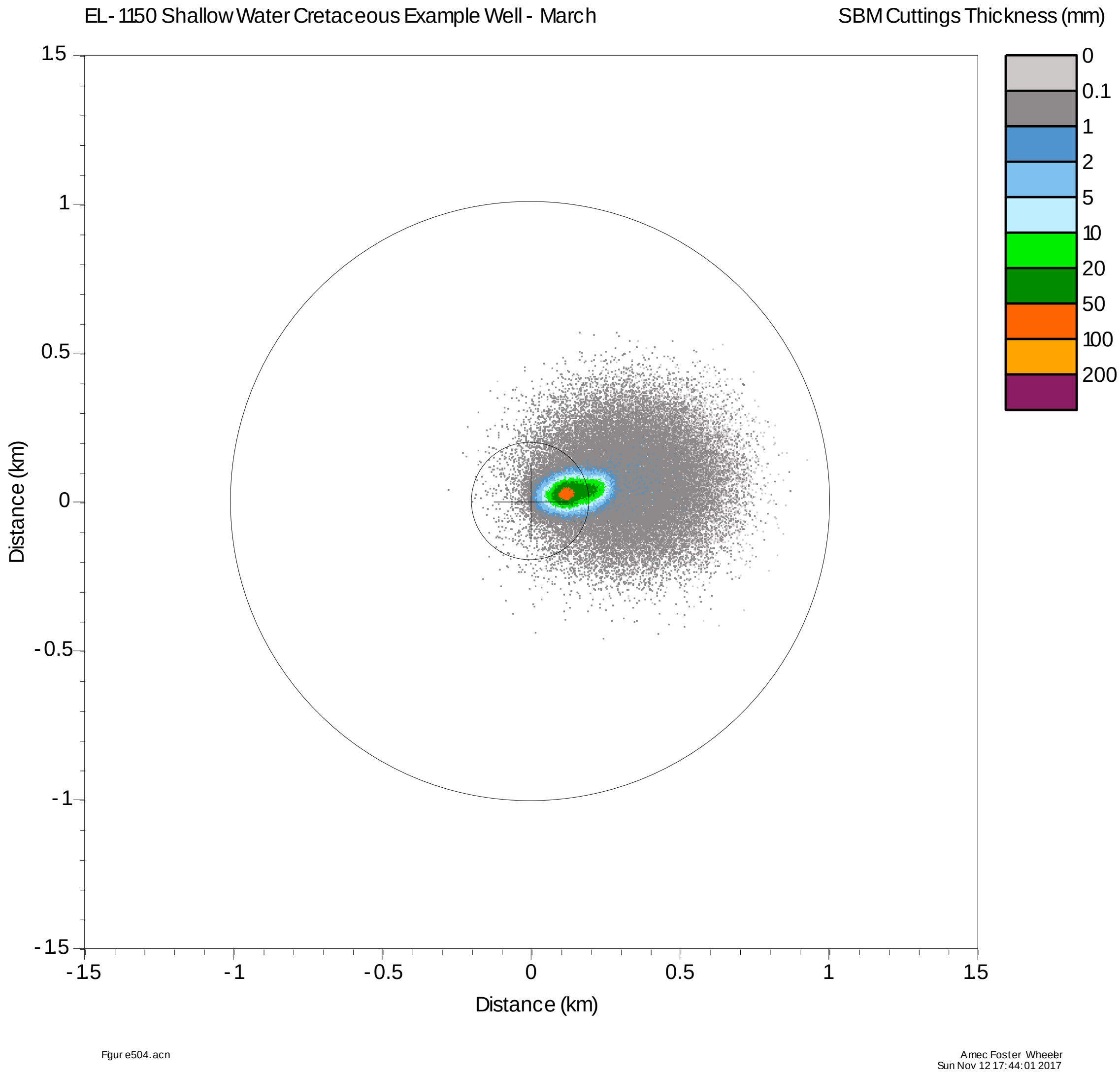
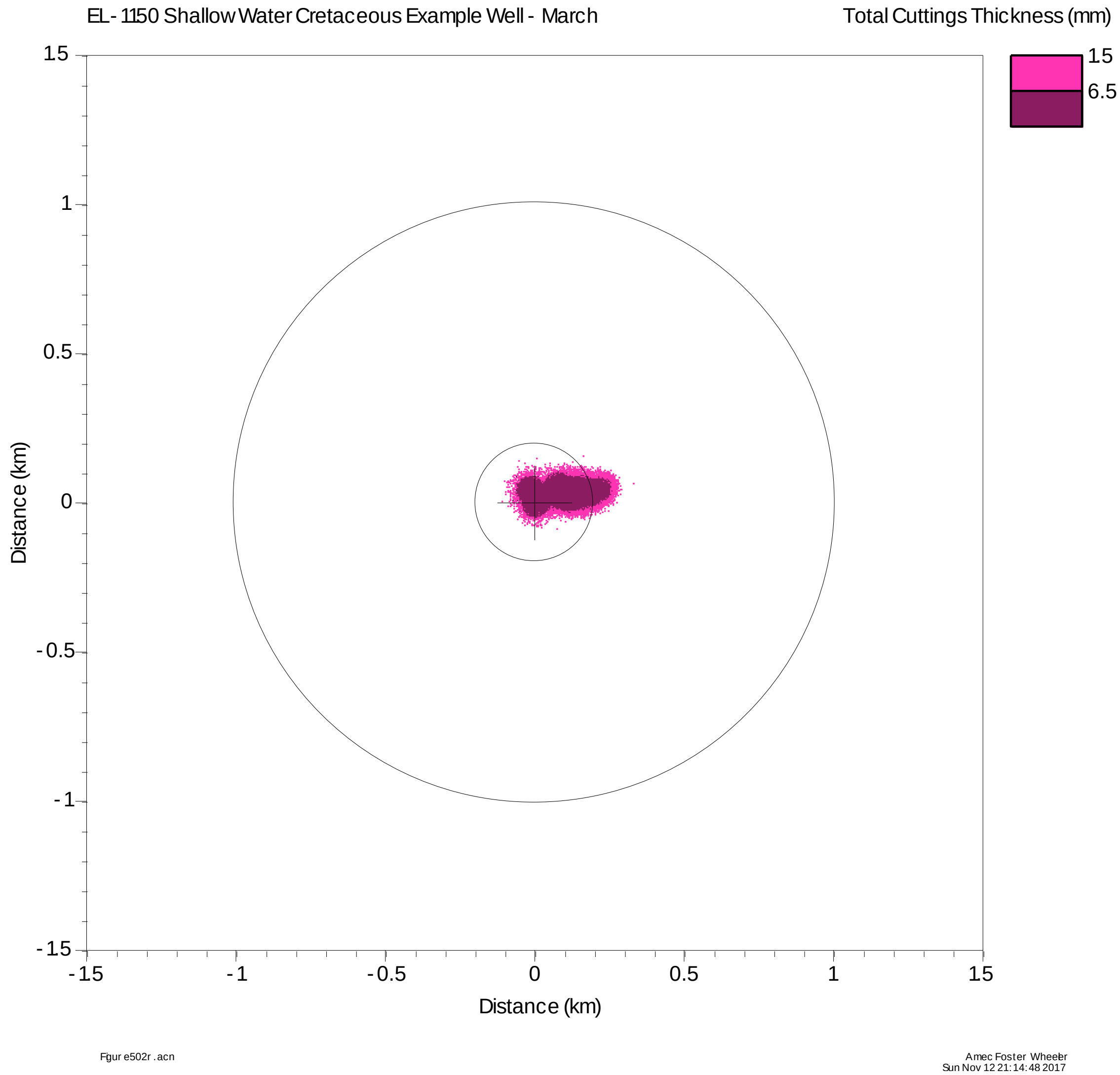


Figure 4-25 Total Drill Cuttings Deposition, PNET Limits, EL-1150 Shallow Water Cretaceous Example Well, March, 1.5-km View



June

Figure 4-26 Total Drill Cuttings Deposition, EL-1150 Shallow Water Cretaceous Example Well, June, Project Area View

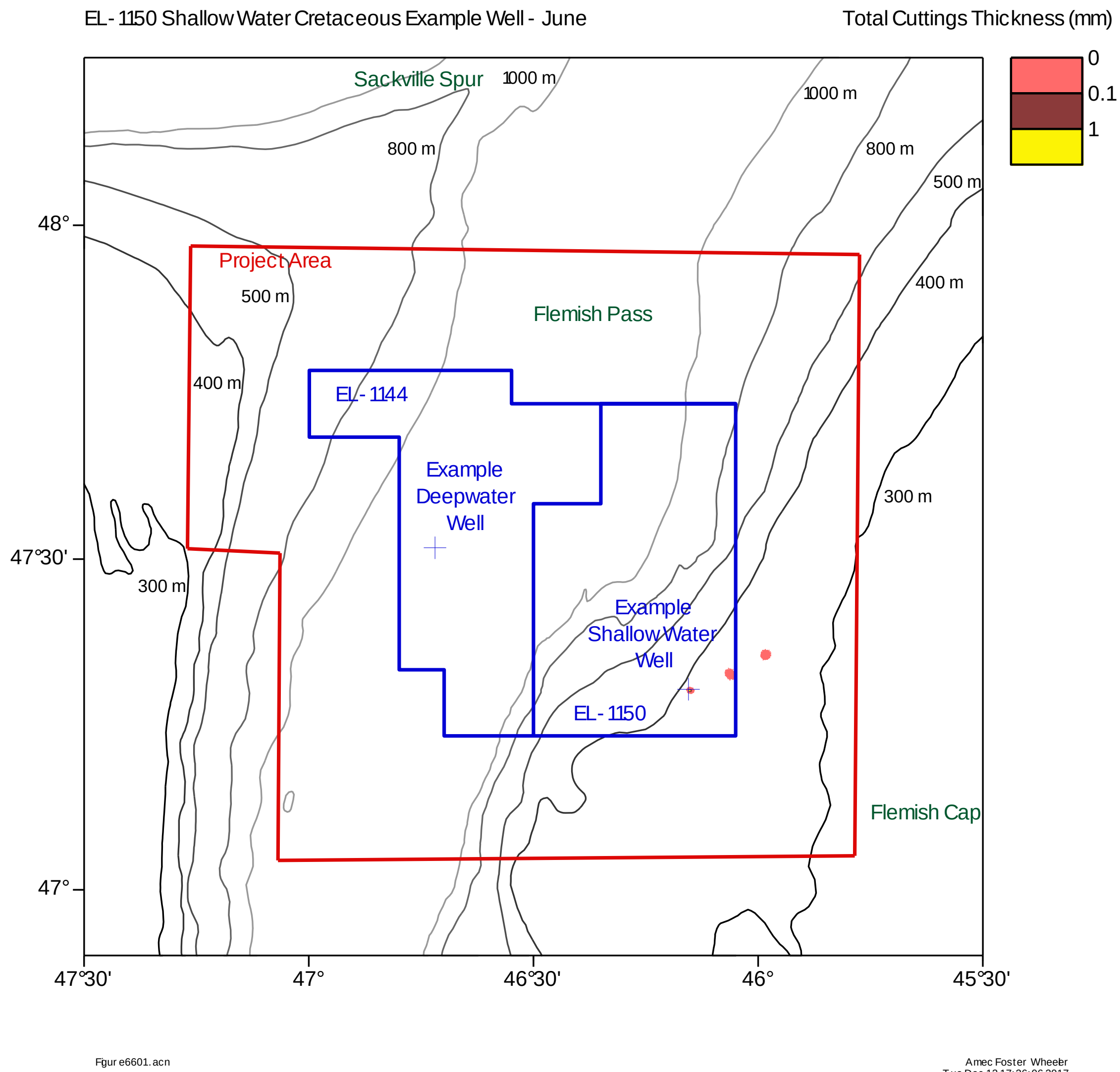


Figure 4-27 Total Drill Cuttings Deposition, EL-1150 Shallow Water Cretaceous Example Well, June, 1.5-km View

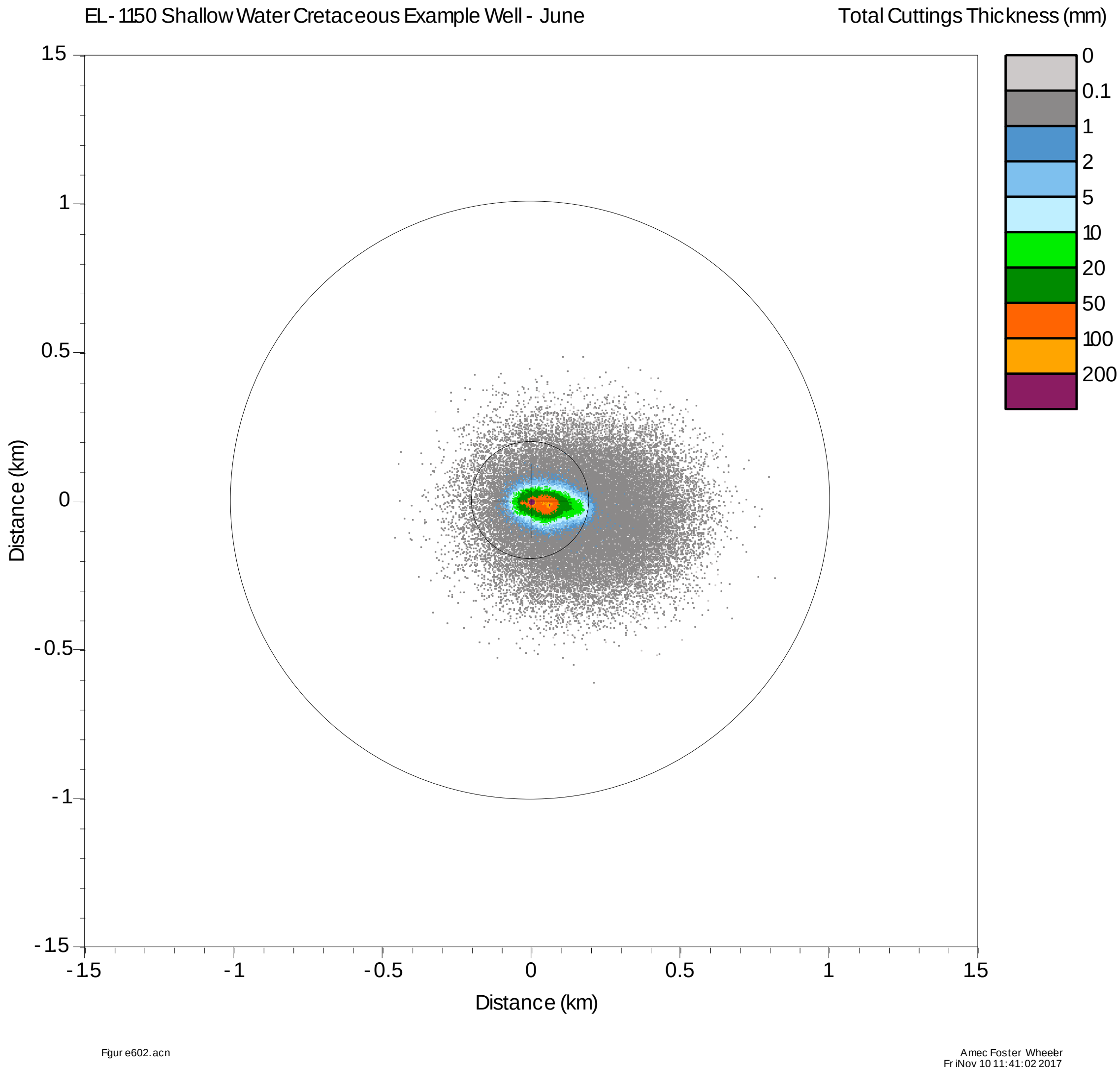


Figure 4-28 WBM Drill Cuttings Deposition, EL-1150 Shallow Water Cretaceous Example Well, June, 250-m View

