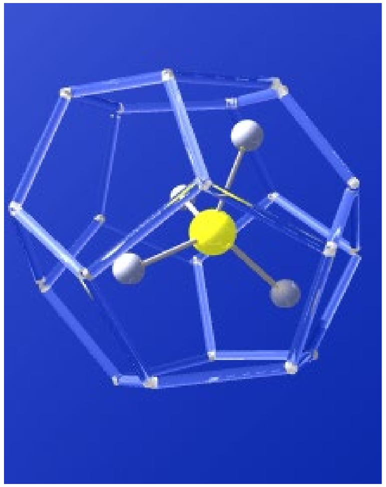
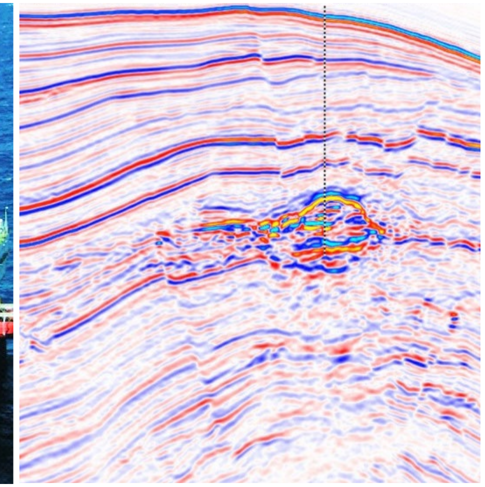



# Gas Hydrates

---

# International R&D Activities


**Timothy S. Collett**

**U.S. Geological Survey**


*Methane Hydrate Advisory Committee Meeting*

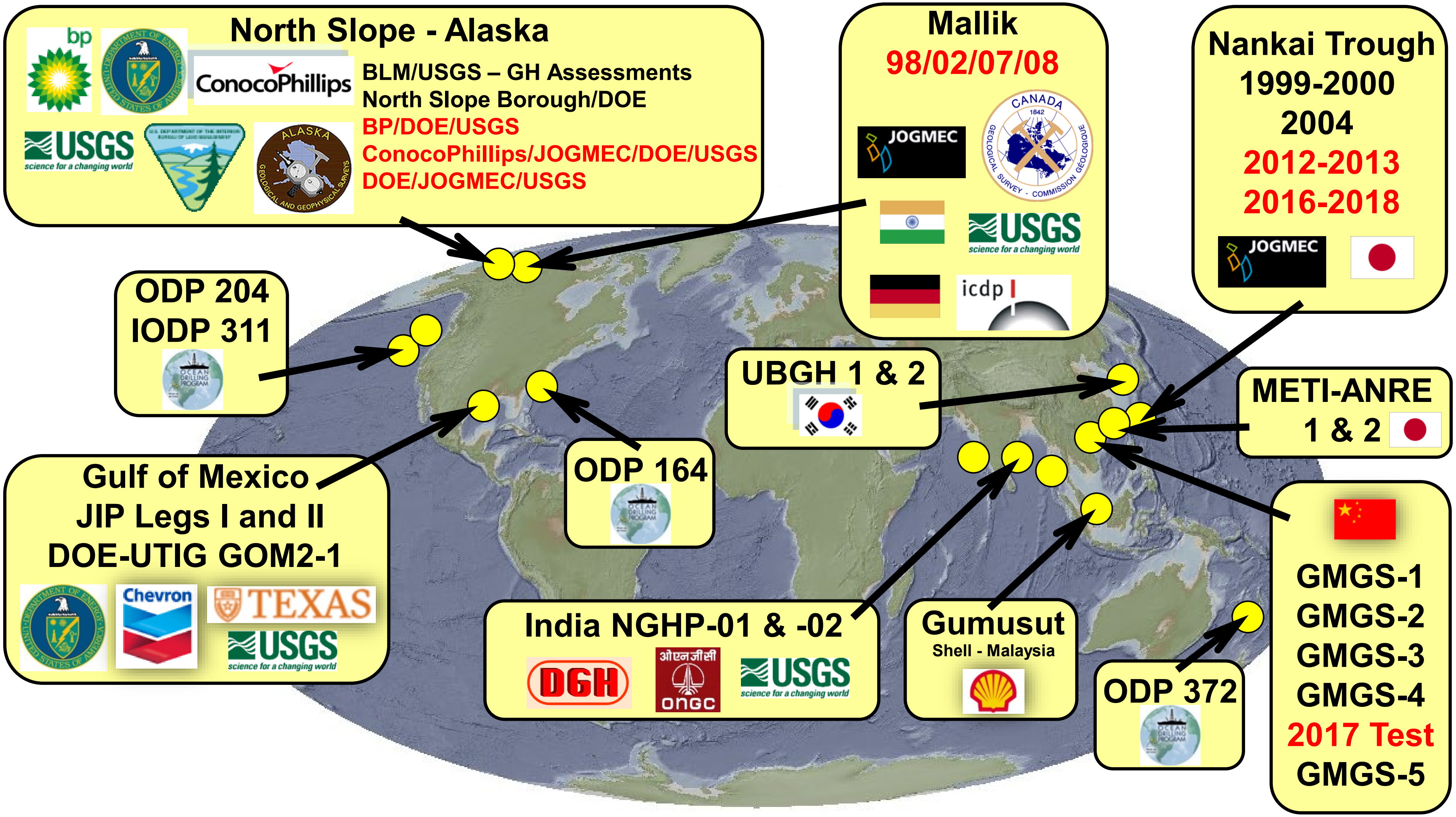
*October 18, 2018*

USGS
science for a changing world

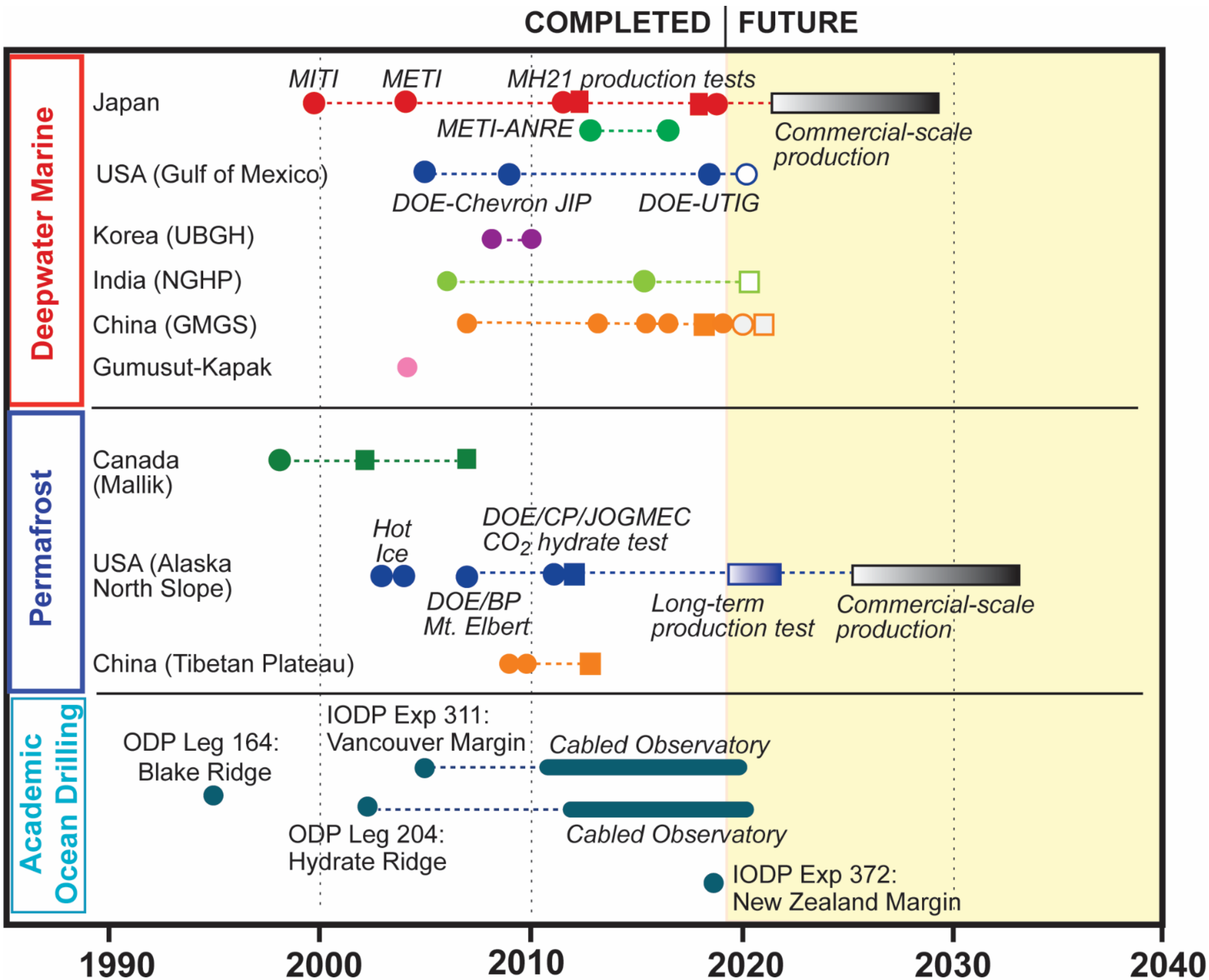
# Briefing Outline

1. Gas hydrate scientific and industry drilling
2. Gas hydrate resource to reserves?
3. International gas hydrate projects
   - Japan
   - China
   - India
   - Korea
   - Other
4. Additional international gas hydrate projects
5. Gas hydrate production testing and modeling
6. Integration of gas hydrate reservoir data
7. Summary

# Gas Hydrate Scientific and Industry Drilling

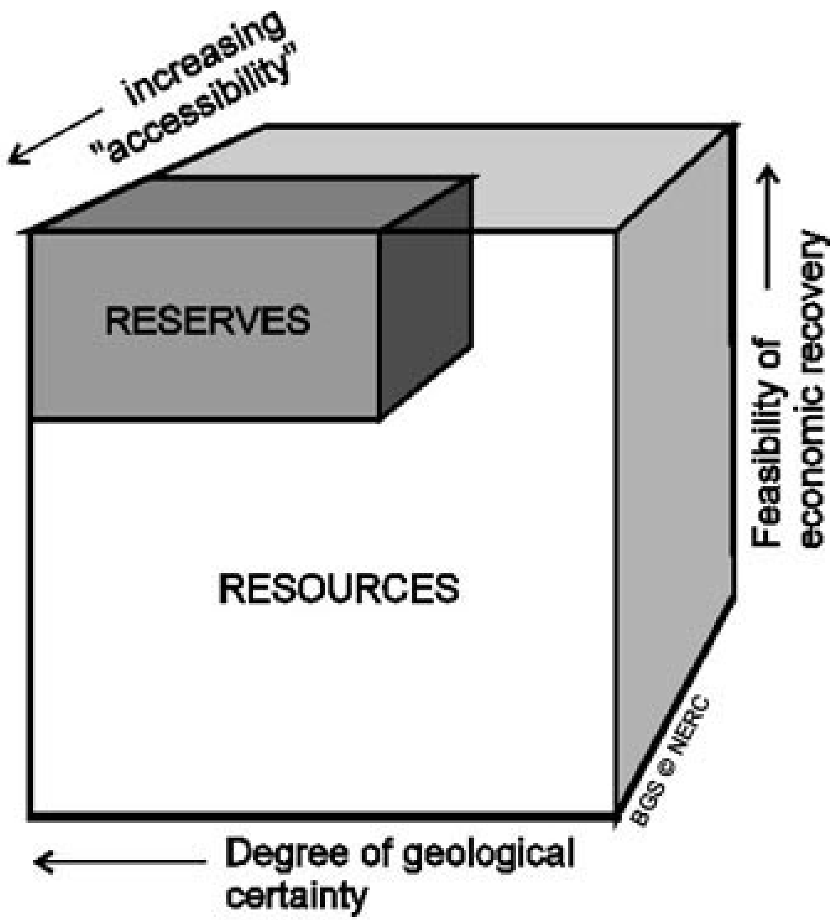


# Gas Hydrate Scientific and Industry Drilling



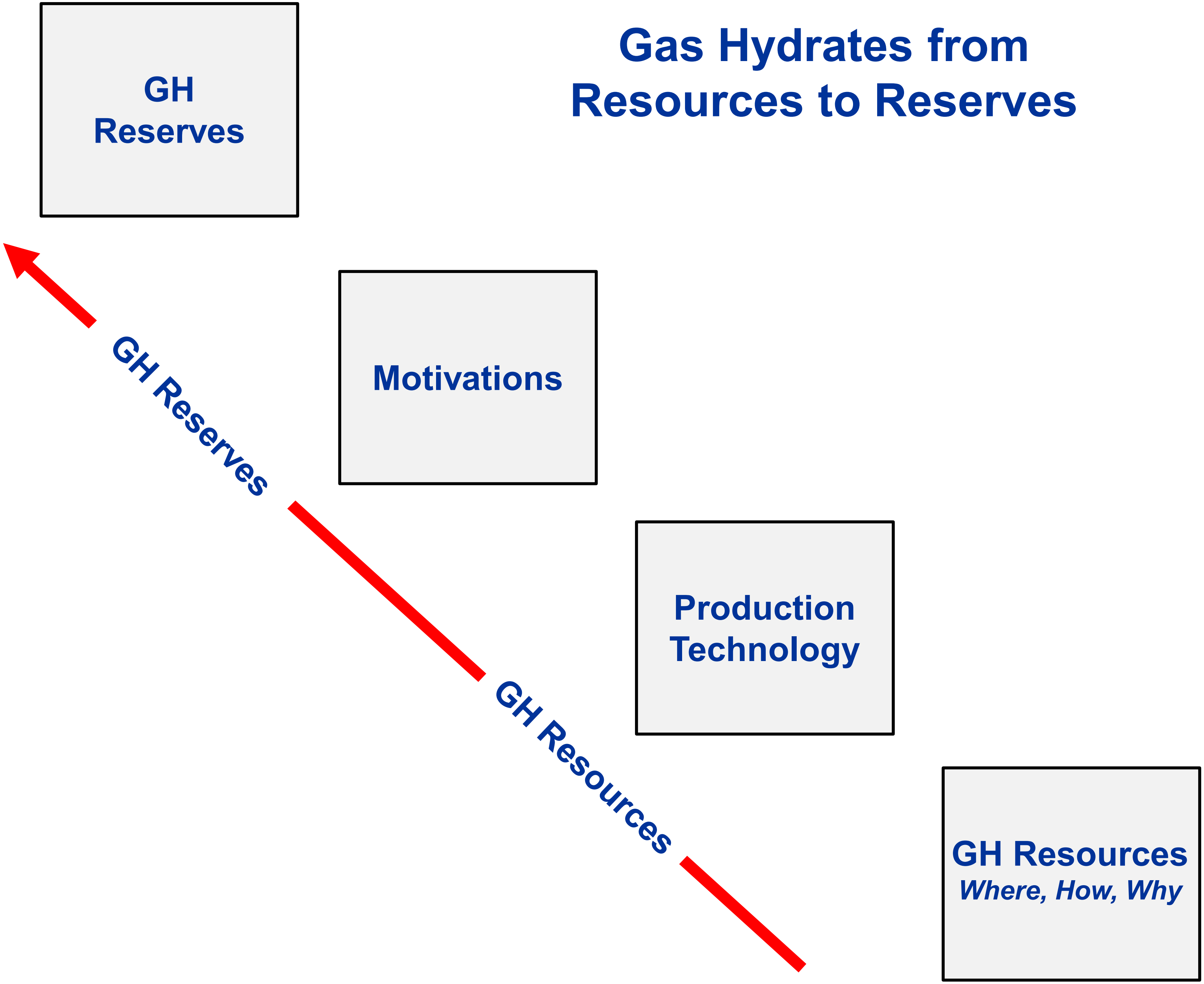
# Gas Hydrate Resource Assessments

## *Resources vs. Reserves*




*In this presentation the term **Resource** refers to the total amount of gas that exists, which is assumed to be the same as the **In Place** volume. This includes gas that is both discovered and undiscovered, economically recoverable or not economically recoverable.*

*Conversely, **Reserves** in this case are gas deposits that are known to exist with a reasonable level of certainty. These reserves are also recoverable economically with the technologies that already exist.*


Gas Hydrates from
Resources to Reserves
GH
Reserves
Motivations
Production
Technology
GH Resources
Where, How, Why
GH Reserves
GH Resources

# Gas Hydrates from Resources to Reserves

GH Reserves

GH Resources

**GH Reserves**

**Motivations**

**Production Technology**

**GH Resources**
*Where, How, Why*

**Development Scenarios**

**Assumed similar to the evolution of other unconventional resources – possibly not**

**Japan Nankai Trough Model: Standalone production with limited to no infrastructure**

**USA Gulf of Mexico (mature development area): Make use of existing infrastructure and backfill declining conventional production**

**Local Market Drivers: Example, Alaska North Slope fuel gas needs and conventional oil reservoir pressure maintenance**

# Gas Hydrates from Resources to Reserves

GH Reserves

GH
Reserves

Motivations

Production
Technology

GH Resources

GH Resources
*Where, How, Why*

**Economics**

**Limited economic forecasting has shown commercialization of GH is possible at about twice the cost of conventional gas production under similar conditions (as bench marked at $3.00 US/MBtu)**

***US: Henry H. price $2.00-4.00 US/MBtu; Residential price $9.00-18.00 US/MBtu***
***Net import 2017 3.0 tcf (11% of consumption)***

***Japan: LNG landed price $7.60 US/MBtu; Residential gas price $43.05 US/MBtu***
***Last 10 year, increase in consumption from 3.0 to 4.7 tcf of gas per year***

***India: LNG landed price $7.45 US/MBtu***
***Last 10 year, increase in consumption from 2.5 to 4.5 tcf of gas per year***
***80% of India's energy is imported***

# Gas Hydrates from Resources to Reserves

GH Reserves

GH Resources

**GH Reserves**

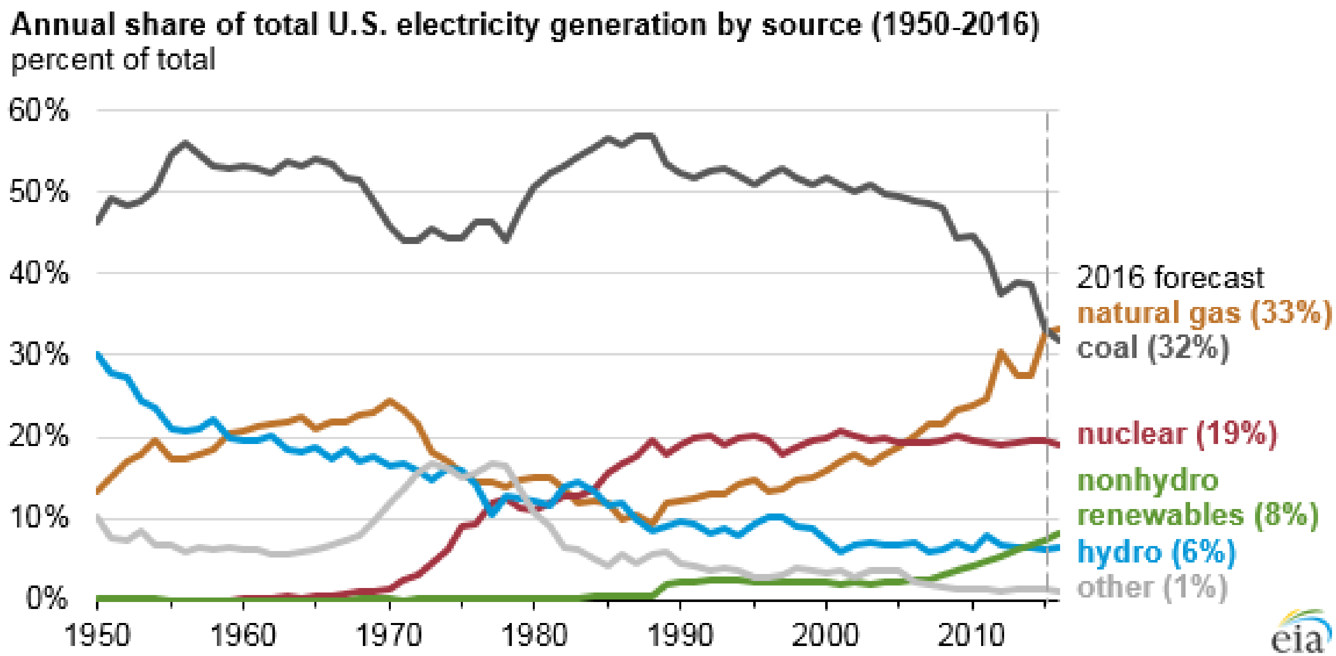
**Motivations**

**Production Technology**

**GH Resources**
***Where, How, Why***

**<u>Economics</u>**

**Global Competition: Emergence of other gas and energy resources**




***Coal being Displaced by Gas and Renewables***

# Gas Hydrates from Resources to Reserves

GH Resources → GH Reserves

**GH Reserves**

**Motivations**

**Production Technology**

**GH Resources**
***Where, How, Why***

**<u>Economics</u>**

**In most cases, unknown resource volume and unproven production technology**

**Field Tests**

– Onshore 60 mscf/d

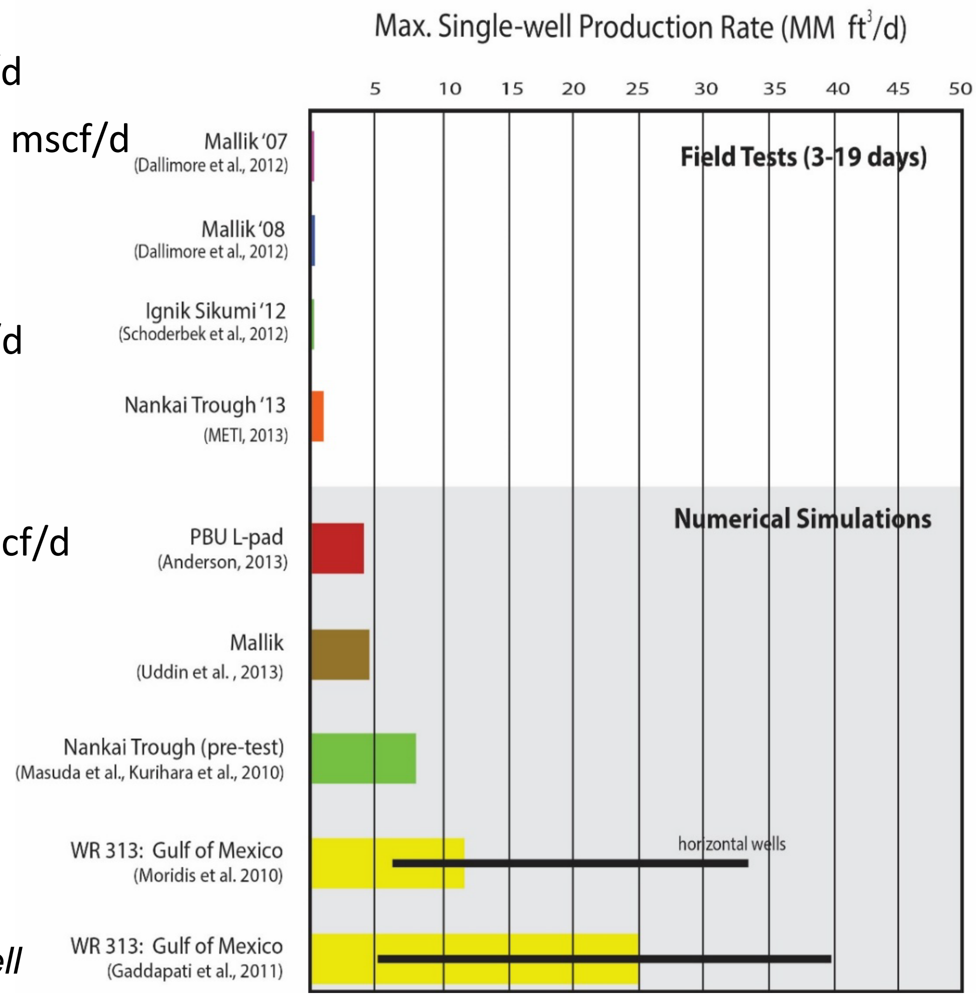
– Offshore 0.7 – 1.2 mscf/d

**Simulation - Onshore**

– Onshore: 4 mmscf/d

**Simulation - Offshore**

– Offshore: 40 mmscf/d




*Modified from Boswell*

# Gas Hydrates from Resources to Reserves

GH Reserves

GH Resources

GH Reserves

Motivations

Production Technology

GH Resources
*Where, How, Why*

**Economics**

**Occurrence in deep water and Arctic environments – high cost, large operators, return on investment challenging (competition)**

| Resource | Production Rate mscf/day (x1,000) | Well Cost USD (x1,000) |
|---|---|---|
| Coalbed Methane | 500 | 1,000 |
| Shale Gas Barnett | 500-2,000 | 3,000-4,000 |
| Shale Gas Woodford | 500-3,500 | 4,000-7,000 |
| Conventional Alaska NS | 7,500 | 5,000-15,000 |
| Conventional Deepwater | | |
| -GOM 1,500-5,000 ft | 90,000 | >50,000 |
| -GOM 5,000-7,500 ft | 100,000 | >100,000 |
| Gas Hydrate Modeling | | |
| -Alaska NS 5-6 °C | 700 | 5,000-8,000 |
| -Alaska NS 10-12 °C | 5,000 | 5,000-8,000 |
| Gas Hydrate Modeling | | |
| -Offshore | 5,000-15,000 | >20,000 |

***Need to reduce development cost or increase production rate.***

# Gas Hydrates from Resources to Reserves

GH Reserves ↑

GH Resources

**GH Reserves**

**Motivations**

**Production Technology**

**GH Resources**
*Where, How, Why*

**Special National Interest and Local Drivers**

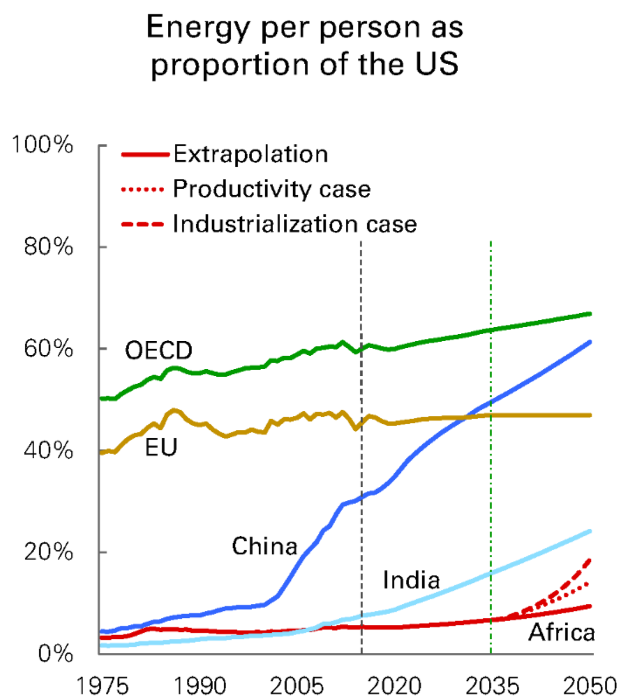
**Impact taxation & climate change policies (royalties, Carbon-tax)**

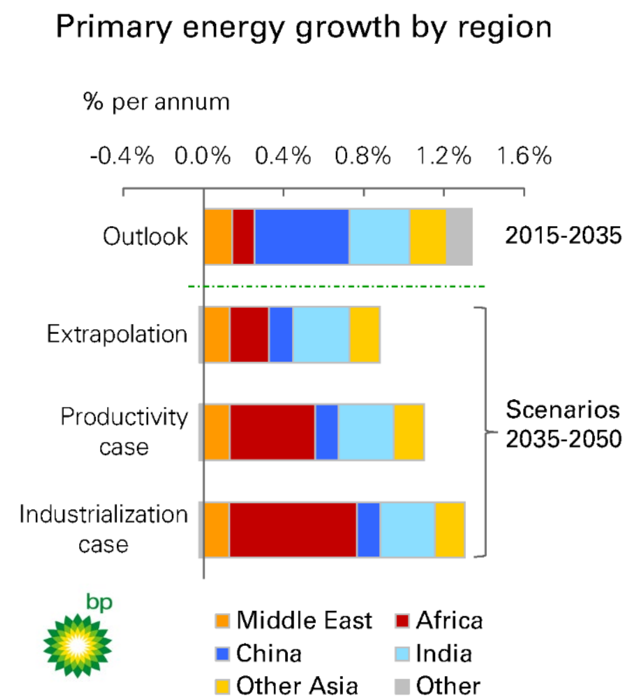
**Establishment of government and industry partnerships**

**Development of purpose built GH development systems**

**Alaska North Slope fuel gas & pressure maintenance**

**Availability of other energy resources (market distance/stability)**



# Gas Hydrates from Resources to Reserves

GH Reserves

GH Resources

**GH Reserves**

**Motivations**

**Production Technology**

**GH Resources**
*Where, How, Why*

**Summary of Challenges**

- In support of gas hydrate production modeling and testing efforts, continue to develop pressure coring equipment and pressure core analysis capabilities.
- "Scientific" production/mechanical testing designed to maximize scientific insight.
- Testing needs to include advance monitor programs to identify and assess mechanical/environmental response/impacts.
- Further development and calibration of gas hydrate production and mechanical models with results from field testing and pressure cores.
- "Demonstration" production/mechanical tests designed to maximize rates and establish deliverability.

***Without special "motivations" will need to reduce development and production cost and/or increase production rates based on current production-mechanical modeling results.***

# Japan

Summary of R&D: Alaska and Nankai: 1995-2018

1998: First Mallik Well

1999: Nankai Discovery Well

2002: Mallik Thermal Production Test

2004: Nankai Exploration Program

2007: Mallik Depressurization Test #1

2008: Mallik Depressurization Test #2

2008: Nankai Trough Resource Assessment

2008: Exploration Approach Published

2012: Collaboration on Ignik Sikumi Program

2012: Preparatory drilling for Nankai Test

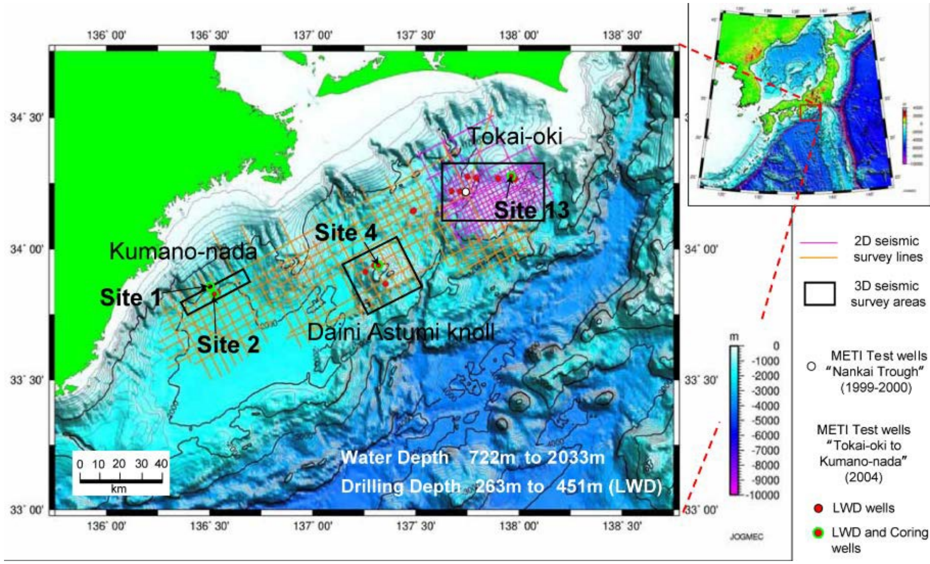
2013: First Nankai Production Test

2014-2018: Production Test Evaluation in Alaska

2016: Preparatory drilling for second Nankai Test

2017: Second Nankai Production Test

2018: Nankai Test Site Characterization




# Japan

2013 and 2017 Production Tests in Nankai Trough

## 2013 Field Experiment

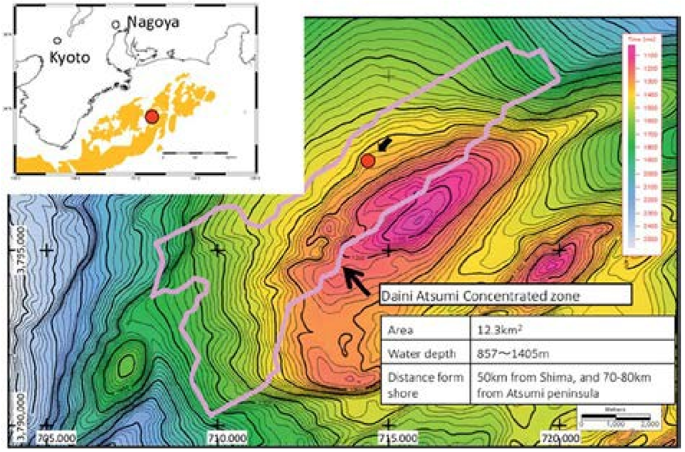
- Demonstration of technical recoverability
- 2 weeks planned: 1 week achieved
- Stable production obtained, but sand production issue

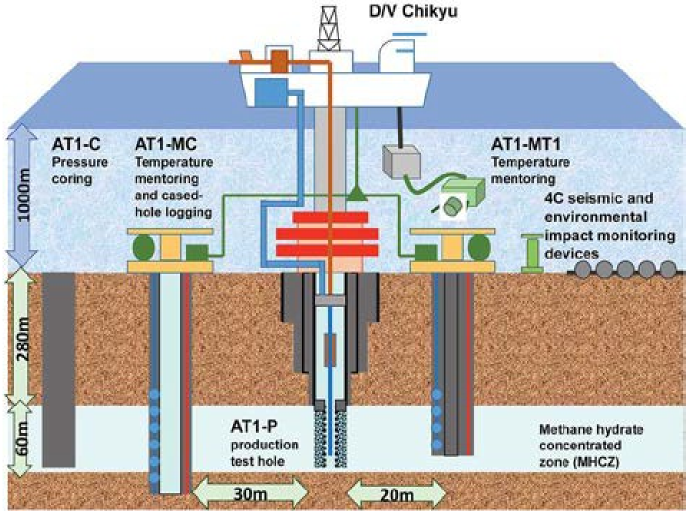
## 2017 Test

- Goal #1: Solve sand production issue
- Goal #2: Demonstrate increased rates over longer flow periods

Outcome: per METI: "As a result of this test, while one of the two production wells suffered the sand-intrusion problem, ANRE achieved a certain level of success from the second well, in which no problems occurred. However, ANRE could not clearly confirm an increase in the production rates at either of the wells, leaving challenges in establishing gas production technologies unsolved."

