Drill Cuttings Dispersion Modelling
Exploration Drilling, EL 1134

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EXECUTIVE SUMMARY

Wood Environment & Infrastructure Solutions, a Division of Wood Canada Limited (Wood) has completed a cuttings dispersion modelling study for ExxonMobil Canada Ltd. (ExxonMobil). The objective of this study is to model drill cuttings release from exploration well drilling in EL 1134, in the Flemish Pass, with the results intended to support the Environmental Impact Statement Addendum for the ExxonMobil Eastern Newfoundland Offshore Exploration Drilling Project (2018-2030) Environmental Impact Assessment (EIS).

Once a well site location has been identified, drill site clearance has been completed and the drilling unit 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 top 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 then returned to the drilling installation 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 recycled and used again.

Drill cuttings are the small pieces of rock, ranging in size from coarse sand to fine silts and clays, created when a drill bit penetrates rock. The material is forced up the annulus of the well hole 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 on the drilling platform 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 Wood, 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). Based on these data cuttings deposition map figures are presented for each scenario. These include footprints of the modelled thicknesses for i) SBM cuttings, ii) WBM cuttings and iii) total cuttings above predicted no effect thresholds (PNET) of 1.5 mm and 6.5 mm.

One site was modelled for drill cuttings discharge located at a water depth of 1,175 m, near the middle of EL 1134 about 35 km northeast of the southwestern corner of the EL 1134. With the potential to drill a well at any time during the year, four model simulation runs or 'scenarios' (for March, June, September, December) are considered to capture the associated seasonal variation in ocean currents. Each scenario model run provides a prediction of the initial cuttings footprints from drilling of a representative (i.e., similar water depth and current regime) well for a given time of year.

One year of measurements from current-meter moorings in the Flemish Pass about 14 km west of the scenario location are employed as inputs to the modelling.

Cuttings from drilling the upper two well sections with WBM are released close to the seafloor. There is little time for the cuttings to be transported any large distances by the ambient currents. Conversely SBM cuttings will be treated as per the Offshore Waste Treatment Guidelines and released near the sea surface.

Consistent with the predominant current directions in this region of the Flemish Pass, discharged WBM and SBM cuttings drift primarily to the south and southwest in each of the four months simulated.

In each month about 56% of the total cuttings material is predicted to initially settle within about 1 km of the wellhead. This includes all WBM cuttings, while, given the water depth of 1,175 m at EL 1134, from 1.2% (December) to 2.5% (June) of the SBM cuttings – the total SBM cuttings volume is about 44% of the total cuttings volume - settle within 4 km. With modelling over a larger domain out to 32 km the percentages are slightly higher, with from 2.5% (December) to 5.8% (June) of SBM cuttings predicted to initially settled. As a result total cuttings reported primarily consist of the WBM cuttings material.

Mean total cuttings thicknesses within 200 m of the wellhead are predicted to range from about 0.5 to 8 mm in all months. Corresponding maximum thicknesses within 200 m range from 8 to 31 mm for the March, June and September scenarios while the December maximum thickness at 150 m away is 80 mm.

From 200 m to 2 km away from the wellhead mean total cuttings thicknesses are predicted to range from about 0.01 mm or less farther than 1 km away in all months (excluding December when the mean is 1 mm) to 4 mm. Corresponding maximum thicknesses within 1 km range from 24 to 97 mm and are located between 250 and 410 m out from the wellhead.

The footprint accumulations are primarily to the south. One exception is seen in March (Figure 5 2) with some of the footprints located about 700-900 m directly to the northeast. This sort of reversal is confirmed with the measured currents – with evidence of coherence at other depths in the vertical - and is briefly also seen in the December measurements. These reversals may be due to topographic wave motions associated with variable wind forcing upstream; eddies or other fluctuations also seem like a possibility. As evident in the monthly current roses presented in the report these reversals are an infrequent occurrence.

The locations of footprints with thicknesses above the predicted no effect thresholds (PNET) of 1.5 mm are confined to within about 800 to 900 m of the wellhead. These patches are primarily to the south with the exception of March where there is also a patch 900 m to the northeast.

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1.0 INTRODUCTION

Wood Environment & Infrastructure Solutions, a Division of Wood Canada Limited (Wood) has been contracted by ExxonMobil Canada Ltd. (ExxonMobil) to complete drill cuttings dispersion modelling for exploration drilling in EL 1134, in the Flemish Pass South Project Area, offshore Eastern Newfoundland.

1.1 Background

ExxonMobil Canada Ltd. (ExxonMobil) and its co-venturers are planning to conduct a program of petroleum exploration / delineation / appraisal drilling and associated activities (herein referred to as exploration drilling) in the eastern portion of the Canada-Newfoundland and Labrador Offshore Area over the period 2018 to 2029 (hereinafter also referred to as the Project).

Drilling activities may occur on other licenses in the Project Area for which ExxonMobil is an operator or a Co-Venturer (i.e., ELs and/or significant discovery licences). For transparency to stakeholders and clarity in terms of the total exploration drilling activity that may be undertaken by the Operator in the Project Area, these licenses are also included in the effects assessment.

The Project includes the drilling, testing, and eventual decommissioning of exploratory wells within the ELs identified above, including EL 1134, using one or more drilling installations, which may include a semi-submersible and/or drill ship. The Project Area – Southern Section is shown in Figure 1-1. Over the course of the anticipated duration of the Project, it is estimated that up to 35 wells could be drilled, with specific wellsite 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 drilling unit 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 top 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 then returned to the drilling installation 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 recycled and used again.

Drill cuttings are the small pieces of rock, ranging in size from coarse sand to fine silts and clays, created when a drill bit penetrates rock. The material is forced up the annulus of the well hole 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 on the drilling platform 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 from exploration well drilling in EL 1134 with the results intended to support the Environmental Impact Statement Addendum for the ExxonMobil Eastern Newfoundland Offshore Exploration Drilling Project (2018-2030) Environmental Impact Assessment (EIS).

One drilling location is considered as representative for variations in water depth across EL 1134. 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 ocean currents. Each scenario model run provides a prediction of the cuttings footprints from drilling of a representative (i.e., similar water depth and current regime) well for a given time of year[1]. This report presents details of the model methods, inputs and results.

[1] The modelling presented in this report is a followup to the original drill cuttings dispersion modelling completed at a Jeanne d'Arc Basin (JDB) location (see Figure 1-1) also in the Project Area – Southern Section (Amec Foster Wheeler 2017b)

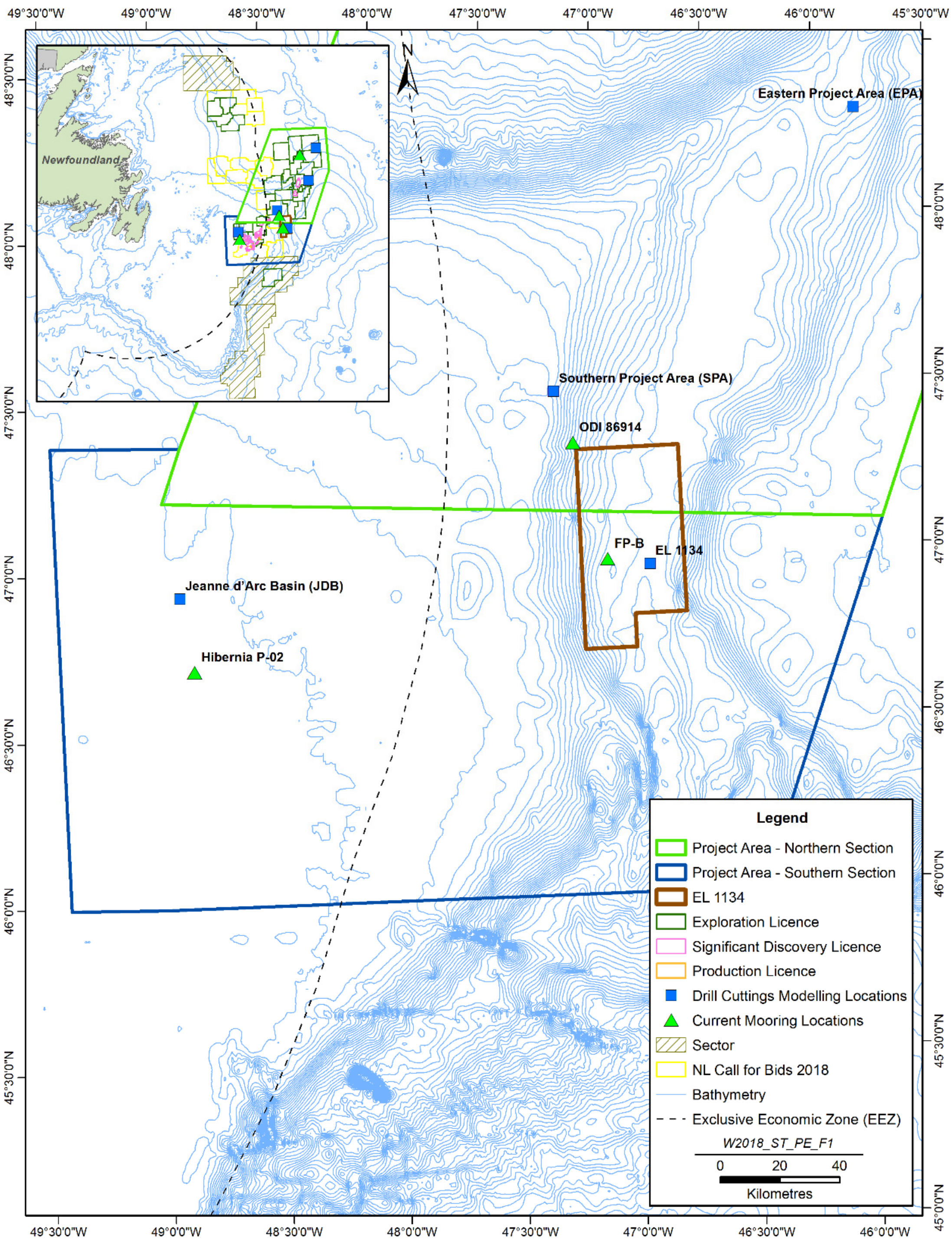

Figure 1-1 Project Area, Drill Cuttings Modelling and Current Mooring Locations

2.0 MODEL INPUTS

2.1 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, including drilling location, drill cuttings volumes and drilling schedule.

The modelling location EL 1134 “Flemish Pass South Project Area” is shown in Table 2-1

Table 2-1: Drill Cuttings Modelling Location

Location	Latitude (N)	Longitude (W)	Water depth (m)
EL 1134	46° 58.’ 48”	46° 50’ 56”	1,175

A summary of the well hole sections, drilling duration and drill cuttings volumes together with release locations associated is presented in Table 2-2. One well yields 420 m^3 of drill cuttings material comprised of 235 m^3 WBM cuttings and 185 m^3 SBM cuttings.

35 day duration is assumed.

Table 2-2: Well Hole Section Drilling and Drill Cuttings Volumes

Well hole section (hole size)	Section depth (m) [1]	# Days drilling each hole section	Start day of drilling hole section	Cuttings volume (m^3) [2]	Release location
Conductor (1067 mm)	75	2	1	80	Seabed [3]
Surface (711 mm)	400	2	6	155	Seabed [4]
Intermediate (445 mm)	900	3	13	80	Subsea [5]
Production (311 mm)	2,265	14	22	105	Subsea [5]

1. Section depths are the bottom of the section below mud line (BML), e.g., the production casing runs from 900 to 2,265 m below the seabed. Intervals may or may not be vertical.
2. Cuttings volumes include ‘washout’
3. WBM cuttings from conductor section are released directly at the seabed: estimate 2 m above seabed allowing for some initial upward momentum as cuttings materials exit the well hole.
4. WBM cuttings from surface section are released ~1-2 m above seabed: similarly estimate 4 m above seabed allowing for some initial upward momentum
5. SBM cuttings from intermediate and production sections released from the MODU at an estimated 14 m below the sea surface.

2.2 Drill Cuttings Characterization

A characterization of the drill cuttings released during the drilling program is used in the dispersion model (Section 3.1) to predict their fall (settling) in the ocean until they settle on the seabed (or drift outside the model geographical domain).

The characterizations employed here are those presented in the previous modelling for the JDB location (Figure 1-1) in the Project Area – Southern Section (Amec Foster Wheeler 2017b). That modelling used results of sieve analysis by Core Laboratories of four 2014 cuttings samples from the HMDC Hibernia P-02 1A well – located about 3.5 km southeast of the JDB location – to define the composition. The mean of samples at depths of 2,050 m and 2,400 m were taken as the percent of material composition for the top three sections. The reservoir section characterization assumed is the mean of two samples at depths 2,650 m and 3,090 m.

This cuttings particle size composition is presented in Table 2-3. These are estimates: the actual compositions of the drill cuttings will depend on rate of penetration, rotary table speed, hydraulics, bit selection, 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.

Table 2-3: Cuttings Particle Size Percent Composition

	Measured Weight Percent Material					
Cuttings Type, Well Section	COARSE SAND	MEDIUM SAND	FINE SAND	V. FINE SAND	COARSE-MEDIUM SILT	FINE SILTS-CLAYS
WBM, conductor and surface	0.0	0.3	1.0	4.9	3.9	90.0
SBM, intermediate	0.0	0.3	1.0	4.9	3.9	90.0
SBM, production	0.0	0.7	2.8	7.7	5.6	83.1

It is assumed that the cuttings will enter the sea in a relatively disaggregated form. The model considers the 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 2-3, the associated particle fall velocities are also essential for the deposition modelling. Table 2-4 lists, for each particle type, its diameter and associated fall velocity, estimated from particle diameter following Sleath (1984).

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

$$w = 4.2\sqrt{D},\ D > 0.0001\ m \qquad (1)$$

$$w = 92\ \times 10^4\ D^2, D \leq 0.0001\ m \qquad (2)$$

where

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

Table 2-4: Cuttings Particle Size Characterization

	Cuttings Material					
	COARSE SAND	MEDIUM SAND	FINE SAND	V. FINE SAND	COARSE-MEDIUM SILT	FINE SILTS-CLAYS
Particle diameter (mm)	0.595	0.297	0.149	0.074	0.031	0.005
Particle fall velocity (m/s)	0.102	0.072	0.051	0.005	0.001	0.001

Based on equation (2), the settling velocities for the two smallest particles are 0.0009 and 2.3×10^{-6} 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 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). The 'base case' values of 0.001 m/s for the two smallest particle types as reported in Table 2-4, were deemed the most reasonable and selected for the model runs. These slightly smaller values (0.001 rather than 0.005) also provide a somewhat more conservative estimate in terms of how far horizontally the cuttings may disperse, given that a measure of flocculation is assumed.

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.

Measurements from current-meter moorings in the Flemish Pass (Loder and Geshelin 2003, Geshelin and Loder 2004) were selected for model input. Data from the first two deployments from the FP-B site (Figure 1-1) covering the period 29 June 2002 to 19 July 2003 were kindly provided by John Loder, DFO. To align with the model, a one year long record was kept to run from 1900 h on 29 June 2002 to 1800 h on 29 June 2003. The model recycles the currents at the end of any given year in the simulation of the well drilling, e.g., a June simulation will start with currents from the 2002 record and after 1900 h on 29 June continue with the 29 June 2003 values.

The FP-B measurements from depths 114, 514 and 1,109 m were selected to represent near-surface, mid-depth and near-bottom currents for the model. The model advects particles (equations 1-3) with currents at the depth corresponding to the depth the particles have settled to at each model time step.

