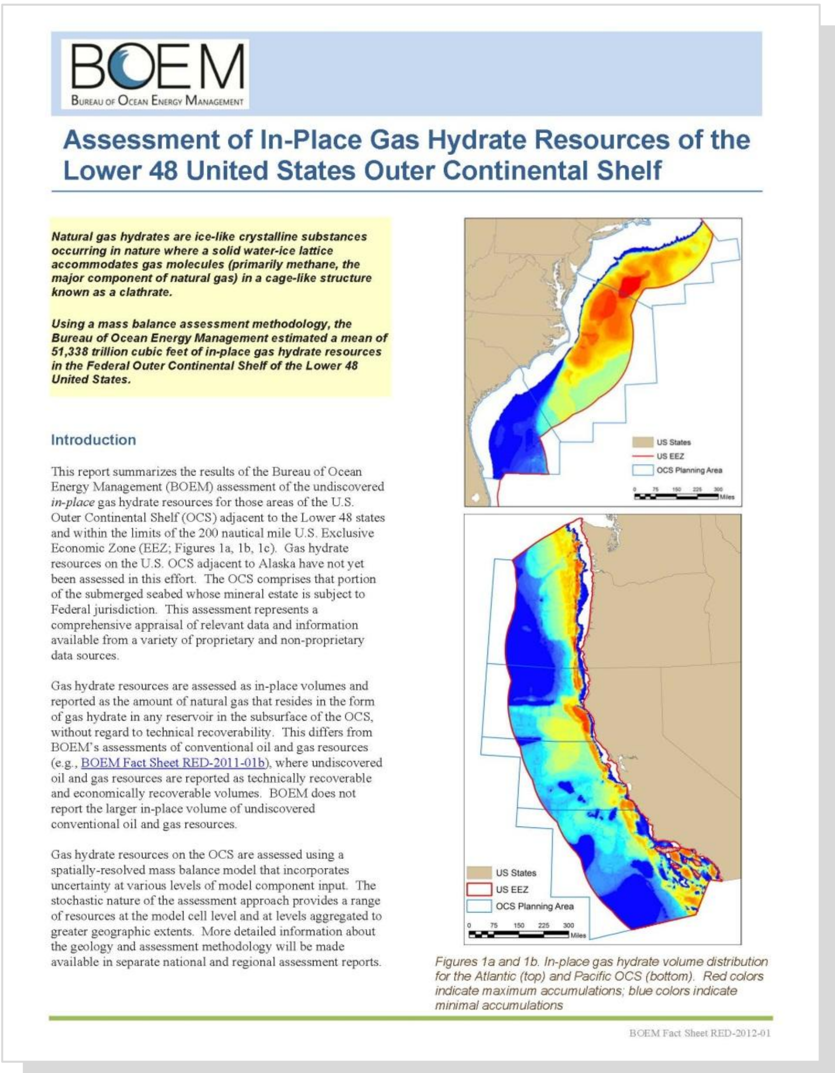

BUREAU OF OCEAN ENERGY MANAGEMENT

Assessment of In-Place Gas Hydrate Resources of the Lower 48 United States Outer Continental Shelf

Natural gas hydrates are ice-like crystalline substances occurring in nature where a solid water-ice lattice accommodates gas molecules (primarily methane, the major component of natural gas) in a cage-like structure known as a clathrate.

Using a mass balance assessment methodology, the Bureau of Ocean Energy Management estimated a mean of 51,338 trillion cubic feet of in-place gas hydrate resources in the Federal Outer Continental Shelf of the Lower 48 United States.

Introduction

This report summarizes the results of the Bureau of Ocean Energy Management (BOEM) assessment of the undiscovered *in-place* gas hydrate resources for those areas of the U.S. Outer Continental Shelf (OCS) adjacent to the Lower 48 states and within the limits of the 200 nautical mile U.S. Exclusive Economic Zone (EEZ; Figures 1a, 1b, 1c). Gas hydrate resources on the U.S. OCS adjacent to Alaska have not yet been assessed in this effort. The OCS comprises that portion of the submerged seabed whose mineral estate is subject to Federal jurisdiction. This assessment represents a comprehensive appraisal of relevant data and information available from a variety of proprietary and non-proprietary data sources.

Gas hydrate resources are assessed as in-place volumes and reported as the amount of natural gas that resides in the form of gas hydrate in any reservoir in the subsurface of the OCS, without regard to technical recoverability. This differs from BOEM's assessments of conventional oil and gas resources (e.g., BOEM Fact Sheet RED-2011-01b), where undiscovered oil and gas resources are reported as technically recoverable and economically recoverable volumes. BOEM does not report the larger in-place volume of undiscovered conventional oil and gas resources.

Gas hydrate resources on the OCS are assessed using a spatially-resolved mass balance model that incorporates uncertainty at various levels of model component input. The stochastic nature of the assessment approach provides a range of resources at the model cell level and at levels aggregated to greater geographic extents. More detailed information about the geology and assessment methodology will be made available in separate national and regional assessment reports.

Figures 1a and 1b. In-place gas hydrate volume distribution for the Atlantic (top) and Pacific OCS (bottom). Red colors indicate maximum accumulations; blue colors indicate minimal accumulations

Update on BOEM Lower 48 Assessment

A presentation to the
Methane Hydrate Advisory Committee

Matthew Frye
Resource Evaluation Division
BOEM – Herndon, VA
matt.frye@boem.gov
6 June 2013

BOEM Resource Evaluation Division gas hydrate webpage:

http://www.boem.gov/Oil-and-Gas-Energy-Program/Resource-Evaluation/Gas-Hydrates/index.aspx

Update on BOEM Lower 48 Assessment
Matthew Frye
BOEM – Herndon, VA
6 June 2013

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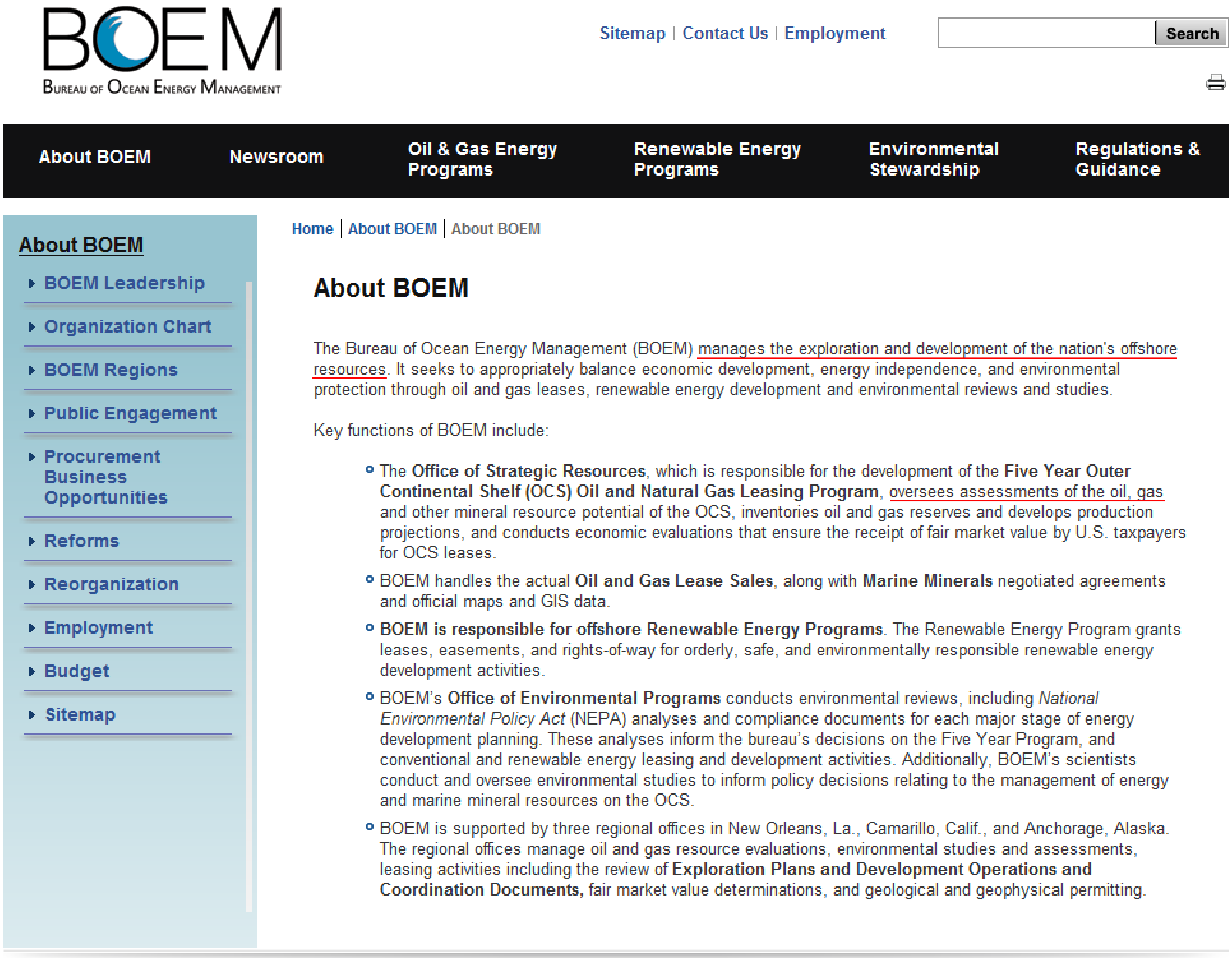

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Offshore Development Lifecycle – U.S. OCS

Oil and Gas Production on the US OCS

Reserve Estimation

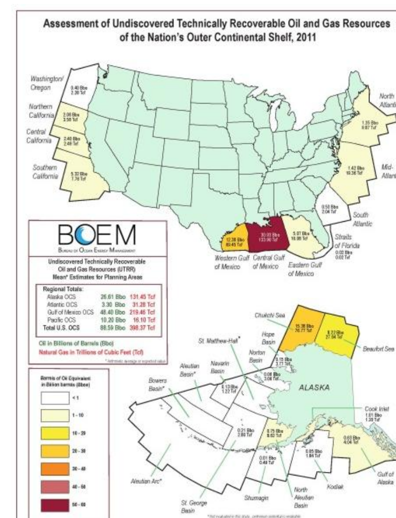
Exploratory & Development Well Drilling

Lease / Tract Award
(“fair market value determination”)

Lease Sale

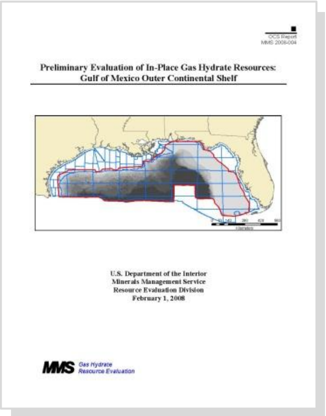
5-Year Program

Assessment of Undiscovered Oil & Gas Resources



BOEM Gas Hydrate Assessment Efforts – A Timeline:

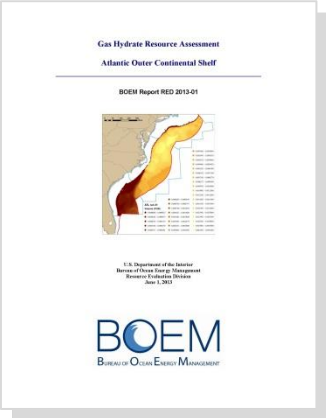
c. 2003	MMS begins resource assessment of gas hydrate on OCS previous assessment by USGS (1995) Methodology + GOM input files
2008	GOM assessment results / documentation released
2009	Atlantic model / input files
2011	Pacific model / input files
2012	Lower 48 assessment Fact Sheet released
2013	Atlantic full documentation released; Pacific to follow
2014	Alaska OCS


OCS Report
MMS 2008-004

Preliminary Evaluation of In-Place Gas Hydrate Resources: Gulf of Mexico Outer Continental Shelf

U.S. Department of the Interior
Minerals Management Service
Resource Evaluation Division
February 1, 2008

MMS Gas Hydrate Resource Evaluation


Gas Hydrate Resource Assessment

Atlantic Outer Continental Shelf

BOEM Report RED 2013-01

U.S. Department of the Interior
Bureau of Ocean Energy Management
Resource Evaluation Division
June 1, 2013

BOEM
Bureau of Ocean Energy Management

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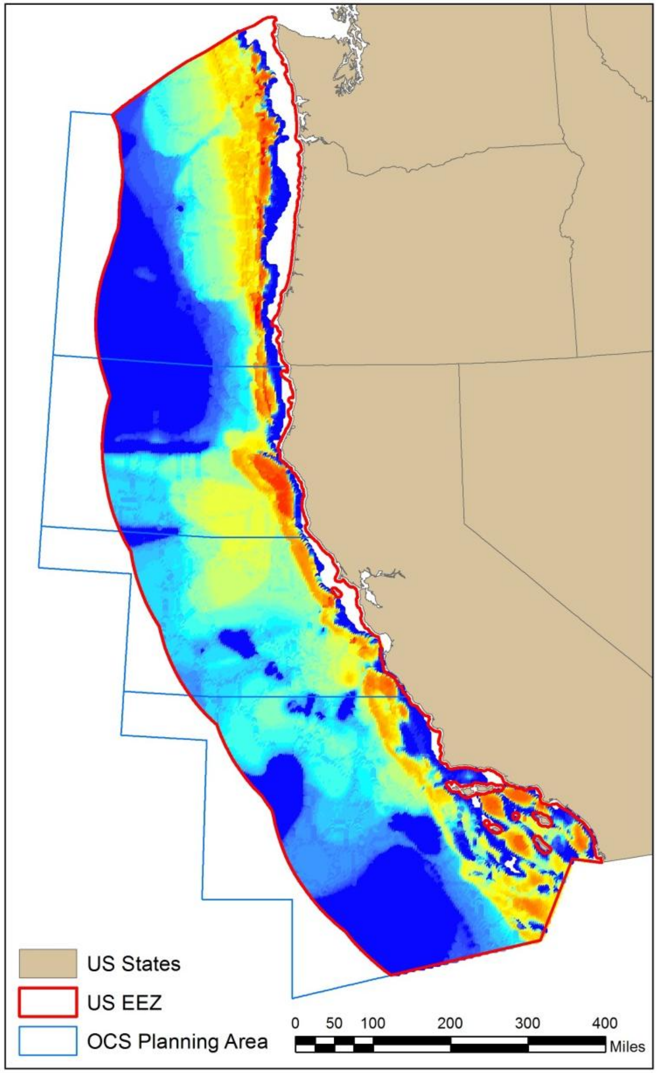
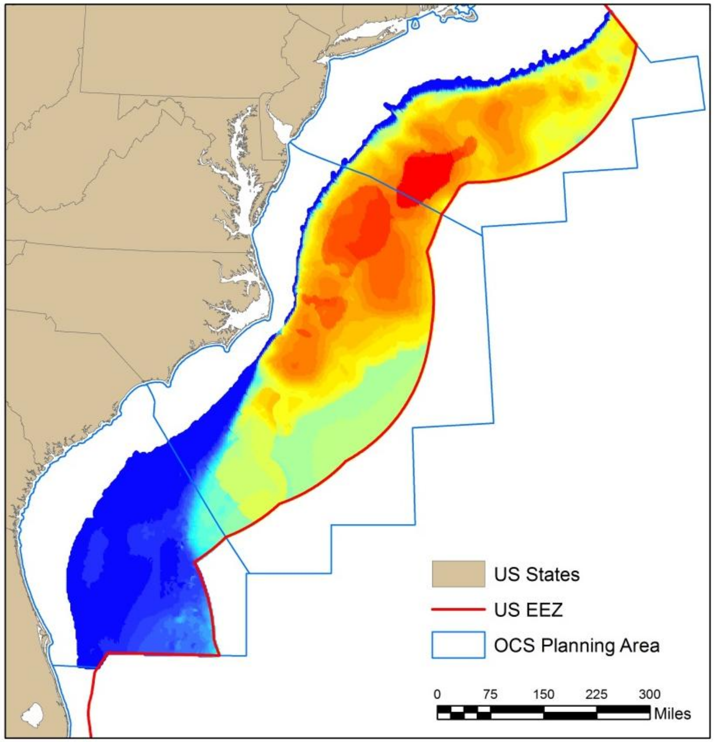
Matthew Frye
BOEM – Herndon, VA
6 June 2013



from BOEM Fact Sheet RED-2012-01

Region	In-Place Gas Hydrate Resources					
	95%		Mean		5%	
	tcf	tcm	tcf	tcm	tcf	tcm
Atlantic OCS	2,056	58	21,702	614	52,401	1,483
Pacific OCS	2,209	63	8,192	232	16,846	477
Gulf of Mexico OCS	11,112	314	21,444	607	34,423	974



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Evolution of BOEM model structure

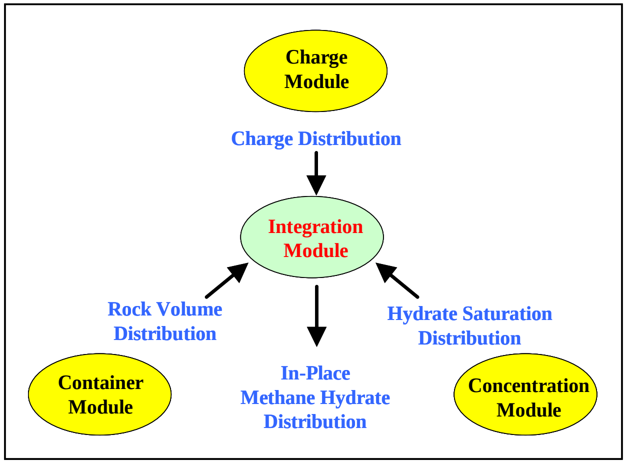
Module	Model	Pacific Model	Atlantic Model	2008 Gulf of Mexico Model
Container	Gross HSZ thickness	Thickness constrained by sediment thickness input	present, but no real impact	constrained by Salt input
Container	Undersaturated Zone	Inversely proportional to charge (0 to 200 m)	Symmetric beta (0 to 400 m)	Inversely proportional to charge (0 to 200 m)
Charge	Sediment Thickness	Spatial input	Spatial input (ISO 1 and ISO 2)	Estimated from gamma distributions
Charge	Migration	100% vertical	100% vertical	Combination of vertival & dip driven
Charge	Migration Efficiency	Function of BSR	Function of BSR	Randon draw from beta(4, 10) distribution
Charge	Generation	Proximal cell smoothing	Not Modeled	Not Modeled
Input	Sand Percent	Depofacies approach	Direct mapping (seismic/well)	Direct mapping (seismic/well)
Input	Seafloor Age	Constrains thickness age	Not Modeled	Not Modeled
Input	Total Organic Carbon	Spatial allocation of empirical data (4 unique areas)	single distribution	single distribution
Input	Geothermal Gradient	Spatial allocation of empirical data (2 unique areas)	single distribution	single distribution
Input	Surficial Anomaly	Not Modeled	Not Modeled	Presence changes gas composition used in Container module and adds fracture saturation to Concentration module
Input	Salt	Not Modeled	Not Modeled[1]	Subseafloor depth to salt influences HSZ thickness
Input	BSR	Used for Migration Efficiency	Used for Migration Efficiency	Not Modeled[2]
Process	Gen			

The following inputs were developed for the Pacific based on local information, and may comprise a different functional form than the same inputs in the GOM: GTG, WBT, TOC, Quality

[1]While shallow salt has not been included in the Atlantic assessment model, it is noted that a ssw/nne trend of piercement salt features of limited areal extent is recognized in the Carolina Trough.

[2]BSRs were not included in the original GOM model; MMS now has identified over 150 BSRs in the GOM.