- Well #1: Approximately 35,000 $m^3$ in total in 12 days
- Well #2: Approximately 200,000 $m^3$ in total in 24 days



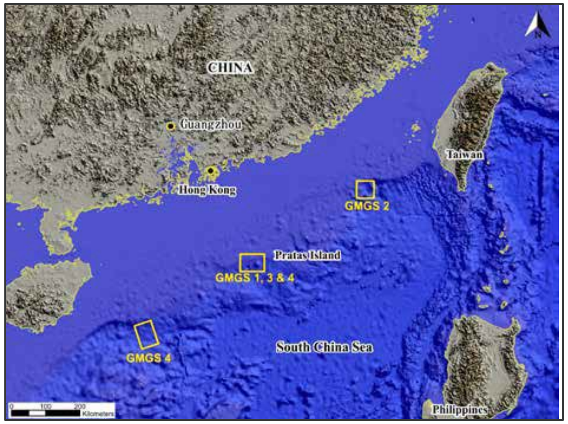

*Fujii et al., 2015. Konno et al., 2017*

# China

Very Active Program

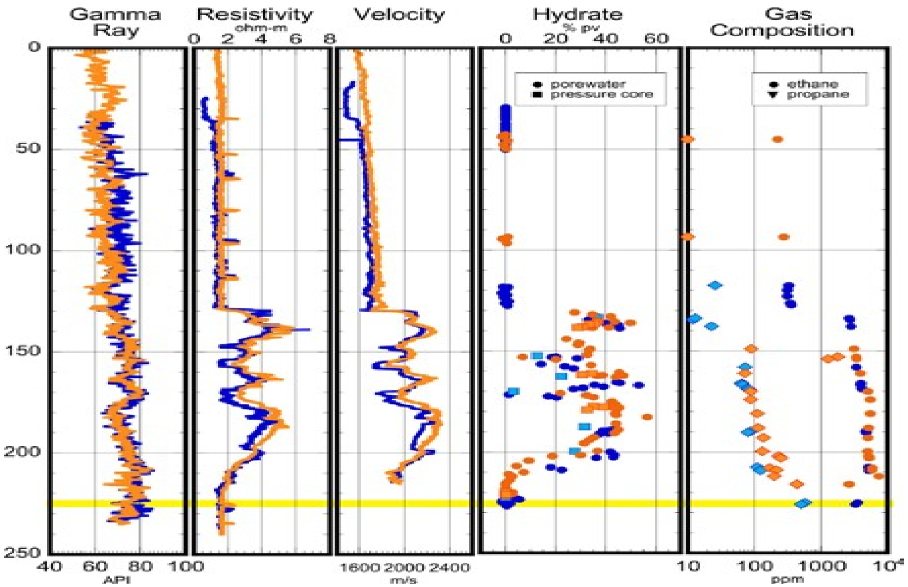
### GMGS-1 (2007), GMGS-2 (2013), GMGS-3 (2015) and GMGS-4 (2016)

- Primary focus is Pearl River mouth basin (Shenhu area)
- GMGS-4 added new area to the south (Xisha area); 58 days/ 21 sites
- Reservoirs appear to be clay-rich silt with $S_{gh.}$ up to 40% (anomalous)
- Lateral heterogeneity over short distances.
- 20-90 m thick at BGHS: Some Structure II GH




### Onshore Testing Underway

- Permafrost-associated: Thermogenic; Fractured-rock reservoirs
- Tibetan Plateau (Qilian) and Manchuria (Mohe)




*Yang et al., FITI, 2017*

# China

2017 Production Test

**Bluewhale 1 & 2**
CPOE Operator
CNPC Client
First deployment – SCS GH testing

Test site in South China Sea
Test zone ~250 mbsf
WD = 1,266 m

Ministry of Land and Resources
60 days → 309,000 $m^3$

The highest output in one day is 35,000 $m^3$ (1.2 mmcf/day), and the average output a day is about 16,000 $m^3$ /day (0.6 mmcf/day)

China Geological Survey
80 billion metric tons of reserves

New gas hydrate center CNOOC-Beijing

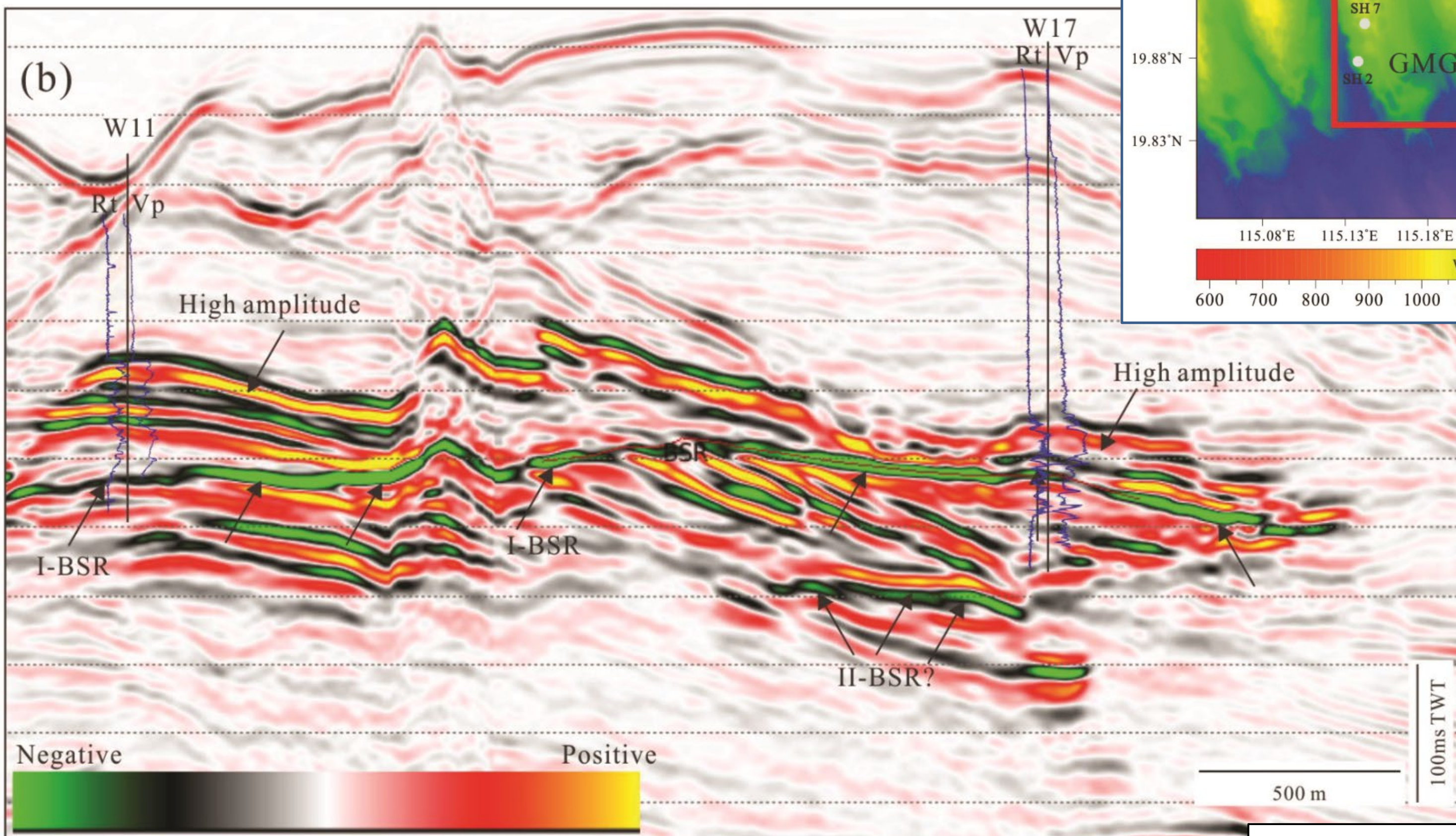
GMGS-5 (2018) geoscience expedition

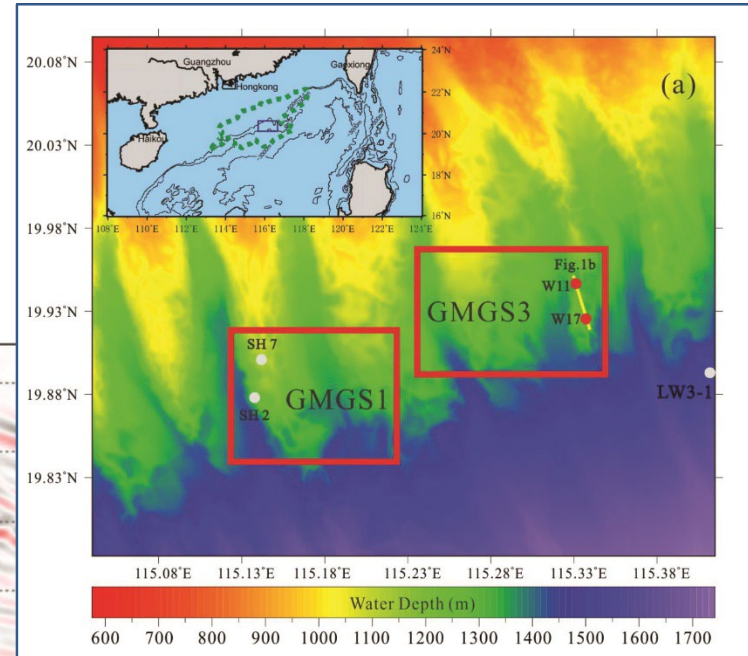
*GMGS-6 (2019) geoscience expedition?*

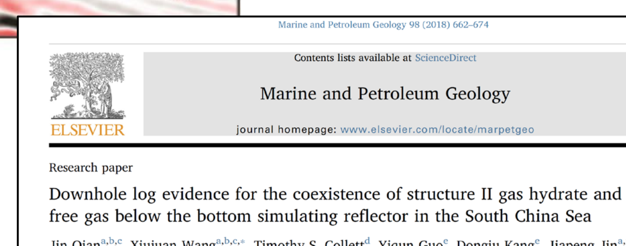
*2020 second production test ?*

# GMGS-3 (2015) W11 & W17

- Seismic profile through Sites W11 to W17
- Resistivity (Rt) and P-wave velocity (Vp) logs



Marine and Petroleum Geology 98 (2018) 662–674
Contents lists available at ScienceDirect
Marine and Petroleum Geology
journal homepage: www.elsevier.com/locate/marpetgeo

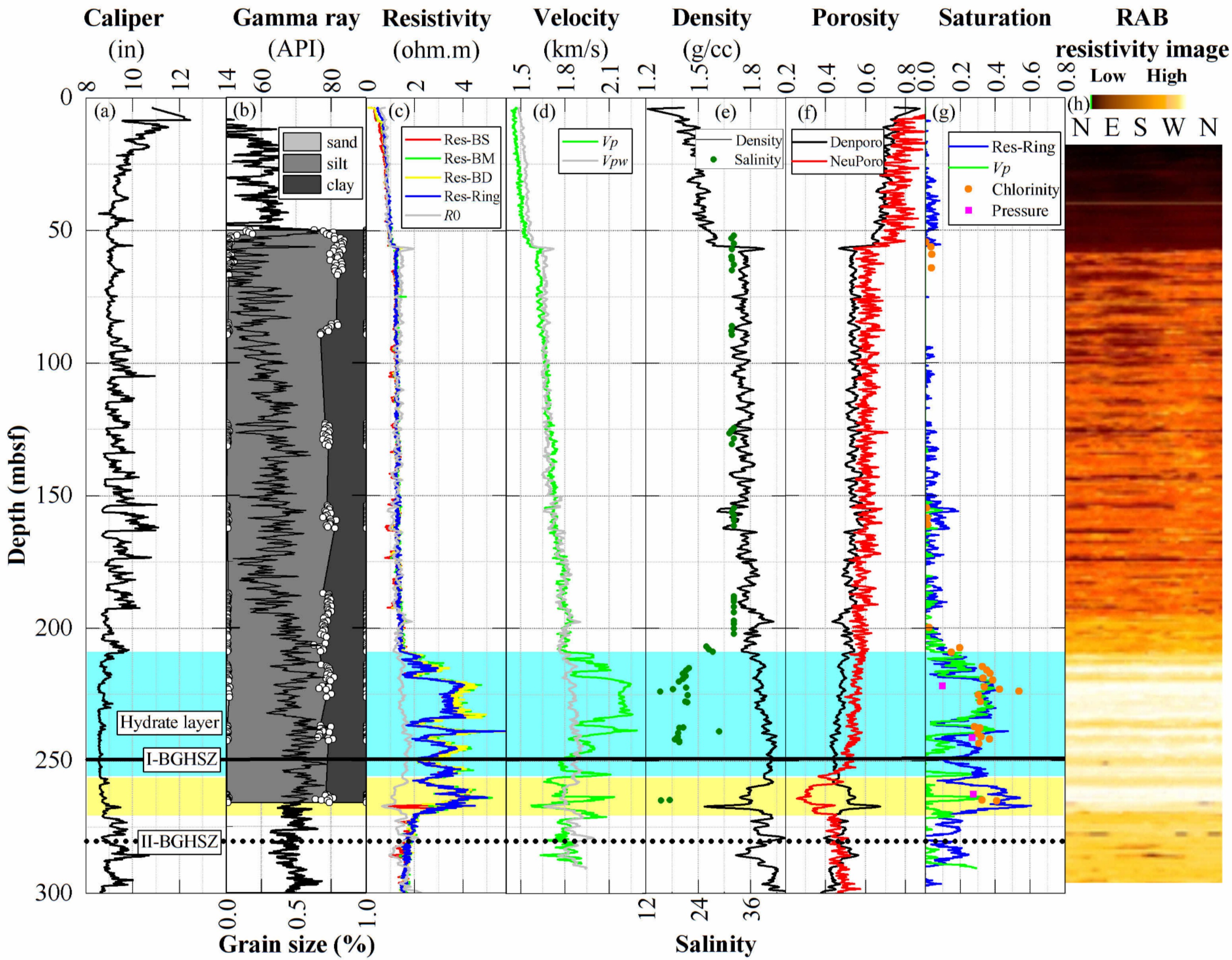
ELSEVIER

Research paper

Downhole log evidence for the coexistence of structure II gas hydrate and free gas below the bottom simulating reflector in the South China Sea


Jin Qian[a,b,c], Xiujuan Wang[a,b,c,*], Timothy S. Collett[d], Yiqun Guo[e], Dongju Kang[e], Jiapeng Jin[a,f]

# GMGS-3 (2015) W17



# India

DOE-MoPNG MoU; USGS-DGH MoU

## India-US Collaboration

- Planning, execution of NGHP-01 and NGHP-02
- Evaluation and publication of Scientific Results from NGHP-01 (USGS, NETL, LBNL, GT, Scripps, OSU)
- Geophysical site review for NGHP-02 exploratory drilling
- Evaluation of NGHP-02 pressure cores (USGS, AIST)
- Geomechanical production simulations for potential NGHP-03 sites (NETL, LBNL, USGS)
- Evaluation and publication of Scientific Results from NGHP-02 (USGS, NETL, LBNL)
- Operational planning for NGHP-03

Contents lists available at ScienceDirect

Marine and Petroleum Geology

journal homepage: www.elsevier.com/locate/marpetgeo

ELSEVIER

Research paper

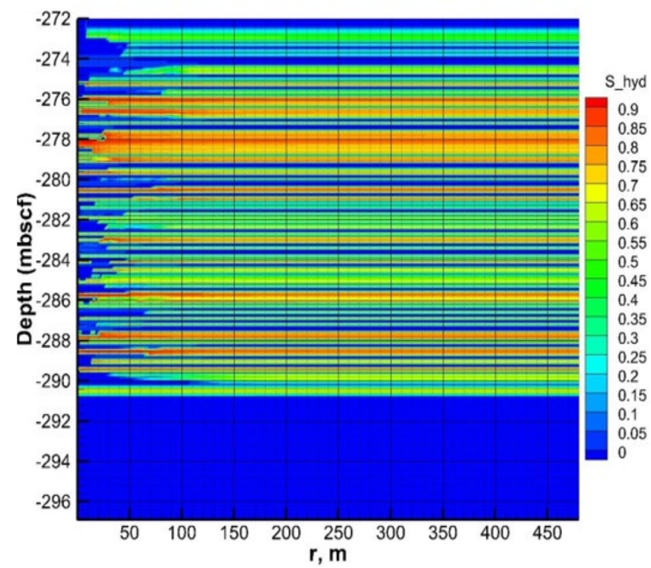
Geologic implications of gas hydrates in the offshore of India: Results of the National Gas Hydrate Program Expedition 01

Timothy S. Collett[a,*], Ray Boswell[b], James R. Cochran[c], Pushpendra Kumar[d], Malcolm Lall[e], Aninda Mazumdar[f], Mangipudi Venkata Ramana[g], Tammisetti Ramprasad[f], Michael Riedel[h], Kalachand Sain[i], Arun Vasant Sathe[j], Krishna Vishwanath[e], NGHP Expedition 01 Scientific Party

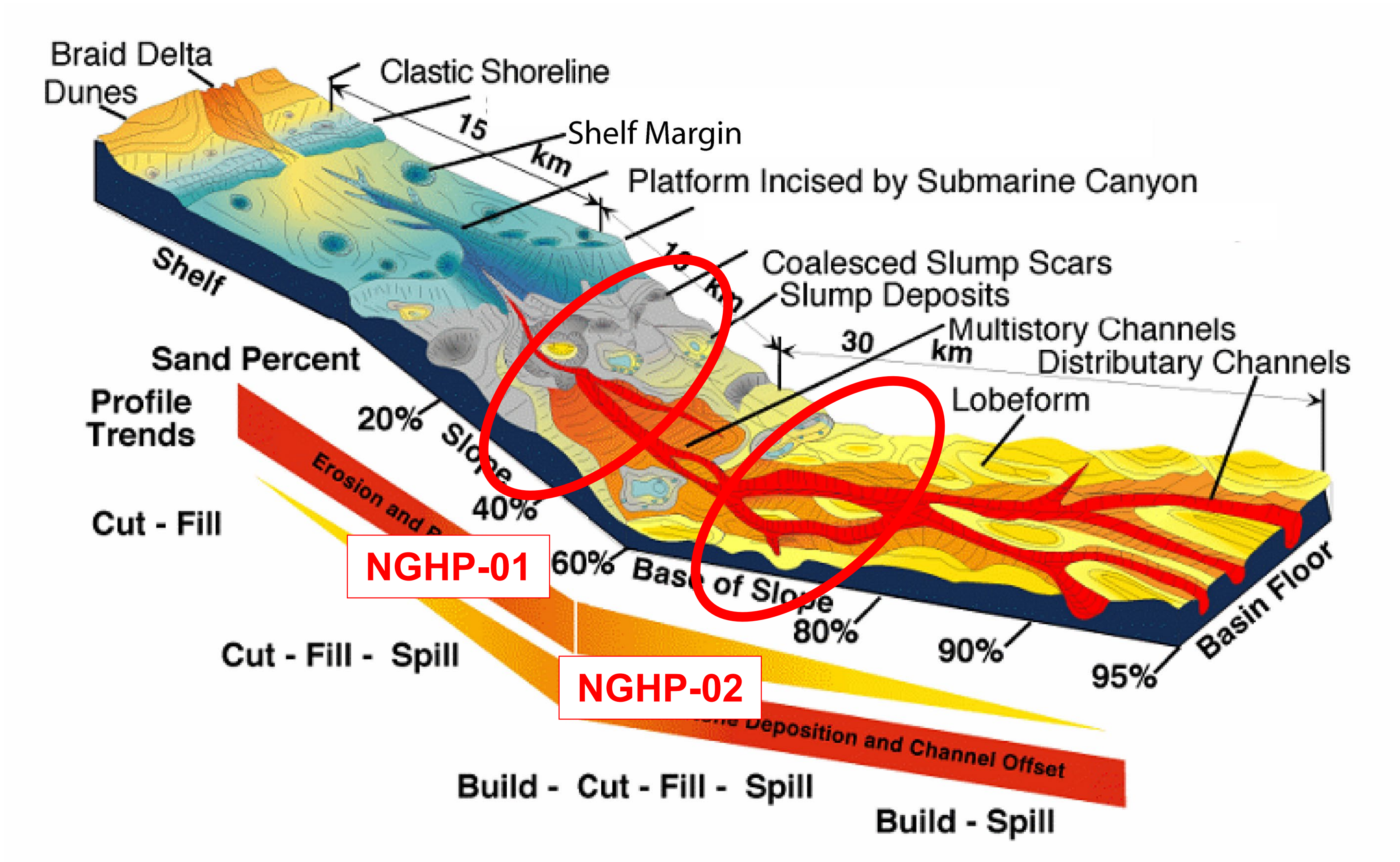
*Science Results for NGHP-01*

*NGHP-02 p-cores arrive at USGS labs in Woods Hole*

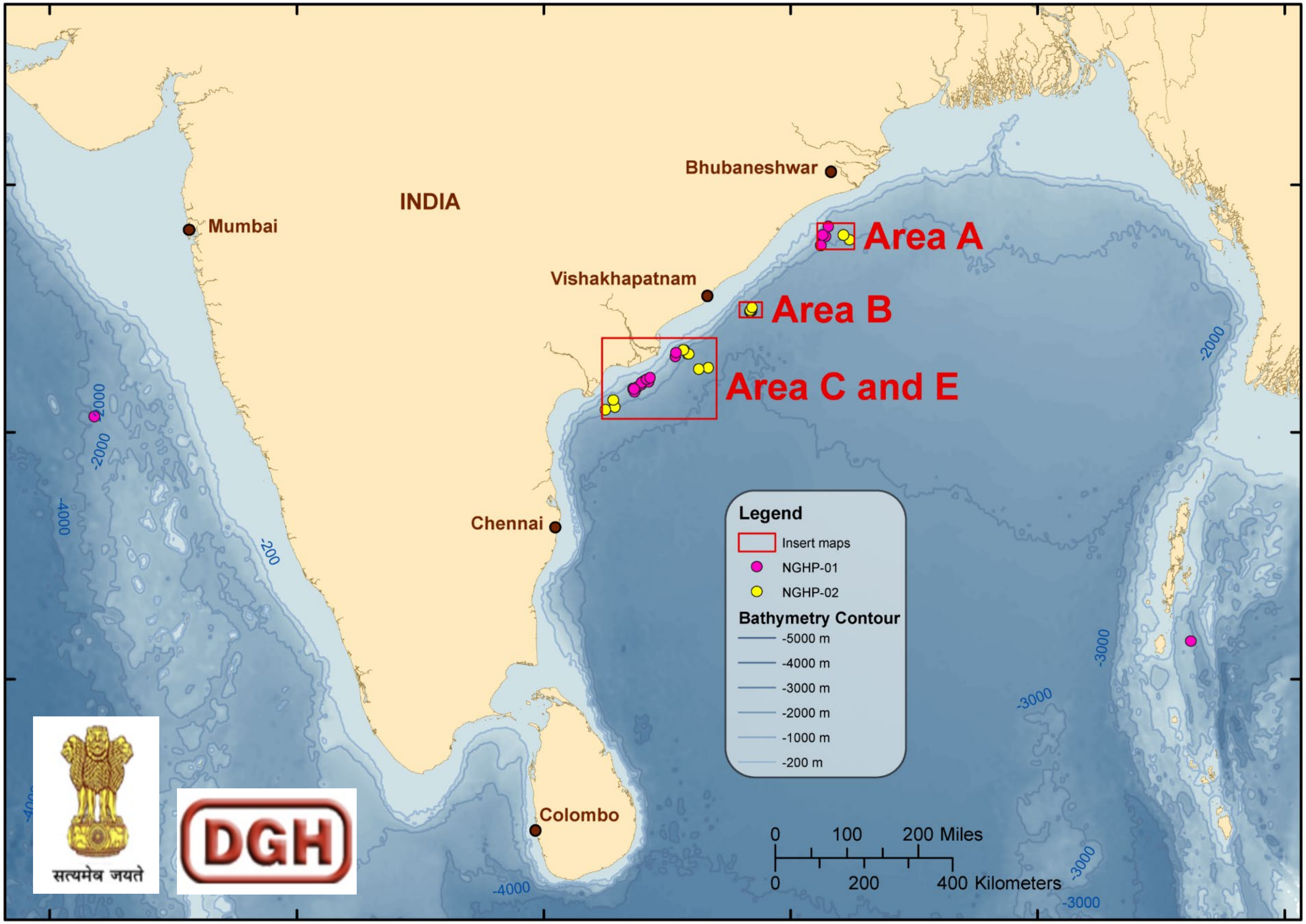
*NETL modeling for potential NGHP-03 Site 16*

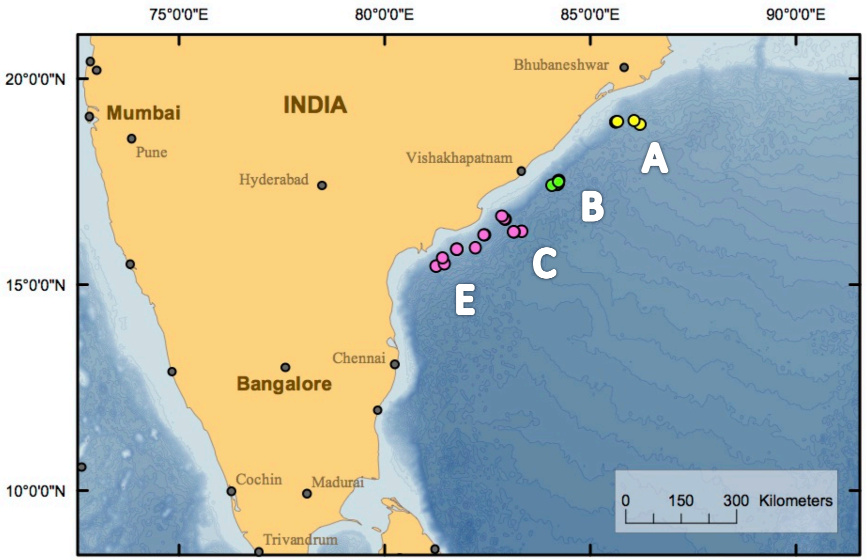


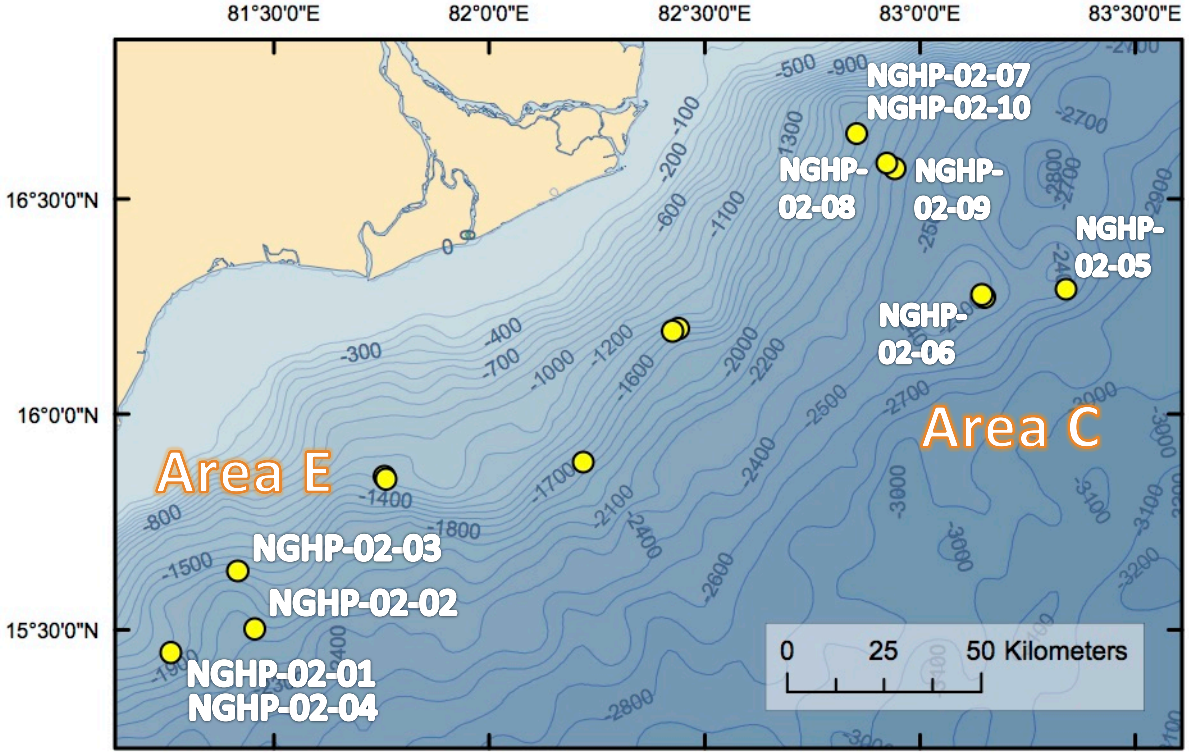
# Deep Water Shelf-Slope-Basin Deposition



# India NGHP-01 (2006) and NGHP-02 (2015)






## Area C (6 sites)

**Site NGHP-02-05**

**Site NGHP-02-06**

**Site NGHP-02-07**

**Site NGHP-02-08**

**Site NGHP-02-09**

**Site NGHP-02-10**

# India NGHP-02: Area C Gas Hydrate System

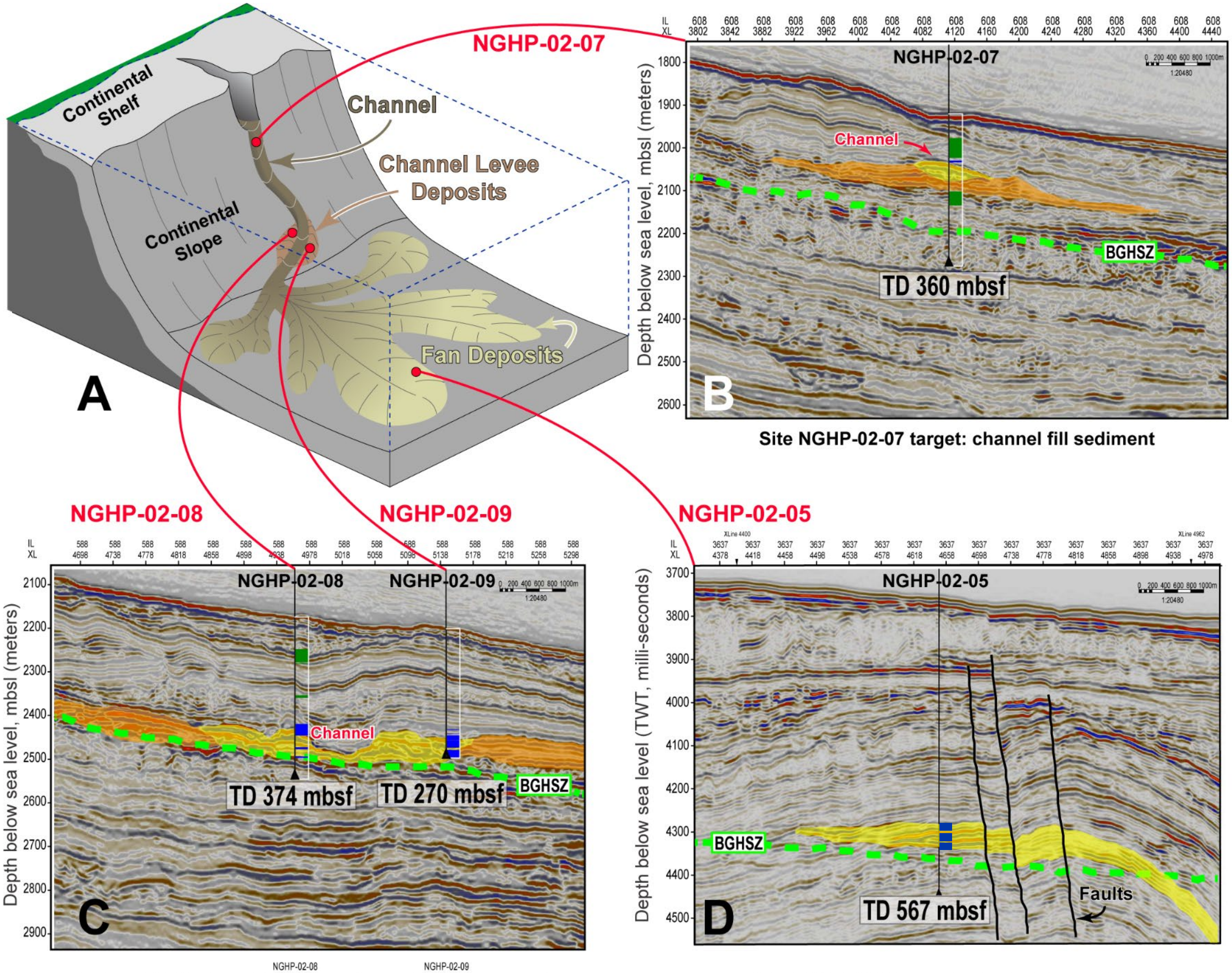
Analysis LWD data from the Area-C along with the available 3-D seismic data volumes, reveals a fully developed gas hydrate system along the outer continental slope margin of the D6 and D9 Blocks in the Krishna-Godavari Basin.

Prominent channel features drilled in Holes NGHP-02-07-A and -10A, appears to be linked to the down slope deep-sea channel levee system targeted by Holes NGHP-02-08-A and -09-A and the more distal middle to outer fan sequences drilled in Holes NGHP-02-05-A and -06-A.

Hole NGHP-02-08-A appears to have penetrated a 26-m-thick interval of what appears to be a sand-rich levee deposit with high gas hydrate saturations over about 20 m of the drilled reservoir section. Hole NGHP-02-09-A, selected to test the same levee system on the opposite bank of the same channel drilled a 53 m thick reservoir section that appears to be mostly gas-hydrate-bearing.

Holes NGHP-02-05-A and -06-A both encountered a relative thick succession of middle to outer fan deposits with individual well log inferred sand reservoir sections measuring more than 50 m in thickness. Hole NGHP-02-05-A encountered a relatively thick section of thinly bedded gas hydrate-bearing turbidite sands just above the BSR at this site.