Table 2-5: Monthly Current Statistics, FP-B

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Near-Surface 114 m	Min (cm/s)	2	3	2	2	1	5	3	3	2	6	7	5
	Mean (cm/s)	34	32	34	21	18	21	21	20	18	22	27	32
	SD (cm/s)	13	13	14	10	9	7	8	6	5	6	6	9
	Max (cm/s)	71	65	77	42	51	37	43	38	32	45	44	66
Mid-Depth 514 m	Min (cm/s)	2	1	1	1	1	1	1	1	4	6	7	4
	Mean (cm/s)	19	20	20	15	12	14	11	13	16	16	17	19
	SD (cm/s)	5	7	8	7	6	4	4	4	4	3	3	5
	Max (cm/s)	33	41	43	33	30	26	23	23	25	24	26	33
Near-Bottom 1,109 m	Min (cm/s)	1	1	1	1	1	1	1	1	1	1	1	1
	Mean (cm/s)	12	12	15	15	11	12	10	13	14	12	11	10
	SD (cm/s)	5	7	7	6	7	4	5	5	4	4	5	5
	Max (cm/s)	27	31	40	36	30	22	22	23	24	26	26	28

Statistics reported in the Table are for the full (first two deployments) June 2002 to July 2003 record

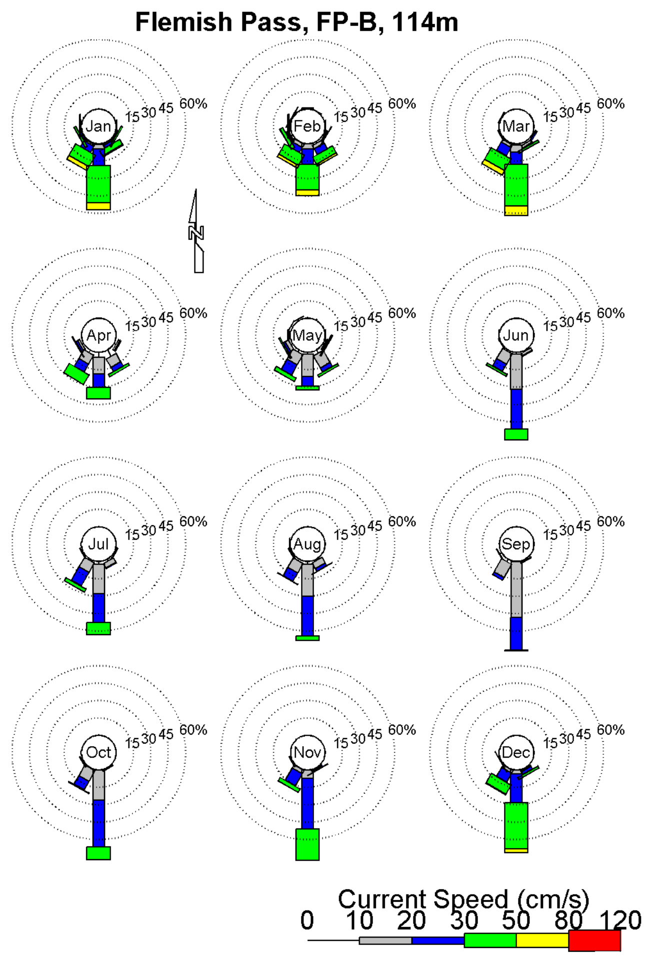

Figure 2-1 Monthly Current Roses, FP-B, Near-Surface

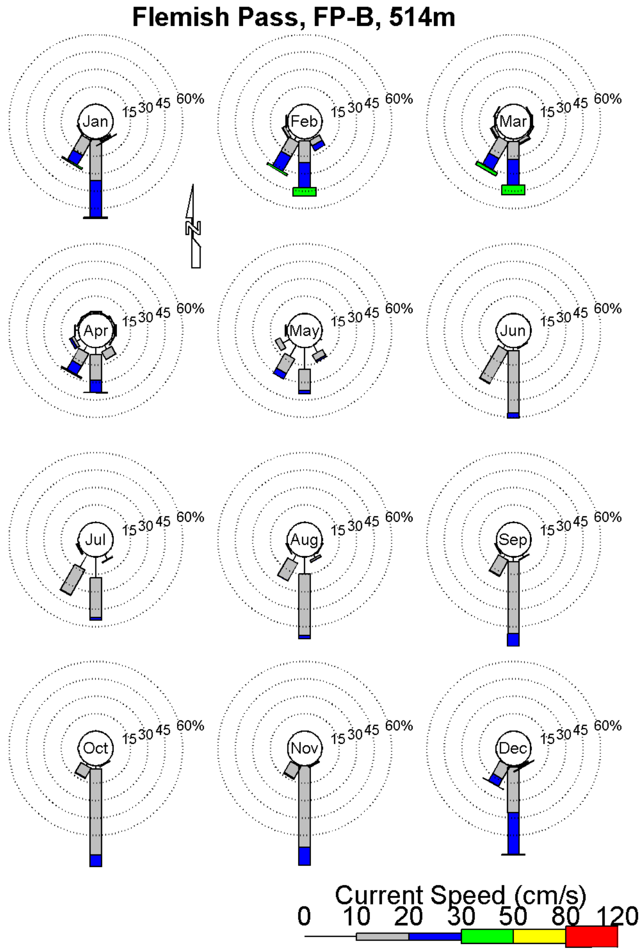

Figure 2-2 Monthly Current Roses, FP-B, Mid-Depth

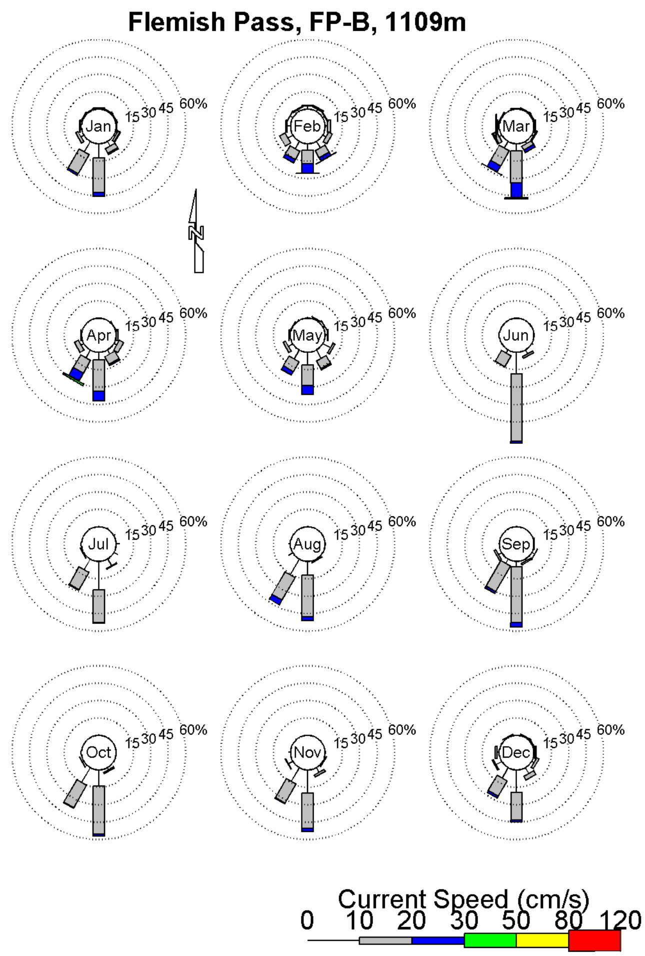

Figure 2-3 Monthly Current Roses, FP-B, Near-Bottom

Appendix A presents monthly time series plots of current speed and direction at the three depths. The months are presented as a 'calendar year' from January to December: the actual input record as noted above runs from 29 June 2002 to 29 June 2003.

3.0 MODEL METHOD

3.1 Advection-Diffusion Algorithm

The analysis of drill cuttings discharges is accomplished using the AMEC Advection Dispersion Model (ADM). The ADM is an advection-diffusion numerical computer model where the dispersion of cuttings released from a single point is governed by advection and turbulent diffusion in the horizontal and vertical planes. The ADM was developed based on corporate experience and modelling algorithms including those from the Terra Nova (Hodgins and Hodgins 1998) and White Rose (Hodgins and Hodgins 2000) cuttings fate modelling studies, and has been used, for numerous offshore operators including the Hebron Project Comprehensive Study Report modelling study (AMEC 2010) and Hebron Project Environmental Assessment Amendment (Amec Foster Wheeler 2017a), and the White Rose Extension Project (now West White Rose Project) (AMEC 2012, Amec Foster Wheeler 2016).

In the model, the governing transport-diffusion equation is solved using a particle tracing technique. Sets of discrete cuttings particles are released over time, with each particle having an associated mass. 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 sand, silt and clay. These particle sizes are assumed to be generally representative of the materials likely to be encountered in the area and generated using water-based muds (WBM) or synthetic-based muds (SBM).

At any given time, a cuttings 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 term to model turbulent diffusion is added to the displacements. For each time step 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 used to encompass the drilling area and possible domain for the deposition of the cuttings. 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 and thickness of materials are calculated for each grid cell. These spatial cuttings thickness footprints are the primary model output.

The transport (and spatial extent) and fate of the cuttings are modelled as a function of time. A given sequence of wells, with each well employing a schedule of drilling with associated cuttings release, is employed to simulate the release as a function of time (days). For each day for which materials are released, and for each different size class of material (i.e., the cobble-pebble, granule, two sand sizes, fines and silt-clay in Table 2-4), a collection of particles are discharged. Particles are assigned a weight apportioned on the number of days drilling and the volume of cuttings associated with the particular well section (Table 2-2). 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 (Table 3-1), a new location for a given particle is calculated.

Table 3-1: Model Time Steps for Cuttings Particles

	Cuttings Material					
Particle Parameter	COARSE SAND	MEDIUM SAND	FINE SAND	V. FINE SAND	COARSE-MEDIUM SILT	FINE SILTS-CLAYS
Time Step, Δt (s)	20	20	40	60	600	600
# Particles per Δt	1	1	2	3	30	30
# Steps per day	4,320	4,320	2,160	1,440	144	144

The path of each cuttings 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 (3) to (5).

$$x_{n+1} = x_n + u \times \Delta t + x' \times Rx \quad (3)$$

$$y_{n+1} = y_n + v \times \Delta t + y' \times Ry \quad (4)$$

$$z_{n+1} = z_n + w \times \Delta t + z' \times Rz \quad (5)$$

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), e.g., Table 2-4
- 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. The turbulent part of the flow field arises from subgrid scale motions that are not resolved in the tidal+non-tidal current data and lead to a random diffusion of particles within the grid. For a particle which moves a distance that is a uniformly distributed random displacement (hence R in [-1,1]) in the range (-x′, …, x′) in time step Δt its solution of the diffusion equation gives $x',y'=(6Ah\Delta tp)^{1/2}$, with Ah a turbulent eddy diffusivity coefficient set=0.1 m^2/s. The model integration time step Δt depends on settling velocity. Values for x′ for coarse sand to fine silts and clays range from 6 m to 46.5 m. For example, at any time for a coarse particle, the x′Rx term might range from say -6 m to 6 m. Grid cell sizes simply determine where particles are within the grid, and for example, in which grid cell they are placed when they reach the seabed, but have no effect on the diffusion. There is a similar treatment for y′Ry. The z′ component is a uniformly distributed random displacement in the vertical, in the range +0.05*w*Δt, i.e., an uncertainty of +5% in the distance fallen each time step.

A grid of the seabed is used in the model to track the spatial extent of depositions. As each particle reaches the bottom it is deposited in the nearest grid cell. The model grid is a Cartesian grid of size centred at the drill cuttings scenario location (i.e., at the wellhead or template location) and extending out a finite distance both in X (East-West) and Y (North-South) directions. At least two grid cell sizes are typically employed, one to resolve dispersion patterns about the wellhead or template, e.g., ≈+4 km, and a coarser one to provide a farther-field coverage out to many kilometres, with the extent tuned during early model runs.

A grid of the seabed is used in the model to track the spatial extent of the cuttings 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 are used. A 32 m cell provides coverage out to 32 km, while 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 a uniform water depth of 1,175 m.

The following parameters are calculated for each grid cell, with cuttings thickness, T, being of primary interest.

$$C = W \times 1000 / A \quad (6)$$

$$T = C / \gamma \quad (7)$$

$$OC = OCinitial \times W / (A \times h \times (1-n) \times \gamma s) \quad (8)$$

where

- W = cuttings (dry) 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)
- OCinitial = initial oil concentration
- h = sediment mixing depth (0.08 m)
- n = seabed porosity (0.4)
- γs = specific weight of cuttings (2,596 kg/m^3)

3.2 Limitations and Assumptions

Limitations of the modelling include (ExxonMobil's) best estimates of the following variables for the well drilling (see also Section 2.0):

- cuttings volumes
- discharge schedule
- particle characterization (i.e., percentage of sands and fines)

Assumptions include:

- ocean currents used are assumed representative of conditions at and near the drilling location

- cuttings enter the sea in a relatively disaggregated form with sand materials remaining disaggregated in their fall to the seabed and fines assumed to aggregate into flocs of diameter approximately 0.1 mm and settle with a constant speed
- the dispersion model does not consider processes at the benthic boundary layer. This could include resuspension of cuttings with the potential for sediment mobilization based on current speed, e.g., clays and fines potentially mobilizing at lower current speeds, sands requiring higher speeds to move. Breakup of flocculates might be expected to reduce near-bottom concentrations, i.e., particles resuspend and are advected away by the ambient currents. Bioturbation is another process and difficult to quantify for the intensity and rate of reworking that might take place at any of the locations. These post-depositional processes are difficult to model and data are scarce. The implications of not modelling these processes can result in over-prediction of benthic impacts (IOGP 2016); predicted thicknesses are likely conservative in the sense that subsequent resuspension and further transport would likely render the thicknesses smaller.

4.0 MODEL OUTPUTS

Model output files contain 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
- depth z (m)
- 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/m2)
  - cuttings thickness(mm)
  - number of particles of each of six types (cobble-pebble, granule, two sands, fines and silt-clay)

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.

5.0 RESULTS

The cuttings model tracks and outputs separately, the WBM, SBM and total (WBM plus SBM) deposition results. Model results include 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. Conversely SBM cuttings, treated and released in accordance with the OWTG, will be released near the sea surface (14 m assumed, see Table 2-2).

The amounts of WBM and SBM cuttings material modelled to settle for selected distances from the well site (origin) are presented in Table 5-1. In Table 5-2 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. The maximum thicknesses are the one largest thickness observed in each 'distance from well site' bin. The notes under Table 5-2 list the location of each month's maximum total cuttings thickness, e.g., in June the largest thickness is 94 mm, 410 m to the south of the well site.

Table 5-1: Cuttings Material Settled by Distance

EL1134		Distance from Well Site										
		0-10m	10-100m	100-200m	200-500m	500m-1km	1-2km	2-4km	4-5km	5-31km	> 31km	
Month	**Cuttings Type**	% Material Settled										**% Material Unsettled** (WBM, SBM)
Mar	Total	0.3	1.2	1.7	18	35	0.2	0.5	0.2	-	-	-, 95
Jun	Total	0.4	1.6	1.4	33	19	0.2	1	<0.01	-	-	-, 94
Sep	Total	0.3	1.1	1.9	18	35	0.1	1	<0.01	-	-	-, 97
Dec	Total	0.4	2.1	11	25	17	0.02	0.5	0.04	-	-	-. 98

Total cuttings include WBM+SBM. Row percentages for total cuttings settled sum to ~57%: about 94 to 98% of the SBM cuttings (which represent about 44% of the total cuttings volume) fail to settle within the 32 km model domain.

In each month about 56% of the total cuttings material is predicted to initially settle within about 1 km of the wellhead. This includes all WBM cuttings, while, given the water depth of 1,175 m at EL 1134, from 1.2% (December) to 2.5% (June) of the SBM cuttings - the total SBM cuttings volume is about 44% of the total cuttings volume - settle within 4 km. With modelling over a larger domain out to 32 km the percentages are slightly higher, with from 2.5% (December) to 5.8% (June) of SBM cuttings predicted to initially settled. As a result total cuttings reported primarily consist of the WBM cuttings material.