- Spatial, mass-balance model remains intact
- Resources reported as “in-place” volumes
- Biogenic gas only
- Adaptation of model structure and input files to reflect local geology and data availability
- No introduction of Geologic Risk



Update on BOEM Lower 48 Assessment

Matthew Frye

BOEM – Herndon, VA

6 June 2013

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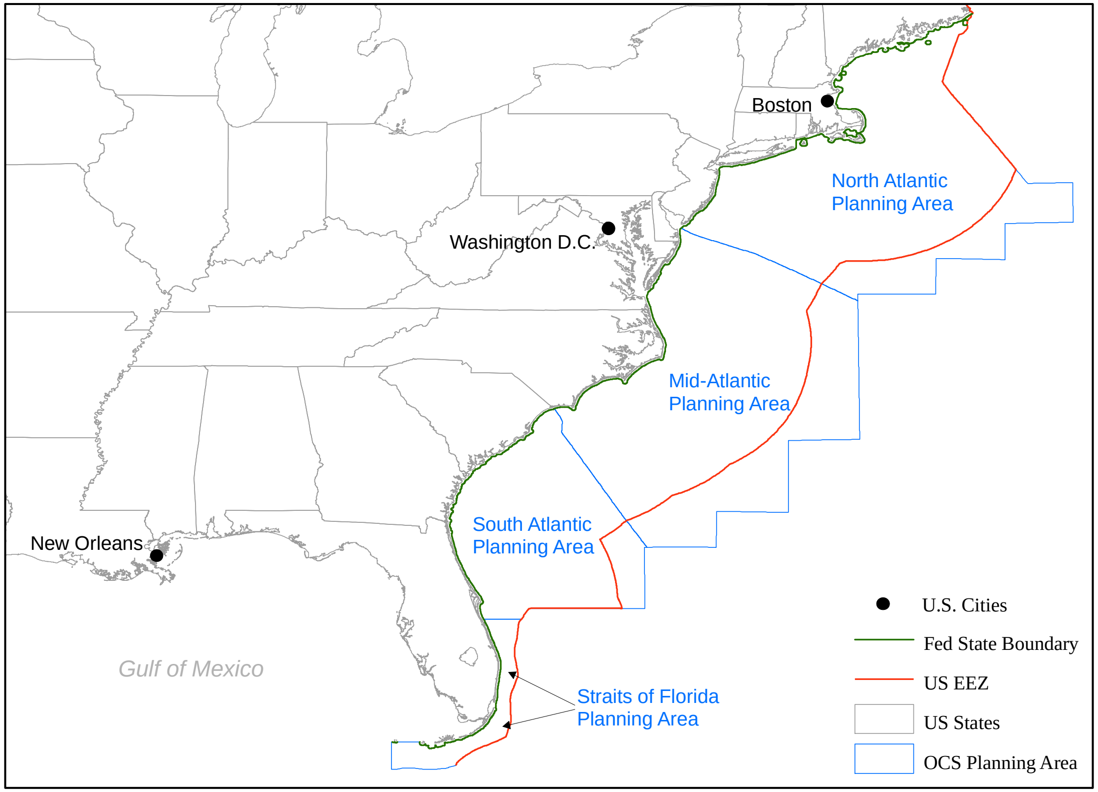
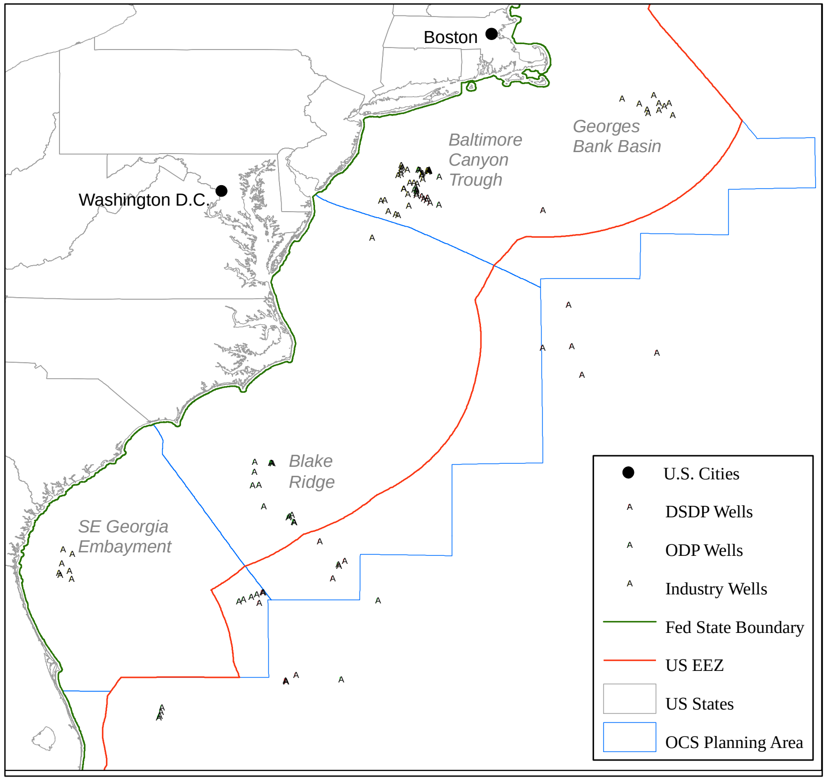
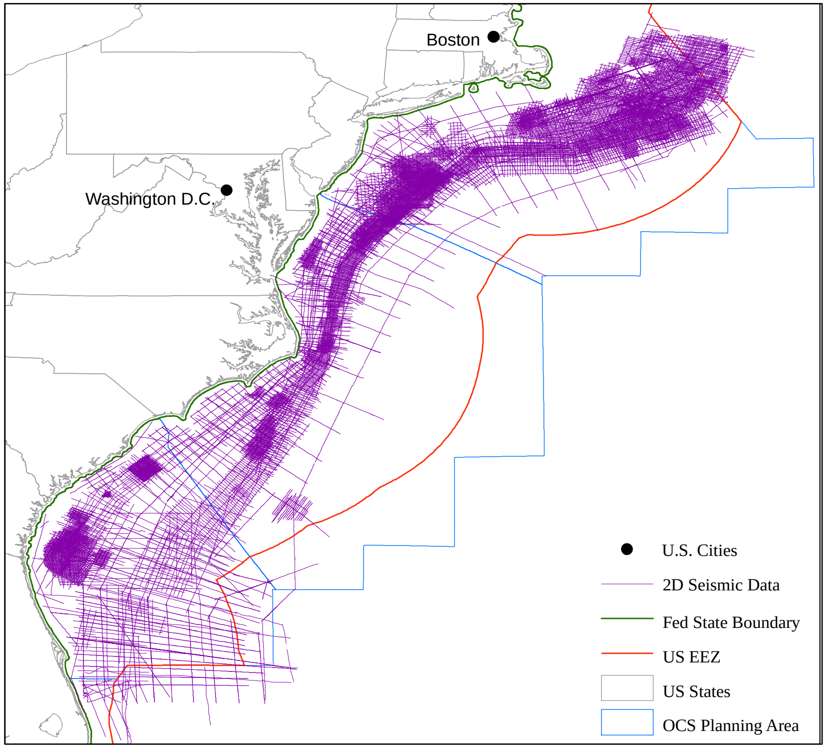


North Atlantic, Mid-Atlantic, South Atlantic, Straits of Florida comprise a total area in excess of 269 million acres (420,000 mi^2; 1,089,128 km^2).

For this assessment, the Atlantic OCS has been partitioned into 57,066 cells of size 3 km x 3 km, with a total study area measuring approximately 514,000 km^2

Bill Shedd & Jesse Hunt (retired) BOEM GOMR – Atlantic GH assessment champions (spatial)





51 permitted wells, including five stratigraphic test wells drilled between 1975 and 1979 and 46 industry wells drilled between 1977 and 1984.

50 ODP/DSDP wells used

access to over 200,000 line miles (~320,000 line km) of 2-D multi-channel seismic data.

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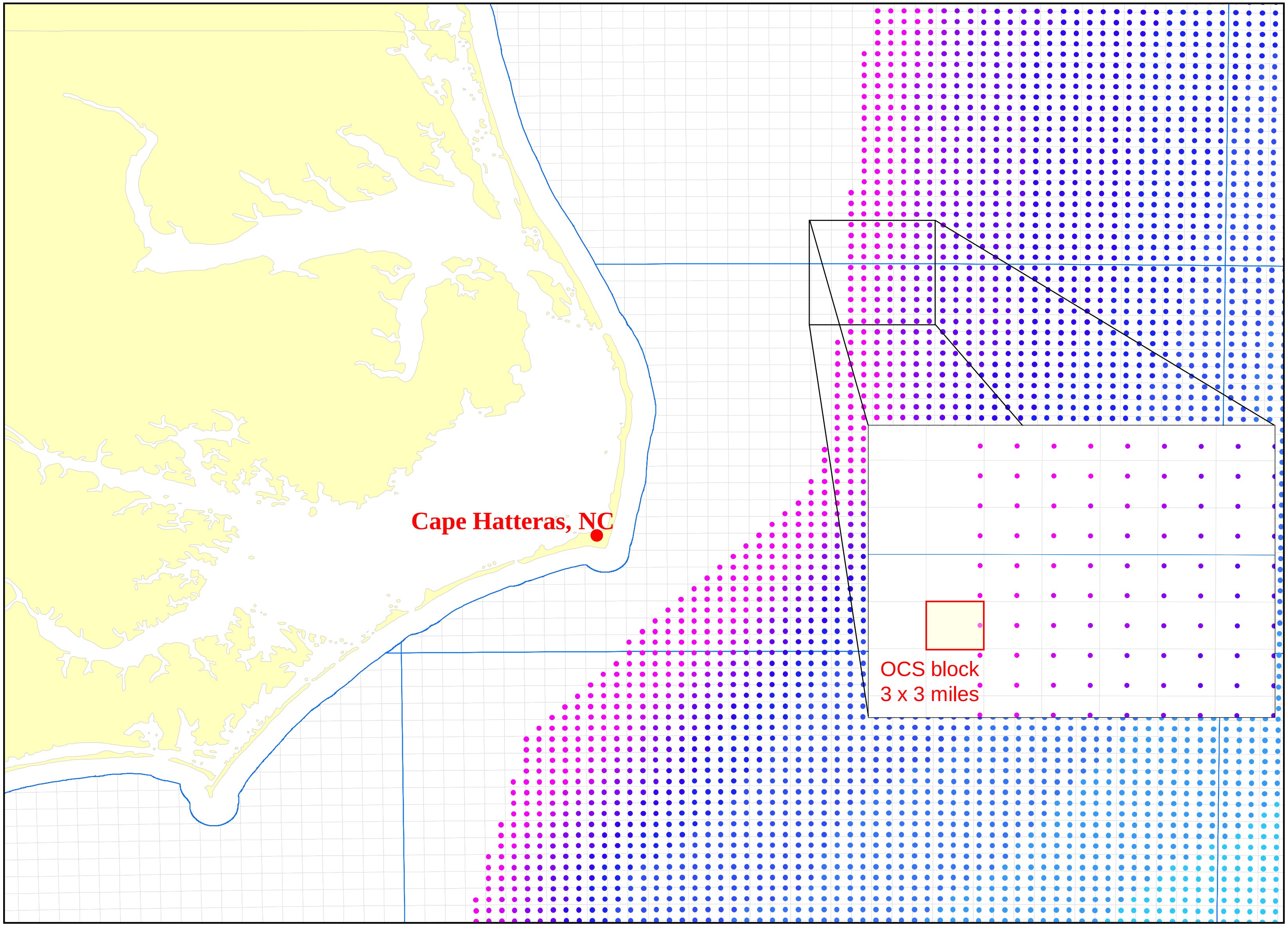
BOEM – Herndon, VA
6 June 2013



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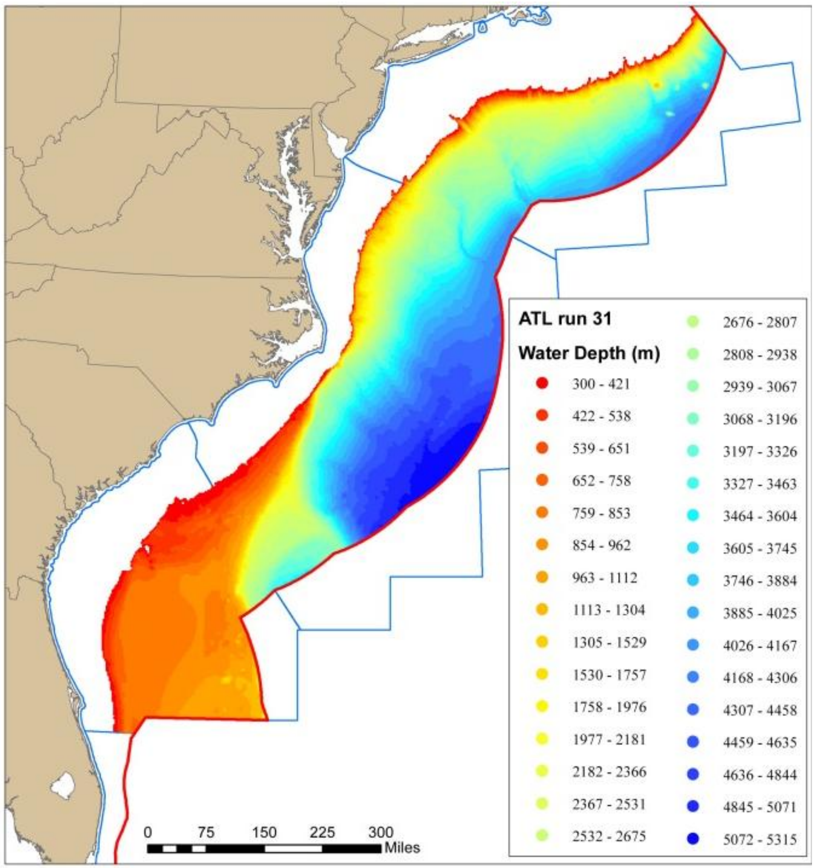
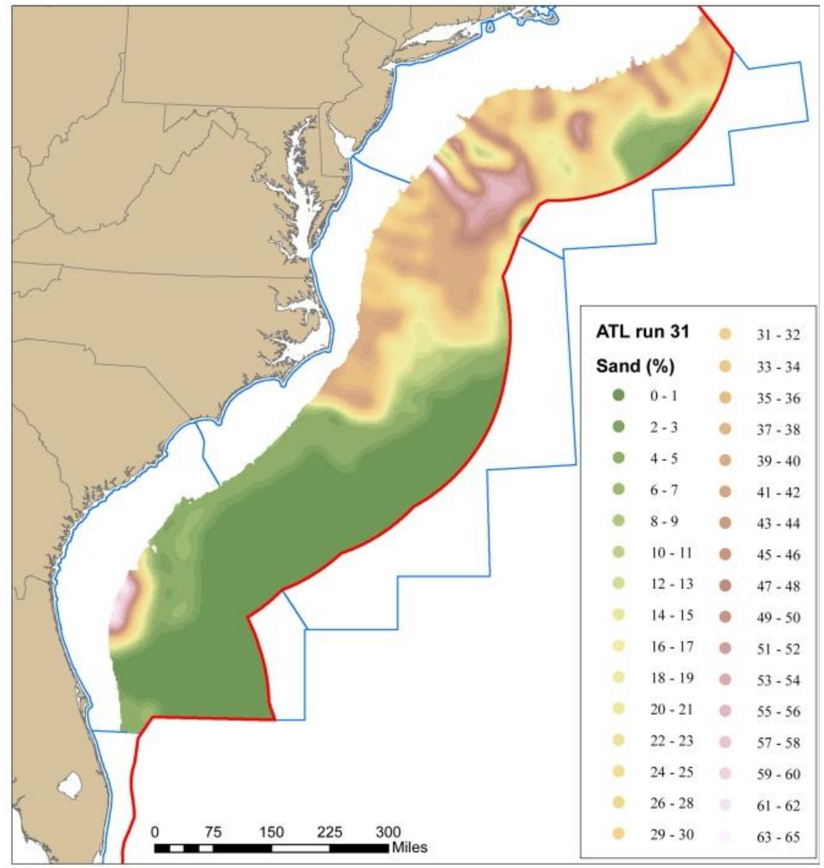
BOEM Bureau of Ocean Energy Management

Spatial Inputs – Atlantic OCS

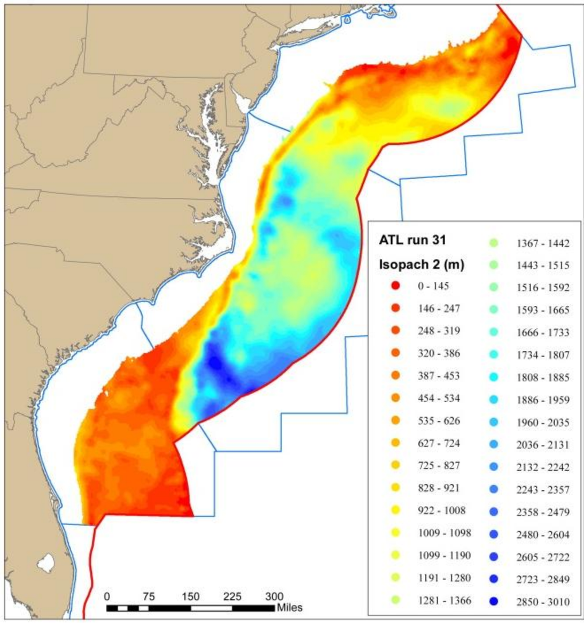


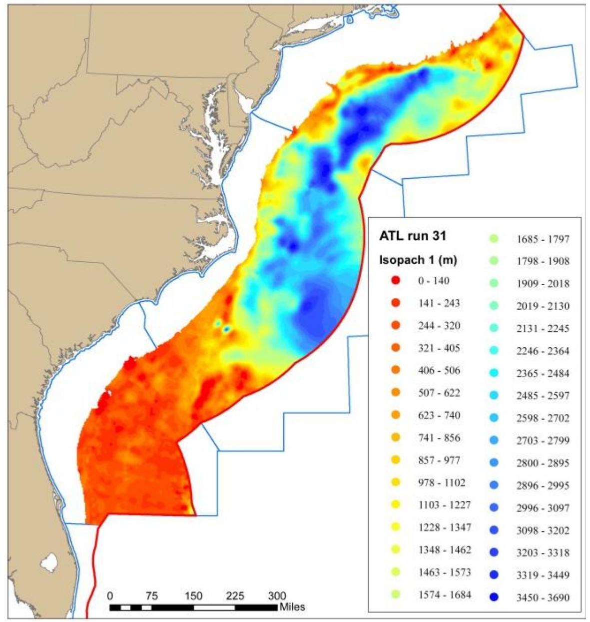


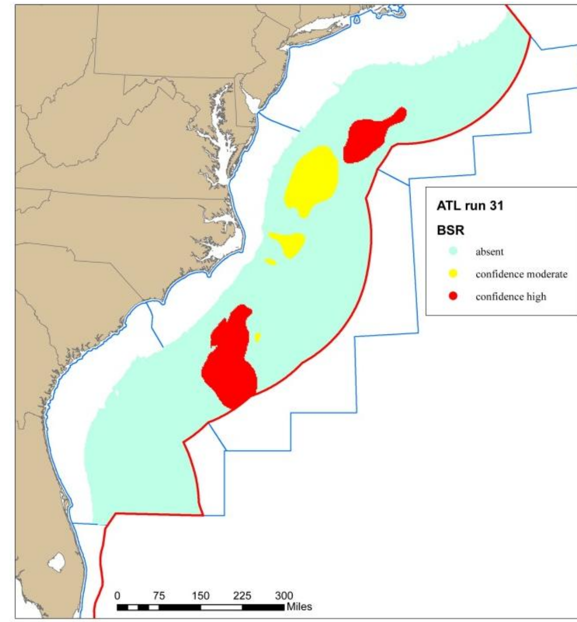
Water Depth → HSZ

Sand % → GH Concentration
Gas Generation

Spatial Inputs – Atlantic OCS







ISO1 ⟶ Gas Generation

ISO2 ⟶ Gas Generation

BSR ⟶ Migration Efficiency

SF to Base Pleistocene

Top Pliocene to base Tertiary

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6 June 2013

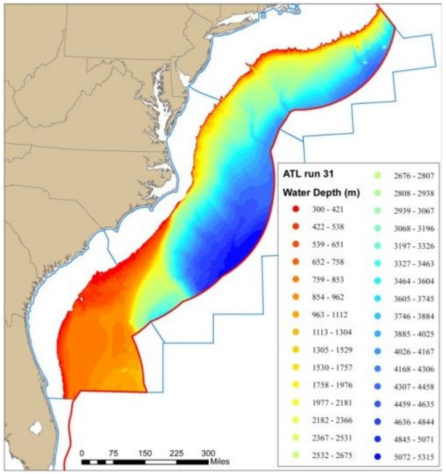
Stability Equation (modified from Milkov and Sassen, 2001)

$$f(WD) = -\{(GTG \times \varepsilon) \times HSZthk/1000\} - \{ae^{b \times WD} + c + \upsilon\} + \{(\delta \times \ln(HSZthk + WD) - \gamma) - \lambda\}$$

- $-\{(GTG \times \varepsilon) \times HSZthk/1000\}$: geothermal gradient expression
- $\{ae^{b \times WD} + c + \upsilon\}$: water bottom temperature
- $\{(\delta \times \ln(HSZthk + WD) - \gamma) - \lambda\}$: phase stability expression
- geothermal gradient expression + water bottom temperature: sediment temperature expression

where,

WD	= water depth in meters
GTG	= geothermal gradient, in °C/km
ε	= multiplicative term for the influence of local salt on sed temp
HSZthk	= thickness of the hydrate stability zone in meters
δ	= slope of phase stability equation
γ	= intercept of phase stability
υ	= error of water bottom temperature equation
λ	= additive term for the influence of local salt on phase stability
a, b, & c	= parameters of water bottom temperature equation



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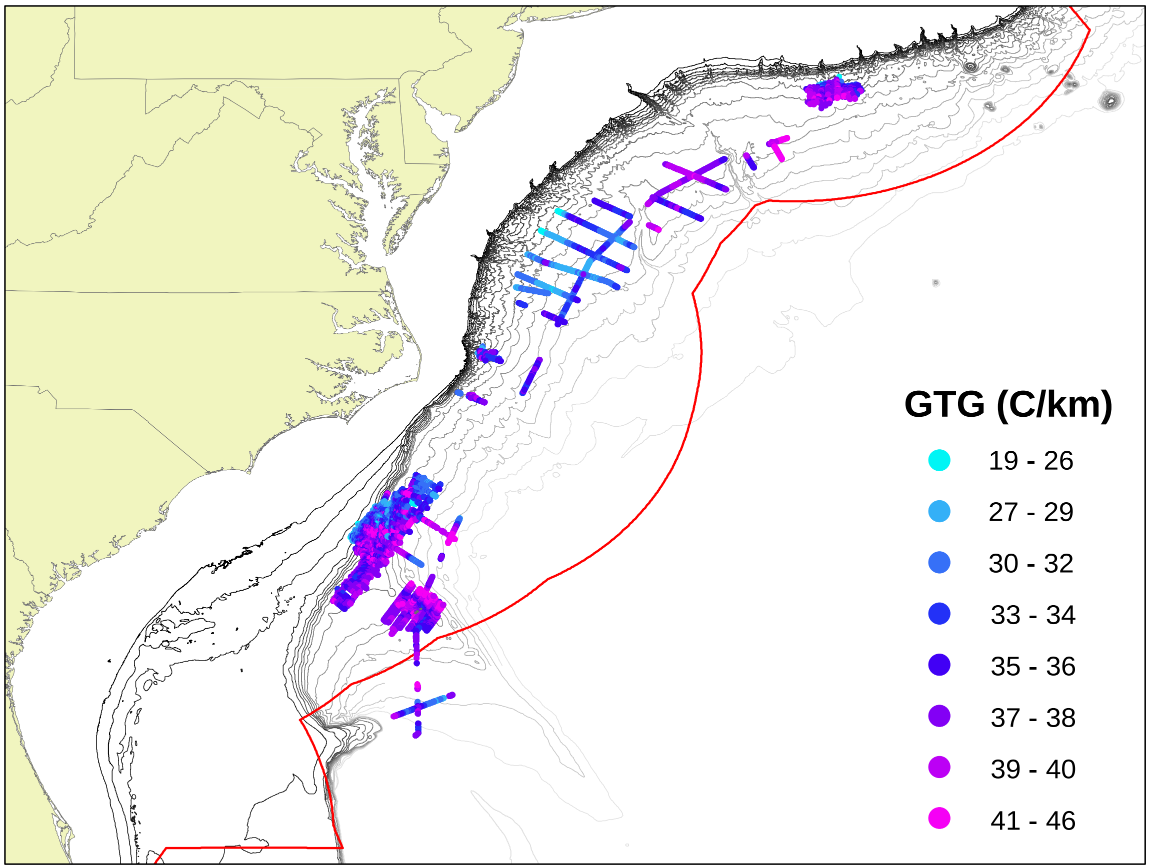
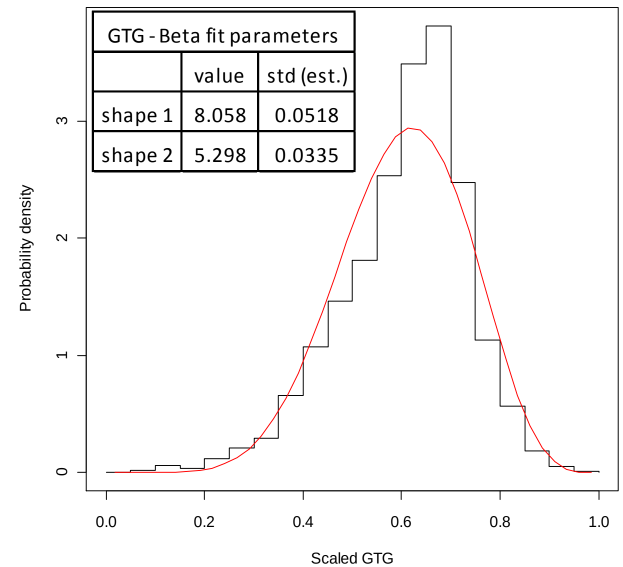
Non-Spatial Input – Geothermal Gradient