# Krishna-Godavari Gas Hydrate System
## *Channel-Levee and Fan Systems*




Site NGHP-02-07 target: channel fill sediment

Site NGHP-02-08, -09 targets: channel levee sediment

Site NGHP-02-05 target: stacked fan sediment

**Seismic profile legend**

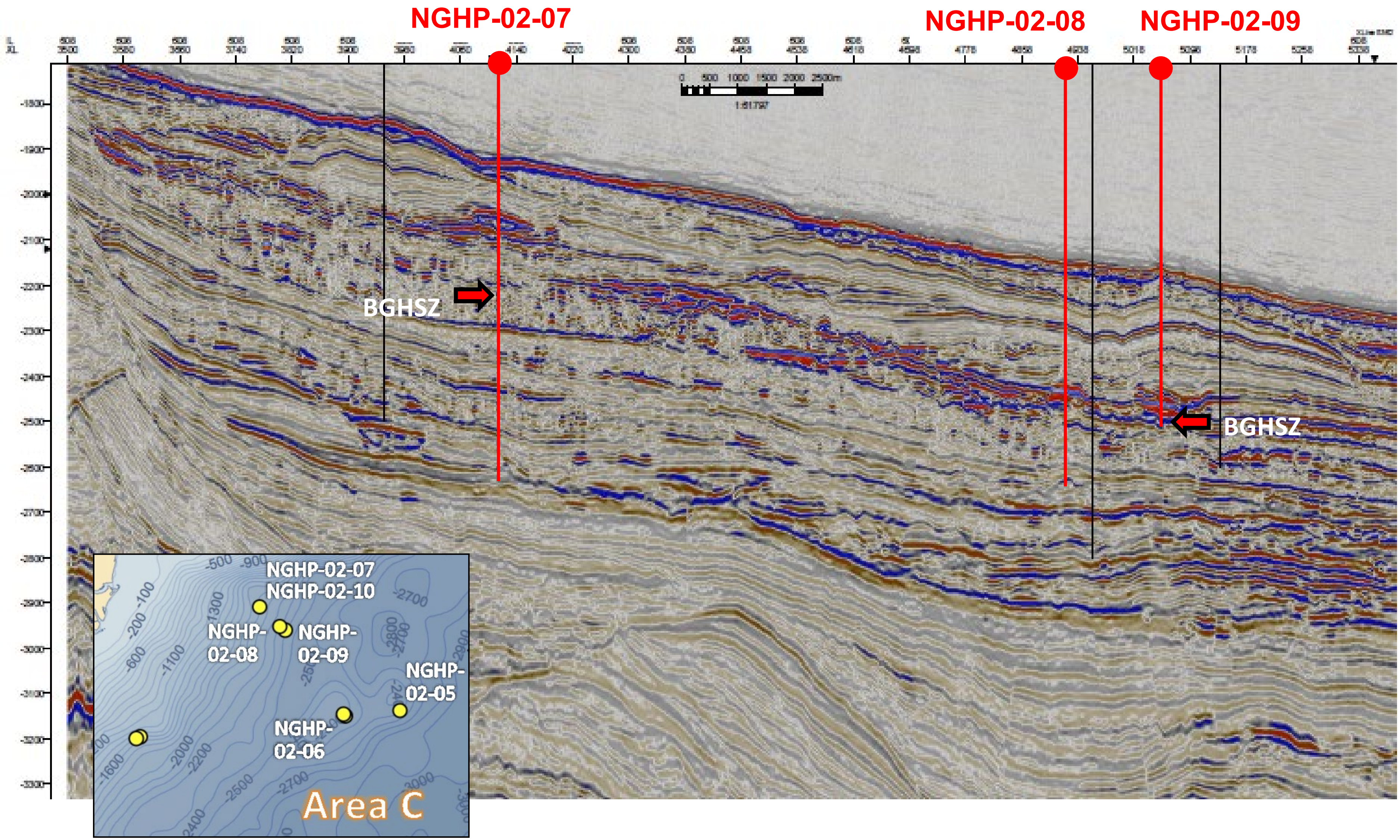
- Coarse-grained, sand-rich sediment (yellow)
- Coarse-grained, silt-rich sediment (orange)

**Archie-inferred downhole gas hydrate distribution**

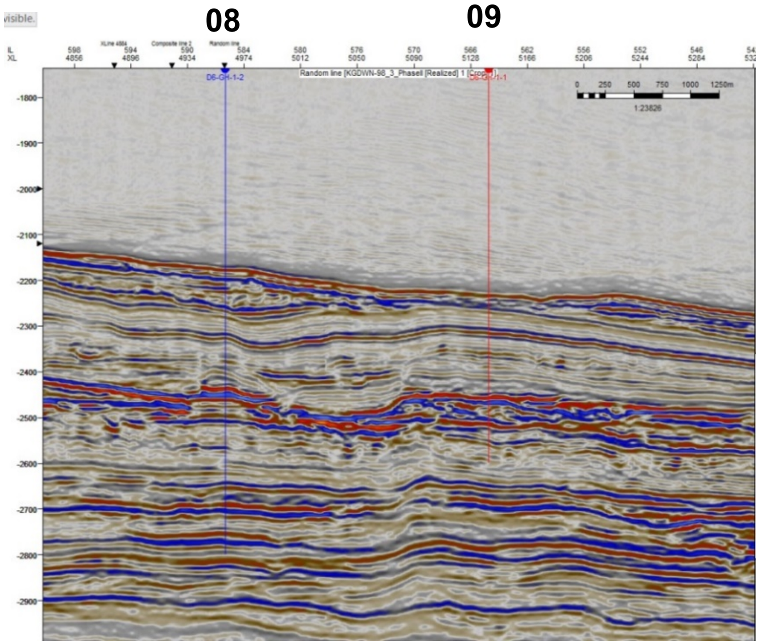
- Gas hydrate-filled fractures (grain displacing) (green)
- Gas hydrate in existing pore space (pore-occupying) (blue)

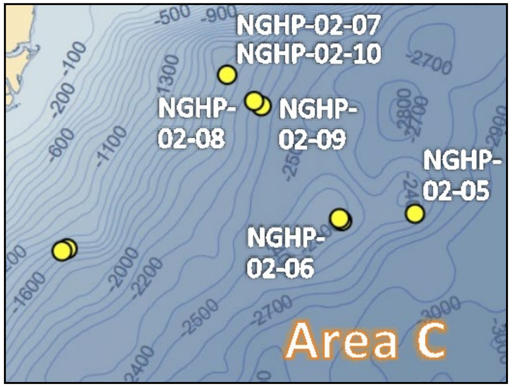
# Krishna-Godavari Gas Hydrate System

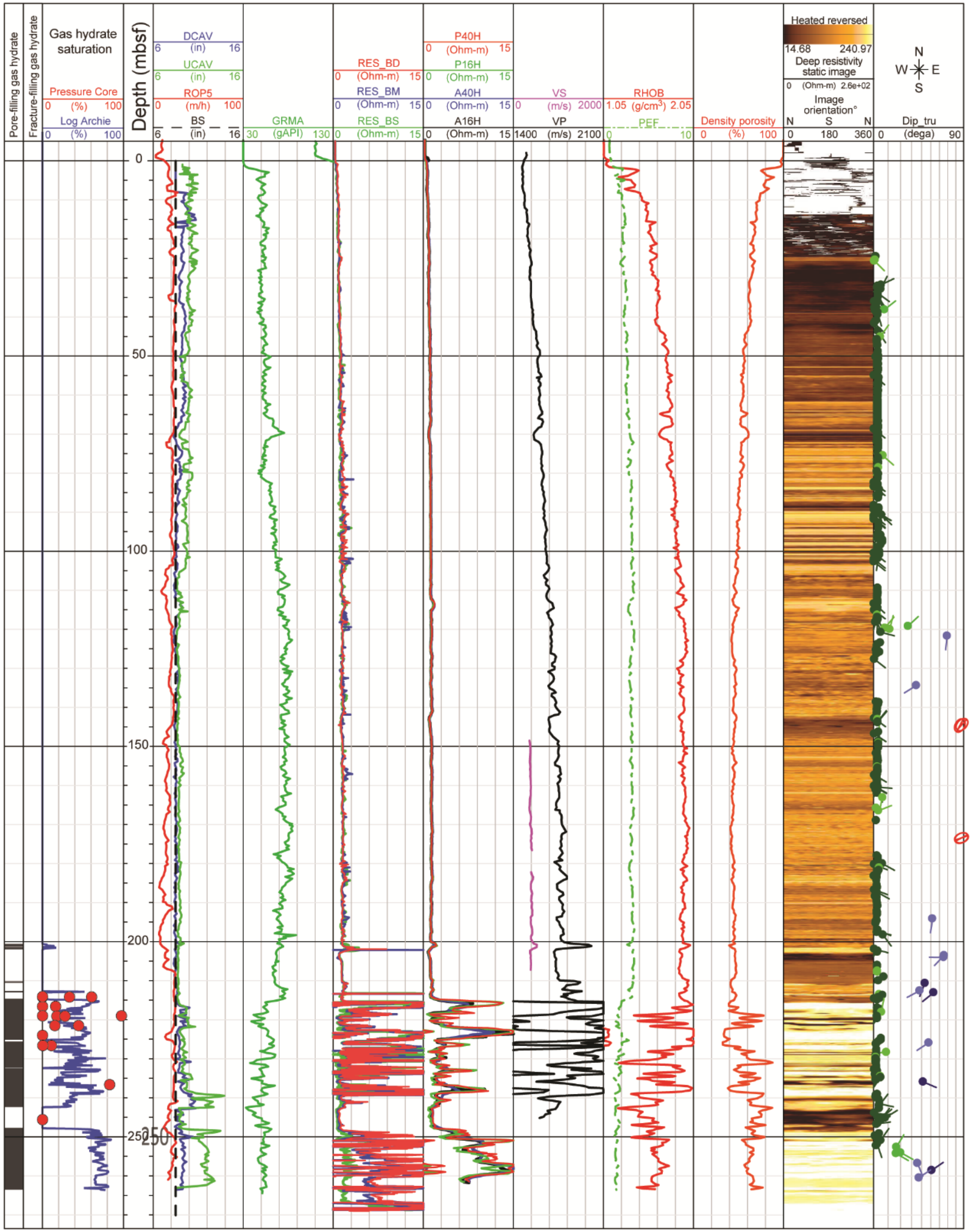
## *Slope-Rise Channel-Levee System*



# NGHP-02-09



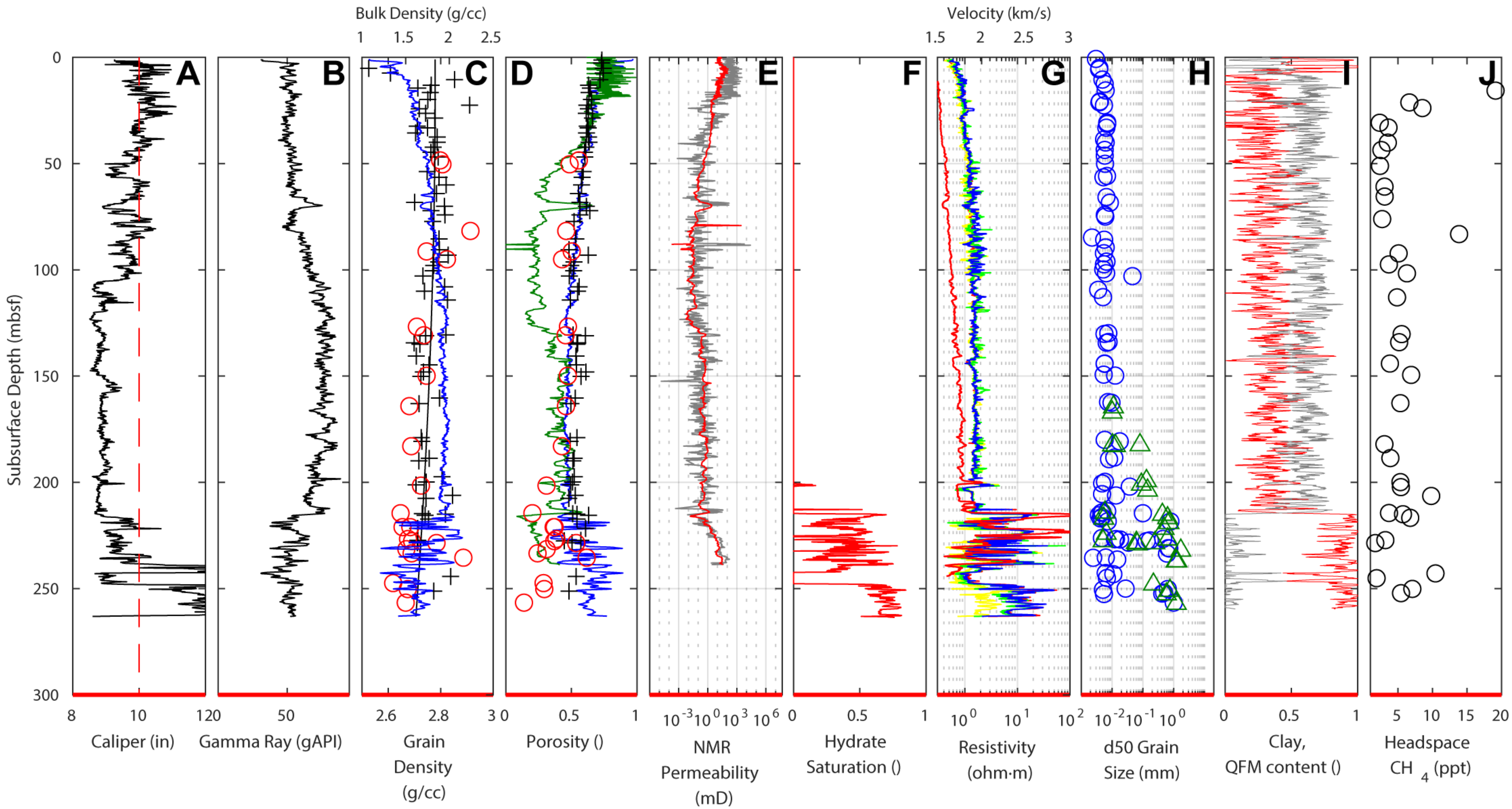




**Area C**

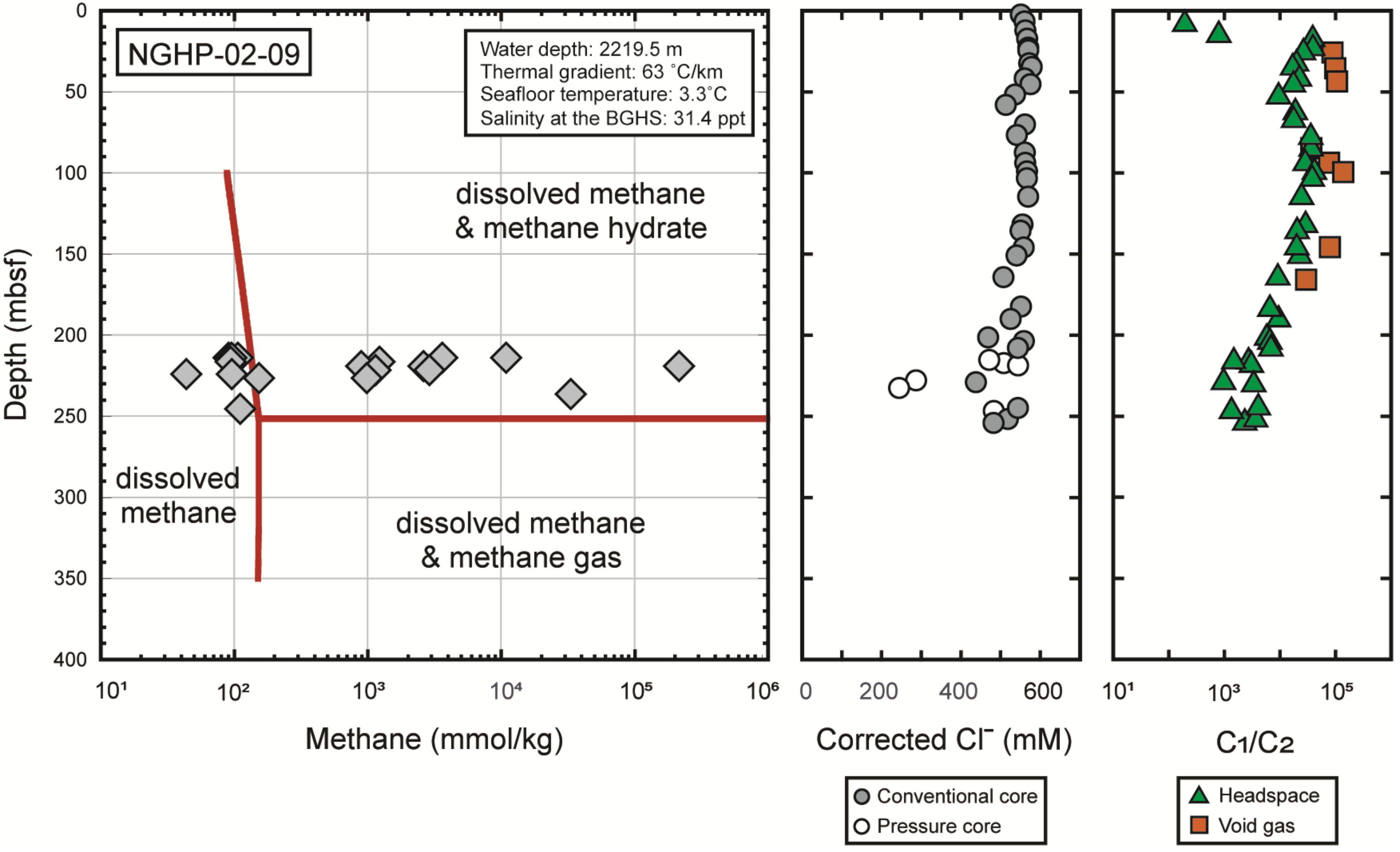
**Krishna-Godavari Gas Hydrate System**

***Slope-Rise Channel-Levee System***

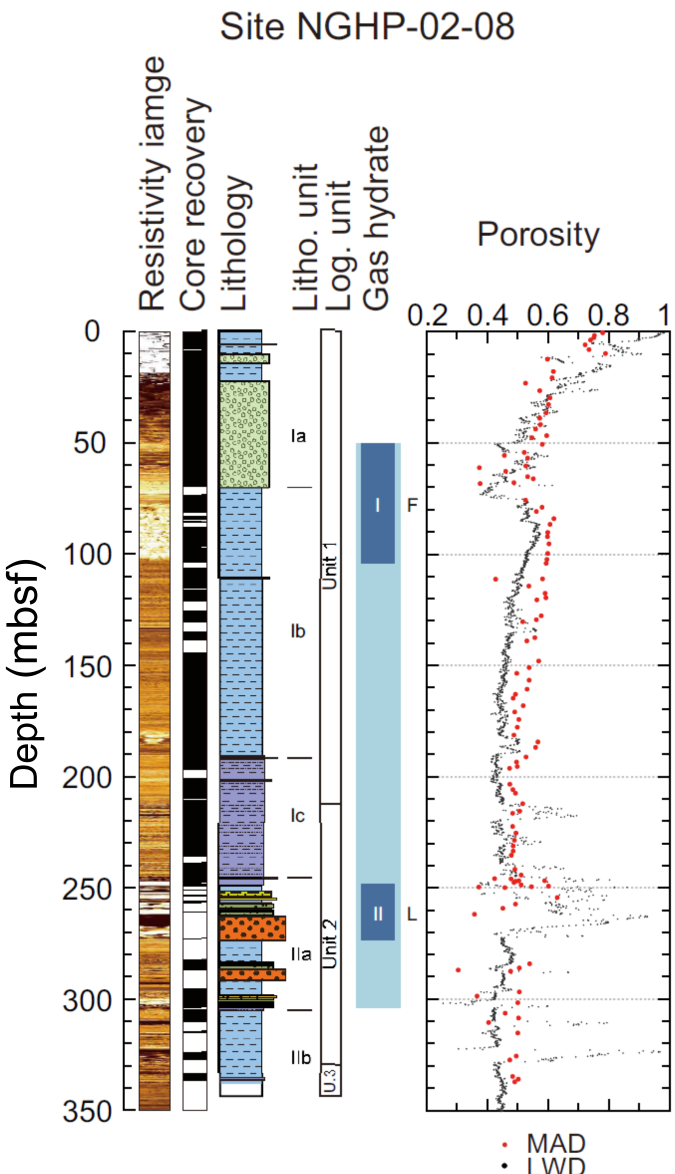
# India NGHP-02: Area-C   Site NGHP-02-09

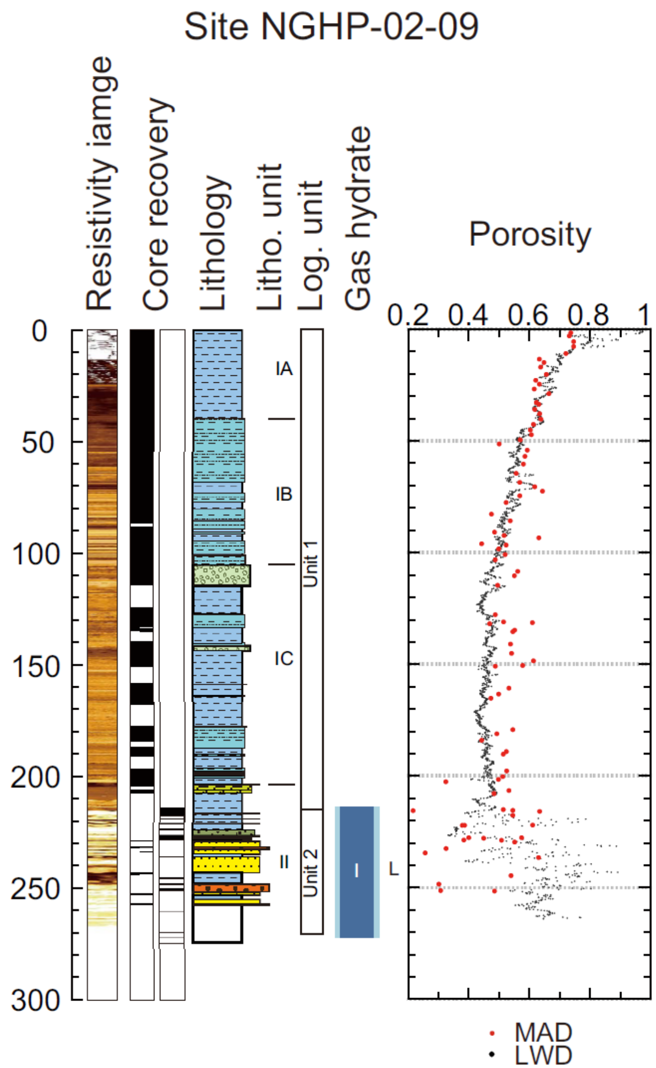


# India NGHP-02: Area-C   Site NGHP-02-09



# India NGHP-02: Area-C   Sites NGHP-02-08 & -09




**Core NGHP-02-09B-35P**

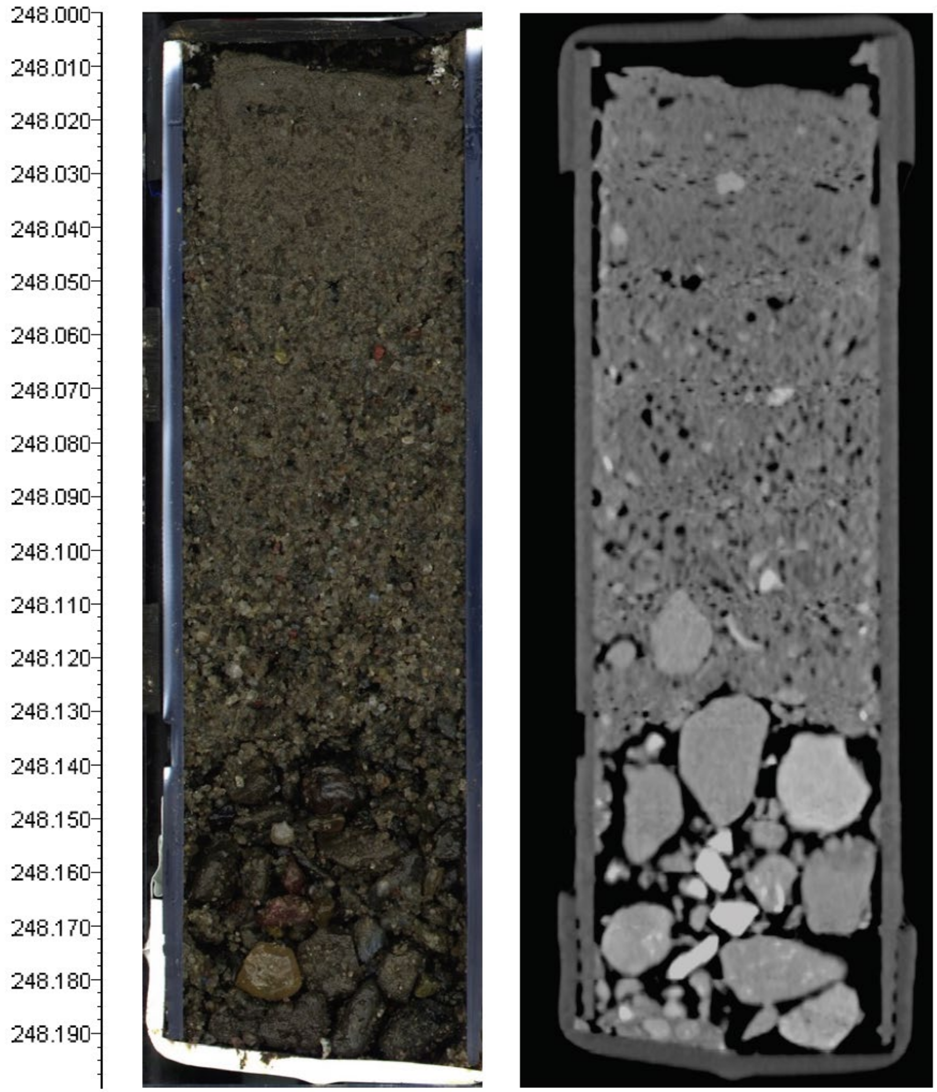
# NGHP-02-09-9P & -10X Core Images

## *Coarse sand sediment layers*

804-C8029C-9P; 248.0–248.2

Depth | Image, split section image | Image, X-ray CT scanning

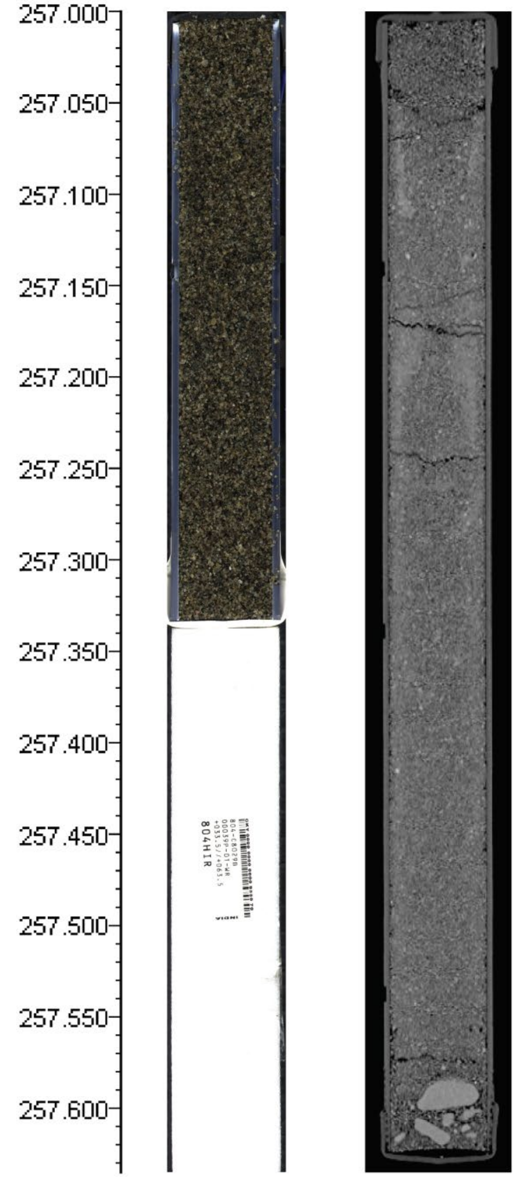
Depth DSF, MSI




804-C8029B-39P; 257.0–257.635

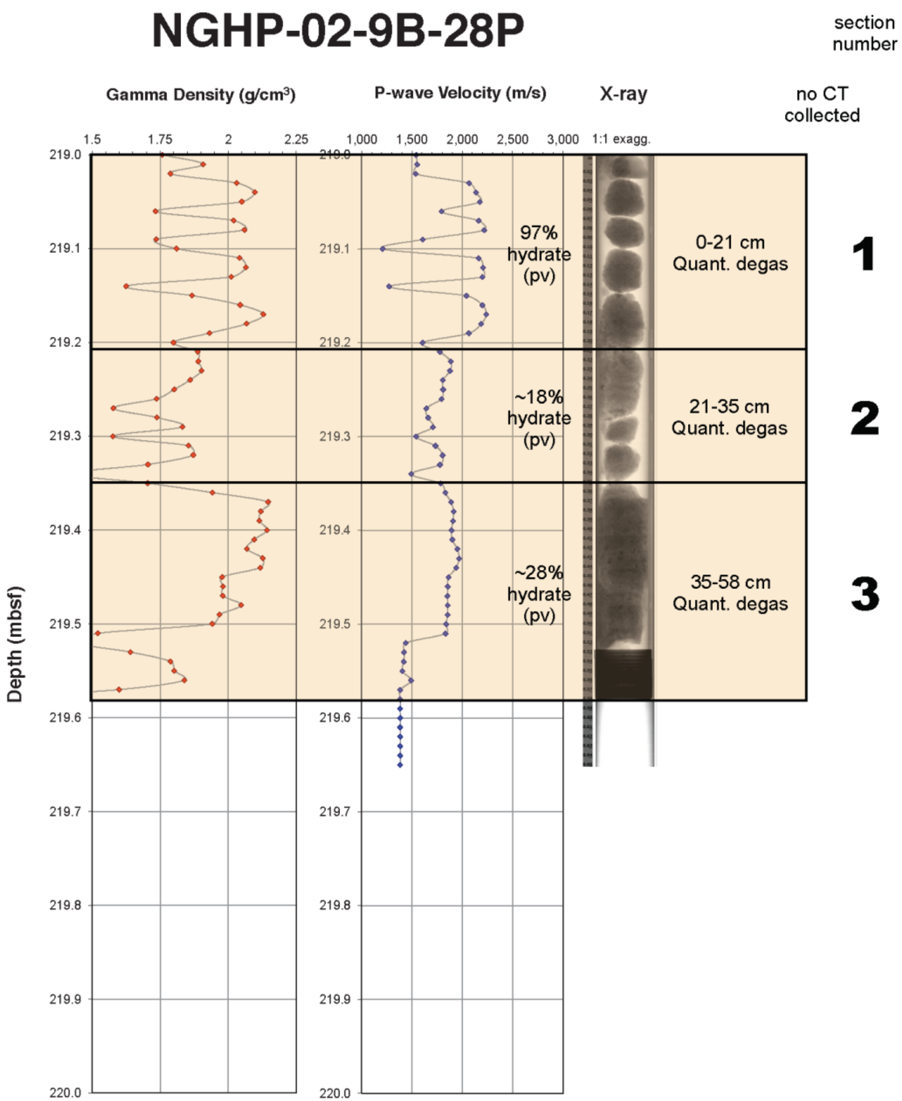
Depth | Image, split secti | Image, X-ray CT

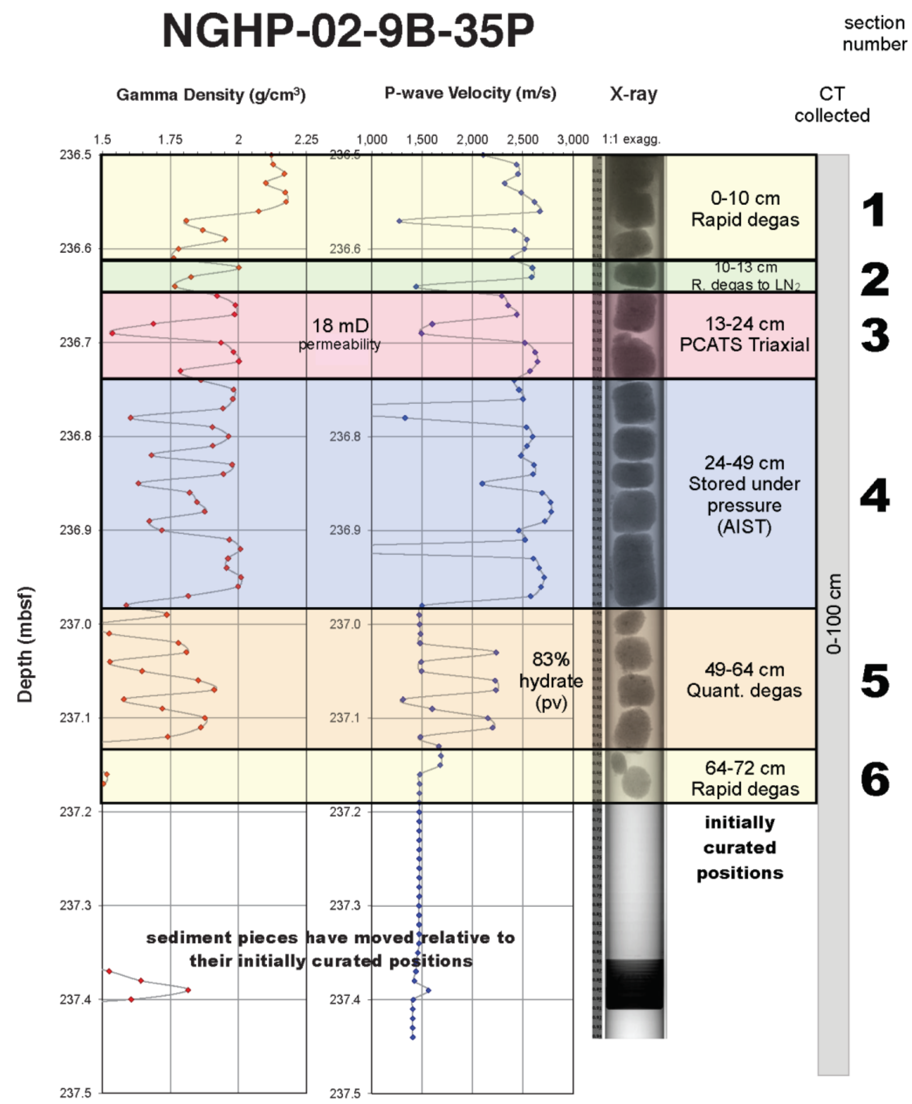
Depth DSF, MSI



# NGHP-02 Area C Sites 08/09: Channel-Levee System

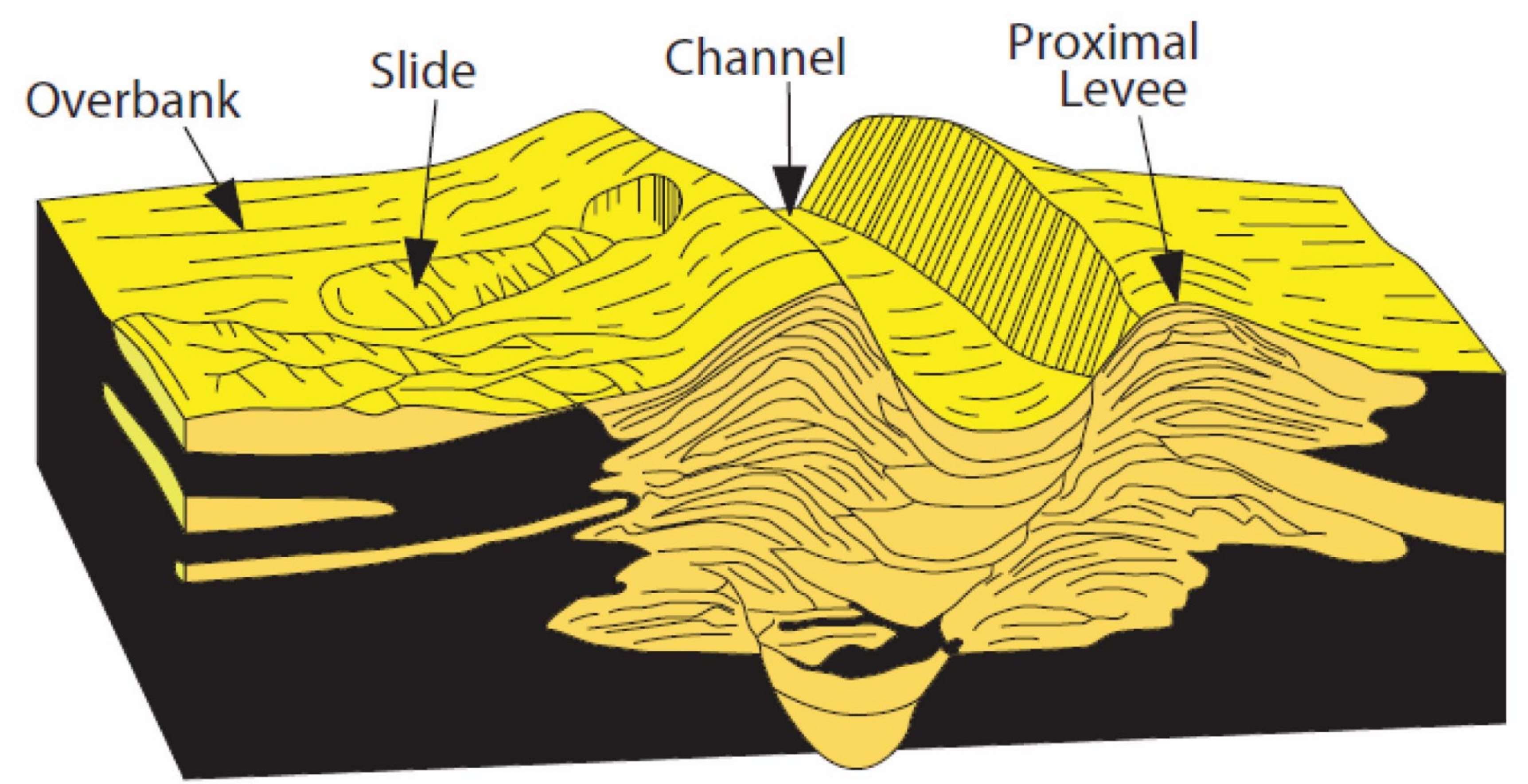
## *Pressure Cores – typical GH-bearing reservoir section*