Table 5-2: Cuttings Thickness by Distance

EL1134		Distance from Well Site									
		0-10m	10-100m	100-200m	200-500m	500m-1km	1-2km	2-4km	4-5km	5-31km	> 31km
Cuttings Type		Cuttings Thickness (mm)									
	March										
Total	Mean	5	0.5	0.4	2	2	0.01	0.01	0.01	-	-
	Maximum	12	13	8	86[1]	26	1	0.05	0.07	-	-
	June										
Total	Mean	7	1	0.5	4	2	<0.01	0.01	<0.01	-	-
	Maximum	31	20	8	97 [2]	25	0.05	0.07	0.01	-	-
	September										
Total	Mean	5	1	1	3	3	0.01	0.01	<0.01	-	-
	Maximum	22	22	9	95 [3]	24	1	0.01	<0.01	-	-
	December										
Total	Mean	8	1	2	3	3	0.8	0.01	0.01	-	-
	Maximum	22	15	80[4]	69	26	1	0.07	0.04	-	-

[1] at (0.25 km, 190°); [2] at (0.41 km, 184°); [3] at (0.37 km, 193°); [4] at (0.15 km, 141°)

Consistent with the predominant current directions in this region of the Flemish Pass, discharged WBM and SBM cuttings drift primarily to the south and southwest in each of the four months simulated.

Mean total cuttings thicknesses within 200 m of the wellhead are predicted to range from about 0.5 to 8 mm in all months. Corresponding maximum thicknesses within 200 m range from 8 to 31 mm for the March, June and September scenarios while the December maximum thickness at 150 m away is 80 mm.

From 200 m to 2 km away from the wellhead mean total cuttings thicknesses are predicted to range from about 0.01 mm or less farther than 1 km away in all months (excluding December when the mean is 1 mm) to 4 mm. Corresponding maximum thicknesses within 1 km range from 24 to 97 mm and are located between 250 and 410 m out from the wellhead.

A set of three cuttings deposition map figures are presented for each of the four seasonal scenarios. These include footprints of the modelled thicknesses for i) SBM cuttings, ii) WBM cuttings and iii) total cuttings above predicted no effect thresholds (PNET) of 1.5 mm and 6.5 mm. These maps are shown in Figure 5-1 to Figure 5-12.

The PNET thresholds are shown to assist in the assessment of potential biological effects of drill cuttings deposition. 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).

Different distance scales are set to best illustrate the spatial extent and show detailed resolution in the footprint maps, e.g., 18 km is used for SBM cuttings and 2 km for the WBM and PNET thresholds maps in an attempt to use consistent scales between seasons to facilitate comparison of results. The total cuttings with PNET limits footprints include radii drawn at 500 m, 1 km and 2 km.

As noted above, the footprint accumulations are primarily to the south. One exception is seen in March (Figure 5-2) with some of the footprints located about 700-900 m directly to the northeast. This sort of reversal is confirmed with the measured currents – with evidence of coherence at other depths in the vertical - and is briefly also seen in the December measurements. These reversals may be due to topographic wave motions associated with variable wind forcing upstream; eddies or other fluctuations also seem like a possibility (J. Loder, pers. comm.). As evident in the monthly current roses presented in the report these reversals are an infrequent occurrence.

The locations of footprints with thicknesses above the PNET of 1.5 mm are confined to within about 800 to 900 m of the wellhead. These patches are primarily to the south with the exception of March where there is also a patch 900 m to the northeast.

March

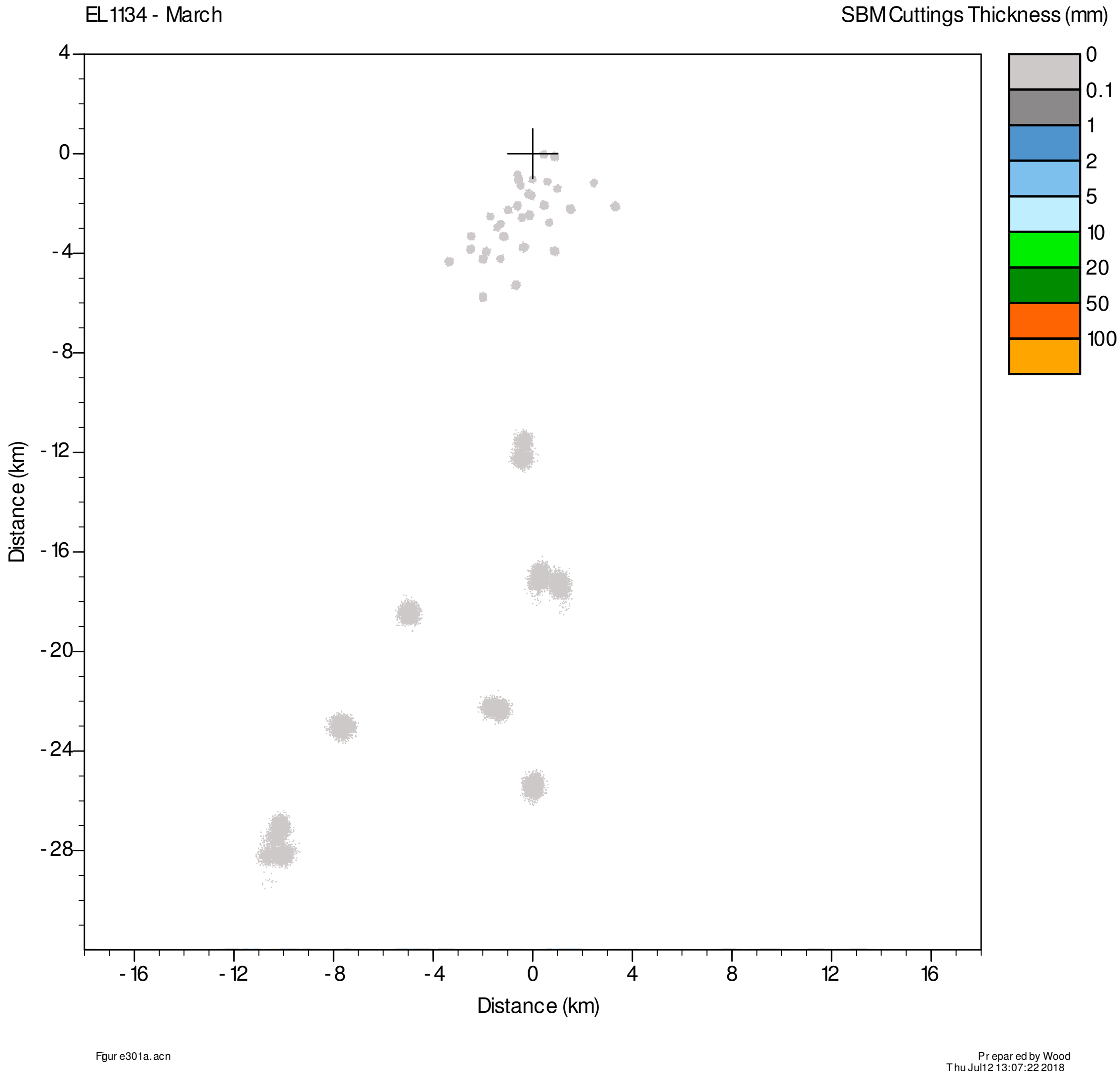

Figure 5-1 SBM Drill Cuttings Deposition, EL 1134, March, 18-km View

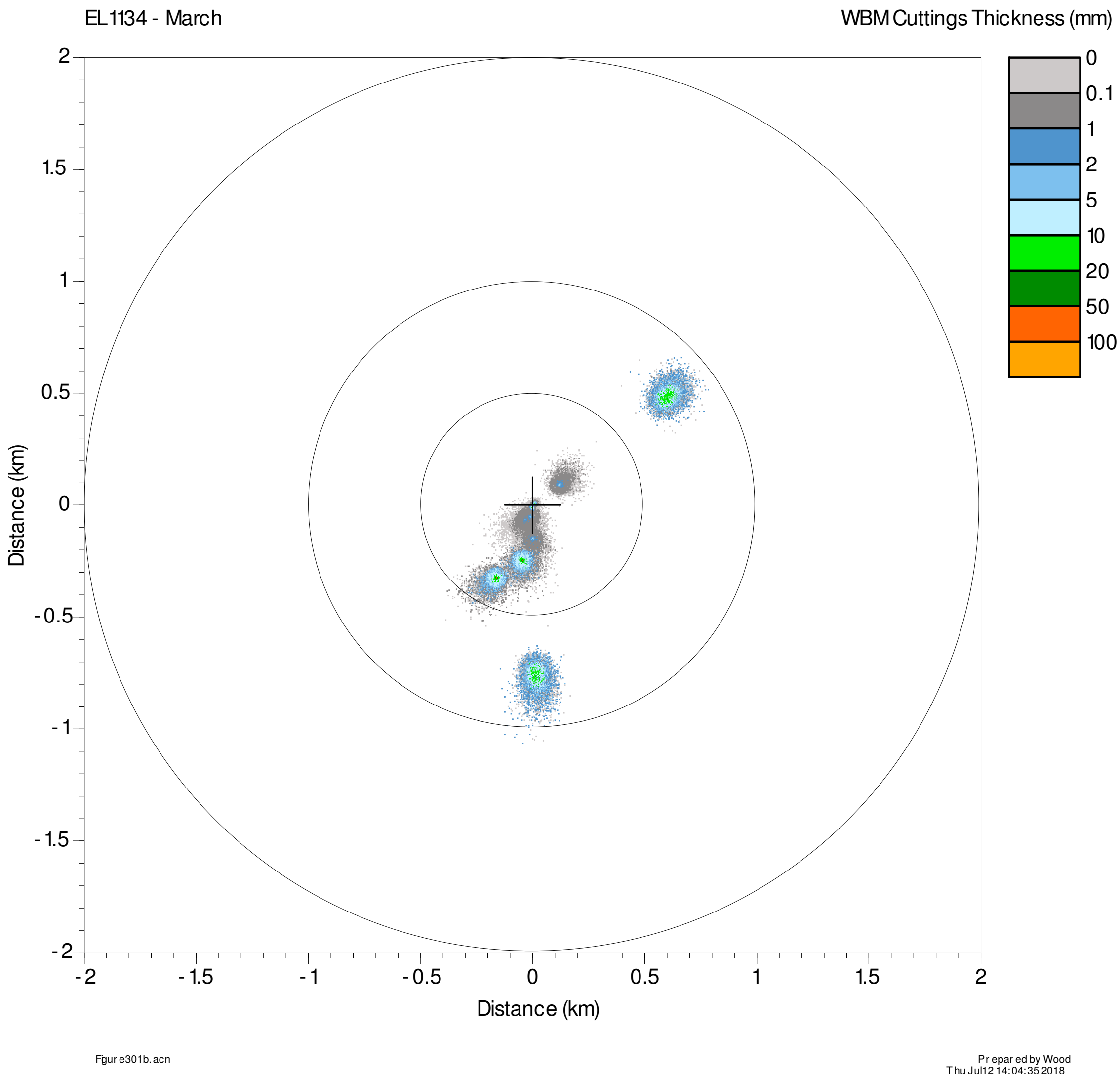

Figure 5-2 WBM Drill Cuttings Deposition, EL 1134, March, 2-km View

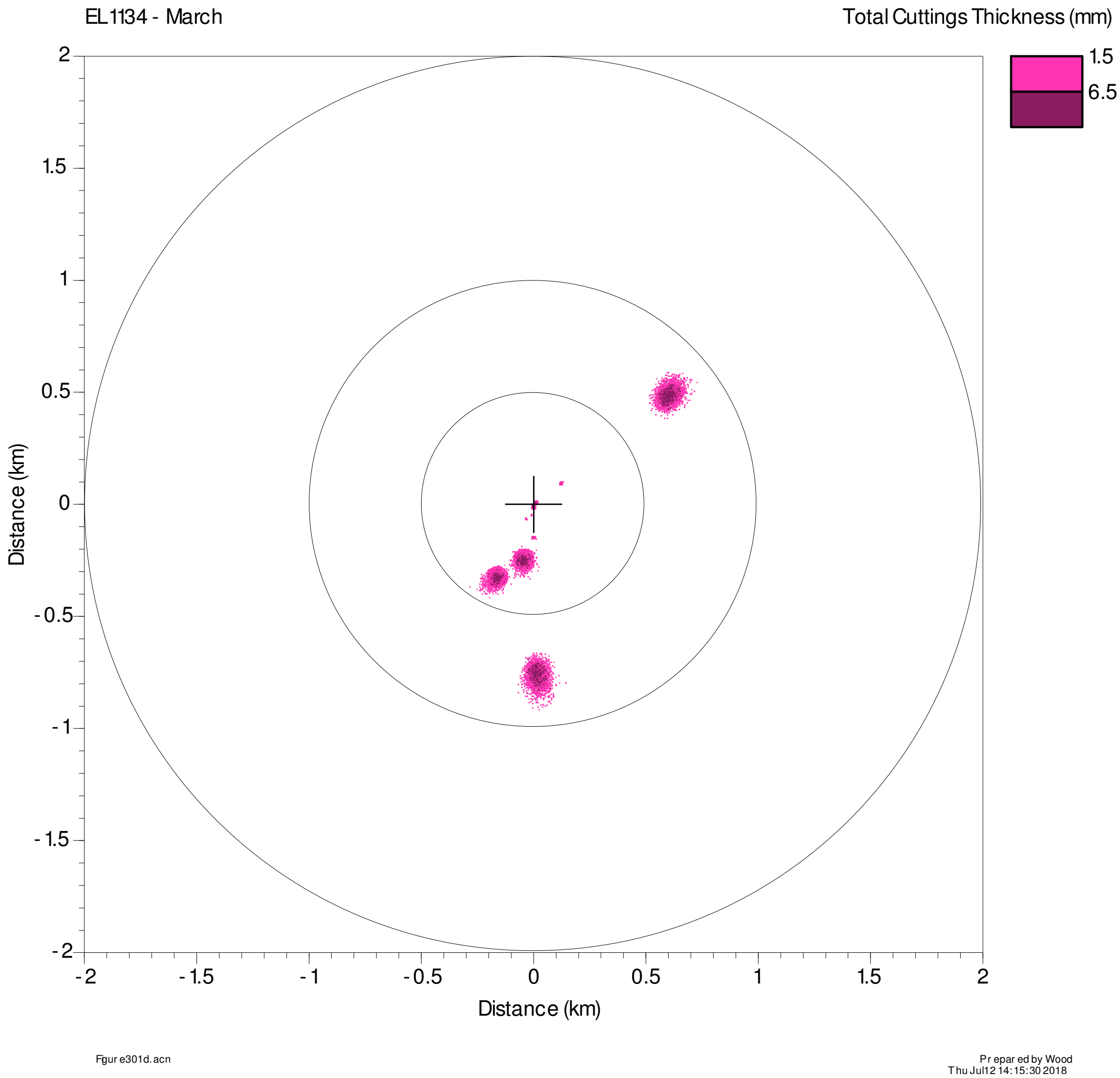

Figure 5-3 Total Drill Cuttings Deposition, PNET Limits, EL 1134, March, 2-km View

