Major Field Programs

DOE Gas Hydrate Program

Alaska North Slope Field Testing

Prior Alaska Field Programs

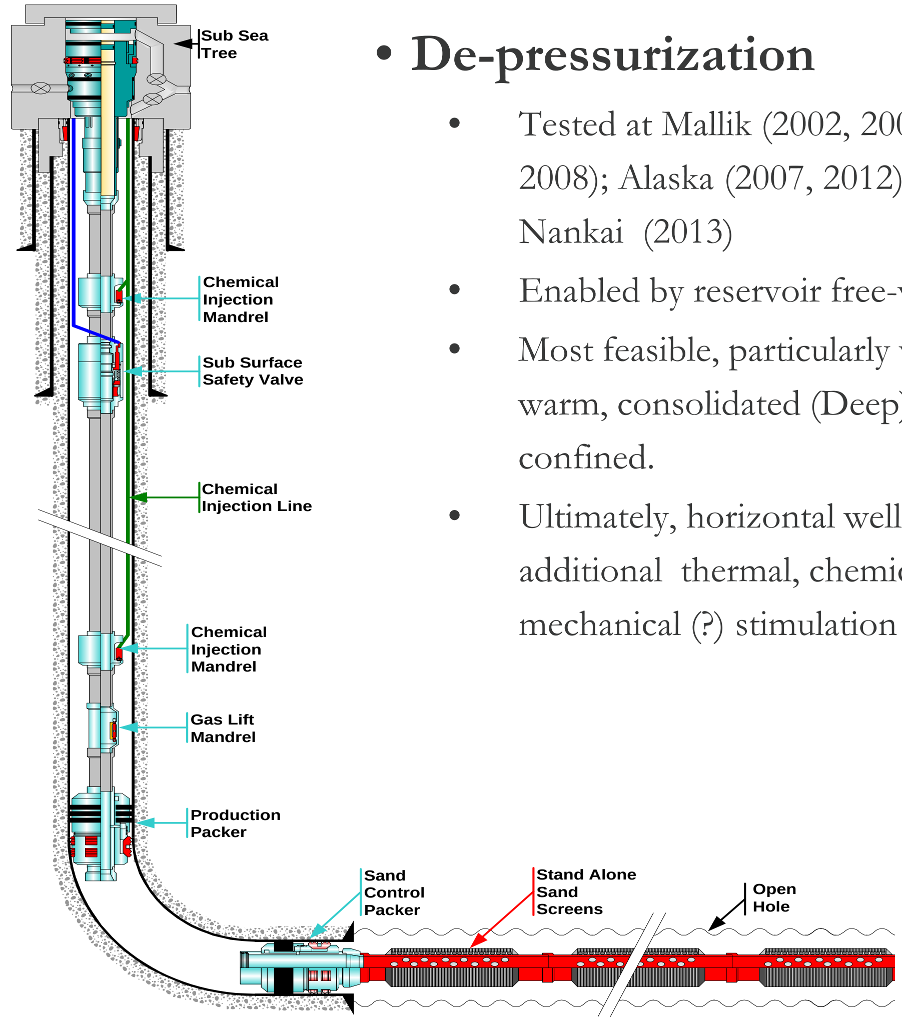
Conducted in Partnership with Industry and Academia

- **"Hot Ice" (2004)**
  - Failed to encounter Gas Hydrate. A major impetus for the full incorporation of Petroleum Systems concepts in GH exploration and Evaluation
- **"Mt. Elbert" (2007)**
  - Successful demonstration of GH exploration and evaluation methodology → USGS 2008 GH Tech Recoverable Assessment
  - Successful demonstration of safe conduct of scientific field program within an area of active industry operations
  - Acquisition of extensive scientific data → leap forward in modeling capabilities and relevance → development of key petrographic parameters → Scientific Volume with 24 papers including 57 scientists from 24 different organizations.
- **"Iġnik Sikumi" (2011-2012)**
  - Successful field test of injection into GH reservoirs. Successful demonstration of maintenance of mechanical stability through engineering controls. Demonstration of sufficient heat transfer to maintain production at aggressive drawdown.
  - Confirmation of formation of complex mixed hydrates upon injection. Confirmation of the ability to effect limited, bulk exchange of CH_4 for CO_2. Confirmation of the superiority of depressurization wrt production rate.

Gas Hydrate Production Technology

Depressurization will be the basis of initial commercial systems

- **Thermal**
  - Tested at Mallik (2002)
  - Tests and Modeling → Not feasible
  - Near-well bore maintenance/stimulation
- **Chemical**
  - Injection: Costly? Ineffective?
  - CO_2-CH_4 exchange – challenge of free-water; limited permeability; complex thermodynamics
  - Stimulation/mechanical stability?
- **Mining**
  - Studies underway in China. Generally slurry production and separation

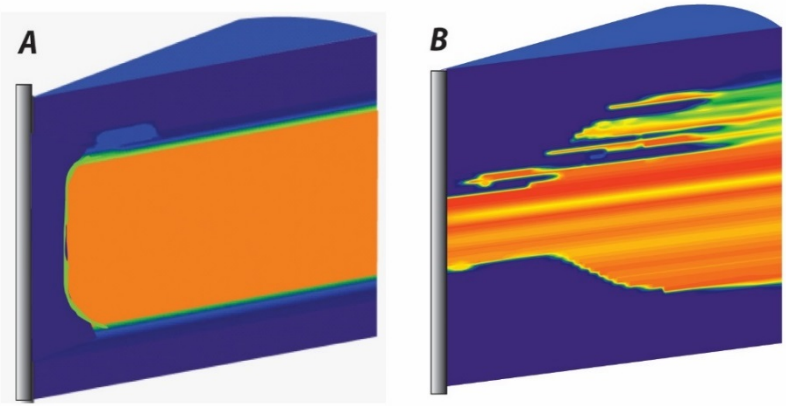


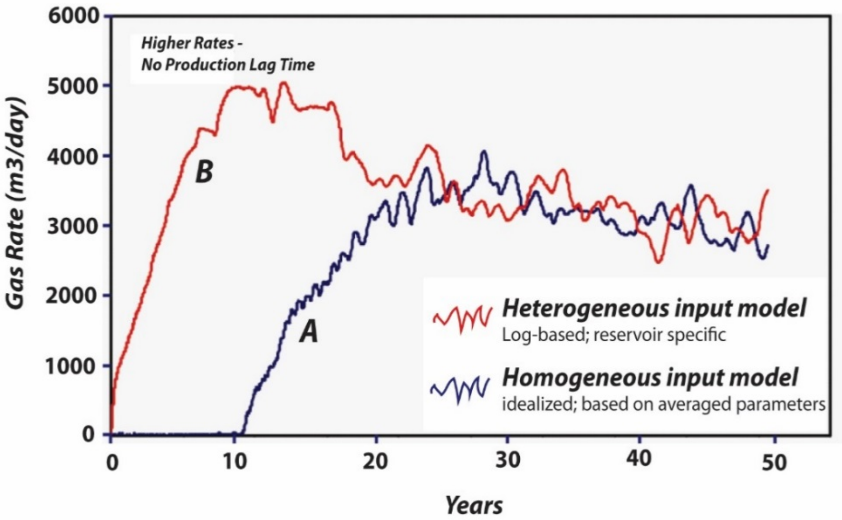
- **De-pressurization**
  - Tested at Mallik (2002, 2007, 2008); Alaska (2007, 2012); Nankai (2013)
  - Enabled by reservoir free-water
  - Most feasible, particularly when warm, consolidated (Deep), and confined.
  - Ultimately, horizontal wells w/ additional thermal, chemical, mechanical (?) stimulation

Gas Hydrate Production Potential

Insights From Numerical Simulation

- **Early 2000s (pessimism)**
  - Low rates, long lag times, large cumulatives but very long production profiles
- **At present (cautious optimism)**
  - Incorporation of vertical geologic heterogeneity shows potential to eliminate lag, increase peak, and accelerate peak.
- **Challenges & Current Topics**
  - Impact of permeable boundaries (vertical and lateral) are a major challenge
  - Initial permeability still poorly known: had been assessed as low (~0.1 md) but recent analyses suggest it may be much higher (10s of md) in some settings
  - Permeability evolution with dissociation is uncertain
  - Integration of geomechanical effects is a major priority
  - Thin bed effects: internal heat transfer
  - Fines migration in changing geochemical environments is uncertain
  - Continued lack of field validation data remains the major R&D challenge





Observed and Modeled Production Rates

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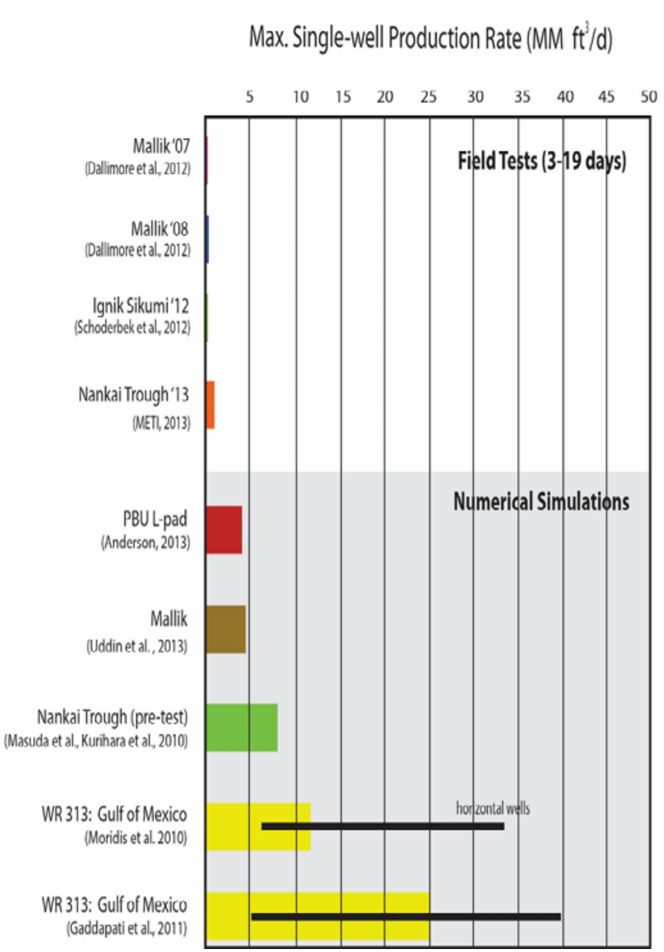
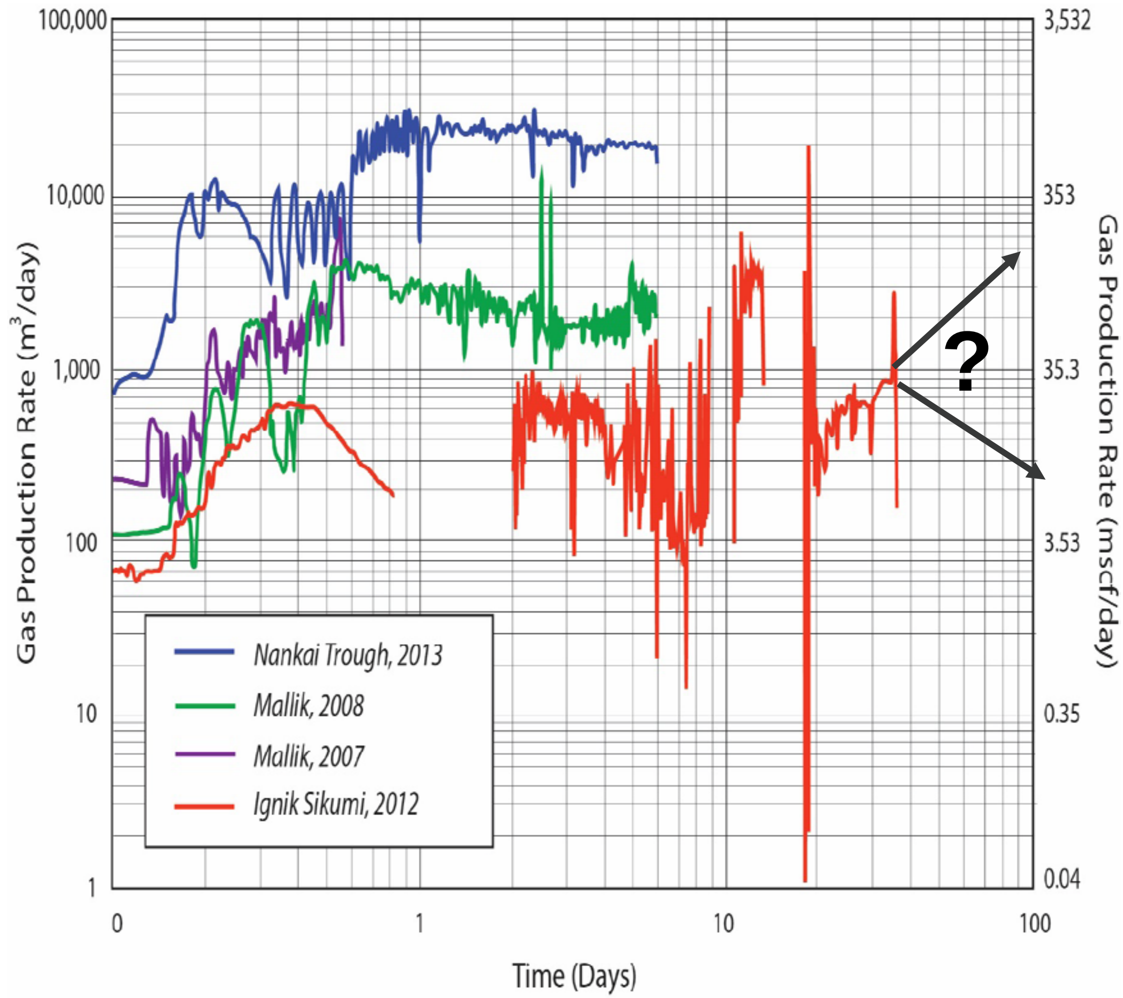
Depressurization-based Production