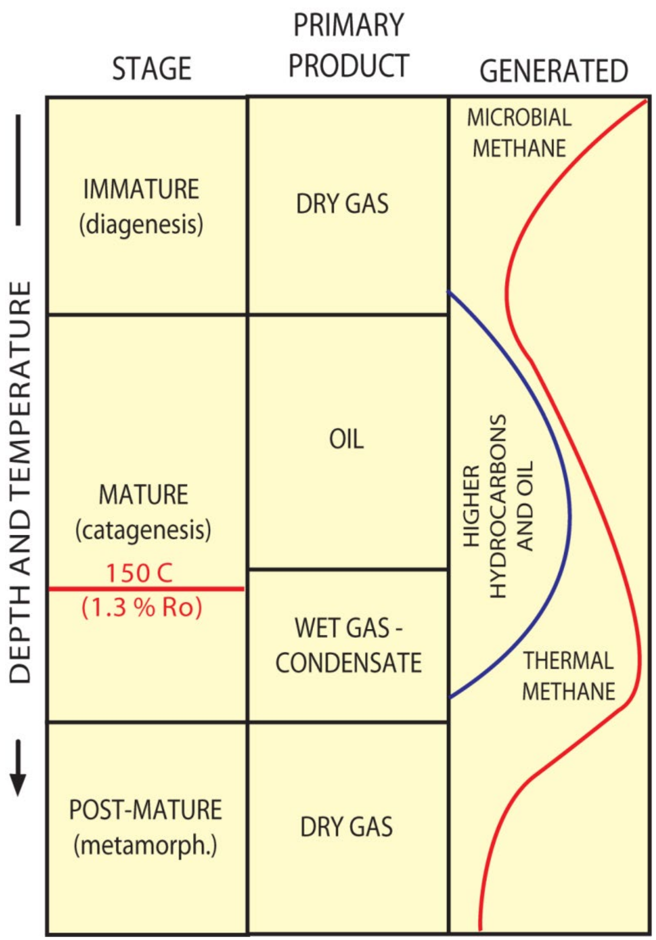



# NGHP-02 Area C Sites 08/09: Channel-Levee System

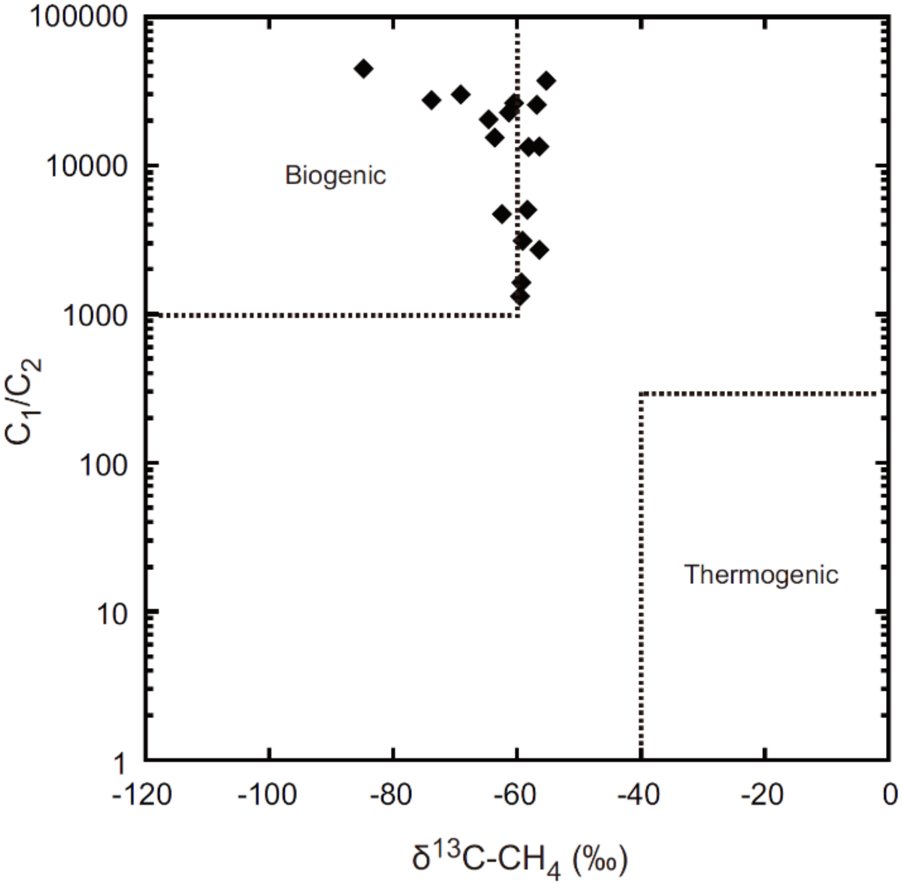
## *Analog depositional model*



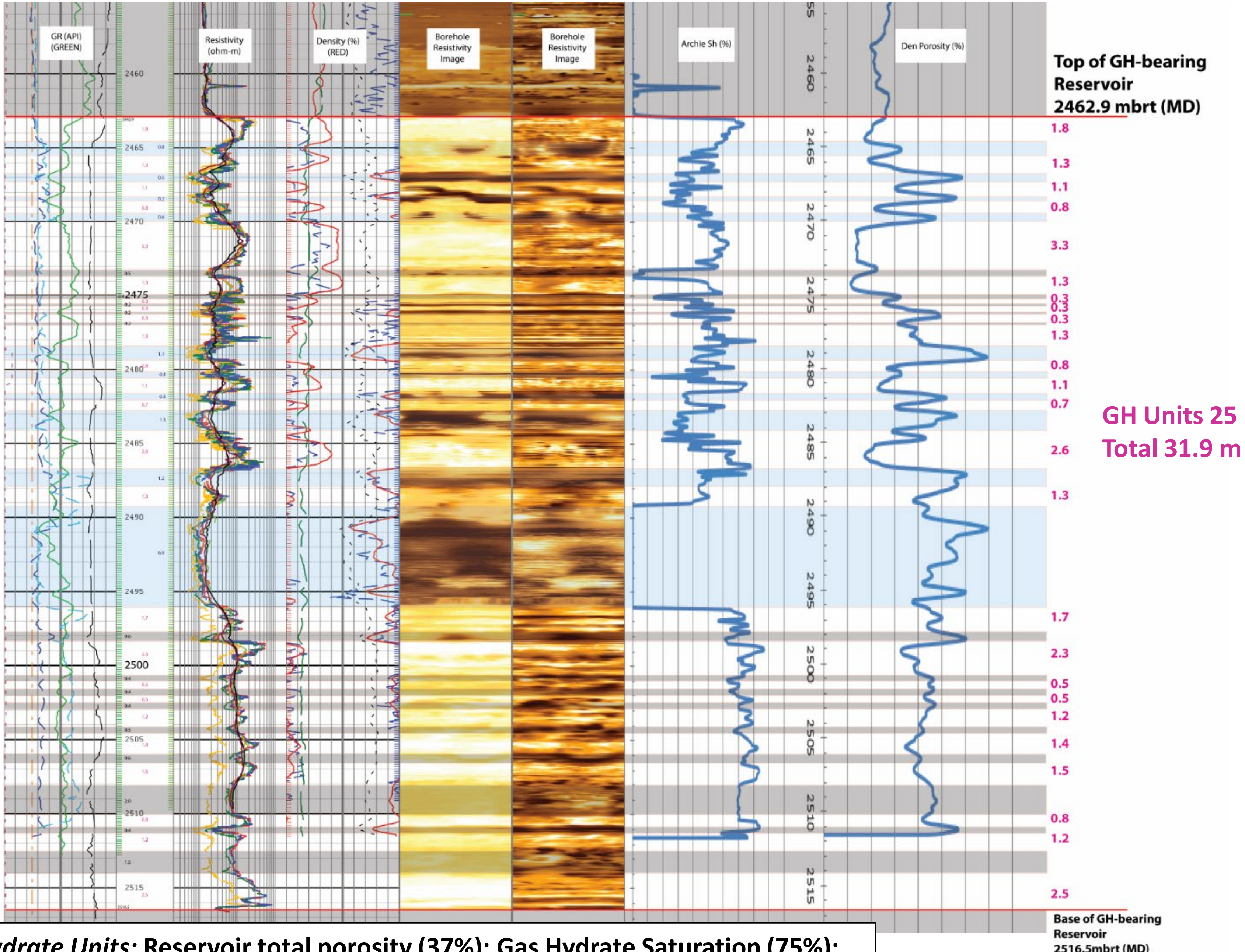
# Gas Hydrate System
## *Gas Source*



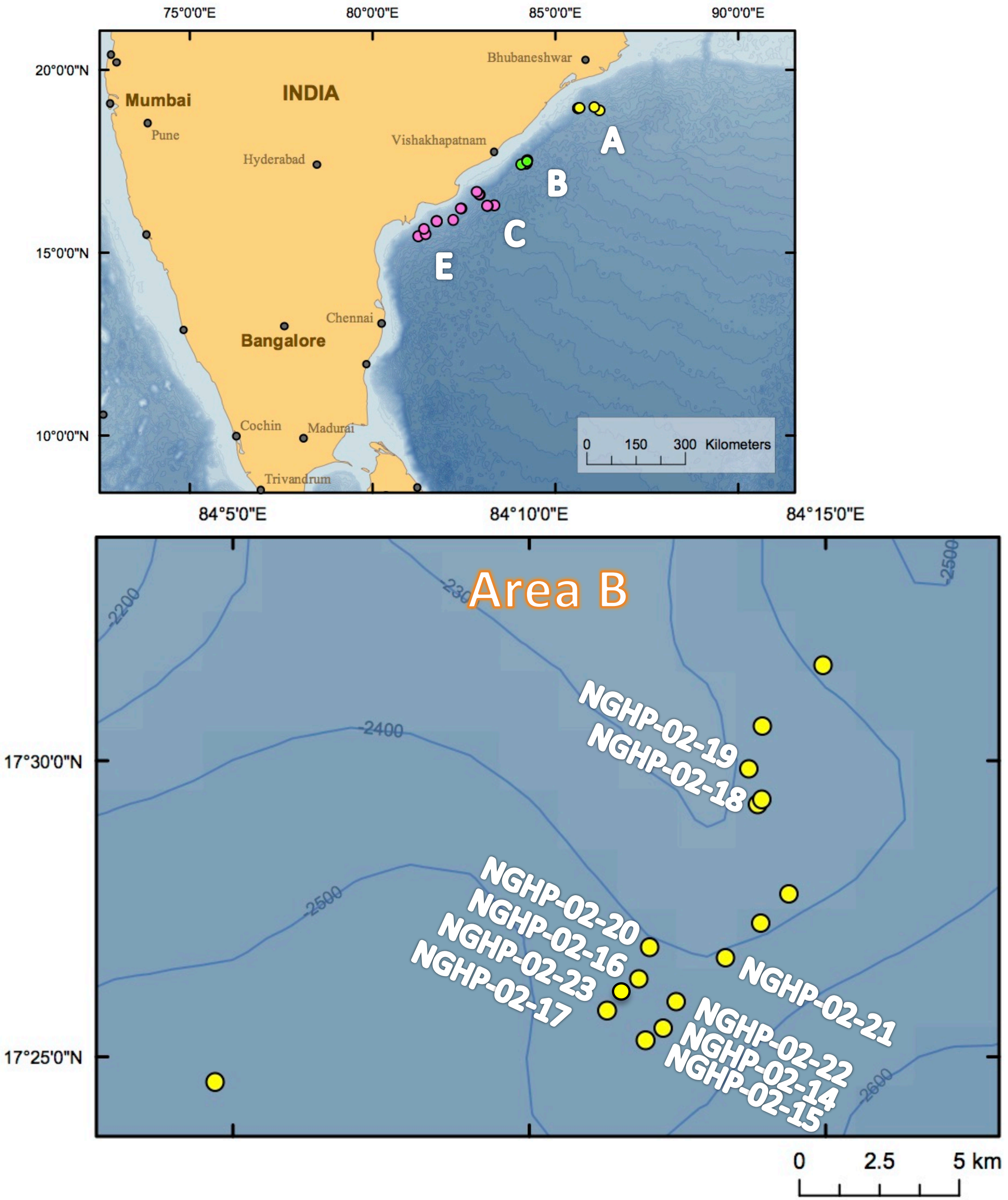

**Area C NGHP-02-08**
**Headspace Gas Analysis**



# Area C: Site NGHP-02-09 Reservoir Model




*Gas Hydrate Units:* **Reservoir total porosity (37%); Gas Hydrate Saturation (75%); Effective permeability (two assumed cases 10 mD and 0.1 mD)**




# Area B (12 sites)

Site NGHP-02-14
Site NGHP-02-15
Site NGHP-02-16
Site NGHP-02-17
Site NGHP-02-18
Site NGHP-02-19
Site NGHP-02-20
Site NGHP-02-21
Site NGHP-02-22
Site NGHP-02-23
Site NGHP-02-24
Site NGHP-02-25

# India NGHP-02: Area B Gas Hydrate System

The main feature of Area-B is a large regional elongated anticlinal structure (the L1 Block structure) that is aligned perpendicular to the slope.

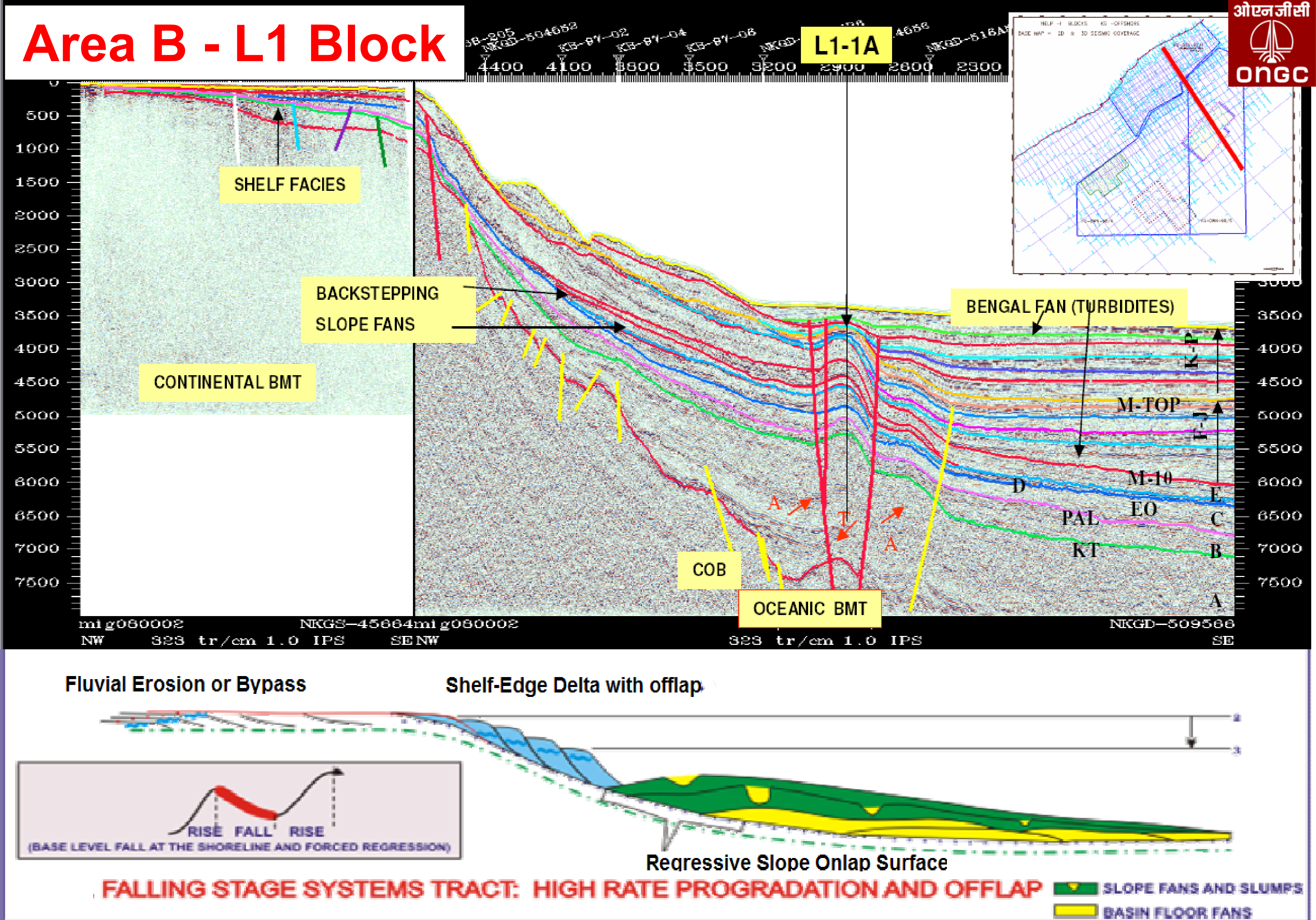
Two potential reservoir systems were identified in Area-B, including an “upper” reservoir faces (R1) and a second “lower” (R2) reservoir section with both reservoir faces characterized by apparent peak-leading seismic events above the BSR.

The “upper” reservoir faces (R1) is characterized by a relatively complex occurrence of both pore-filling and fracture-filling gas hydrates.

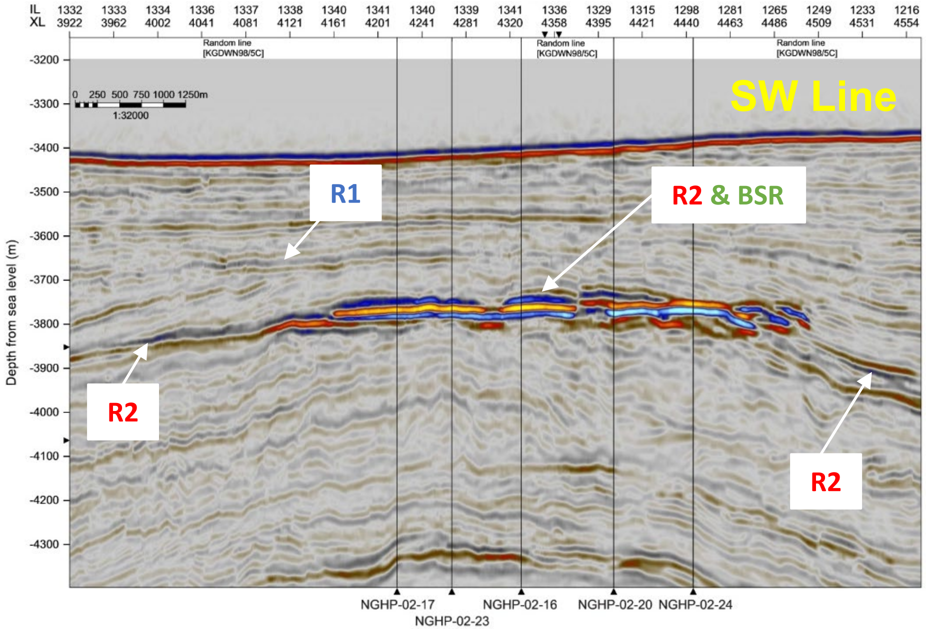
The “lower” reservoir faces has proven to be more perspective for highly saturated and thick gas hydrate occurrences. The LWD data from Holes NGHP-02-16-A and -17-A that were drilled to test the “lower” reservoir faces just above the BSR, have shown the presence of 18 and 19 m, respectively, of highly concentrated gas-hydrate occurrences.

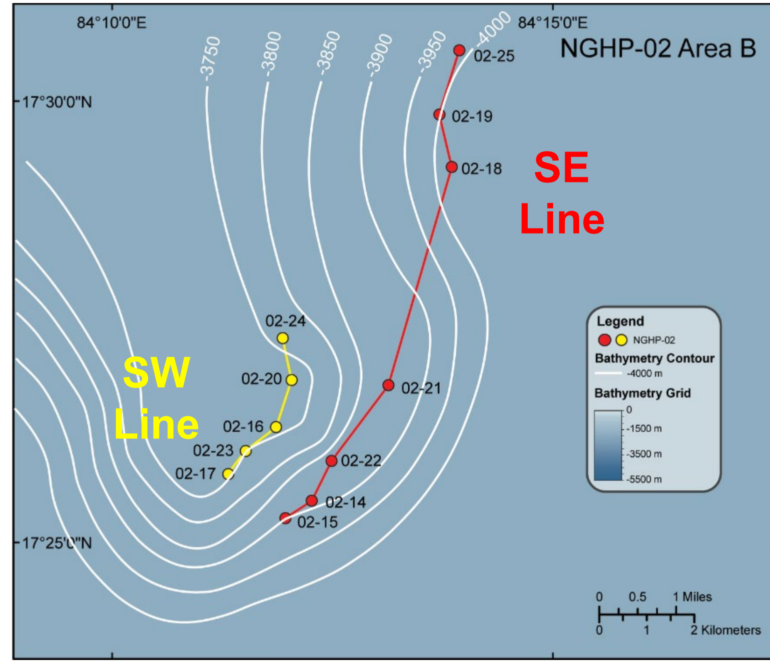
The unprecedented opportunity to drill 12 LWD penetrations through in the L1 Block gas hydrate accumulation and to core the gas hydrate system at five sites have provided one of the most complete three-dimensional petrophysical-based view of any known gas hydrate reservoir system in the world.

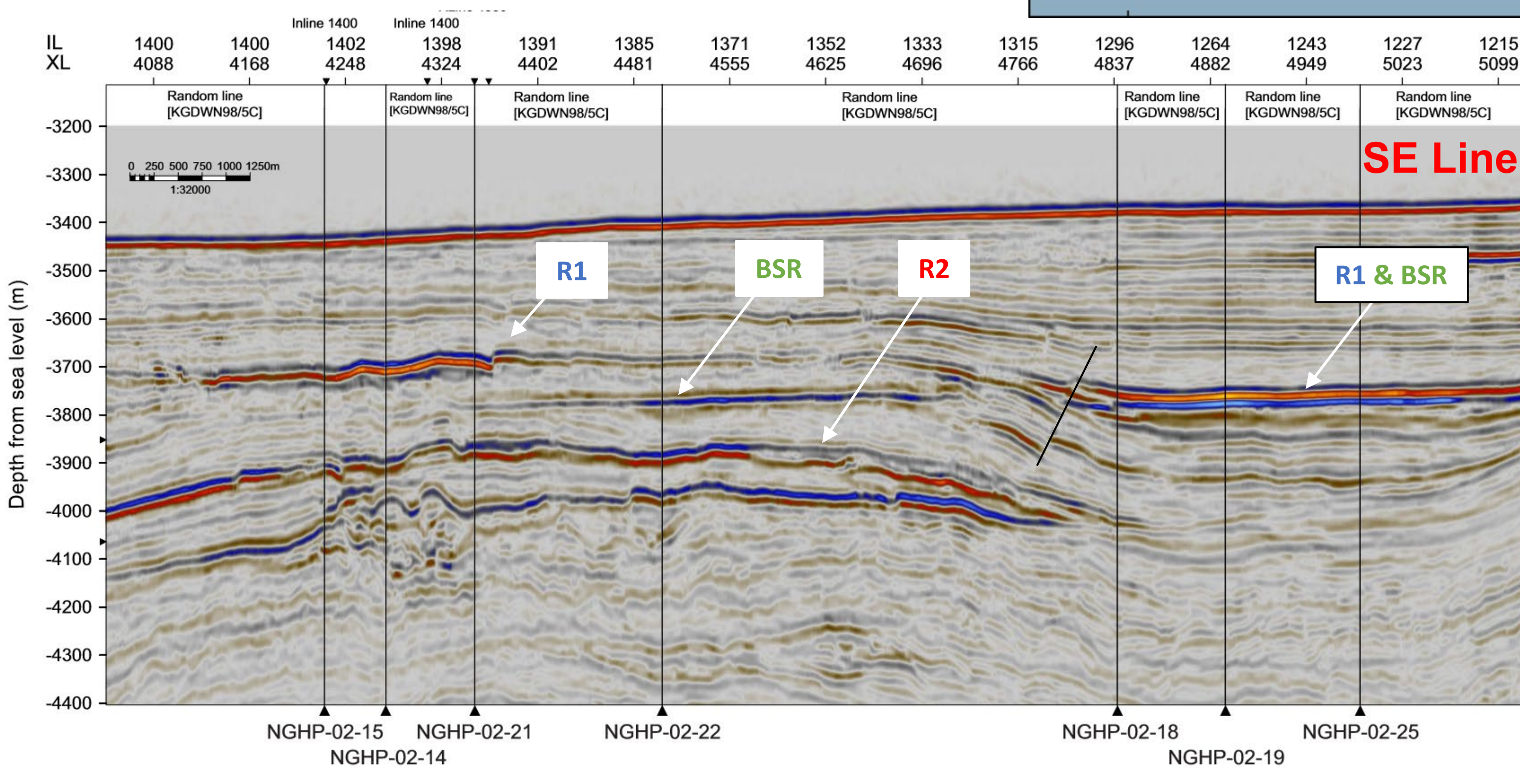
# Area B - L1 Block




Source: WOB, Mumbai

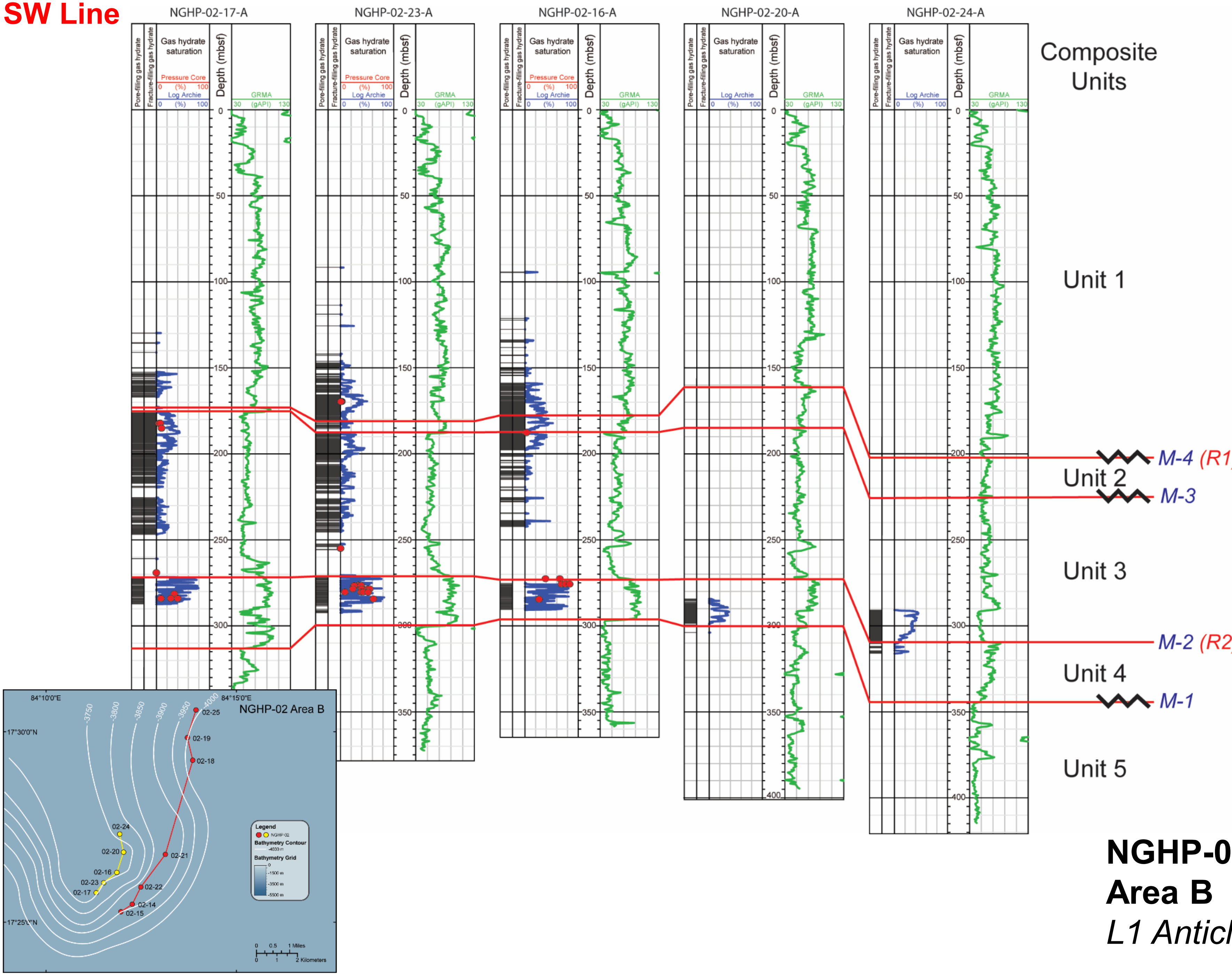


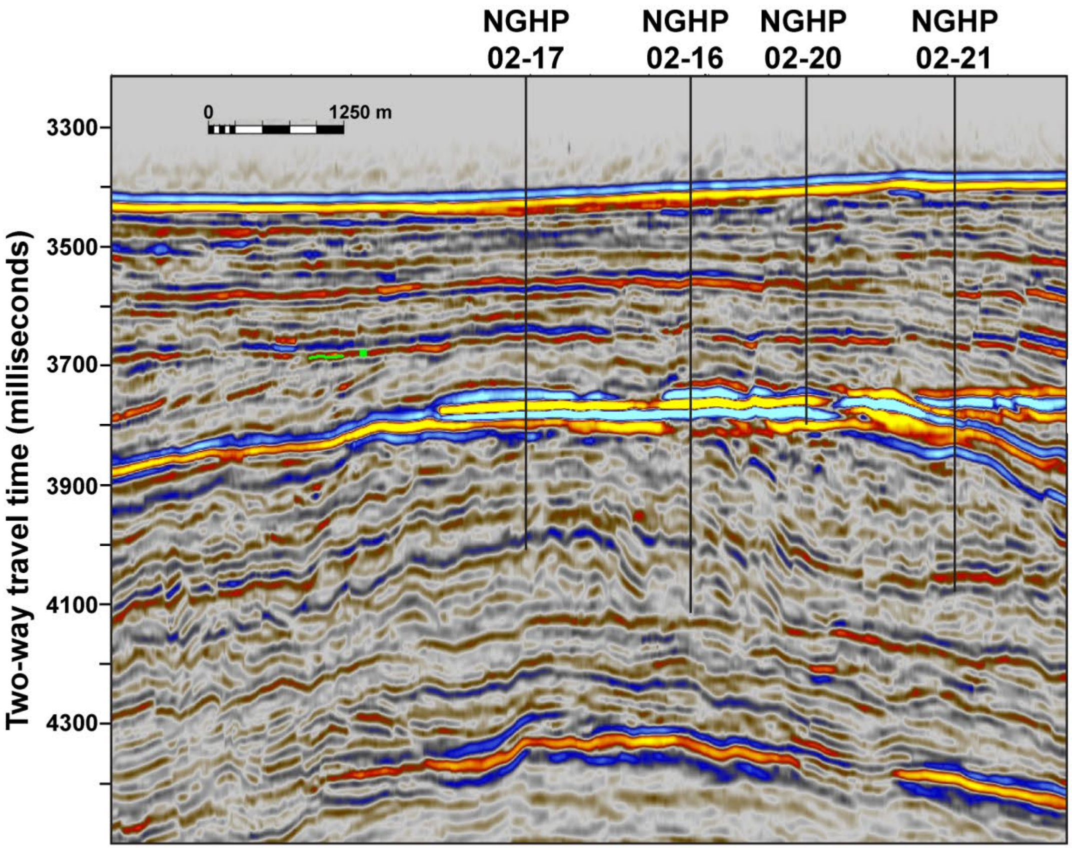

**NGHP-02**
**Area B**
*L1 Anticline*

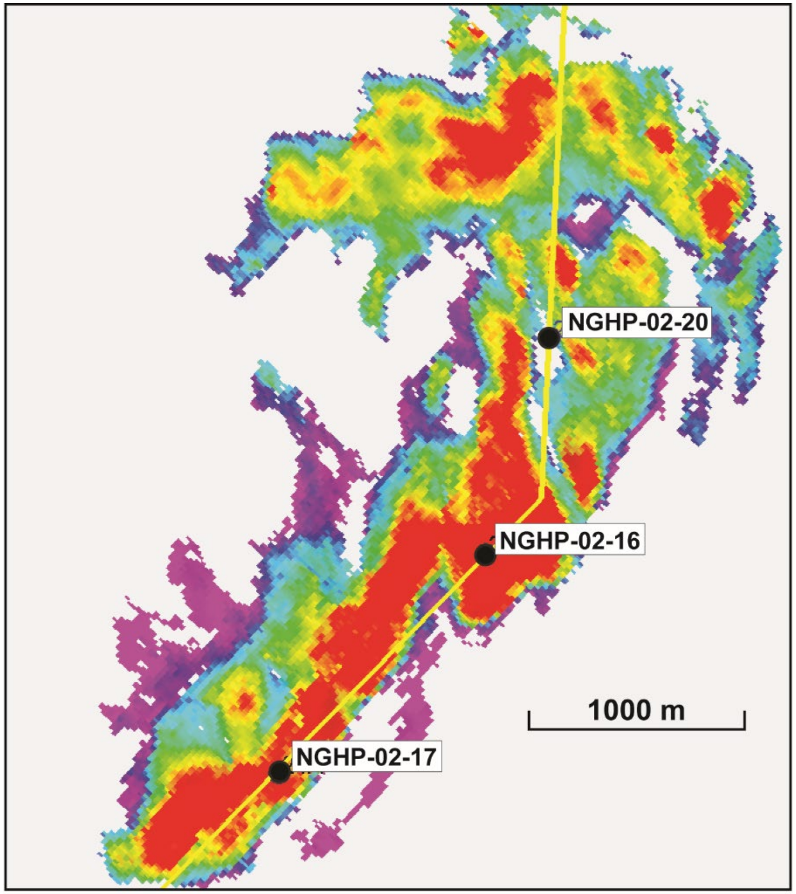
# SW Line



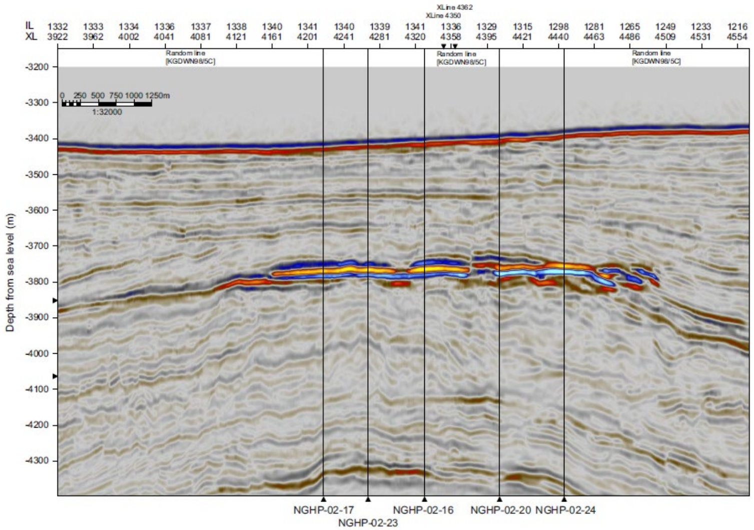

**NGHP-02**
**Area B**
*L1 Anticline*

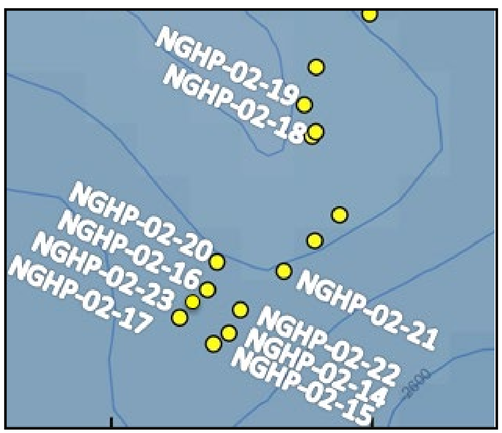
# NGHP-02: Area B Gas Hydrate Accumulation
## *Lower (R2) Reflector/Reservoir*