June

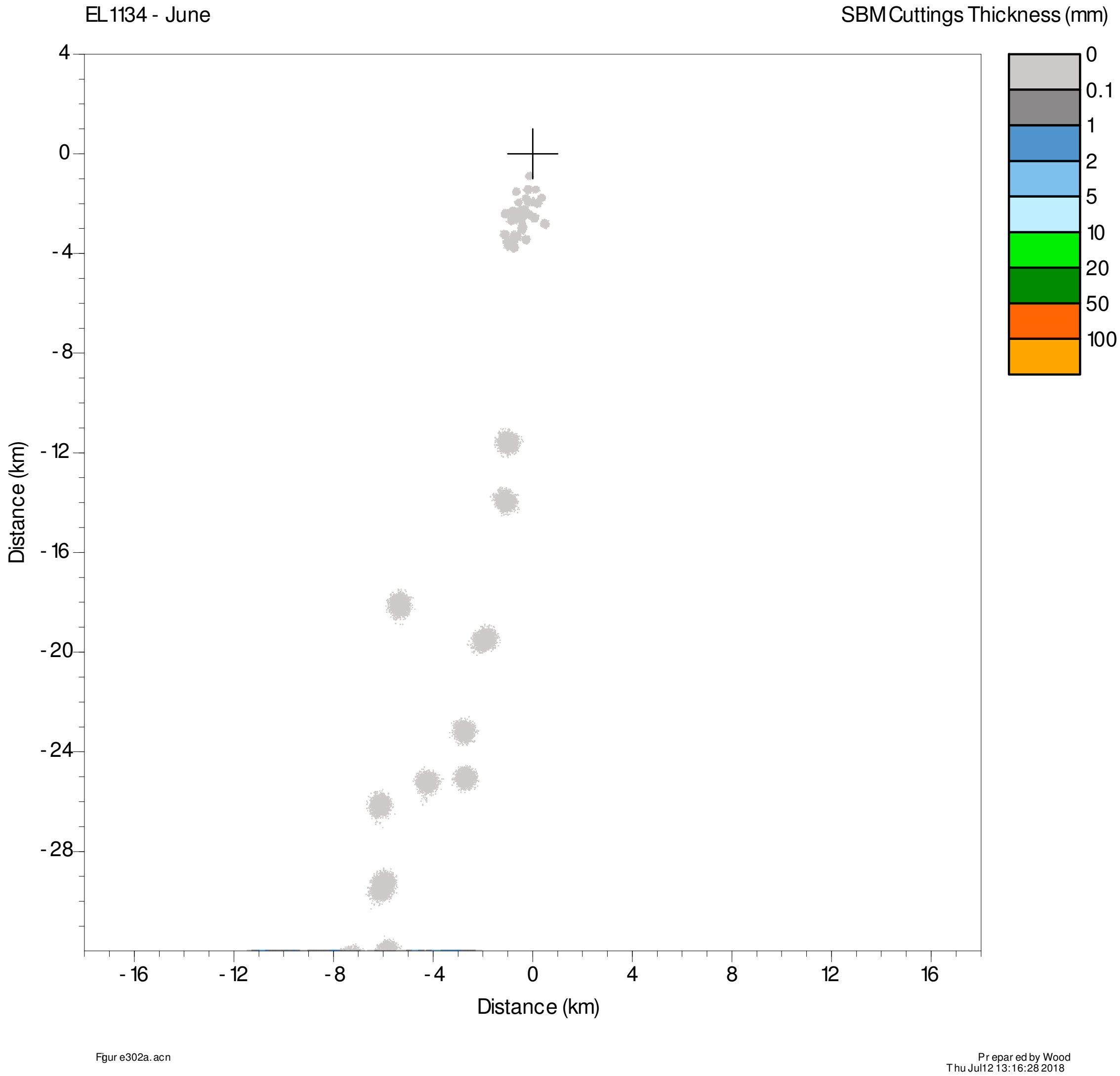

Figure 5-4 SBM Drill Cuttings Deposition, EL 1134, June, 18-km View

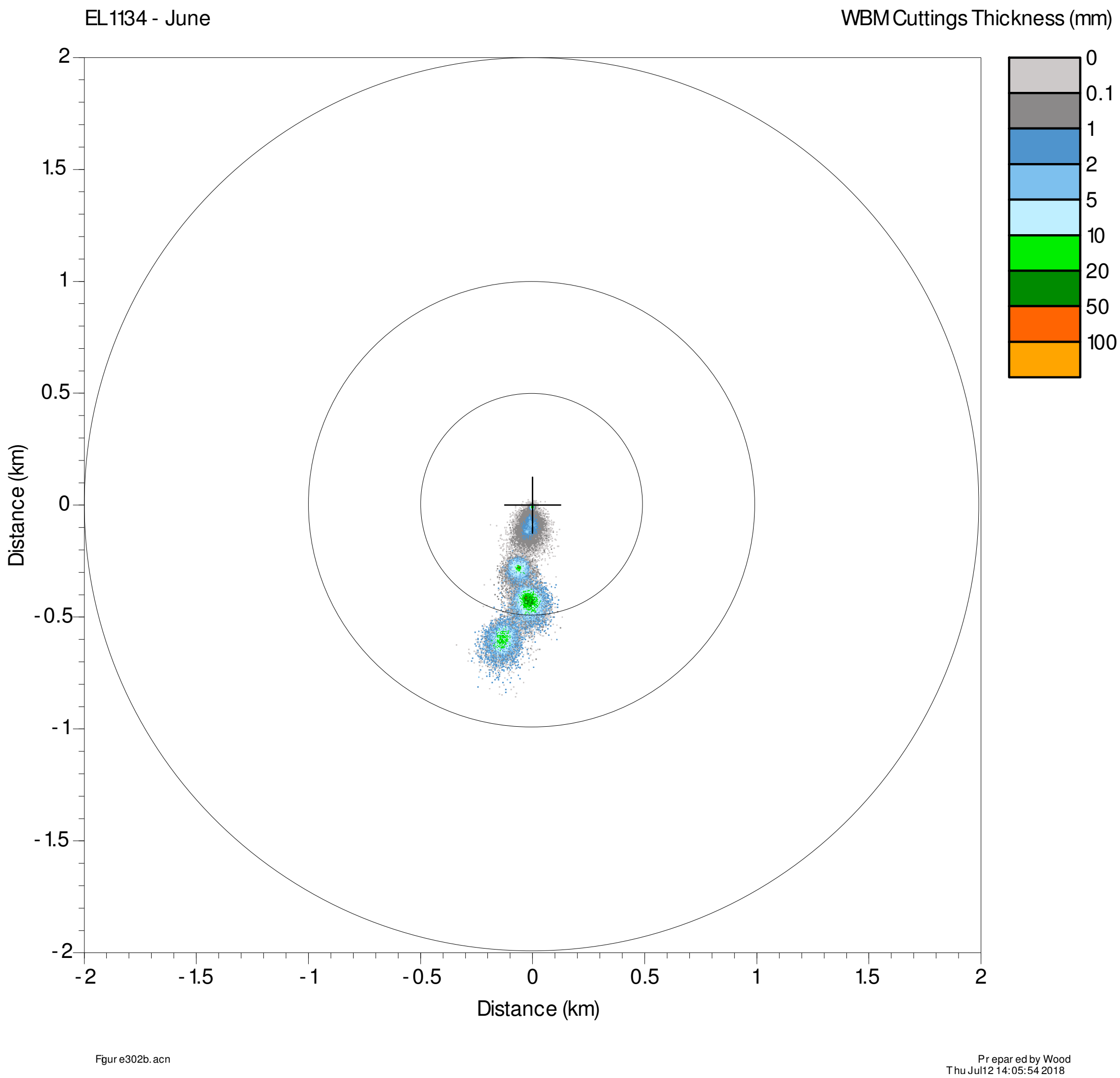

Figure 5-5 WBM Drill Cuttings Deposition, EL 1134, June, 2-km View

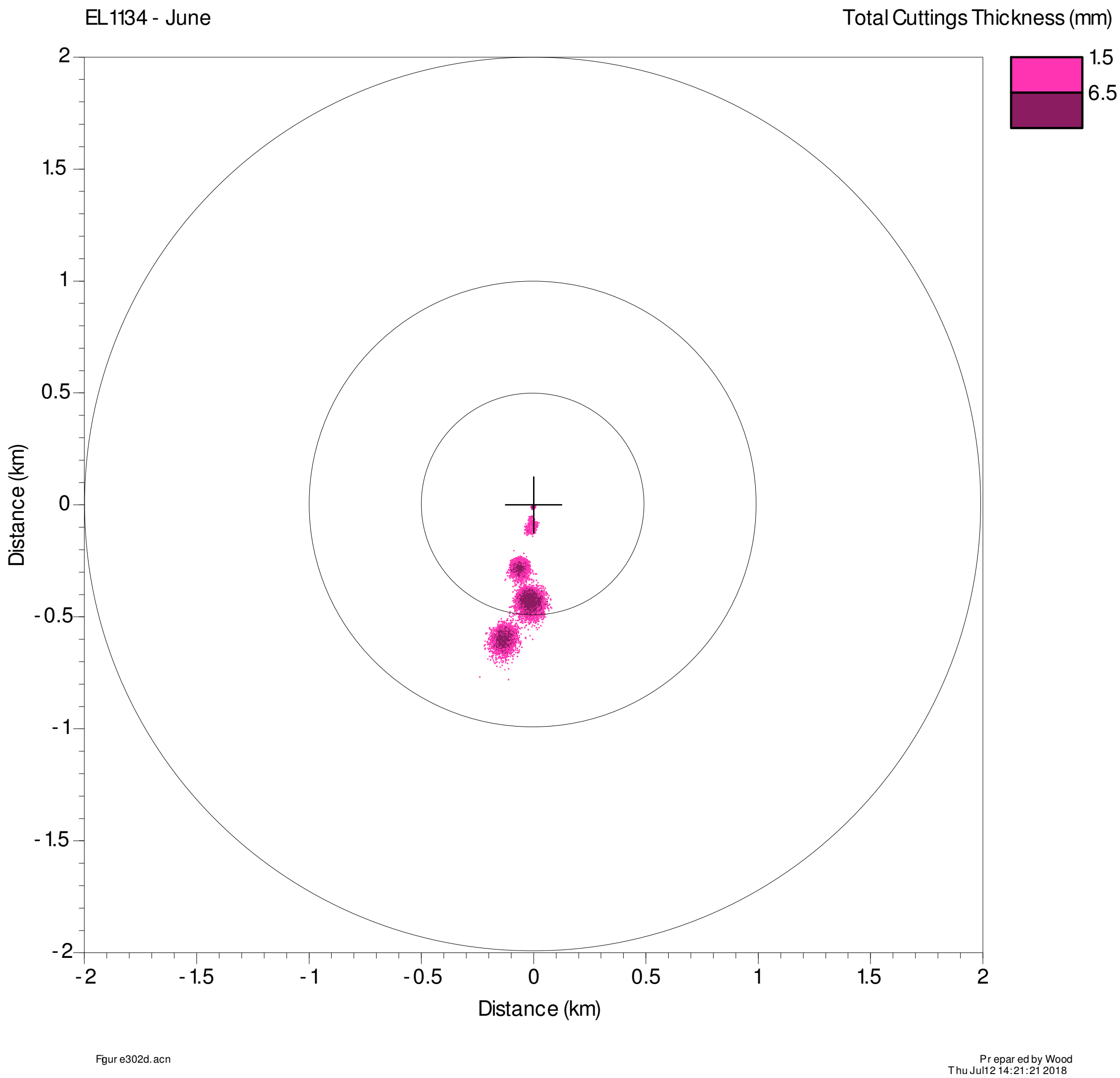

Figure 5-6 Total Drill Cuttings Deposition, PNET Limits, EL 1134, June, 2-km View