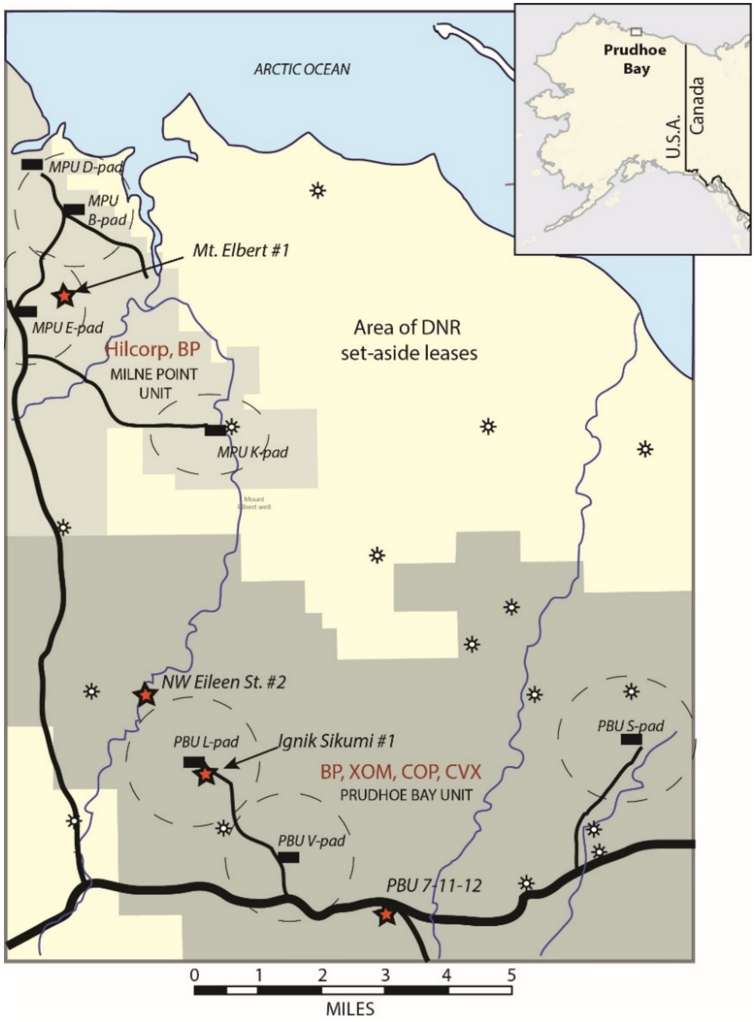




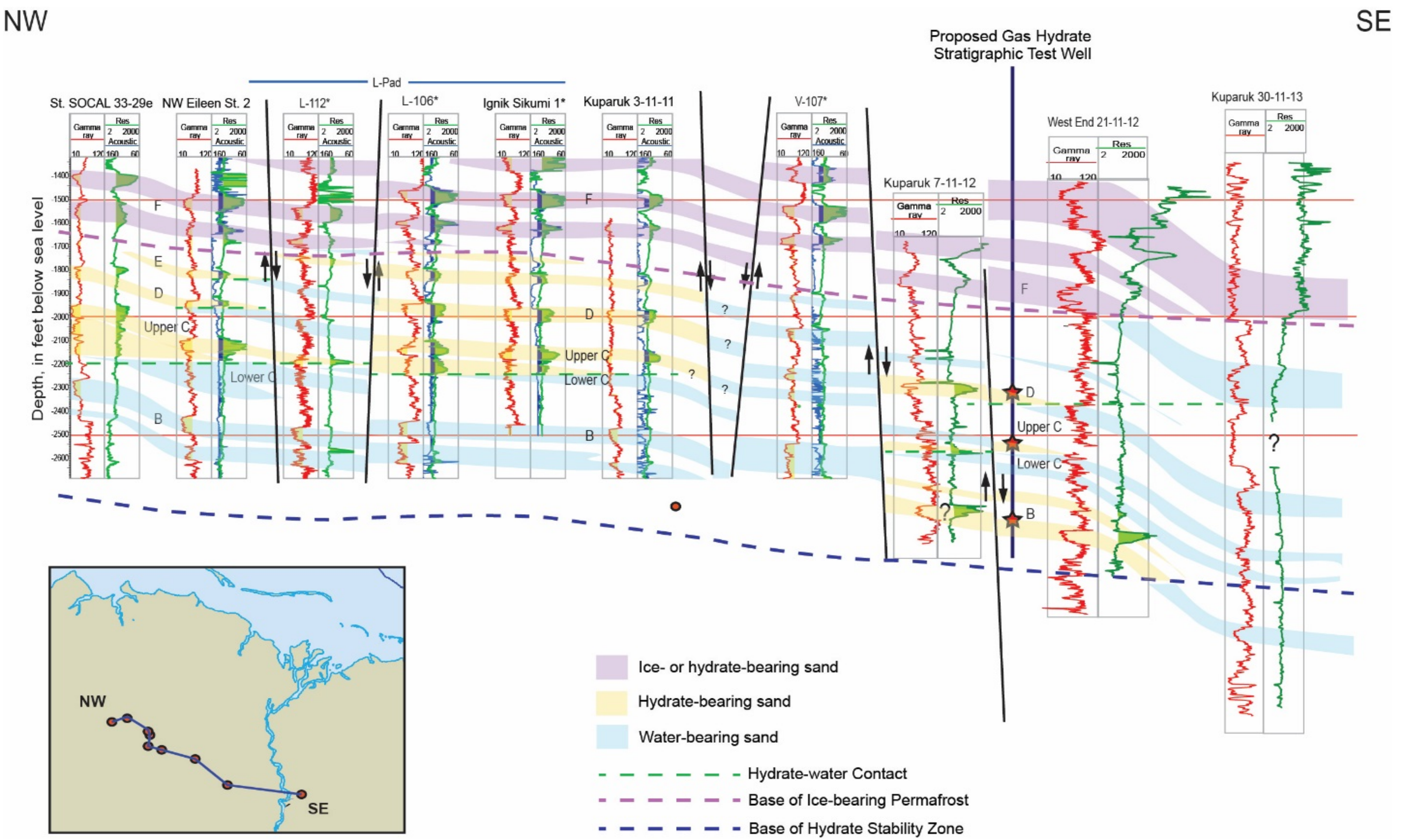
Ongoing Effort Towards Long-term Test

Pursuing All Options

- 2009-2010: geologic and thermal modeling studies confirm bottom-hole location within PBU. BP/NETL/USGS develop plans for short-term exchange test, w. sidetrack for long-term depressurization test.
- 2010: BPXA testing plan deferred: NETL-CPAI agree to proceed w/ exchange test from ice pad as CPAI tract operation.
- 2011-2012: Ignik Sikumi program: Despite $0 2011 DOE budget, engagement with DOE Office of Science and JOGMEC enables test.
- 2013: BPXA elects to close-out DOE project. ConocoPhillips also closes out project.
- 2013: Statoil indicates interest in enabling a project with DOE and JOGMEC.
- 2013-2014: DNR sets-aside lands: DNR-DOE and JOGMEC-NETL MoUs. DOE solicitation offered – no response.
- 2014-2015: DOE-JOGMEC-USGS analysis of State lands reveals high geologic/operational risk.
- DNR-DOE secure renewed interest of operators in tests within the units. Focus shifts to PBU 7-11-12 site.
- 2016: DOE-JOGMEC-USGS obtain permission to view PBU seismic at DNR. Draft plan presented to the WIOs.