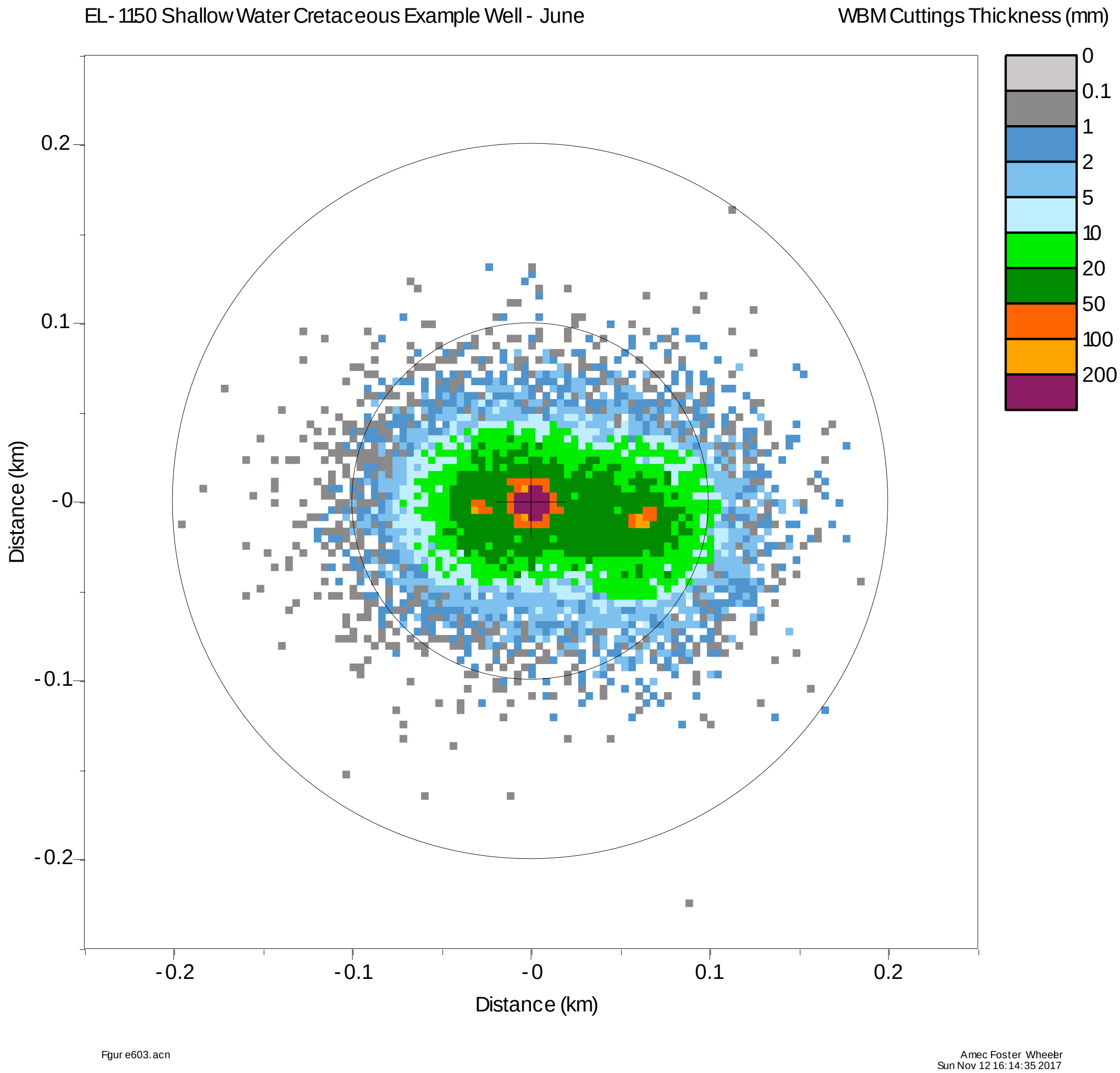


Figure 4-29 SBM Drill Cuttings Deposition, EL-1150 Shallow Water Cretaceous Example Well, June, 1.5-km View

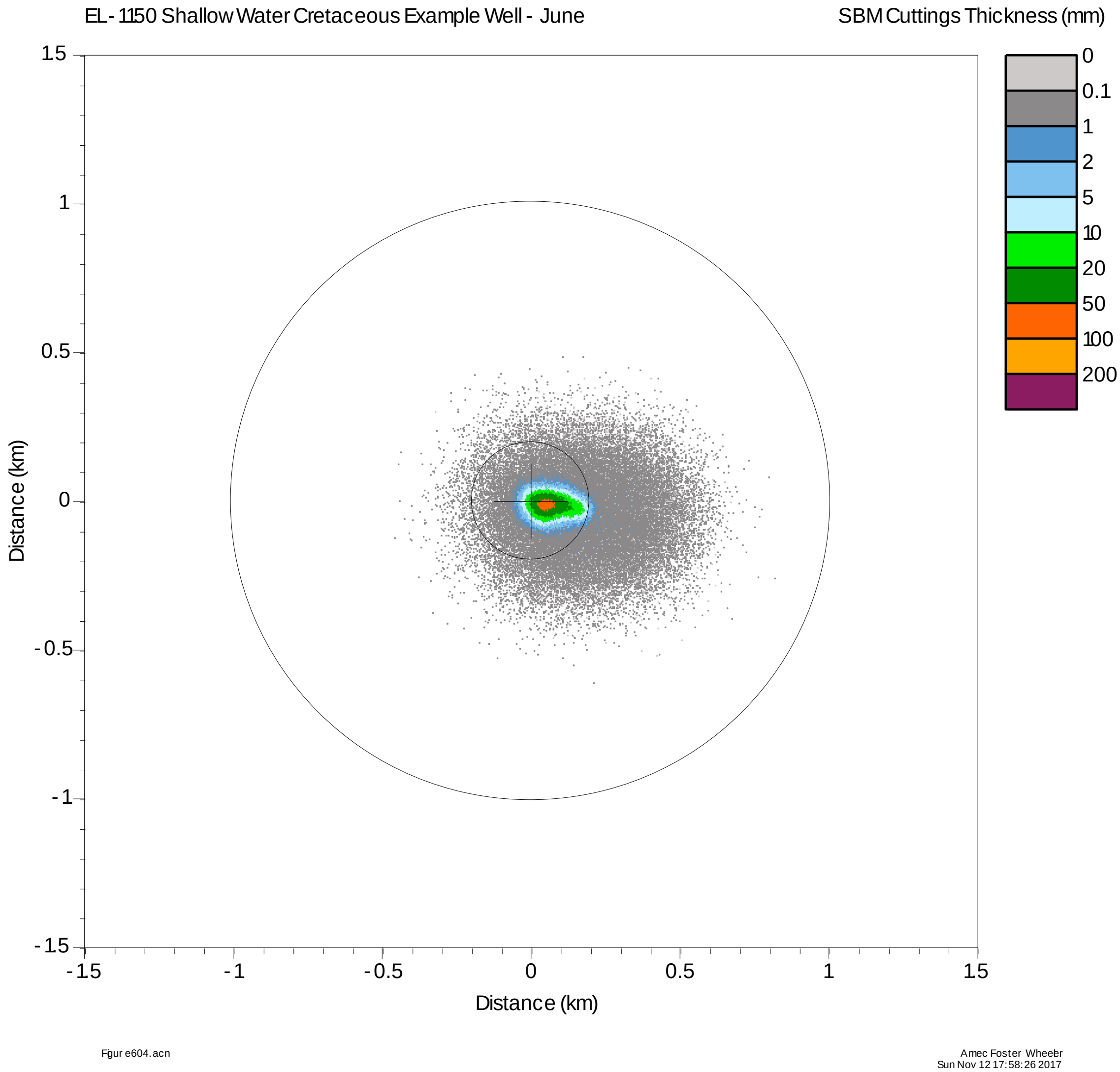
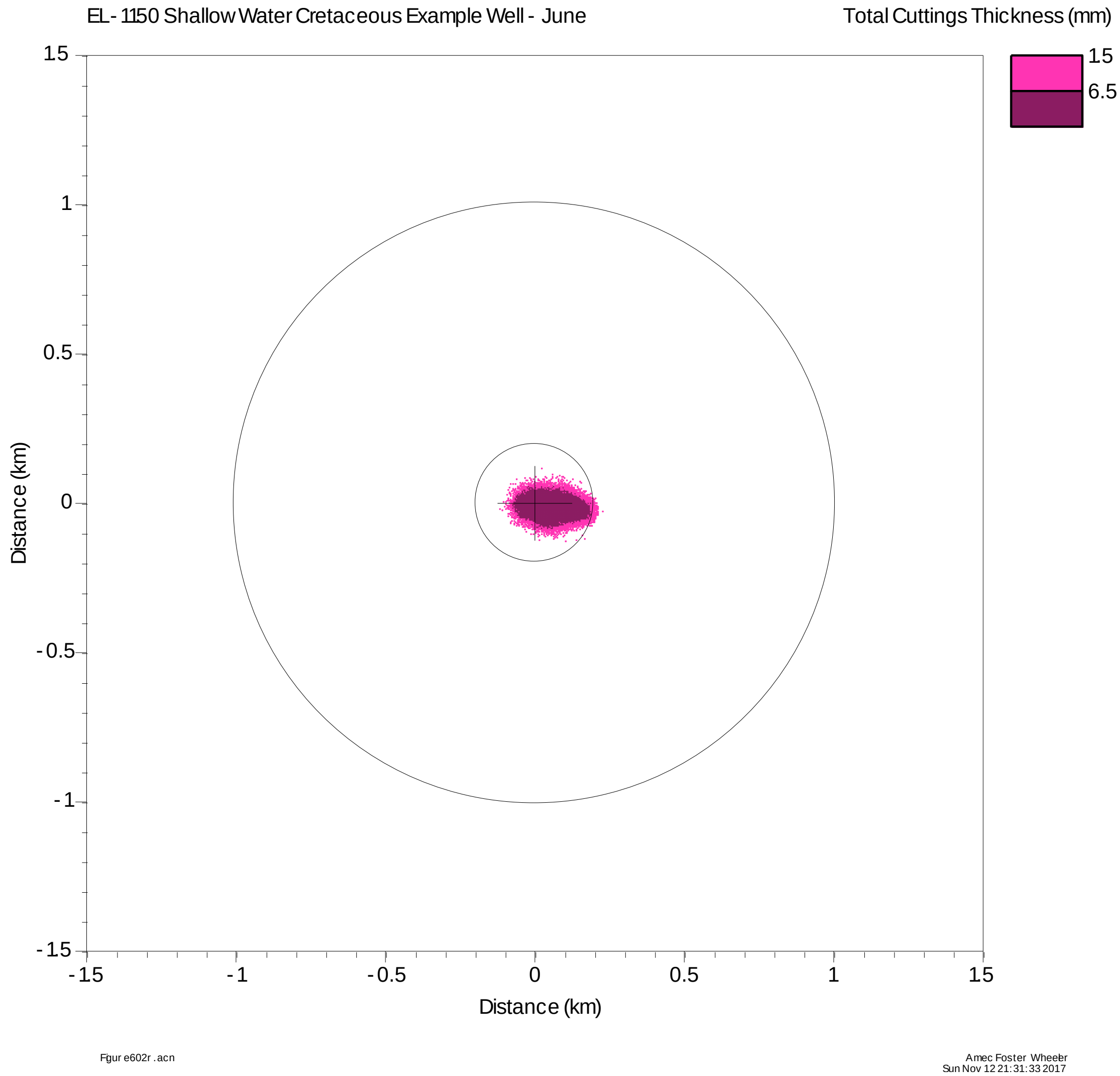


Figure 4-30 Total Drill Cuttings Deposition, PNET Limits, EL-1150 Shallow Water Cretaceous Example Well, June, 1.5-km View



September

Figure 4-31 Total Drill Cuttings Deposition, EL-1150 Shallow Water Cretaceous Example Well, September, Project Area View

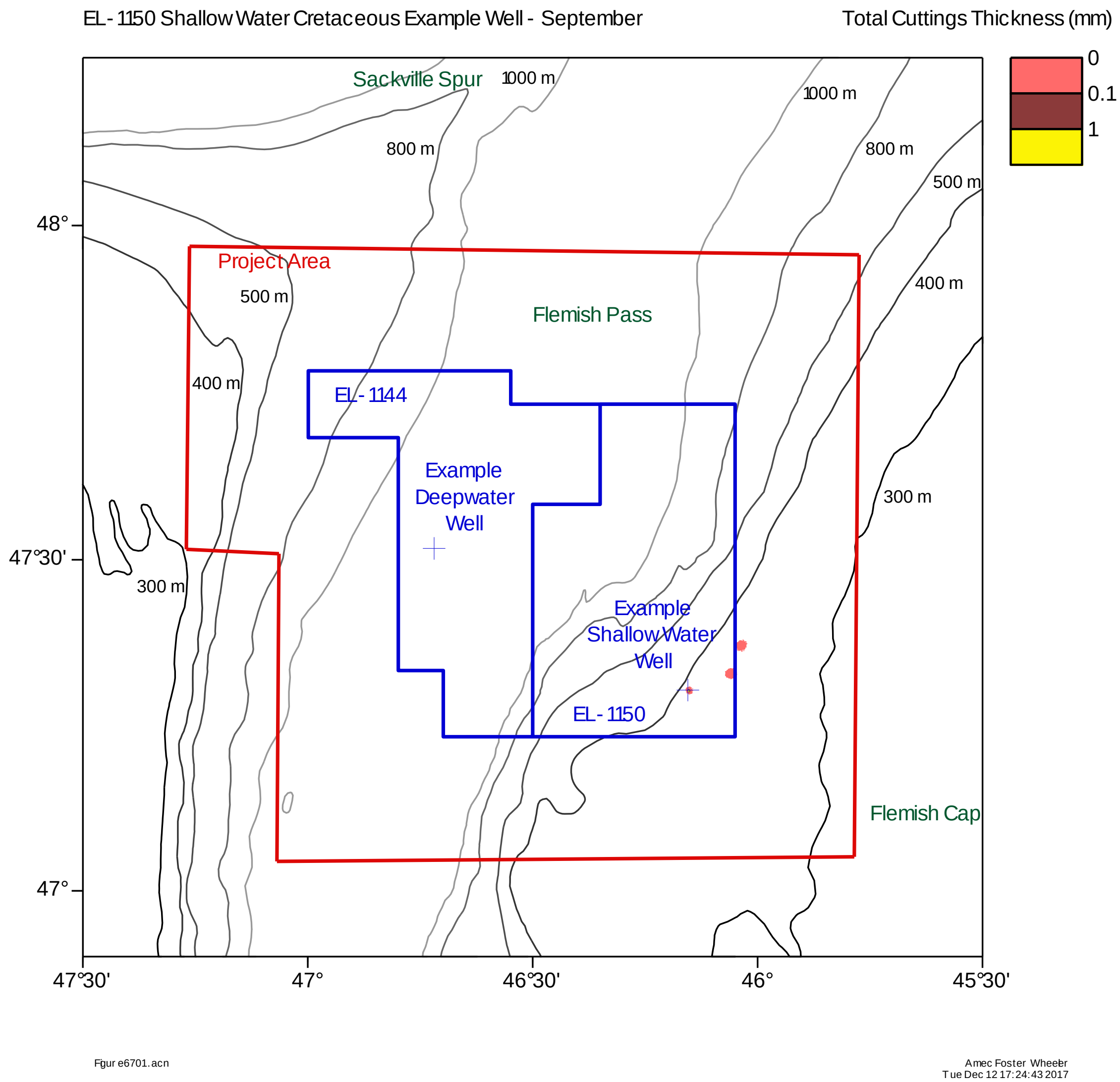


Figure 4-32 Total Drill Cuttings Deposition, EL-1150 Shallow Water Cretaceous Example Well, September, 1.5-km View