September

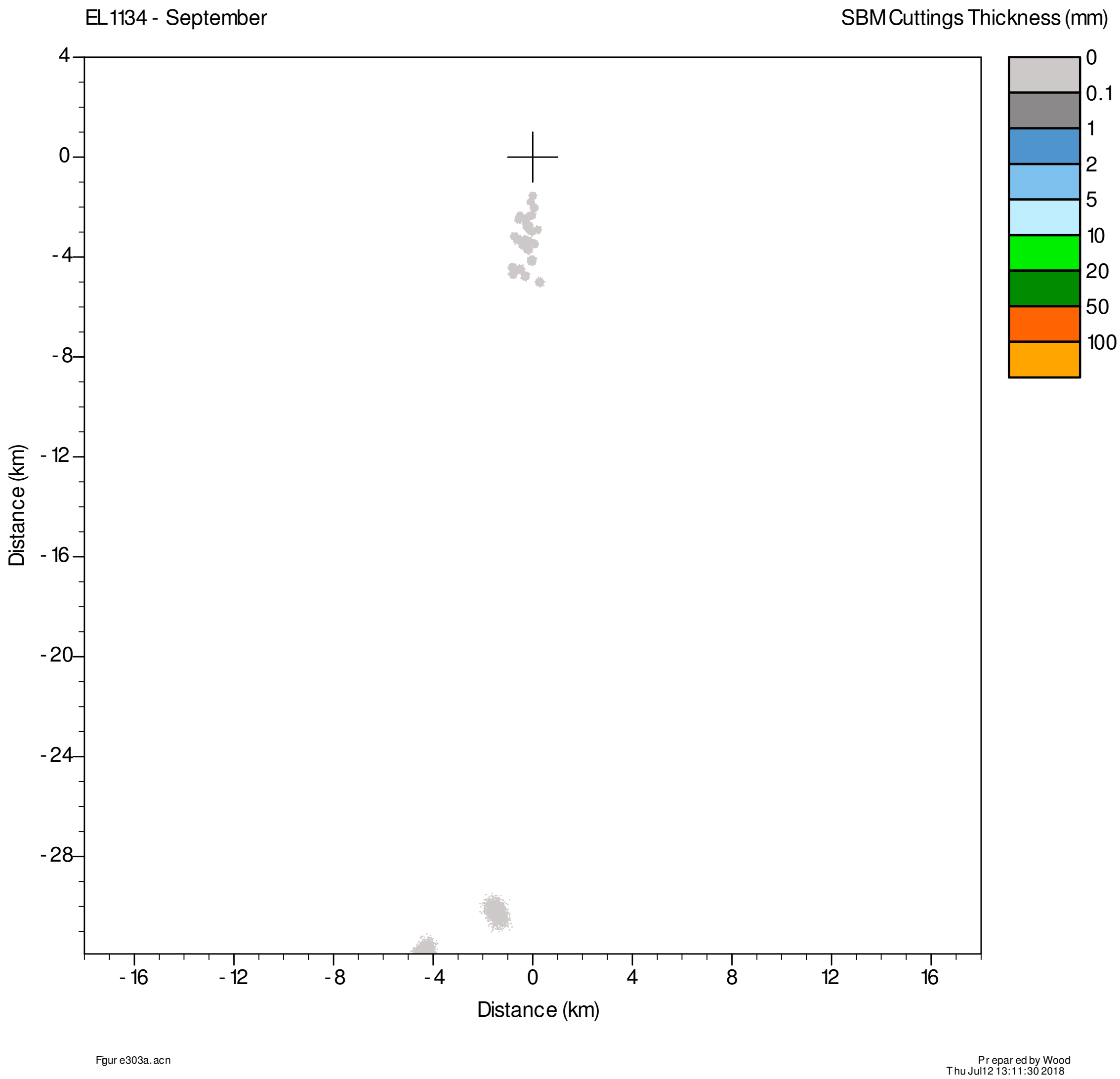

Figure 5-7 Total Drill Cuttings Deposition, EL 1134, September, 18-km View

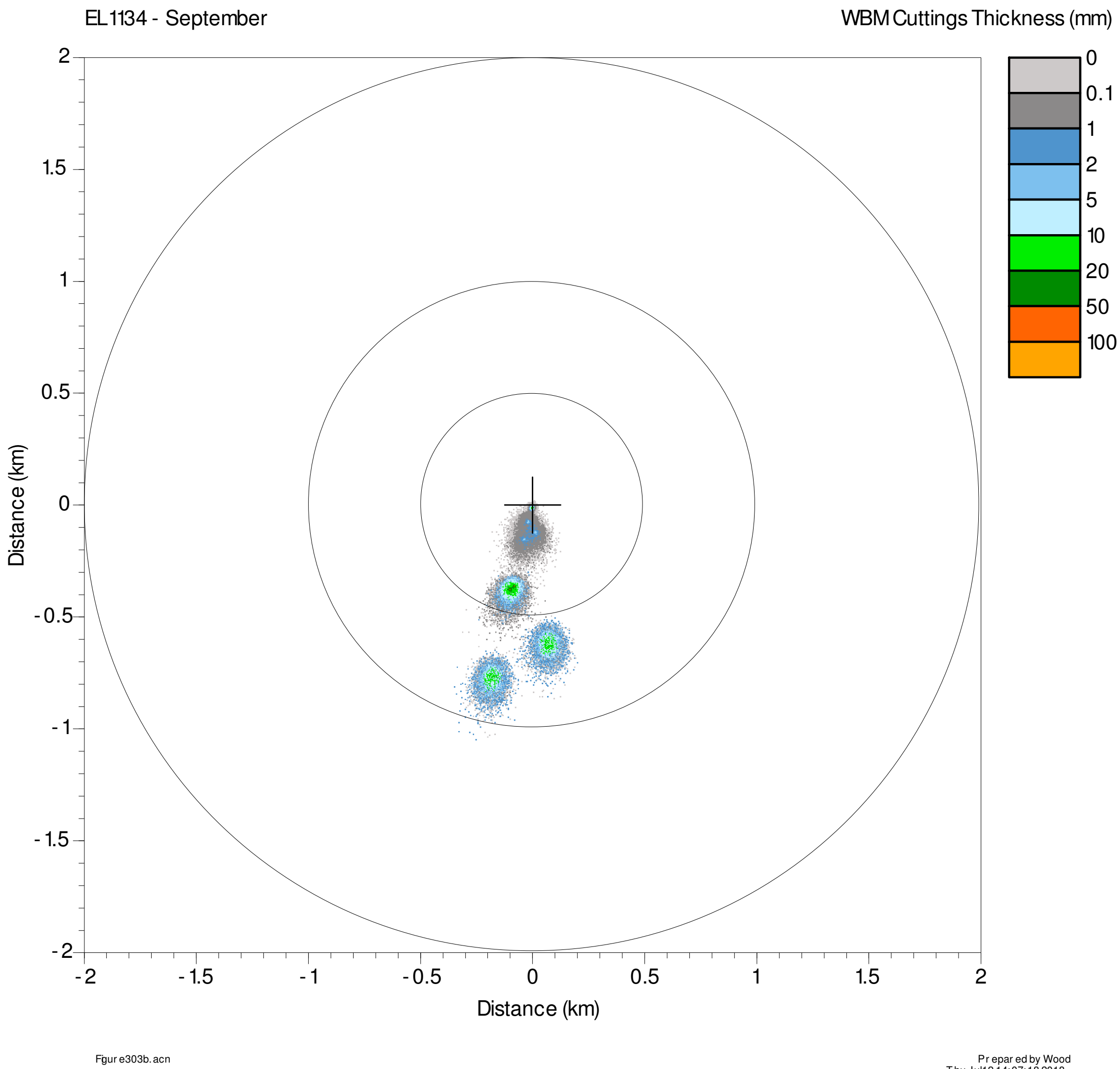

Figure 5-8 WBM Drill Cuttings Deposition, EL 1134, September, 2-km View

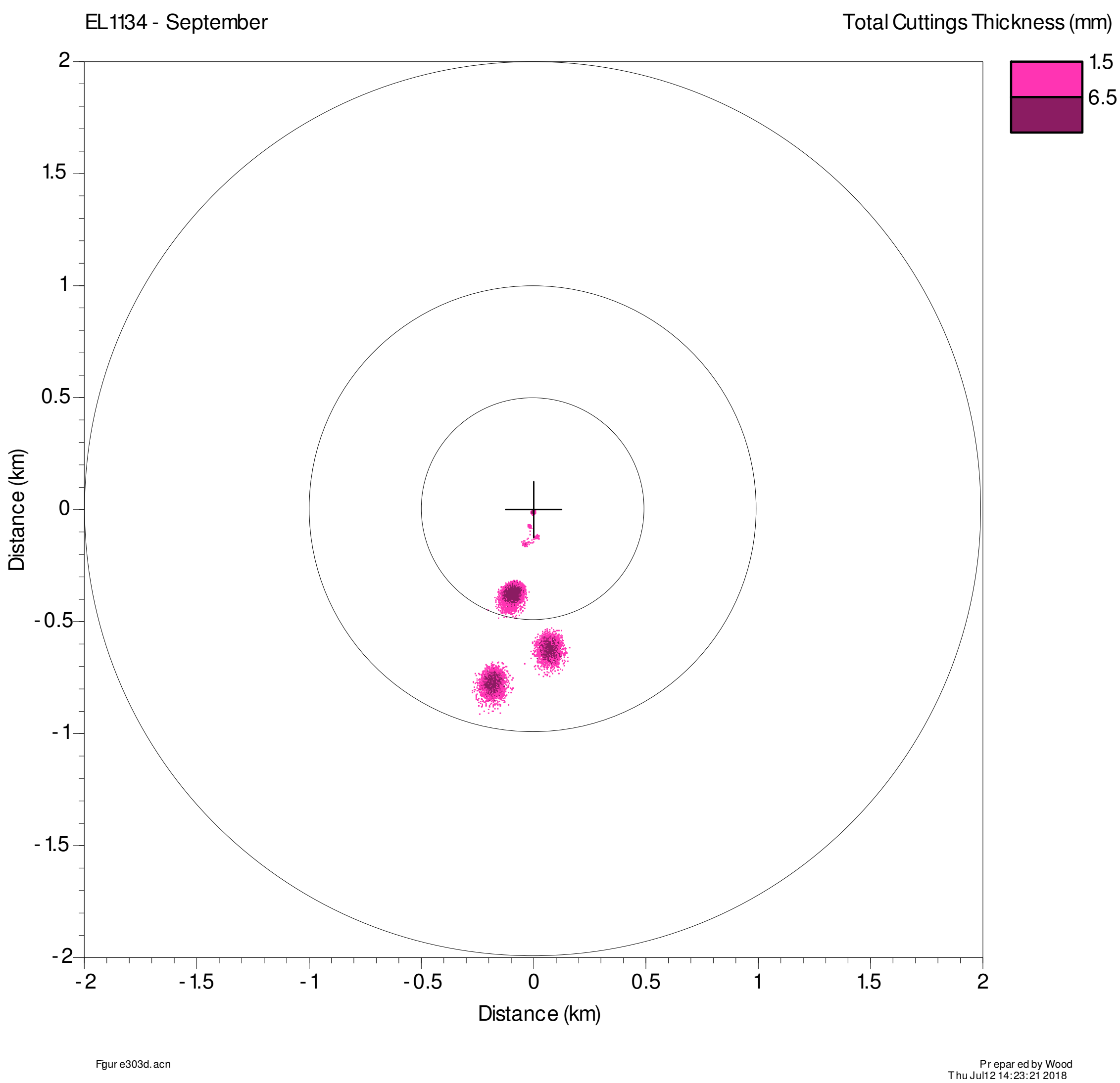

Figure 5-9 Total Drill Cuttings Deposition, PNET Limits, EL 1134, September, 2-km View

December

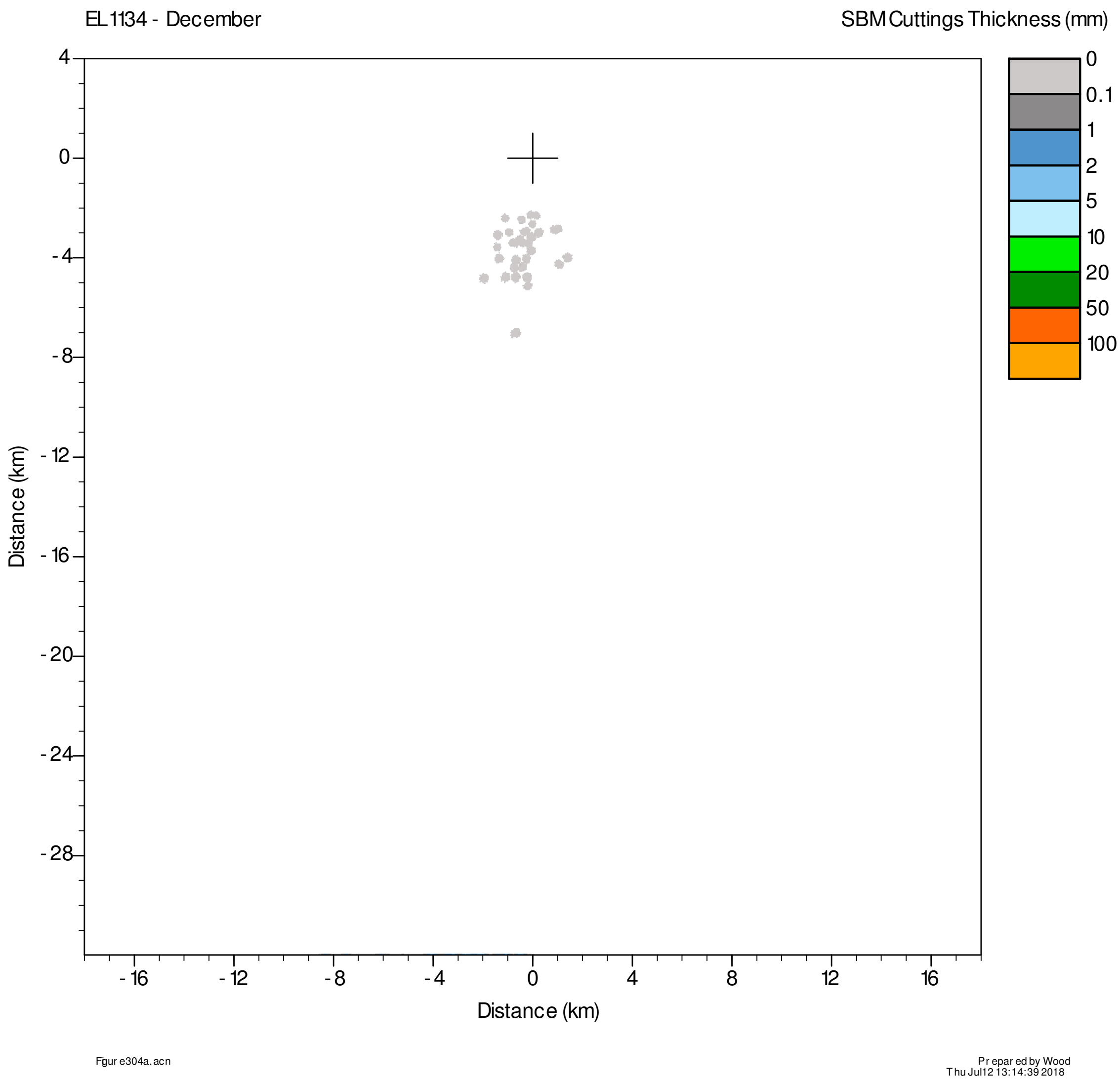

Figure 5-10 Total Drill Cuttings Deposition, EL 1134, December, 18-km View

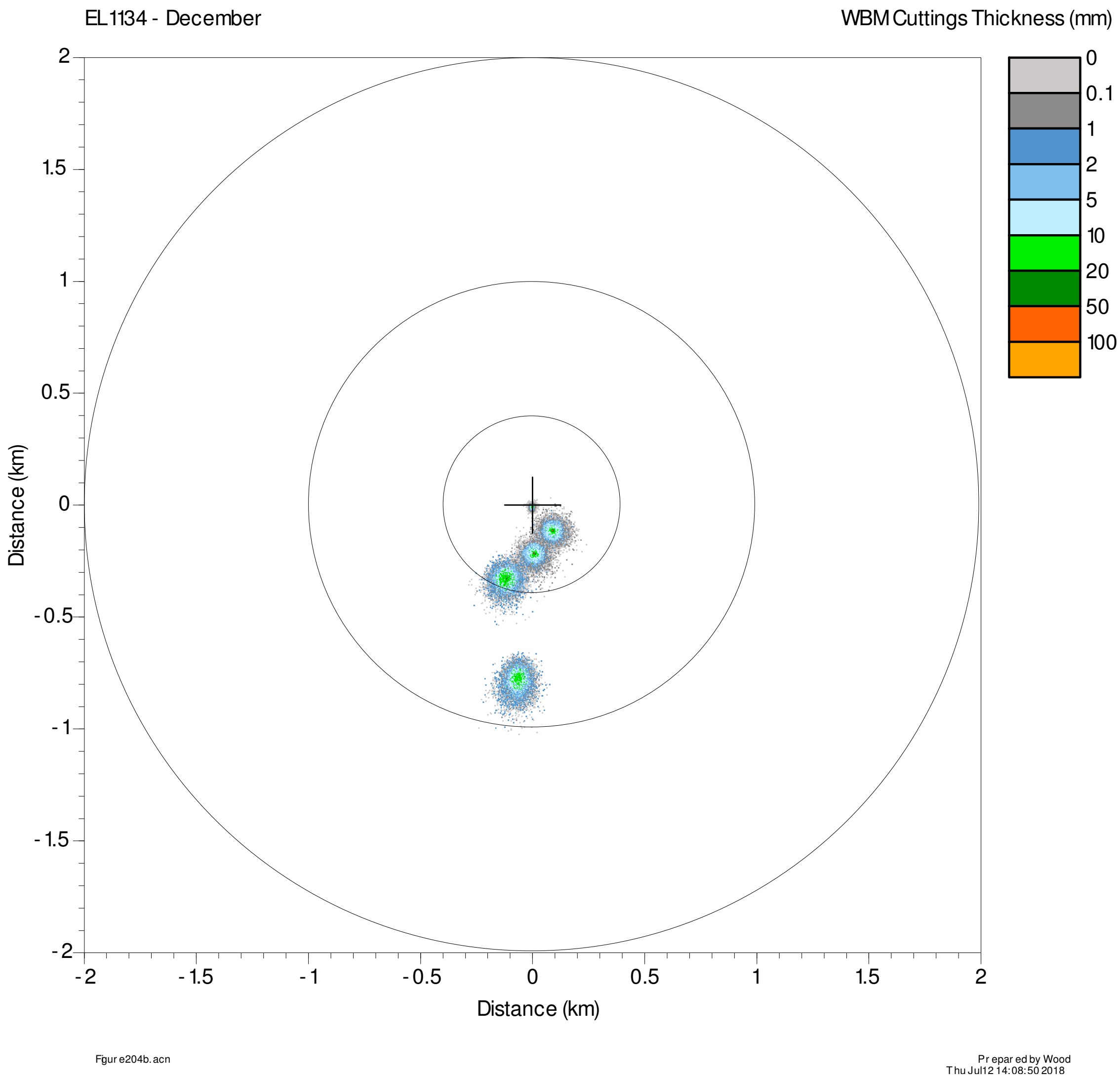

Figure 5-11 WBM Drill Cuttings Deposition, EL 1134, December, 2-km View

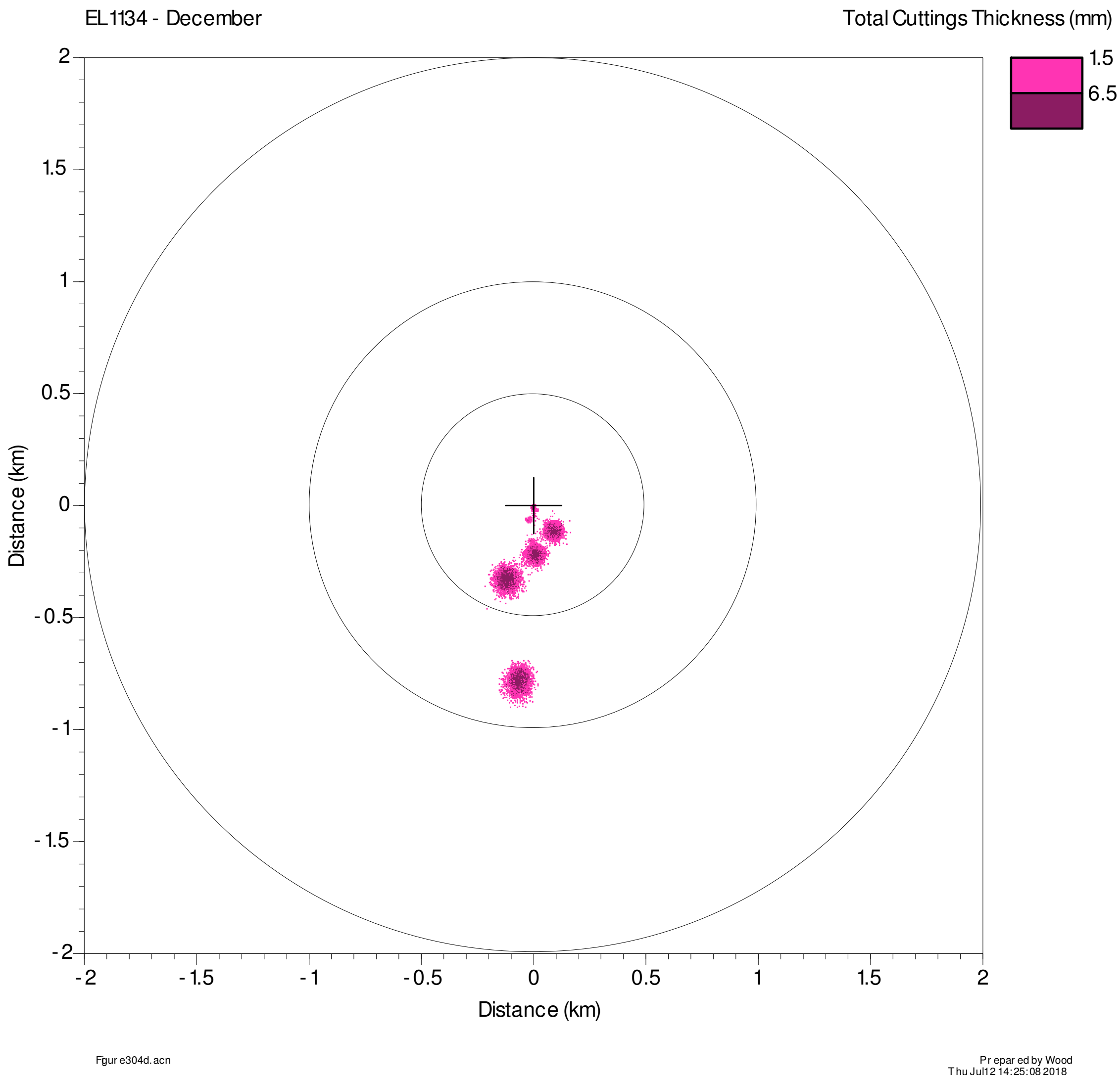

Figure 5-12 Total Drill Cuttings Deposition, PNET Limits, EL 1134, December, 2-km View

s

6.0 CLOSURE

This report presents the data and methods used to model drill cuttings release for exploration drilling in EL 1134, offshore Eastern Newfoundland. Modelling scenarios during four seasons are considered. Results presented include cuttings footprints and statistics on percent of material settled and mean and maximum cuttings thicknesses.

