Environmental
Studies
Research
Fund

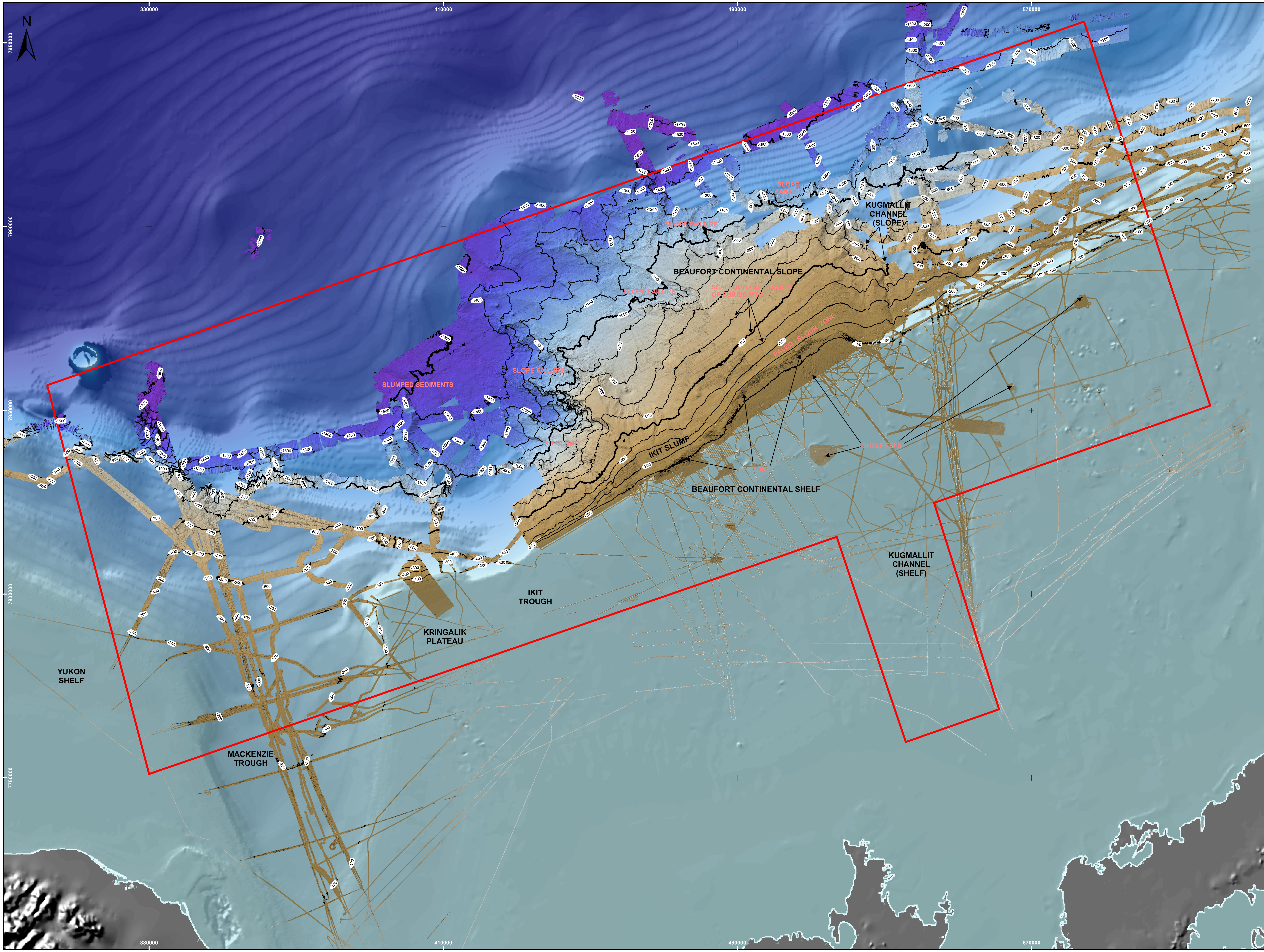
208-2-Enclosures

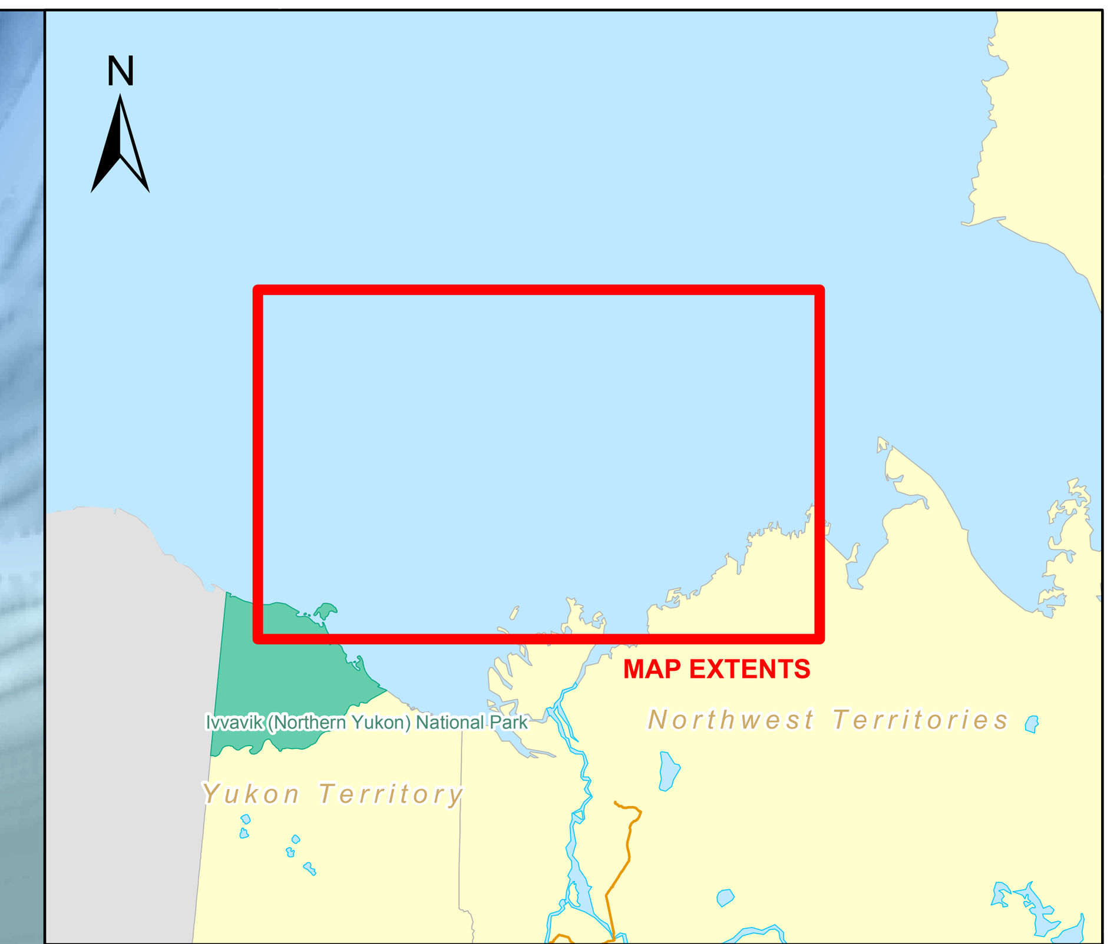
Regional Assessment of Seabed Geohazard Conditions Canadian Beaufort Outer Shelf and Upper Slope: Legacy Data Synthesis

Évaluation régionale des géorisques du fond marin, plate-forme continentale externe et talus supérieur de la portion canadienne de la mer de Beaufort : synthèse des données existantes

Canada

August 2016





LEGEND AND NOTES

- Study Area
- Major Contours (500m interval)
- Minor Contours (100m interval)

MULTIBEAM BATHYMETRY COMPILED FROM DATASETS COLLECTED BY THE GSC AND UNIVERSITY OF NEW BRUNSWICK

IMAGE SHADING PARAMETERS: AZIMUTH 315°, ELEVATION 45°, VERTICAL EXAGGERATION 10X.

DIGITAL TERRAIN MODEL (DTM) RESOLUTION = 25M

DEPTH (m): 14 – 1935

MAP PROJECTION DETAILS

ASSUMED NAD83 UTM ZONE 8
GRS80 ELLIPSOID
SEMI-MAJOR AXIS 6378137.00
INVERSE FLATTENING 298.257222101
6° UNIVERSAL TRANSVERSE MERCATOR
ZONE 8 CENTRAL MERIDIAN: 135° W
SCALE FACTOR AT C.M.: 0.9996
FALSE EASTING: 500,000M
FALSE NORTHING: 0M