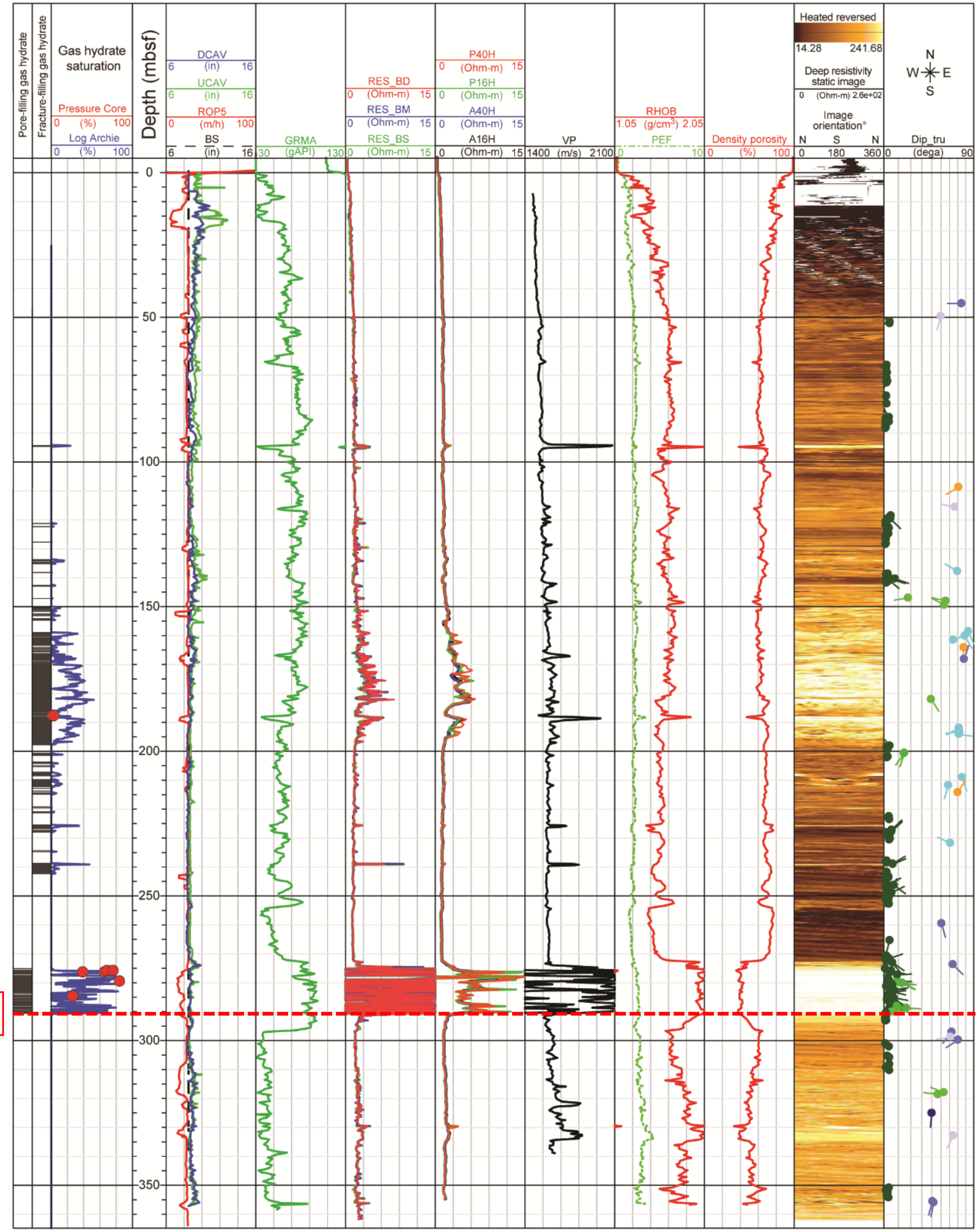


# NGHP-02-16

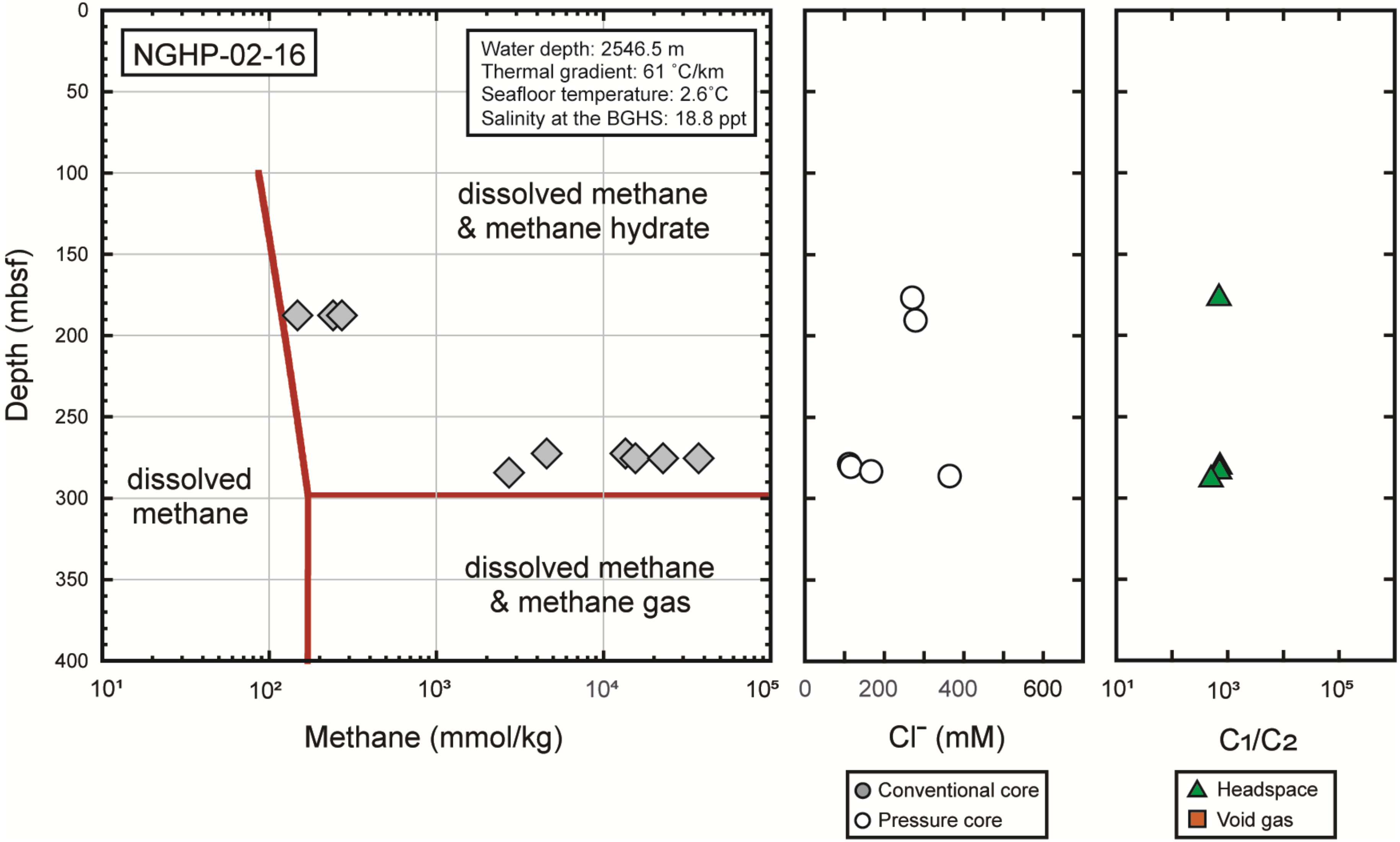


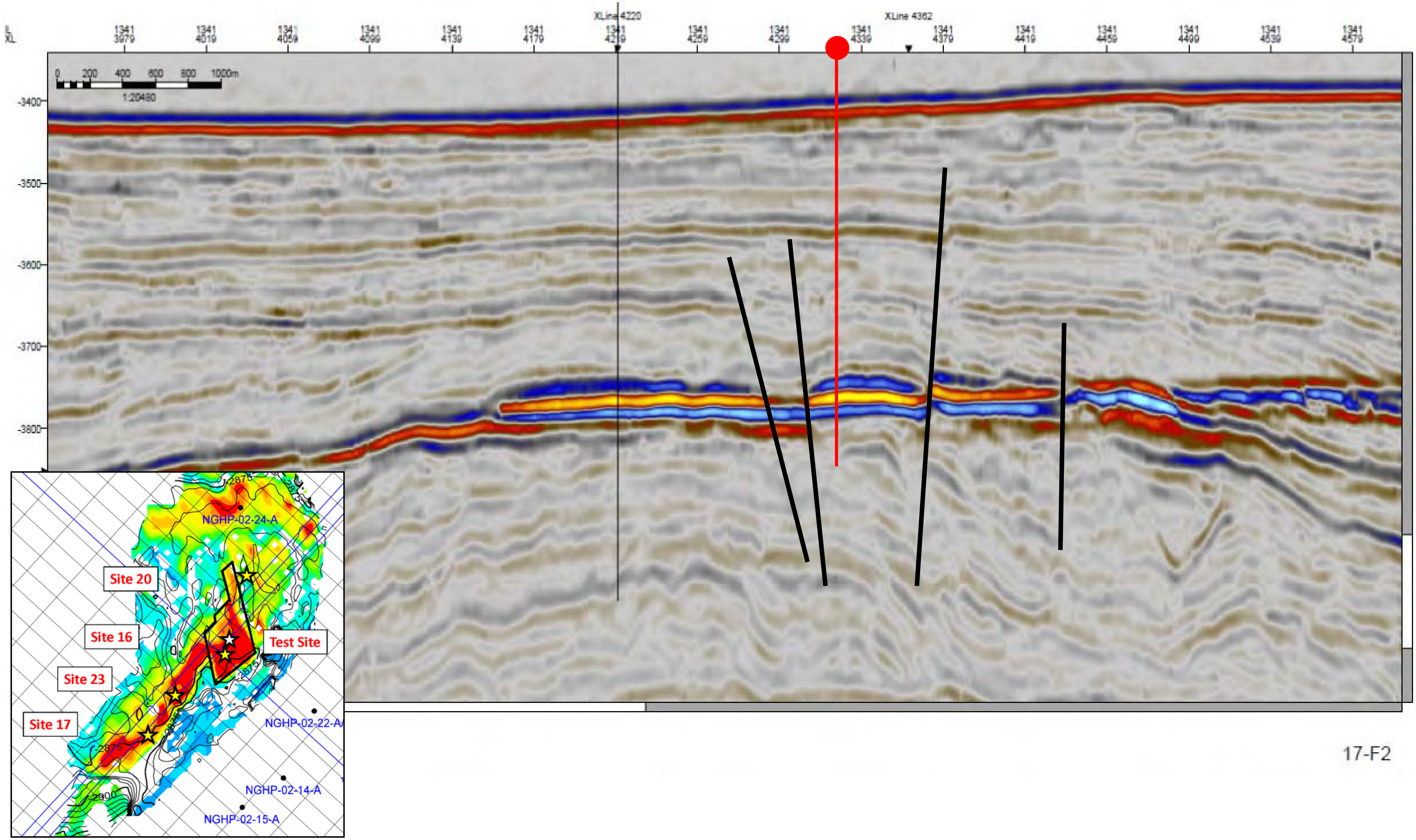




**Area B**
**Krishna-Godavari Gas Hydrate System**
***Toe-of-Slope to Outer Basin Floor Fan***

# India NGHP-02: Area-B   Site NGHP-02-16



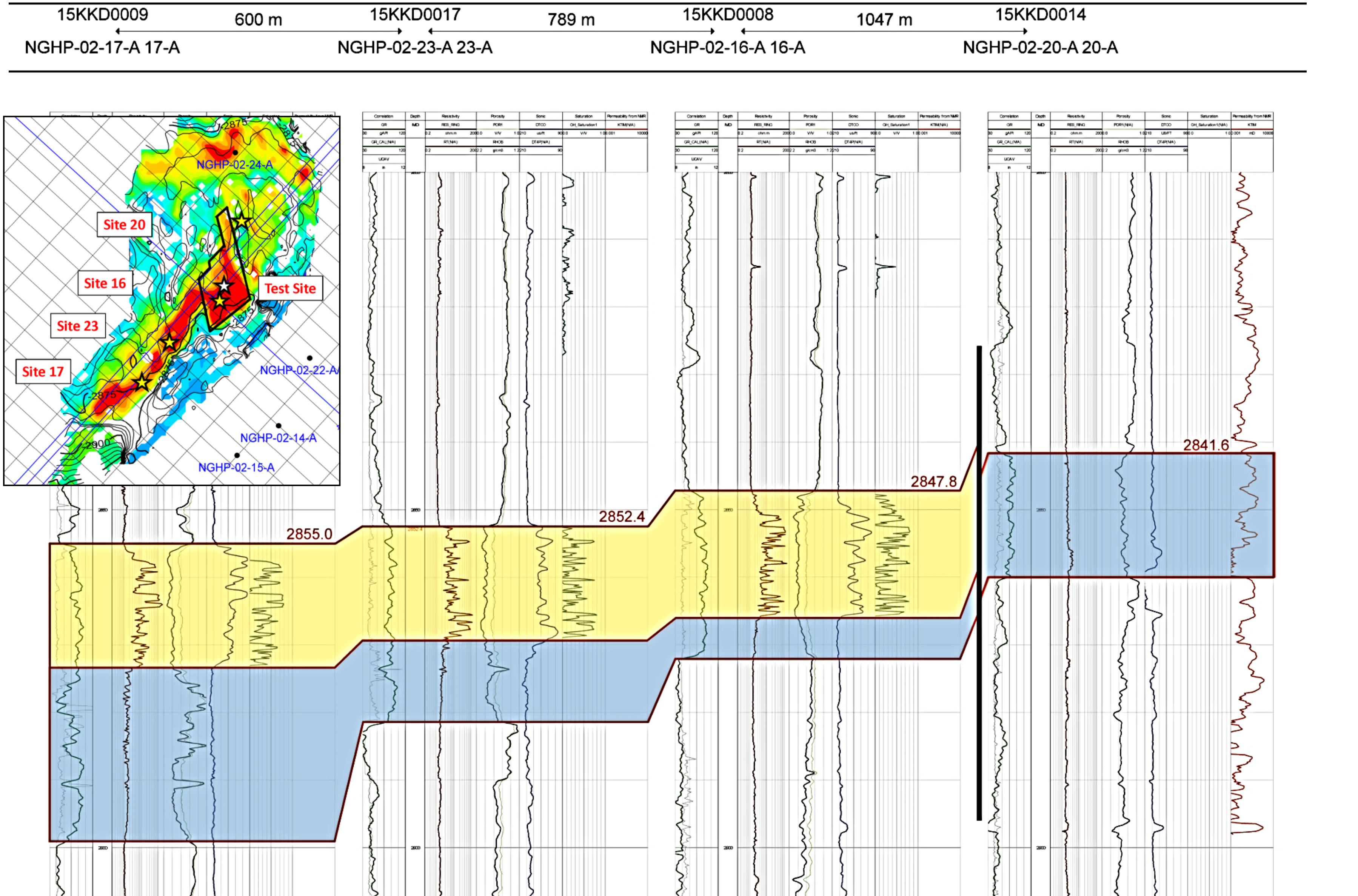
# NGHP-02: Area-B Lower (R2) Reflector/Reservoir




17-F2

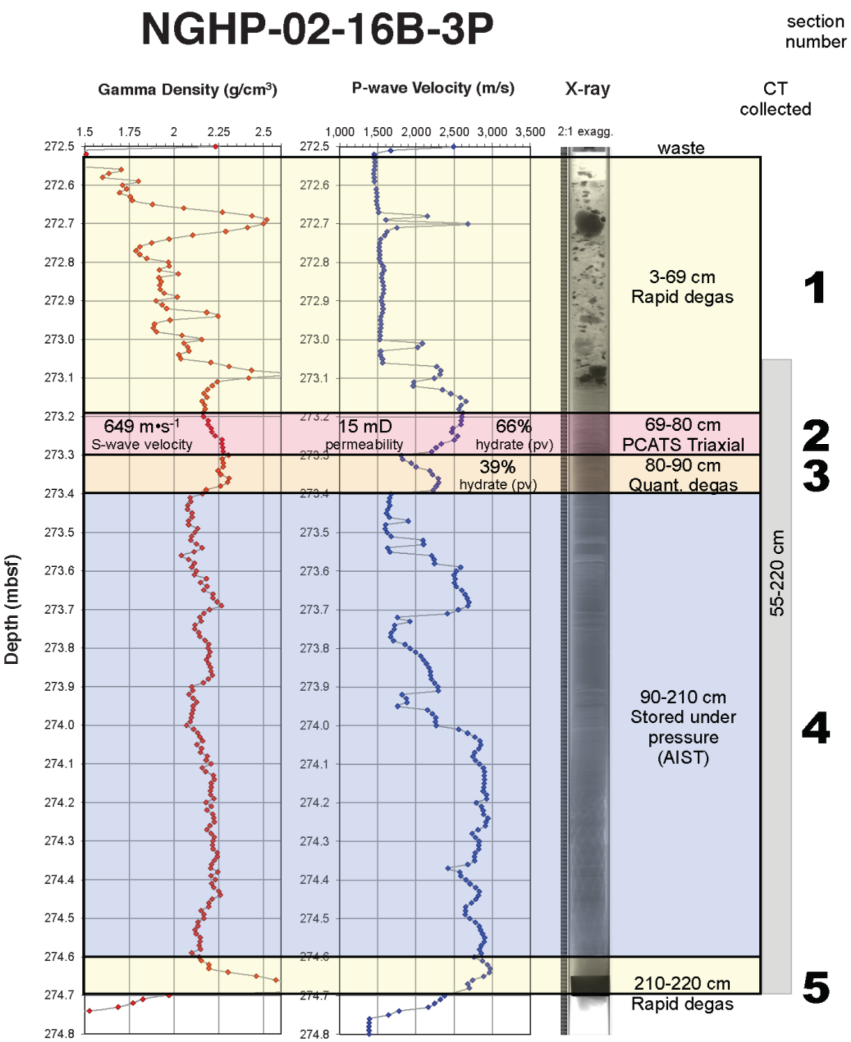
# NGHP-02: Area B Lower (R2) Reflector/Reservoir

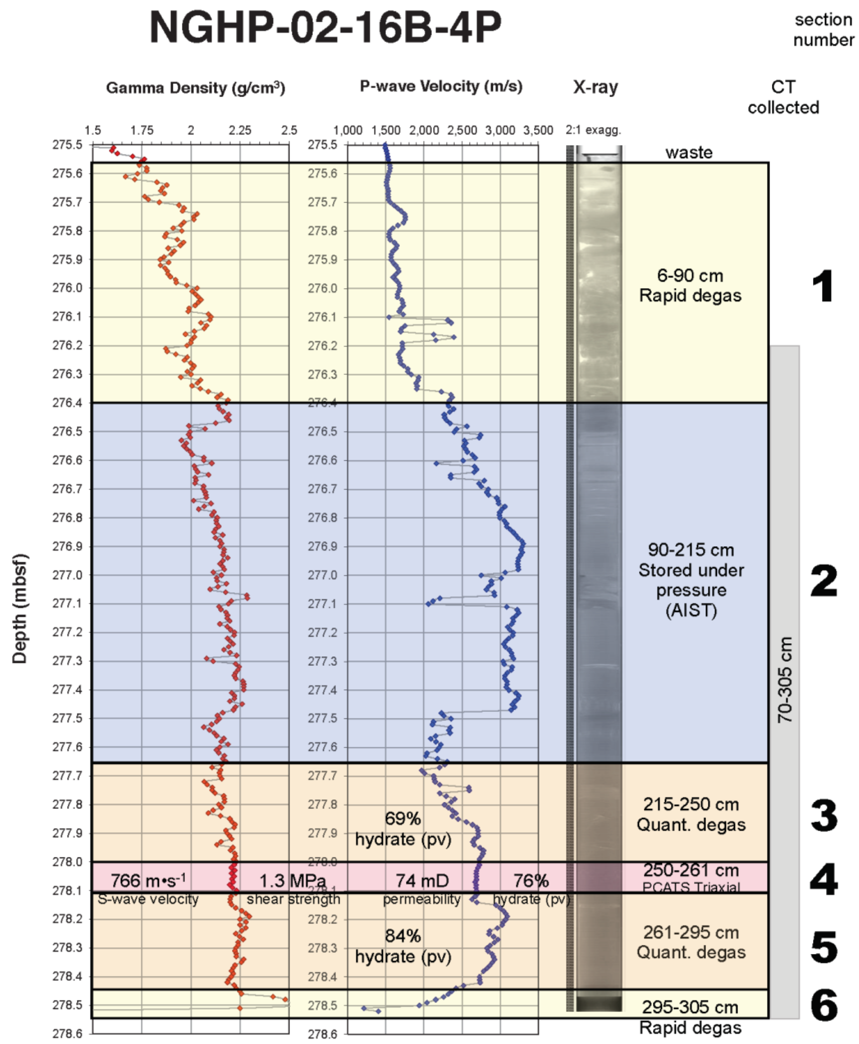
## *Log Section - Holes NGHP-02-17A -23A -16A -20A*



# NGHP-02: Area B Lower (R2) Reflector/Reservoir

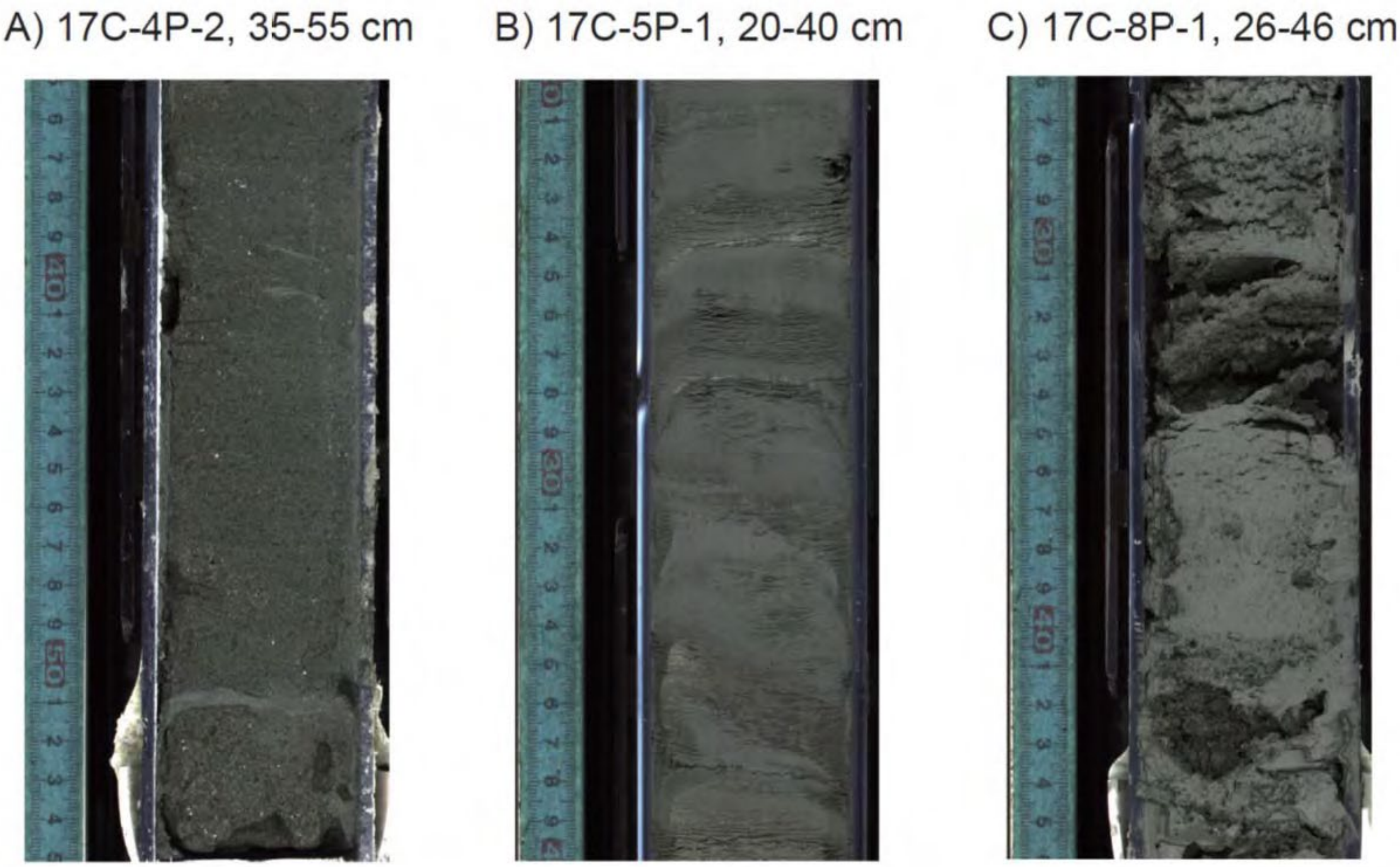
## *Pressure Cores – typical GH-bearing reservoir section*



# NGHP-02: Area B Lower (R2) Reflector/Reservoir

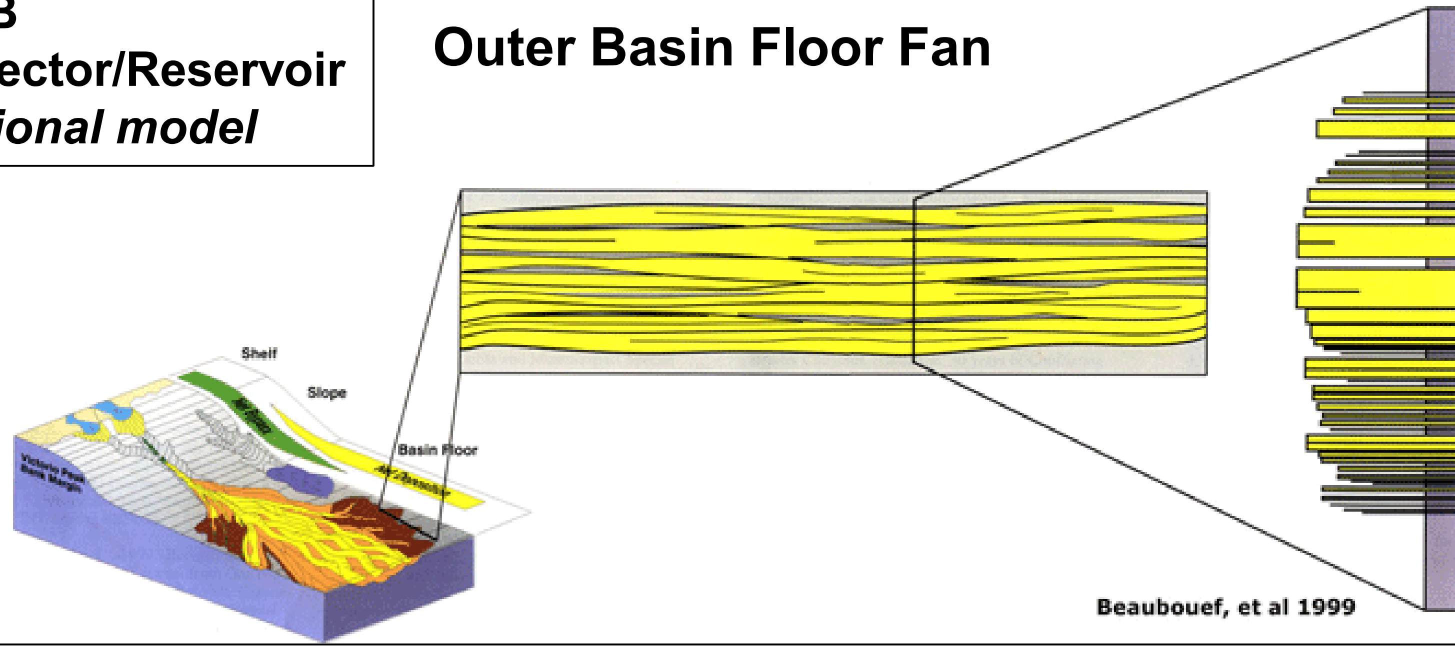
## *Pressure Cores – core derived lithology*



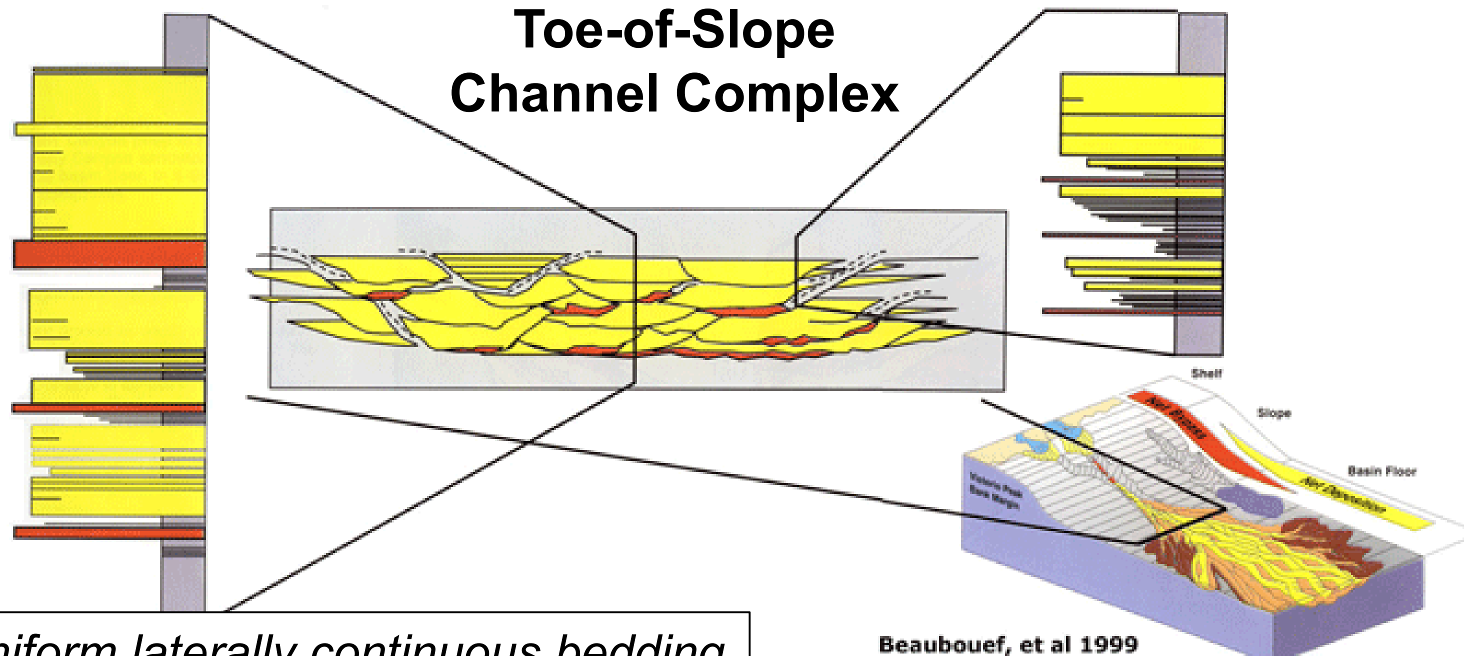

***A) Massive gray sand; B) Thin silt layers interlayered with silty clay; C) Gray clay***

**NGHP-02 Area-B**
**Lower (R2) Reflector/Reservoir**
***Analog depositional model***

## Outer Basin Floor Fan



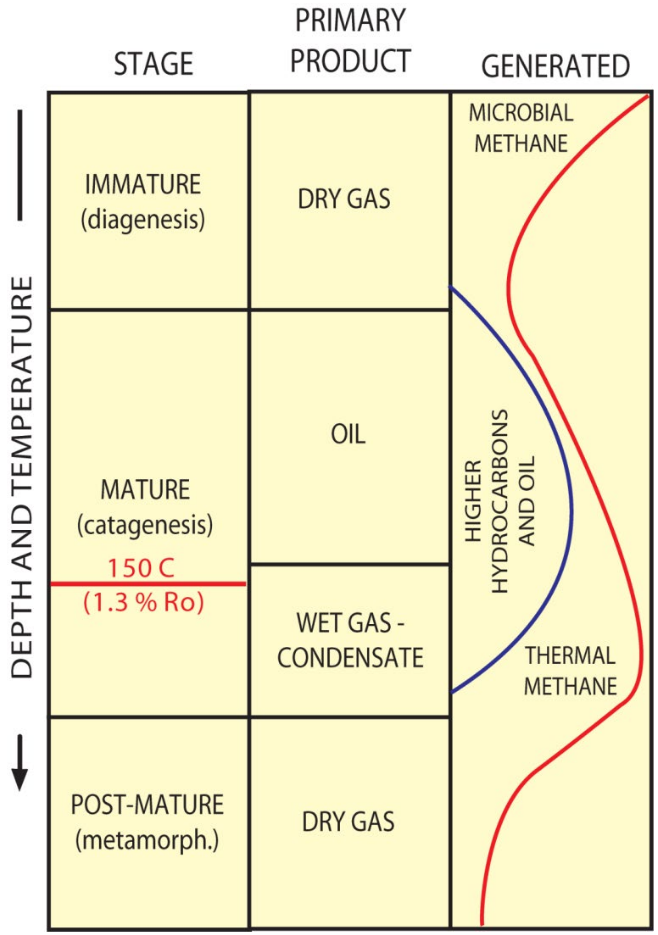

## Toe-of-Slope Channel Complex

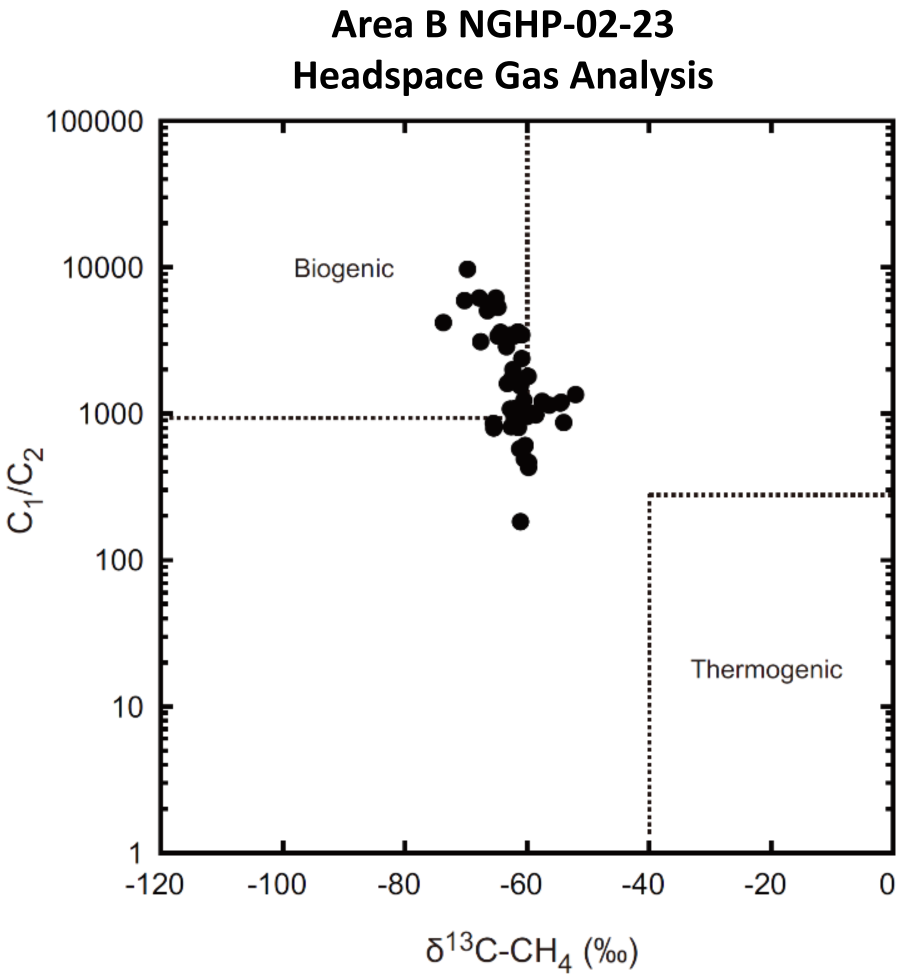



*Characteristic uniform laterally continuous bedding*

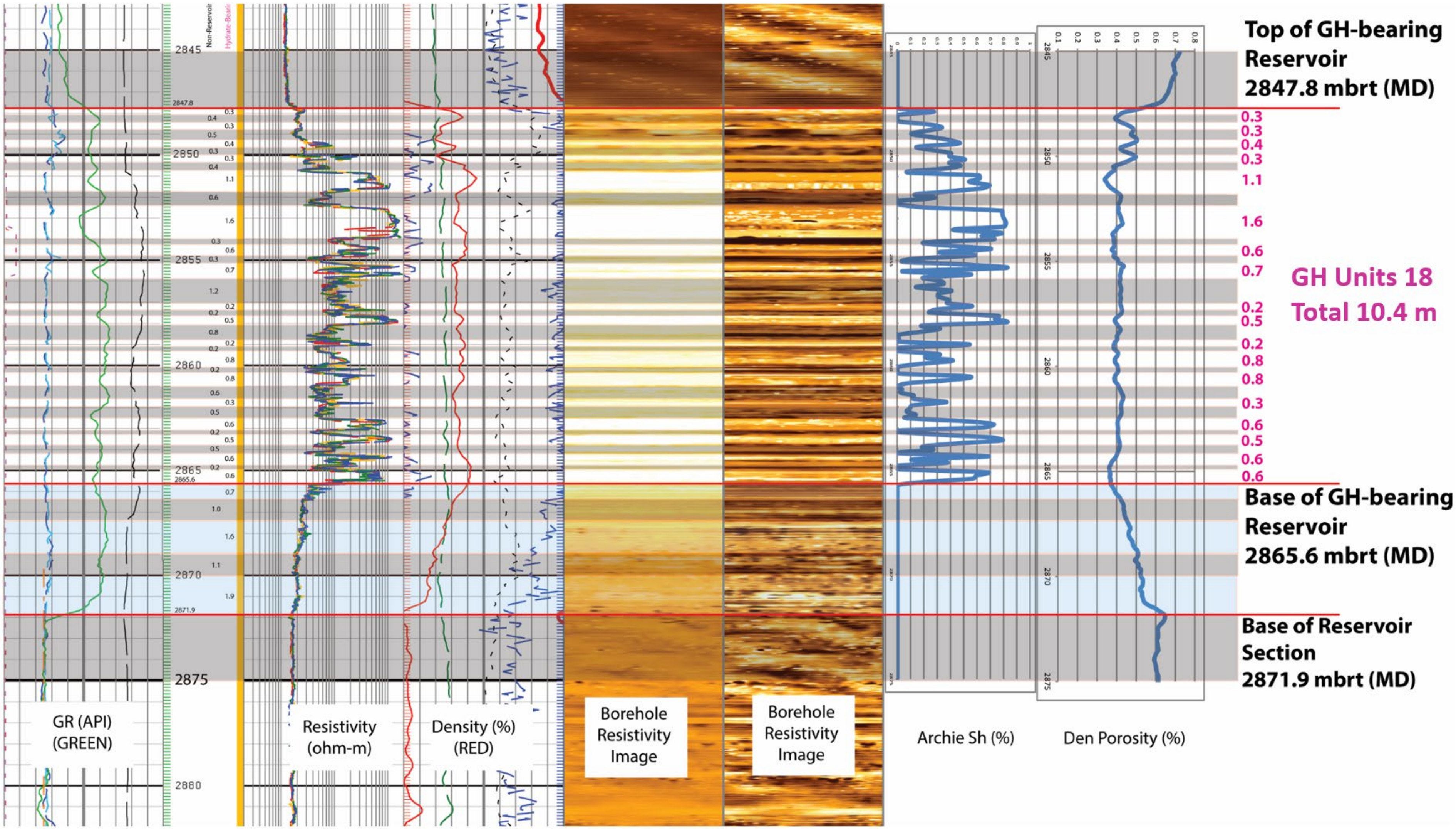
# Gas Hydrate Petroleum System

## *Gas Source*



# Area B: Site NGHP-02-16 Reservoir Model




***Gas Hydrate Units:*** **Reservoir total porosity (40%); Gas Hydrate Saturation (80%); Effective permeability (two assumed cases 10 mD and 0.1 mD)**