Yours sincerely,

Wood Environment & Infrastructure Solutions,
a Division of Wood Canada Limited

Prepared by:	Reviewed by:
John McClintock, B.Math. Senior Marine Scientist	Trajce Alcinov, M.Sc. Senior Oceaongrapher

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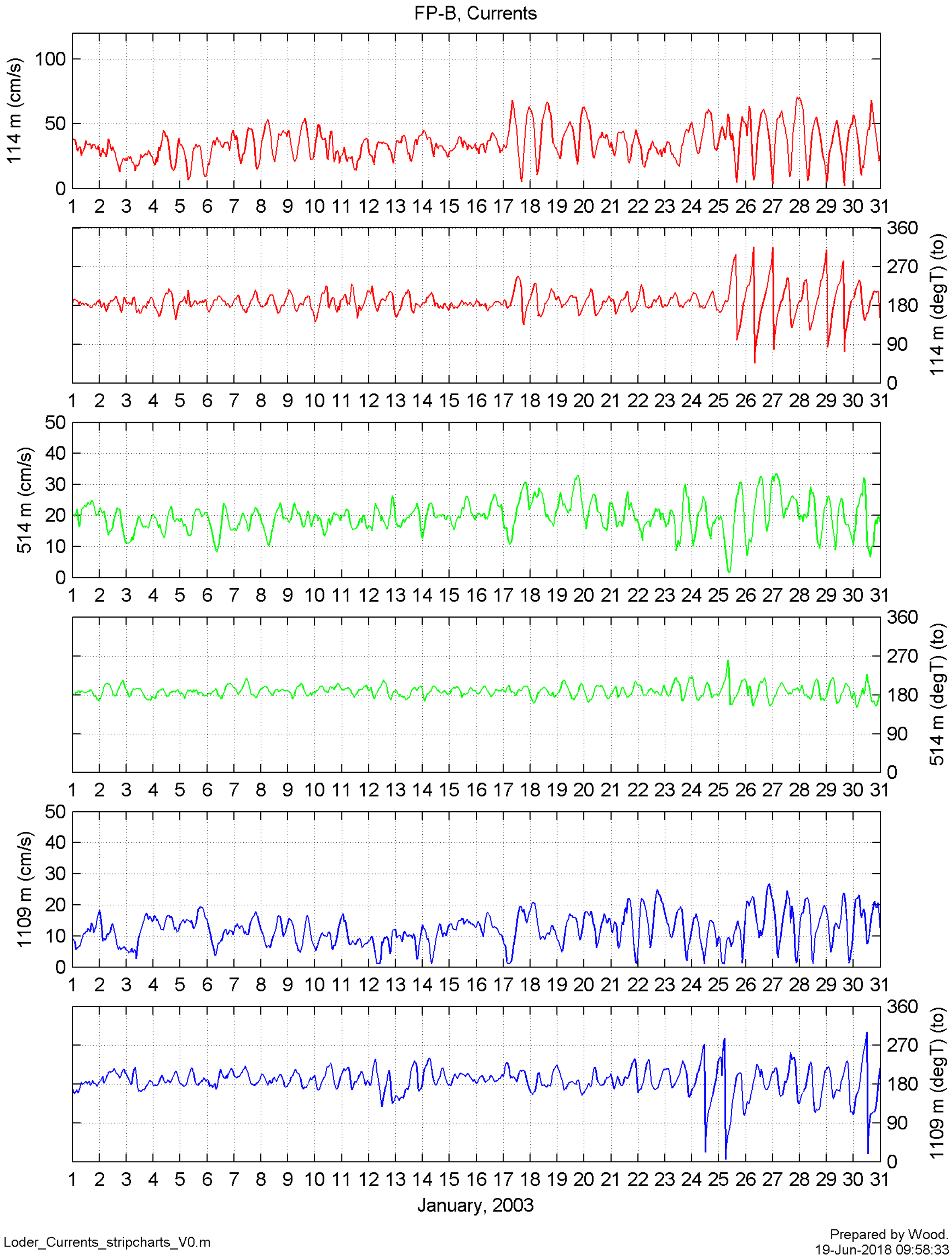
APPENDIX A: OCEAN CURRENTS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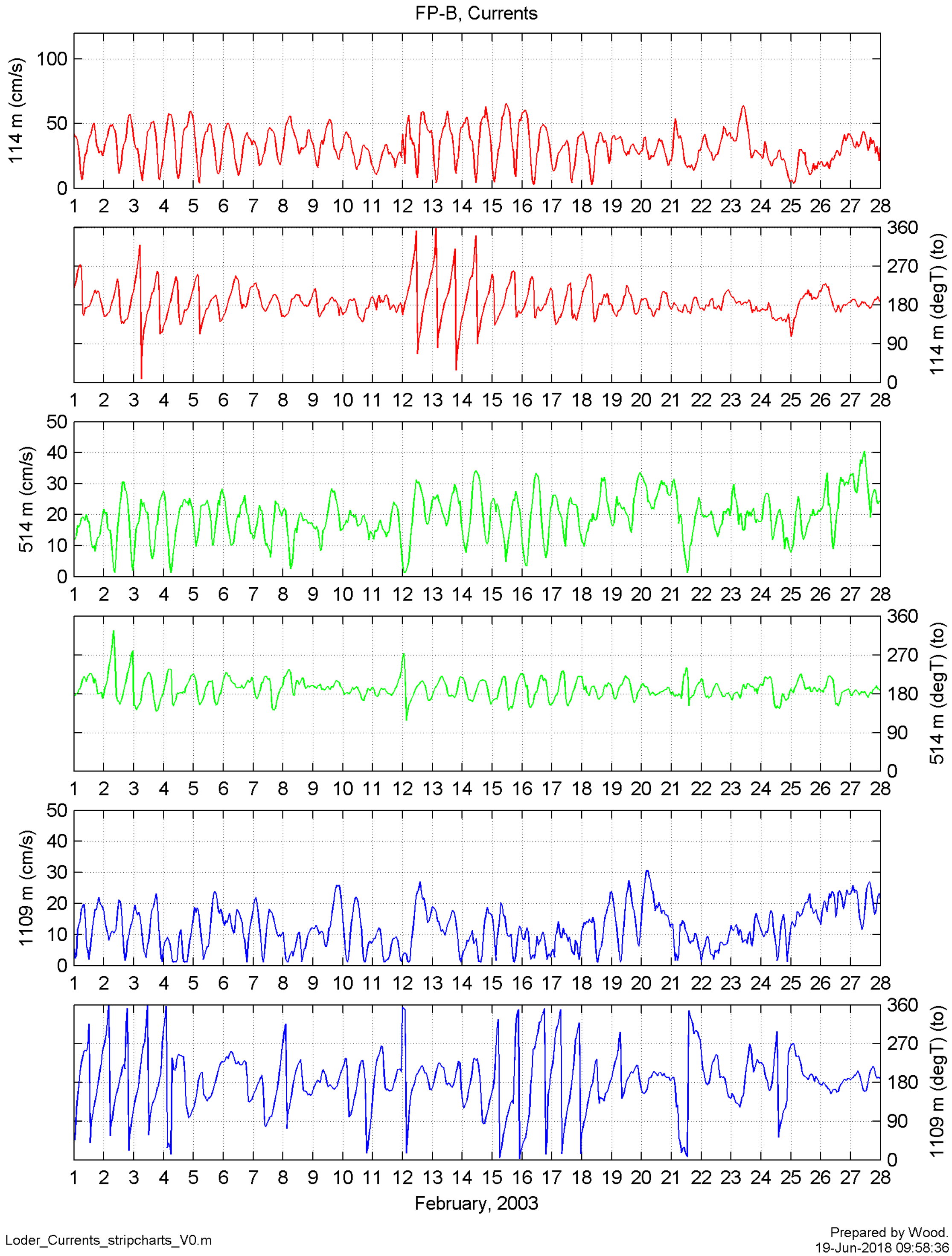
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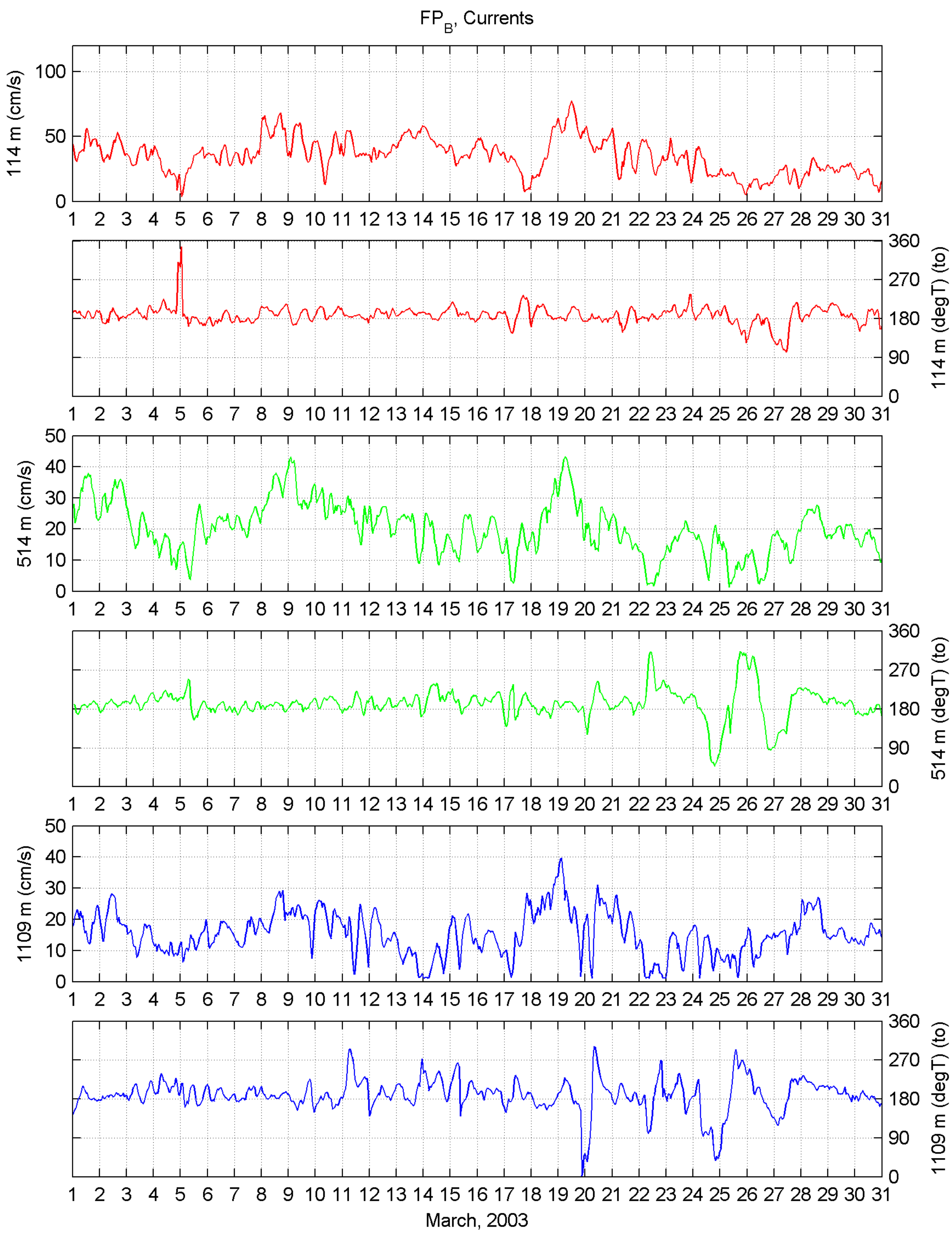