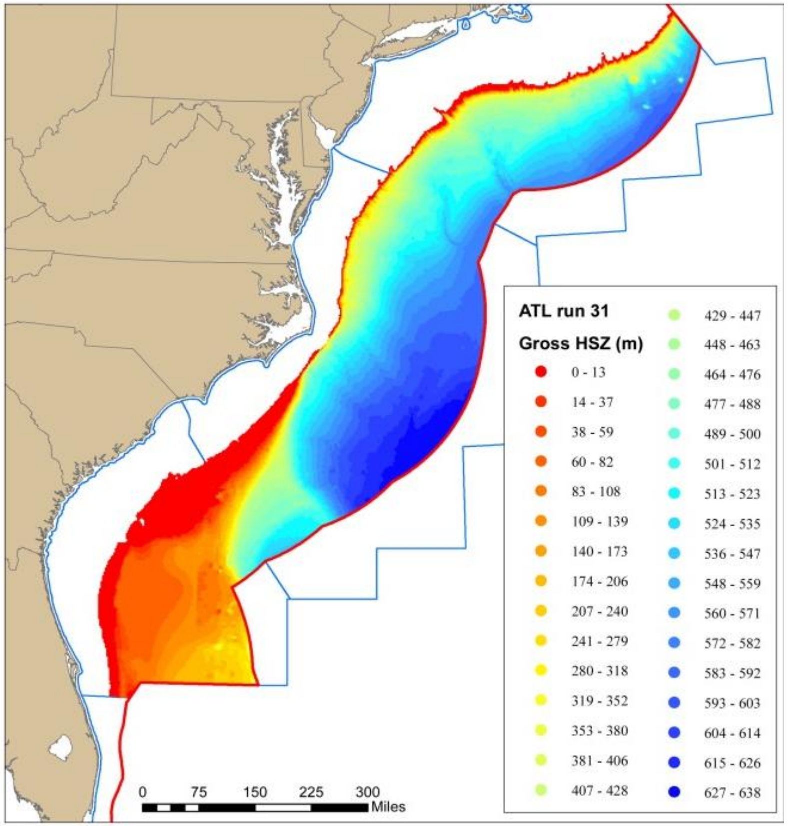




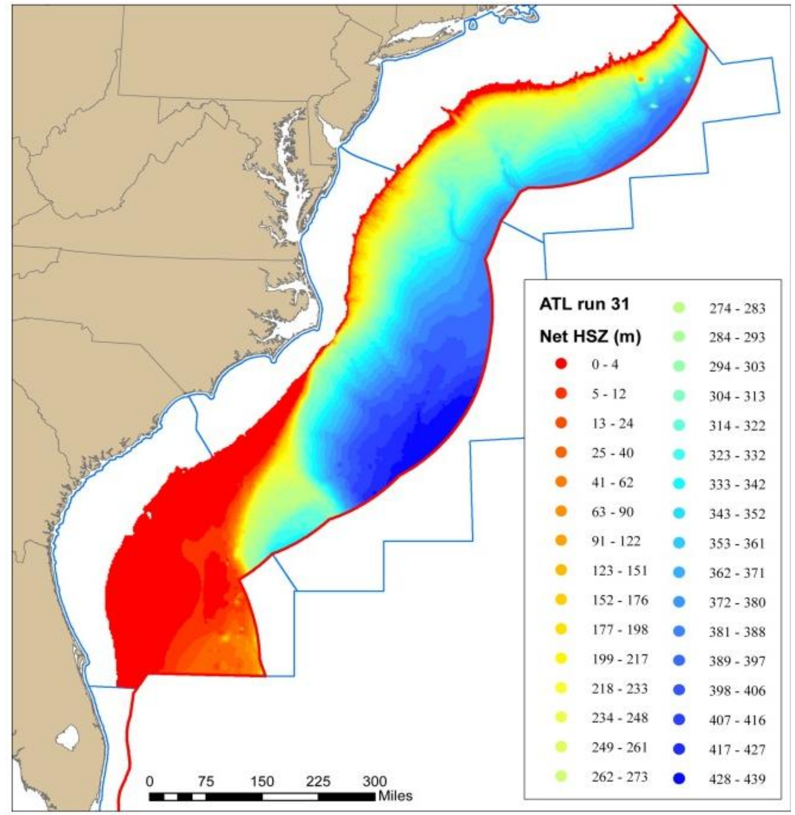
GTG - Beta fit parameters		
	value	std (est.)
shape 1	8.058	0.0518
shape 2	5.298	0.0335

Mean = 33.6 °C/km

Spatial Outputs – Hydrate Stability Zone



Gross HSZ



Net HSZ

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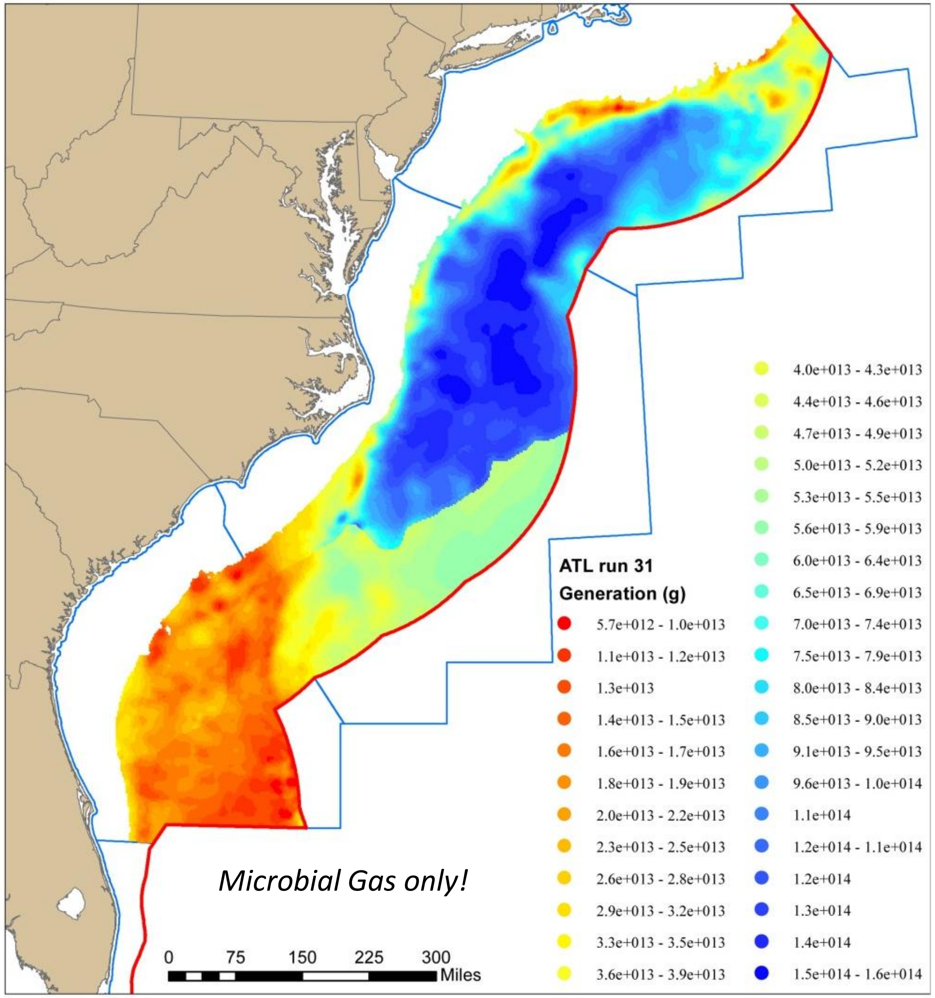
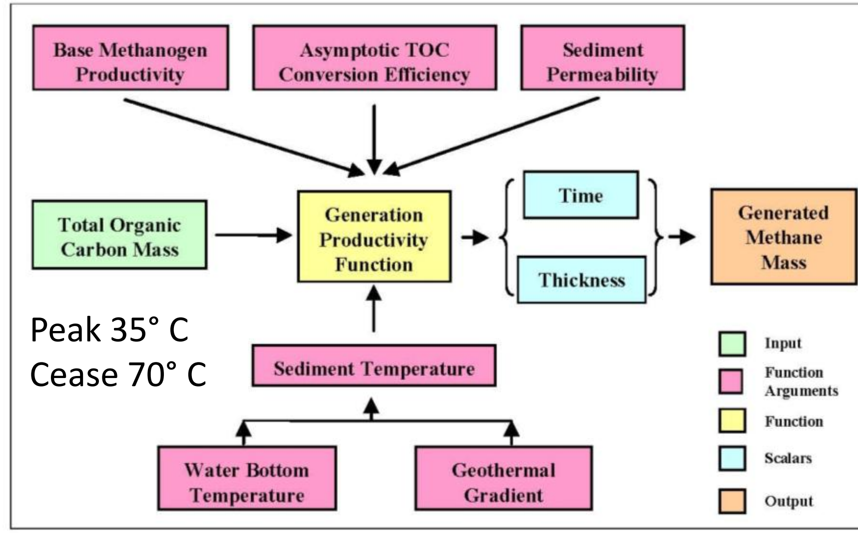
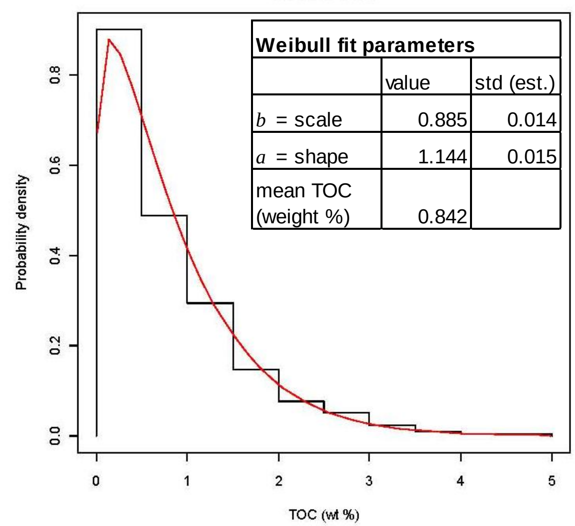
Spatial Outputs – Gas Generation

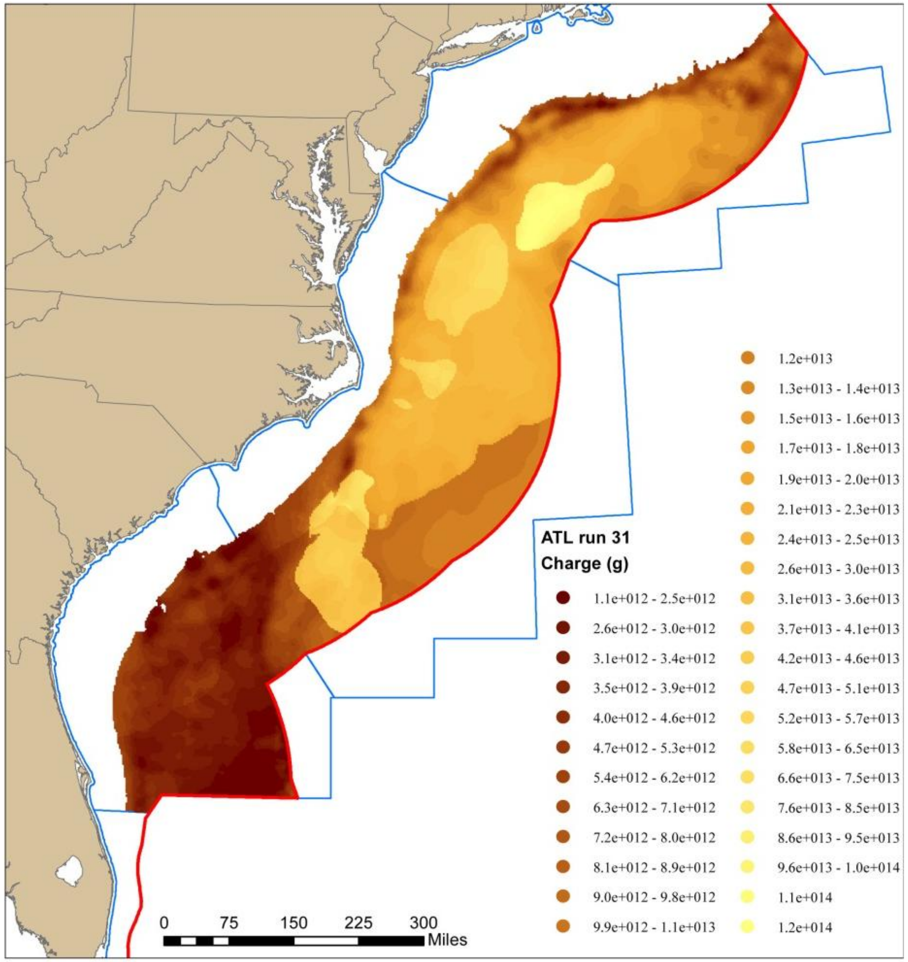






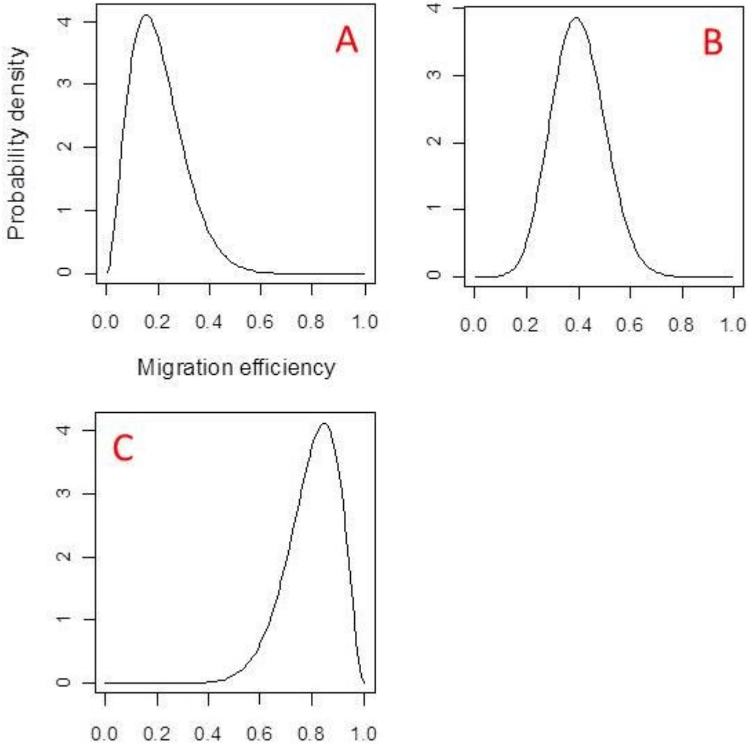
BR93, HC500, HC544, HC598, HC599, HC676, HC857, HC902, WI273, WI372, WI495, WI586, WI587, COST B-2, COST B-3, and DSDP/ODP scientific wells from Leg 1, Leg 11 (Boyce, 1972), Leg 43 (Cameron, 1979), Leg 44 (Myers, 1978), Legs 51 and 52 (White, 1979), Leg 76 (Sheridan et al., 1983), Leg 93 (Meyers, 1987), Leg 95 (Poag et al., 1987), Leg 150 (Mountain et al., 1994), Leg 164 (Paull et al., 1996), Leg 166 (Eberli et al., 1997), Leg 171 (Norris et al., 1998), and Leg 172 (Keigwin et al., 1998).

Spatial Outputs – Charge



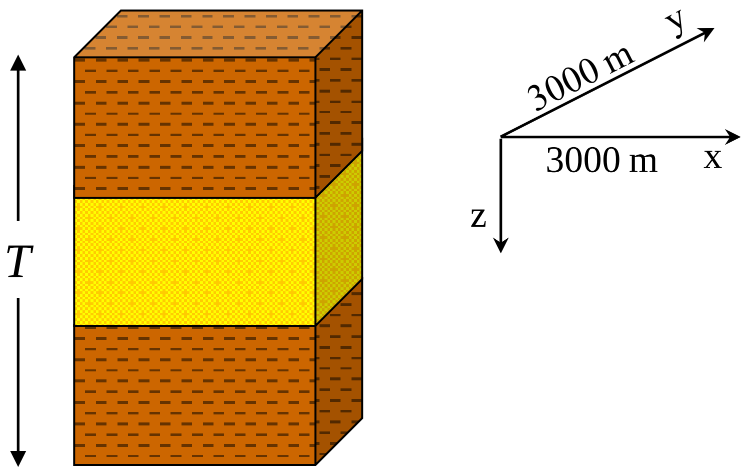
Migration efficiency recognizes:

- Gas not expelled from fm.
- Gas trapped below HSZ
- Gas expelled at seafloor



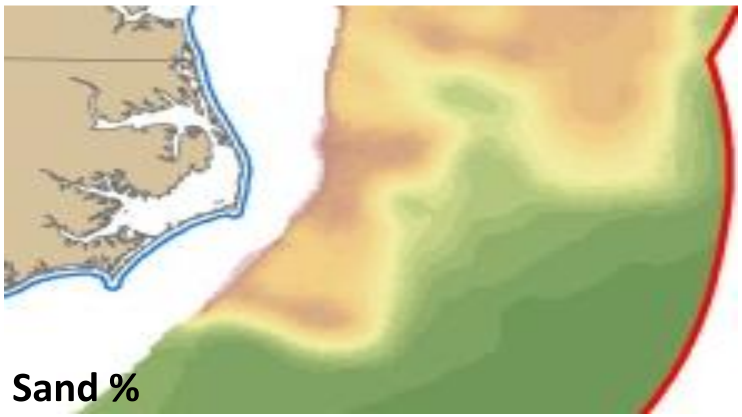
Sand Void = (Volume)(Porosity)
Volume Sand = (x)(y)[(T)(sand%)]
Porosity Sand = $f(d)$

Shale Void = (Volume)(Porosity)
Volume Shale = (x)(y)[(T)(1-sand%)]
Porosity Shale = $f(d)$



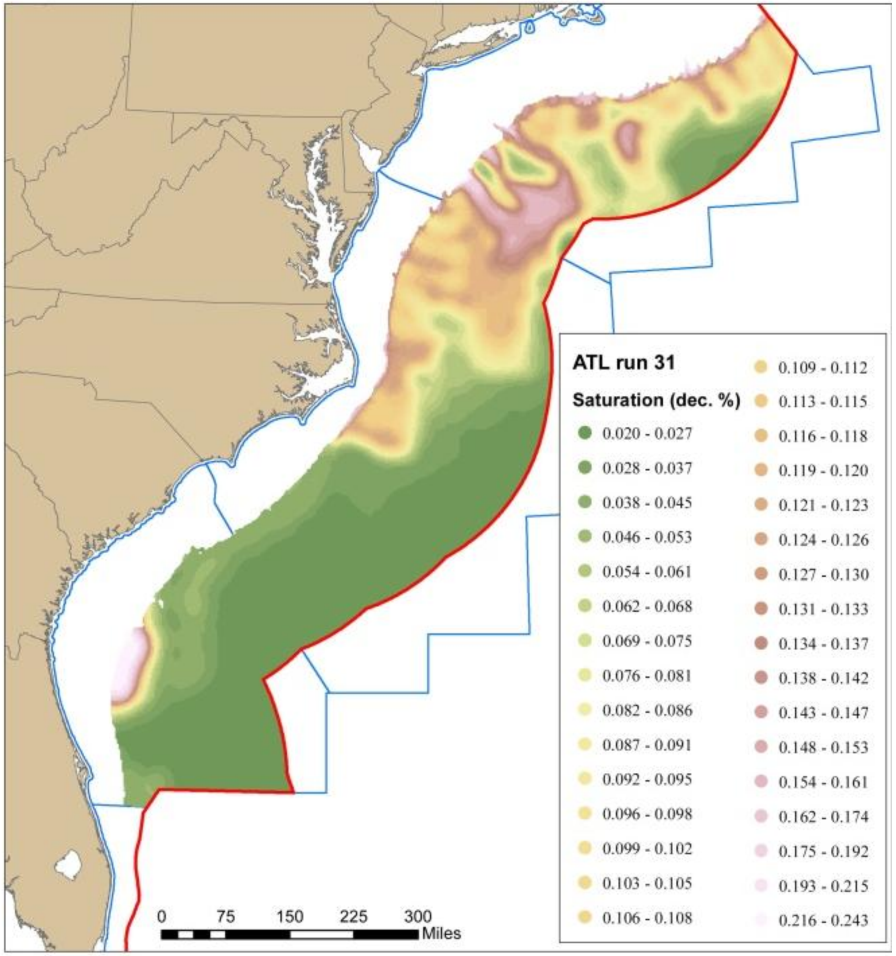
From Container Module:
(T) Net HSZ thickness
(d) Midpoint depth net HSZ

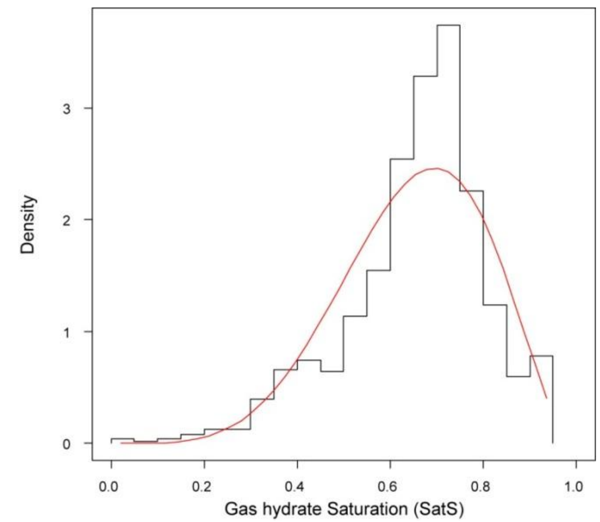
From input file:
sand %

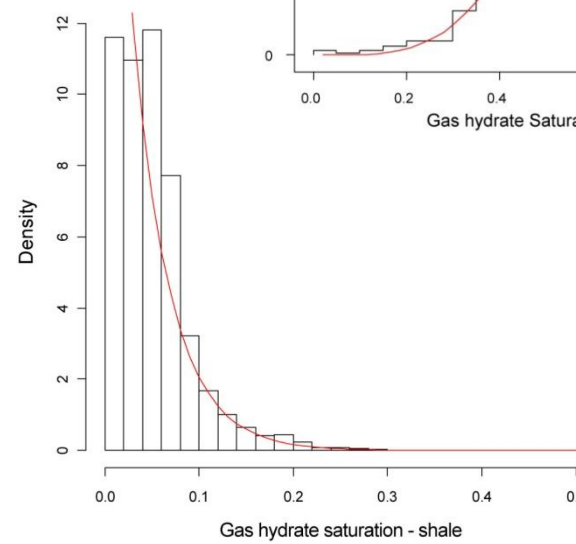


Leave here with some volume of pore space in the HSZ…….