# NGHP-02 Most Significant Accomplishments

- Acquired LWD and core data confirmed the presence reservoir-quality sands in most every site established during NGHP-02, with gas hydrate occurrences closely matching pre-drill predictions.
- NGHP-02 drilling has confirmed the project developed depositional models for the sand-rich depositional faces in the Krishna-Godavari and Mahanadi Basins.
- Established the existence of a fully developed gas hydrate system in Area-C of the Krishna-Godavari Basin, discovery of interconnected depositional system.
- Discovered the thickest known gas-hydrate-bearing sand reservoir system in the world associated with the Area-C Site NGHP-02-08 and -09 channel-levee prospects.
- The acquisition of closely spaced LWD and core holes in the Area-B L1 Block gas hydrate accumulation have provided one of the most complete three-dimensional petrophysical-based view of any known gas hydrate reservoir system in the world.
- Area-B and Area-C contain important world class gas hydrate accumulations and represent ideal sites for consideration of future gas hydrate production testing.

# JOURNAL OF MARINE AND PETROLEUM GEOLOGY SPECIAL ISSUE

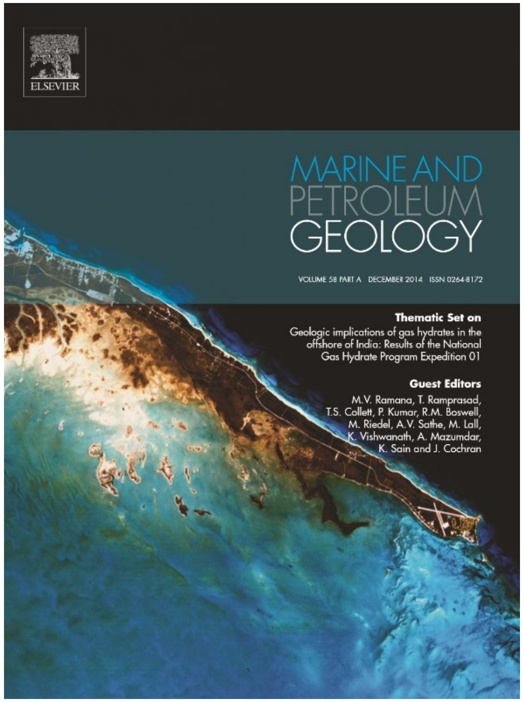
**Title: Marine Gas Hydrate Reservoir Systems Along the Eastern Continental Margin of India: Results of the National Gas Hydrate Program Expedition 02**

**Guest Editors: M. Pratap, S.K. Singh, K.K. Chopra, P. Kumar, Y. Yamada, N. Tenma, K. Sain, U.S. Sahay, R. Boswell, W. Waite (Managing Guest Editor: T.S. Collett)**

**<u>Contents</u>**

Preface
Operational and Scientific Accomplishments and Summaries
NGHP-02 Pre-Expedition Drill-Site Evaluation
Lithostratigrahic and Paleoenvironmental
Physical Properties
Inorganic Geochemistry
Organic Geochemistry
Microbiology
Pressure Core Acquisition and Analysis
Well Log Analysis
Seismic Characterization
Gas Hydrate Production and Mechanical Testing and Modeling

***Status as of 14-OCT-2018 – Total of 50 Submissions***



# JOURNAL OF MARINE AND PETROLEUM GEOLOGY SPECIAL ISSUE

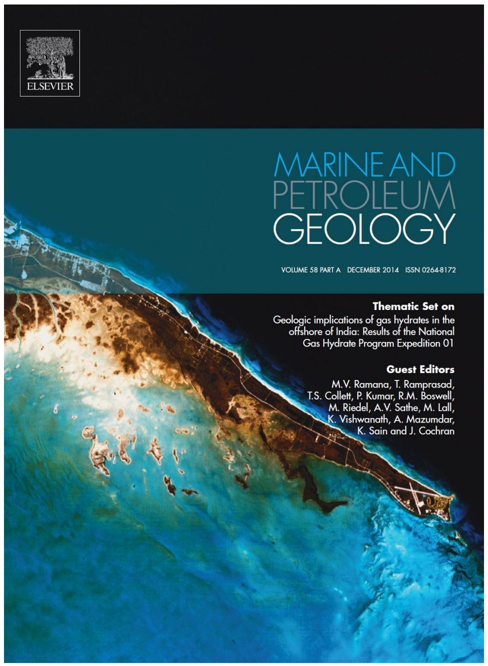
## JMPG NGHP-02 Expedition Summary Papers

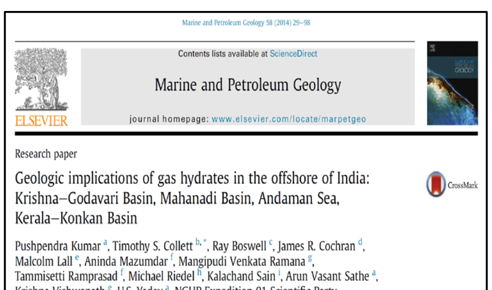
**India National Gas Hydrate Program Expedition 02 Summary of Scientific Results: Gas Hydrate Systems along the Eastern Continental Margin of India**
Timothy S. Collett, Ray Boswell, William F. Waite, Pushpendra Kumar, Mahendra Pratap, Sandip Kumar Roy, Krishan Chopra, Sunil Kumar Singh, Yasuhiro Yamada, Norio Tenma, John Pohlman, Margarita Zyrianova

**India National Gas Hydrate Program Expedition 02 Summary of Scientific Results: Evaluation of Natural Gas Hydrate-Bearing Pressure Cores**
Ray Boswell, Jun Yoneda, William Waite

**India National Gas Hydrate Program Expedition 02 Summary of Scientific Results: Numerical Simulations of Gas Hydrate Reservoirs**
Ray Boswell, Evgeniy Myshakin, George Moridis, Yoshihiro Konno, Timothy S. Collett, Taiwo Ajayi, Yongkoo Seol

**India National Gas Hydrate Program Expedition 02 Operational and Technical Summary**
Pushpendra Kumar, Timothy S. Collett, K. M. Shukla, U. S. Yadav, M. V. Lall , Krishna Vishwanath





Marine and Petroleum Geology 58 (2014) 29–98

Contents lists available at ScienceDirect

Marine and Petroleum Geology

journal homepage: www.elsevier.com/locate/marpetgeo

Research paper

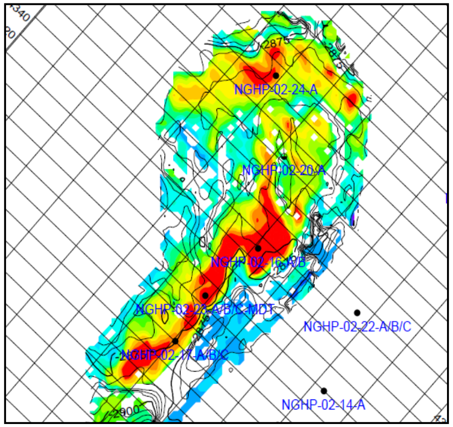
Geologic implications of gas hydrates in the offshore of India: Krishna–Godavari Basin, Mahanadi Basin, Andaman Sea, Kerala–Konkan Basin

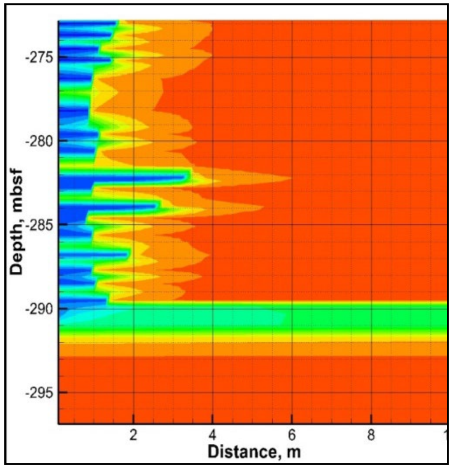
Pushpendra Kumar [a], Timothy S. Collett [b,*], Ray Boswell [c], James R. Cochran [d], Malcolm Lall [e], Aninda Mazumdar [f], Mangipudi Venkata Ramana [g], Tammisetti Ramprasad [f], Michael Riedel [h], Kalachand Sain [i], Arun Vasant Sathe [a], Krishna Vishwanath [e], U.S. Yadav [a], NGHP Expedition 01 Scientific Party

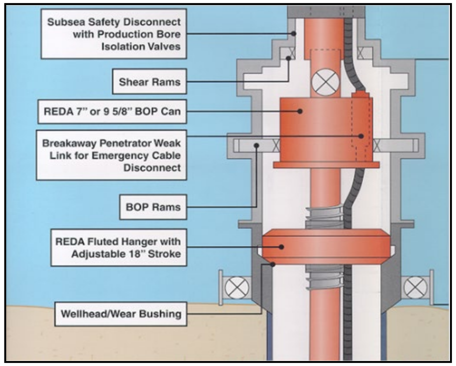
# NGHP Considerations

- Sustained Project Support and Staffing Requirements
  - Sustained support of governmental, industry and academic research institutions engaged in gas hydrate research.
  - Continued development of domestic R&D capabilities through domestic and international governmental and academic partnerships (Japan, US, Korea, China, EU, etc).
  - Identify key industrial experts (engineering, G&G, etc) to support the NGHP-03 design and operational phases.
- International Cooperatives and Reporting
  - Continued develop of domestic and international research partnerships and cooperatives; support and contribute to domestic and international conferences and technical meetings.
  - Publish NGHP-02 Scientific Results Volume, Journal of Marine and Petroleum Geology Special Issue.

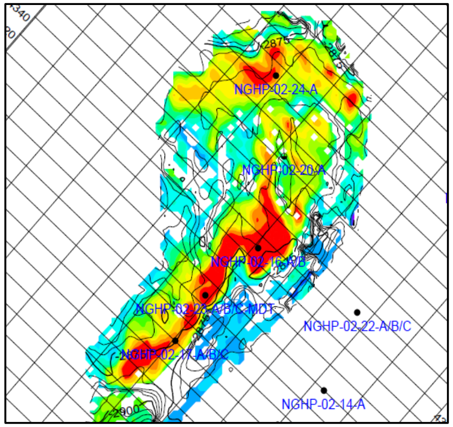
# NGHP-03 Test Planning

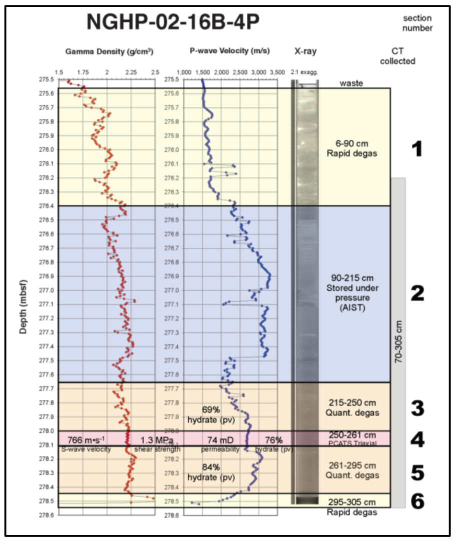


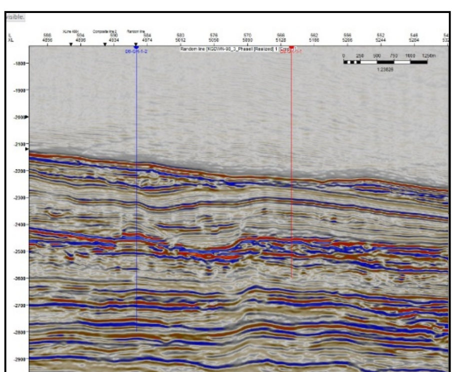




- Test Site Review and Characterization
  - Inventory and assess candidate test sites with existing NGHP and industry data through an integrated G&G review effort.
  - Assess requirements for additional G&G data acquisition and analysis (geophysical data, logging/coring operations, etc).
- Production Test Design
  - Develop and refine production-mechanical models.
  - Numerical simulation of well performance during planned production tests, develop tests procedures and mitigation approaches.
  - Test design to prioritize insight toward field scale reservoir response and economics.
- Operational Planning
  - Flexibility: Project management plan and structure should anticipate and enable changes in operations.
  - Development of an integrated project risk analysis and management process.

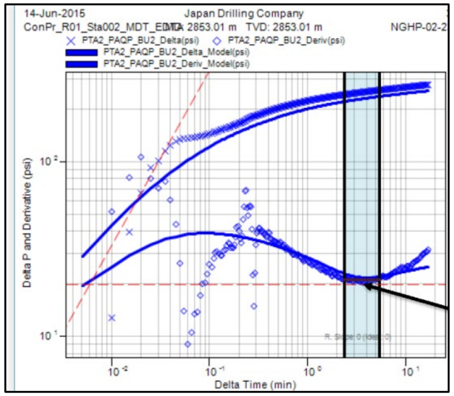


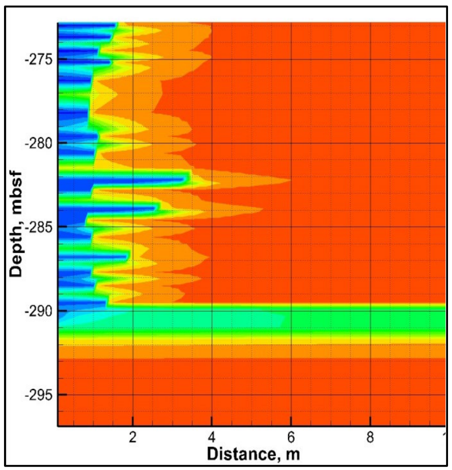



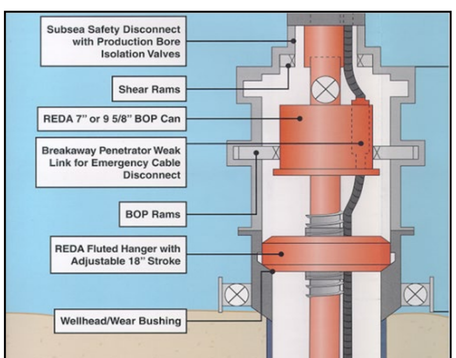



# NGHP-03 Test Planning

- **Test Site Review and Characterization**
  - **Area B/Site 16 – further evaluation needed to confirm nature of reservoir. Optimization of site location for best hydraulic isolation. Can be based on existing data.**
  - **Area C/Site 9 (other areas including KGDWN98-2) – additional data and further evaluation is needed to characterize the reservoir system. New data is needed.**
  - **Update both reservoir models as new data analysis becomes available.**
  - **Field data acquisition for additional site characterization and engineer design would require G&G field operations.**

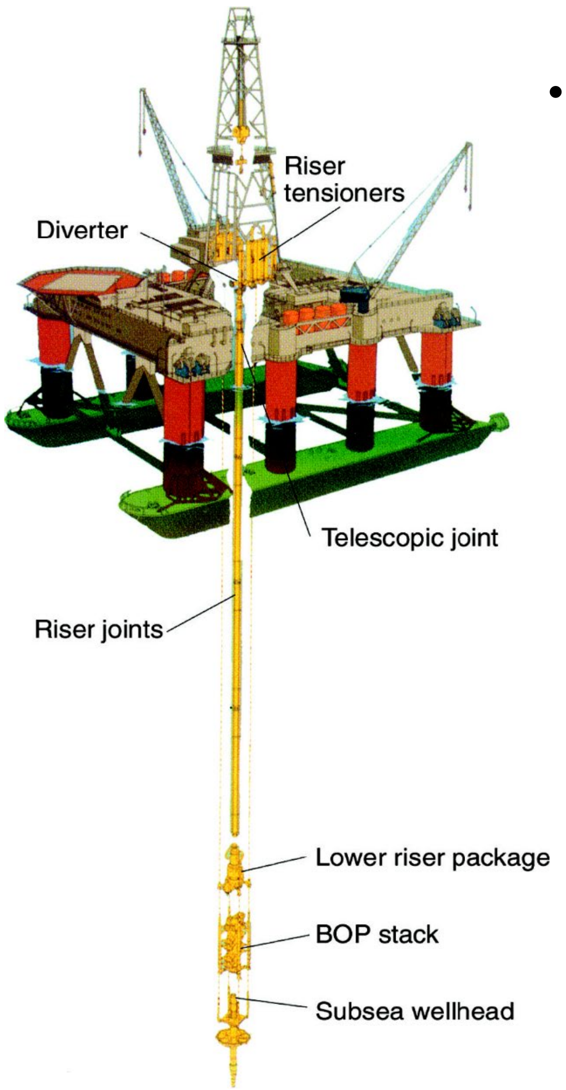



# NGHP-03 Test Planning

- Production Test Design (engineering design)
  - Artificial Lift (ESP, gas lift, multi-phase pump) surface kit, power source, reliability, repair options, redundancy.
  - Sandface completions – Screen type and size and gravel selection dependent on reservoir grain size; simple vs. more advance completions.
  - Subsidence induce failures at reservoir level and seafloor.
  - Flow Assurance - Evaluate chemical or thermal methods for clearing the wellbore (secondary gas hydrate and ice) in response to shutdowns.
  - Met-Ocean conditions and impact on riser and conductor systems.
  - Project time and associated cost.




# NGHP-03 Test Planning

- Operational Planning
  - Establish observation (monitoring) holes; drilling considerations, logging operations (LWD and advanced wireline logs), and instrumentation including T&P gages, distributed systems (DTS, DSS, DAS), etc.
  - Pressure coring operations in support of site characterization studies and acquiring reservoir/petrophysical data needed for production/mechanical modeling and test design.
  - Establish, instrument, and complete main production test hole.
  - Deploy seafloor monitoring system.
  - Conduct pre-test and post-test 3D/4D VSP.
  - Conduct pre-test and post-test 3D/4D seismic survey.
  - Conduct 60 or 90 days of flow testing.
  - Conduct production test monitoring (before, during, and after testing operations).
  - Suspend and/or abandon test wells.

# Republic of Korea

NATIONAL ENERGY TECHNOLOGY LABORATORY

DOE-MKE MoU: NETL-TAMU-KIGAM CA: NETL-GHDO joint funding for NL FWPs

## UBGH-01 (2007)/UBGH-02 (2010)

- USGS support
- DOE support for US scientist participation
- Special Volume publication in 2014

## NETL, USGS, LBNL support for UBGH-03 planning

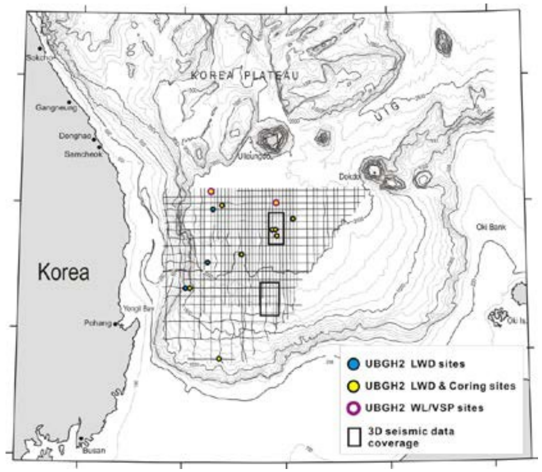
- Site selection advisory committee
- Numerical prediction of production response

## Numerical Simulation Studies

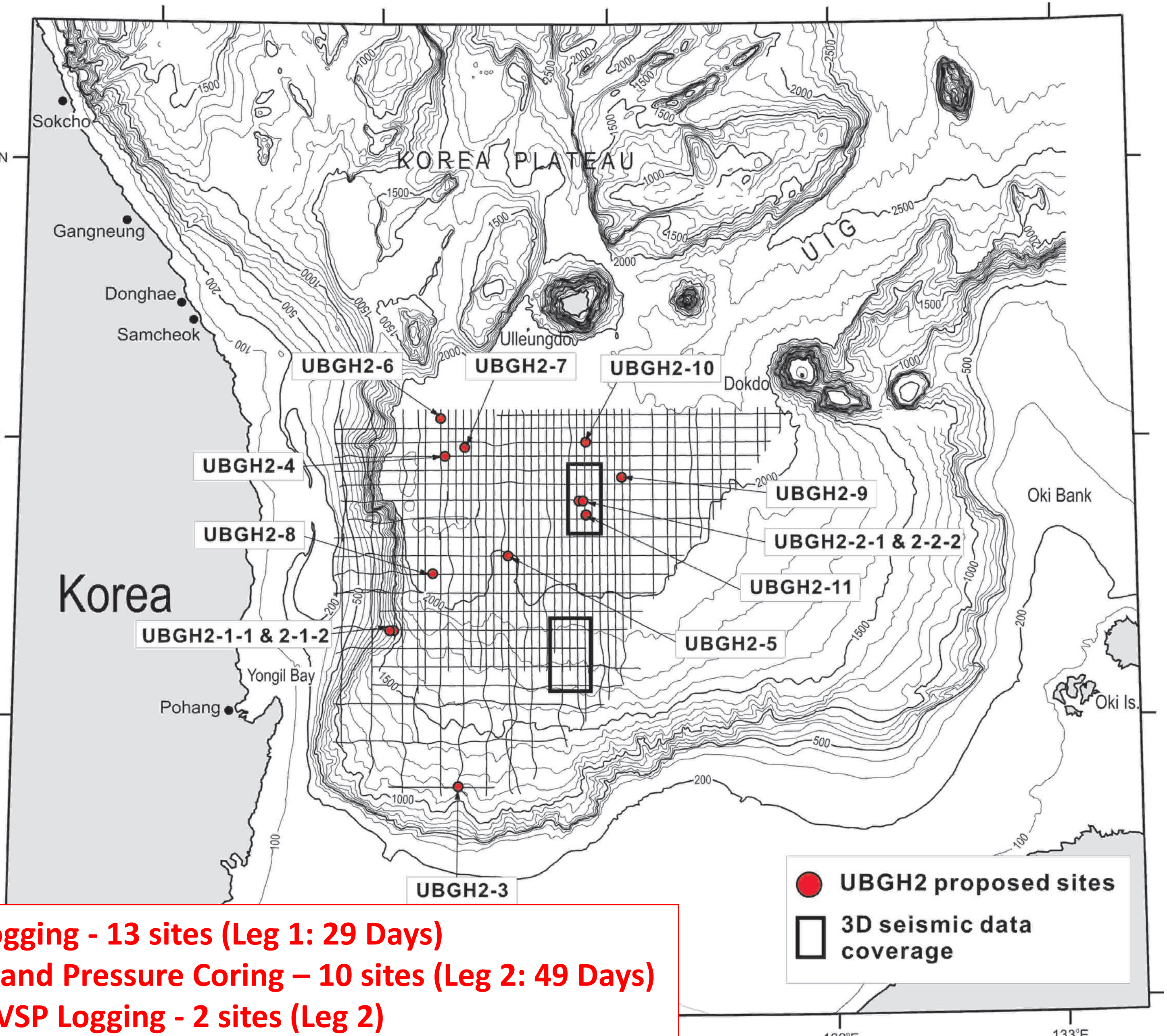
- Ongoing Collaborations KIGAM, LBNL, PNL

## Collaboration with Texas A&M

- Project leverages data KIGAMs unique large-scale reactors

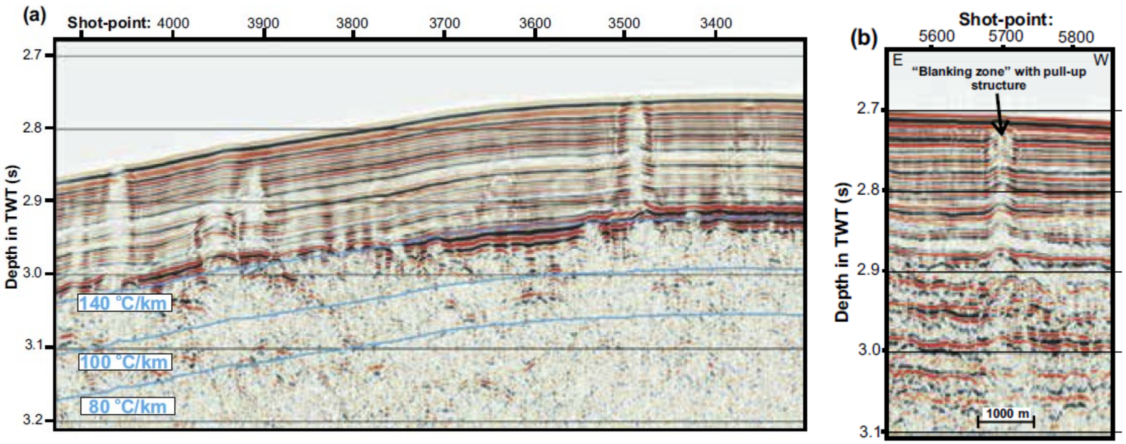




# Ulleung Basin Gas Hydrate Drilling Expedition (UBGH2) 2010

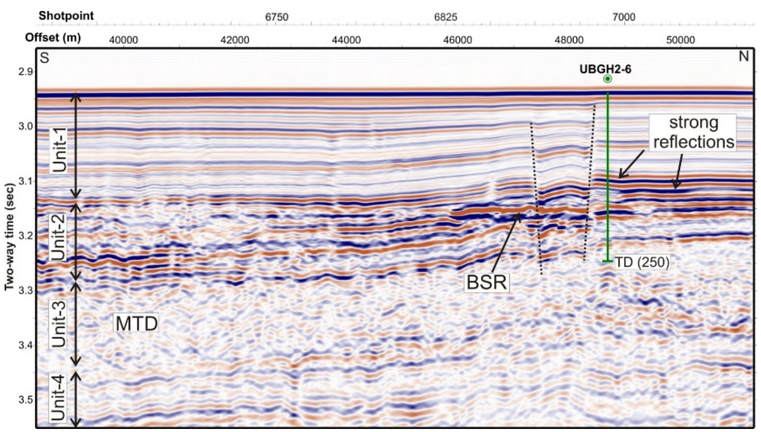


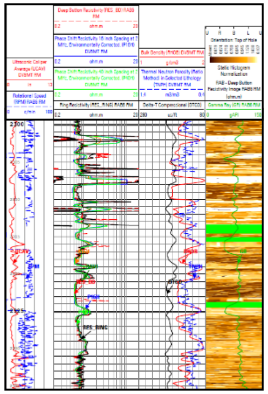

LWD-MWD Logging - 13 sites (Leg 1: 29 Days)
Conventional and Pressure Coring – 10 sites (Leg 2: 49 Days)
Wireline and VSP Logging - 2 sites (Leg 2)

# Ulleung Basin Gas Hydrate Prospects

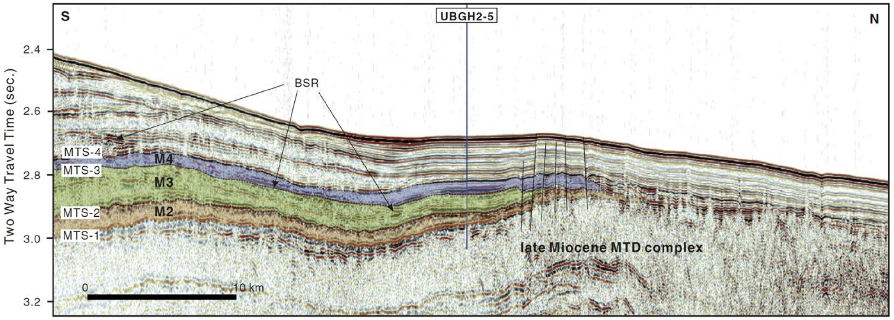


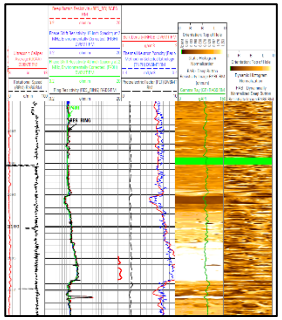

## *Chimney structures*



## *Turbidite sands*



## *Sandy debris flows*

LWD-MWD Logging - 13 sites (Leg 1)
Conventional and Pressure Coring – 10 sites (Leg 2)
Wireline and VSP Logging - 2 sites (Leg 2)

Korea Institute of Geoscience and Mineral Resources

INTERNATIONAL SCHOOL FOR GEOSCIENCE RESOURCES (IS-Geo)
KOREA INSTITUTE OF GEOSCIENCE AND MINERAL RESOURCES (KIGAM)

# Uconventional Oil and Gas Resources Regular Training Course

**Module 3. Gas Hydrate (February 5-9, 2018)**

Day 1. Gas Hydrate Structures, Stability, and Physical Properties by Drs. Lee, Collett, Waite

Day 2. Gas Hydrate Systems and Geophysical Characterization by Drs. Haines, Collett, Ryu

Day 3. Gas Hydrate Production Field, Laboratory, and Modeling Studies by Drs. Seol, Waite

Day 4. Gas Hydrate System Response to Production by Dr. J-Y Lee

Day 5. Gas Hydrate Geohazard, Climate, and Production Research and Challenges by Dr. Collett, Waite, Ryu

Day 6. Vist *R/V Tamhae II*

***Participants from Korea, Cambodia, Indonesia, Laos, Malaysia, Myanmar, Peru, Phillipines, Thailand, Vietnam***

***Instructors Collett, Waite, Haines (USGS); Seol (DOE-NETL); Ryu, Lee (KIGAM)***

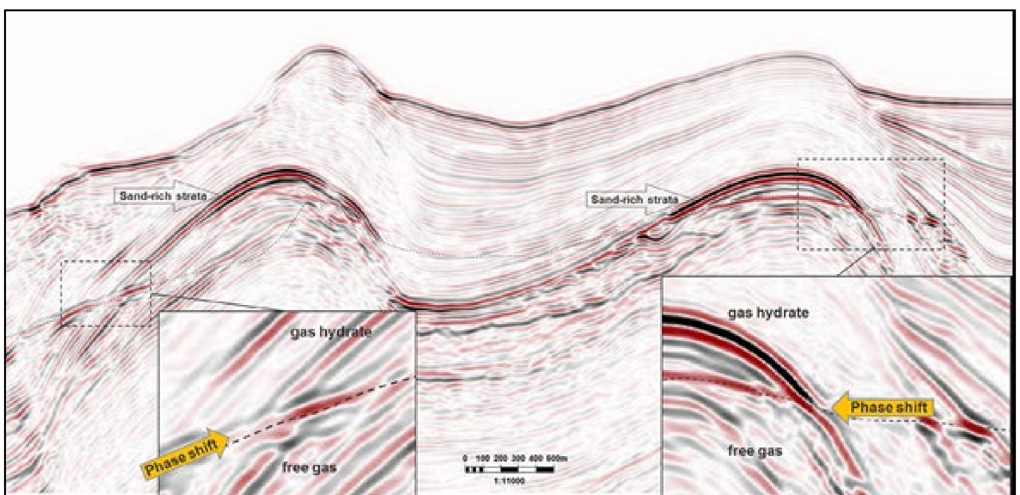
# A Global Review of Gas Hydrate Resource Potential - 2014