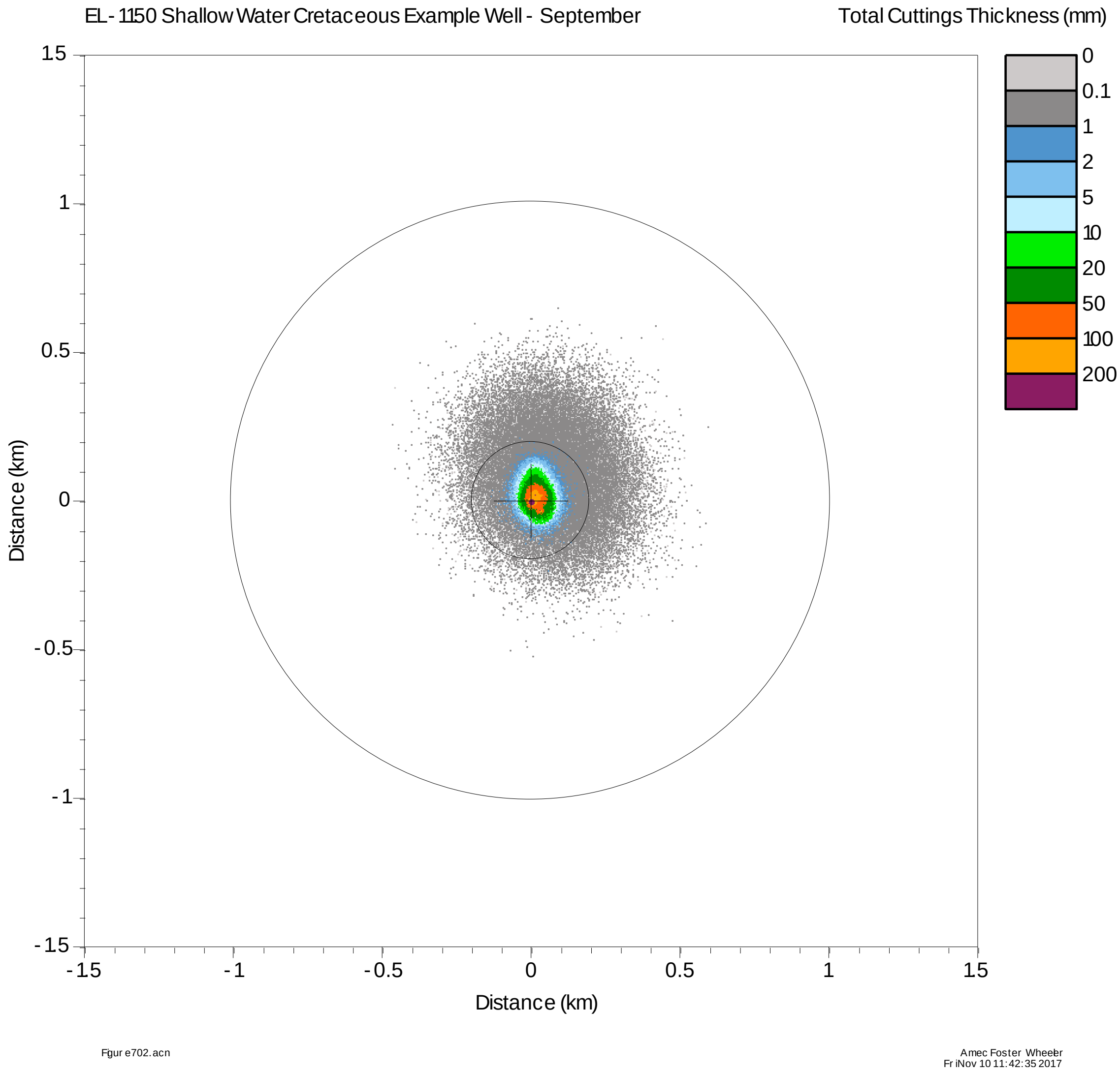


Figure 4-33 WBM Drill Cuttings Deposition, EL-1150 Shallow Water Cretaceous Example Well, September, 250-m View

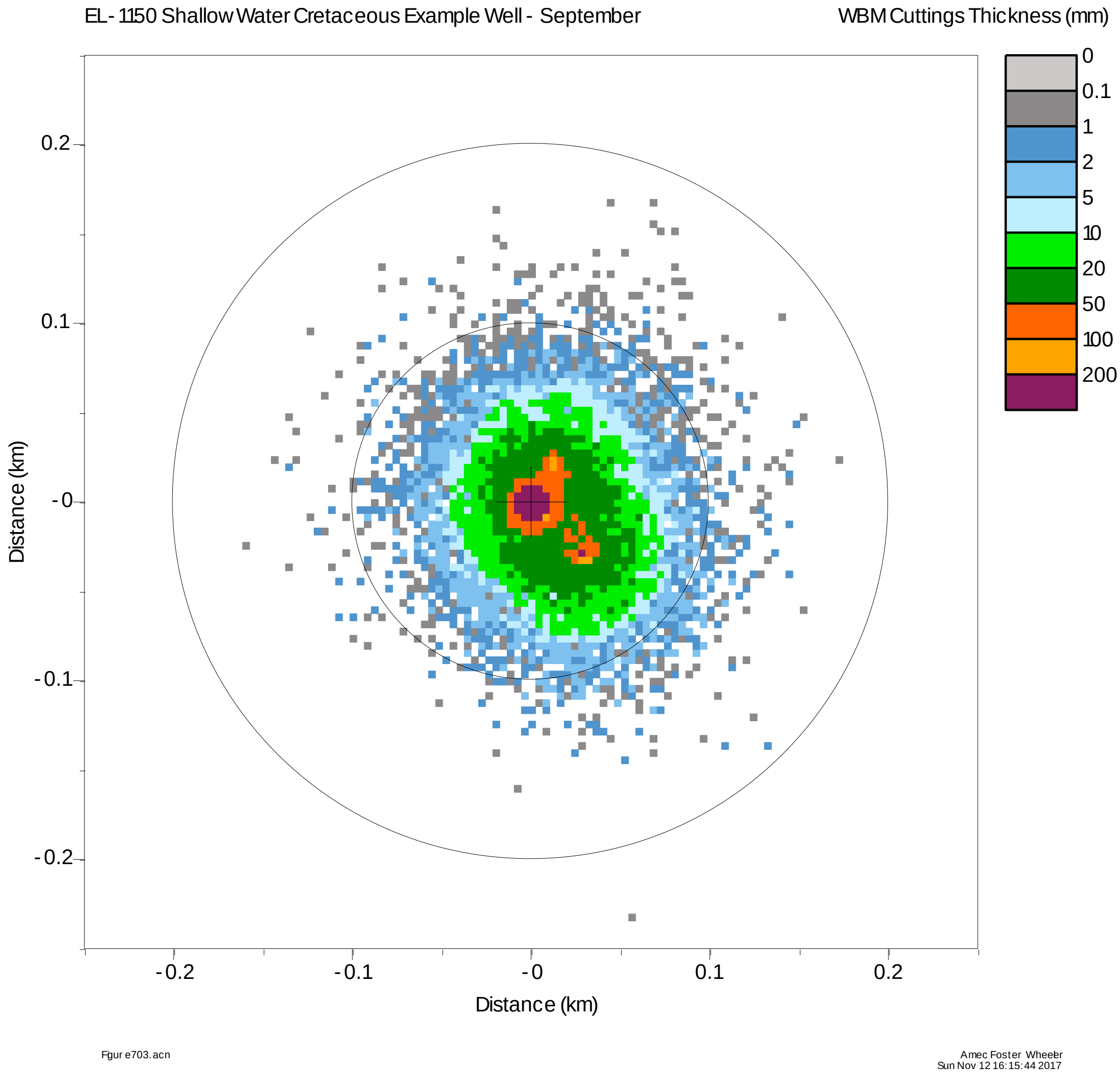


Figure 4-34 SBM Drill Cuttings Deposition, EL-1150 Shallow Water Cretaceous Example Well, September, 1.5-km View

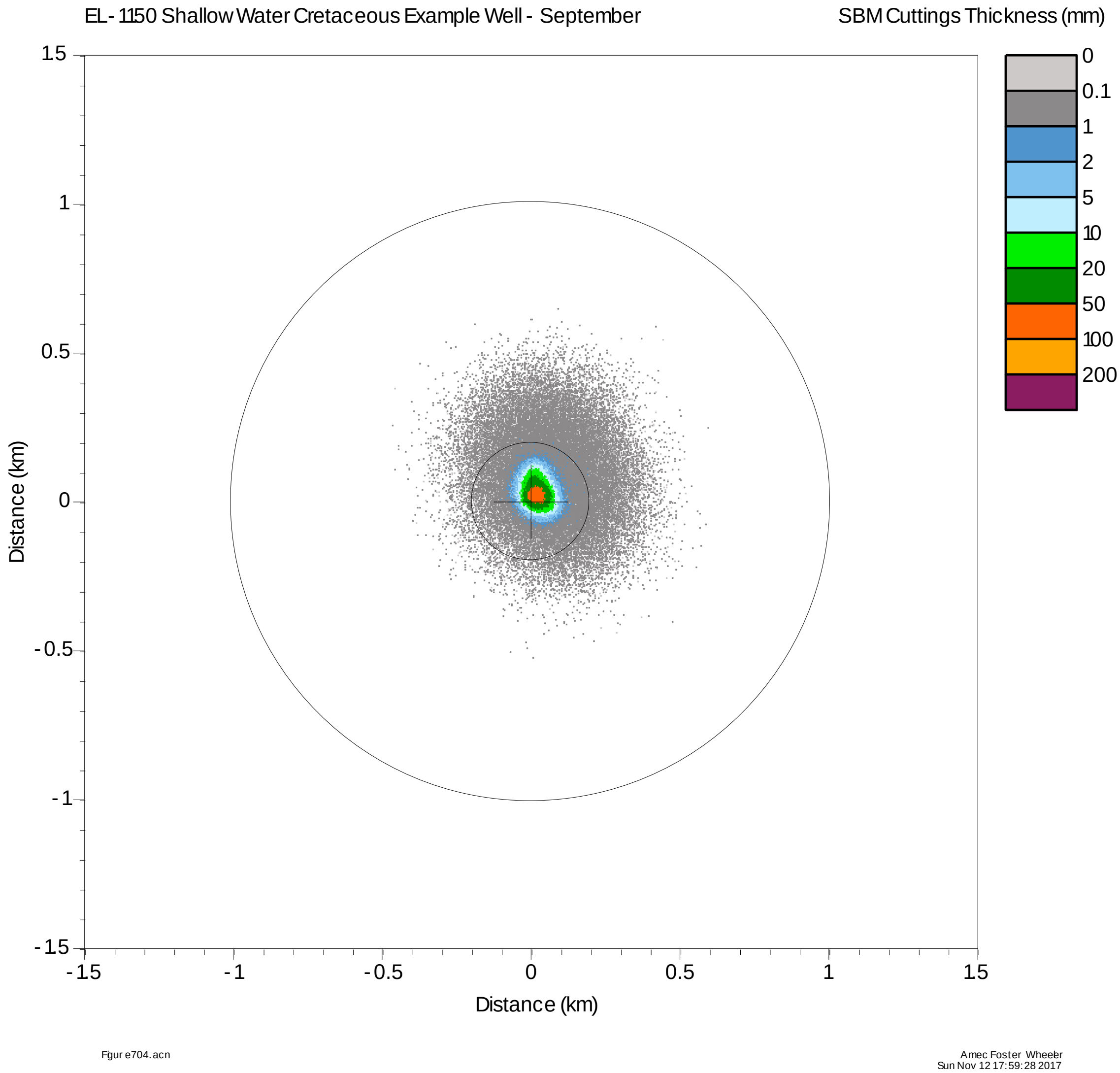
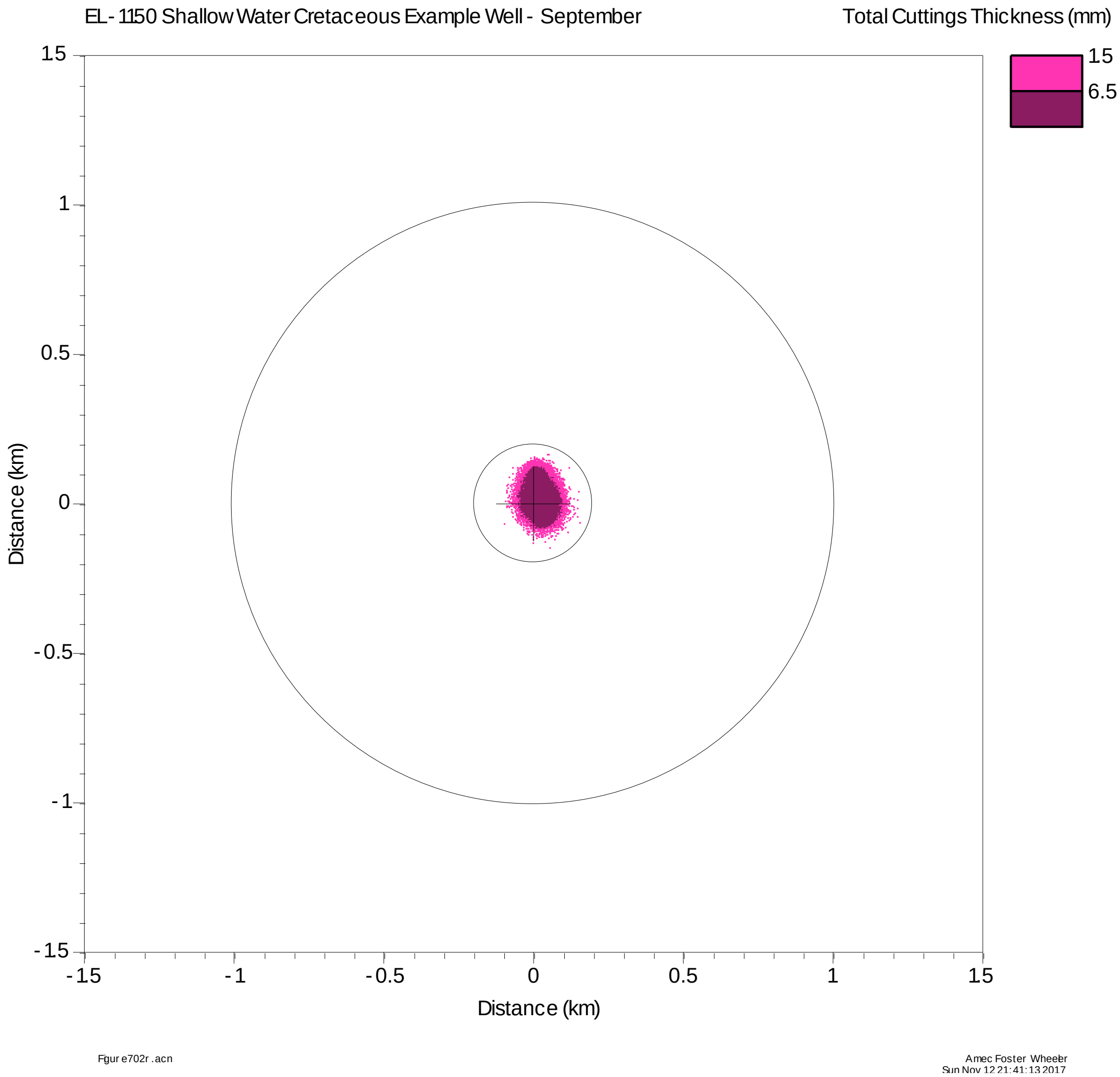


Figure 4-35 Total Drill Cuttings Deposition, PNET Limits, EL-1150 Shallow Water Cretaceous Example Well, September, 1.5-km View



December

Figure 4-36 Total Drill Cuttings Deposition, EL-1150 Shallow Water Cretaceous Example Well, December, Project Area View