Spatial Outputs – Saturation



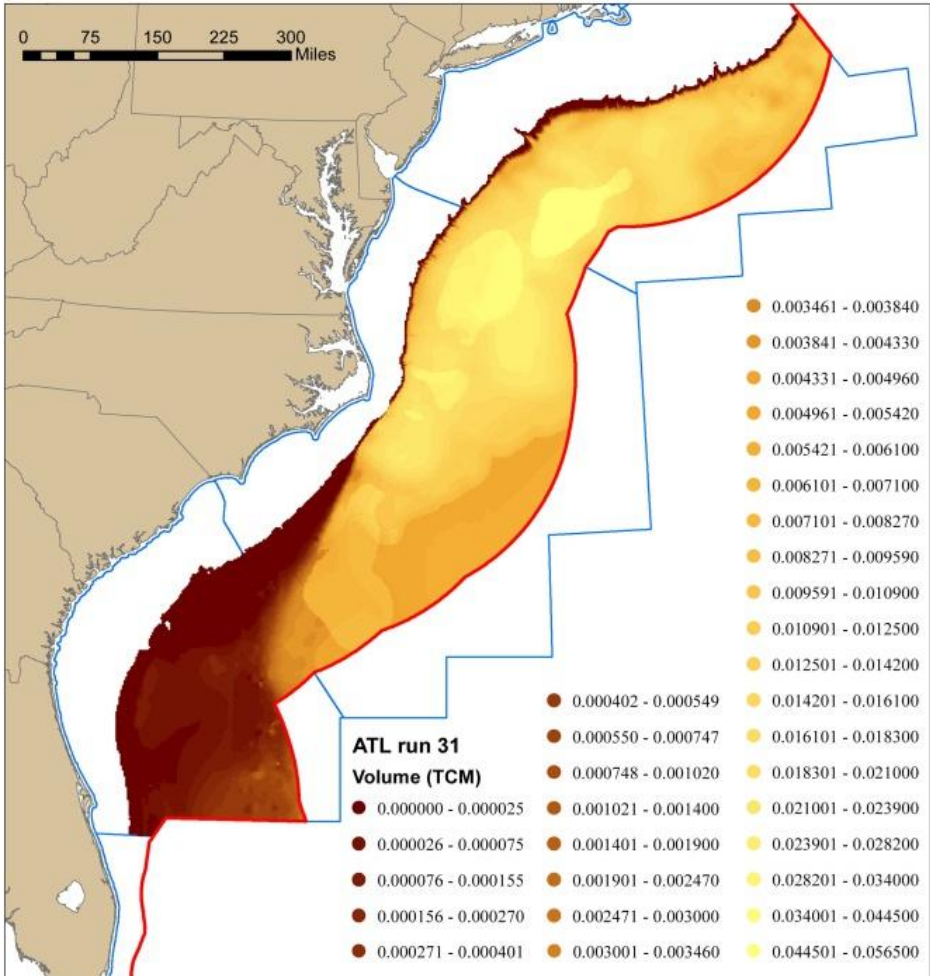




GH Saturation (% bulk rock volume)

……….Conditional on Charge

Spatial Outputs – Volume



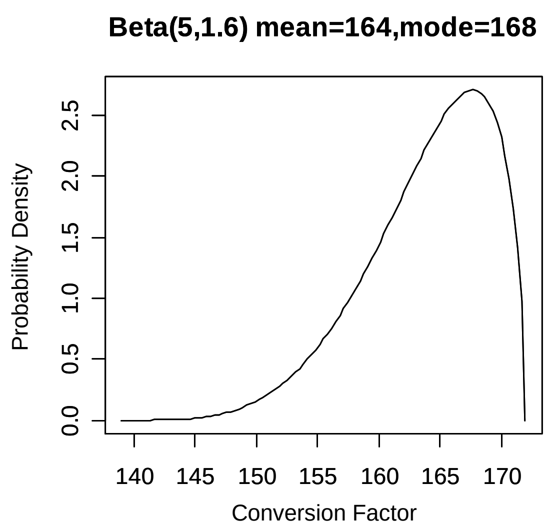
In-Place GH Volume

Per cell values (mean)

Integration Module

For each model cell, we:

- Compare charge to available container → retain smaller of two
- Convert from RTP to STP



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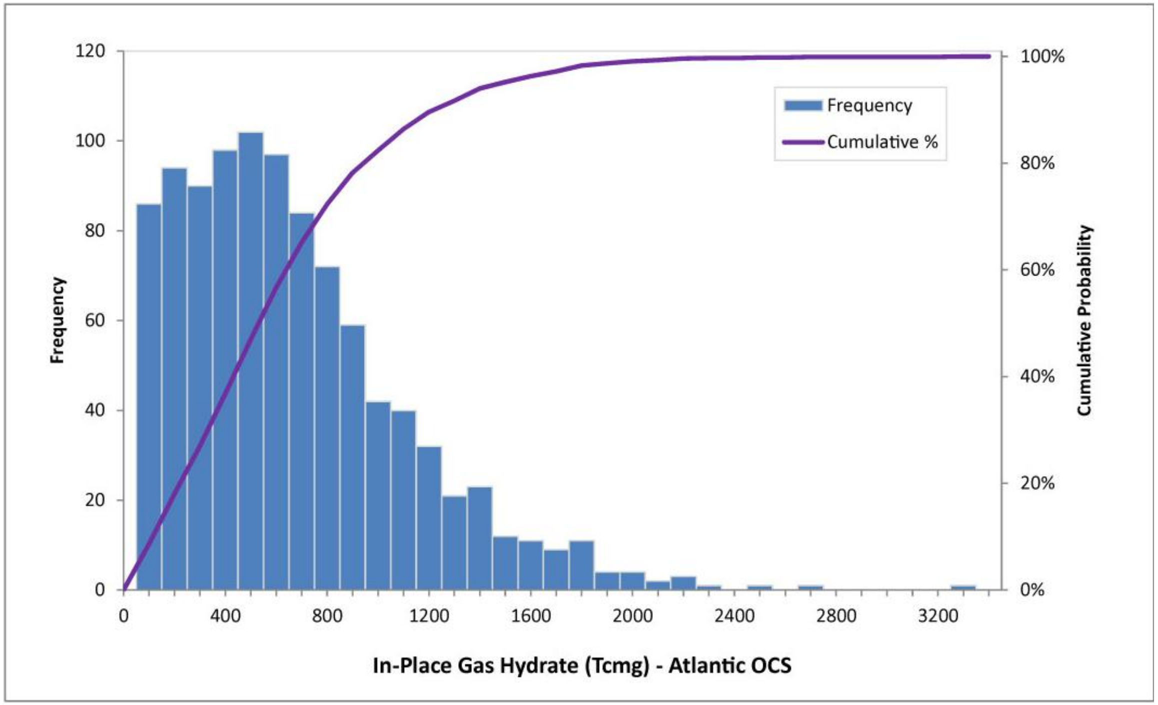
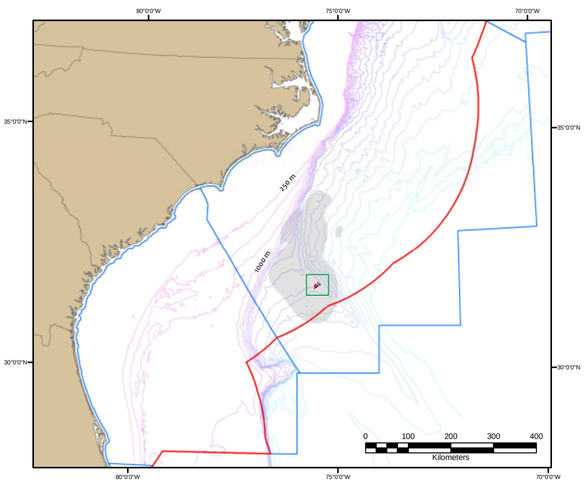
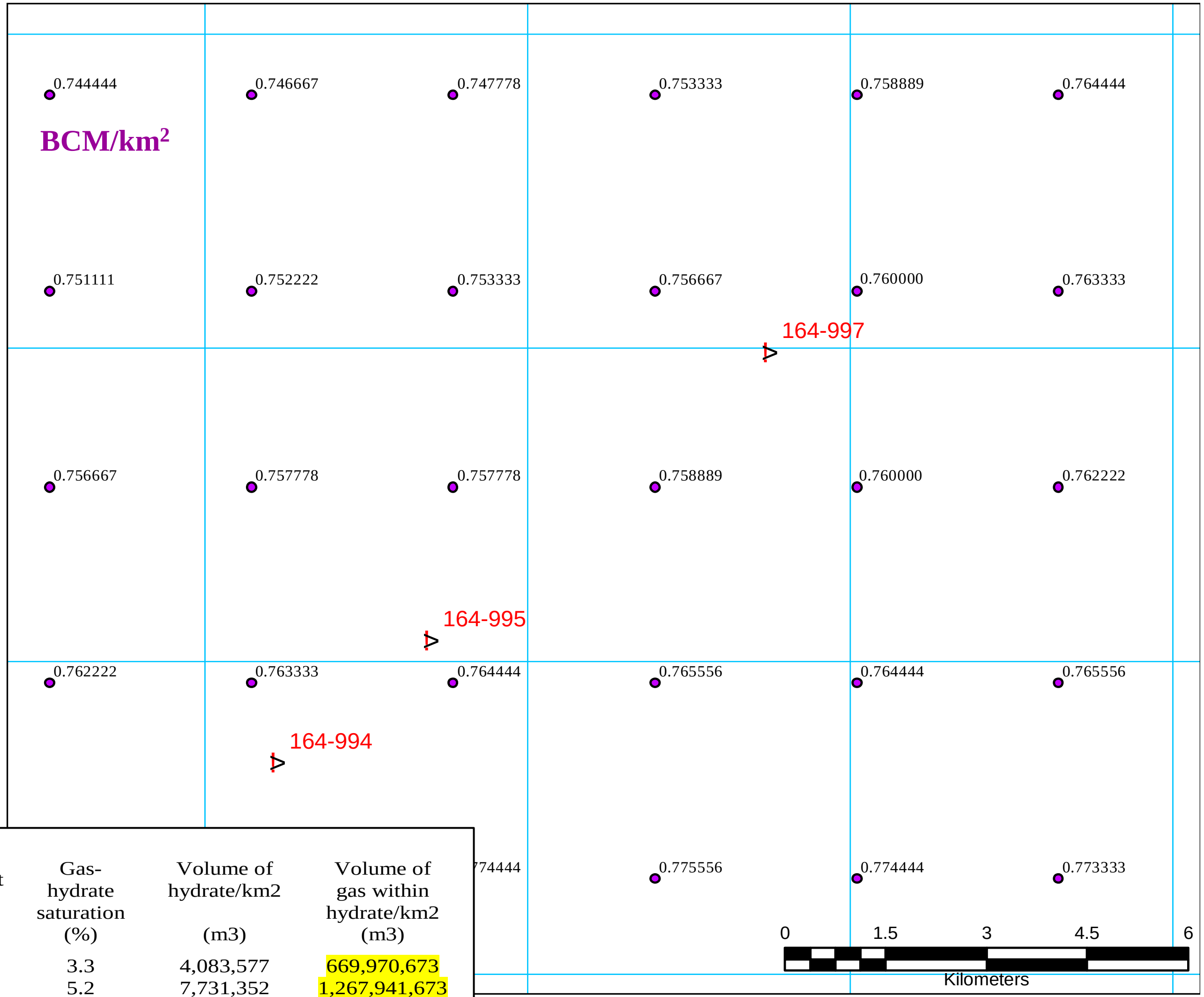
Matthew Frye
BOEM – Herndon, VA
6 June 2013

Statistic	Hydrate Concentration (decimal)	Total Net HSZ (trillions of m^3)	Total Hydrate Charge (trillions of m^3)	Total In-Place Volume (trillions of m^3)	Total In-Place Volume (trillions of ft^3)
Min.	0.015	4482	1.90	1.76	62.13
5%	0.034	10208	63.44	58.22	2056.10
25%	0.048	15598	363.49	280.08	9890.78
50%	0.060	19175	836.33	530.16	18722.41
Mean	0.064	19624	1463.83	614.54	21702.00
75%	0.075	23647	1956.19	845.19	29847.53
95%	0.103	29781	5117.93	1483.82	52400.36
Max.	0.168	40655	13173.50	3261.36	115173.30
Var.	0.000	34606400	3048820.00	199824.00	7056684.65



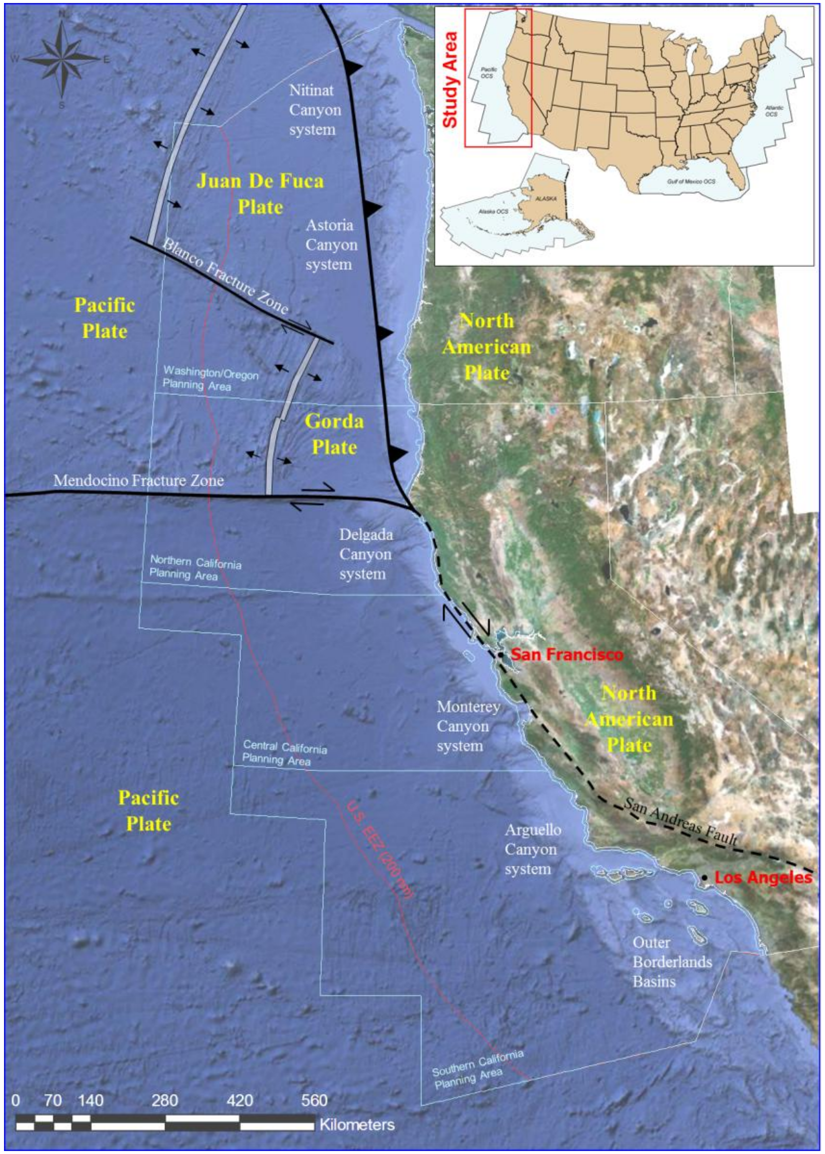
Atlantic OCS
Calibration / Verification
ODP Leg 164 area





Site	Depth of logging Unit 2 (mbsf)	Thickness of hydrate-bearing zone (m)	Sediment porosity (%)	Gas-hydrate saturation (%)	Volume of hydrate/km2 (m3)	Volume of gas within hydrate/km2 (m3)
994	212.0-428.8	216.8	57.0	3.3	4,083,577	669,970,673
995	193.0-450.0	257.0	58.0	5.2	7,731,352	1,267,941,673
997	186.4-450.9	264.5	58.1	5.8	8,839,915	1,449,746,073

Collett and Ladd (2000)



Pacific OCS

- Tectonically complex
- Relatively data-poor
- *Except* that the data that do exist are fairly well distributed
- More opportunities for spatially-resolved inputs
- Full reporting release TBD

Ken Piper (retired) - BOEM Camarillo
Regional champion for GH assessment

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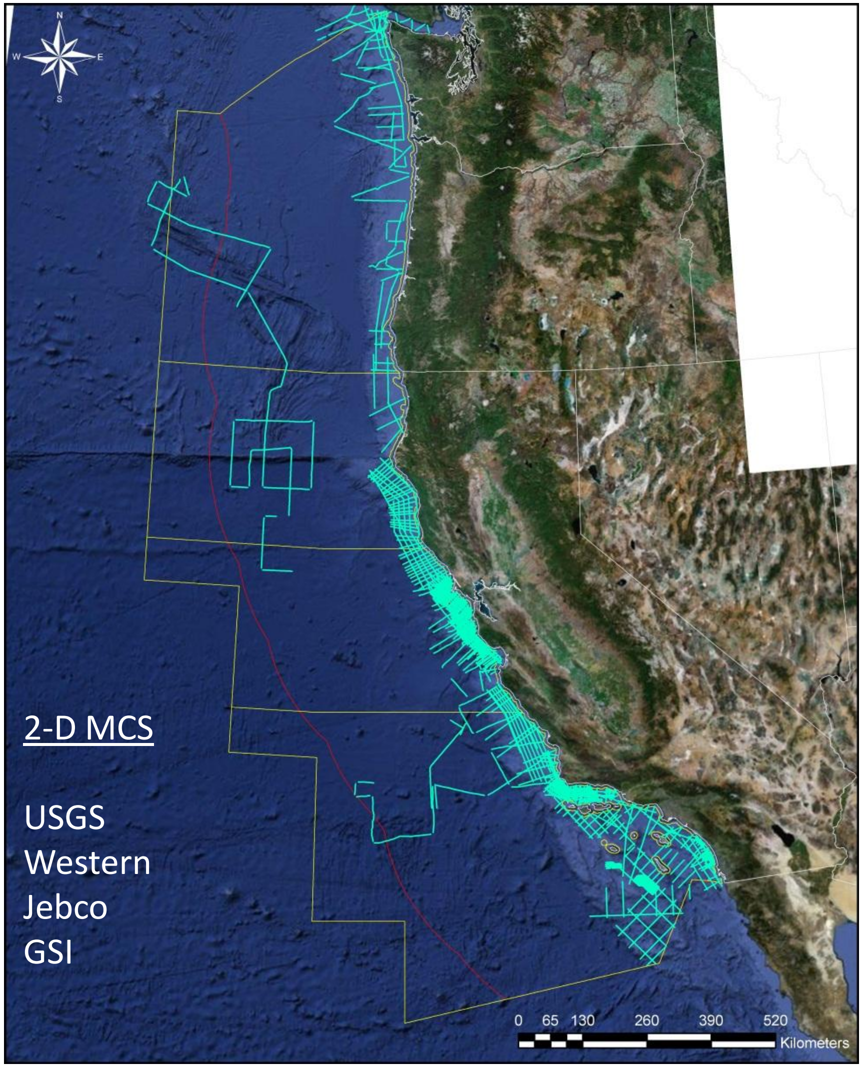
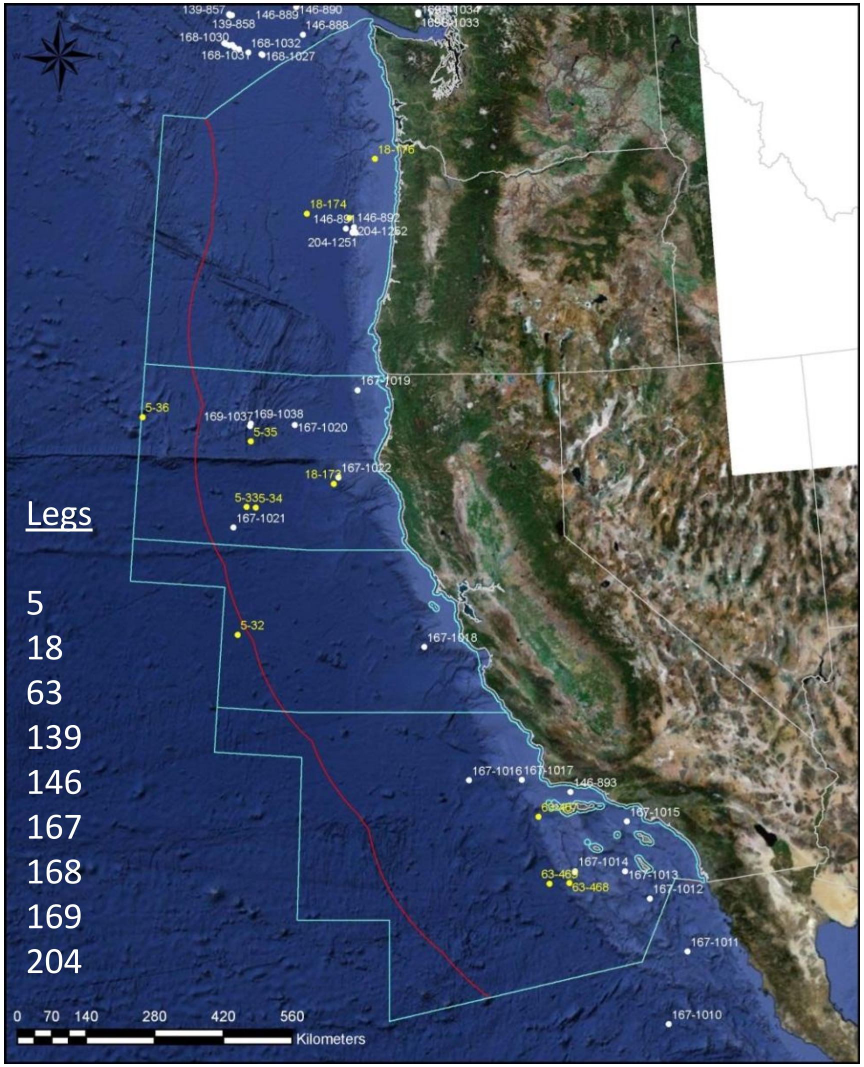
Matthew Frye
BOEM – Herndon, VA
6 June 2013