*Thomas Reichel and Joseph W. Gallagher, Statoil ASA, Oslo, Norway*


Method:
- Start with 567 basins
- GHSZ
- Hydrocarbon system
- Seismic characterization

Hydrocarbon system:
- Hydrocarbon source
- Migration into the GHSZ
- Reservoir (sand)
- Reservoir seal

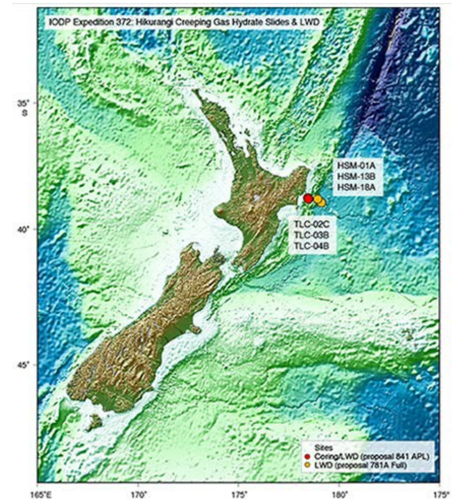
Results:
- Favorable basins 256
- Total of 197 basins evaluated
- Good potential - 14 basins
- Resources - 5 tril cubic meters




# Other International

## New Zealand

- IODP Exp. 372 (Nov-2017 to Jan-2018) "Creeping Deformation"
- NETL supported recent NRL/GNS studies
- NETL supports Stanford U. in NZ PetroMod studies

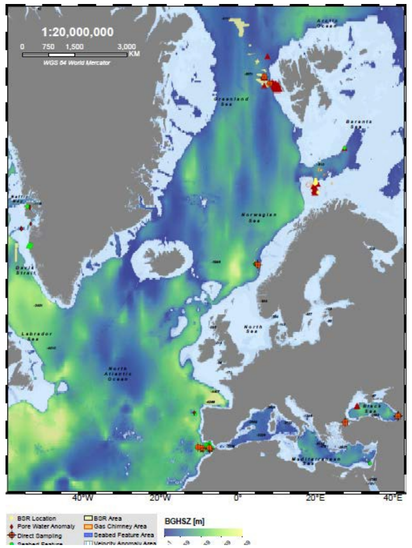



## Europe

- CAGE at University Tromso
- CAGE & MARUM (U. Bremen) expeditions to Svalbard
- "Sugar" Project at GEOMAR - Black Sea MeBO drilling 2017
- MIGRATE (Mediterranean-Israel, Ireland, etc.)
- Engagement with Statoil

## Other

- Taiwan Oct-2018 MeBo drilling (seeps and BSRs)
- Engagement with SENER, IMP (Mexico)
- Engagement with Petrobras (Brazil)
- Ireland, Uruguay, Colombia, S. Africa, Turkey, Vietnam
- Recent publications of gas hydrates offshore Columbia and Malaysia




*MIGRATE (Minshull et al.)*

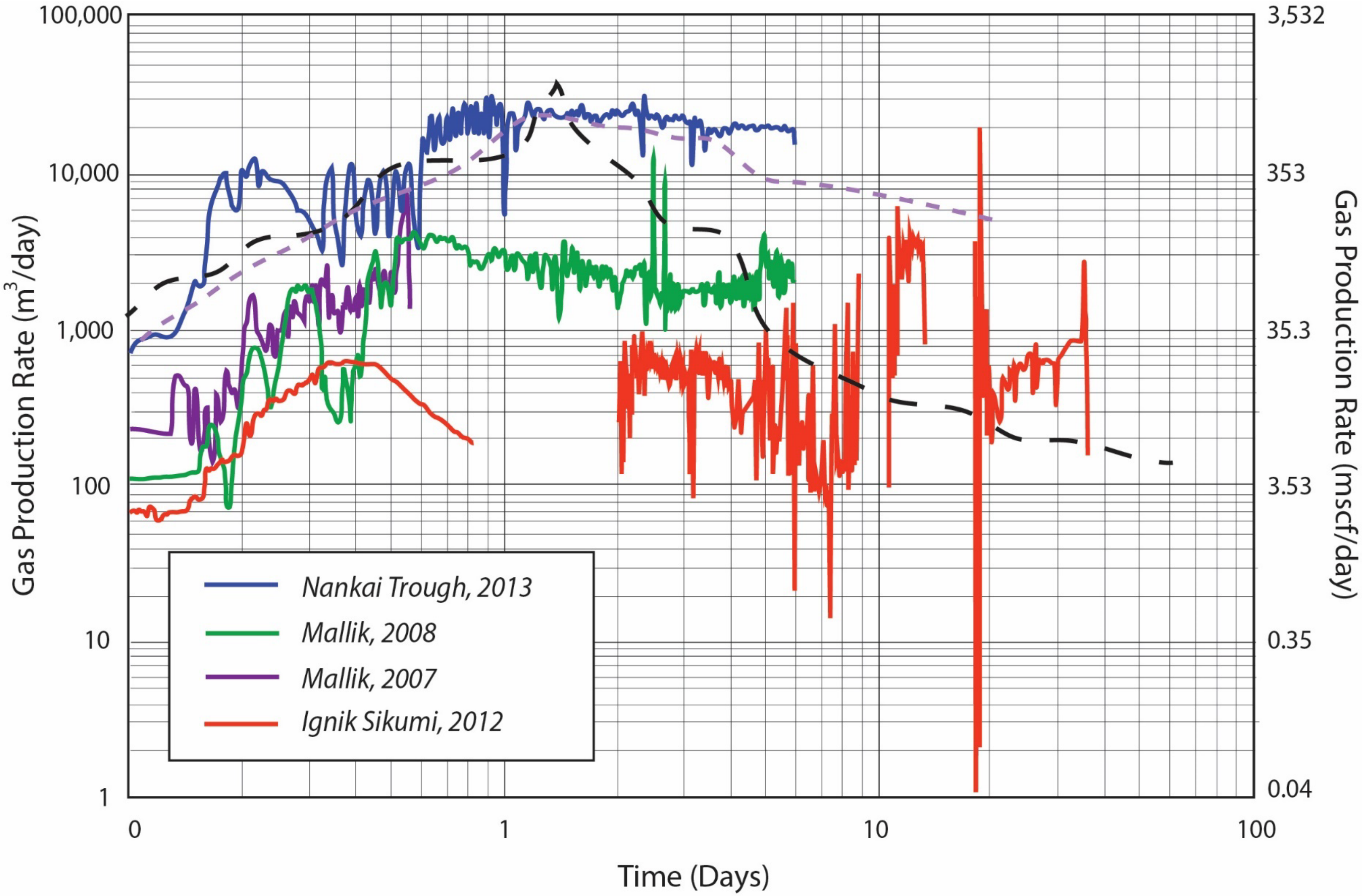
# Gas Hydrate Production R&D





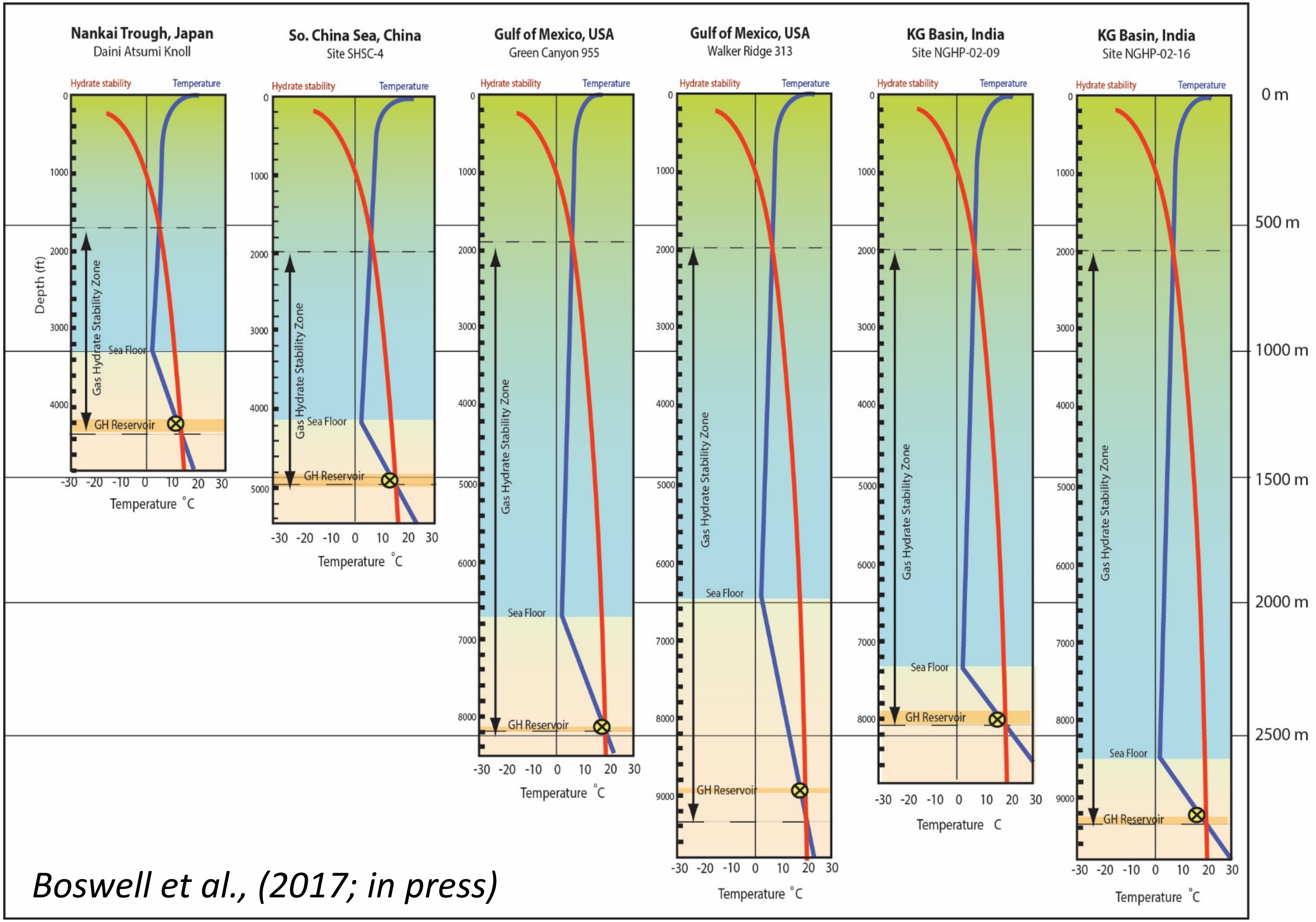
- **Messoyakha (Russia) in the 1970s**
  - Hydrate supported gas production (?)
- **Industry Drill-Stem Tests in the 1970s**
  - NW Eileen St 2; Mallik 1L-38
- **1998, 2002 Mallik (Canada)**
  - Thermal and formation pressure testing
- **2007 BP-DOE-USGS Alaska**
  - Formation pressure testing
- **2007 & 2008 Mallik (Canada)**
  - Depressurization test (6-days)
- **2011-2102 ConocoPhillips-DOE Alaska**
  - $CH_4$-$CO_2$ exchange and depressure test (25-days)
- **2013 Nankai Trough Offshore Test (Japan)**
  - 1st Marine GH production test (6-days)
- **2017 South China Sea Test (China)**
  - Marine GH production test (60-days)
- ***2017 Nankai Trough Test (Japan)***
  - Marine GH production test (two test 10-30 days)
- ***2018-2020 DOE-JOGMEC Alaska***
  - *Extended depressurization testing*
- ***2018-2019 KG Basin Offshore Test (India)***
  - *Extended depressurization test*

# Recent Test Results



# Gas Hydrate Production R&D

## *Global Occurrence of Hydrate-Bearing Sands*




*Boswell et al., (2017; in press)*

# Int'l Gas Hydrate Code Comparison

**2005-2011: Thermodynamics and hydraulics (US, Japan, Canada)**

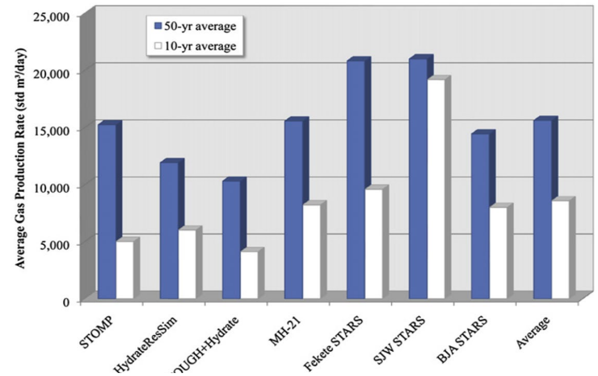
-Wilder et al., 2008 (ICGH-6)    Anderson et al., 2011 (J. Mar Pet Geol 28)

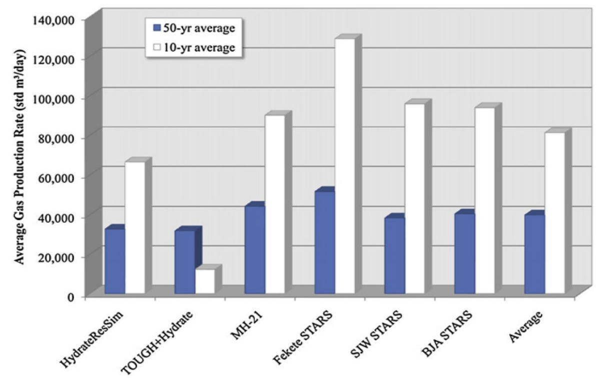
**2017: Integration of geomechanics  (US, Japan, Korea, China, Germany, UK)**

**2017: Collaborative Modeling with Japan and for key sites in India**

**2018: New International Code Comparison Study**

-White (PNNL) et al., 2018-ongoing

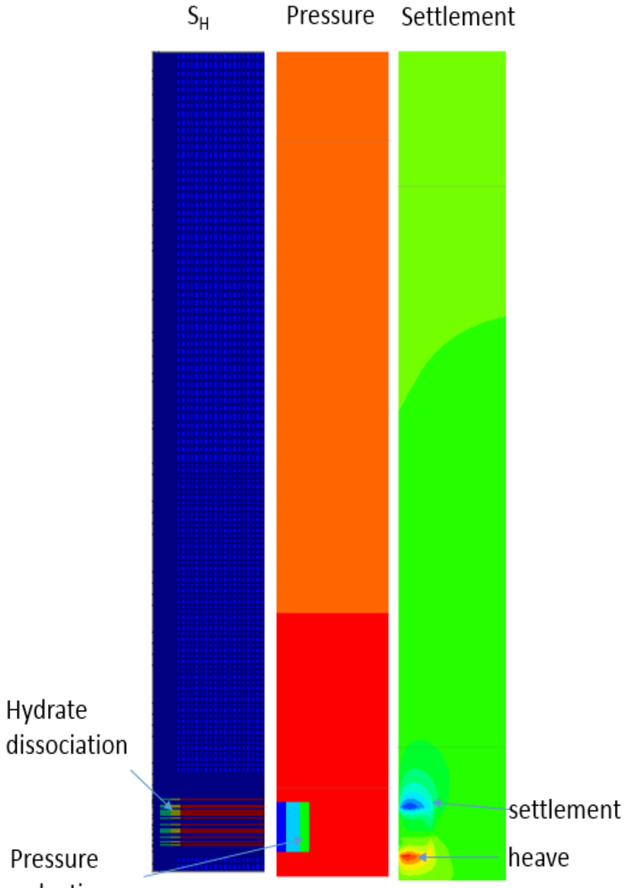



# Geomechanical Production Modeling

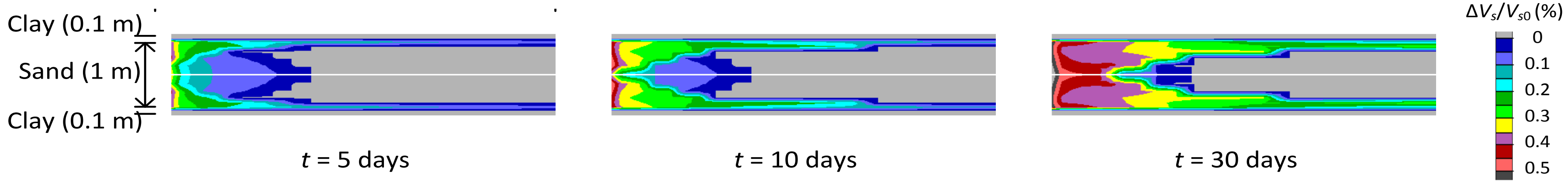
In Support of NGHP-03 Planning

- **NETL and U. Pittsburgh (Lin) Geomechanical Modeling**
- **Two approaches: TplusH+FLAC3D**
  - Coupled approach → maximum settlement of 135 cm; maximum heave of 20 cm
  - De-coupled approach → maximum settlement of 140 cm; maximum heave of 45 cm



Typical Study Scenario

- **NETL and Rensselaer Polytechnic Institute (Uchida) Sand Production Modeling**
  - Sgh = 80%; T= 19.4 C; P = 28.5 Mpa with drawdown to 20 Mpa



# Production Technology Evaluation

Well Completion, Production, Intervention in Support of Alaska Test "Working Group"

- Mud-chiller
- MOBM
- Sidewall pressure coring
- Whole core pressure coring
- Pressure core analyses (onsite and lab-based)
- Full suite LWD and wireline logs
- Monitoring inside and outside casing
- Fiber-optic Temperature Monitoring (DTS)
- Fiber-optic Strain Monitoring (DSS)
- Fiber-optic Acoustic Monitoring (DAS)
- Pressure/Temperature monitoring (gauges)
- Brillouin Scattering System – Strain Monitoring
- VSP (DAS)
- Artificial Lift (ESP, Jet-pumps, etc.)
- Sand control completion

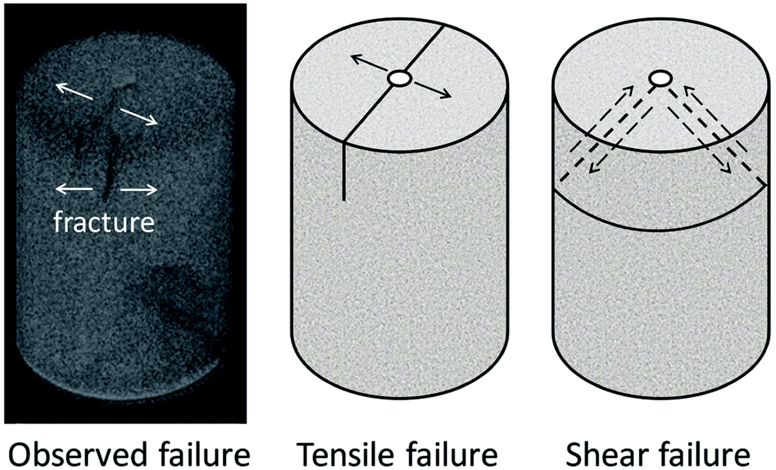
*Examples of tools under consideration*

# Gas Hydrate Production

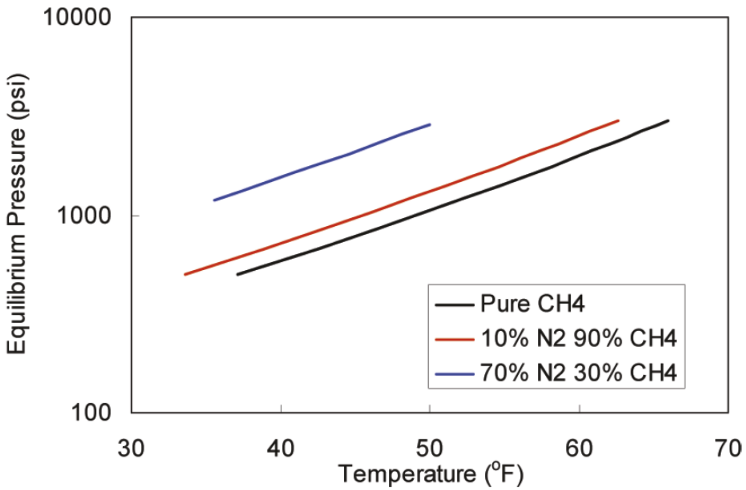
## *"Conventional" and Enhanced Methods*

- **Proven Gas Hydrate Production Technologies**
  - Temperature: Thermal methods
  - Pressure: Depressurization methods
  - Chemical Injection: Methanol, salt
  - Chemical Injection: C02-CH4 Exchange (sequestration)
- **Untested Gas Hydrate Production Technologies**
  - Horizontal Completions
  - Hydraulic Fracturing
  - Enhanced Permeabilities: N2, Methanol

***Hydraulic Fracturing in Methane-Hydrate-Bearing Sand, By Konno et al, 2016***

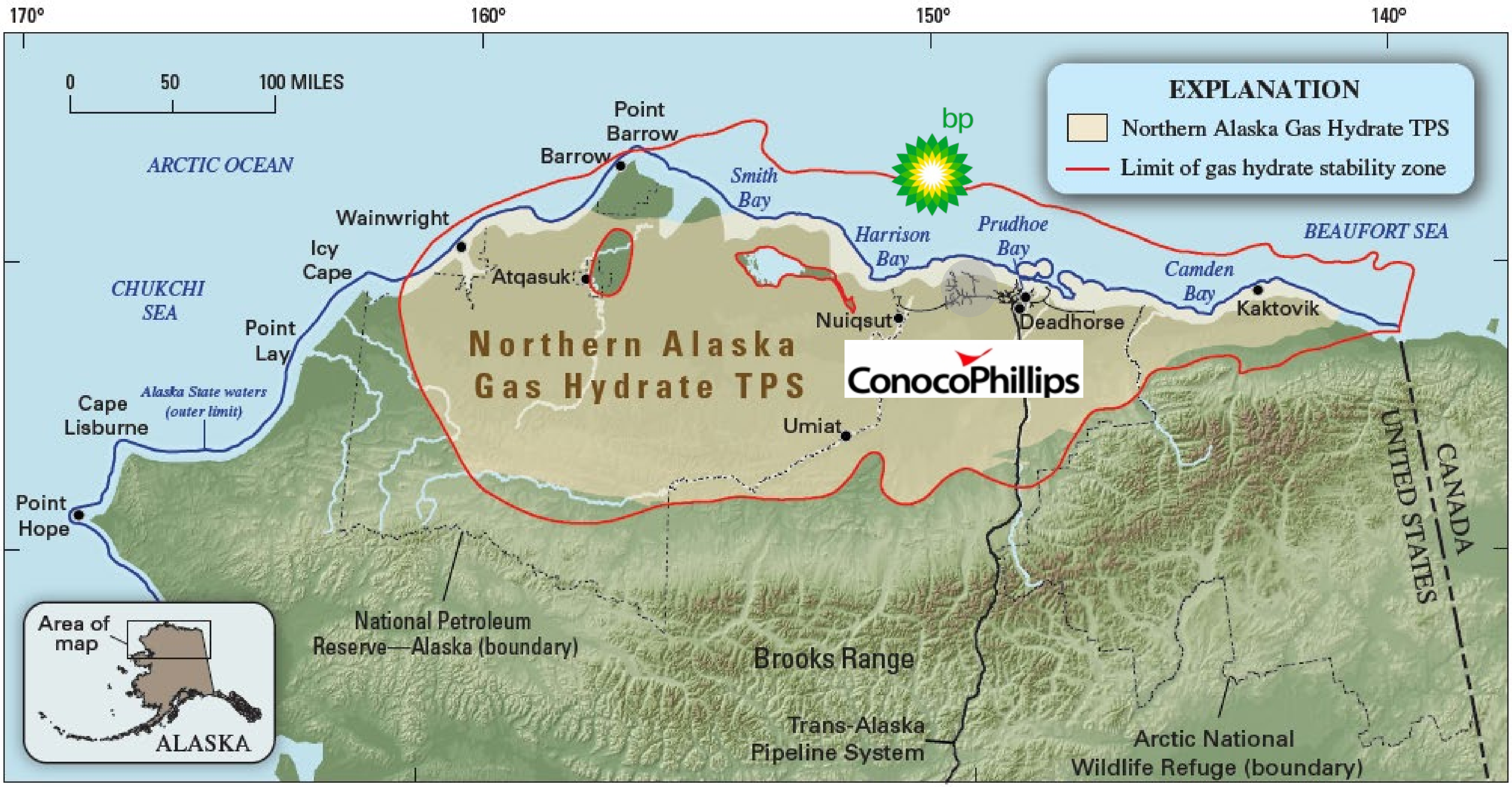



***Hydrate Plug Dissociation via Nitrogen Purge: Experiments and Modeling, By Panter et al, 2011***



# Integration of GH Reservoir Data
## - Pressure (permeability) and Temperature Controls

# Alaska North Slope

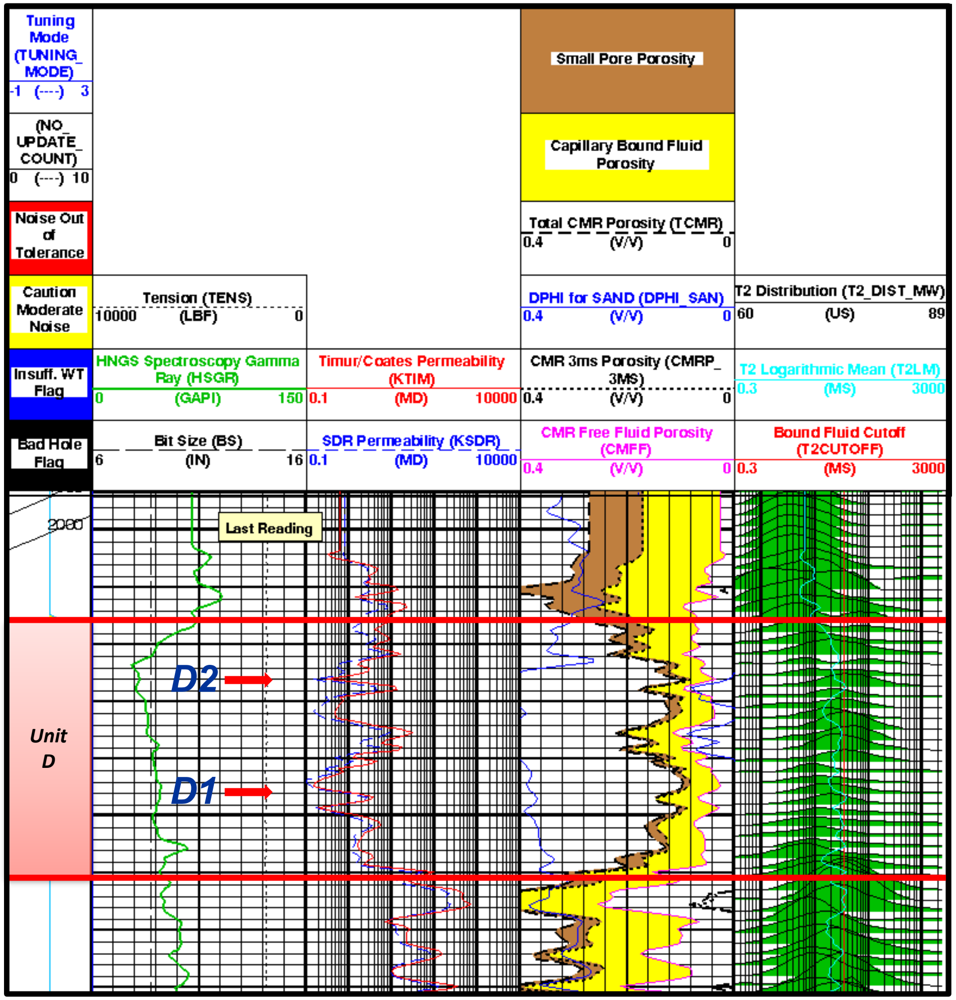



**2007: BPXA Mount Elbert Gas Hydrate Stratigraphic Test**

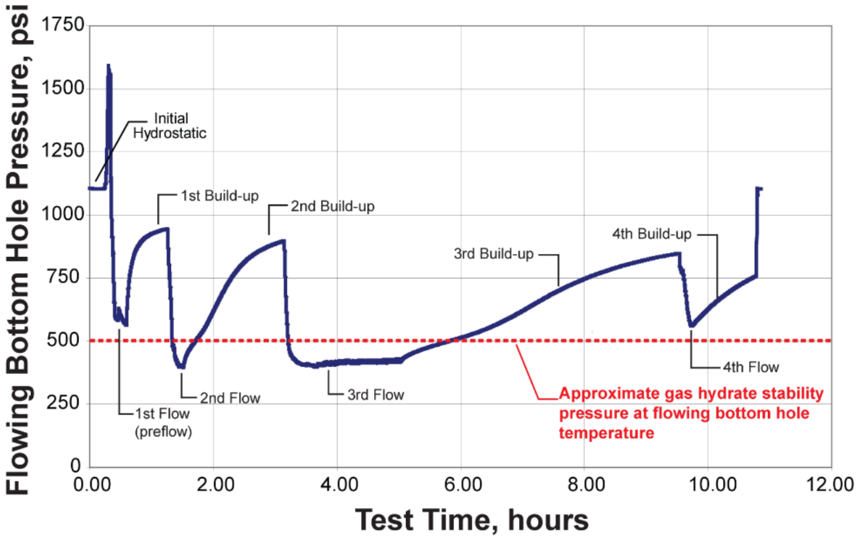
**2011-2012: ConocoPhillips $CO_2$ Displacement Test**

# Alaska North Slope – Mount Elbert Well

## *Reservoir Properties – Effective Permeabilities*




*Mount Elbert 1 – Unit D*




## Gas Hydrate Reservoir Properties

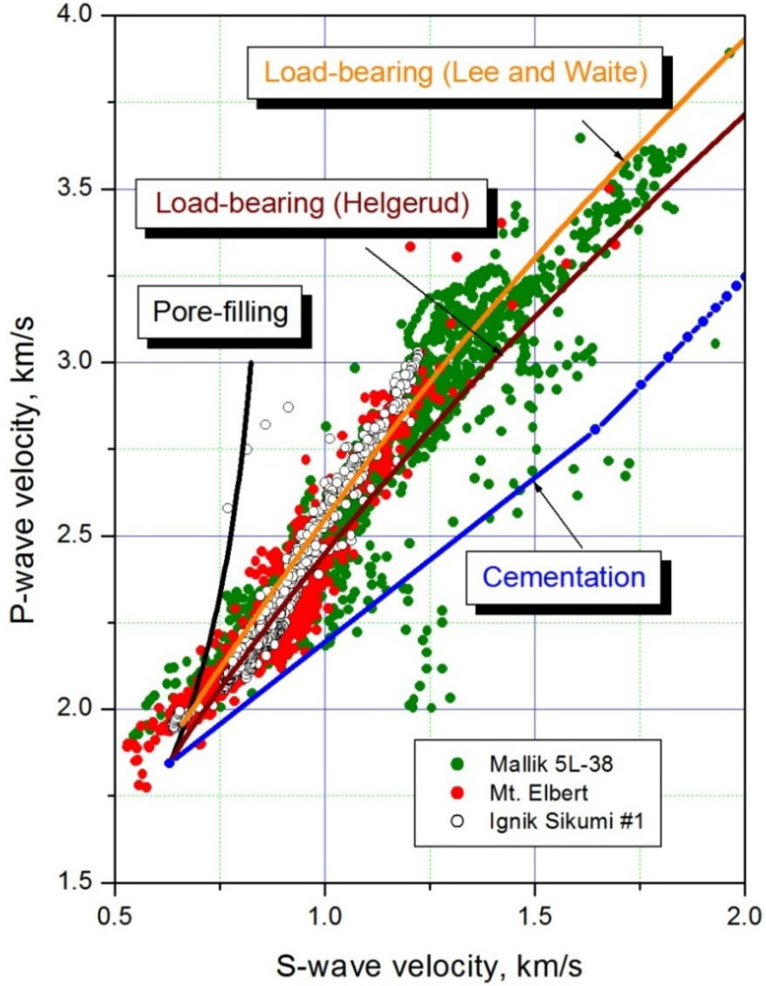
***TC-SDR Effective Perm  0.1 - 1.0 mD***

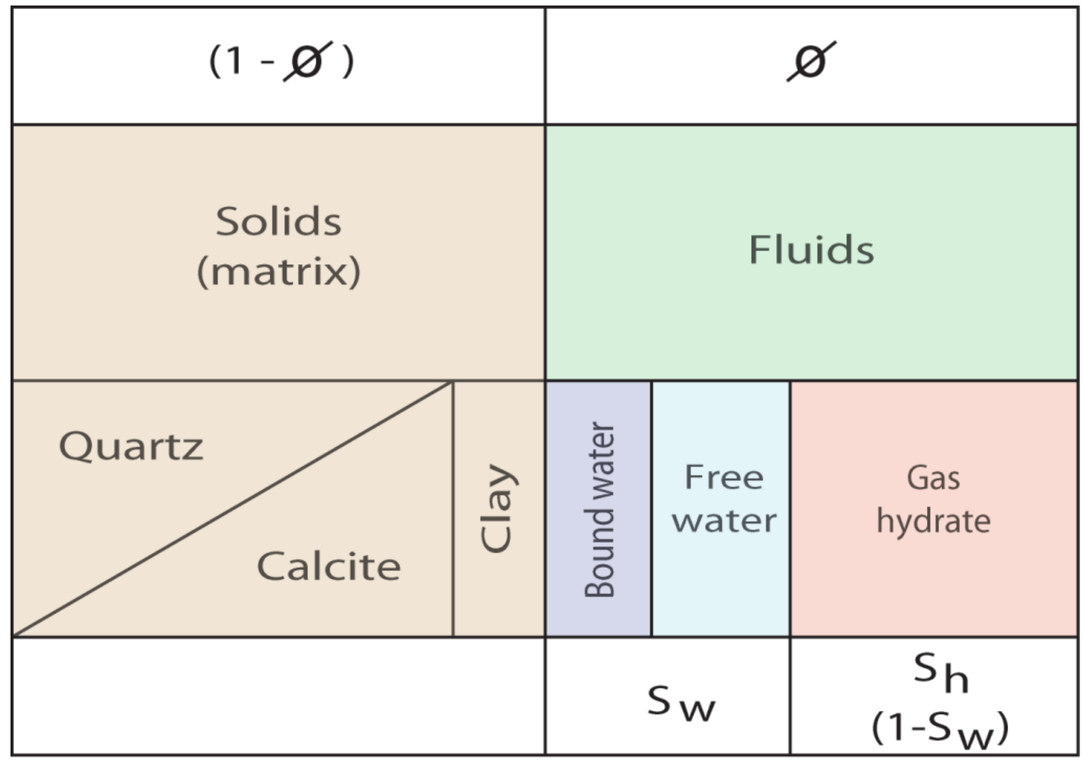
***Sw 25% (15% free water, 10% bound)***

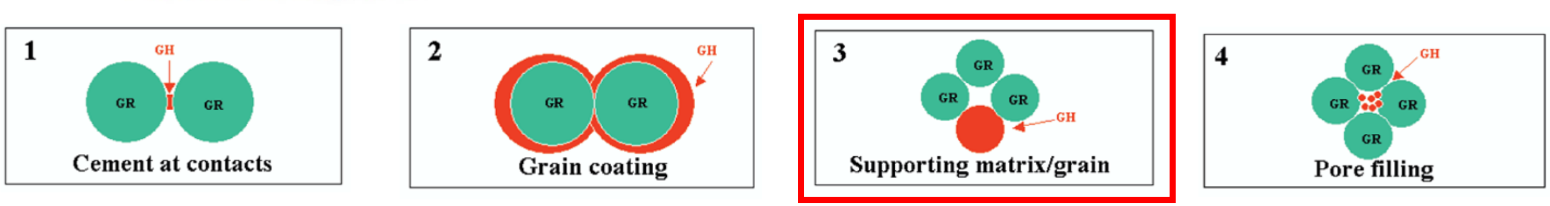
***MDT Effective Perm  0.12 – 0.17 mD***