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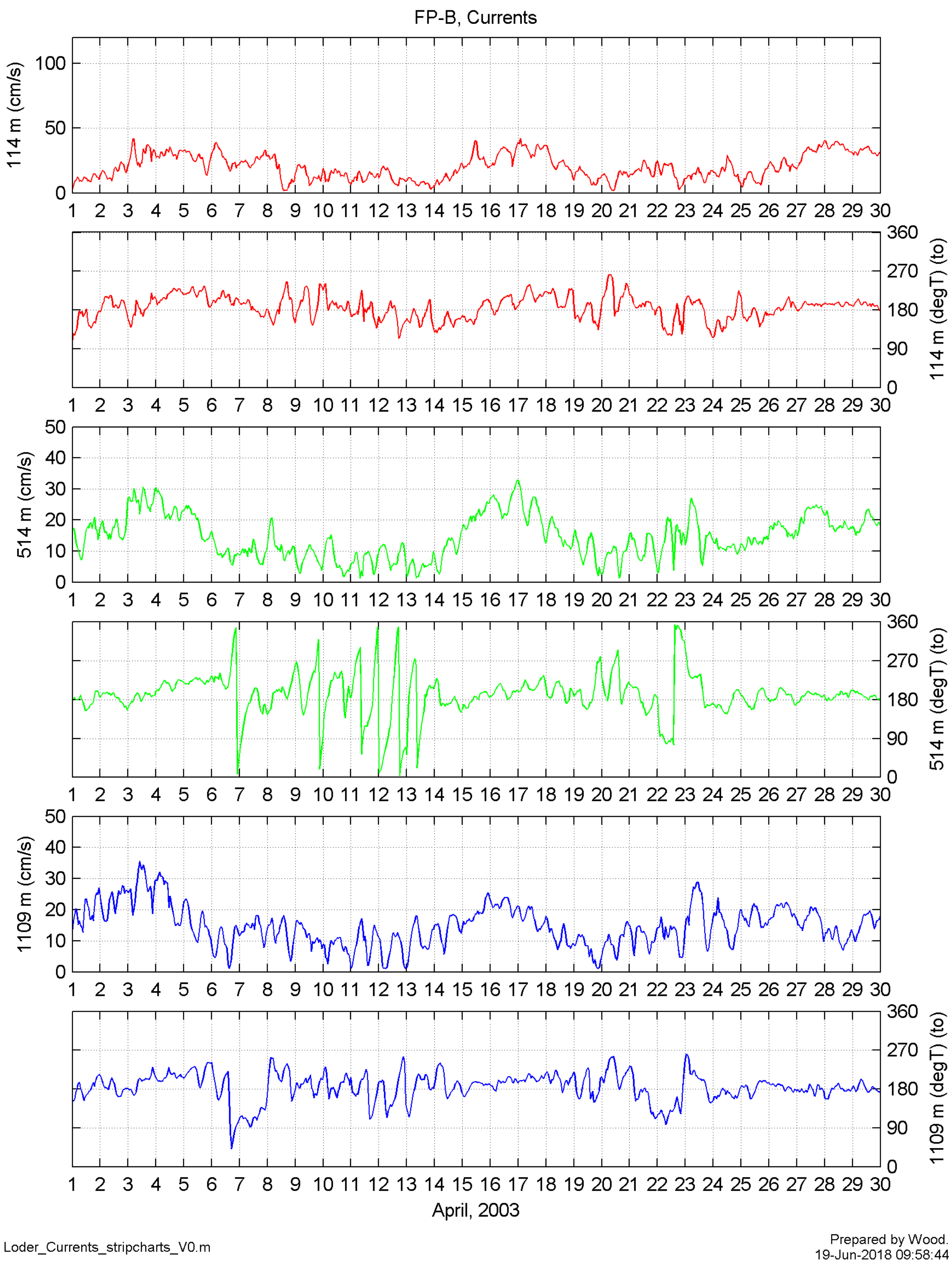
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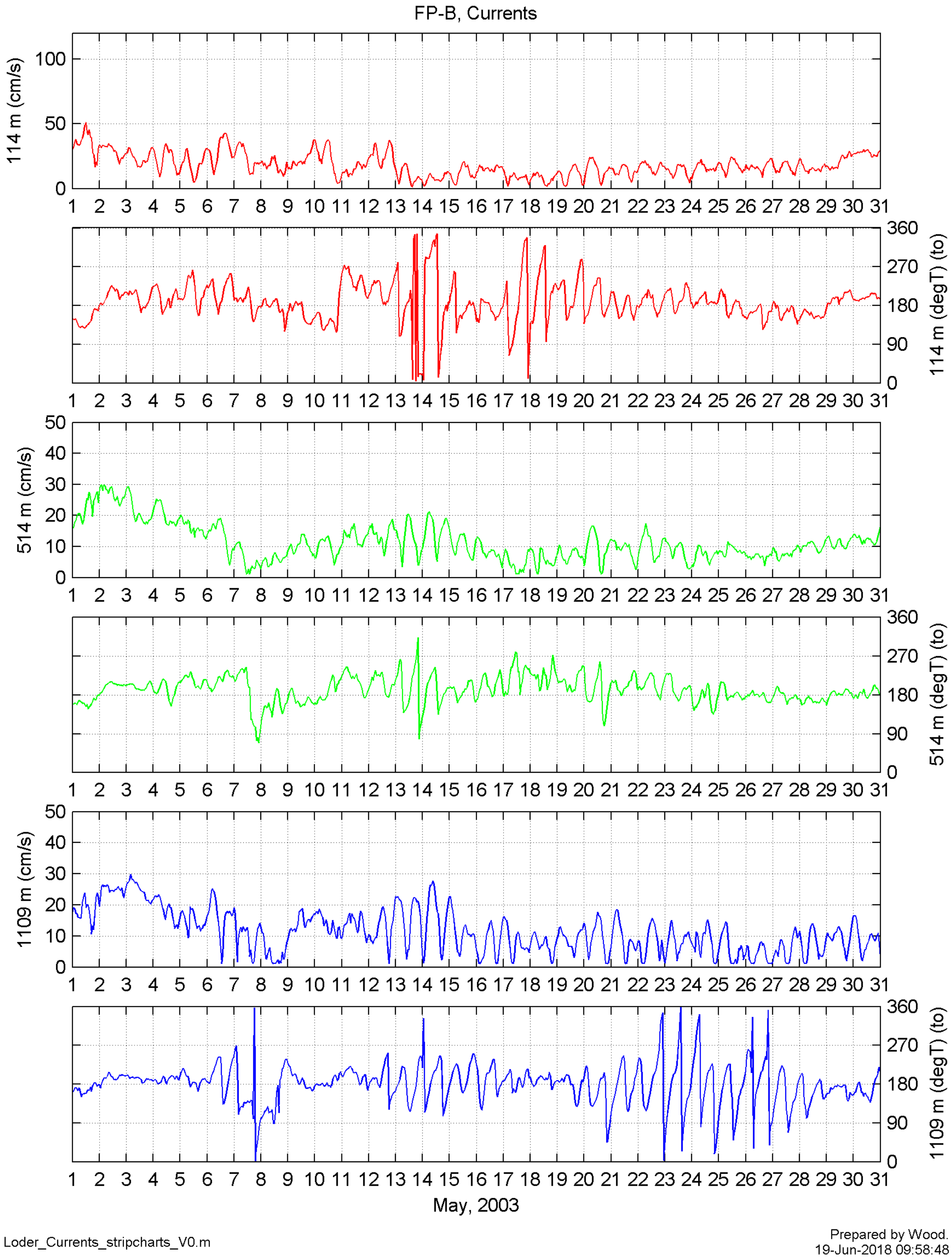
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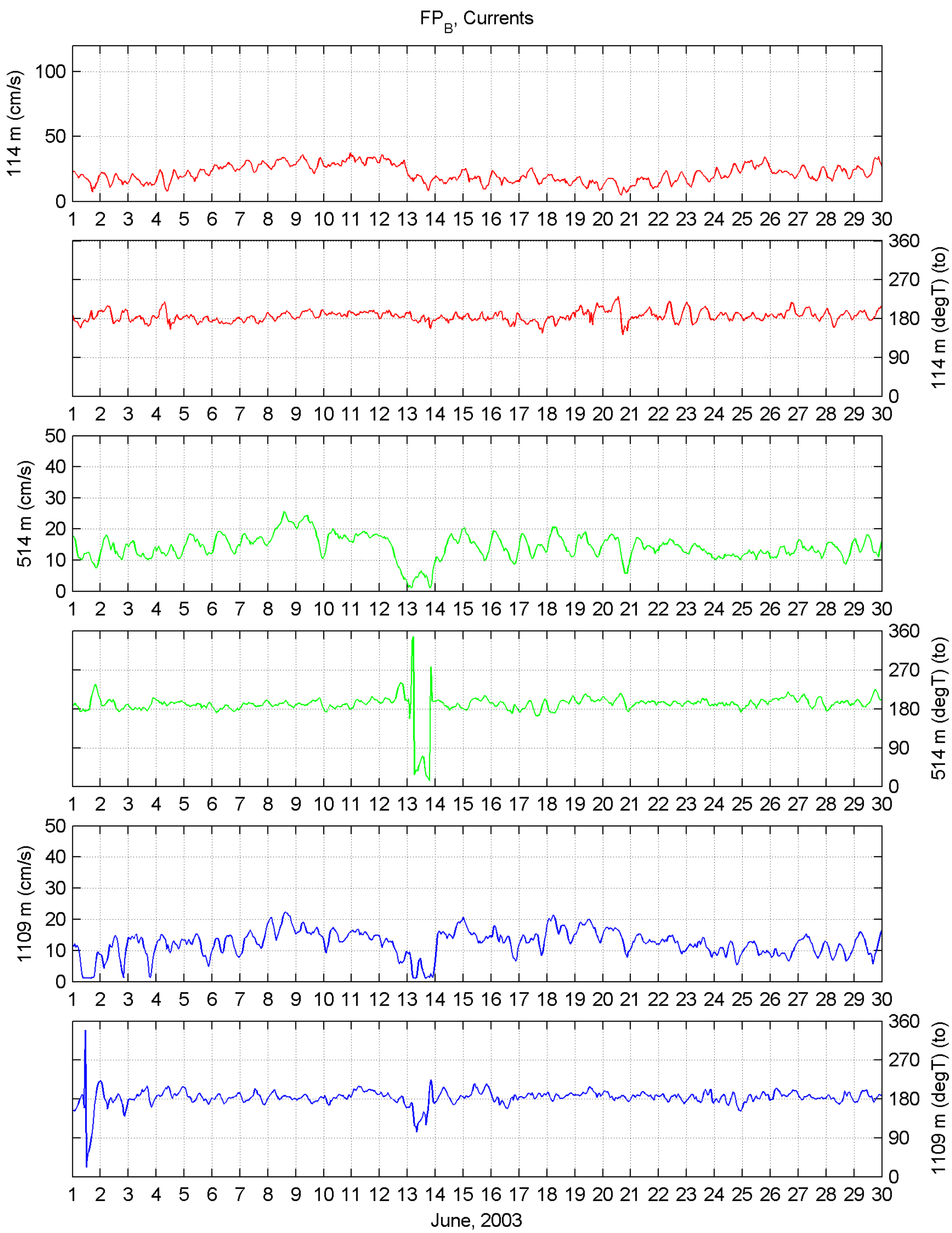
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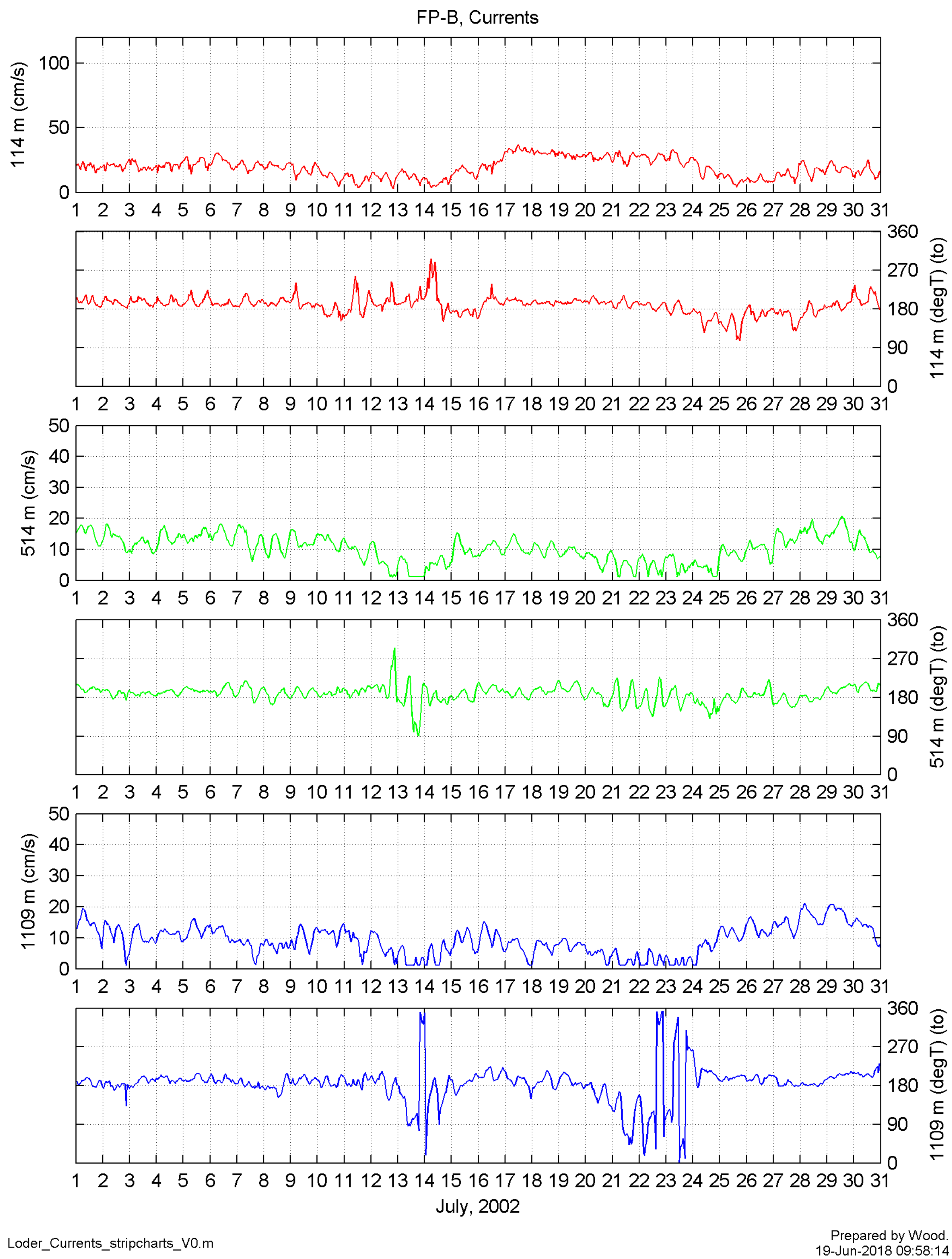
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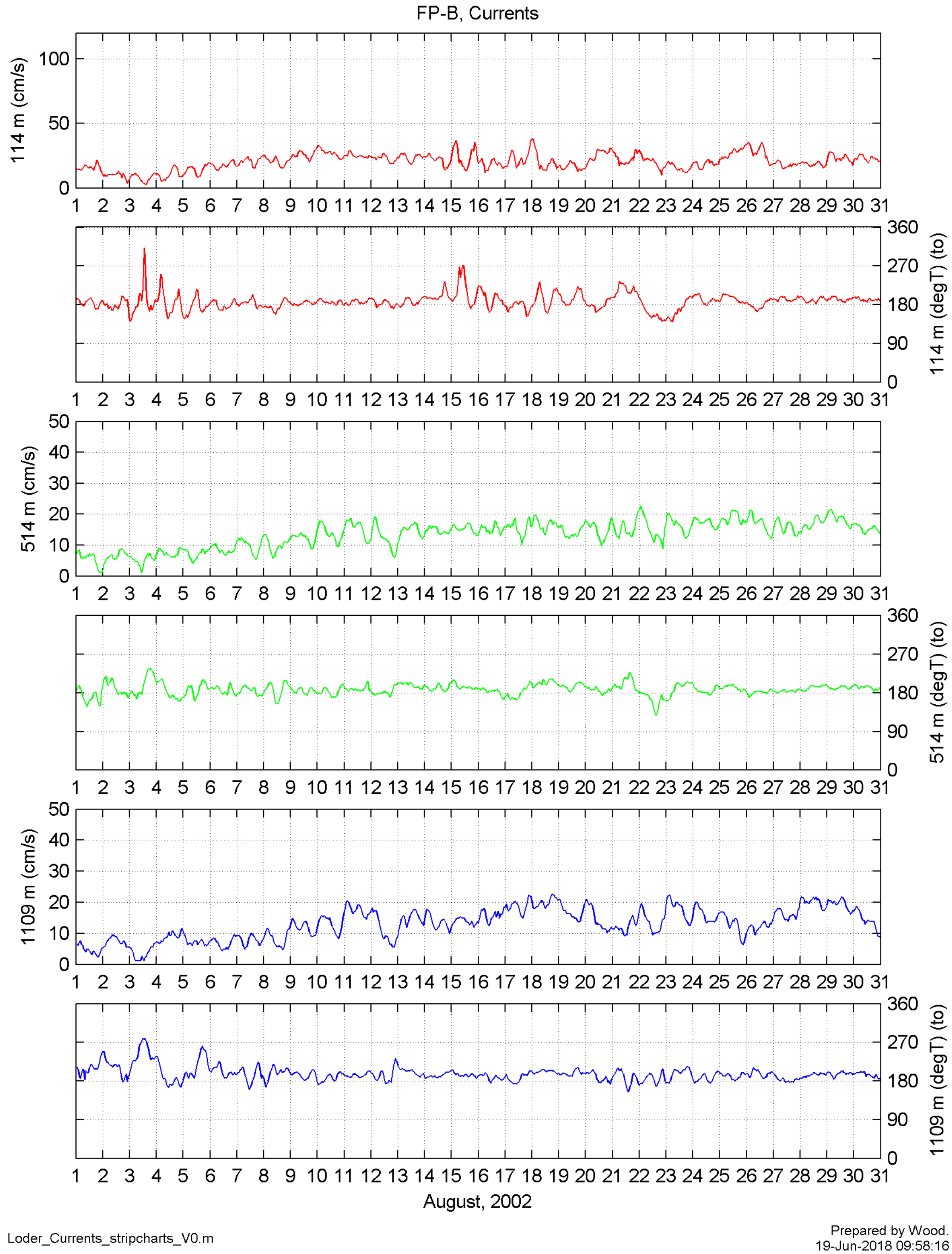
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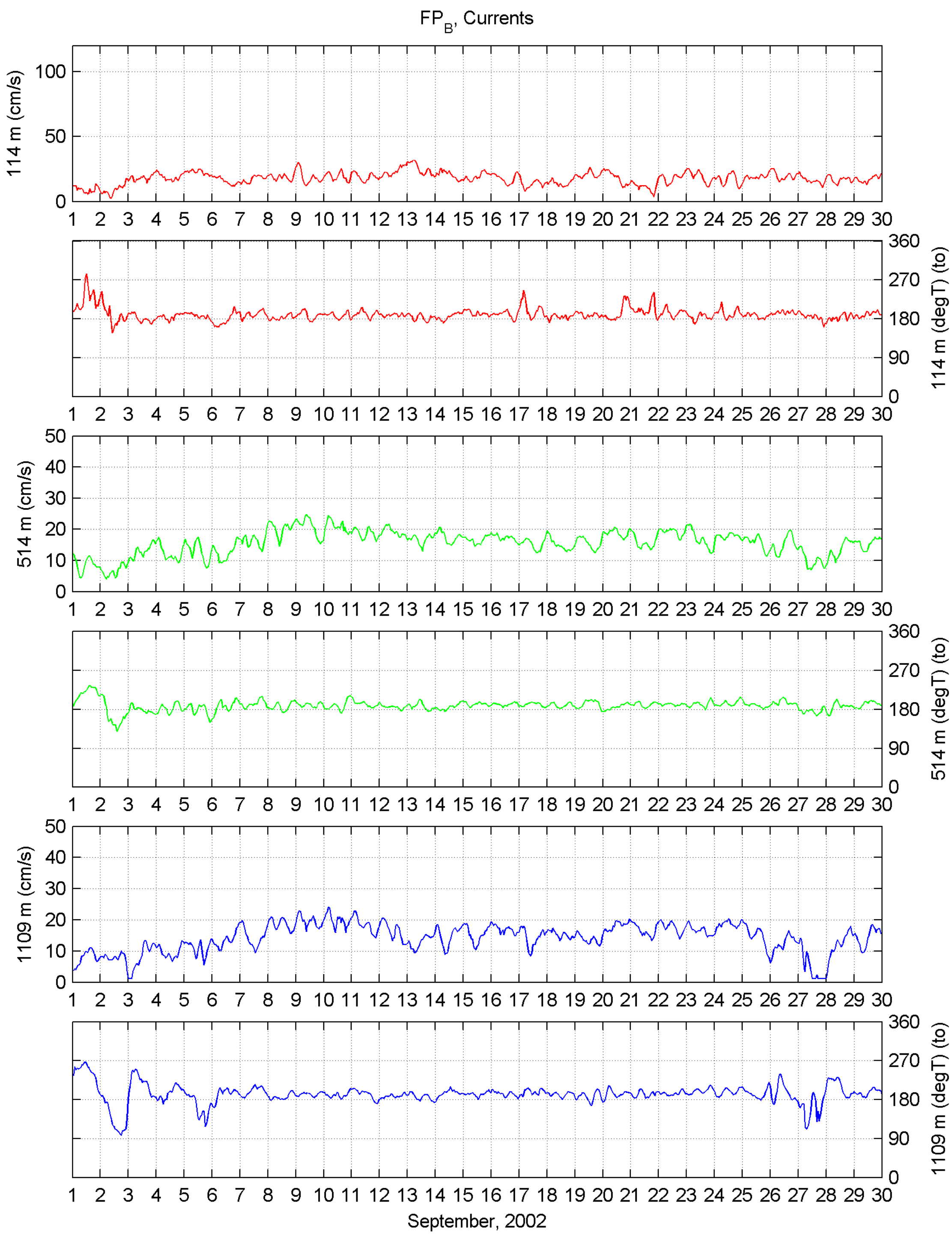