SCALE

5 2.5 0 5 10 15 20 25 30 35 40
Kilometers
Scale 1 : 500,000

PREPARED BY

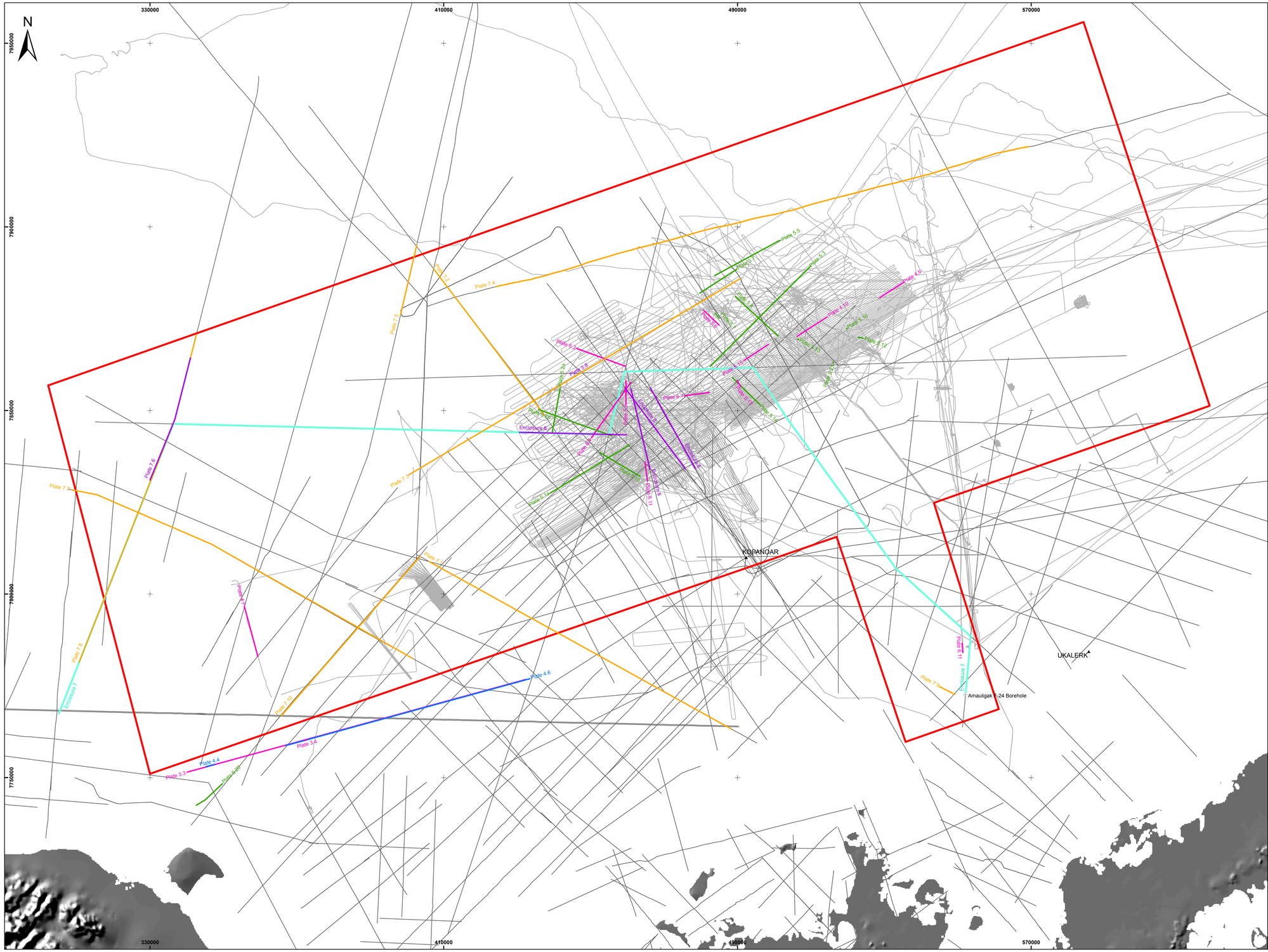
FUGRO GEOSURVEYS
25 Pippy Place
St. John's, NL
Canada, A1B 3X2

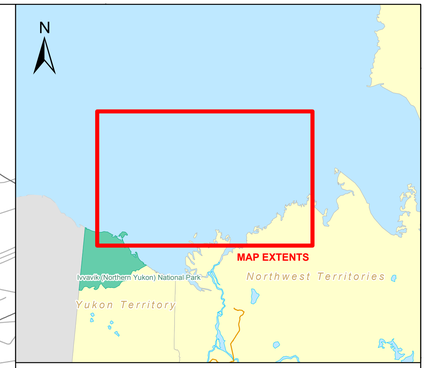
MULTIBEAM BATHYMETRY MAP SOUTHERN BEAUFORT SEA

REV	DATE	DESIGNATION	DRAWN	CHECK'D	APPR'D
0	Aug.26/15	ISSUED FOR FINAL REPORT	CS	CWL	EC
C	Mar. 16/15	DRAFT C FOR SUBMISSION	AC	CWL	EC

JOB NUMBER: 20110068 | DWG No: 20110068-MBB-REG-E01-0

DATE: AUGUST 26, 2015 | ENCLOSURE: 1





LEGEND AND NOTES

- Existing Wells
- Core Locations
- Study Area
- Lease Blocks
- Illustrated Sub-Bottom Profile Lines
- Illustrated 2DHR Profile Lines
- Illustrated Multibeam Profile Lines
- Sub-Bottom Survey Tracklines
- 2DHR Survey Tracklines

MAP PROJECTION DETAILS

ASSUMED NAD83 UTM ZONE 8
GRS80 ELLIPSOID
SEMI-MAJOR AXIS 6378137.00
INVERSE FLATTENING 298.257222101
6° UNIVERSAL TRANSVERSE MERCATOR
ZONE 8 CENTRAL MERIDIAN: 135° W
SCALE FACTOR AT C.M.: 0.9996
FALSE EASTING: 500,000M
FALSE NORTHING: 0M

SCALE

5 2.5 0 5 10 15 20 25 30 35 40
Kilometers
Scale 1 : 500,000

PREPARED BY

FUGRO GEOSURVEYS
25 Pippy Place
St. John's, NL
Canada, A1B 3X2

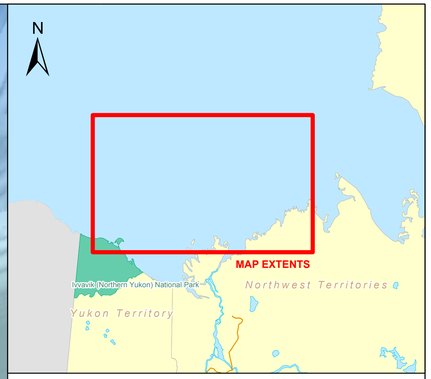
SURVEY TRACKPLOT MAP
SOUTHERN BEAUFORT SEA

REV	DATE	DESIGNATION	DRAWN	CHECK'D	APPR'D
2	Jul. 20/16	SEE CRN 969 FOR REVISION	CS	JF	EC
1	Dec. 03/15	SEE CRN 918 FOR REVISION	AC	CWL	EC
0	Aug. 26/15	ISSUED FOR FINAL REPORT	CS	CWL	EC
C	Mar 16/15	DRAFT C SUBMISSION	AC	CWL	EC

JOB NUMBER: 20110068 | DWG No: 20110068-TRK-REG-E02-2
DATE: JULY 20, 2016 | ENCLOSURE: 2

330000
410000
490000
570000
7950000
7900000
7850000
7800000
7750000

BP10-PC22
16310±431.5 : 111-119cm
BP10-PC24
10440±274.5 : 127-135cm
14290±51.5 : 227-245cm
BP10-PC02
11270±162 : 294-302cm
14290±31 : 509-517cm
750
11520±139.5 : 179-180cm
13480.5±121 : 381cm
BP10-PC21
15701.5±32.5 : 96-104cm
BP10-PC31
3140±171.5 : 303-311cm
4600±199 : 421-429cm
7270±130 : 612-620cm
BP10-PC25
12190±192 : 621-629cm
BP10-PC08
6860±158 : 414-420cm
8270±116 : 681-687cm
2008-801_0073A
40±30 : 0cm
9360±67 : 8cm
9390±64.5 : 15cm
9420±58.5 : 23cm
9430±52 : 25cm
BP10-PC28
10750±172.5 : 0cm
BP10-PC01
1820±166.5 : 116-124cm
CL01
12635.5±49.5 : 590-592cm
BP10-PC26
13910±92 : 75-83.5cm
2008802_0038
7467±47 : 2cm
7505±48 : 14cm
7560±51.5 : 20cm
7581±49 : 22cm
7600±48.5 : 33cm
7475±48 : 43cm
2008-801_0078_GC
7580±54.5 : 68cm
7360±51 : 77cm
CL41
5760±78 : 39-41cm
10240±62.5 : 200-202cm
7499±47 : 344-346cm
CL25
1790±64.5 : 75-81cm
5320±86.5 : 322.5-324cm
2004-804-803
672±48 : 219cm
2250±70 : 221cm
2900±80 : 222cm
4200±91.5 : 224cm
2008802_0046
960±52 : 49cm
2009804_0026PC
7170±74.5 : 179cm
CL03
1314.5±43.5 : 125-129.5cm
7750±83 : 140-142cm
7680±57.5 : 142-144cm
CL09
8813±16 : 421-423
CL04
1322±44 : 93-100cm
8080±60.5 : 135-136cm
2009804_0040PC
4290±87 : 71cm
5530±51.5 : 91cm
5390±69.5 : 109cm
5790±66 : 114cm
5810±65.5 : 114cm
2004-804-0008
7550±53.5 : 51-52cm
7900±64.5 : 71-72cm
7990±74 : 111-112cm
12970±111.5 : 151-152cm
8400±51.5 : 201-203cm
2009804_0019PC
7770±64.5 : 270cm
CL07
5330±80 : 152cm
6080±78 : 262cm
2009804_0013PC
2570±89 : 55cm
5280±72.5 : 141cm
5960±64 : 163cm
6350±56.5 : 186cm
6500±96 : 191cm
8020±63 : 230cm
8100±64.5 : 242cm
Kopanoar I-44 Borings 2,3
*18400 : 80cm
*28000 : 125cm
2002MR_K05_PC01
11040±136 : 704.5-705.5cm
11239±47 : 1000.5-1005.5cm
Uviluk P-66
25890±867 : 94-114cm
GSC-1
*>53000 : 46cm
*66000-96000 : 54cm
*78000-117000 : 73cm
2002MR_K05_PC02
2790±177 : 135-136cm
6700±79 : 560-561cm
8140±80.5 : 813-814cm
Tarsiut N-44
31620±430.5 : 141cm
87NAH-81
720±60.5 : 8.6cm
BH15+00
3800±103.5 : 20.5cm
BH38+00
10690±112.5 : 12.55cm
87NAH-60
1480±88 : 10.8cm
BH34+00
6360±59 : 23.6cm
7130±123 : 23.75cm
87NAH-48
600±51 : 8.4cm
87NAH-75
980±68 : 8.6cm
87NAH-39
660±66 : 7.3cm
2002MR_K05_PC03
310±73 : 27-28cm
330±61.5 : 20-21cm
1540±78.5 : 156.5-157.5cm
3220±80.5 : 369-370cm
4270±96.5 : 480.5-481.5cm
4660±78 : 550.5-551.5cm
6810±81.5 : 634-635cm
2004-804-912A
1316±25 : 93cm