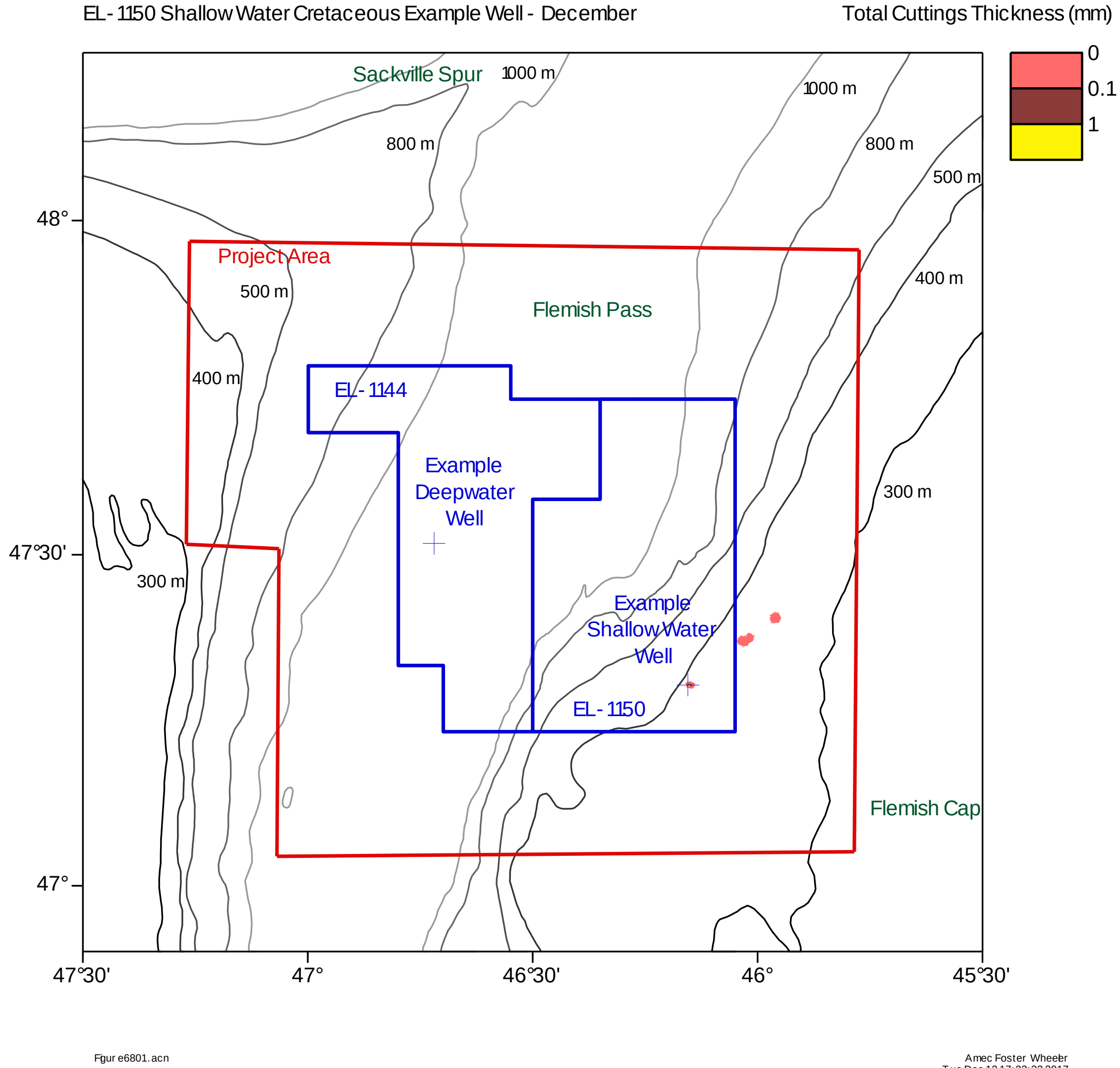


Figure 4-37 Total Drill Cuttings Deposition, EL-1150 Shallow Water Cretaceous Example Well, December, 1.5-km View

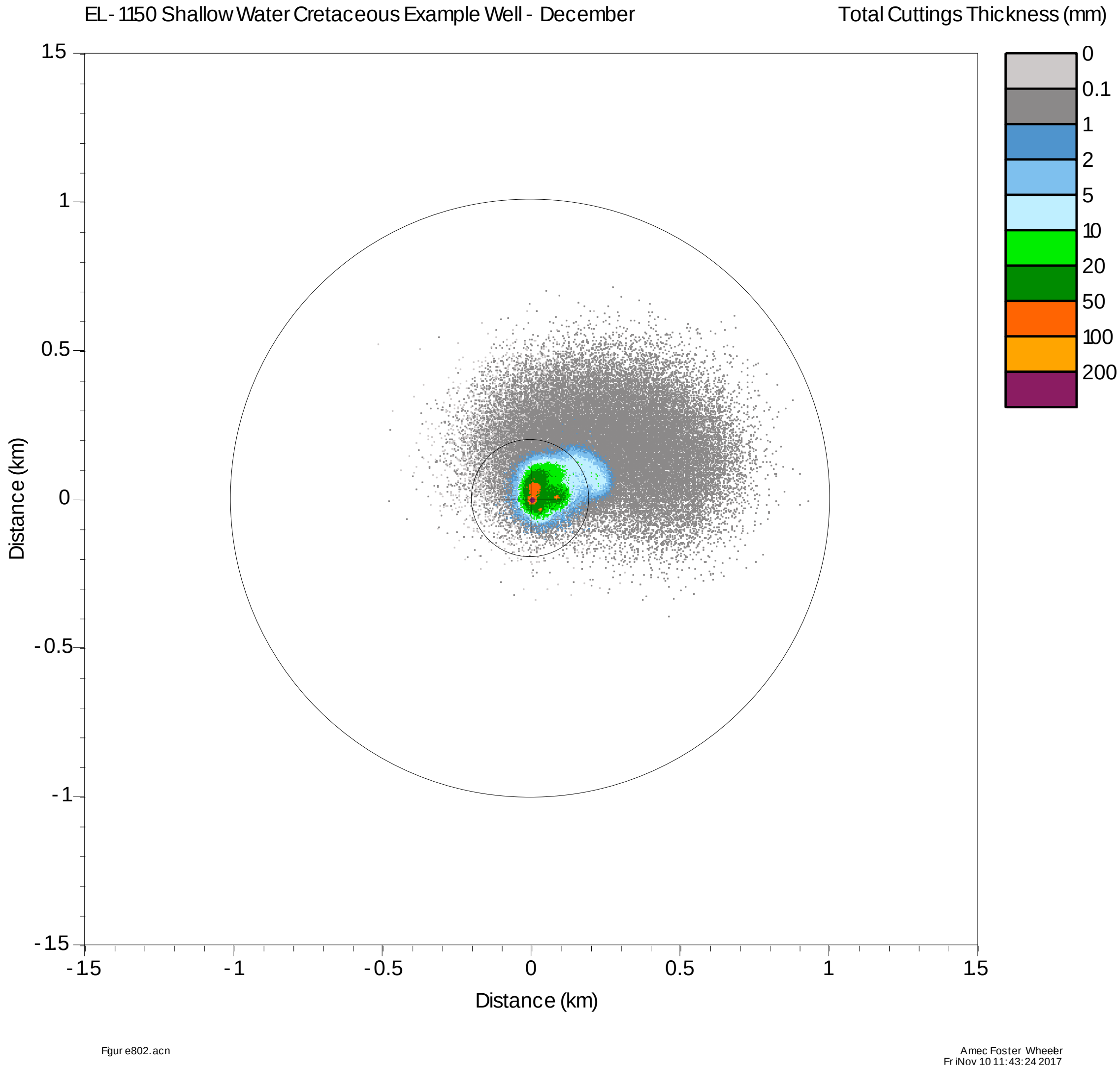

EL-1150 Shallow Water Cretaceous Example Well - December
Total Cuttings Thickness (mm)
0
0.1
1
2
5
10
20
50
100
200
Distance (km)
Distance (km)
Figure802.acn
Amec Foster Wheeler
Fri Nov 10 11:43:24 2017

Figure 4-38 WBM Drill Cuttings Deposition, EL-1150 Shallow Water Cretaceous Example Well, December, 250-m View

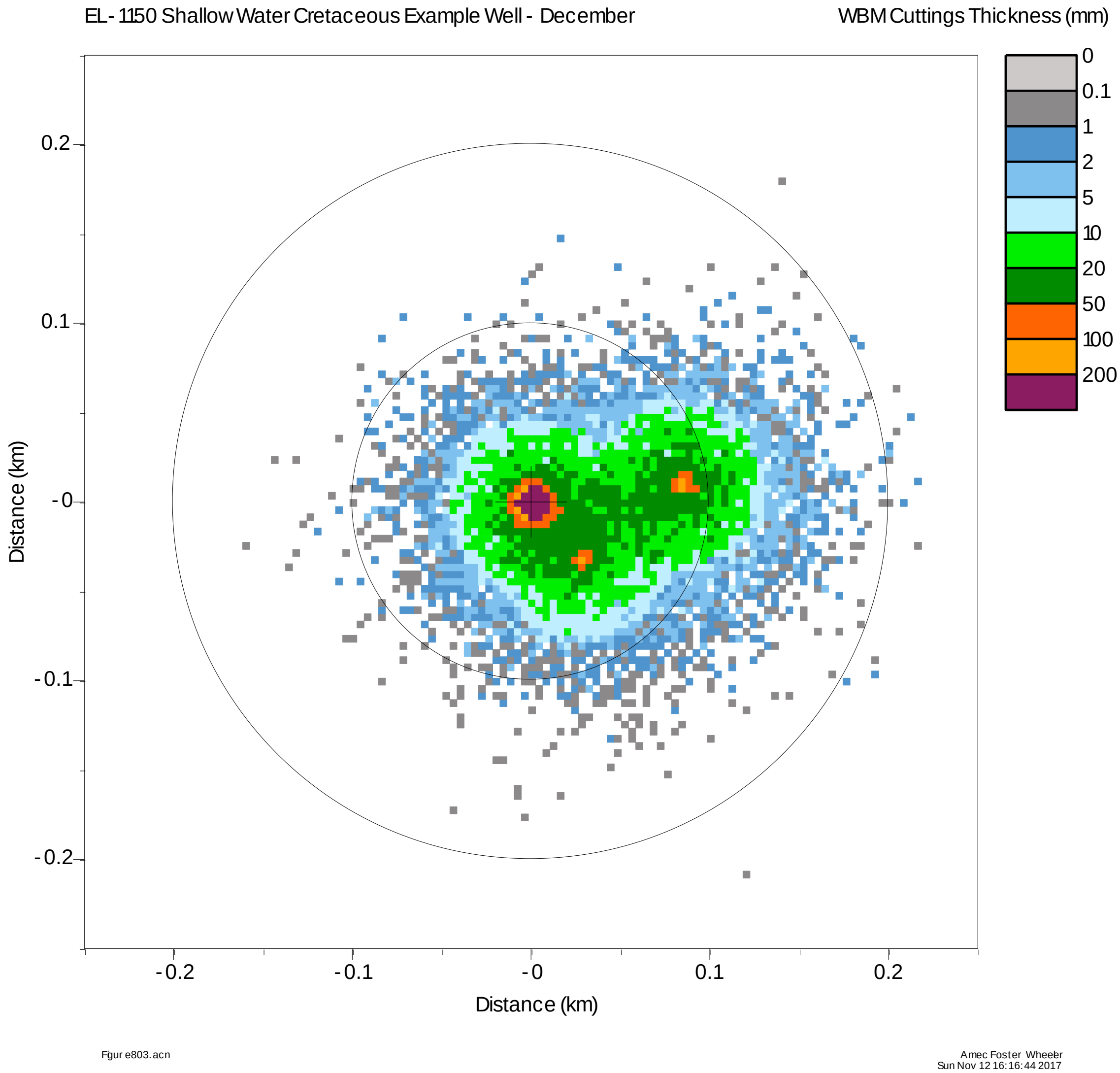


Figure 4-39 SBM Drill Cuttings Deposition, EL-1150 Shallow Water Cretaceous Example Well, December, 1.5-km View

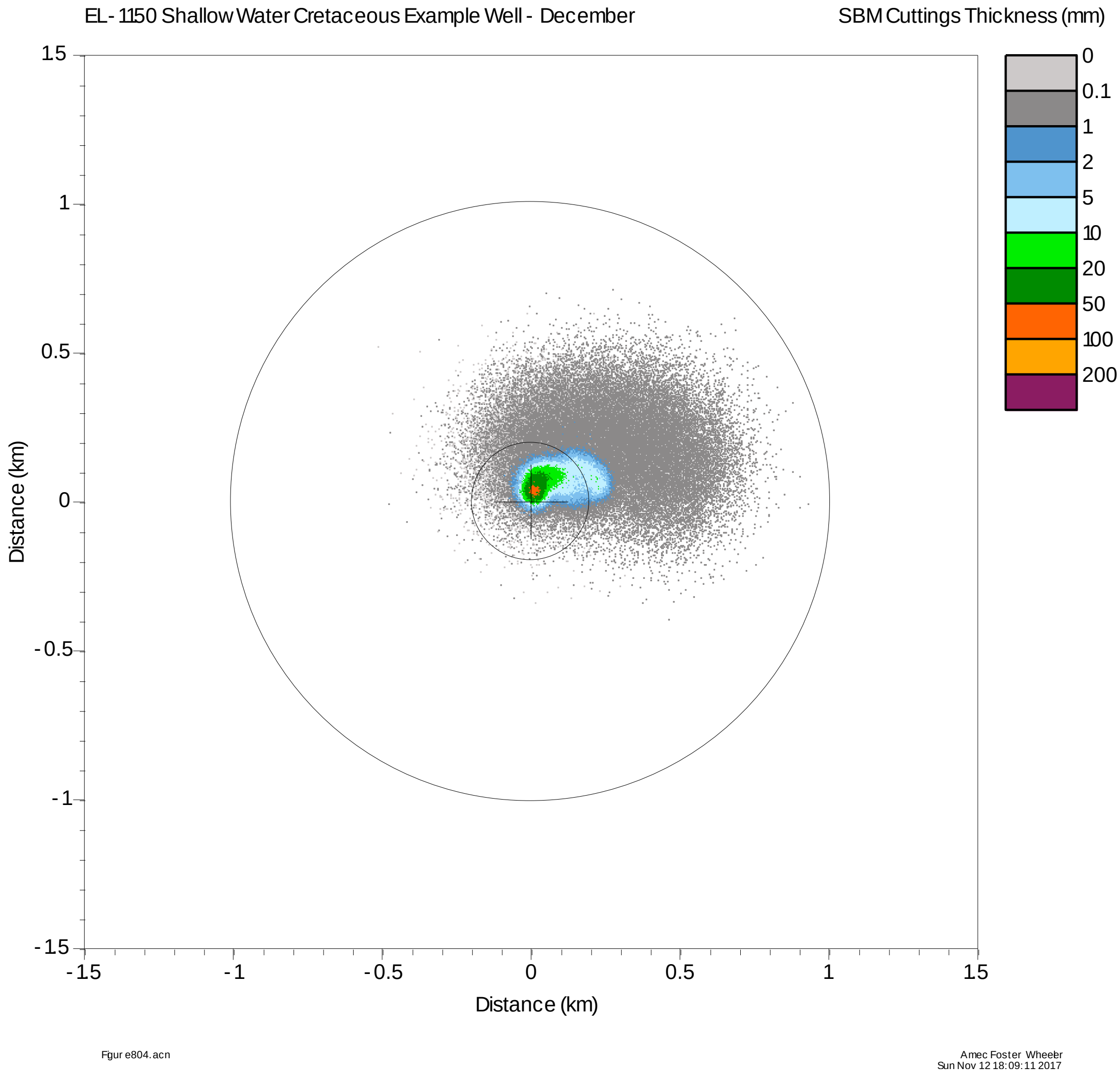
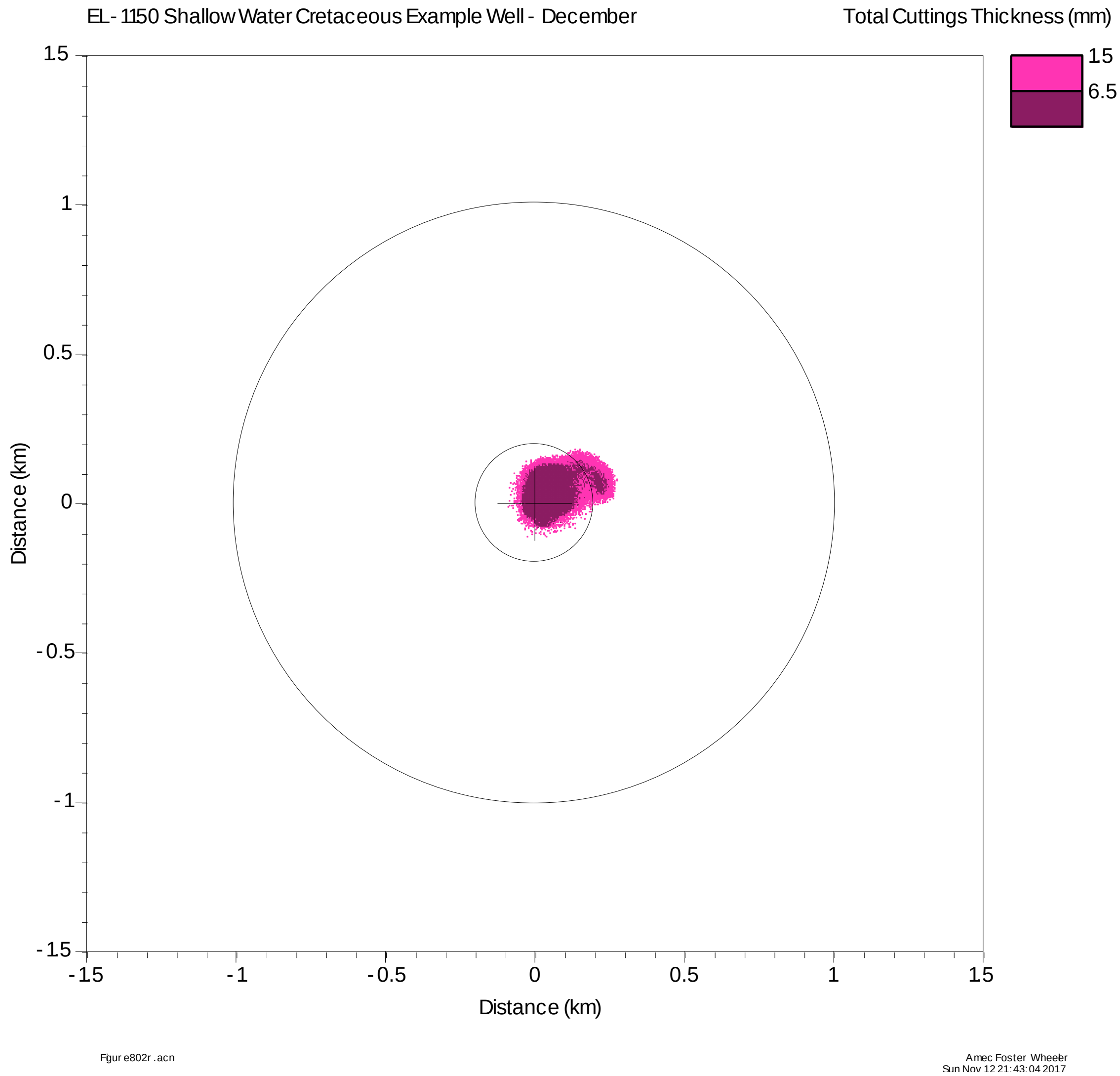