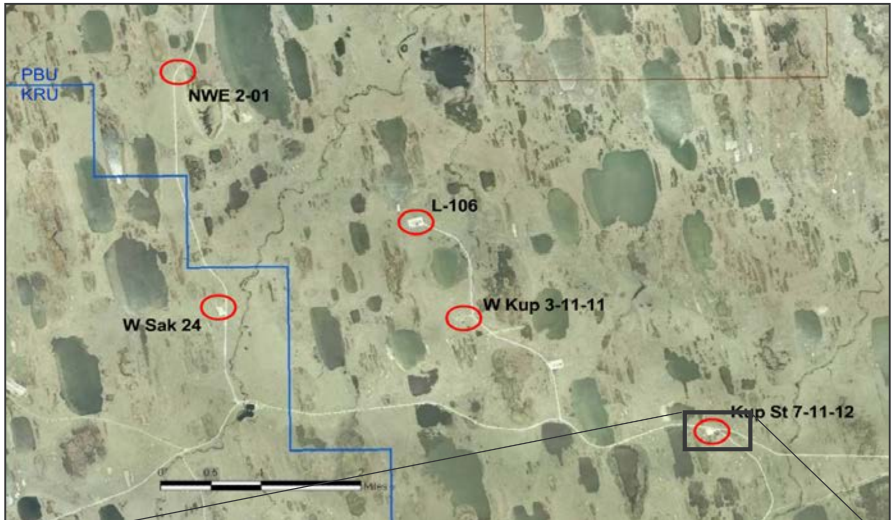
Westend PBU

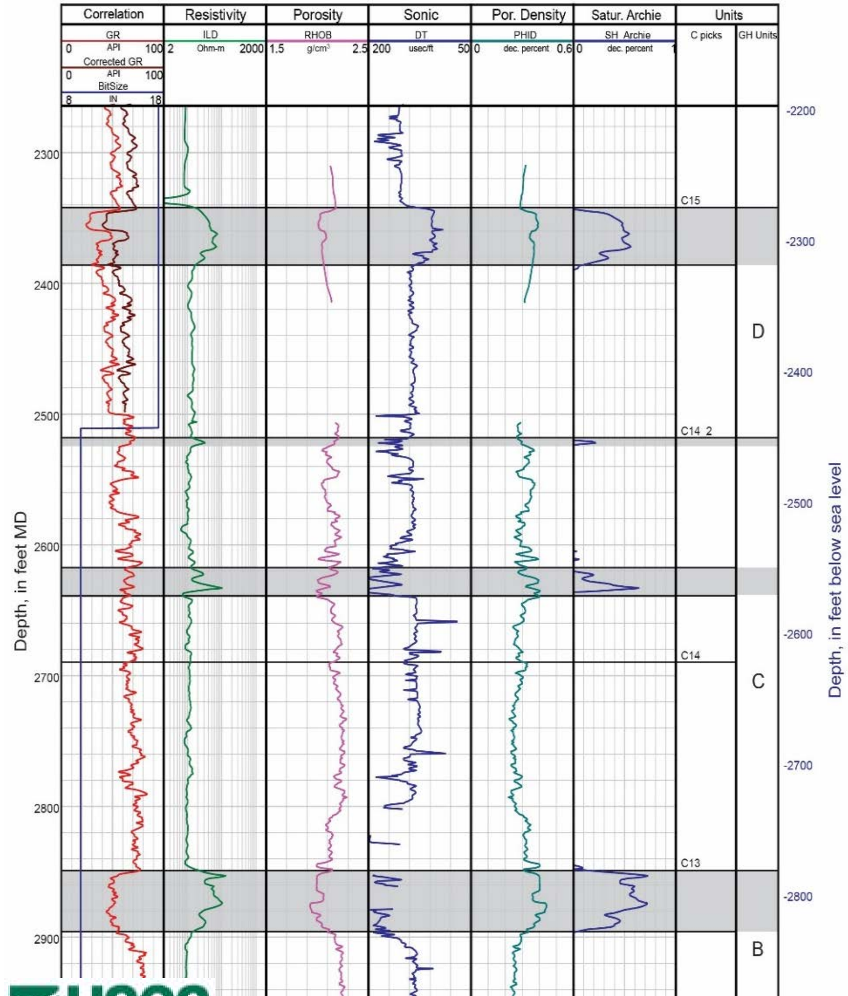


NW
SE
Proposed Gas Hydrate Stratigraphic Test Well
L-Pad
St. SOCAL 33-29e
NW Eileen St. 2
L-112*
L-106*
Ignik Sikumi 1*
Kuparuk 3-11-11
V-107*
Kuparuk 7-11-12
West End 21-11-12
Kuparuk 30-11-13
Gamma ray
Res
Acoustic
Depth, in feet below sea level
F
E
D
Upper C
Lower C
B
NW
SE
Ice- or hydrate-bearing sand
Hydrate-bearing sand
Water-bearing sand
Hydrate-water Contact
Base of Ice-bearing Permafrost
Base of Hydrate Stability Zone

Kuparuk 7-11-12 Well Site (PBU)

Confirmed GH in D sand. Limited GH in C sand. Uncertain GH in B sand.





Long-term Test Opportunity

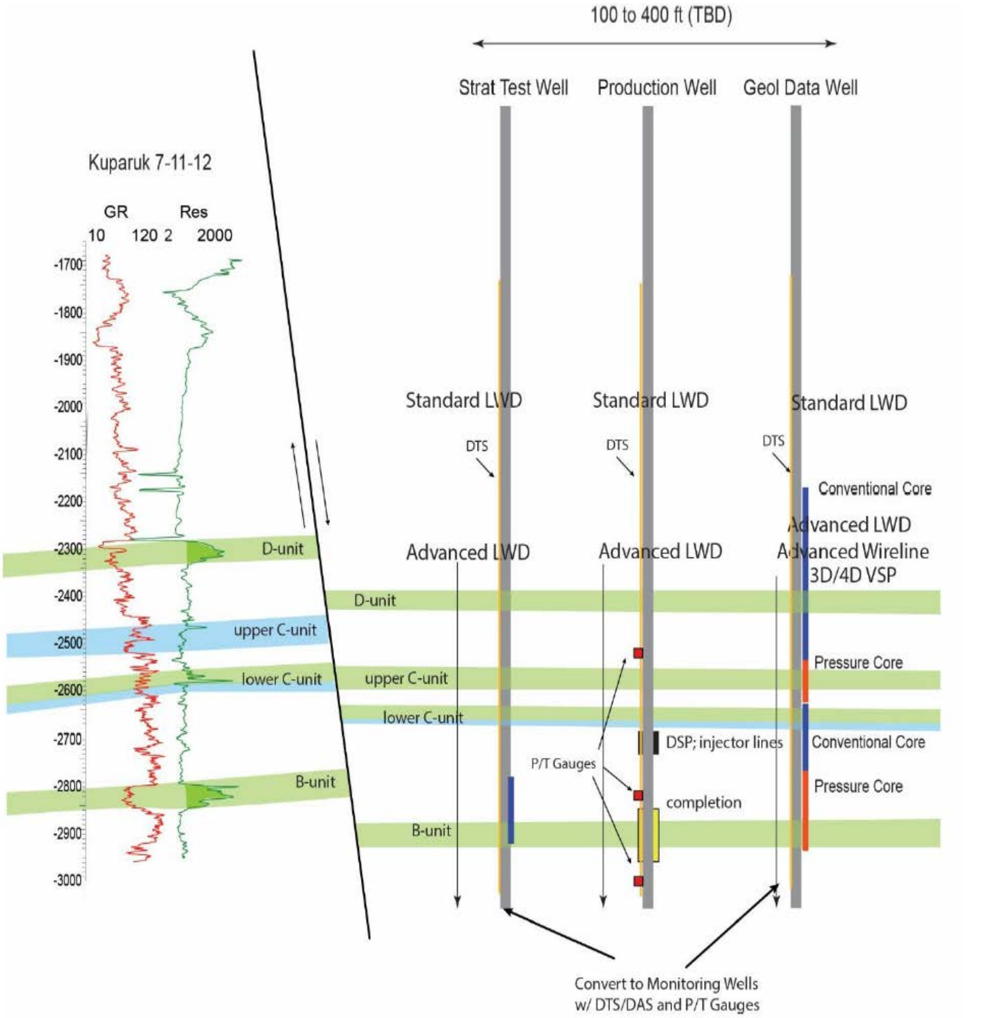
Maximize scientific/engineering insight (over rate demonstration)

- **PBU Kuparuk 7-11-12 offers…**
  - Continual ops of 6 mo (min); opt.18-24 mo. Gas/water handling options
  - Minimized interference with ongoing operations
  - Confirmed GH in one zone (D-sand) of acceptable reservoir quality
- **Confirmation Needed (via Stratigraphic Test Well)**
  - Opportunities in deeper, warmer B-sand (near BGHS)?
  - Hydraulic isolation of test zone (away from sources of free gas or water)?
  - Nature of lateral reservoir boundaries?
  - Grain size information (for test well completion design)
- **Program Design:**
  - Subject to operator/partner requirements/protocols.
  - Depressurization (obtain pre-set or steady rates - scale to commercial) w/ stimulation and intervention options available.
  - Listen to reservoir: Minimal complexity – avoid unproven technologies
  - Full scientific and environmental impact monitoring
  - Design/evaluation well survivability (chem inj./downhole heaters); sand control; robust ESPs

Recent Accomplishments/Forward Plan

Engage PBU WIOs for test at PBU 7-11-12 site

- Seismic data review at DNR was held in June. Preferred BHL identified.
- Results and draft high-level operational plan presented to WIOs.
- Currently seeking definition of project structure that meets the needs of NETL, JOGMEC, and industry partners
- Seeking WIO approval to enable BP engagement to finalize plan (put in context of local operations and infrastructure).
- Seek WIO approval for full field program
- Conduct stratigraphic test
- Establish site, drill instrument science/monitoring wells, drill and test production test well.



GoM: Exploration and Characterization

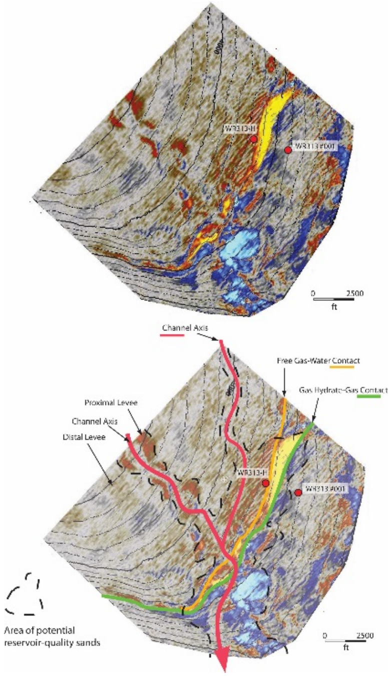
NETL NATIONAL ENERGY TECHNOLOGY LABORATORY

Prior Gulf of Mexico Major Field Projects

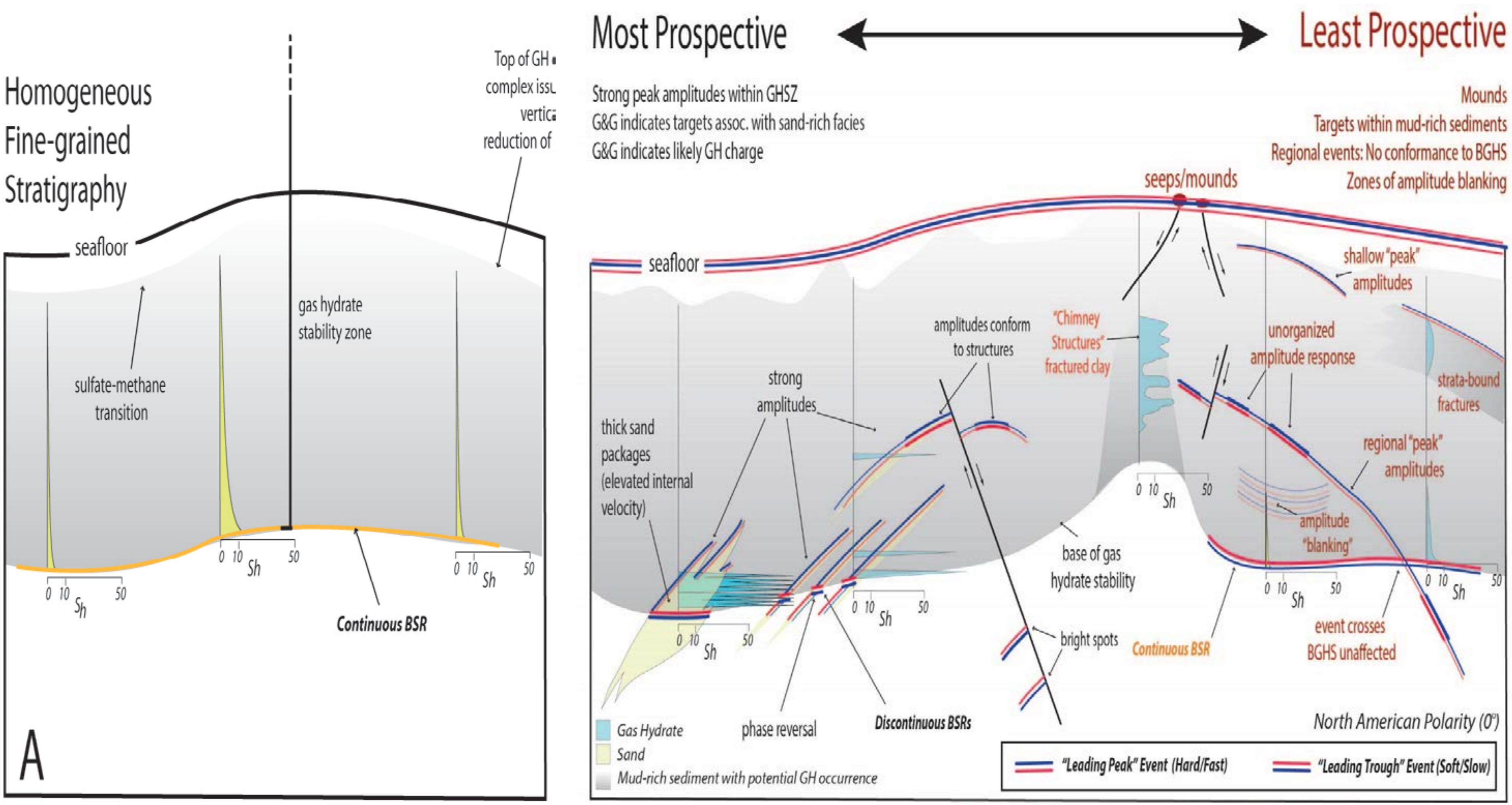
In Partnership with a Chevron-led International “Joint Industry Project”