LEGEND AND NOTES

- Core Locations
- Core Locations on the Continential Slope where Units 1 & 2 are stratigraphically undisturbed. Dates from these cores were used for calculation of post-glacial slope sedimentation rates.
- Study Area
- 10260 ± 110 : 0cm — C_{14} Date : Sample Depth Below Seafloor
- * Uncalibrated C_{14} Date

CORE LOCATIONS ARE ASSUMED TO BE IN NAD83 DATUM

MULTIBEAM BATHYMETRY COMPILED FROM DATASETS COLLECTED BY THE GSC AND UNIVERSITY OF NEW BRUNSWICK

DEPTH (m): 14 – 1935

MAP PROJECTION DETAILS

ASSUMED NAD83 UTM ZONE 8
GRS80 ELLIPSOID
SEMI-MAJOR AXIS 6378137.00
INVERSE FLATTENING 298.257222101
6° UNIVERSAL TRANSVERSE MERCATOR
ZONE 8 CENTRAL MERIDIAN: 135° W
SCALE FACTOR AT C.M.: 0.9996
FALSE EASTING: 500,000M
FALSE NORTHING: 0M

SCALE

5 2.5 0 5 10 15 20 25 30 35 40
Kilometers
Scale 1 : 500,000

PREPARED BY

FUGRO GEOSURVEYS
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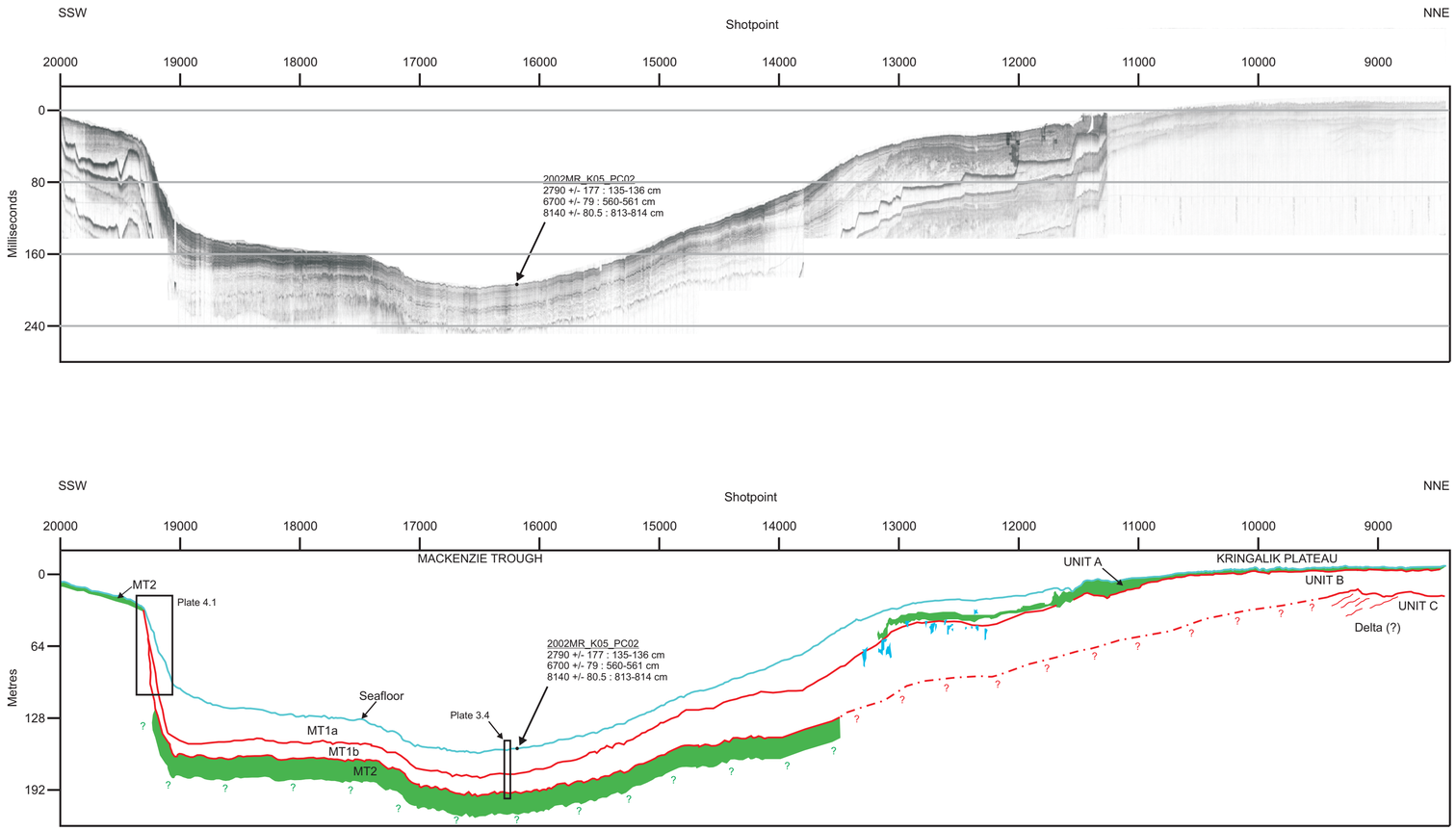
St. John's, NL
Canada, A1B 3X2

MULTIBEAM BATHYMETRY CORE AND BOREHOLE C_{14} DATES SOUTHERN BEAUFORT SEA

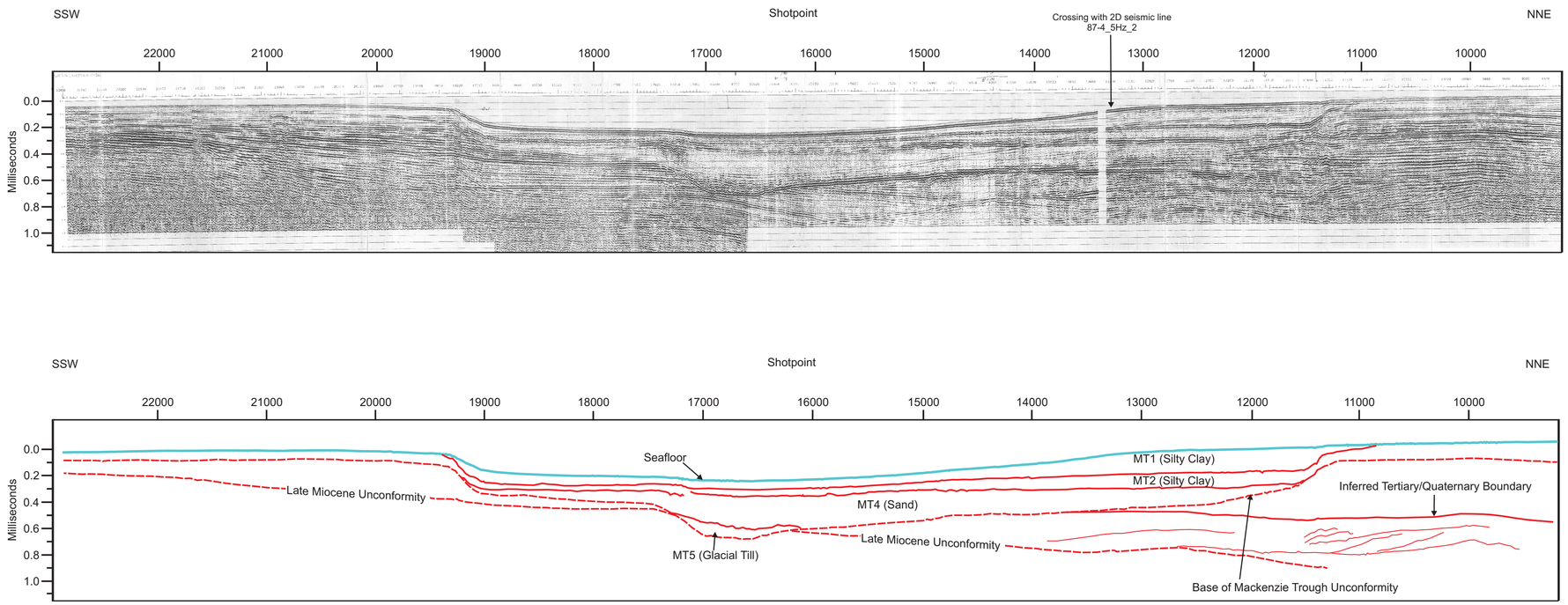
REV	DATE	DESIGNATION	DRAWN	CHECK'D	APPR'D
0	Aug. 26/15	ISSUED FOR FINAL REPORT	CS	CWL	EC
C	Mar. 16/15	DRAFT C FOR SUBMISSION	AC	CWL	EC

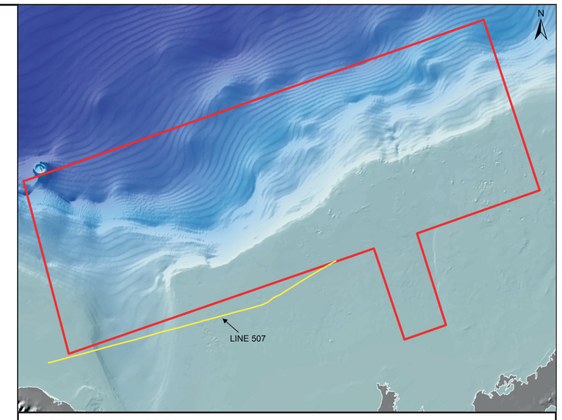
JOB NUMBER: 20110068
DWG No: 20110068-MBB-C14-E03-0
DATE: AUGUST 26, 2015
ENCLOSURE: 3

SUB-BOTTOM SPARKER PROFILE AND INTERPRETATION



SEISMIC PROFILE AND INTERPRETATION





LEGEND AND NOTES

- Ice Keel Turbate
- Possible Gas
- Seafloor
- Acoustic/Seismic Unit Boundary (defined/tentative)
- Unconformity
- Acoustic/Seismic Horizon

DEPTH SCALE ON SUB-BOTTOM PROFILE INTERPRETATION BASED ON AN ASSUMED SOUND VELOCITY OF 1500m/s.