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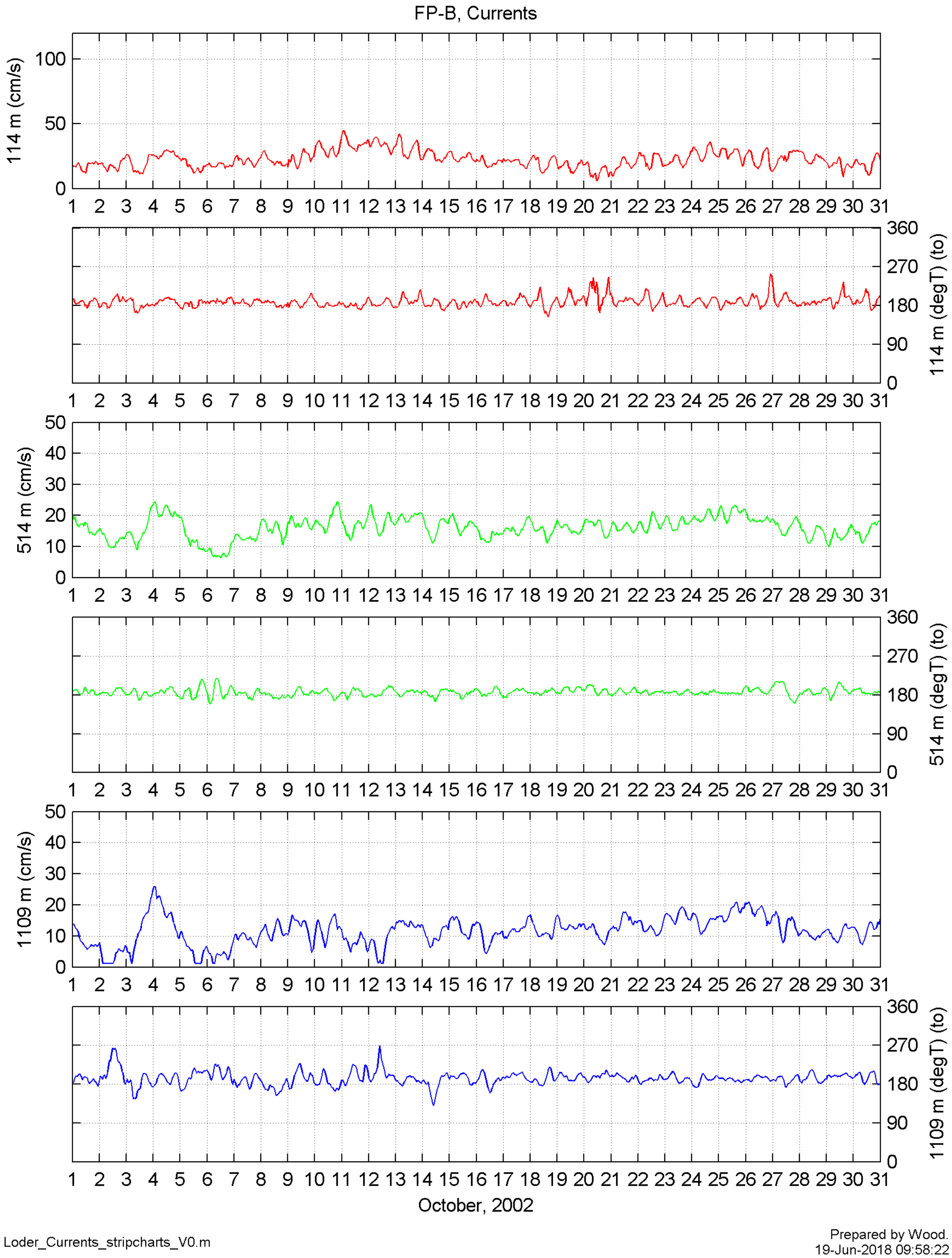
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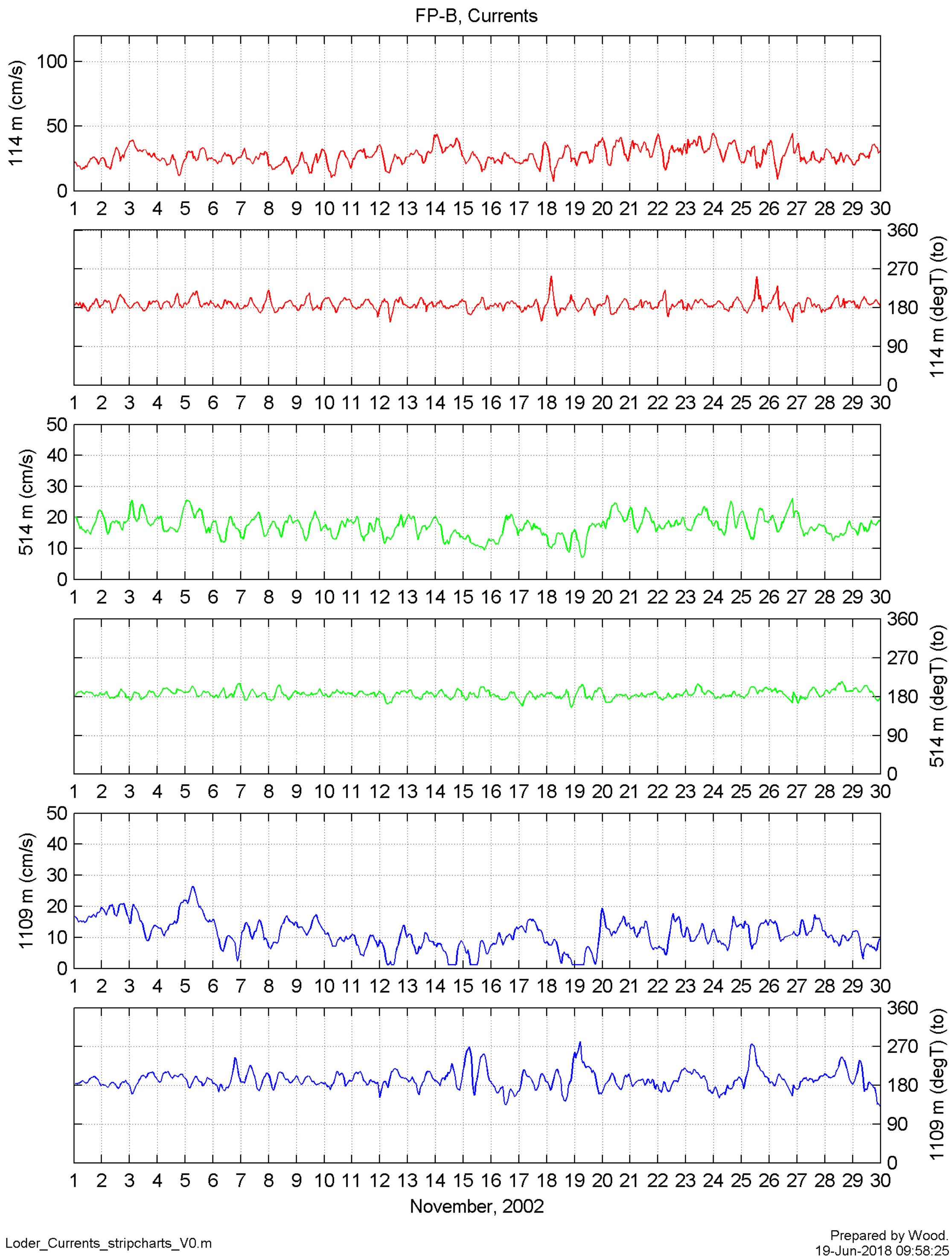
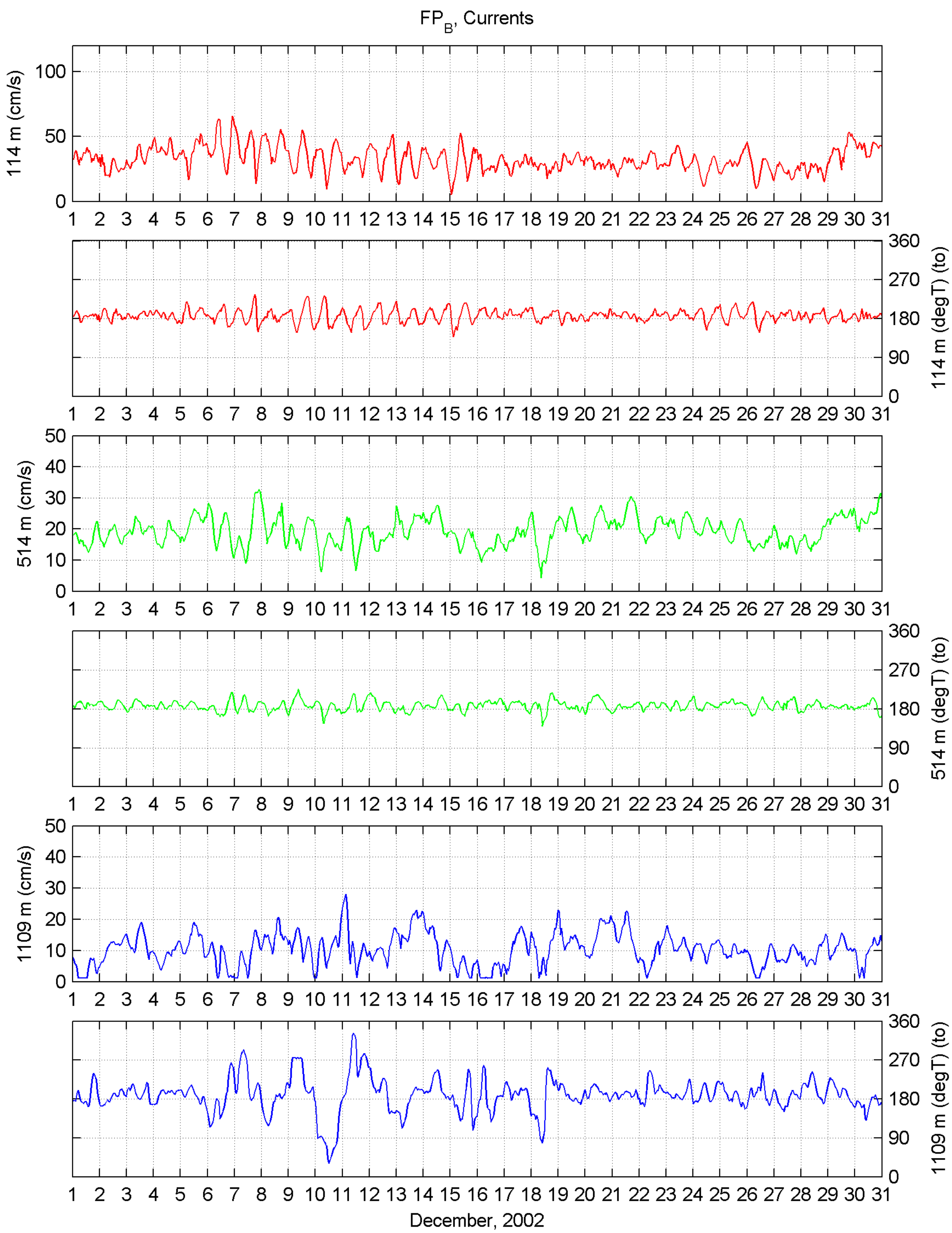
Prepared by Wood.
19-Jun-2018 09:58:22


FP-B, Currents
114 m (cm/s)
114 m (degT) (to)
514 m (cm/s)
514 m (degT) (to)
1109 m (cm/s)
1109 m (degT) (to)
November, 2002
Loder_Currents_stripcharts_V0.m
Prepared by Wood.
19-Jun-2018 09:58:25


FP$_B$, Currents
114 m (cm/s)
114 m (degT) (to)
514 m (cm/s)
514 m (degT) (to)
1109 m (cm/s)
1109 m (degT) (to)
December, 2002