- **JIP Leg I (2005): Assessing drilling hazards**
  - Confirmation of ability to safely drill through GH as it most commonly exists in the GoM.
  - First acquisition of physical property data from cores acquired and maintained under pressure. Full science volume published

- **JIP Leg II (2009): Prospecting for resource-grade deposits**
  - Confirmed the occurrence of GH in sands in the GoM and provided initial test of 2008 BOEM assessment of 5,000+ tcf potential within GoM sands.
  - Confirmation of program-developed G&G prospecting approach. (2 of 3 sites drilled contained high-saturation GH in sand reservoirs. 6 of 7 wells drilled contained GH in accordance with pre-drill predictions).
  - Acquisition of State-of-the-Art LWD data. Publication of Scientific Results Volume featuring DOE-USGS-BOEM-SCHL-Fugro collaboration.
  - Subsequent adoption of program approach within the National Programs in India and Korea and expanded collaboration internationally. Expanded credibility with industry.



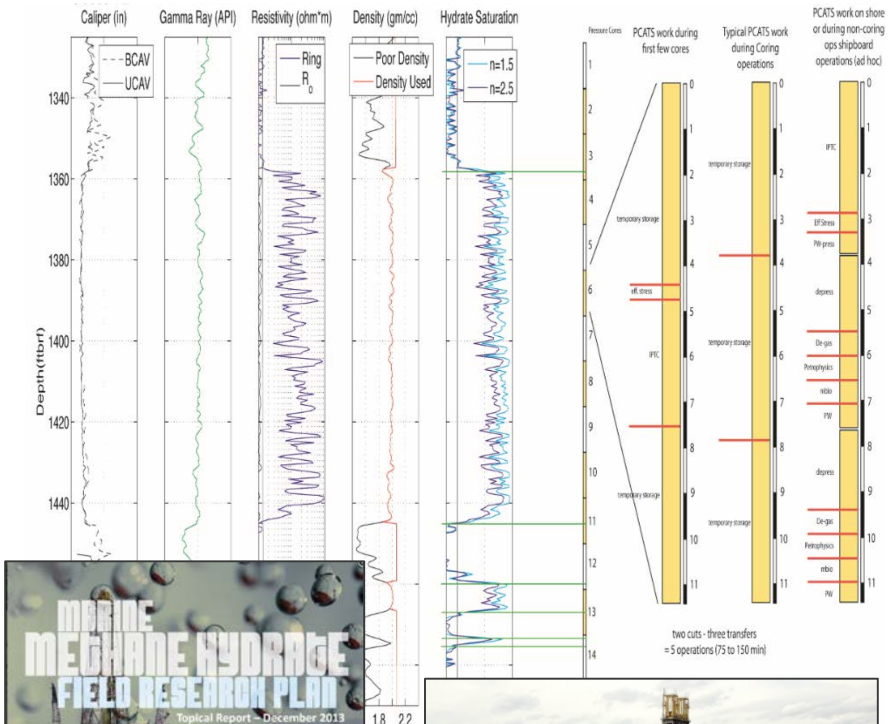
Evolution in Marine GH Exploration



Post JIP Leg-2 Activities

Goal: Gather samples and known sites: Continue Exploration/Resource Confirmation

- **JIP data (no core/gas/fluid samples) left many questions**
  - Reservoir and seal petrophysics
  - What controls hydrate occurrence (thermodynamics; lithology)
  - How are hydrate reservoirs generated and maintained?
  - How common?
- **DOE-USGS-Chevron developed extensive plans for Leg-3 coring within Industry Protocols**
  - GoM JIP increasingly challenged by regulatory uncertainty and increasing internal risk aversion.
  - DOE initiated activities to assess opportunities in other sectors (service industry, IODP)
  - Workshop convened by COL produced a marine science plan →
  - In 2013, Chevron ended the project.
- **In 2014, DOE Solicited and awarded new project (UT-Austin)**

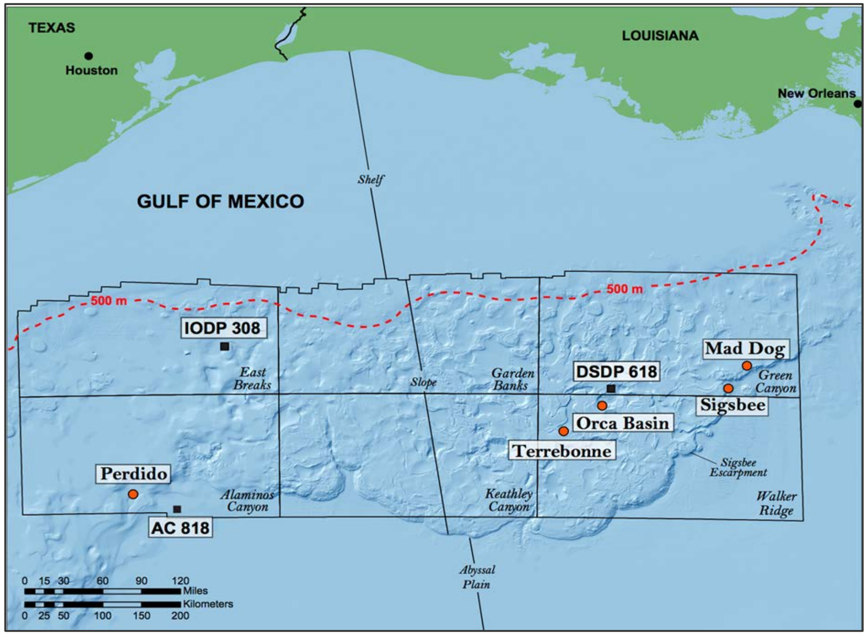


UT-Austin Project: GoM^2

Pressure-coring at known sites and exploration of high-value new sites

Expedition – 1 (Spring 2017)

- Single site, two-hole, test of pressure corer, core transfer and core analysis. 20 deployments.
- Full science program (UT, DOE-NETL, USGS, Geotek)
- Land and shop tests conducted, final corer designs. Two bit configurations to be tested.
- Helix Q4000 contracted: UT expending significant effort in addressing project liabilities.



Expedition – 2 (2019/2020)

- Logging, MDT, and pressure coring at multiple sites.
- FY19 of FY20 from *Joides Resolution* (pending IODP approval)

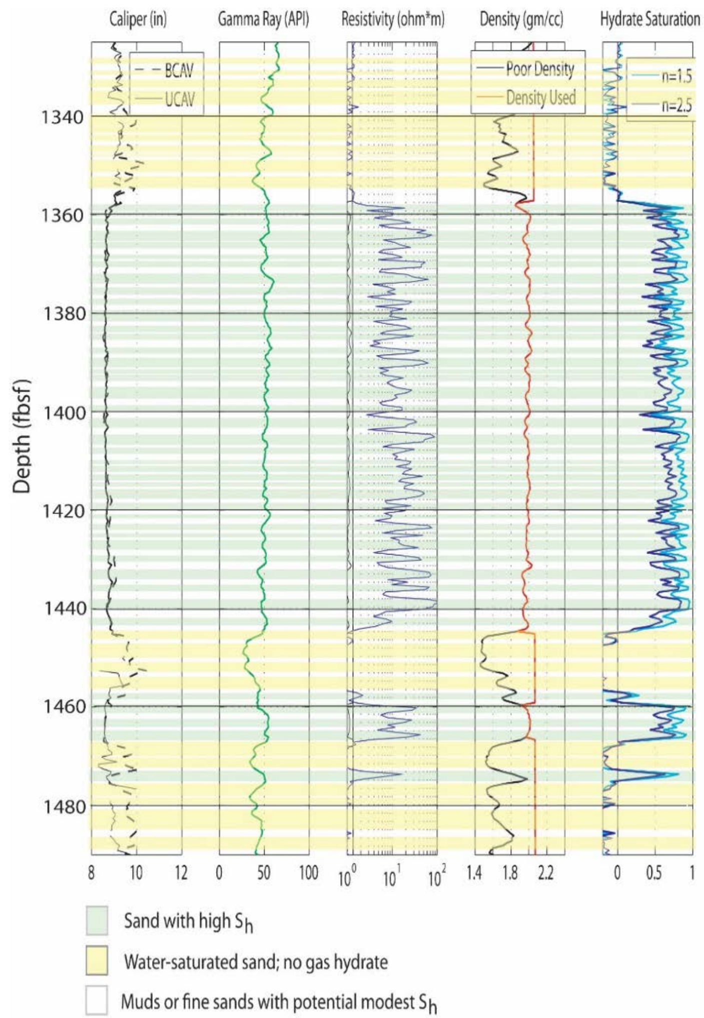
PCTB: PCATs: PCCTs

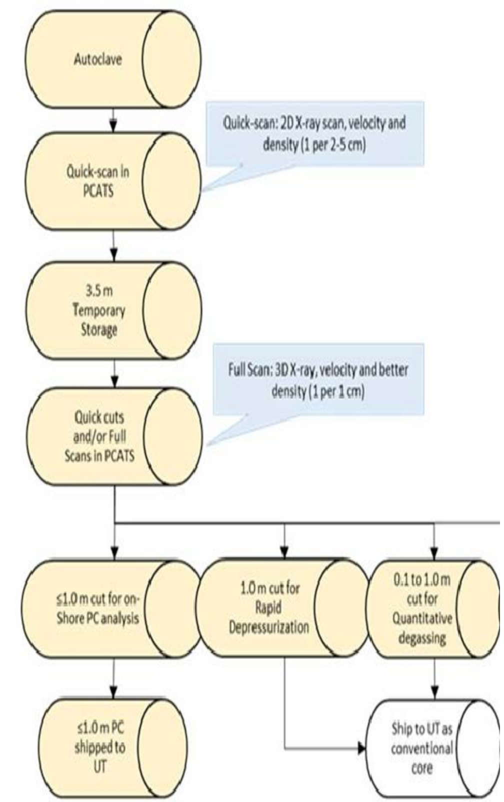
Pressure **C**ore **T**ool w/ **B**allvalve: **P**ressure **C**ore **A**nalysis **T**ool: **P**ressure **C**ore **C**haracterization **T**ools