FUGRO REVISION REFERENCE

REV.	DATE	DESIGNATION	DRAWN	CHECK'D	APPR'D
0	Aug. 26/15	ISSUED FOR FINAL REPORT	CS	CWL	EC
C	Mar. 16/15	DRAFT C SUBMISSION	JF/AC	CWL	EC

SCALE

0 5 10 15 20

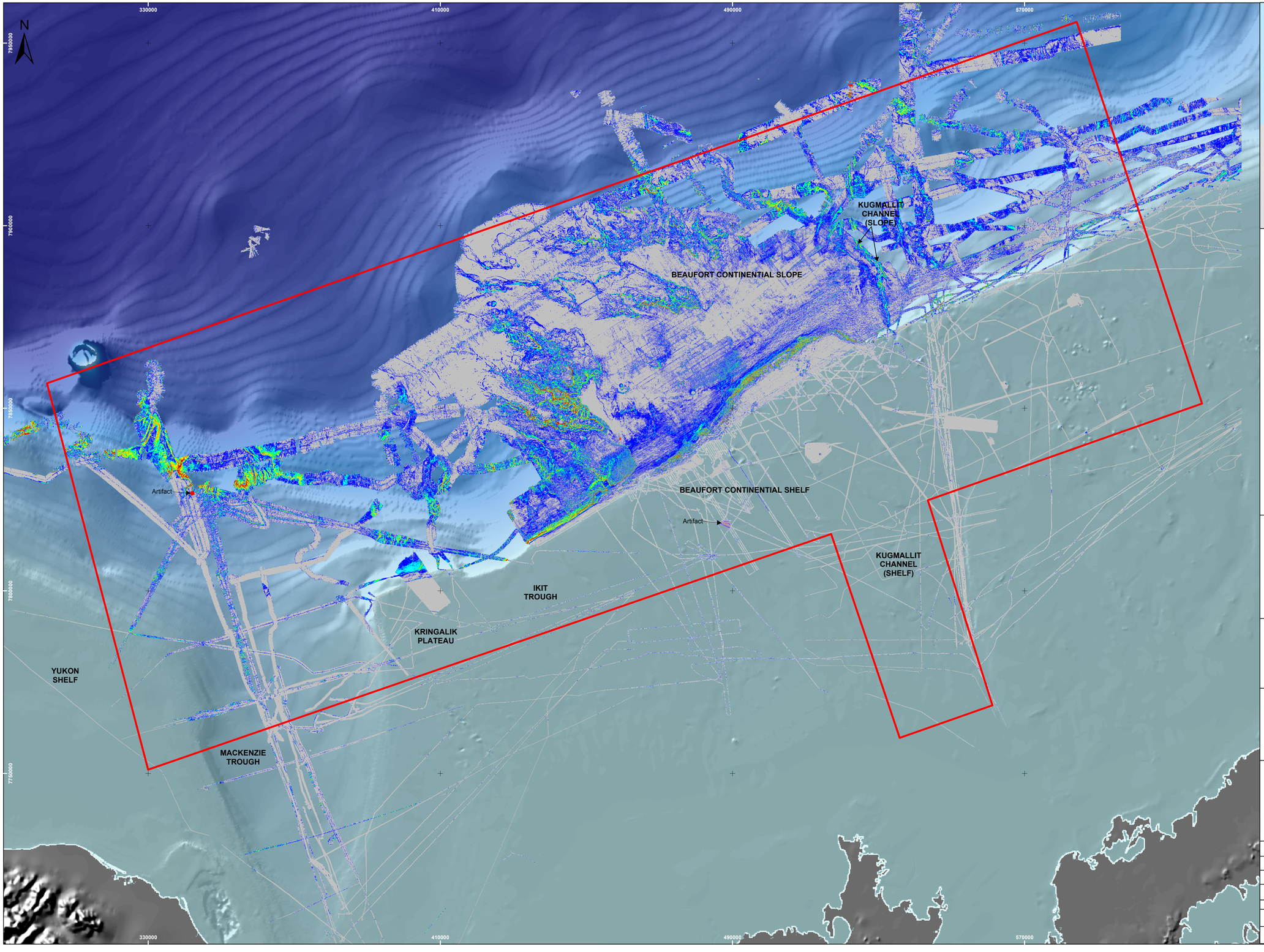
KILOMETRES (km)

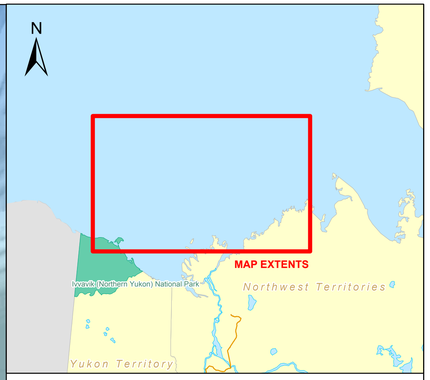
PREPARED BY

FUGRO GEOSURVEYS
25 Pippy Place
St. John's, NL
Canada, A1B 3X2

SUB-BOTTOM AND 2D SEISMIC PROFILE OF LINE 80-507 SOUTHERN BEAUFORT SEA

JOB NUMBER: 20110068	DRAWN BY: JF/AC
DATE: AUGUST 26, 2015	CHECKED BY: CWL
DWG NO: 20110068-PRO-L507-E04-0	ENCLOSURE: 4
	REV 0

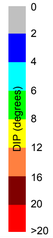




LEGEND AND NOTES

Study Area

MULTIBEAM BATHYMETRY COMPILED FROM DATASETS COLLECTED BY THE GSC AND UNIVERSITY OF NEW BRUNSWICK



MAP PROJECTION DETAILS

ASSUMED NAD83 UTM ZONE 8
GRS80 ELLIPSOID
SEMI-MAJOR AXIS 6378137.00
INVERSE FLATTENING 298.257222101
6° UNIVERSAL TRANSVERSE MERCATOR
ZONE 8 CENTRAL MERIDIAN: 135° W
SCALE FACTOR AT C.M.: 0.9996
FALSE EASTING: 500,000M
FALSE NORTHING: 0M

SCALE

5 2.5 0 5 10 15 20 25 30 35 40
Kilometers
Scale 1 : 500,000

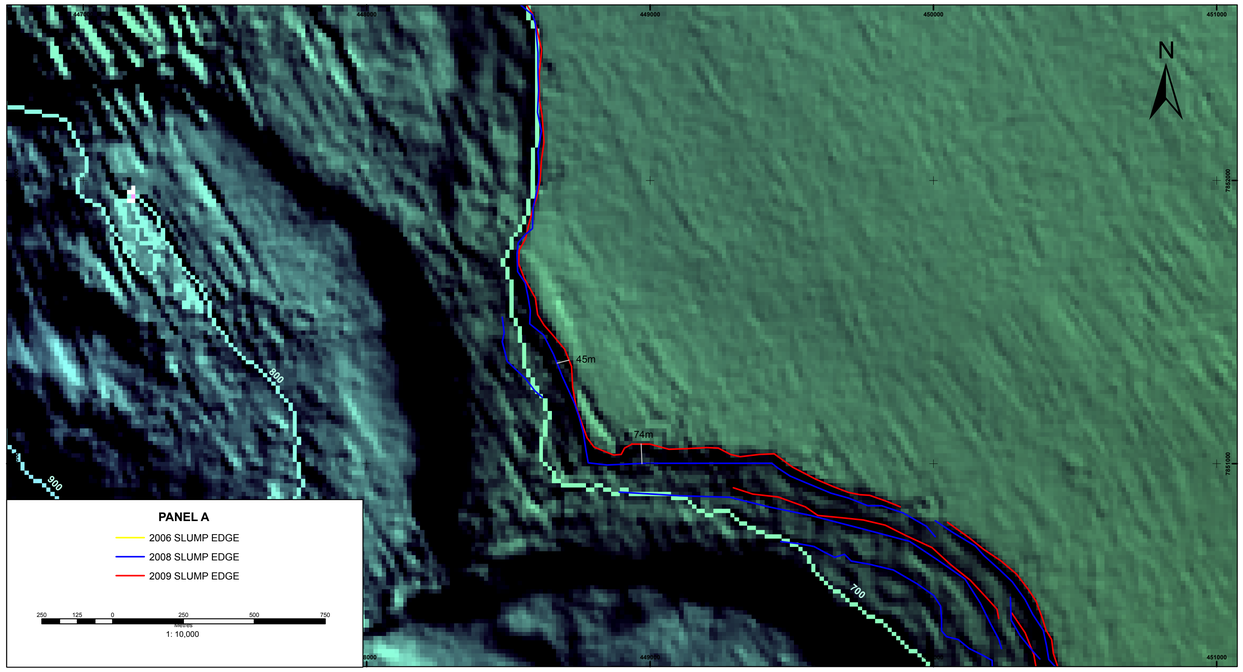
PREPARED BY

FUGRO GEOSURVEYS
25 Pippy Place
St. John's, NL
Canada, A1B 3X2

SEAFLOOR GRADIENT MAP SOUTHERN BEAUFORT SEA

REV	DATE	DESIGNATION	DRAWN	CHECK'D	APPR'D
0	Aug. 26/15	ISSUED FOR FINAL REPORT	CS	CWL	EC
C	Mar. 16/15	DRAFT C SUBMISSION	AC	CWL	EC