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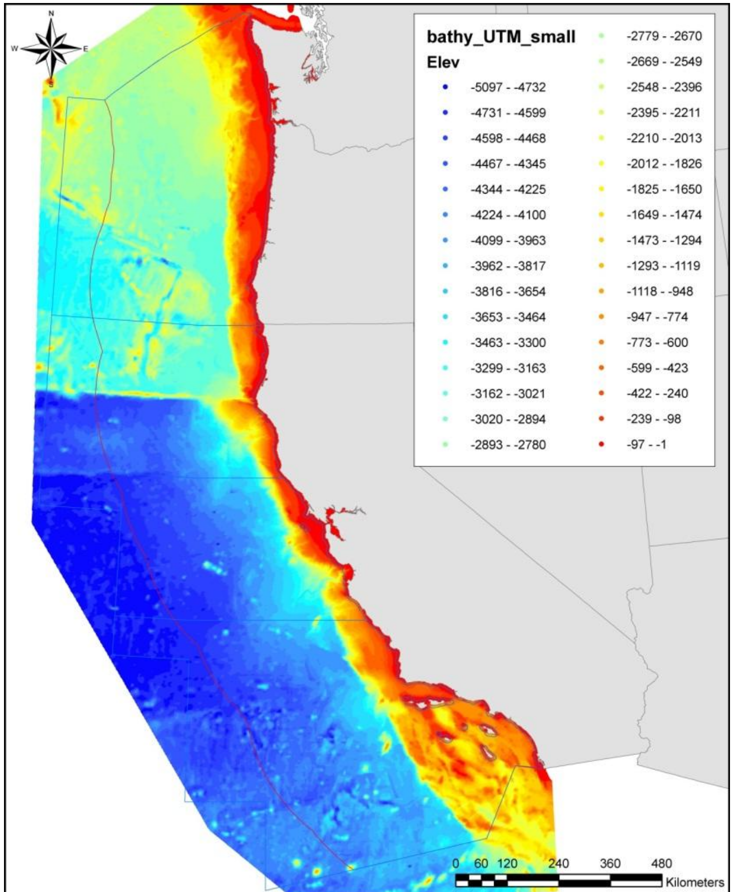
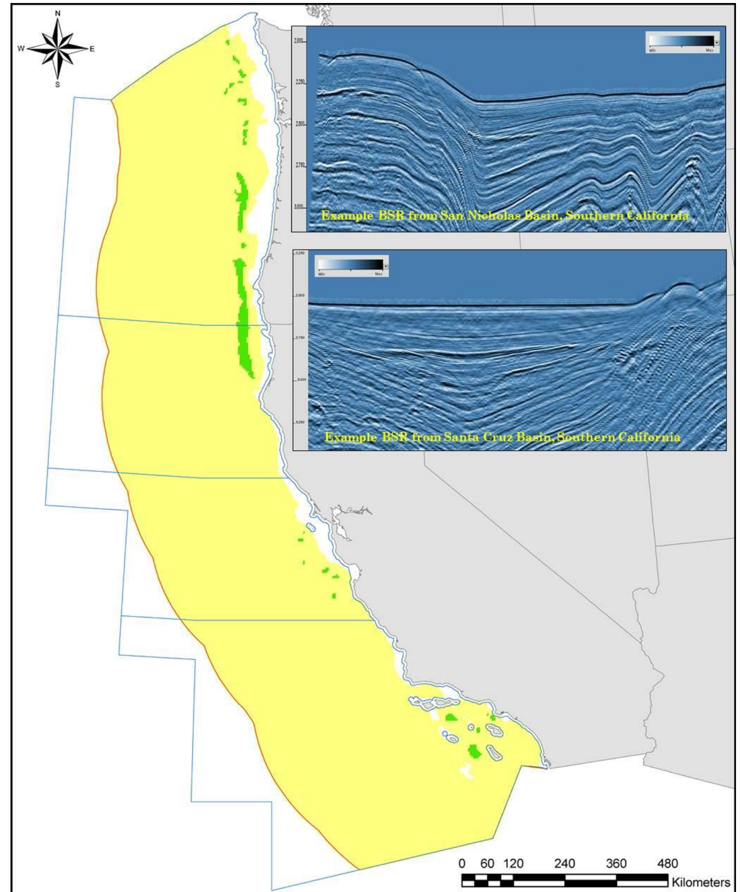
Spatial Inputs – Bathymetry + BSR



Water Depth → HSZ

- ETOPO1 - NOAA

Amante, C. and B. W. Eakins, ETOPO1 1 Arc-Minute Global Relief Model: Procedures, Data Sources and Analysis. NOAA Technical Memorandum NESDIS NGDC-24, 19 pp, March 2009.

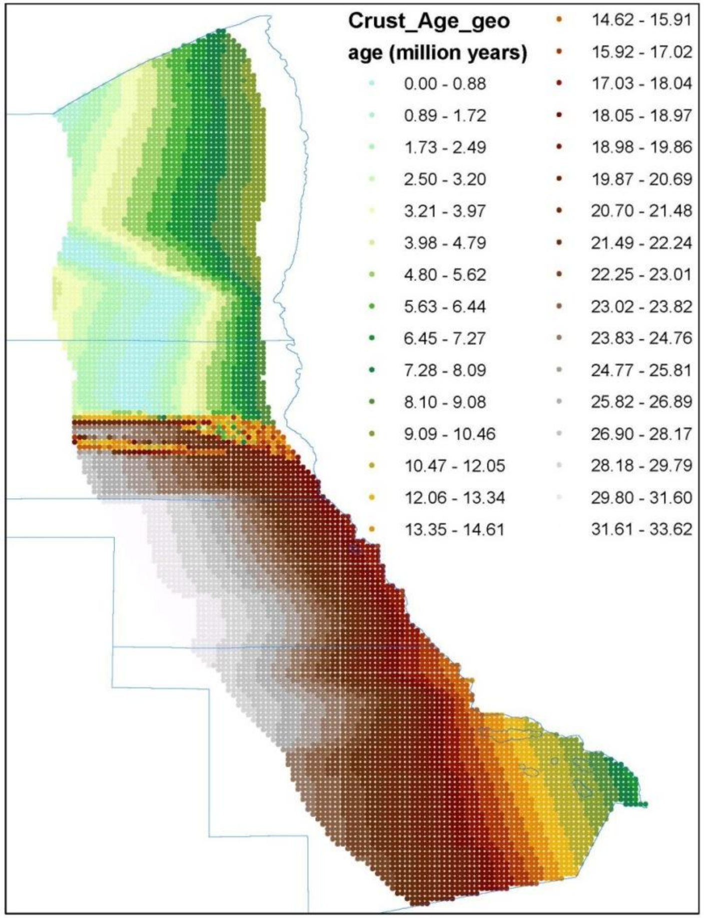


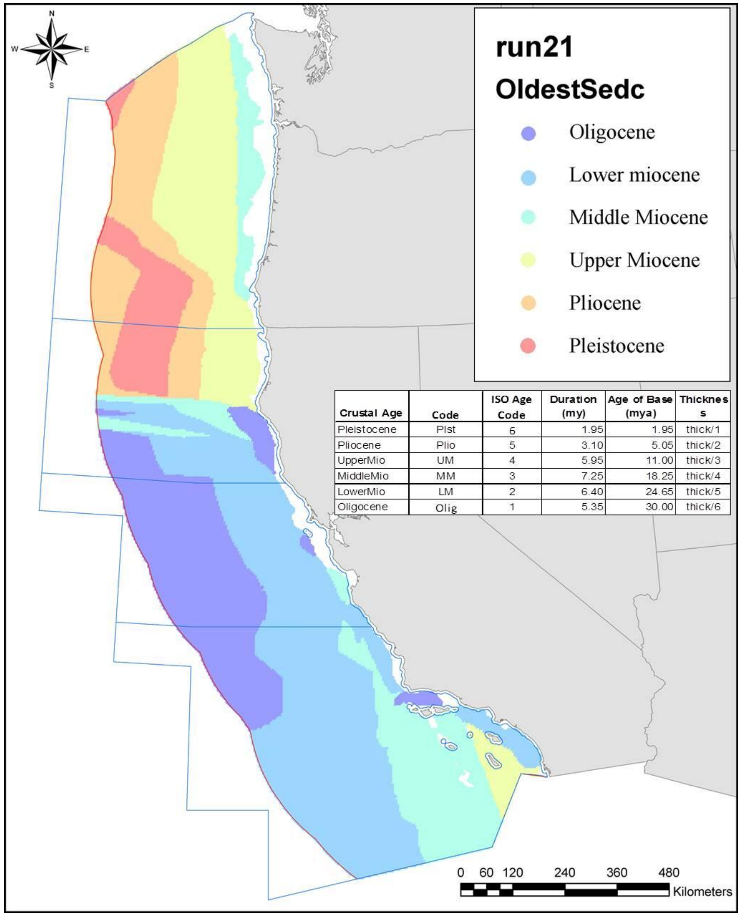
BSR → Migration Efficiency

*limited to areas of seismic data coverage/literature
*no advanced statistical forecasting

Field and Kvenvolden (1985); Trehu et al (2004)

Spatial Inputs – Crust Age





Crustal Age	Code	ISO Age Code	Duration (my)	Age of Base (mya)	Thicknes s
Pleistocene	Plst	6	1.95	1.95	thick/1
Pliocene	Plio	5	3.10	5.05	thick/2
UpperMio	UM	4	5.95	11.00	thick/3
MiddleMio	MM	3	7.25	18.25	thick/4
LowerMio	LM	2	6.40	24.65	thick/5
Oligocene	Olig	1	5.35	30.00	thick/6

Basement Age → Gas Generation

Muller, R. D., M. Sdrolias, C. Gaina, and W. R. Roest (2008), Age, spreading rates, and spreading asymmetry of the world's ocean crust, Geochem. Geophys. Geosyst., 9, Q04006, doi:10.1029/2007GC001743. **Via NOAA/NGDG**

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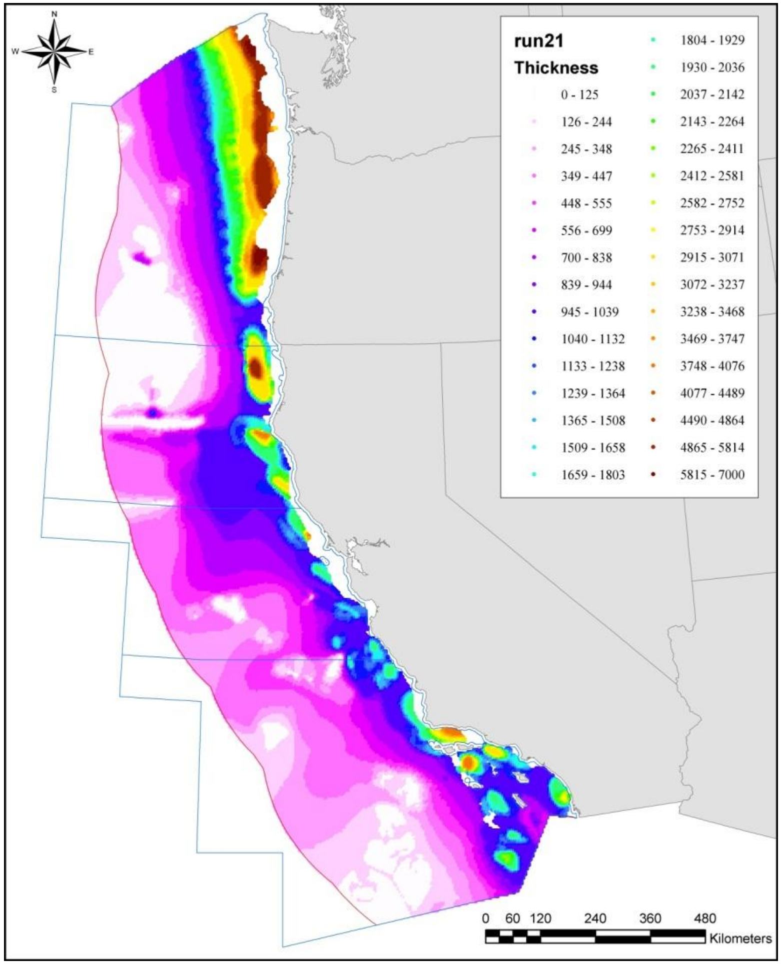
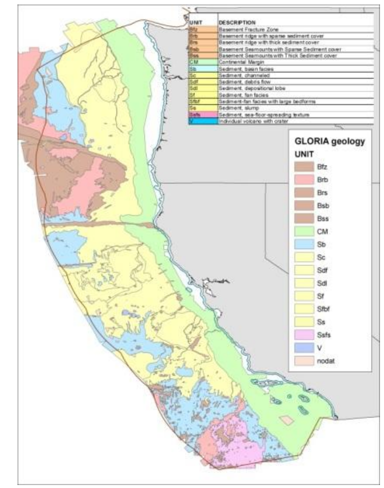
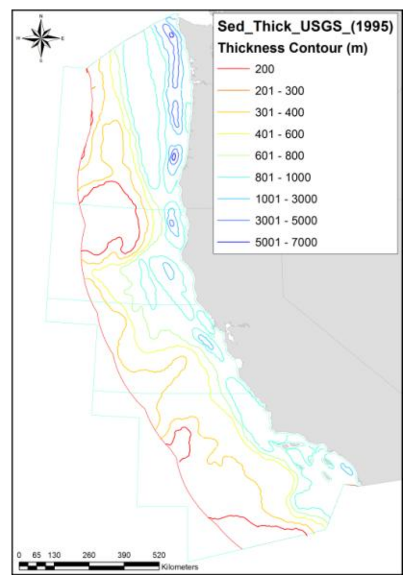
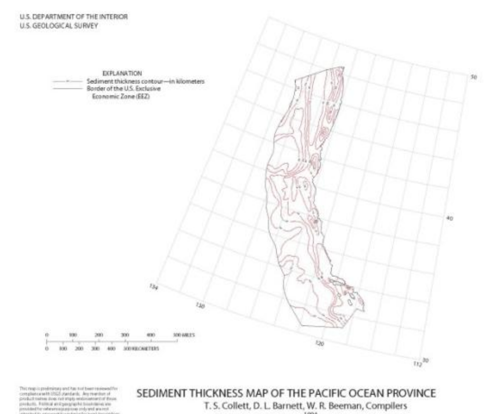
Spatial Inputs – Sediment Thickness



- Seismic Data interp
- Well penetrations
- Modern bathymetry
- BOEM basins







Sediment Thickness → Gas Generation
→ HSZ limitation

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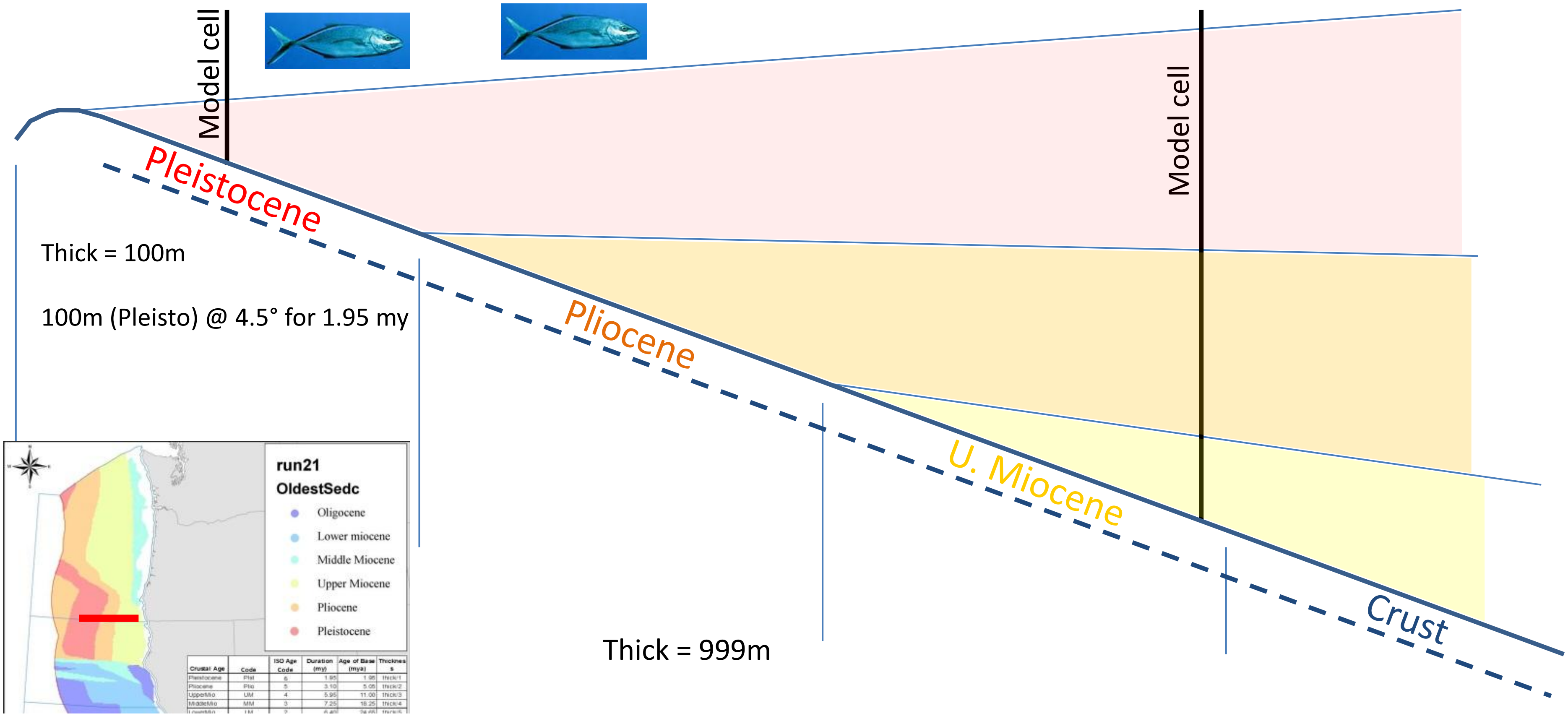
Matthew Frye
BOEM – Herndon, VA
6 June 2013



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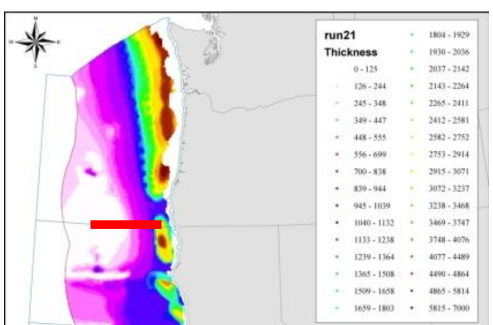