Figure 4-40 Total Drill Cuttings Deposition, PNET Limits, EL-1150 Shallow Water Cretaceous Example Well, December, 1.5-km View



4.3 Model Sensitivity Run

One of the key inputs for modelling the drill cuttings deposition is the volume of material released. The predicted drill cuttings weights, densities and thicknesses seen over a given area are directly proportional to the volume of materials released.

A simple sensitivity run was completed in consideration of the possibility of drilling deeper than the example well designs presented in Table 2-3. The release of an additional 100 m^3 of SBM cuttings in the last well hole section was modelled for both locations. This additional volume will be discharged near surface with a large depth to settle and disperse over; as opposed to additional WBM cuttings material released at the seabed with riserless drilling. The month of March was considered; similar differences could be reasonably anticipated for other months.

No differences in the predicted cuttings thicknesses are evident far away from the well sites. Closer to the wellhead some differences are evident as seen in the 1.5 km views of SBM cuttings thicknesses.

The result of an additional 100 m^3 of material for the EL-1144 Deepwater Jurassic Example Well is shown in Figure 4-41. The difference is as large as an additional 5 mm at 200 to 220 m to the south-southwest. There is a distinct patch of size approximately 250 m by 150 m of increased thickness of 1 mm or more, otherwise there are small differences elsewhere.

Figure 4-42 shows the ‘before’ and ‘after’ PNET views with thickness thresholds of interest 1.5 mm and 6.5 mm. The figures include radii drawn at 200 m and 1 km. There are a few scattered 1.5 mm thickness cells added with the additional 100 m^3 but for the most part negligible differences are indicated.

The result of an additional 100 m^3 of material for the EL-1150 Shallow Water Cretaceous Example Well is shown in Figure 4-43. The difference is as large as about 12 mm at approximately 110 m to the east. There’s a distinct patch similarly sized to that for the EL-1144 location of about 250 m x 120 m of thickness above 1 mm, otherwise there are small differences. Figure 4-43 shows the ‘before’ and ‘after’ PNET views. There are some additional 1.5 mm thickness cells out to about 200 m to the east although these are pretty well scattered for the most part.

These predicted differences, from the two sensitivity runs, are still within the effects assessment for the full set of scenario results presented in Sections 4.1 and 4.2 above, i.e., the footprints remain localized to the wellhead within about 500 m or less.

Figure 4-41 SBM Drill Cuttings Thickness Difference, EL-1144 Deepwater Jurassic Example Well, March Sensitivty Run, 1.5-km View

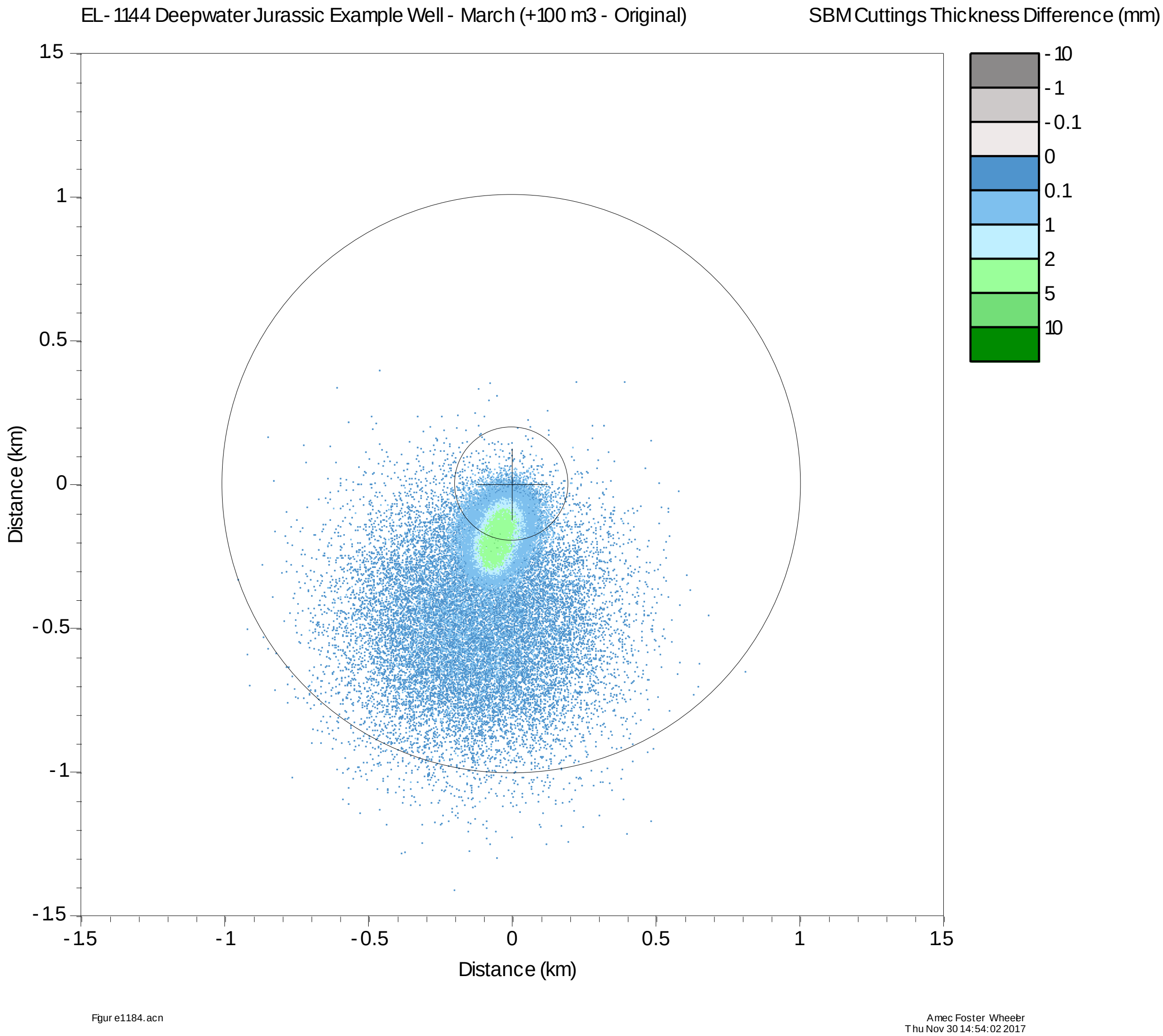
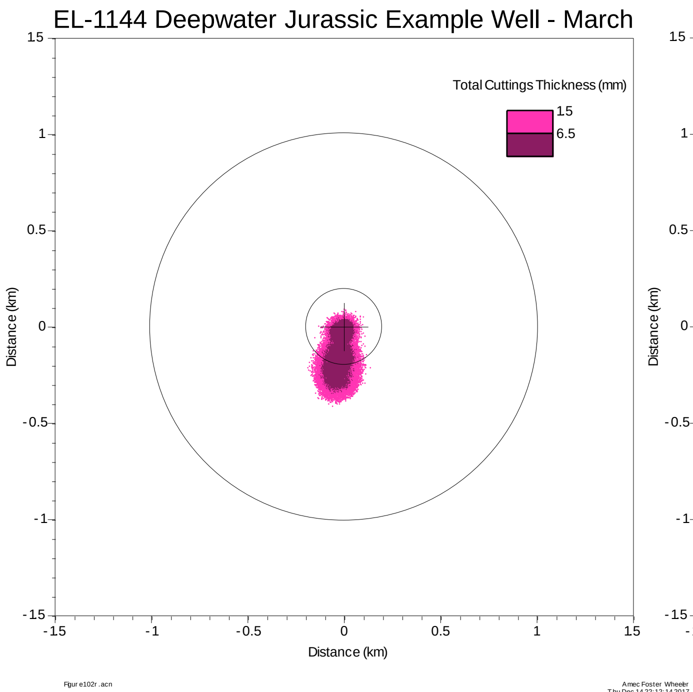


Figure 4-42 Total Drill Cuttings Thickness Difference, EL-1144 Deepwater Jurassic Example Well, March Sensitivity Run, PNET Limits



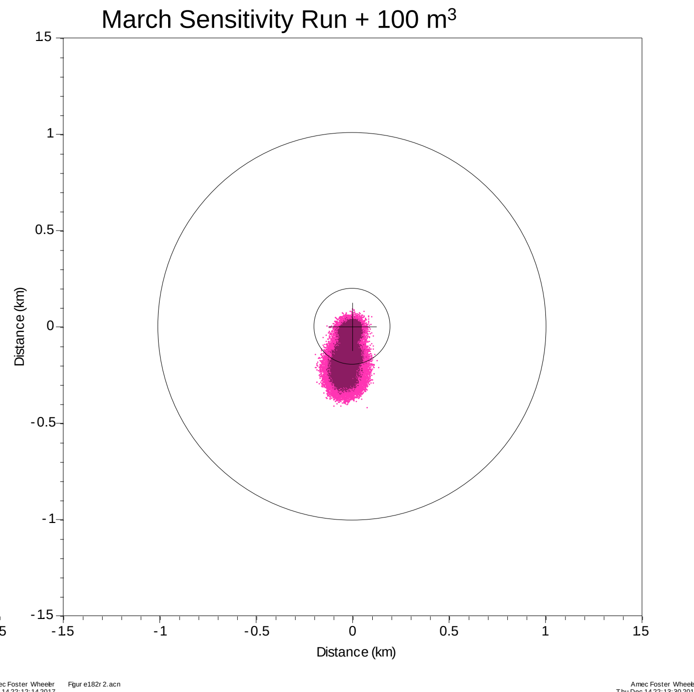


Figure 4-43 SBM Drill Cuttings Thickness Difference, EL-1150 Shallow Water Cretaceous Example Well, March Sensitivity Run, 1.5-km View

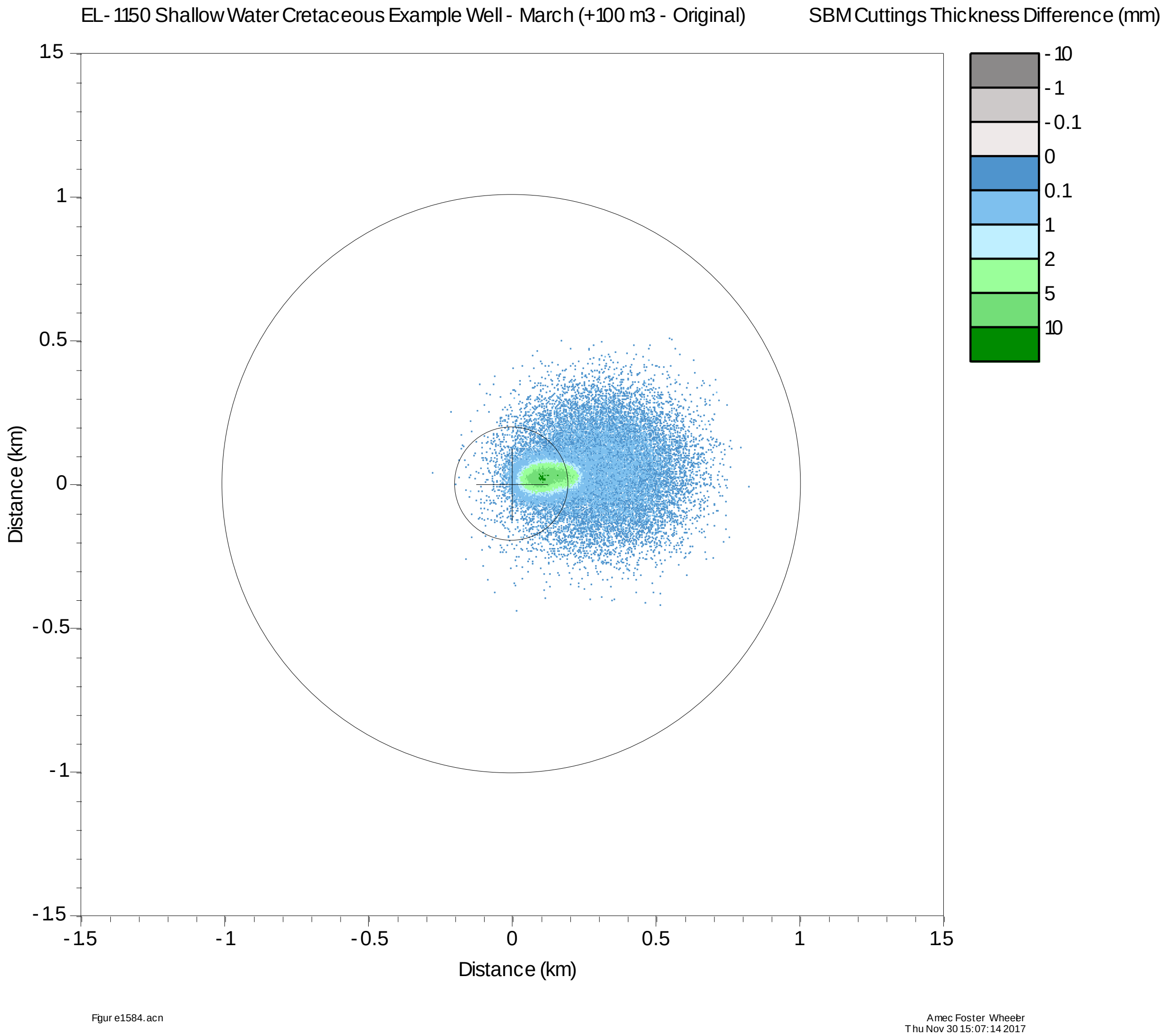
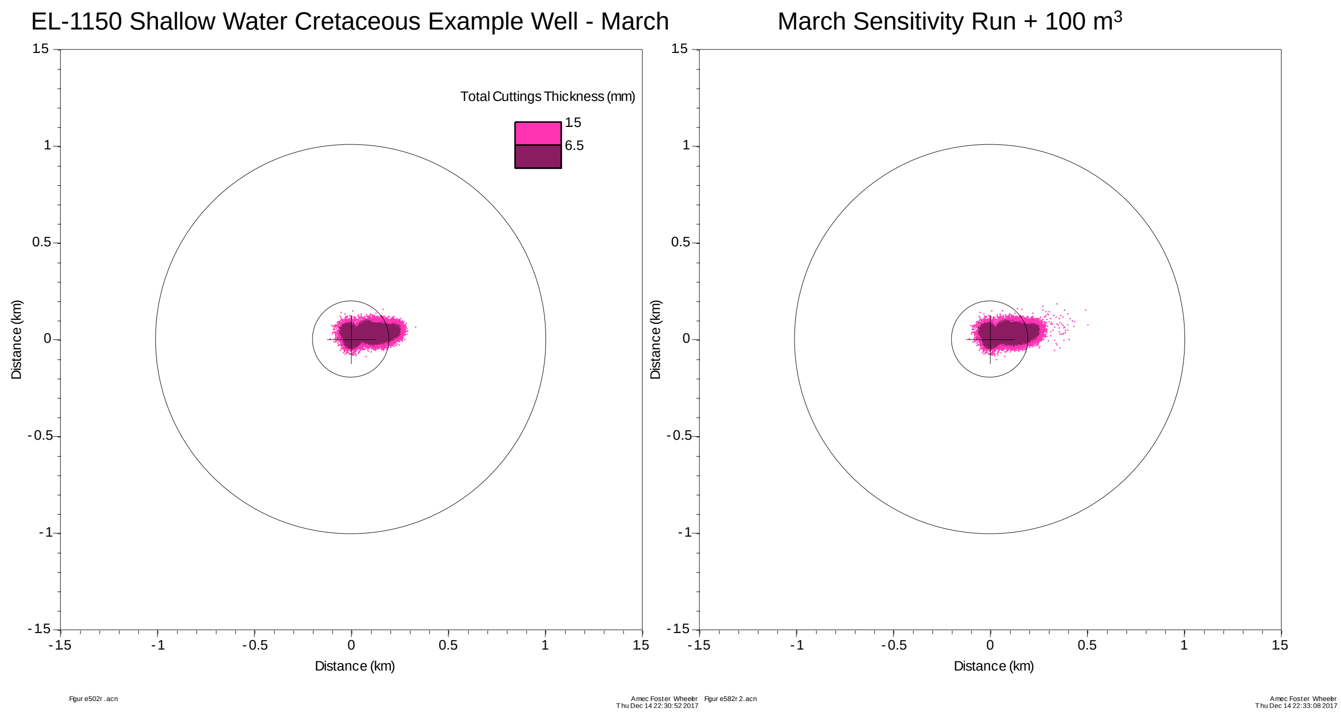