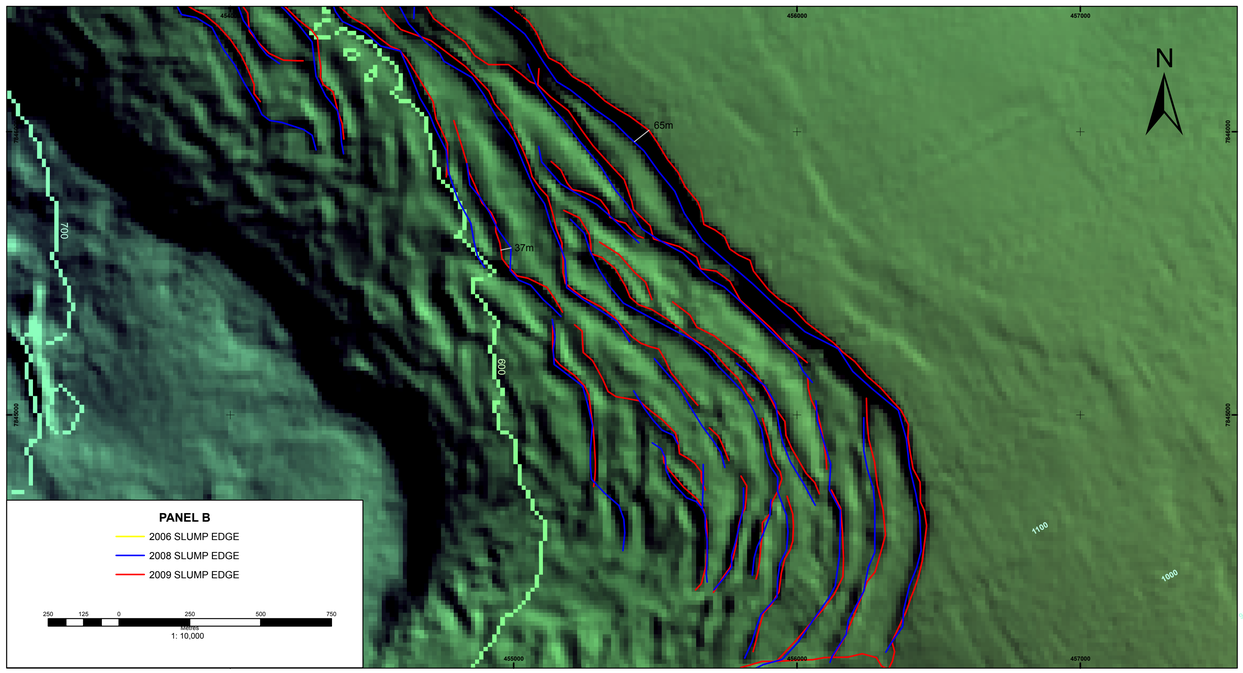
JOB NUMBER: 20110068
DWG No: 20110068-SLP-REG-E05-0
DATE: AUGUST 26, 2015
ENCLOSURE: 5