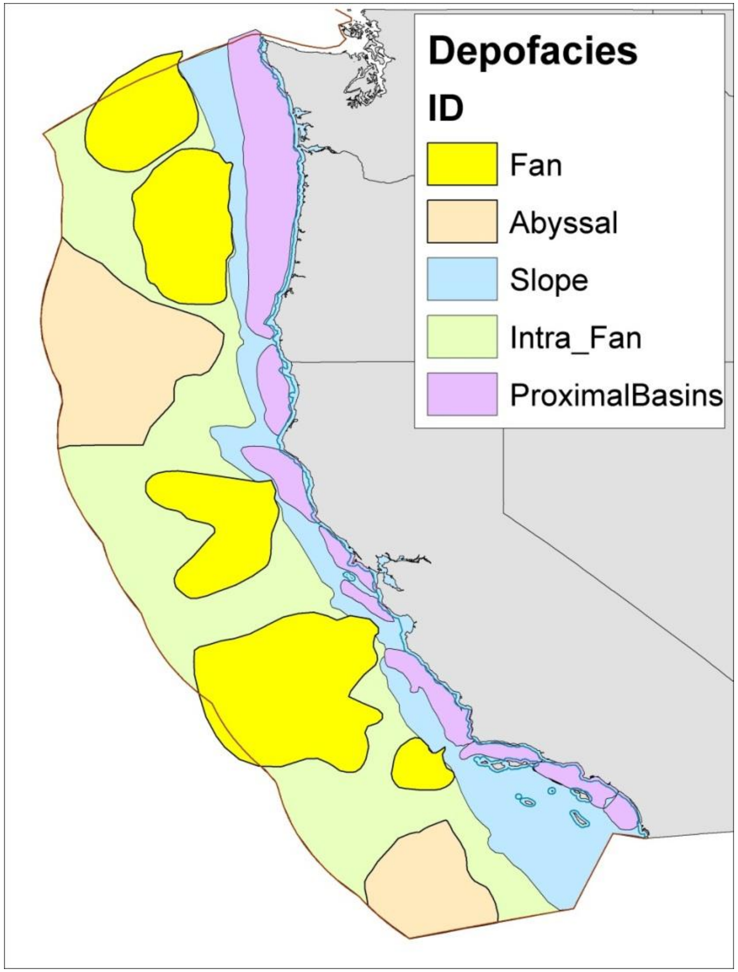
333m (U.Mio) @ 15° for 5.95 my

333m (U.Mio) @ 30° + 333m (Plio) @ 15° for 3.10 my

333m (U.Mio) @ 45° + 333m (Plio) @ 30° + 333m (Pleisto) @ 15° for 1.95 my

GTG = 45° C/km

Spatial Inputs – Depofacies



Depofacies → GH Concentration
Gas Generation

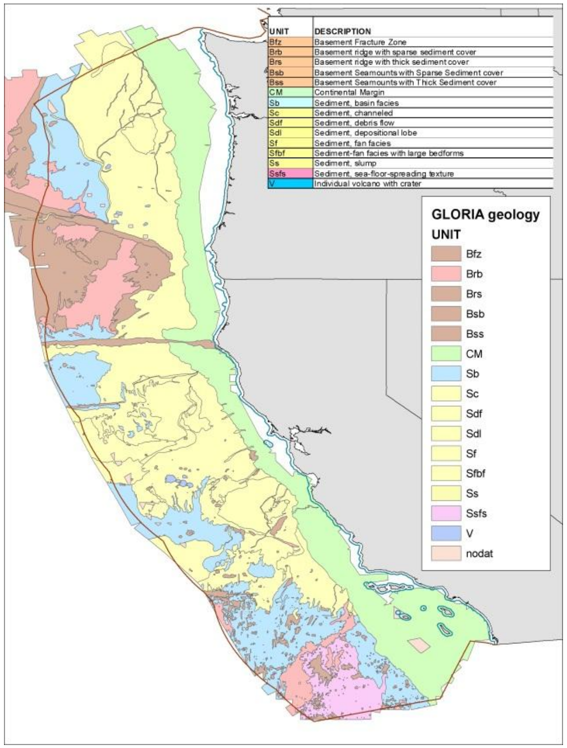
End Member Lithology – Sand and Shale

Pacific Margin Depofacies	
Facies name	**Description**
Proximal Basin	Sand-rich; rapid, focused sedimentation in structurally-controlled basins
Slope	Mud-rich; often a zone of coarse sediment bypass; intra-proximal basin
Submarine Fan	Sand-rich; coincident with named fan features; includes channel, levee, lobe, debris flow, etc.
Intra-Fan	Mostly mud-rich; occasional thin, low concentration turbidites
Abyssal Basement	Basement ridge, fractures, and seamounts with varying thickness of sediment cover; mostly sand-starved

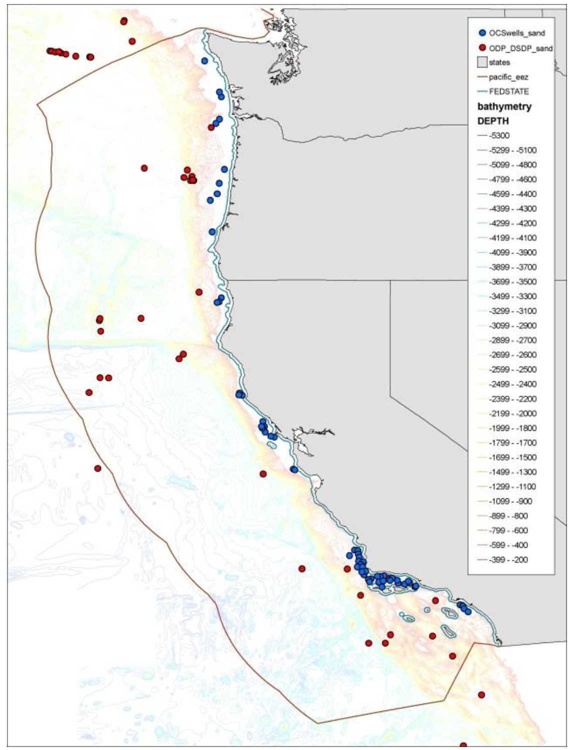
		Beta parameters			
Name	ID	Shape 1	Shape 2	Mean	Std Dev
Proximal Basins	1	0.670	1.926	0.258	0.231
Slope	2	0.966	13.626	0.066	0.063
(Submarine) Fan	3	3.677	7.085	0.342	0.138
Intra Fan	4	1.747	57.802	0.029	0.022
Abyssal	5	1.788	120.140	0.015	0.011

↑ Sand %

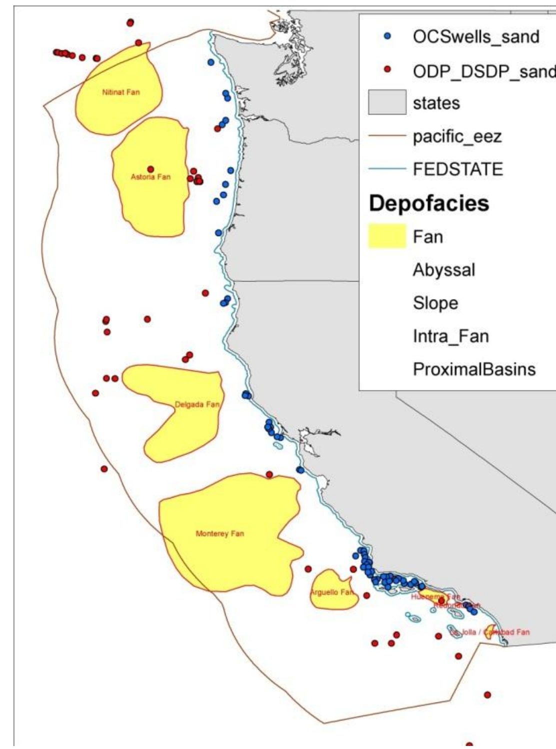
Spatial Inputs – Development of the Depofacies Model



GLORIA interpretation
(USGS OFR 91-396)



Modern seafloor expression
Wellbore penetrations



Deep water fan morphology
(various literature, eg Nelson, Normark)

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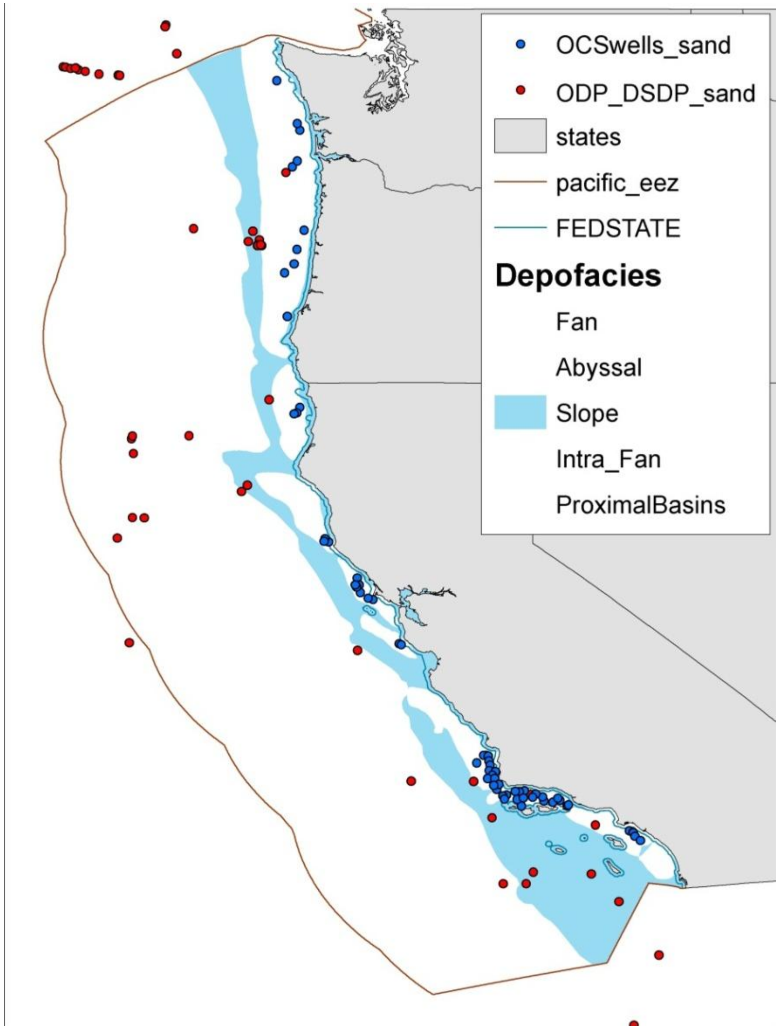
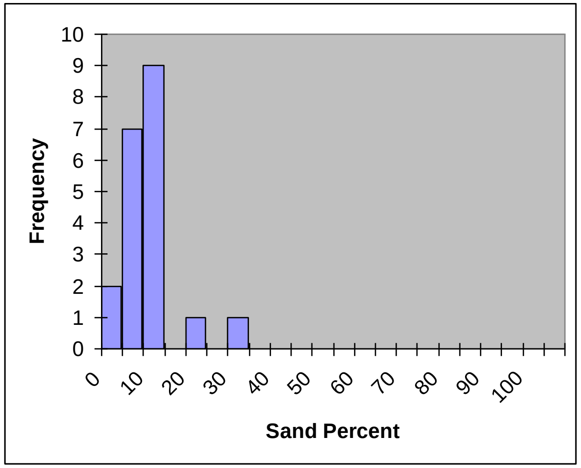
Spatial Inputs – Example of the Depofacies Model





Slope: The slope depofacies comprises those geographical areas landward of the abyssal basin floor that are not included in the Proximal Basin facies. In the northern POCS, this includes areas landward of the subduction zone; in the southern POCS, the definition is more closely controlled by seafloor morphology. Continental slope facies are typically mud-dominated, but do include localized sand-rich depocenters of both shelf-edge deltas and the incised valley / proximal channel facies of submarine fans.

For this study, we have sand data from a total of eighteen (18) well data points (17 ODP/DSDP + 1 OCS well), plus an additional two ODP wells (Leg 146 sites 889 and 890) just north of the U.S. OCS. A histogram of the sand percent data from these 20 wells shows a mean value 6.6 %.

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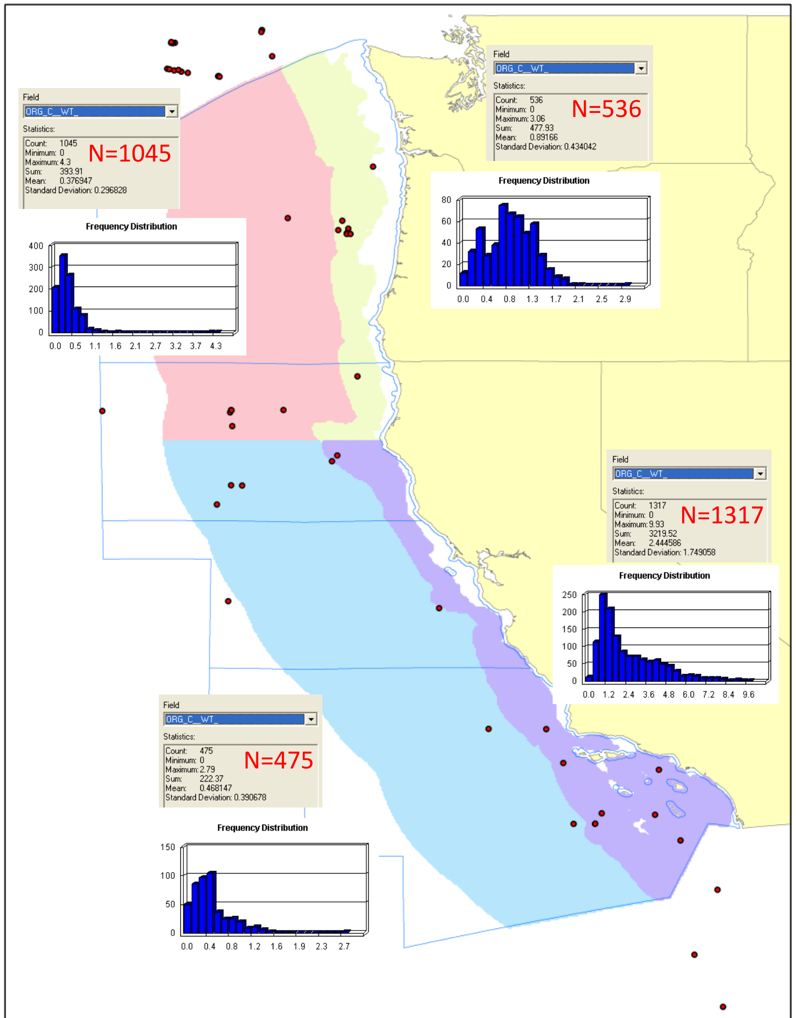
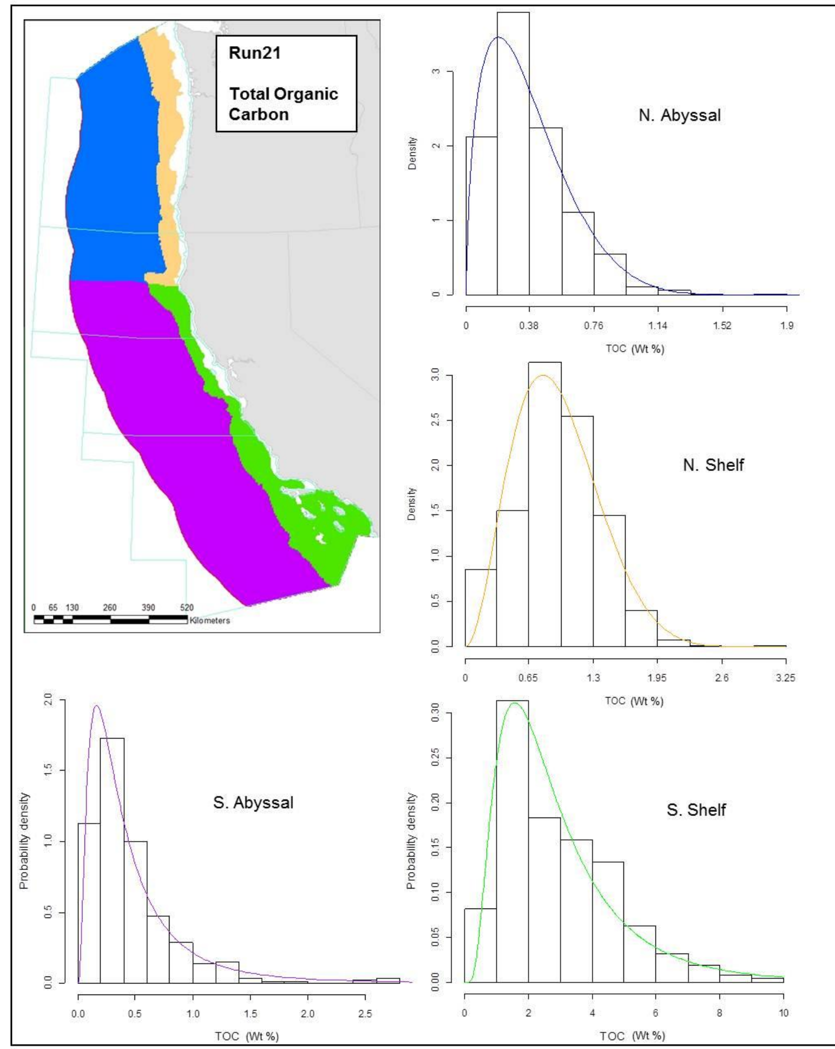
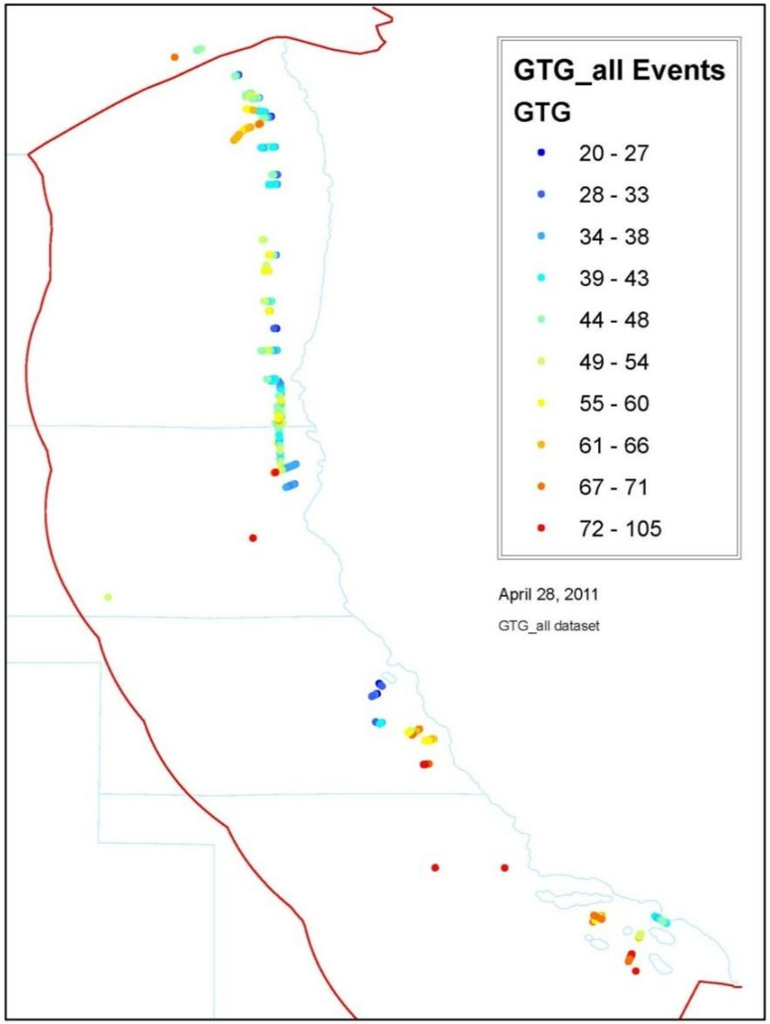
Matthew Frye
BOEM – Herndon, VA
6 June 2013

Partial Spatial Inputs – TOC

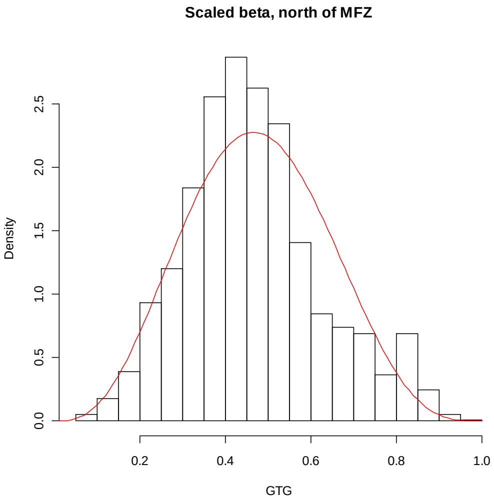


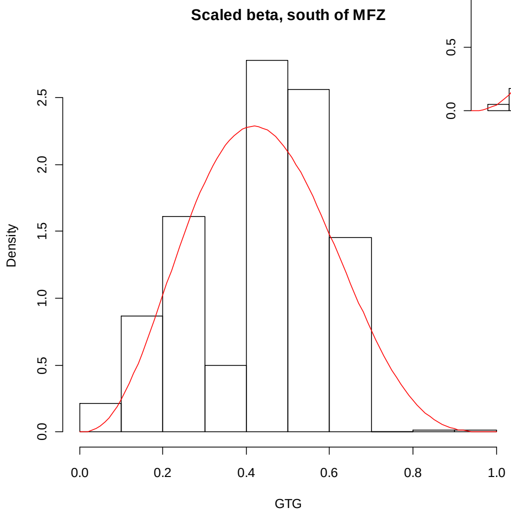


Partial Spatial Inputs – GTG



	Shape 1	Shape 2	Min	Mean	Max	Std Dev
N of fault	4.071	4.508	15.000	43.474	75.000	9.681
S of fault	3.723	4.784	15.000	54.385	105.000	14.480