GoM^2: Expedition-1

Confirm Tool Readiness: Pursue Science Objectives at Green Canyon 955

- **PCTB Development:**
  - Land test (12/2015) → modifications and bench test (06/2016)
  - Lessons learned from evolution of p-coring tools.
- **Science Objectives:**
  - Petroleum System: gas source; reservoir quality; permeability
  - Petrophysics and pore-scale occurrence of GH
  - Reservoir Architecture and lateral heterogeneity?
  - Controls on GH occurrence; top, middle, and bottom





GoM² Expedition-2

IODP Proposal to test end-members of natural systems

State

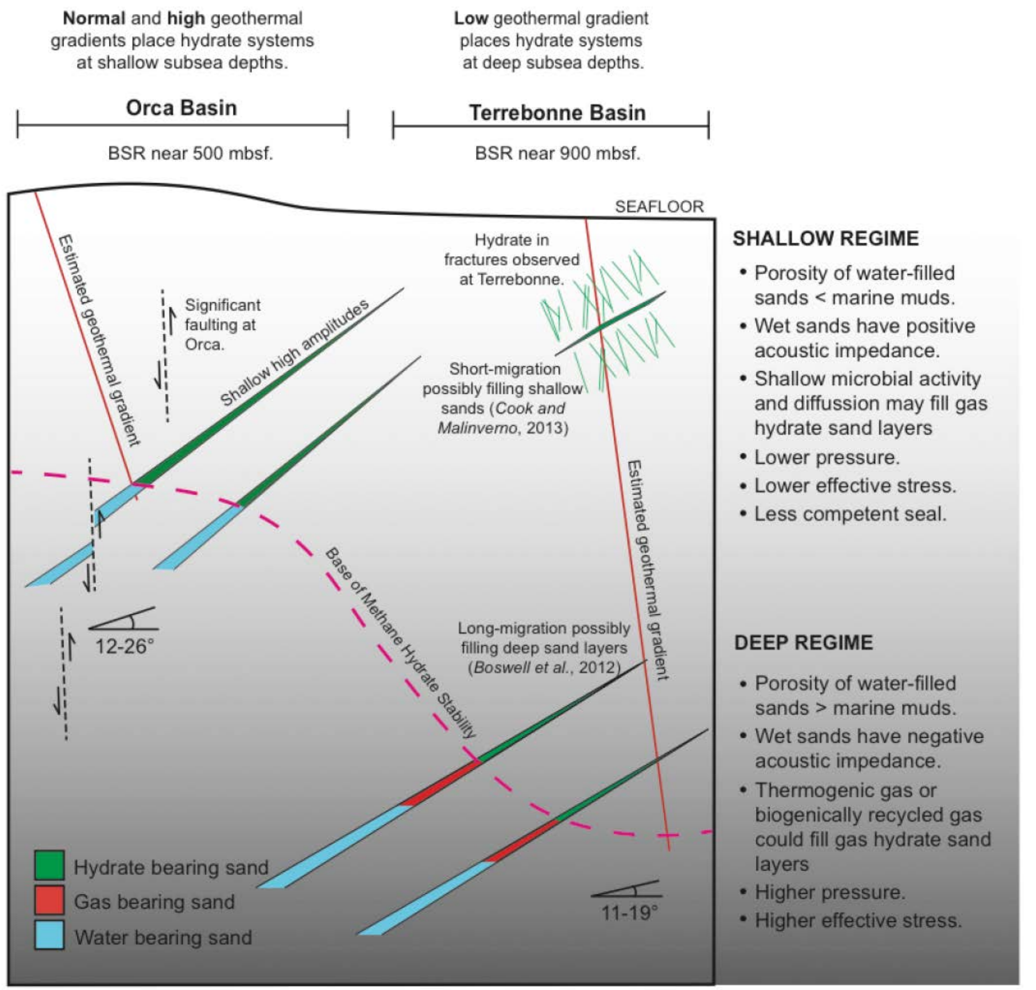
- Characterize methane source: methane habit within pore space.

Genesis

- Infer history, evolution and controls. Biogenic v. thermogenic; short- v. long-migration.
- Thermogenic sourcing long-ignored in GH assessment. Now being seen in many places. Potential for GH below BS_IGHS.

Response to Perturbation

- Via MDT testing. Petrophysics of fluid/gas flows. Critical information only available from cores and relevant to resource, hazard, and environment role issues



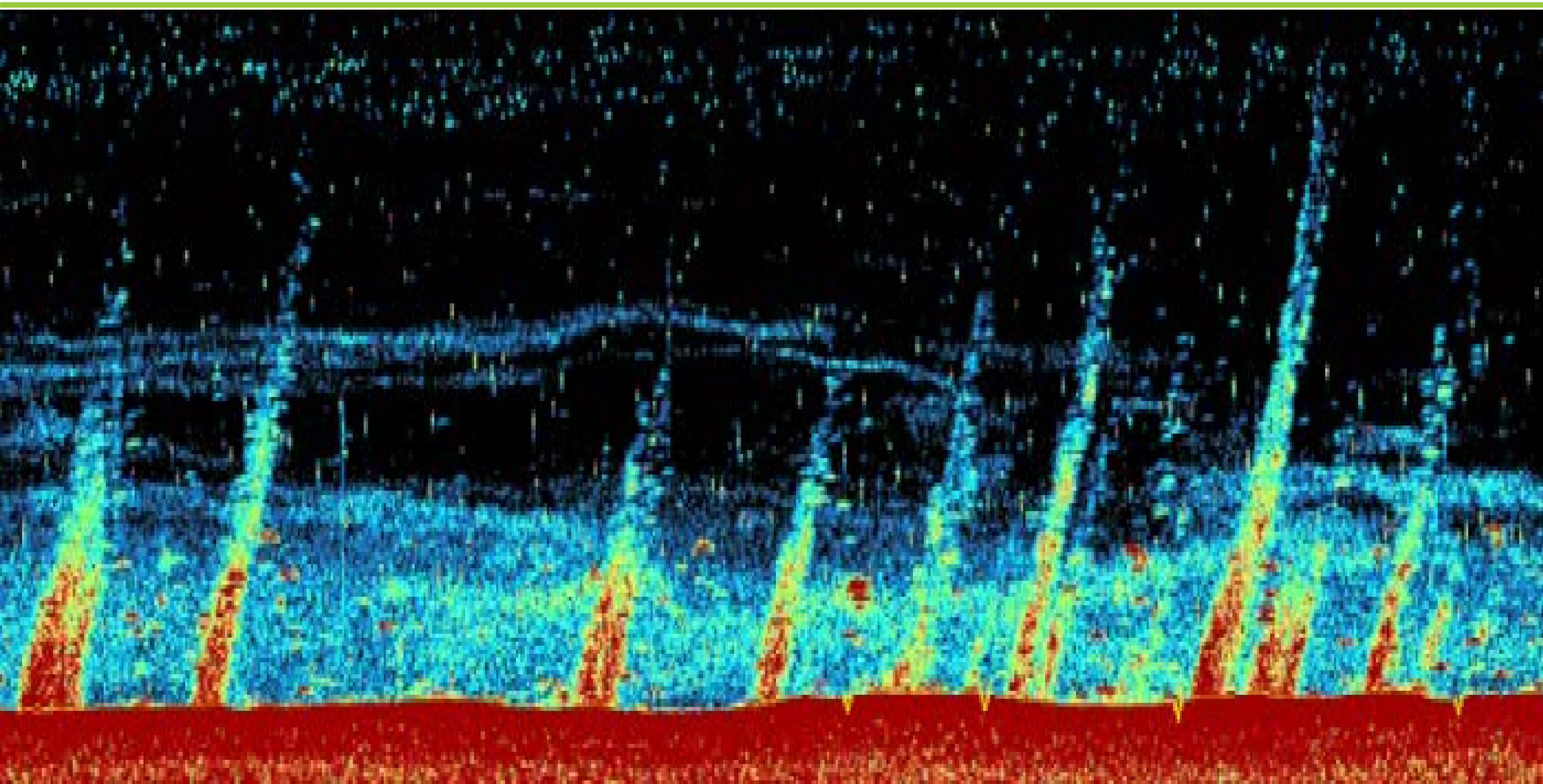
GoM Drilling/Coring: Next Steps

- **Exp-1 (GC955) → March 1 to June 1, 2017**
  - Ship contract and project risk-management structure in final stages
  - G&G (siting control/core points) planning continues
  - Operational planning (mud program, core handling) continues; serious time constraint issues.
  - Logistical planning (permits) continues
- **IODP CPP #887 / Exp-2 (Terrebone-Orca-Mad Dog)**
  - Submitted/Revised Proposal: April/Oct 2015
  - Science Evaluation Panel: Jan and June 2016 (Excellent concept – refinement of well locations needed)
  - EPSP Safety Review: July 2016 (Data quality and well placement issues)
  - Project Team: Data reprocessing/site recommendation revisions (Jan 2017)
  - 2nd EPSP Safety Review & JR Facilities Board: TBD

Proponents

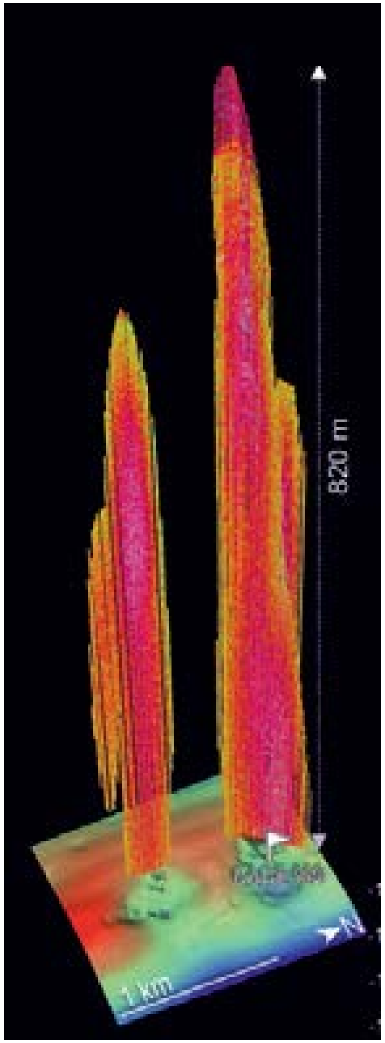
- *P. Flemings (UT-Austin)*
- *T. Collett (USGS)*
- *R. Colwell (Oregon St.)*
- *A. Cook (Ohio St.)*
- *D. Divins (UNH)*
- *D. Goldberg (LDEO)*
- *G. Guerin (LDEO)*
- *A. Malinverno (LDEO)*
- *D. Sawyer (Ohio St.)*
- *E. Solomon (U. Wash.)*

Gas Hydrates and the Environment



Is CH_4 from Gas Hydrate Relevant?