PANEL A

2006 SLUMP EDGE
2008 SLUMP EDGE
2009 SLUMP EDGE

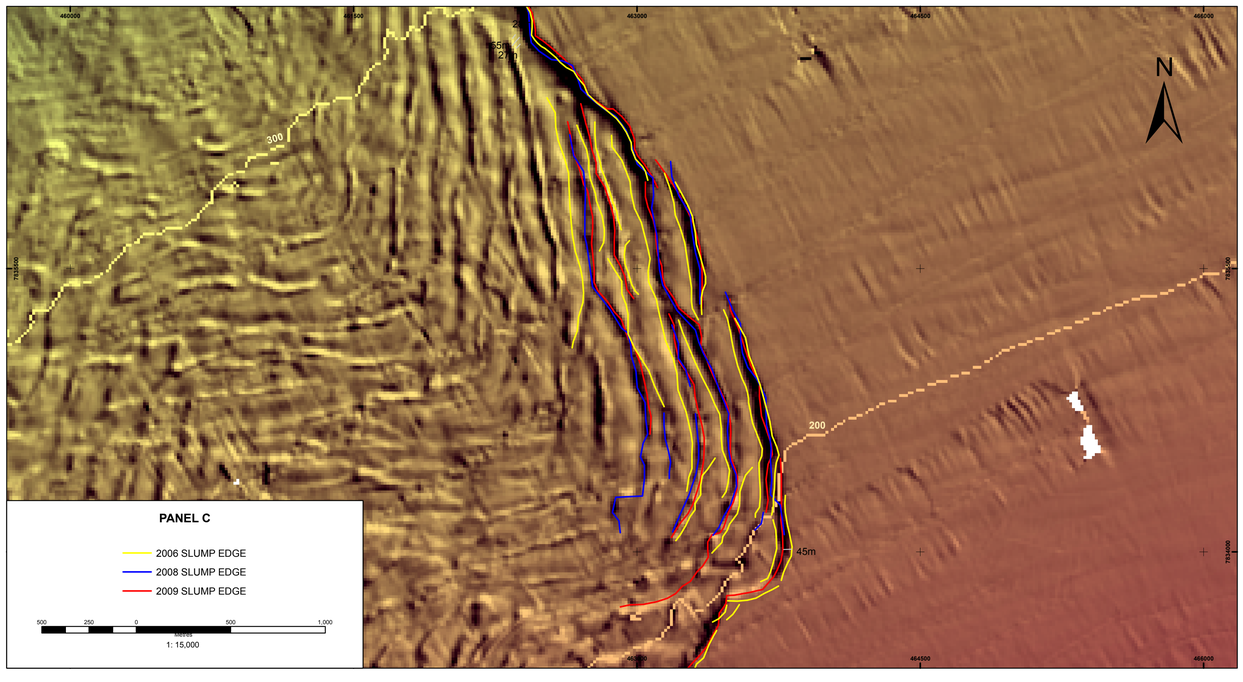
250 125 0 250 500 750
Metres
1: 10,000



PANEL B

2006 SLUMP EDGE
2008 SLUMP EDGE
2009 SLUMP EDGE

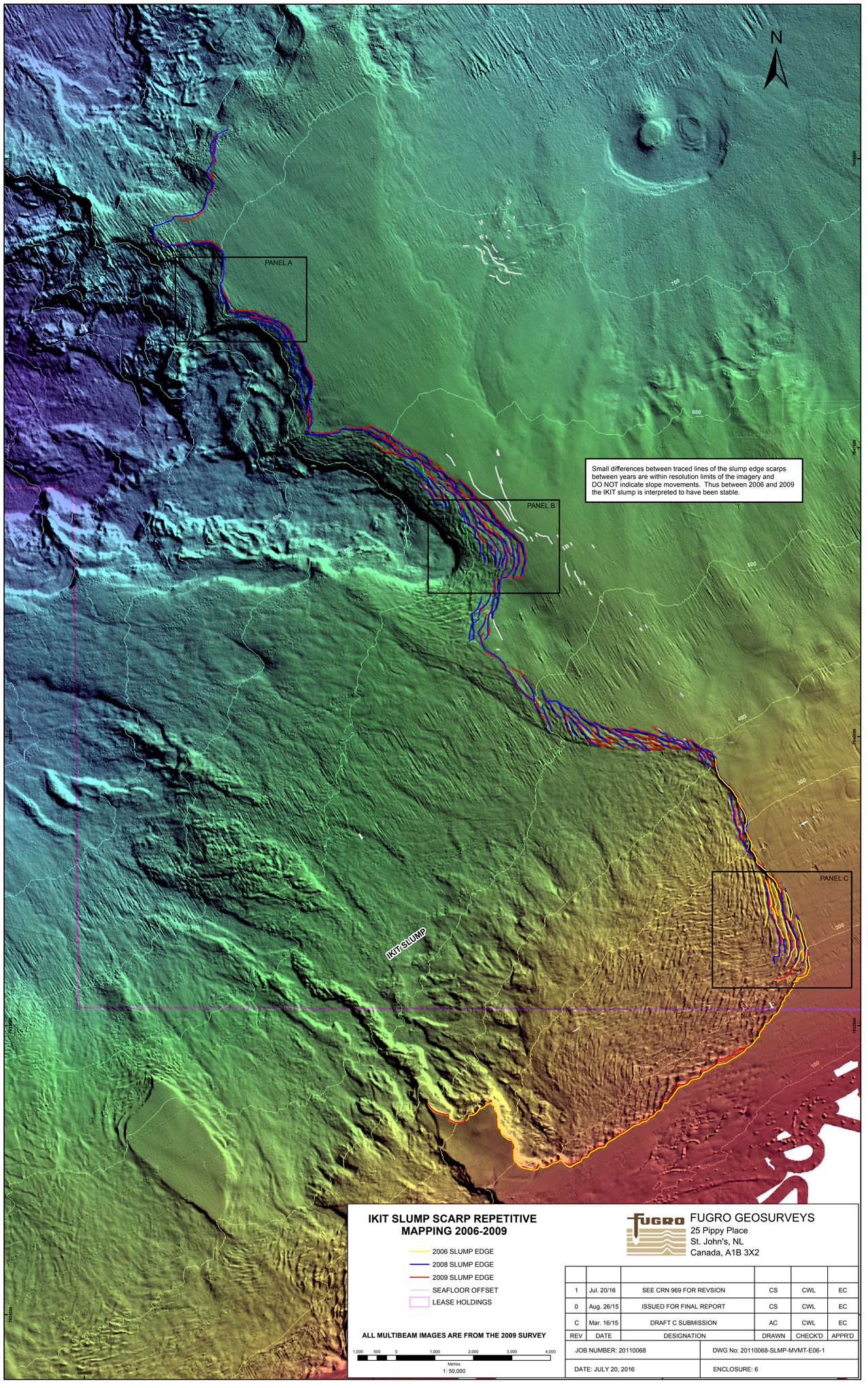
250 125 0 250 500 750
Metres
1: 10,000



PANEL C

2006 SLUMP EDGE
2008 SLUMP EDGE
2009 SLUMP EDGE

500 250 0 500 1,000
Metres
1: 15,000



IKIT SLUMP SCARP REPETITIVE MAPPING 2006-2009

2006 SLUMP EDGE
2008 SLUMP EDGE
2009 SLUMP EDGE
SEAFLOOR OFFSET
LEASE HOLDINGS

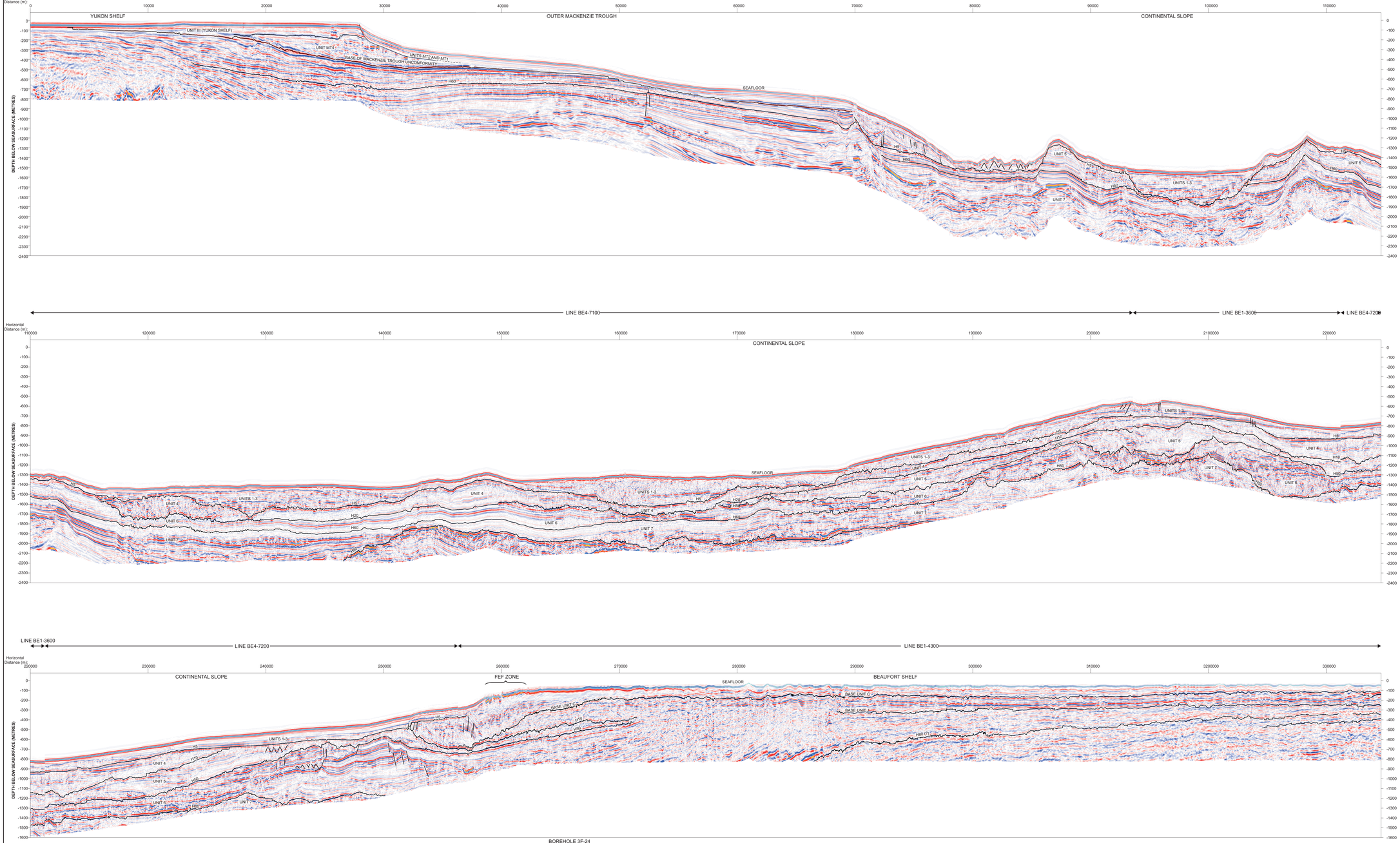
ALL MULTIBEAM IMAGES ARE FROM THE 2009 SURVEY

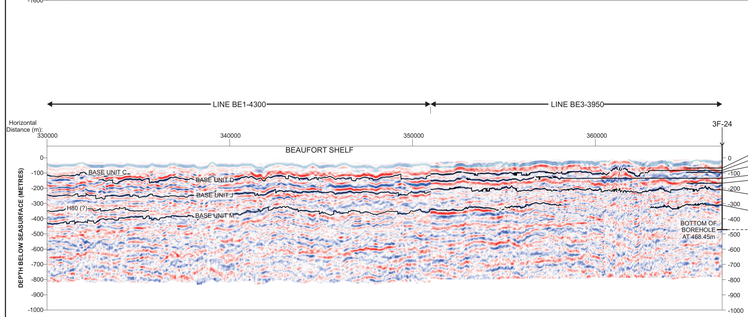
1,000 500 0 1,000 2,000 3,000 4,000
Metres
1: 50,000

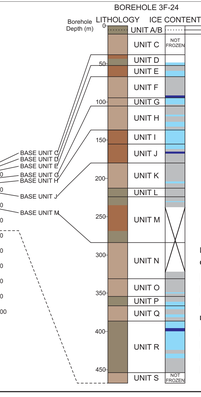
FUGRO GEOSURVEYS
25 Pippy Place
St. John's, NL
Canada, A1B 3X2

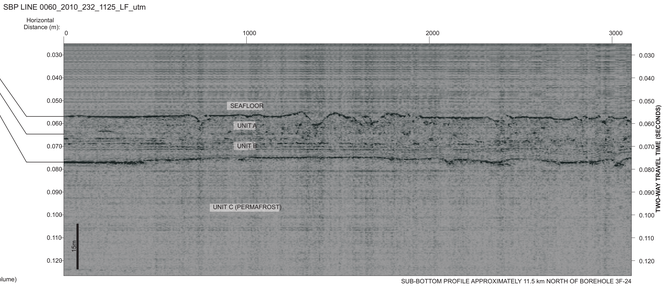
REV	DATE	DESIGNATION	DRAWN	CHECK'D	APPR'D
1	Jul. 20/16	SEE CRN 969 FOR REVSION	CS	CWL	EC
0	Aug. 26/15	ISSUED FOR FINAL REPORT	CS	CWL	EC
C	Mar. 16/15	DRAFT C SUBMISSION	AC	CWL	EC

JOB NUMBER: 20110068	DWG No: 20110068-SLMP-MVMT-E06-1
DATE: JULY 20, 2016	ENCLOSURE: 6

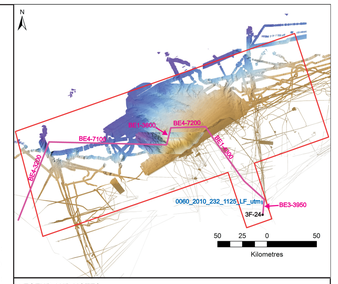








SUB-BOTTOM PROFILE APPROXIMATELY 11.5 km NORTH OF BOREHOLE 3F-24



LEGEND AND NOTES

Seafloor

Acoustic Seismic Horizon

DEPTH SCALE ON SUB-BOTTOM PROFILE INTERPRETATION BASED ON AN ASSUMED SOUND VELOCITY OF 1500m/s.

FUGRO REVISION REFERENCE

REV.	DATE	DESIGNATION	DRAWN	CHECK'D	APPR'D
0	Aug. 26/15	ISSUED FOR FINAL REPORT	CS	CWL	EC
C	Mar. 27/15	DRAFT C SUBMISSION	AC	CWL	EC

SCALE

0 5 10 15 20

KILOMETRES (km)

PREPARED BY

FUGRO GEOSURVEYS
25 Pippy Place
St. John's, NL
Canada, A1B 3X2

SEISMIC PROFILE ACROSS YUKON SHELF - OUTER MACKENZIE TROUGH - CONTINENTAL SLOPE - BEAUFORT SHELF - AMAULIGAK 3F-24 BOREHOLE SOUTHERN BEAUFORT SEA

JOB NUMBER: 20110068	DRAWN BY: AC
DATE: AUGUST 26, 2015	CHECKED BY: CWL
DWG NO: 20110068-PRO-ARB-E07-0	ENCLOSURE: 7
	REV 0

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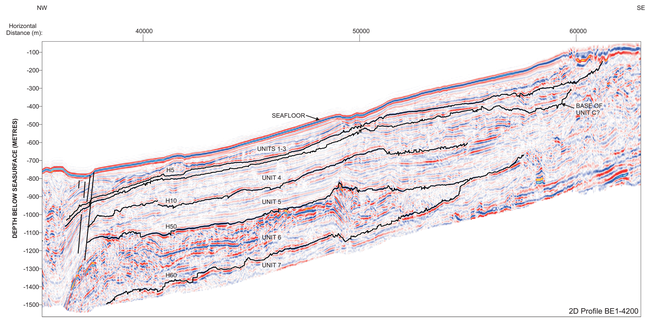
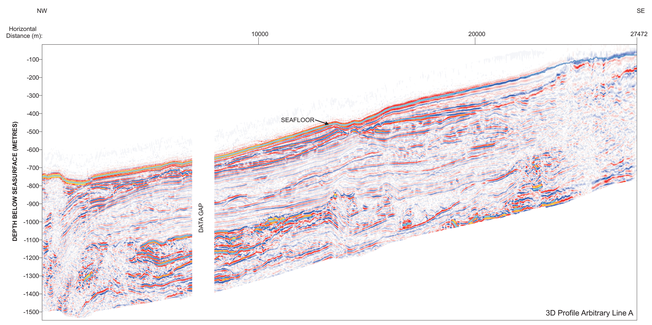
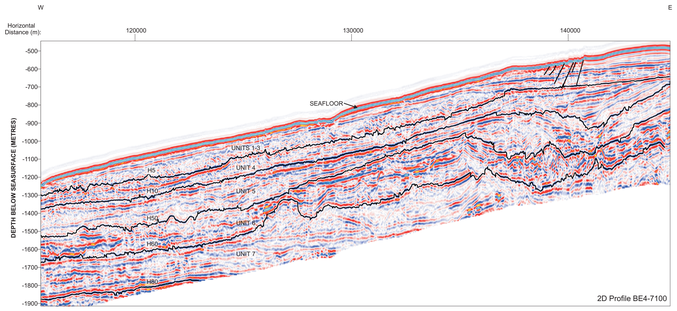