Figure 4-44 Total Drill Cuttings Thickness Difference, EL-1150 Shallow Water Cretaceous Example Well, March Sensitivity Run, PNET Limits



4.4 Summary

The drill cuttings dispersion modelling considered two well designs expected to represent the range of wells that could be drilled in the Project Area. These are a Deepwater Jurassic Well Design and a Shallow Water Cretaceous Well Design. With the possibility either well type is selected for drilling in either of the exploration licences EL-1144 and EL-1150 license blocks, two example modelling locations are were considered with one in each EL in order to represent the variations in ocean currents and water depth likely to be encountered. The Deepwater example well design was modelled for EL-1144 and the Shallow Water example well design was modelled for EL-1150 (Figure 1-1). With the potential to drill multiple wells and at any time during the year, four model simulation runs or ‘scenarios’ for March, June, September, December were considered at each location, i.e., a total of eight scenarios were completed.

EL-1144 Deepwater Jurassic Example Well

In all four monthly simulations, all of WBM cuttings released at the wellhead are predicted to settle within 500 m. Given their released close to the seafloor there is little time for these cuttings to be transported large distances by the ambient currents. Over 93 percent settle within 100 m. WBM cuttings are predicted to drift as far as from 210 m in September to 280 m in December. Maximum WBM cuttings thicknesses, allowing for anticipated slumping of the ‘pile’ are estimated to be on the order of 0.7 to

1.4 m. Maximum thickness values fall to about 0.21 to 0.26 m within 100 m. Mean WBM cuttings thicknesses within 100 m are about 19 mm in all months.

The SBM cuttings released from the MODU at the sea surface settle generally within 2 km, with over 90 percent settling within 500 m. The farthest these cuttings settle, within 2 km, ranges from 1.4 km in March to 1.7 km in September. Only 3.5 percent of the total SBM cuttings from one well drift farther away and settle with thicknesses less than 0.1 mm. These small amounts of fine sand and silt-sized SBM cuttings are predicted to drift to the south and south-southwest up to about 25 km in June, 46 km in March and 54 km in September and December. Mean SBM cuttings thicknesses out to 200 m generally range from 1 to 10 mm with the exception in September, that with very light currents, the mean thickness is 37 mm within 10 m of the wellhead. The predicted maximum SBM cuttings thicknesses are all located to the south-southwest and range from 38 mm at 150 m from the wellhead in June, to 48 mm at the wellhead in September.

The predicted areas of total cuttings thickness above the predicted no effect thresholds (PNET) value of 1.5 mm are confined to a patch of about 550 m by 280 m oriented to the south-southwest. The areas are generally offset about 50 to 100 m to the north of the wellhead. The largest area is about 700 m by 260 m in September. The predicted areas of total cuttings thickness above the 6.5 mm threshold are about an average size of 400 m by 150 m in March, June and December; in September the area is smaller, about 180 m by 150 m, and symmetrical about the wellhead in evidence of the light currents.

EL-1150 Shallow Water Cretaceous Example Well

Over 99 percent of the WBM cuttings released at the wellhead are predicted to settle within 200 m, with settling of small amounts predicted to drift as 260 m in March and 240 m during the other months. Maximum WBM cuttings thicknesses, allowing for anticipated material slumping are estimated to be on the order of 0.45 to 0.9 m. Maximum thickness values fall to about 0.18 to 0.21 m within 100 m. Mean WBM cuttings thicknesses within 100 m are 12 to 13 mm in all months.

The SBM cuttings released from the MODU at the sea surface settle generally within 1 km, with over 94 percent settling within 500 m. The farthest these cuttings settle, within 1 km, ranges from 720 m in September to 940 m in March and December. Only 3.6 percent of the total SBM cuttings from one well drift farther away and settle with thicknesses less than 0.1 mm. These small amounts of fine sand and silt-sized SBM cuttings are predicted to drift to the northeast up to about 12 km in September, 15 km in June and 18 km in March and December. Mean SBM cuttings thicknesses out to 100 m generally range from less than 1 mm in March to 43 mm in September (with the very light currents) within 10 m of the wellhead. The predicted maximum SBM cuttings thicknesses are all located to the east in all months (except to the north in December) and range from 84 mm at 50 m from the wellhead in June, to 99 mm at 40 m in September.

The predicted areas of total cuttings thickness above the PNET value of 1.5 mm are confined to an average size, over the four months, of about 320 m by 220 m. These areas are oriented primarily to the east in March and June and to the north in September and northeast in December. The areas are generally offset about 50 to 100 m to the west, or south or southwest. The largest area is about 350 m by 240 m in December. The predicted areas of total cuttings thickness above the 6.5 mm threshold are similar in all months averaging 250 m by 150 m in size; the largest footprint is predicted in December at about 260 m by 180 m.

5.0 CLOSURE

This report presents the data and methods used to model drill cuttings dispersion for Nexen exploration drilling at two Flemish Pass example well locations. Results from the modelling are presented which include cuttings footprints and cuttings thickness statistics for four seasonal predictions at each location.

Yours sincerely,

Amec Foster Wheeler Environment & Infrastructure,
a Division of Amec Foster Wheeler Americas Limited

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<Original signed by>	<Original signed by>
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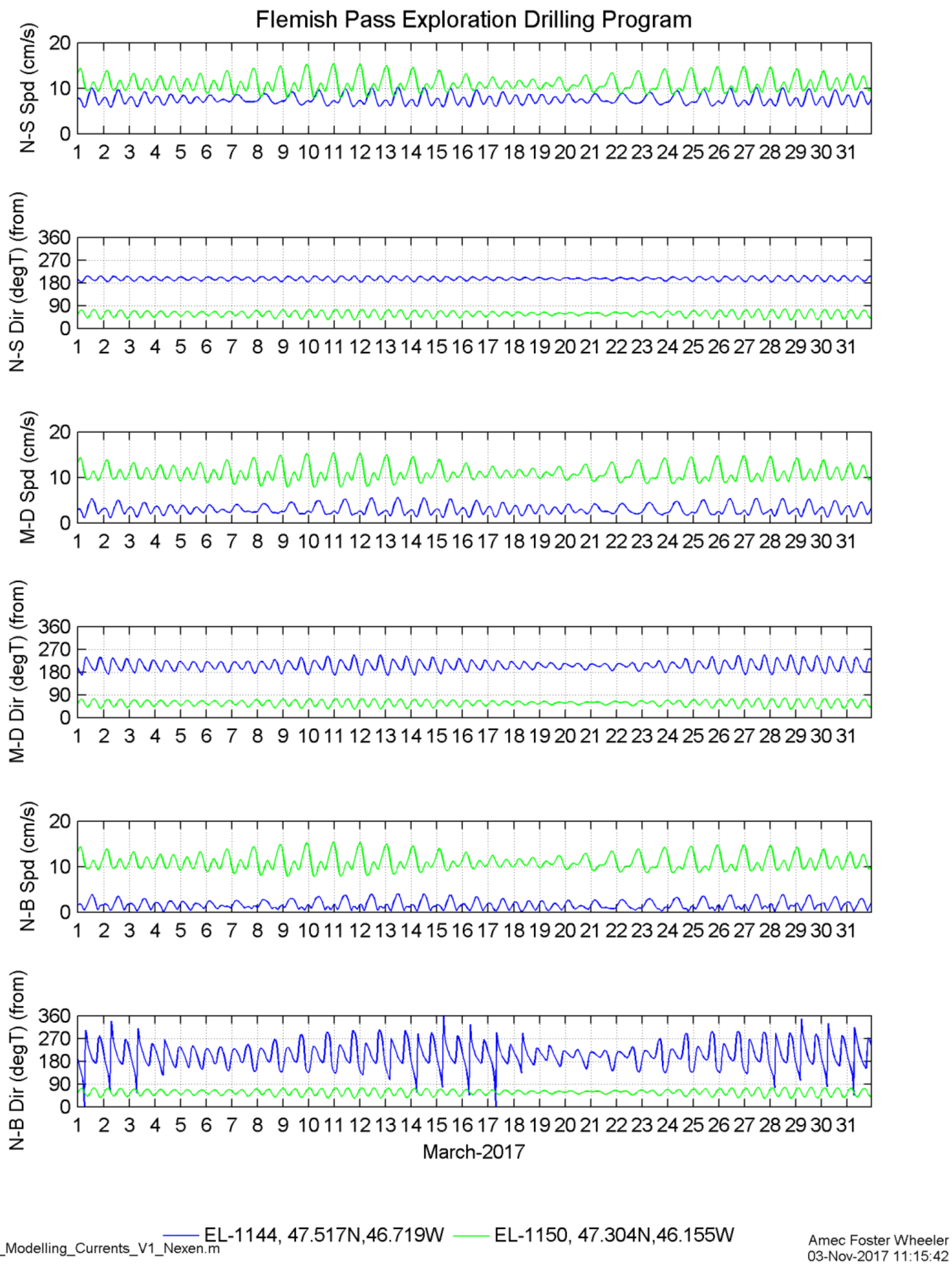
APPENDIX A-1: OCEAN CURRENTS FOR MODELLING LOCATIONS