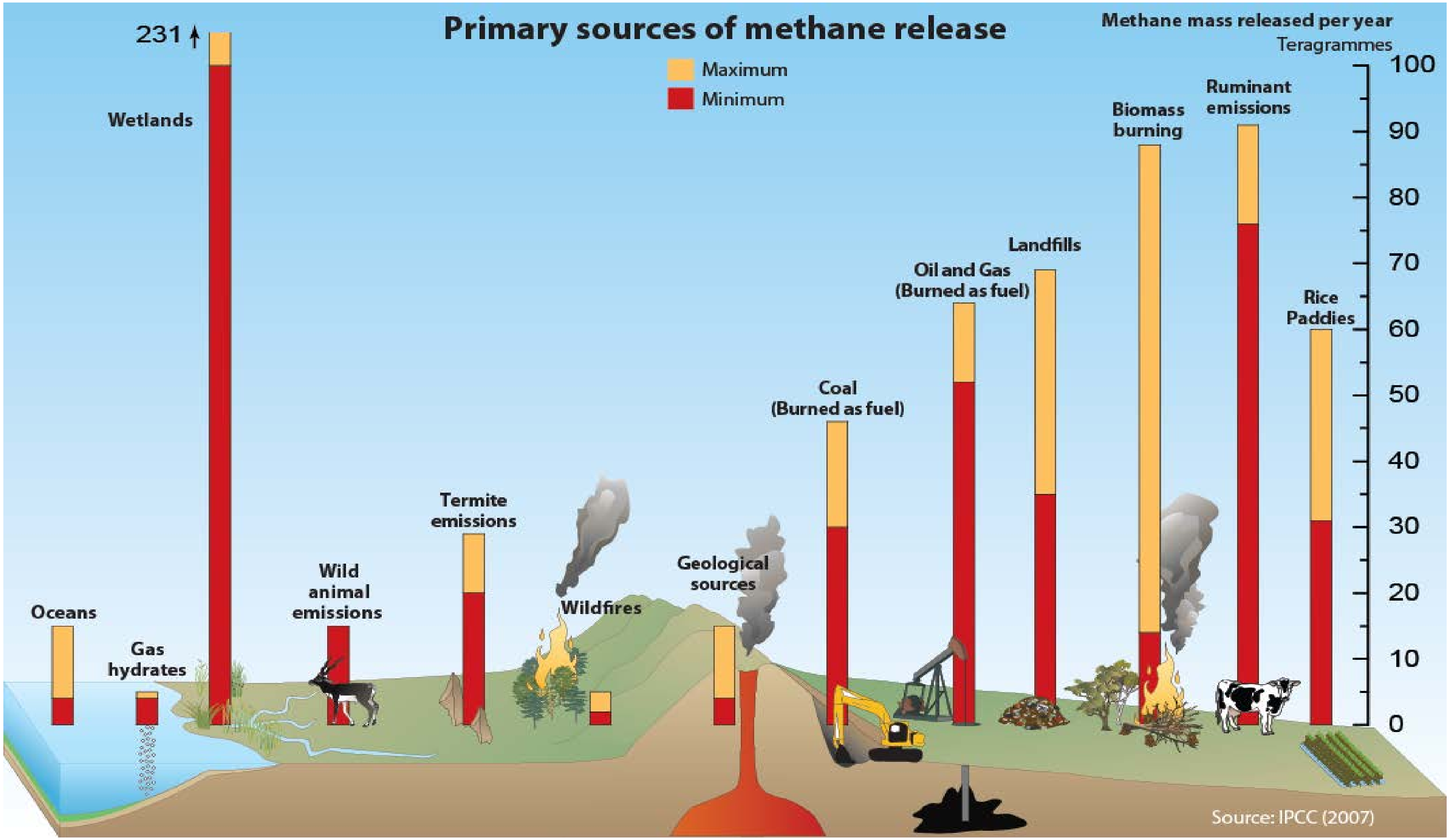
Probably not at present, and possibly not in the foreseeable future: but not definitively known



- CH_4 >> CO_2 per molecule (84x over 20 yrs: 25x over 100 yrs).
- CO_2 >>> CH_4 in atmosphere (~400 pm CO_2: ~ 1.8 ppm CH_4) →
- CO_2 > CH_4 in terms of radiative forcing
- Annual CH_4 flux to atmosphere is ~500+ Tg/yr: BUT… 130 Tg/y discrepancy between top-down and bottom-up inventories.
- CH_4 increasing 3x faster (150%+ in CH_4; 50% in CO_2 since onset of Industrial Age)
- 5 tg/y assigned to GH NOW (0 is possible, 10 may be possible); yet it is one source that could be linked to changing climate (it likely has in the past)

GH sources 1% of Atms CH_4:

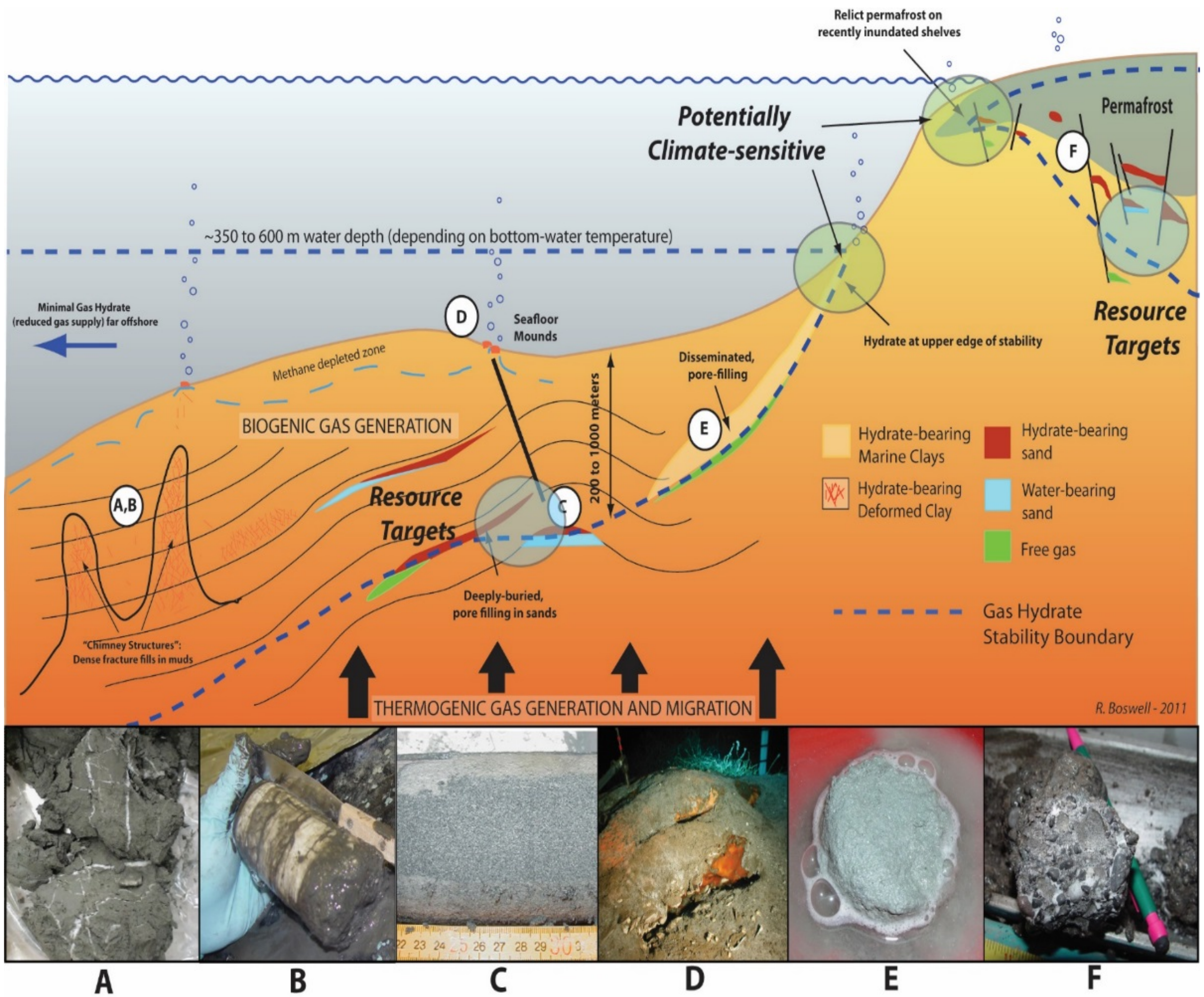
IPCC's (2007): Not well grounded in scientific data



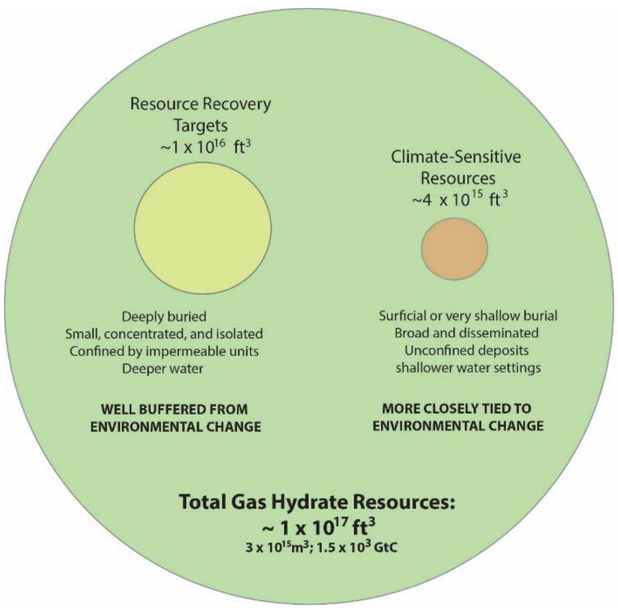
Gas Hydrate – Relevance to Climate

NATIONAL ENERGY TECHNOLOGY LABORATORY

Not all gas hydrate is well coupled to the Ocean-Atmospheric system



- **Deep Marine "Feather edge" (<5%)**
  - constant equilibration to **BWT** (climate, circulation)
- **Arctic shelves (<1%)**
  - Thermal stress due to sea-water inundation



Gas Hydrate – Response to Climate?

Summary

Intriguing Observations

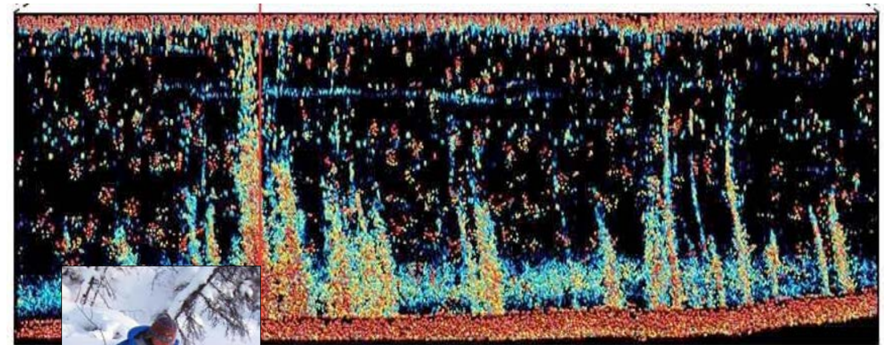
- Extensive venting near landward edge of GHSZ (Svalbard)
- CH_4-saturated seawater on shallow Shelf offshore Siberia
- Venting features on Atlantic shelves
- Active de-gassing onshore arctic

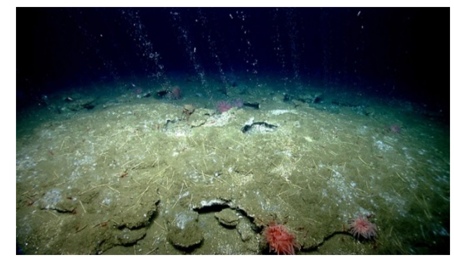
Unanswered Questions

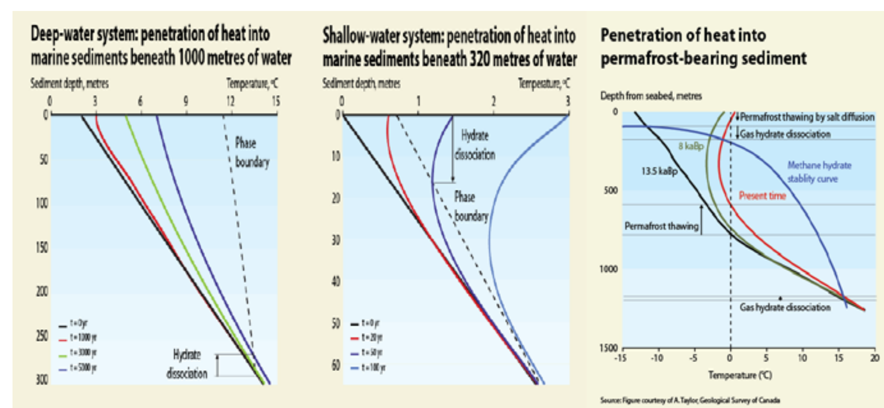
- New or Newly-Discovered?
- What is the source of CH_4?
- Recent warming, post-glacial, natural variability?
- What is the GH inventory in the potentially-impacted areas?
- What perturbation is needed to mobilize CH_4 and what are the rates of the processes?
- Role of natural sinks?
- What impacts could GH-derived CH_4 have (atmosphere and ocean)?