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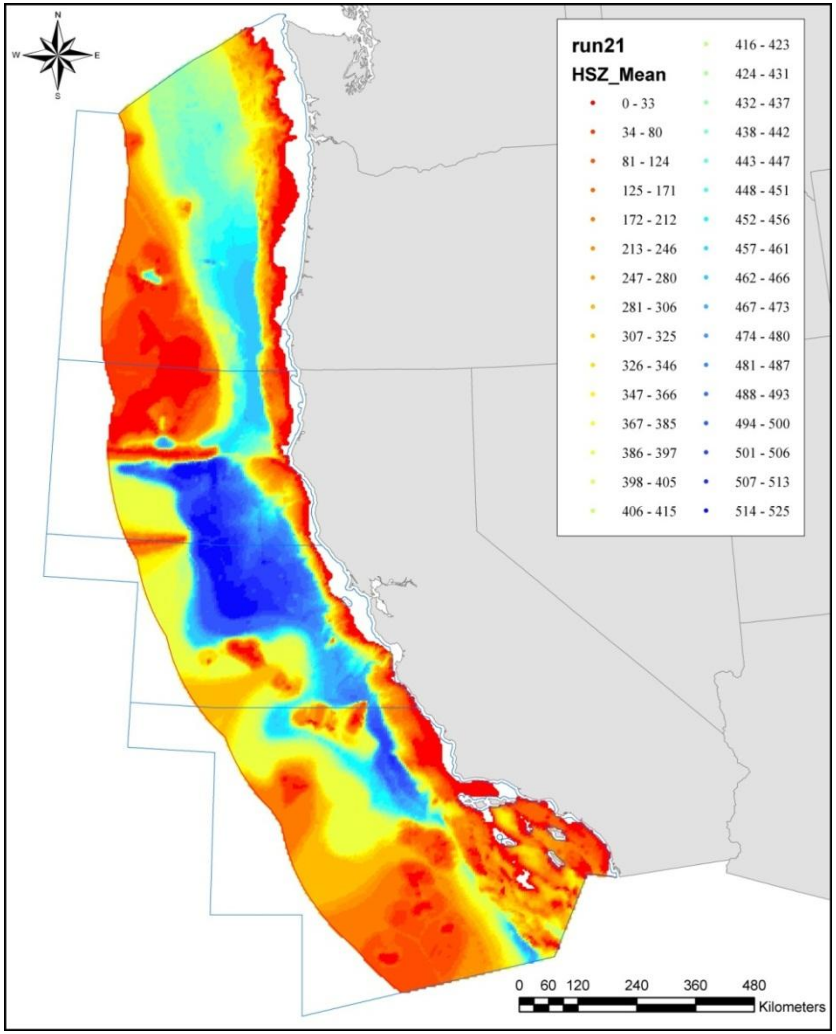
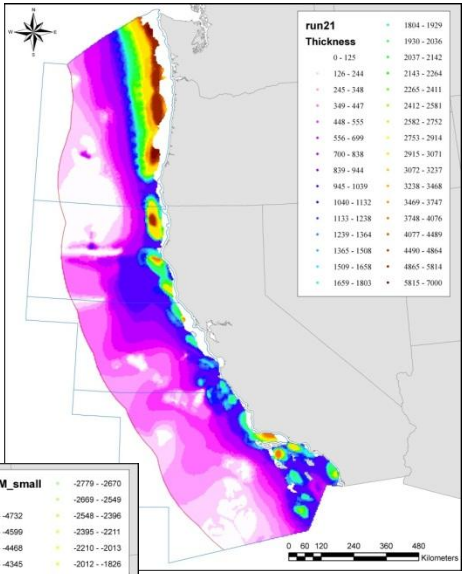
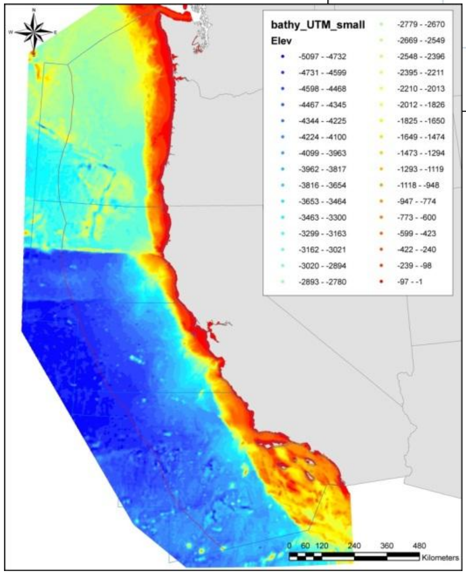
Spatial Outputs – Stability Zone



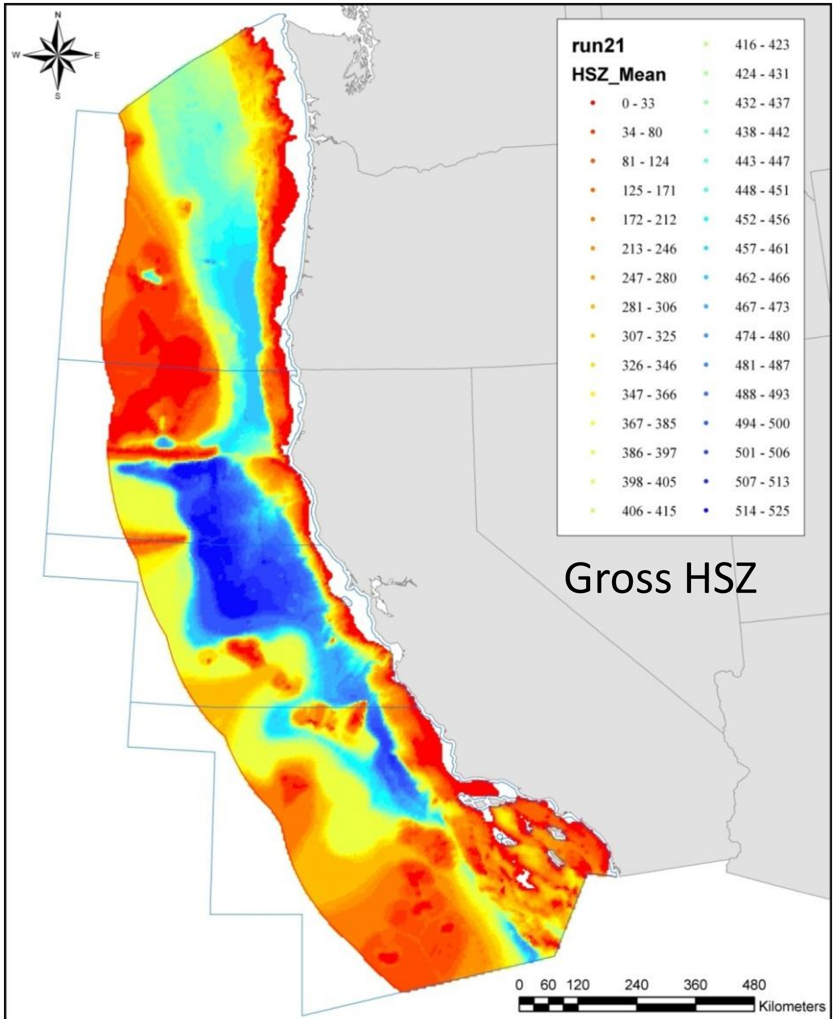
HSZ limited by thickness

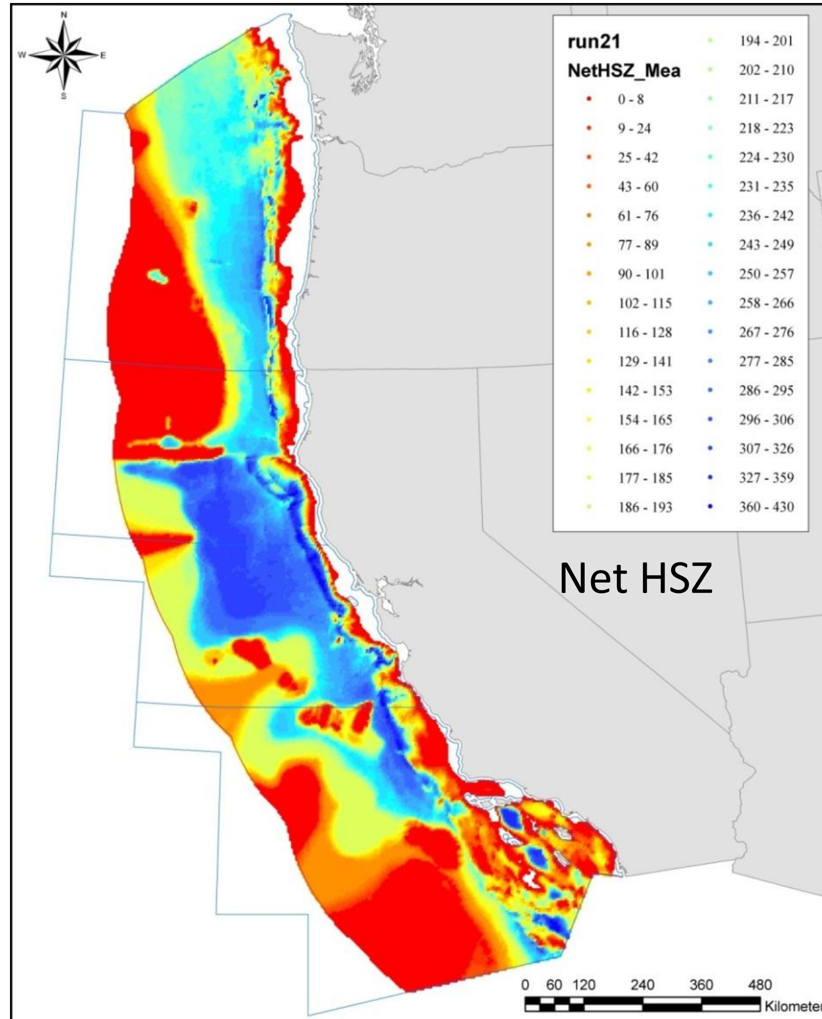
(Not an issue in ATL)
(Similar to salt in GOM)



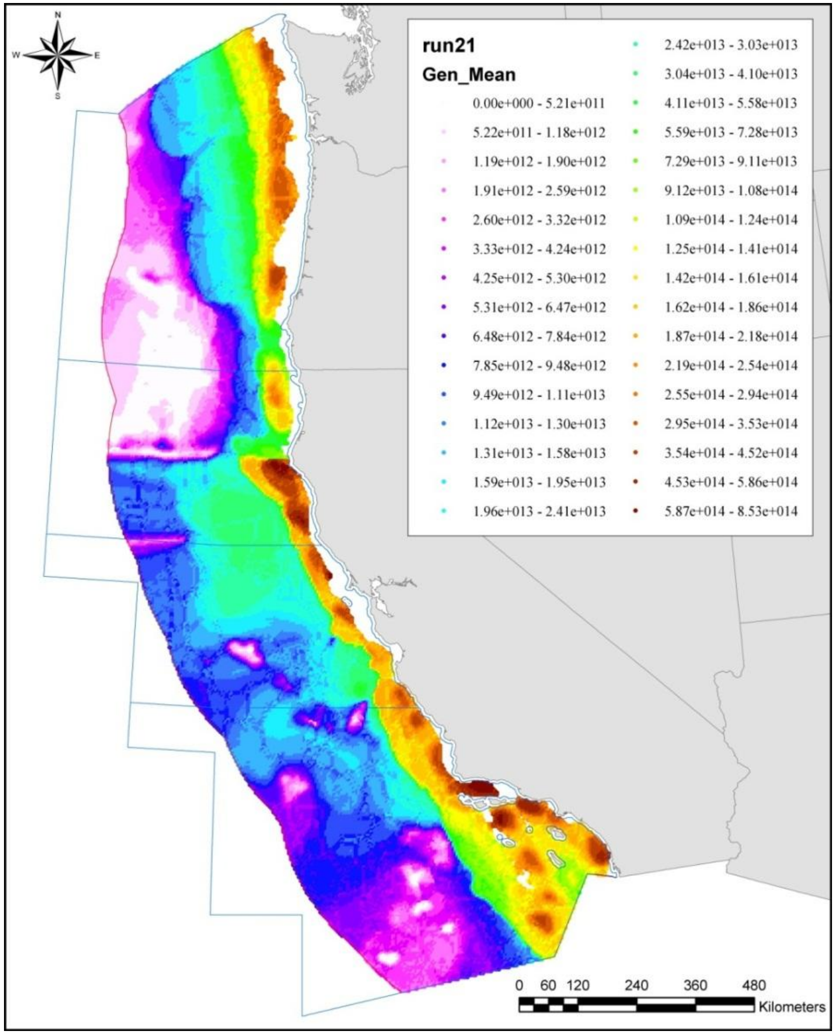


Spatial Outputs – Stability Zone



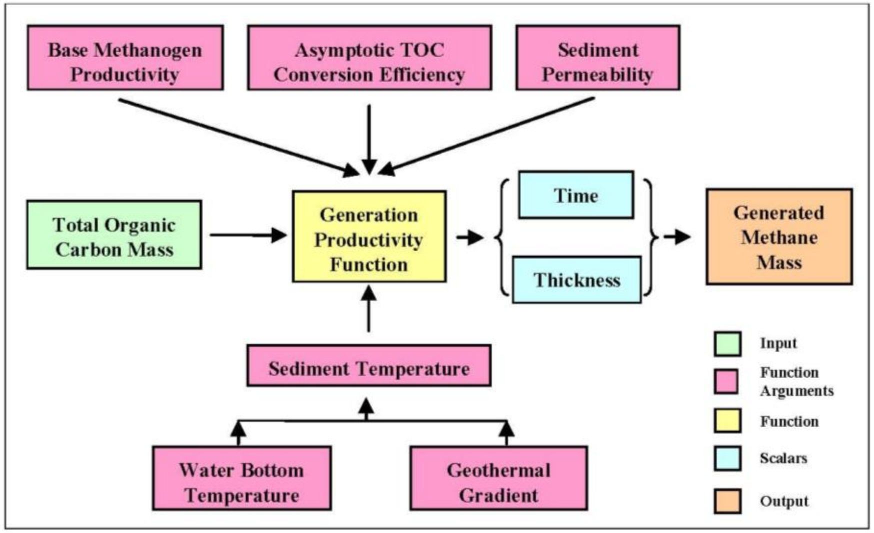


Spatial Outputs – Gas Generation

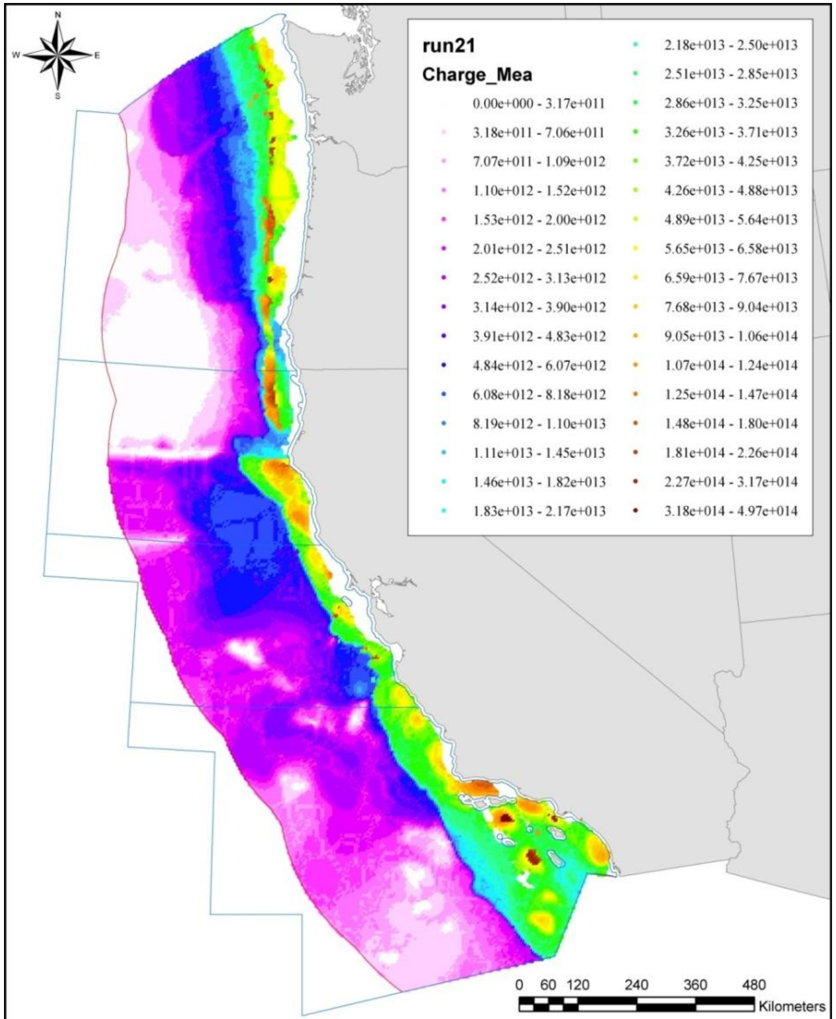


Spatial Influences:

- Sediment Thickness
- Crust Age (time)
- Depofacies distribution (permeability)
- TOC variability
- GTG variability

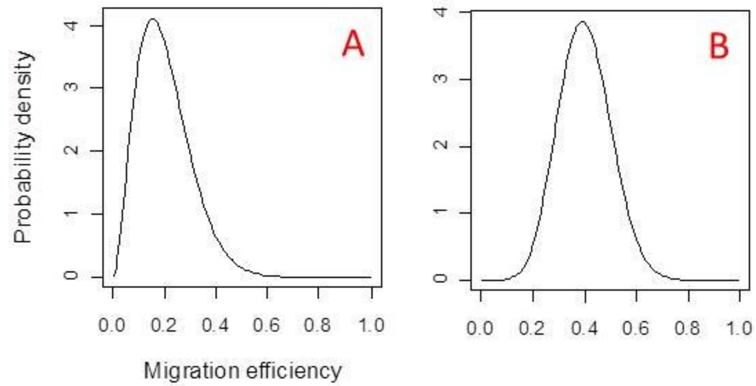


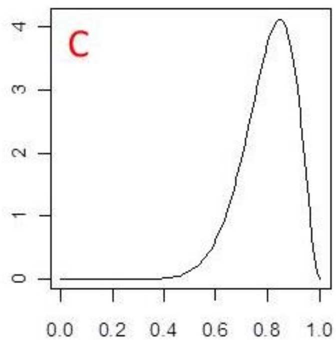
Spatial Outputs – Charge



Migration efficiency recognizes:

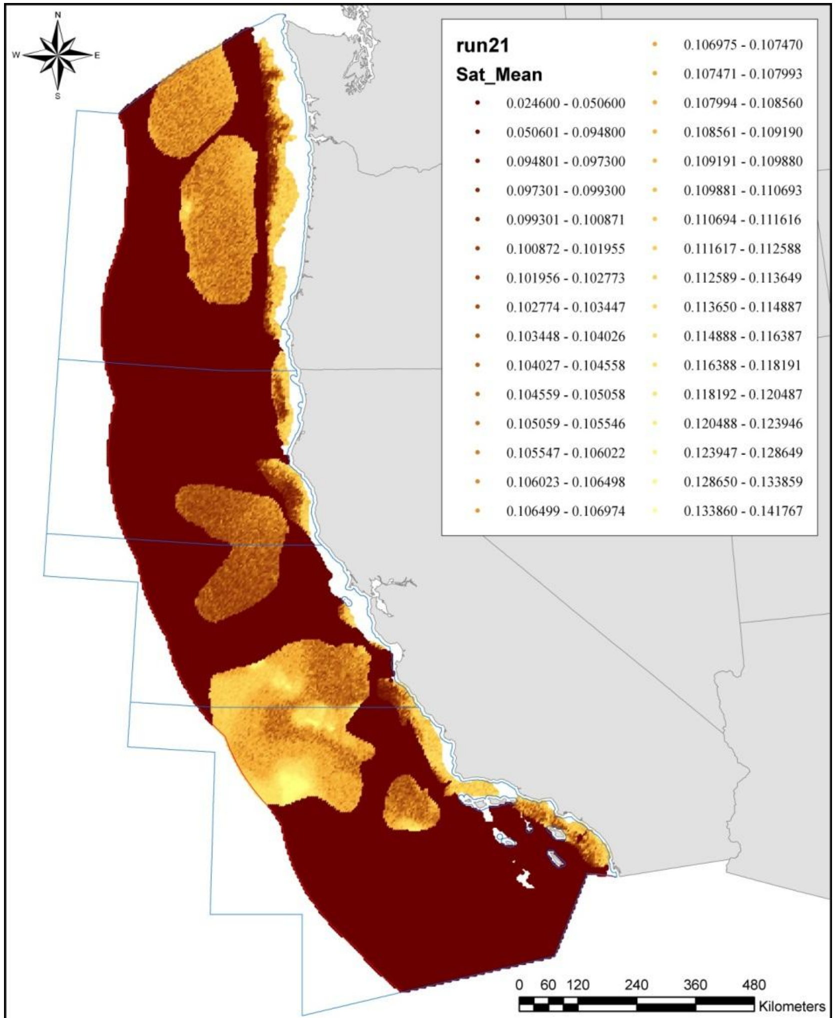
- Gas not expelled from fm.
- Gas trapped below HSZ
- Gas expelled at seafloor





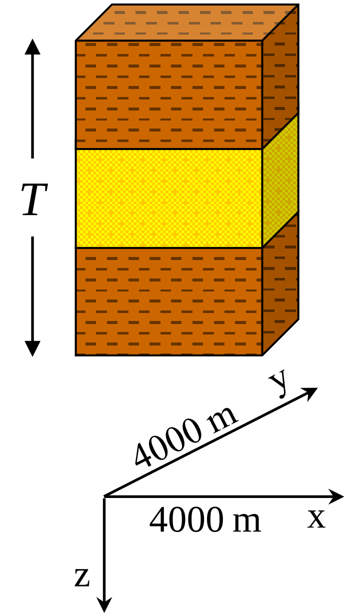
- Carried from ATL model
- Compatible w 204 sites

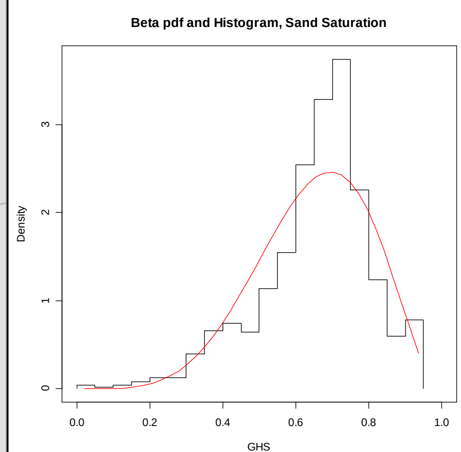
Spatial Outputs – Saturation

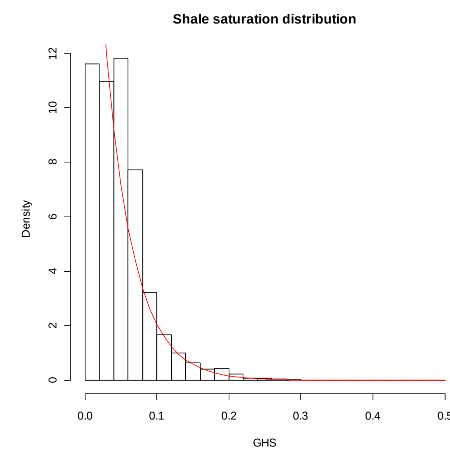


Sand Void = (Volume)(Porosity)
Volume Sand = (x)(y)[(T)(sand%)]
Porosity Sand = $f(d)$