Flemish Pass Exploration Drilling Program
N-S Spd (cm/s)
N-S Dir (degT) (from)
M-D Spd (cm/s)
M-D Dir (degT) (from)
N-B Spd (cm/s)
N-B Dir (degT) (from)
March-2017
EL-1144, 47.517N,46.719W
EL-1150, 47.304N,46.155W
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Amec Foster Wheeler
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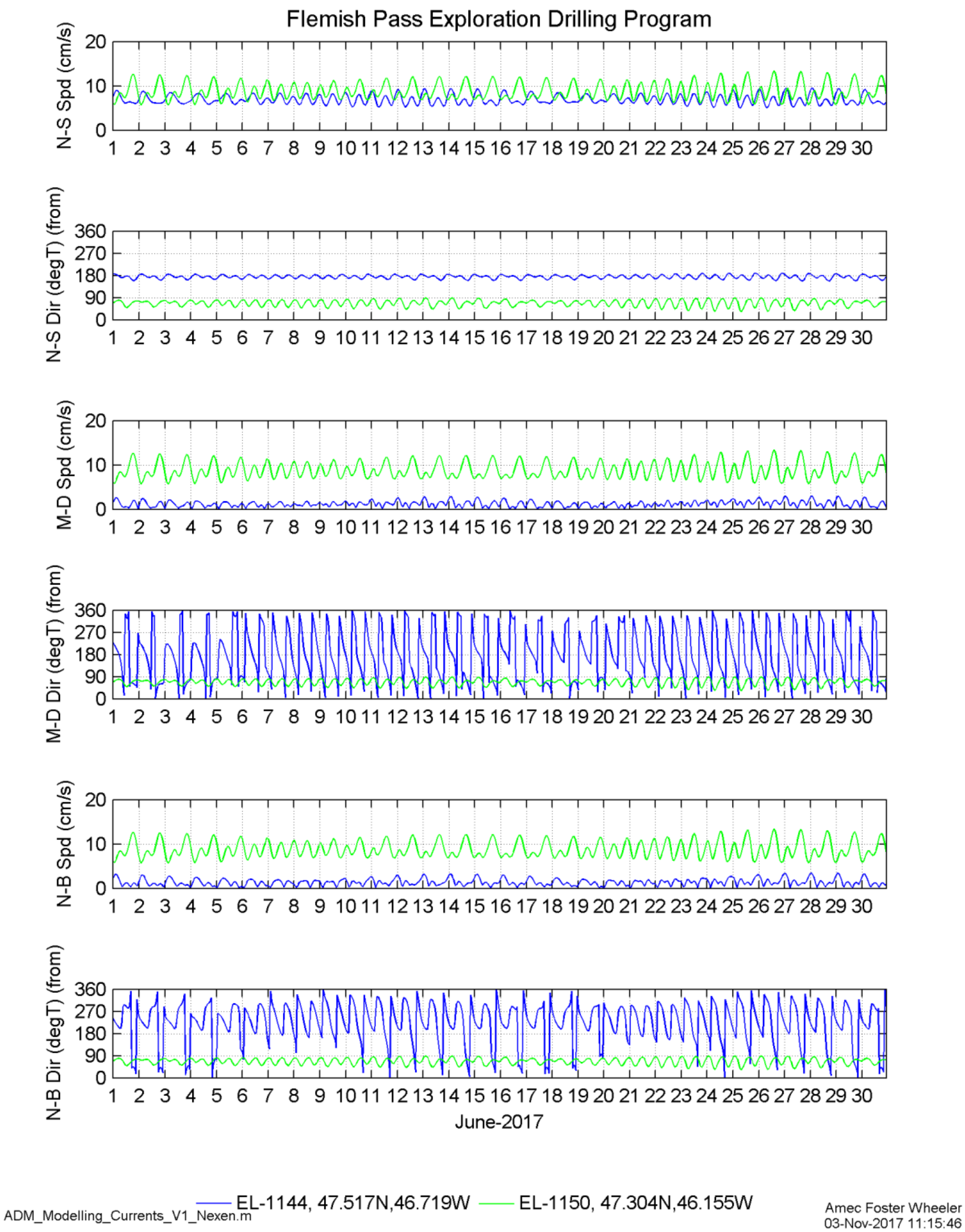
Flemish Pass Exploration Drilling Program
N-S Spd (cm/s)
N-S Dir (degT) (from)
M-D Spd (cm/s)
M-D Dir (degT) (from)
N-B Spd (cm/s)
N-B Dir (degT) (from)
June-2017
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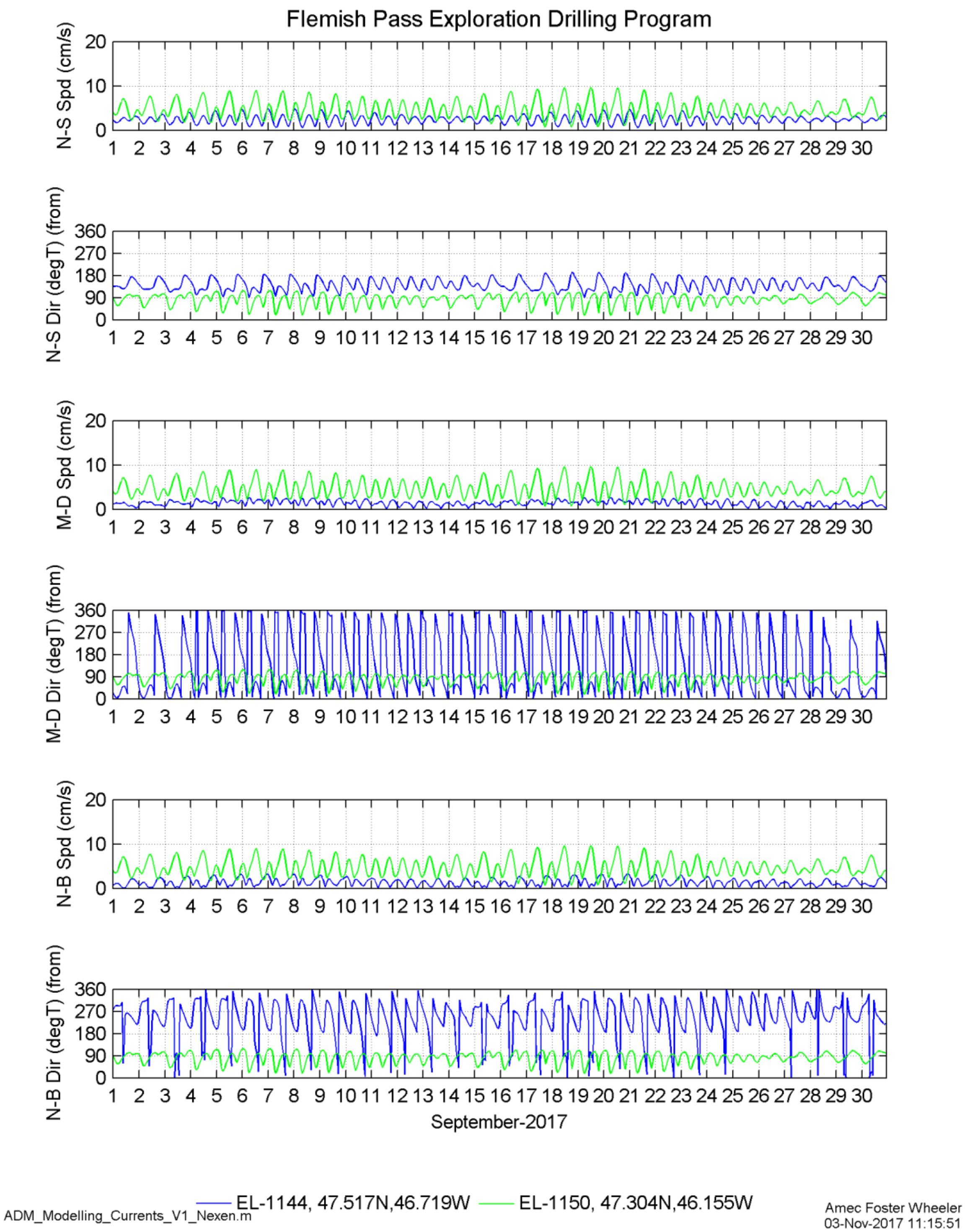
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N-S Spd (cm/s)
N-S Dir (degT) (from)
M-D Spd (cm/s)
M-D Dir (degT) (from)
N-B Spd (cm/s)
N-B Dir (degT) (from)
September-2017
EL-1144, 47.517N,46.719W
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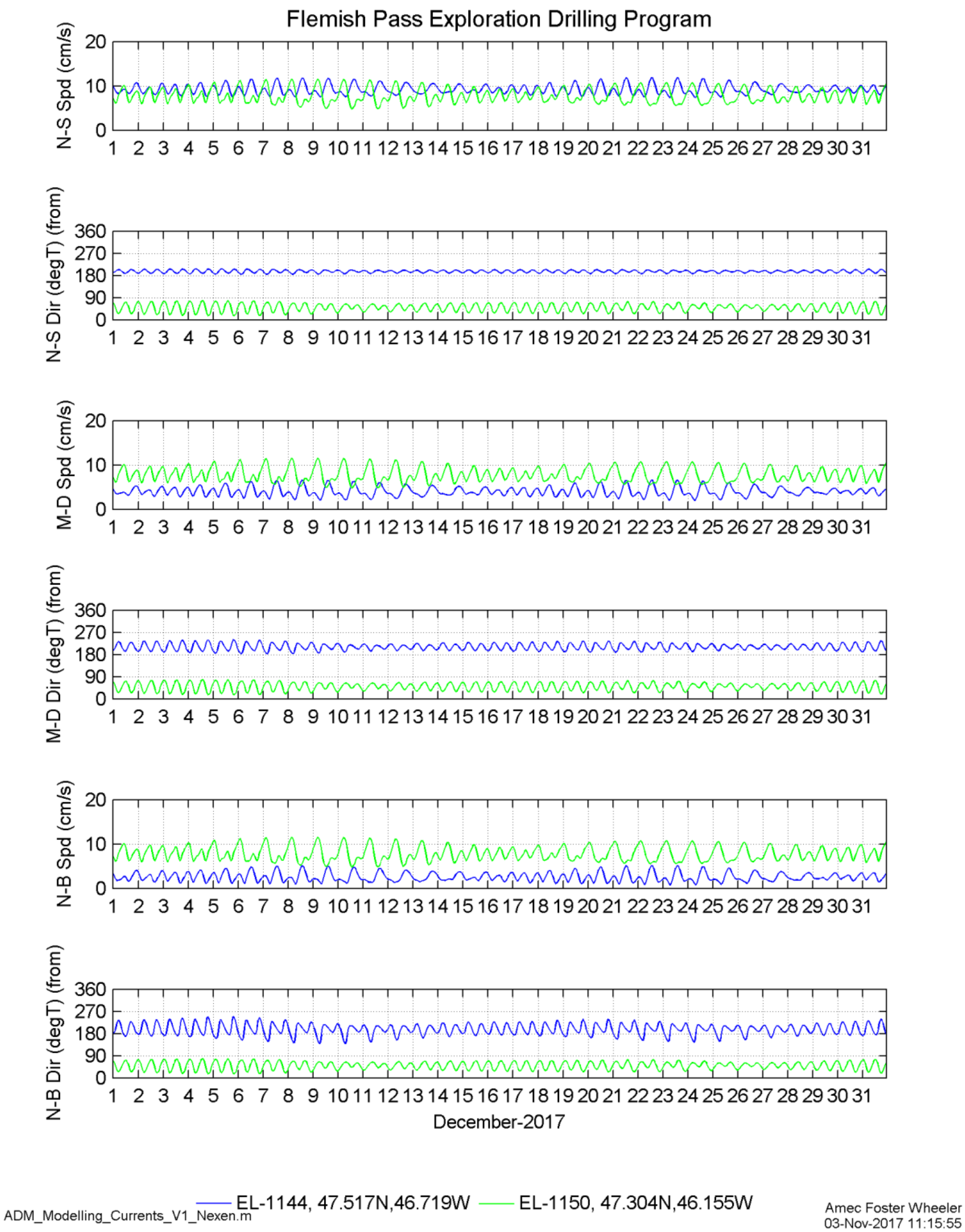
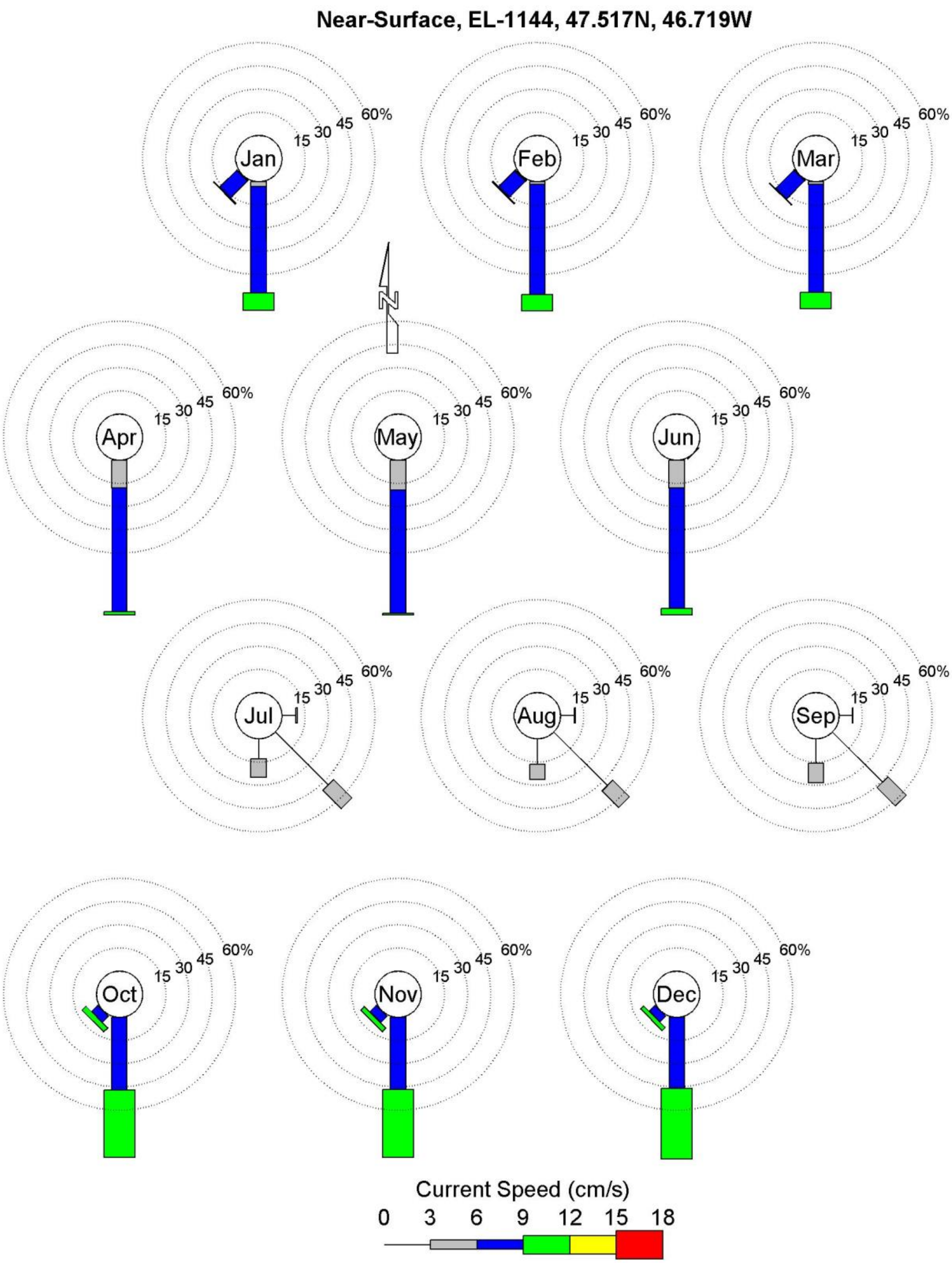
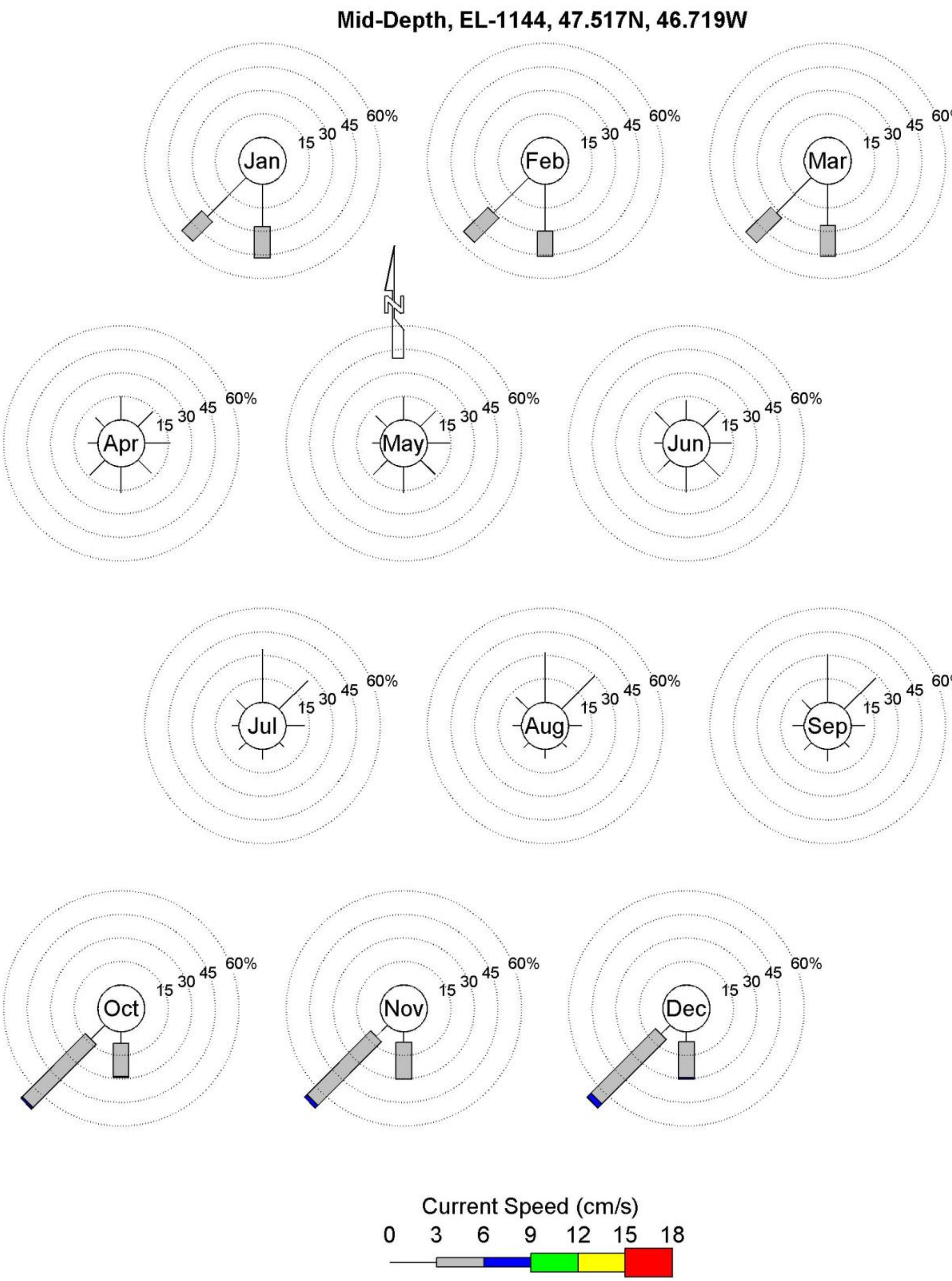
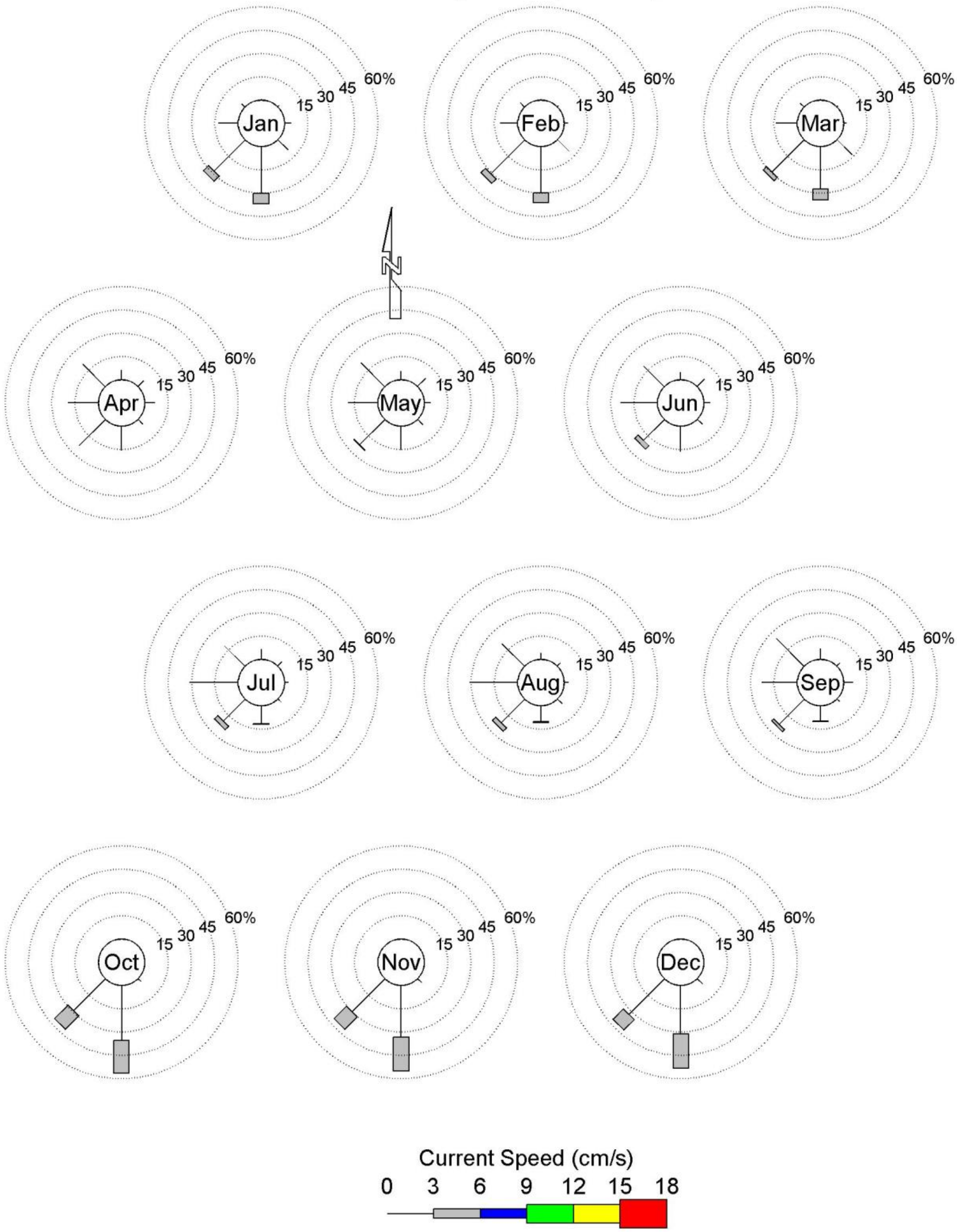
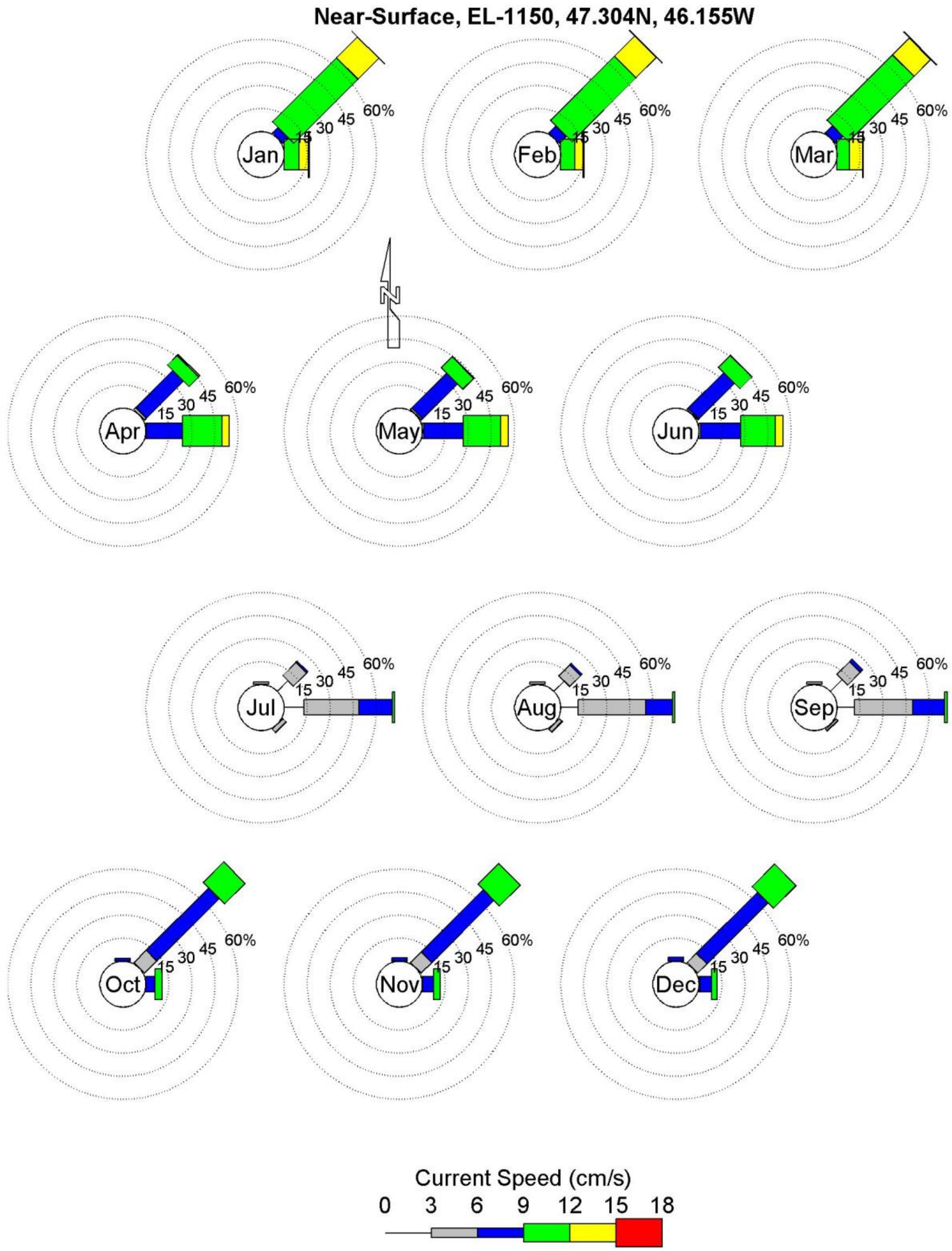