GH–derived CH_4 is likely a secondary concern to CO_2 (and to other CH_4 sources) in GCC, both currently and in the near future. But proof is complex…

Ongoing projects are accessing large external resources to assess dynamics in climate-sensitive areas

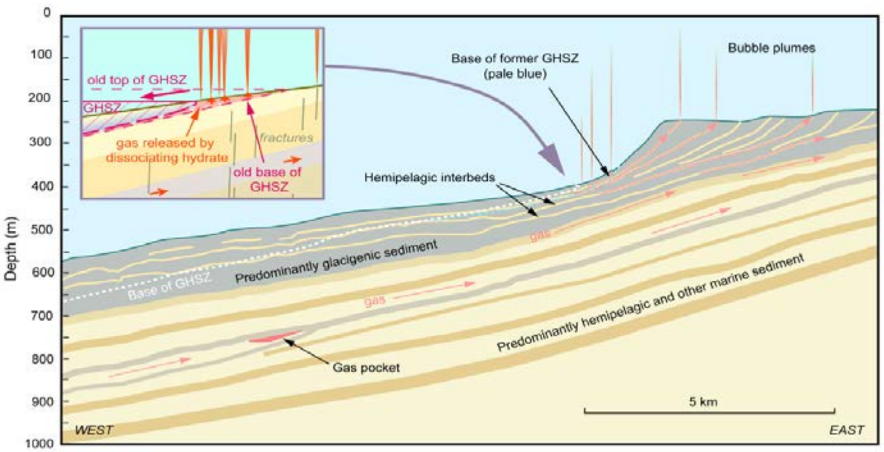






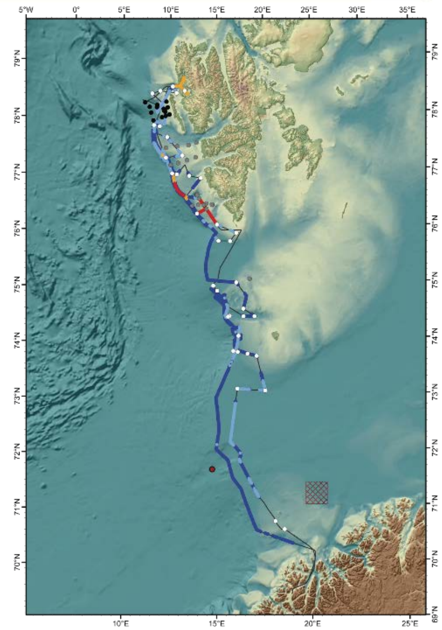
North Atlantic/Svalbard

Numerous Observed Seeps: What is the cause?



- **Westbrook et al. (2008):** attributed numerous observed seeps to GH response to recent warming
- **Reagan et al. (2011):** GH dissociation could resemble what has been observed
- **Thatcher et al. (2013):** likely deeper, active of migrating methane that interacts with the GHSZ

- **Extensive field studies conducted at CAGE (U. Tromso; Norway) and MARUM (U. Bremen; Germany).**
  - DOE support to UNH and Oregon State → 3 CAGE and 2 MARUM cruises
  - Model development at OSU: Instr. for atmos. CH_4 measurement
  - MeBO coring through upper limit of GHSZ



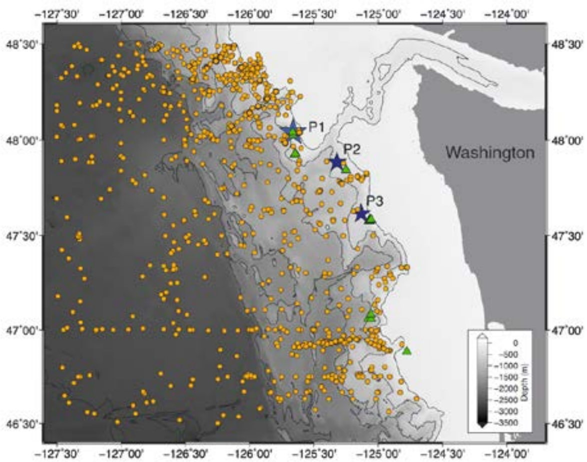
- **Emerging consensus that**
  - seepage is much older than recent: >1000 yrs
  - sources are commonly deeper than hydrate and migration is influenced by a variety of factors.

Cascadia Margin

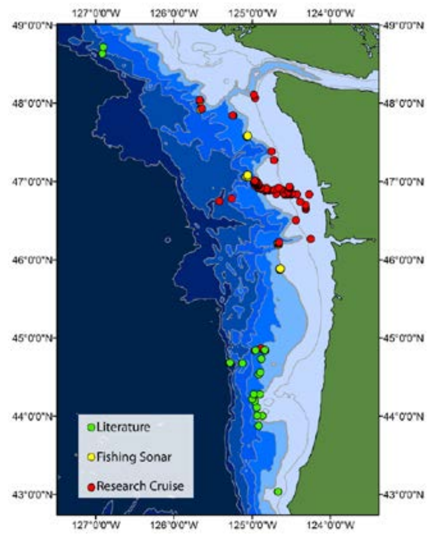
U. Washington

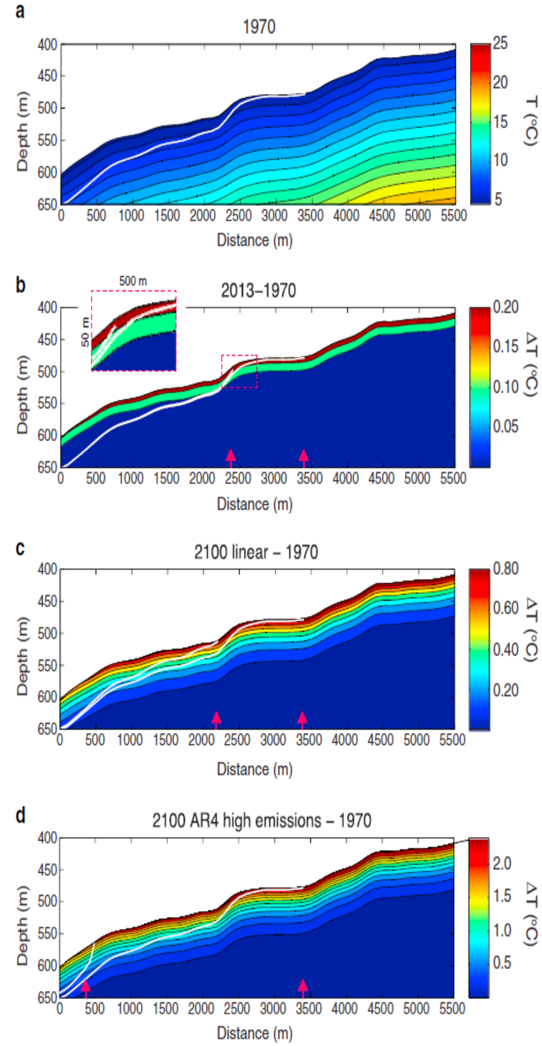
Hautala, et al. 2014

- **Current Status**
  - 0.3° C T increase since 1970.
  - = 1 km withdrawal of BGHS.
  - Another 0.3-2 km retreat possible through 2100.



- **GH system response**
  - Geographic correlation between seeps and BGHS
  - 2014 survey of active plumes from the area of GHS withdrawal
  - 2016 survey of 400 additional seeps
  - PW freshening common; Noble gas ratios at seeps just above BGHS show no compelling indication of GH
  - Likely the seeps are long-lived and driven by mineral dehydrate/submarine GW discharge (not GH destabilization)

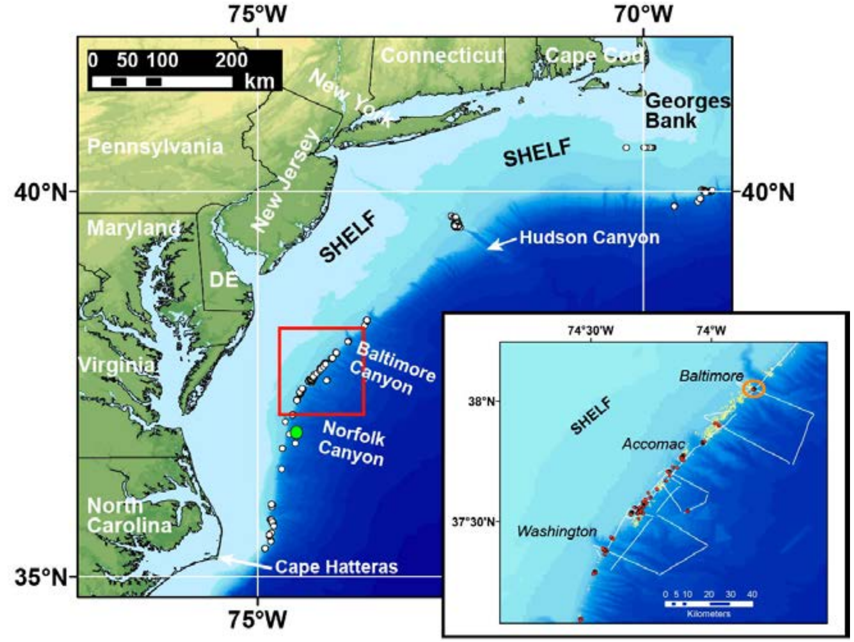


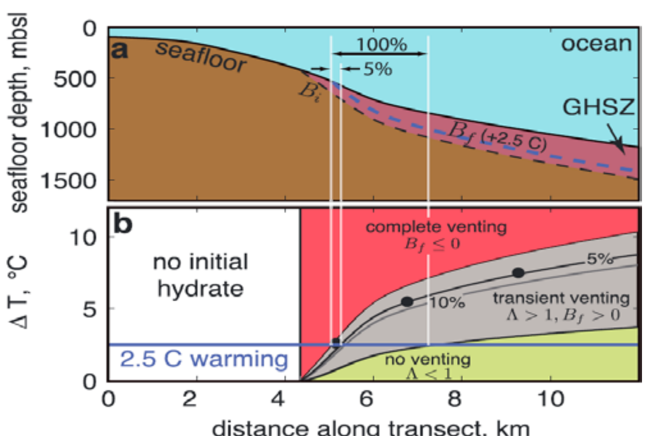


Atlantic Margin

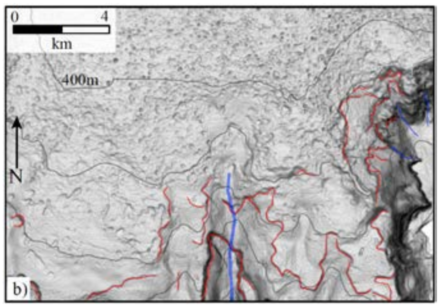
USGS-led with numerous collaborators

- 2011-2013 NOAA data identified 570 seeps on UNAM.
- Two 2015 USGS cruises gathered chemical/geophysical data
- Numerous CH_4 seeps observed in GHSZ
- Is methane injection limited to the retreating edge, or does a wider swath engage?
- Ocean/atmospheric chemistry implications?