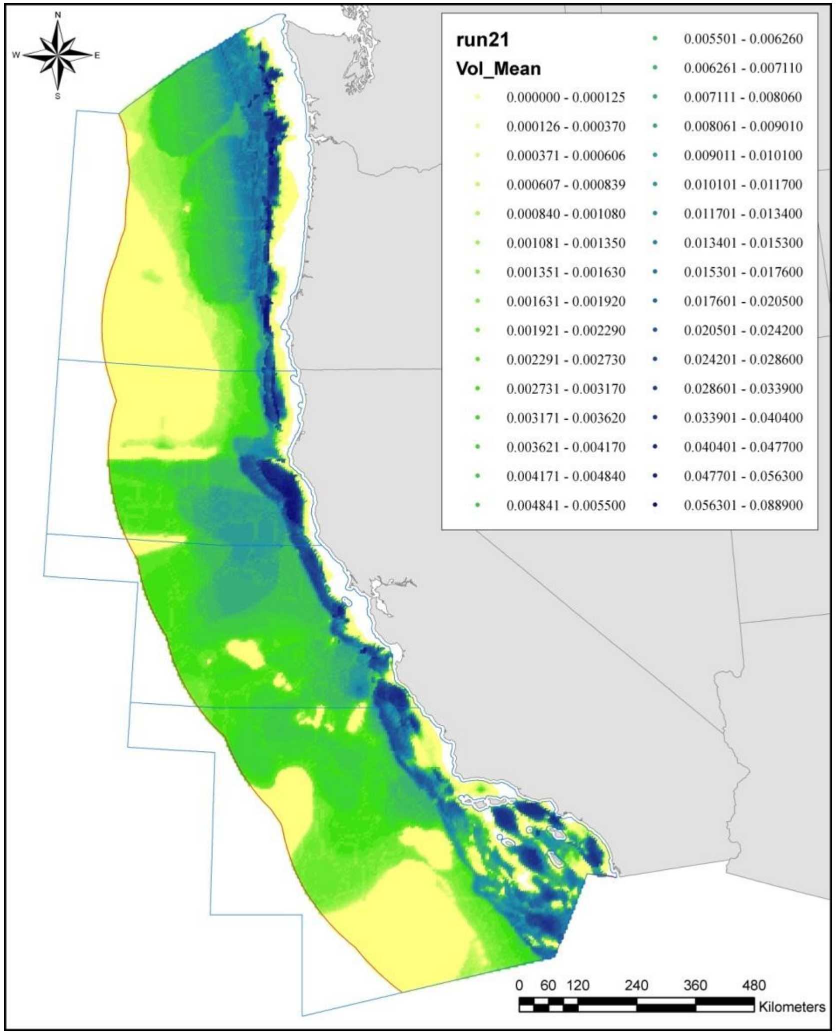
Shale Void = (Volume)(Porosity)
Volume Shale = (x)(y)[(T)(1-sand%)]
Porosity Shale = $f(d)$







Spatial Outputs – In Place Volume



Region	In-Place Gas Hydrate Resources					
	95%		Mean		5%	
	tcf	tcm	tcf	tcm	tcf	tcm
Atlantic OCS	2,056	58	21,702	614	52,401	1,483
Pacific OCS	2,209	63	8,192	232	16,846	477
Gulf of Mexico OCS	11,112	314	21,444	607	34,423	974

Largest accumulations in near-shore basins:

- Thick sedimentary sections
- Higher TOC
- Greater sand component
- Sufficiently old/mature column
- Enhanced migration efficiency

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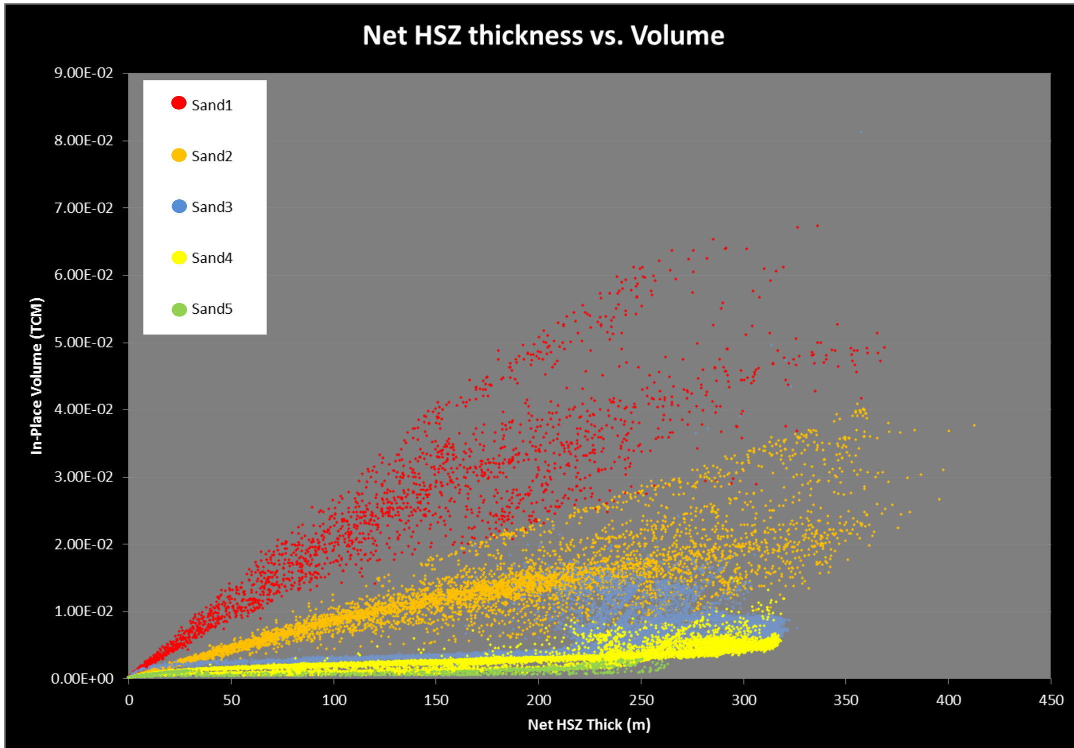
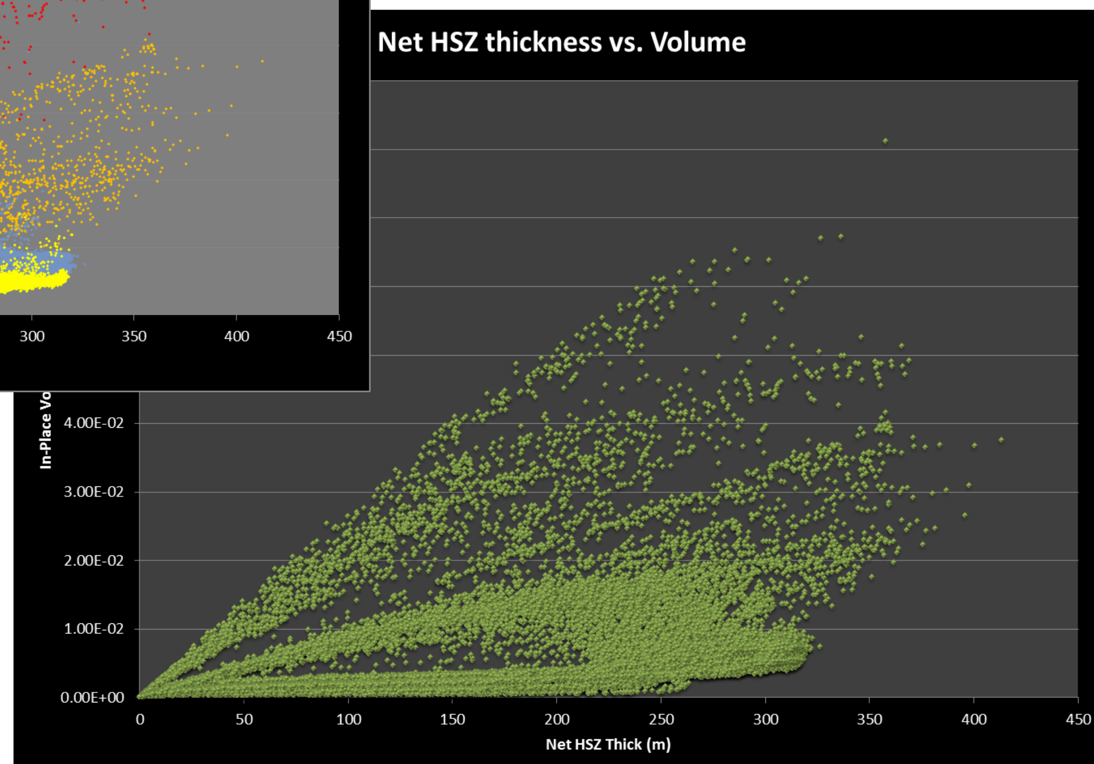
BOEM – Herndon, VA
6 June 2013



Tabular data available for analysis:

- Sensitivity
- QC
- Limitations



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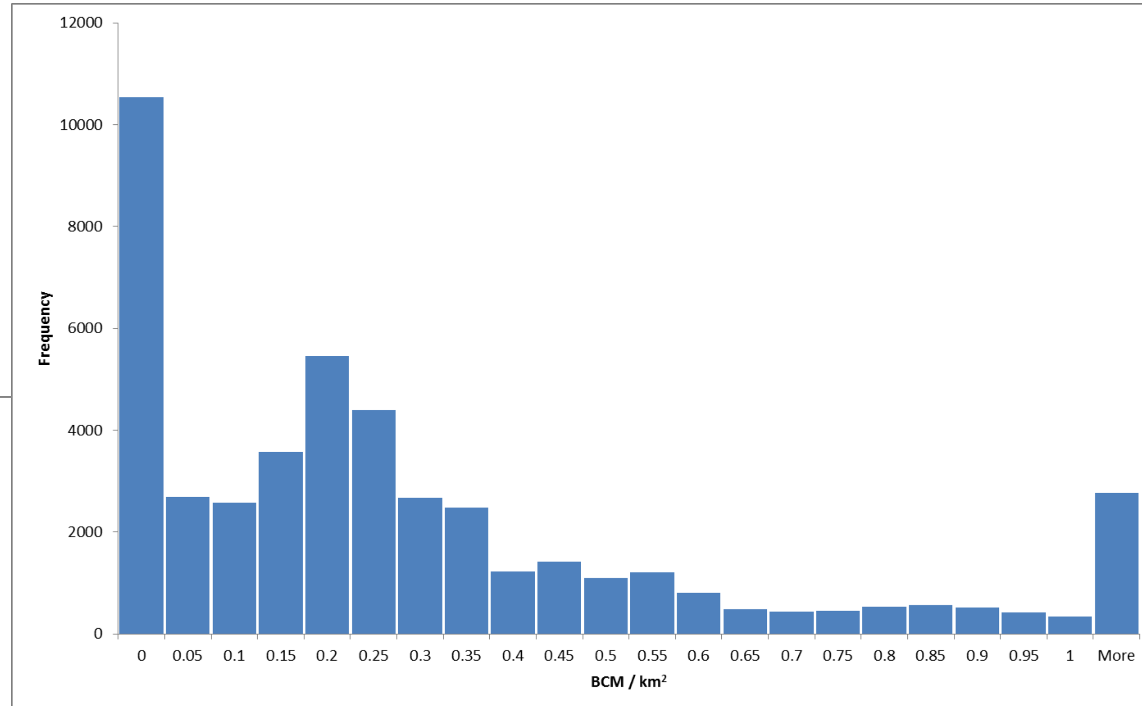
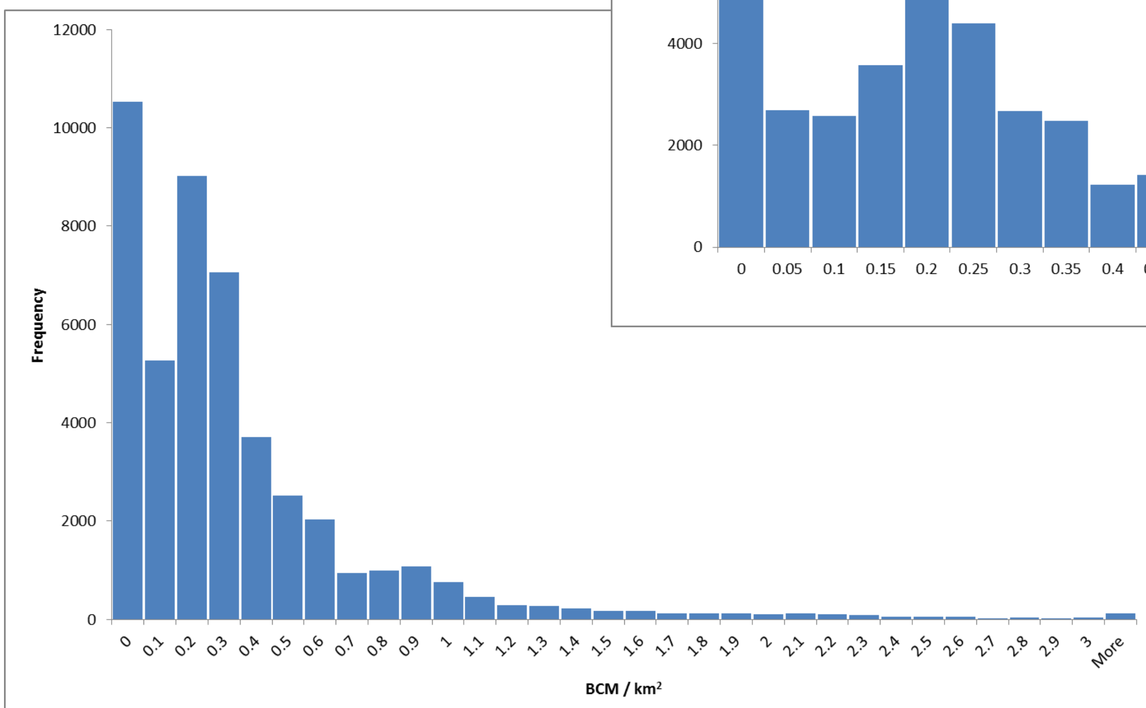
Pacific Resource Density

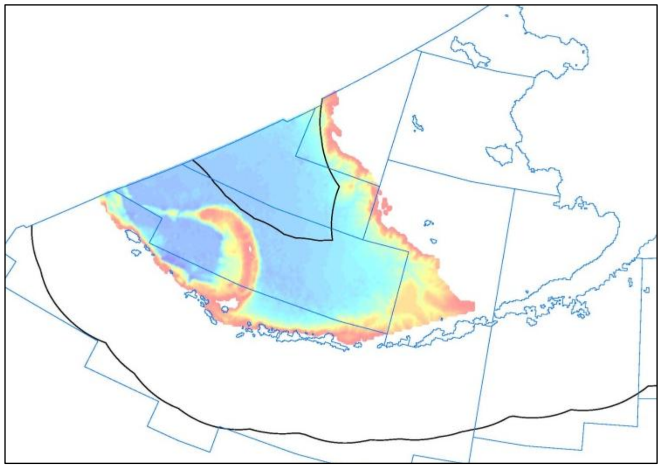
Units BCM/km^2

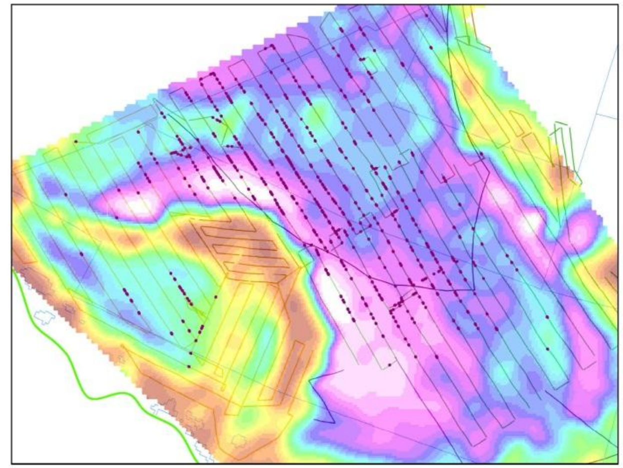


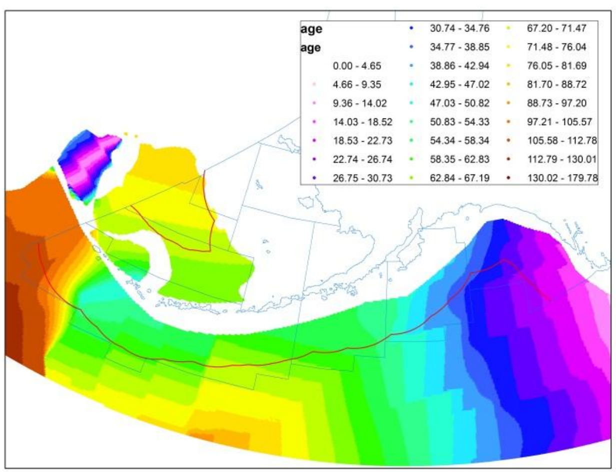


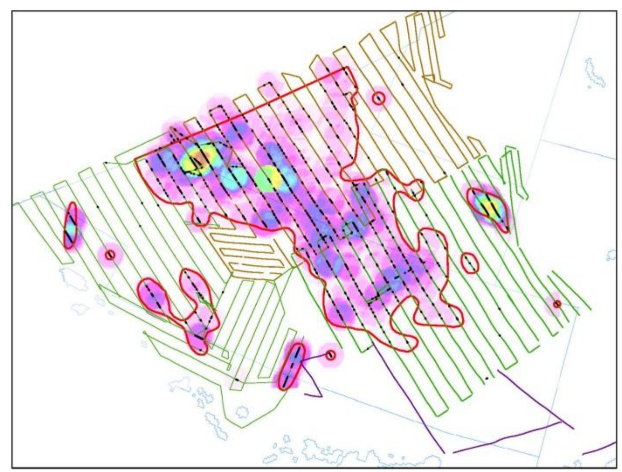
Statistics: resource density (BCM/km2)	
Mean	0.310445834
Median	0.18125
Standard Deviation	0.438355356
Minimum	0
Maximum	5.06875
Sum	14498.75179
Count	46703

Path Forward: Pacific Reporting, Alaska DW (Bering, Beaufort, Trench, Gulf of Alaska)









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Matthew Frye
BOEM – Herndon, VA
6 June 2013

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Assessment of In-Place Gas Hydrate Resources of the Lower 48 United States Outer Continental Shelf

Natural gas hydrates are ice-like crystalline substances occurring in nature where a solid water-ice lattice accommodates gas molecules (primarily methane, the major component of natural gas) in a cage-like structure known as a clathrate.

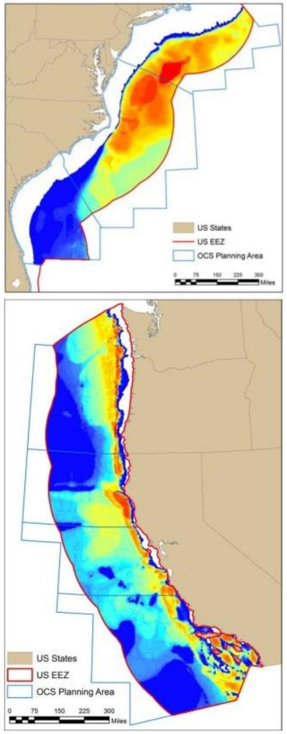
Using a mass balance assessment methodology, the Bureau of Ocean Energy Management estimated a mean of 51,338 trillion cubic feet of in-place gas hydrate resources in the Federal Outer Continental Shelf of the Lower 48 United States.

Introduction

This report summarizes the results of the Bureau of Ocean Energy Management (BOEM) assessment of the undiscovered *in-place* gas hydrate resources for those areas of the U.S. Outer Continental Shelf (OCS) adjacent to the Lower 48 states and within the limits of the 200 nautical mile U.S. Exclusive Economic Zone (EEZ; Figures 1a, 1b, 1c). Gas hydrate resources on the U.S. OCS adjacent to Alaska have not yet been assessed in this effort. The OCS comprises that portion of the submerged seabed whose mineral estate is subject to Federal jurisdiction. This assessment represents a comprehensive appraisal of relevant data and information available from a variety of proprietary and non-proprietary data sources.

Gas hydrate resources are assessed as in-place volumes and reported as the amount of natural gas that resides in the form of gas hydrate in any reservoir in the subsurface of the OCS, without regard to technical recoverability. This differs from BOEM's assessments of conventional oil and gas resources (e.g., BOEM Fact Sheet RED-2011-01b), where undiscovered oil and gas resources are reported as technically recoverable and economically recoverable volumes. BOEM does not report the larger in-place volume of undiscovered conventional oil and gas resources.

Gas hydrate resources on the OCS are assessed using a spatially-resolved mass balance model that incorporates uncertainty at various levels of model component input. The stochastic nature of the assessment approach provides a range of resources at the model cell level and at levels aggregated to greater geographic extents. More detailed information about the geology and assessment methodology will be made available in separate national and regional assessment reports.



Figures 1a and 1b. In-place gas hydrate volume distribution for the Atlantic (top) and Pacific OCS (bottom). Red colors indicate maximum accumulations; blue colors indicate minimal accumulations

Thank You !

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6 June 2013

BOEM Resource Evaluation Division gas hydrate webpage:

http://www.boem.gov/Oil-and-Gas-Energy-Program/Resource-Evaluation/Gas-Hydrates/index.aspx