Flemish Pass Exploration Drilling Program
N-S Spd (cm/s)
0
10
20
N-S Dir (degT) (from)
0
90
180
270
360
M-D Spd (cm/s)
M-D Dir (degT) (from)
N-B Spd (cm/s)
N-B Dir (degT) (from)
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31
December-2017
EL-1144, 47.517N,46.719W
EL-1150, 47.304N,46.155W
ADM_Modelling_Currents_V1_Nexen.m
Amec Foster Wheeler
03-Nov-2017 11:15:55

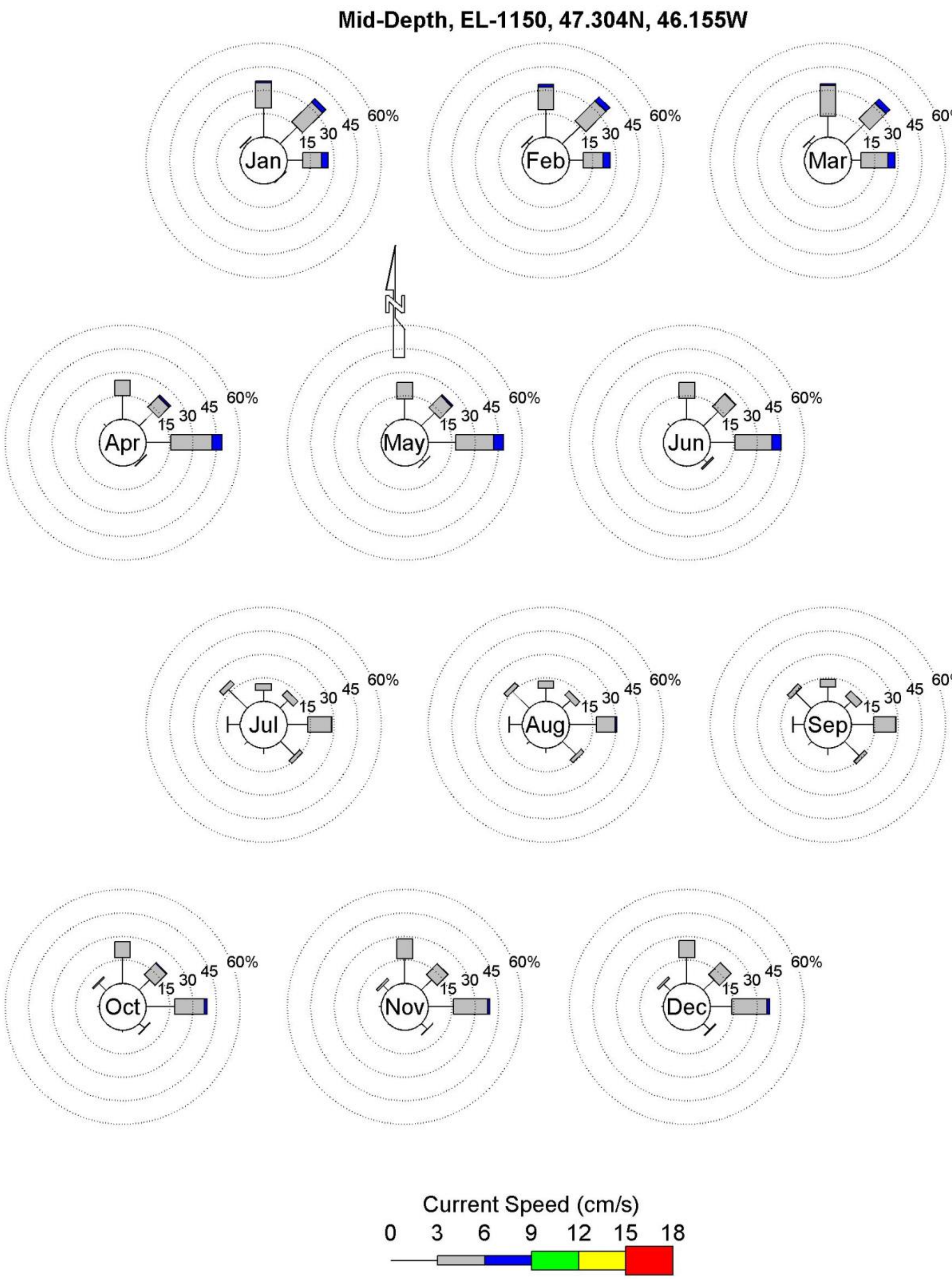

Near-Surface, EL-1144, 47.517N, 46.719W
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
15 30 45 60%
N
Current Speed (cm/s)
0 3 6 9 12 15 18

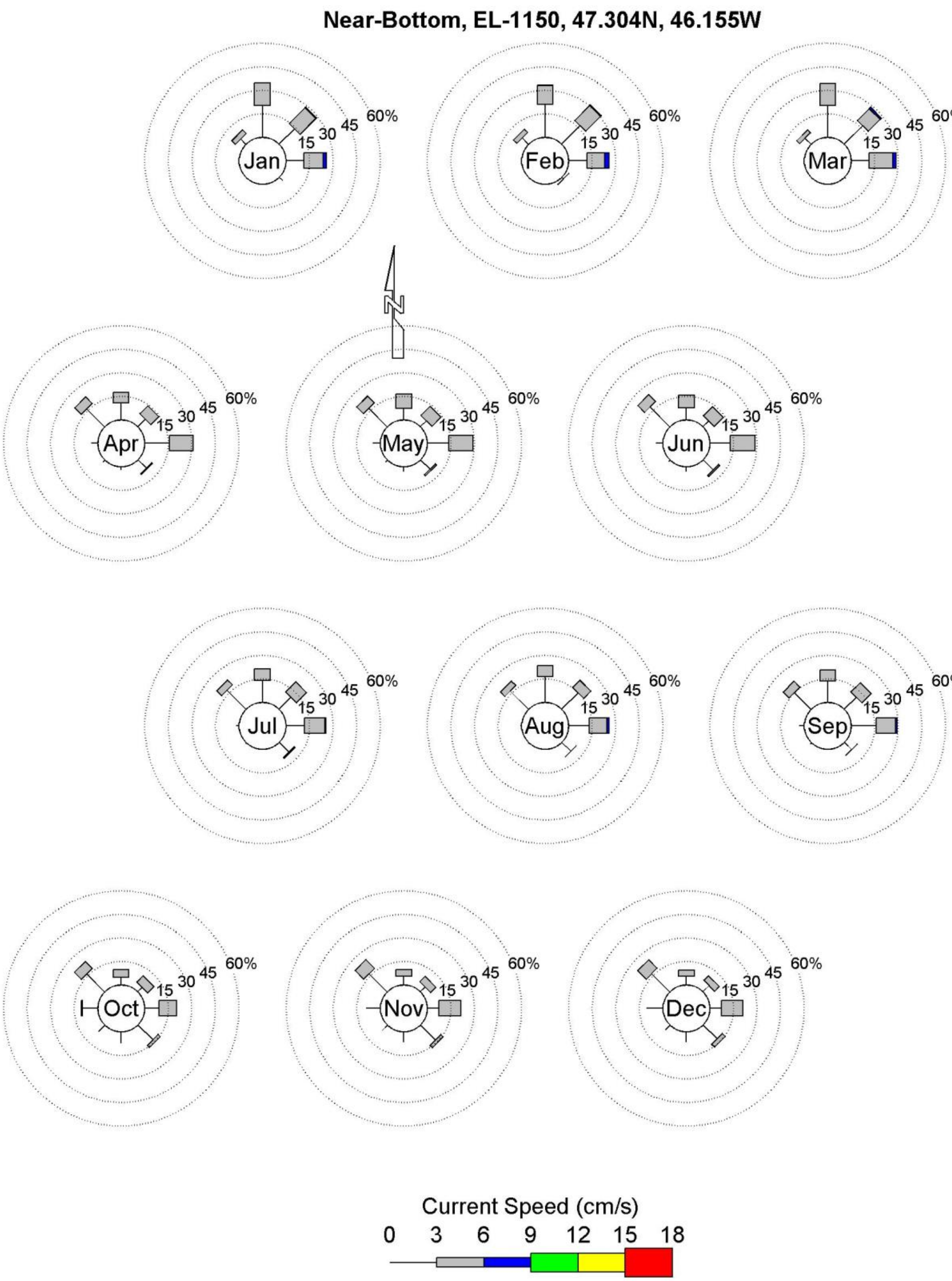

Mid-Depth, EL-1144, 47.517N, 46.719W
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
15 30 45 60%
N
Current Speed (cm/s)
0 3 6 9 12 15 18

Near-Bottom, EL-1144, 47.517N, 46.719W




Near-Surface, EL-1150, 47.304N, 46.155W
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
15 30 45 60%
Current Speed (cm/s)
0 3 6 9 12 15 18


Mid-Depth, EL-1150, 47.304N, 46.155W
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
15
30
45
60%
N
Current Speed (cm/s)
0 3 6 9 12 15 18


Near-Bottom, EL-1150, 47.304N, 46.155W
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
15
30
45
60%
N
Current Speed (cm/s)
0 3 6 9 12 15 18