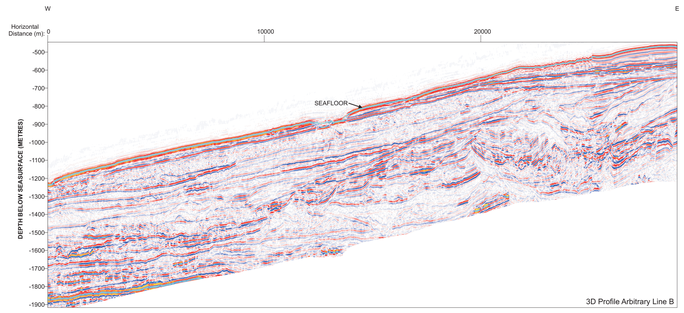
COMPARISON BETWEEN AN ION GXT 2D SEISMIC PROFILE (ABOVE)
AND CORRESPONDING PROFILE (BELOW) FROM THE IOL 3D VOLUME



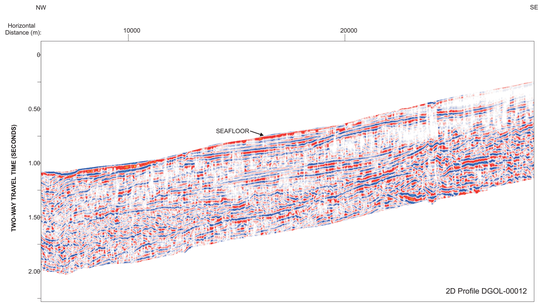
B)



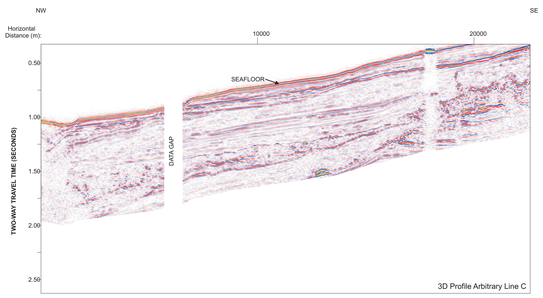
COMPARISON BETWEEN AN ION GXT 2D SEISMIC PROFILE (ABOVE)
AND CORRESPONDING PROFILE (BELOW) FROM THE IOL 3D VOLUME



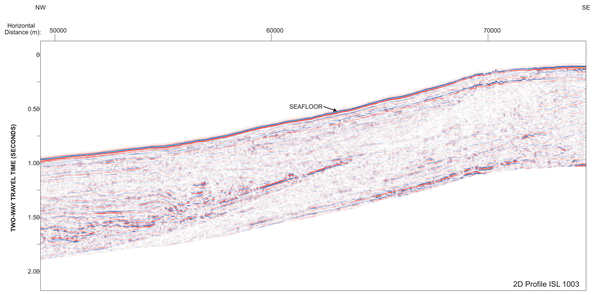
C)



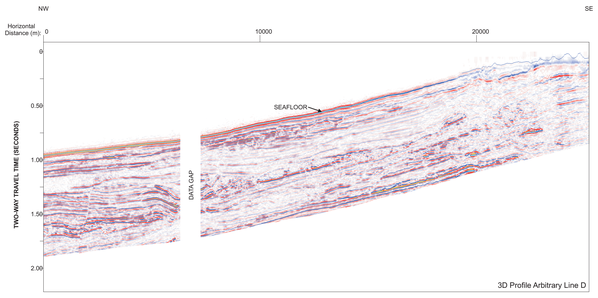
COMPARISON BETWEEN A 2D SEISMIC PROFILE OF LEGACY DATA (ABOVE)
AND CORRESPONDING PROFILE (BELOW) FROM THE IOL 3D VOLUME

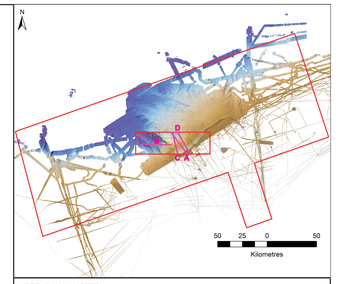


D)



COMPARISON BETWEEN A RECENT 2D SEISMIC PROFILE COLLECTED BY THE GSC (ABOVE)
AND CORRESPONDING PROFILE (BELOW) FROM THE IOL 3D VOLUME





LEGEND AND NOTES

- Seafloor
- Acoustic Seismic Horizon

FUGRO REVISION REFERENCE

REV.	DATE	DESIGNATION	DRAWN	CHECK'D	APPR'D
0	Aug.26/15	ISSUED FOR FINAL REPORT	CS	CWL	EC
C	Mar. 16/15	DRAFT C FOR SUBMISSION	AC	CWL	EC

SCALE

0 5 10 15 20
KILOMETRES (km)

PREPARED BY

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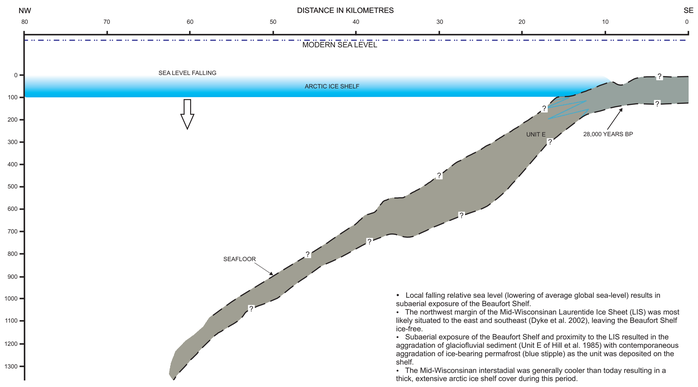
2D AND 3D SEISMIC PROFILE COMPARISONS SOUTHERN BEAUFORT SEA

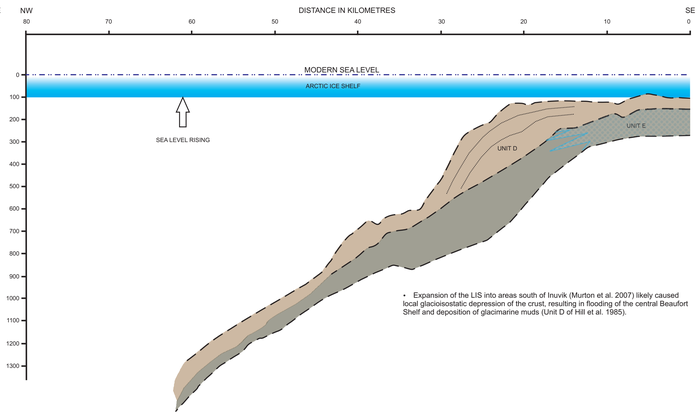
JOB NUMBER: 20110068	DRAWN BY: AC
DATE: AUGUST 26, 2015	CHECKED BY: CWL
DWG NO: 20110068-PRO-3D2D-E08-0	ENCLOSURE: 8
	REV 0

APPROXIMATELY 30,000 - 21,000 YEARS BP



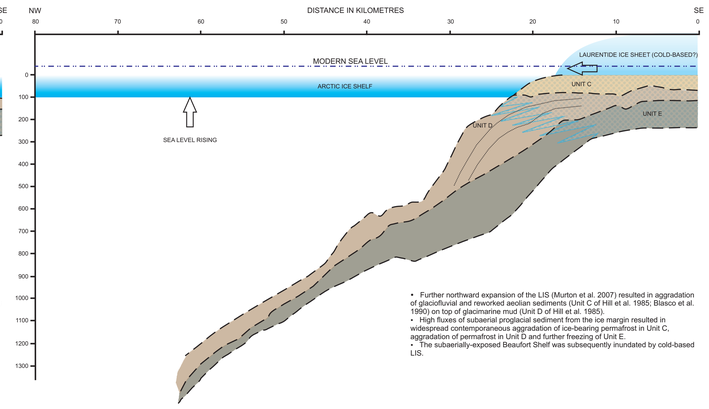
- Local falling relative sea level (lowering of average global sea-level) results in subaerial exposure of the Beaufort Shelf.
- The northwest margin of the Mid-Wisconsinan Laurentide Ice Sheet (LIS) was most likely situated to the east and southeast (Dyke et al. 2002), leaving the Beaufort Shelf ice-free.
- Subaerial exposure of the Beaufort Shelf and proximity to the LIS resulted in the aggradation of glaciofluvial sediment (Unit E of Hill et al. 1985) with contemporaneous aggradation of ice-bearing permafrost (blue stipple) as the unit was deposited on the shelf.
- The Mid-Wisconsinan interstadial was generally cooler than today resulting in a thick, extensive arctic ice shelf cover during this period.

APPROXIMATELY 21,000 YEARS BP



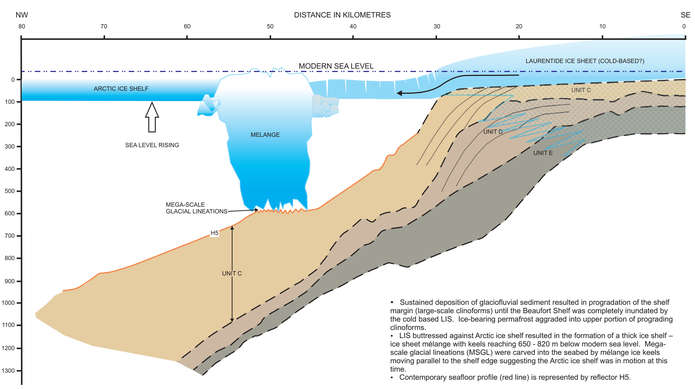
- Expansion of the LIS into areas south of Inuvik (Murton et al. 2007) likely caused local glacioisostatic depression of the crust, resulting in flooding of the central Beaufort Shelf and deposition of glacimarine muds (Unit D of Hill et al. 1985).