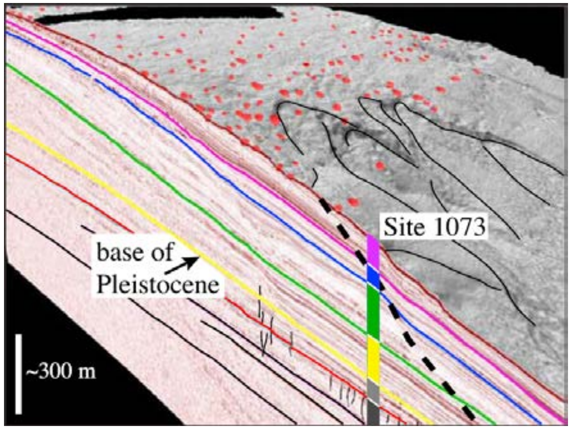




Darnell et al., 2015



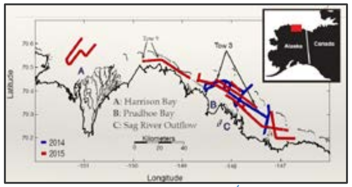
Brothers et al., 2014

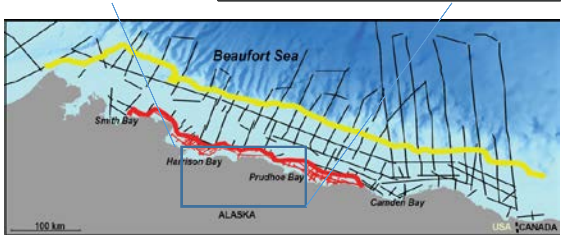


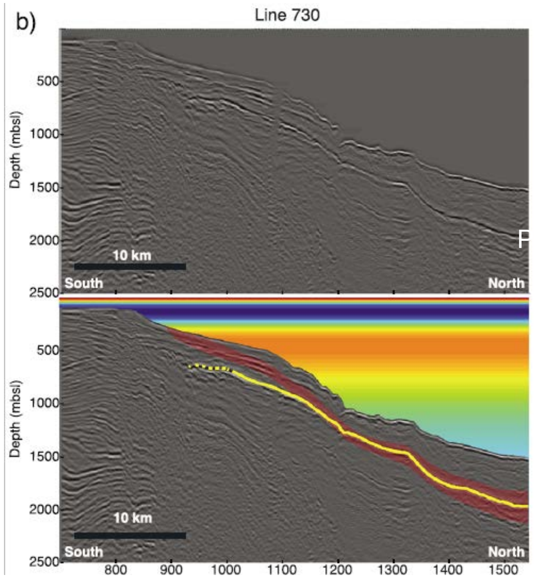
Beaufort Shelf and Slope

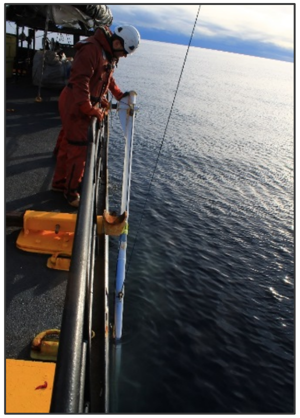
USGS – SMU - Scripps

- **Relict Permafrost:**
  - USGS seismic studies suggest very limited extent.
  - UCSD EM surveys agree, indicate greater heterogeneity, complex interactions with river outflows; lack of GH trapped beneath remaining PF
- **Deep Marine Gas Hydrate**
  - Imaged BGHS is much deeper than calculated BGHS due to current conditions
  - 2016 Heat Flow survey w/ 97% success rate
  - Thermal Cond. as expected, but heat flow incredibly high (>100 mW/m^2)
  - Widespread hydrate dissociation along the margin and along deeply into the



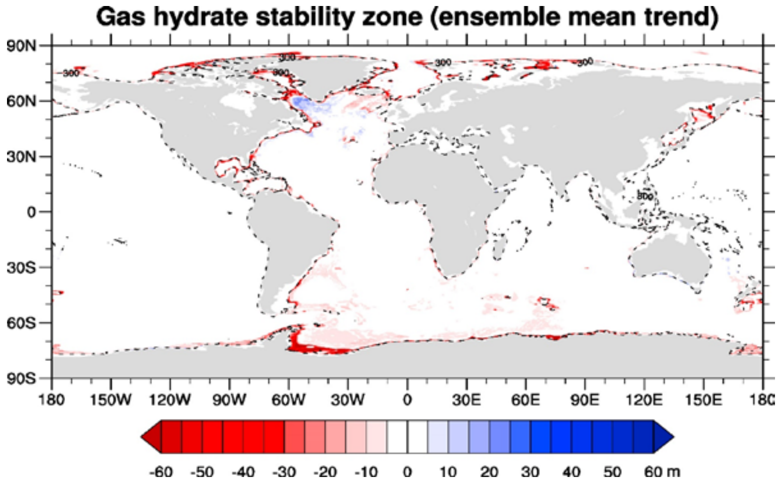




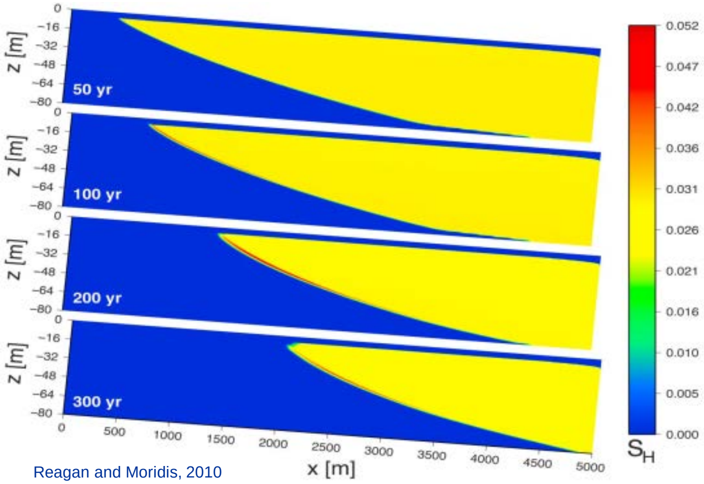


Modeling

- **Increasingly, models incorporate**
  - Proper characterization of sinks/traps in sediment, in water, and in air
  - GH thermodynamics
  - Oceanographic regional variation
- **Data needs**
  - GH inventories in relevant settings
  - Observation and attribution of CH_4 release
  - Time-series observation of GH systems
- **Deep marine: Impact appears minor in comparison to other CH4 sources**
- **Permafrost-associated: Despite easier route, limited in-place GH volumes means limited impact**



Kretschmer et al., 2015

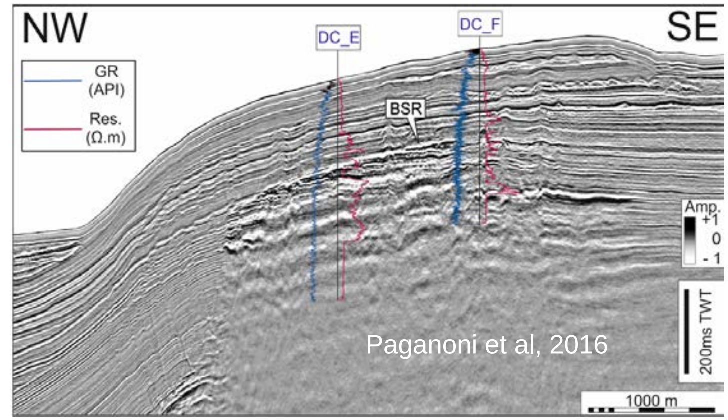


Reagan and Moridis, 2010

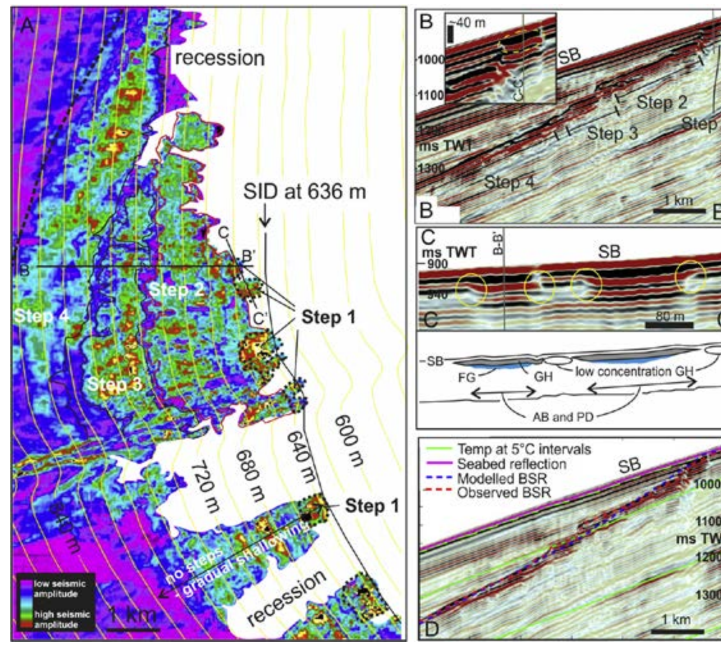
Some Selected Recent Developments

Gas Hydrate in the Natural Environment

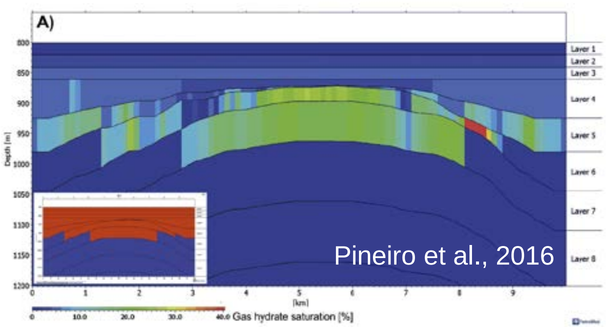
- **Ice Shelves**
  - Formation and removal over climate cycles creates cyclic establishment of shallow marine GHSZs
- **Non-microbial gas**
  - Many prior assessments assume that virtually all GH CH_4 is locally-sourced and biogenic.
  - Thermogenic sources now being interpreted more commonly. dBSRs: $BS_{II}GHS$
  - Abiotic methane over slow spreading ridges
- **Petroleum Systems Modeling**
  - Schlumberger PetroMod for basin-scale modeling of evolution of GH systems with time
- **Seafloor Stability**
  - GH role in slow creep on continental slopes (NZ)



Paganoni et al, 2016



Davies et al., 2015



Pineiro et al., 2016

THANK YOU