APPROXIMATELY 21,000 - 19,000 YEARS BP



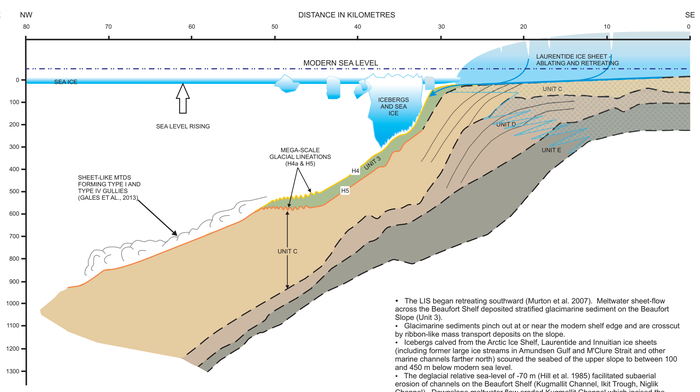
- Further northward expansion of the LIS (Murton et al. 2007) resulted in aggradation of glaciofluvial and reworked aeolian sediments (Unit C of Hill et al. 1985; Blasco et al. 1990) on top of glacimarine mud (Unit D of Hill et al. 1985).
- High fluxes of subaerial proglacial sediment from the ice margin resulted in widespread contemporaneous aggradation of ice-bearing permafrost in Unit C, aggradation of permafrost in Unit D and further freezing of Unit E.
- The subaerially-exposed Beaufort Shelf was subsequently inundated by cold-based LIS.

APPROXIMATELY 19,000 - 16,000 YEARS BP



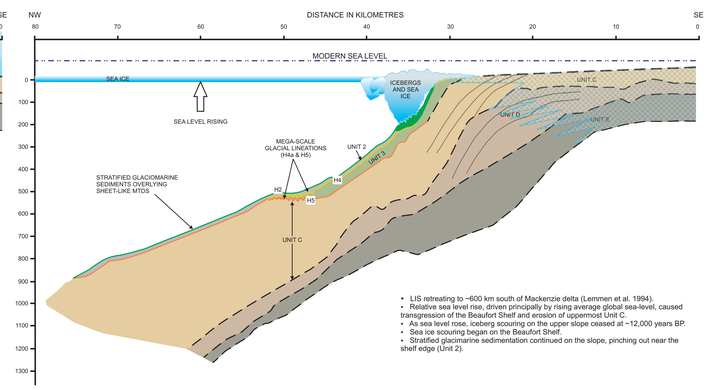
- Sustained deposition of glaciofluvial sediment resulted in progradation of the shelf margin (large-scale clinoforms) until the Beaufort Shelf was completely inundated by the cold based LIS. Ice-bearing permafrost aggraded into upper portion of prograding clinoforms.
- LIS buttressed against Arctic ice shelf resulted in the formation of a thick ice shelf – ice sheet mélange with keels reaching 650 - 820 m below modern sea level. Mega-scale glacial lineations (MSGL) were carved into the seabed by mélange ice keels moving parallel to the shelf edge suggesting the Arctic ice shelf was in motion at this time.
- Contemporary seafloor profile (red line) is represented by reflector H5.

16,000 - 13,000 YEARS BP



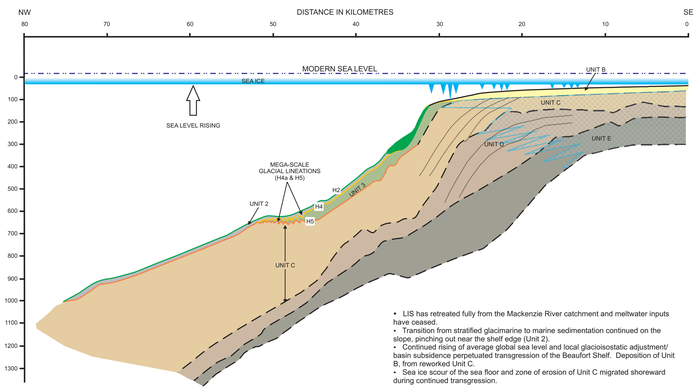
- The LIS began retreating southward (Murton et al. 2007). Meltwater sheet-flow across the Beaufort Shelf deposited stratified glacimarine sediment on the Beaufort Slope (Unit 3).
- Glacimarine sediments pinch out at or near the modern shelf edge and are crosscut by ribbon-like mass transport deposits on the slope.
- Icebergs calved from the Arctic Ice Shelf, Laurentide and Innuitian ice sheets (including former large ice streams in Amundsen Gulf and M'Clure Strait and other marine channels farther north) scoured the seabed of the upper slope to between 100 and 450 m below modern sea level.
- The deglacial relative sea-level of -70 m (Hill et al. 1985) facilitated subaerial erosion of channels on the Beaufort Shelf (Kugmallit Channel, Ikit Trough, Niglik Channel). Downslope meltwater flow eroded Kugmallit Channel which incised the slope and can be traced on the modern seafloor to present water depths of at least 750 m.

13,000 - 12,000 YEARS BP



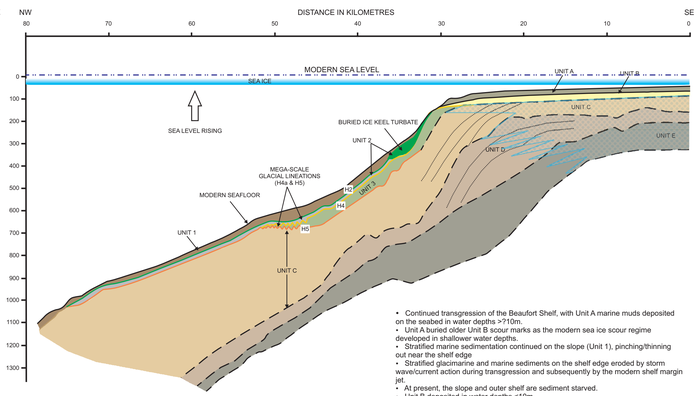
- LIS retreating to ~600 km south of Mackenzie delta (Lemmen et al. 1994).
- Relative sea level rise, driven principally by rising average global sea-level, caused transgression of the Beaufort Shelf and erosion of uppermost Unit C.
- As sea level rose, iceberg scouring on the upper slope ceased at ~12,000 years BP.
- Sea ice scouring began on the Beaufort Shelf.
- Stratified glacimarine sedimentation continued on the slope, pinching out near the shelf edge (Unit 2).

12,000 - 9,000 YEARS BP



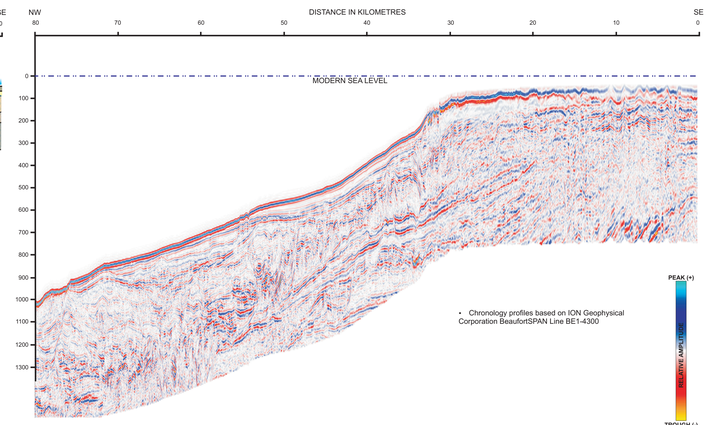
- LIS has retreated fully from the Mackenzie River catchment and meltwater inputs have ceased.
- Transition from stratified glacimarine to marine sedimentation continued on the slope, pinching out near the shelf edge (Unit 2).
- Continued rising of average global sea level and local glacioisostatic adjustment/ basin subsidence perpetuated transgression of the Beaufort Shelf. Deposition of Unit B, from reworked Unit C.
- Sea ice scour of the sea floor and zone of erosion of Unit C migrated shoreward during continued transgression.

9,000 YEARS BP TO PRESENT

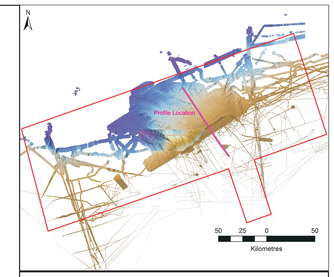


- Continued transgression of the Beaufort Shelf, with Unit A marine muds deposited on the seabed in water depths >?10m.
- Unit A buried older Unit B scour marks as the modern sea ice scour regime developed in shallower water depths.
- Stratified marine sedimentation continued on the slope (Unit 1), pinching/thinning out near the shelf edge
- Stratified glacimarine and marine sediments on the shelf edge eroded by storm wave/current action during transgression and subsequently by the modern shelf margin jet.
- At present, the slope and outer shelf are sediment starved.
- Unit B deposited in water depths <16m.

ION GXT LINE BE1-4300



- Chronology profiles based on ION Geophysical Corporation BeaufortSPAN Line BE1-4300

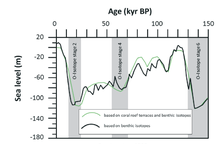


LEGEND AND NOTES

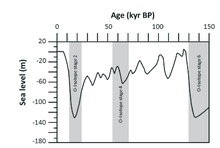
- Seafloor
- Horizon H2
- Horizon H4
- Horizon H5
- Clinoform
- Sediment Flow
- Permafrost

CONTINENTAL SLOPE — BEAUFORT SHELF

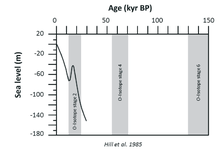
- Unit 1 — Ice Keel Turbate — Unit A
- Unit 2 — Unit B
- Unit 3 — Unit C
- Unit D
- Unit E



Rohling et al. 1998



Chappell and Shackleton 1986



Hill et al. 1985

FUGRO REVISION REFERENCE

REV.	DATE	DESIGNATION	DRAWN	CHECK'D	APPR'D
1	Dec.03/15	ISSUED FOR FINAL REPORT - CRN No. 918 FOR CHANGES	AC	CWL	EC
0	Aug.26/15	ISSUED FOR FINAL REPORT	CS	CWL	EC
C	Mar.16/15	DRAFT C SUBMISSION	JF/AC	CWL	EC

SCALE

PREPARED BY

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LATE QUATERNARY EVOLUTION OF THE SOUTHERN BEAUFORT SEA

JOB NUMBER: 20110068	DRAWN BY: JF/AC
DATE: DECEMBER 3, 2015	CHECKED BY: CWL
DWG NO: 20110068-GEO-MOD-E09-1	ENCLOSURE: 9 REV 1