# Gas Hydrate Reservoir Models

## *Pore-Filling (load-bearing) Growth Habit*



# Reservoir Properties

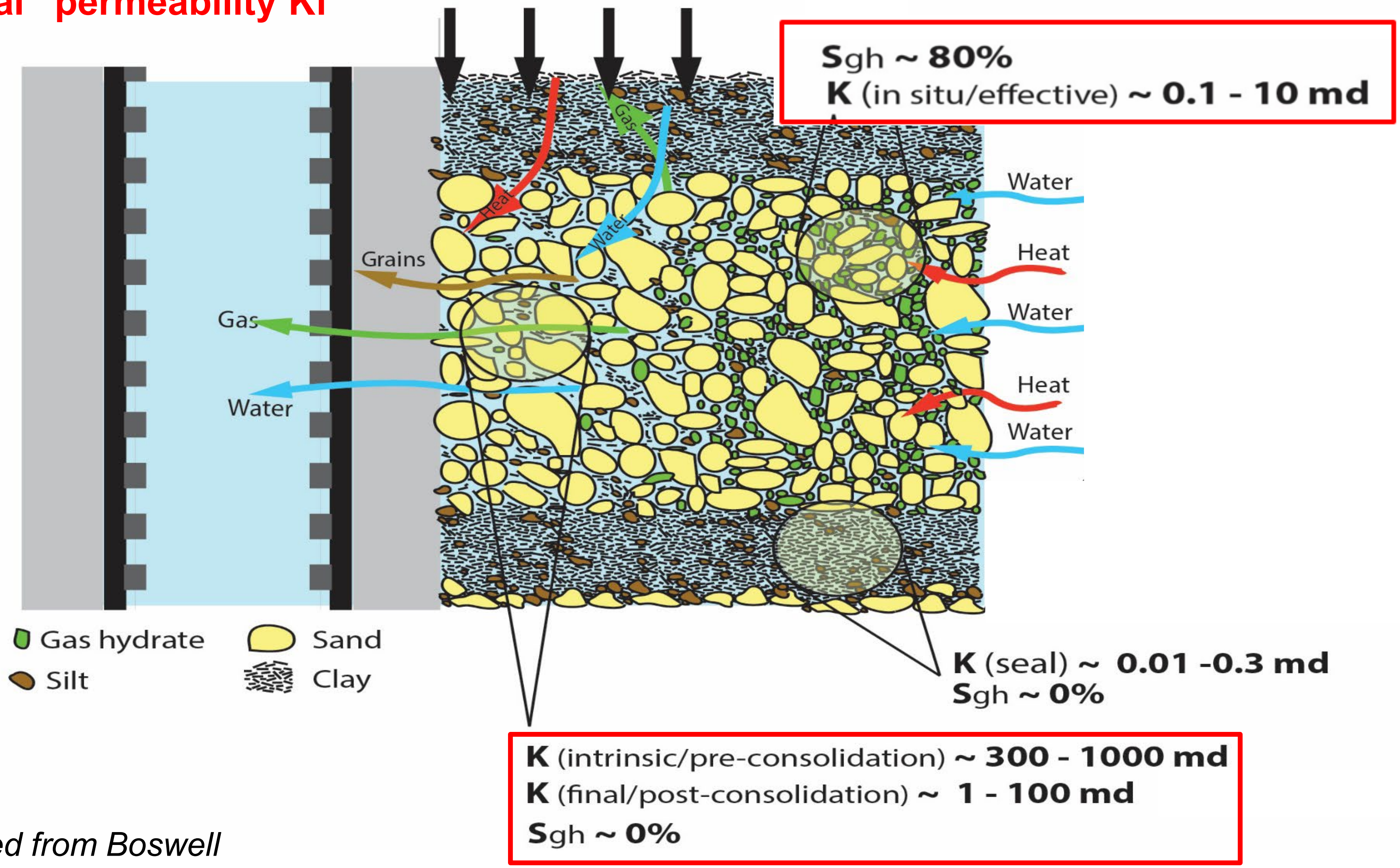
## *Pressure and Temperature Controls*

**Reservoir Permeability (pressure) Controls**

- "Initial" intrinsic permeability Ki
- Effective permeability Ke
- "Final" permeability Kf

**Source of Heat**

- Conductive heat flow: Reservoir & bounding units
- Convective heat flow: Reservoir fluids



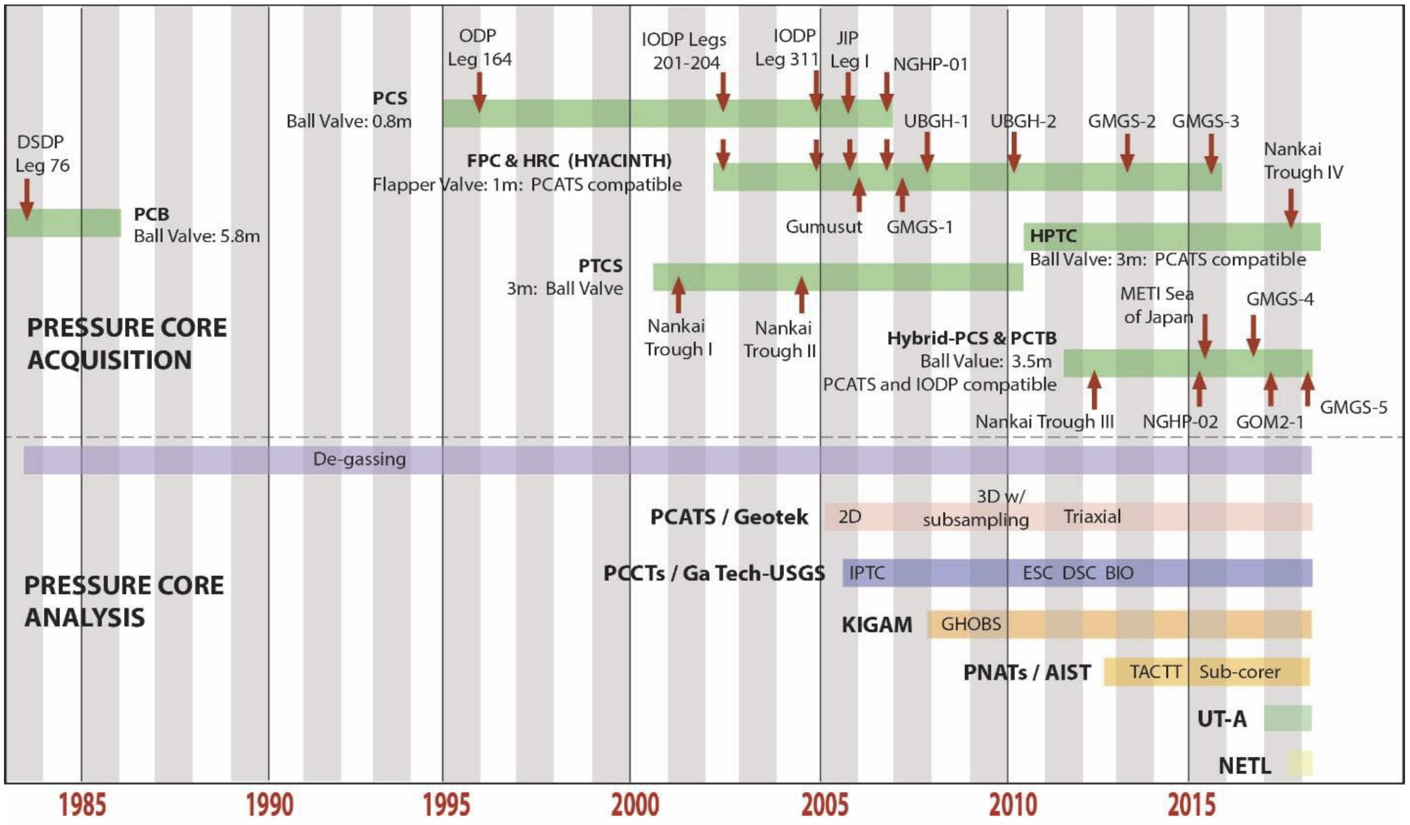

*Modified from Boswell*

# Pressure Coring Technology

Shared designs and lessons learned over 3+ decades of pressure core development in the US, Japan, Korea, India, and China

Convergent design toward current PCTB

Alignment on common analysis tool designs



# Pressure Coring Tool
## *Hybrid-PCS Family of Tools*

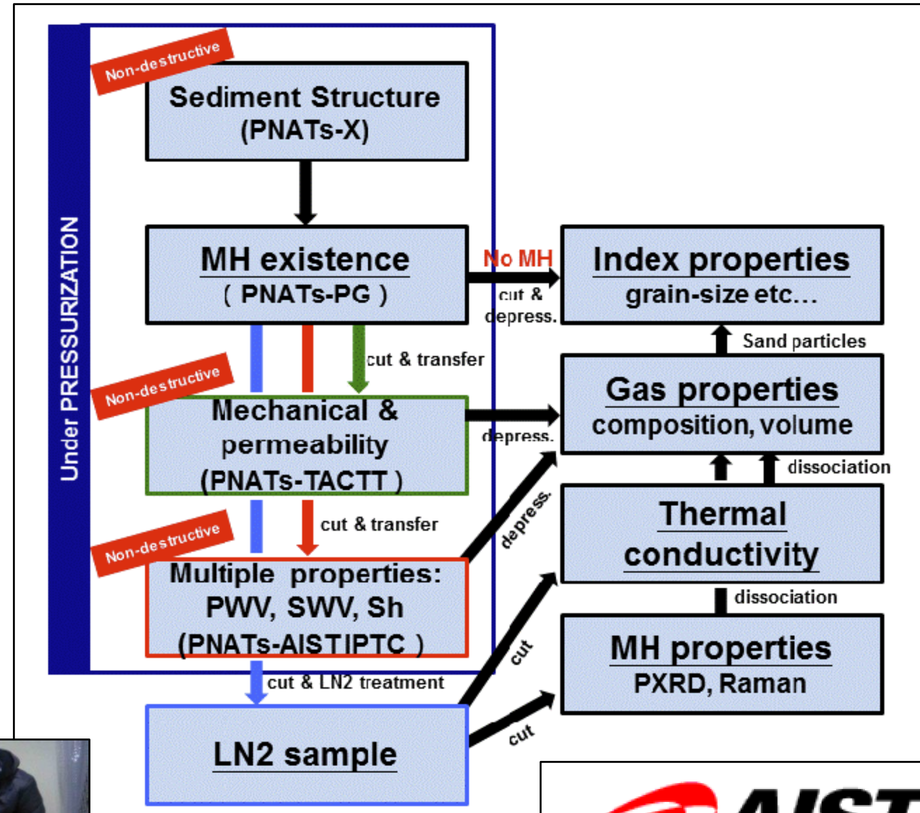
- **Ball valve for full capture of all components**
- **Laboratory analysis under pressurized conditions – PCATS, AIST, USGS, UT**

# Gas Hydrate Pressure Coring

## *Pressure Core Analysis: Geotek-PCATS, AIST, USGS/GT, UT*

GEOTEK CORING

***PCATS***




AIST
NATIONAL INSTITUTE OF ADVANCED INDUSTRIAL SCIENCE AND TECHNOLOGY (AIST)

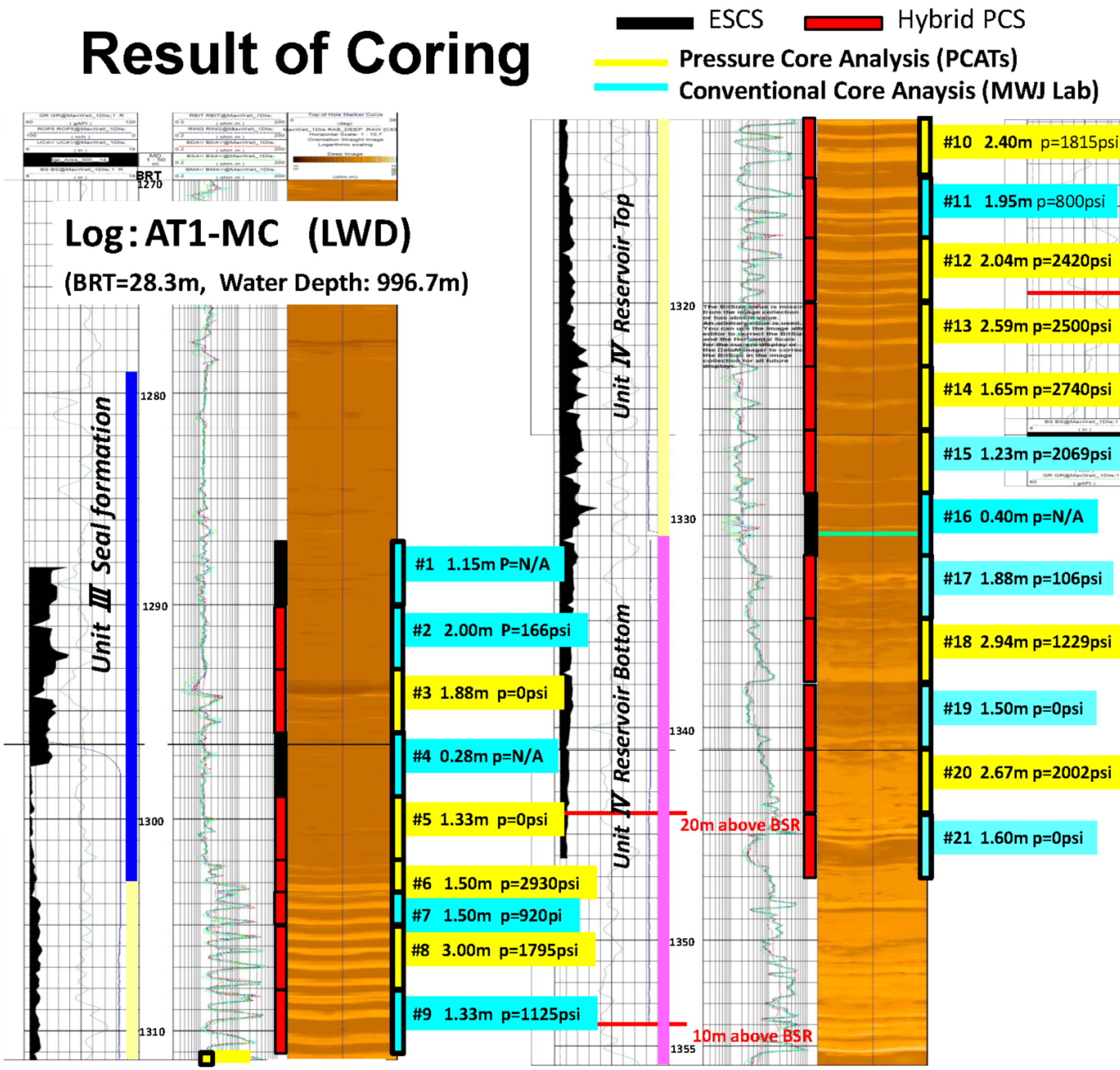
***PCCTS***

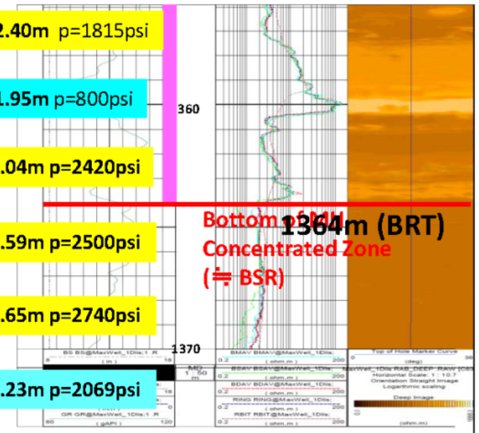
USGS science for a changing world

Georgia Tech

# JOGMEC Gas Hydrate Pressure Coring

## Result of Coring




**C-core: 14.82m**

**P-core: 22.00m**

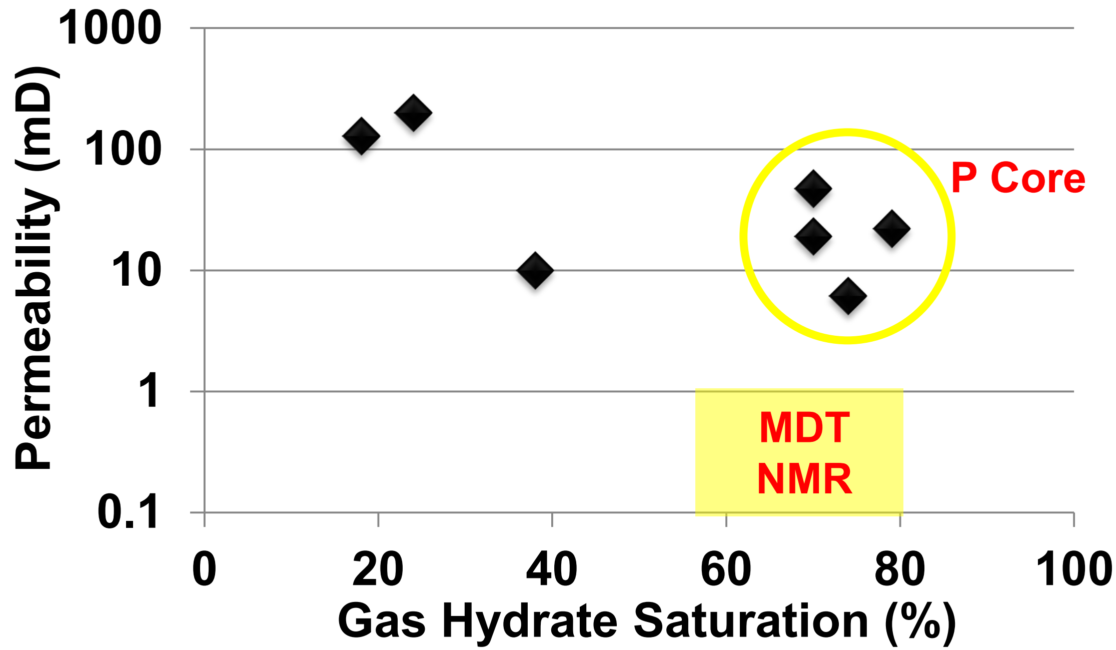
| | |
|---|---|
| Total coring time | 17:30 |
| Average coring time | 4:15 |
| Total Rec. Length | 36.82m |
| Total Drlg Length | 60.00m |
| Total Rec. Rate | 61% |

| | |
|---|---|
| H-PCS Rec. Length | 34.99m |
| H-PCS Total Length | 51.00m |
| H-PCS Rec. Rate | 69% |

# Nankai Trough

## *Gas Hydrate*

## *Pressure Core Analysis*



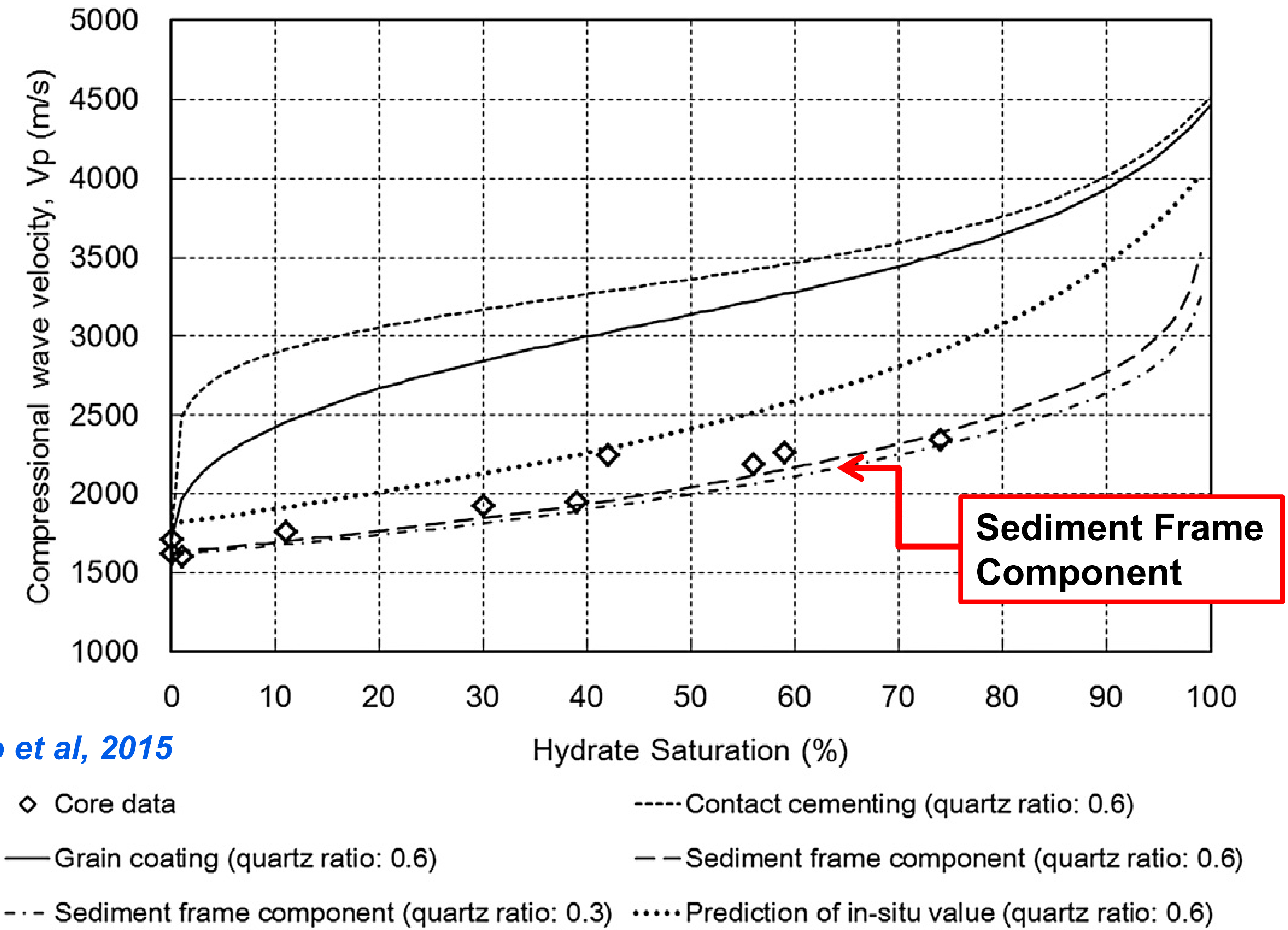

| Hydrate Saturation (%) | Permeability (mD) | JMPG 2015 References |
| --- | --- | --- |
| 18 | 128 | Santamarina |
| 24 | 200 | Konno |
| 38 | 10 | Yoneda |
| **70** | **47** | Konno |
| **70** | **19** | Priest |
| **74** | **6** | Santamarina |
| **79** | **22** | Yoneda |

***NMR log data 0.01-1.0 mD (Fujii et al., 2015)***

***Pressure core analysis "several tens of mD" (Konno et al., 2015)***

# Gas Hydrate Nankai Trough Reservoir Model

## *Pore-Filling (load-bearing) Growth Habit*




*Konno et al, 2015*

# India NGHP-02: Coring-Logging-Testing Operations

**Total of 42 holes were completed in 147 days (plan of 40 holes in 150 days).**
**-Water depths 1,519-2,815 m; sub-sea completions 239-567 mbsf.**

**Total of 25 LWD holes. Drilled/logged section 6659 m.**

**Conventional wireline and pressure cores were acquired in 16 wells, with a total of 390 conventional core runs : 2834 m cored, 2271 m recovered.**
**-104 HPCS (Hydraulic Piston Coring) cores: 909 m cored, 1015 m recovered.**
**-182 ESCS (Extended Shoe Coring) cores: 1,658 m cored, 1,101 m recovered.**
**-Formation temperatures were measured during HPCS using APCT-3.**

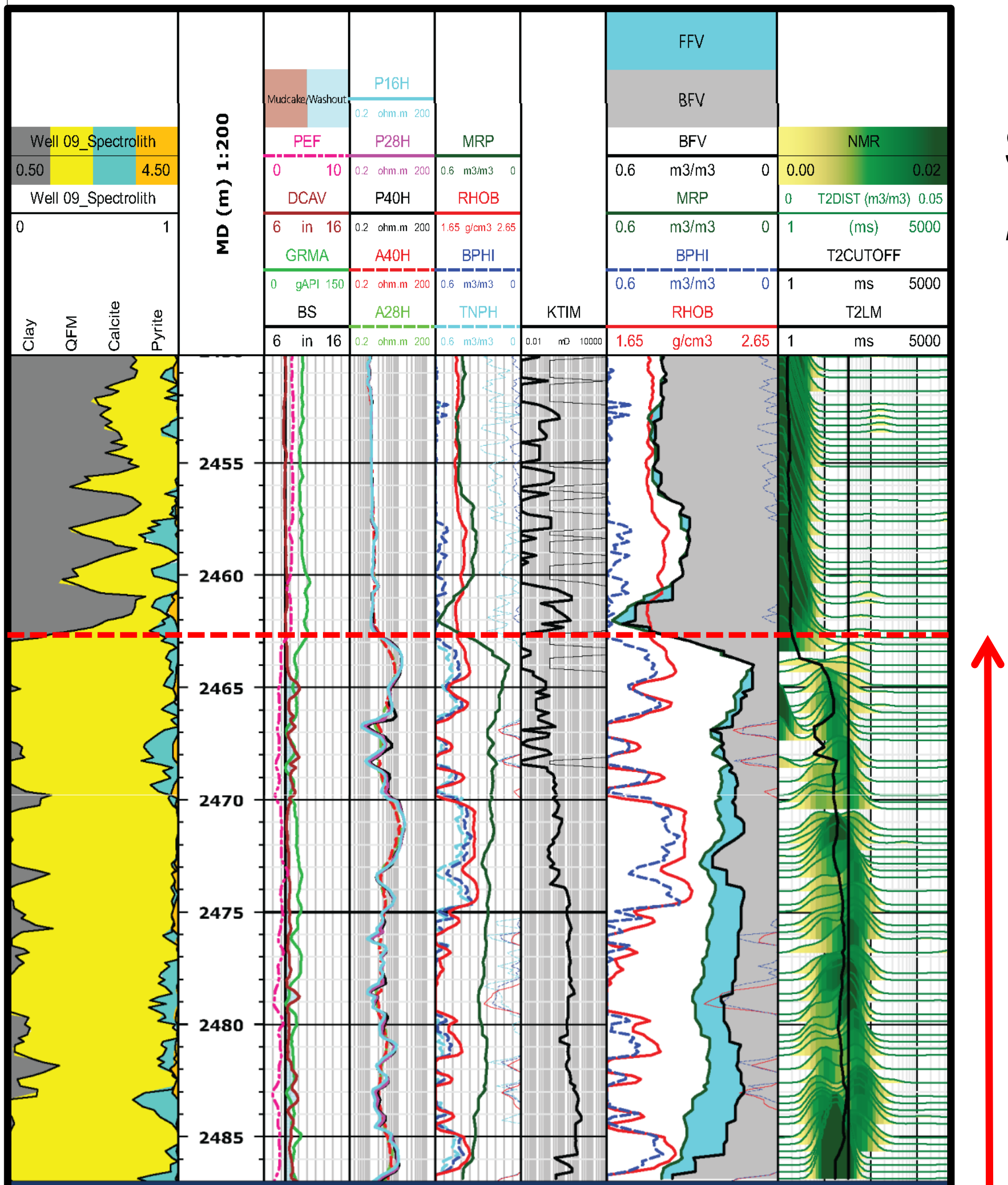
**Total of 104 PCTB (Pressure Coring) cores: 267 m cored, 156 m recovered.**

**Wireline logging conducted in 10 hole, open-ended drill pipe used to successfully re-entered logging tools into completed holes.**

**Wireline (MDT – Modular Dynamic Tester) formation pressure and flow tests successfully conducted in 2 holes.**

# Site NGHP-02-08

## *ProVision Plus LWD Log*



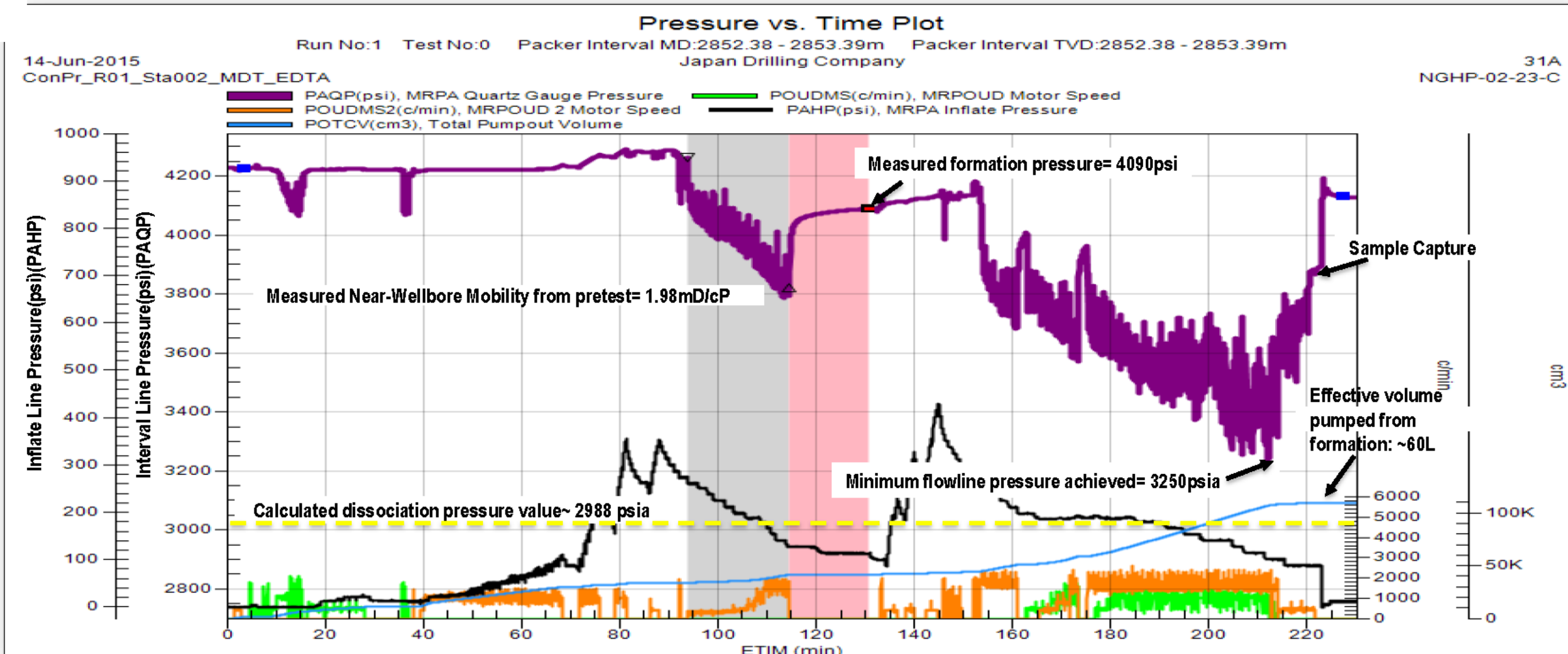

**Gas-hydrate-bearing**
**Sand reservoir section**
**Sh ~ 60%**
**Free water phase ~ 5%**
**K 0.01 – 0.5 mD**

Schlumberger

proVISION Plus Processing
Final Deliverables

# Site NGHP-02-23

## *Modular Dynamic Testing (MDT)*




*Packer inflation on station*
Lower exit port possibly plugged due to RIH on sea bed with ROV. Troubleshooting lower pump and attempting to inflate

*Drawdown*
Pre-Dissocⁿ

*Buildup*
Pre-Dissocⁿ

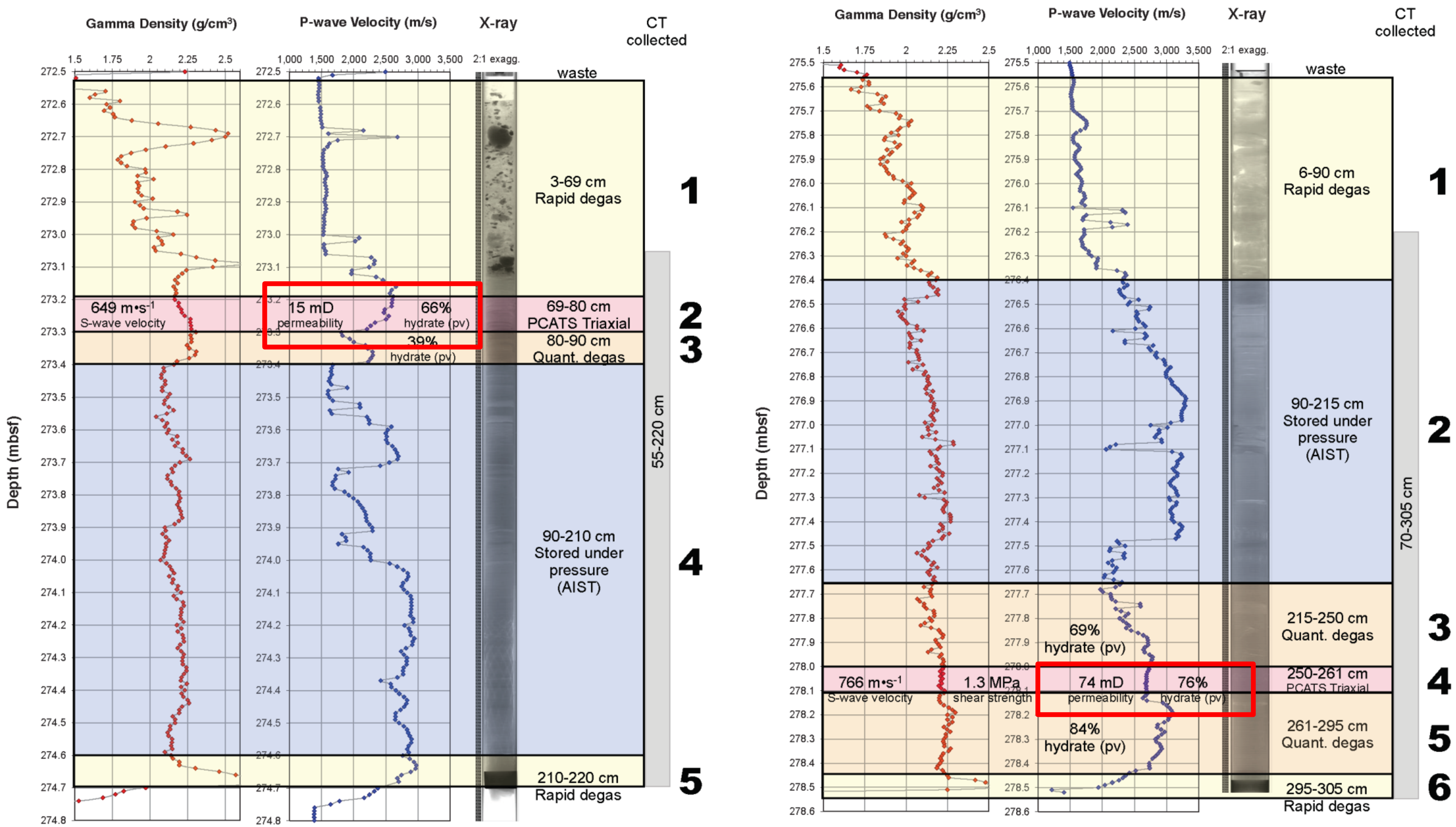
*Re-inflating*
packers before attempting drawdown again

*Drawdown*
with both pumps at maximum speed/ constant power mode with 100% duty cycle to create maximum ΔP

*Deflation*

## *Effective Permeability: MDT test analysis (~0.1 mD)*

# NGHP-02 Pressure Core Analysis




***Pressure-core measurements (>10 mD)***

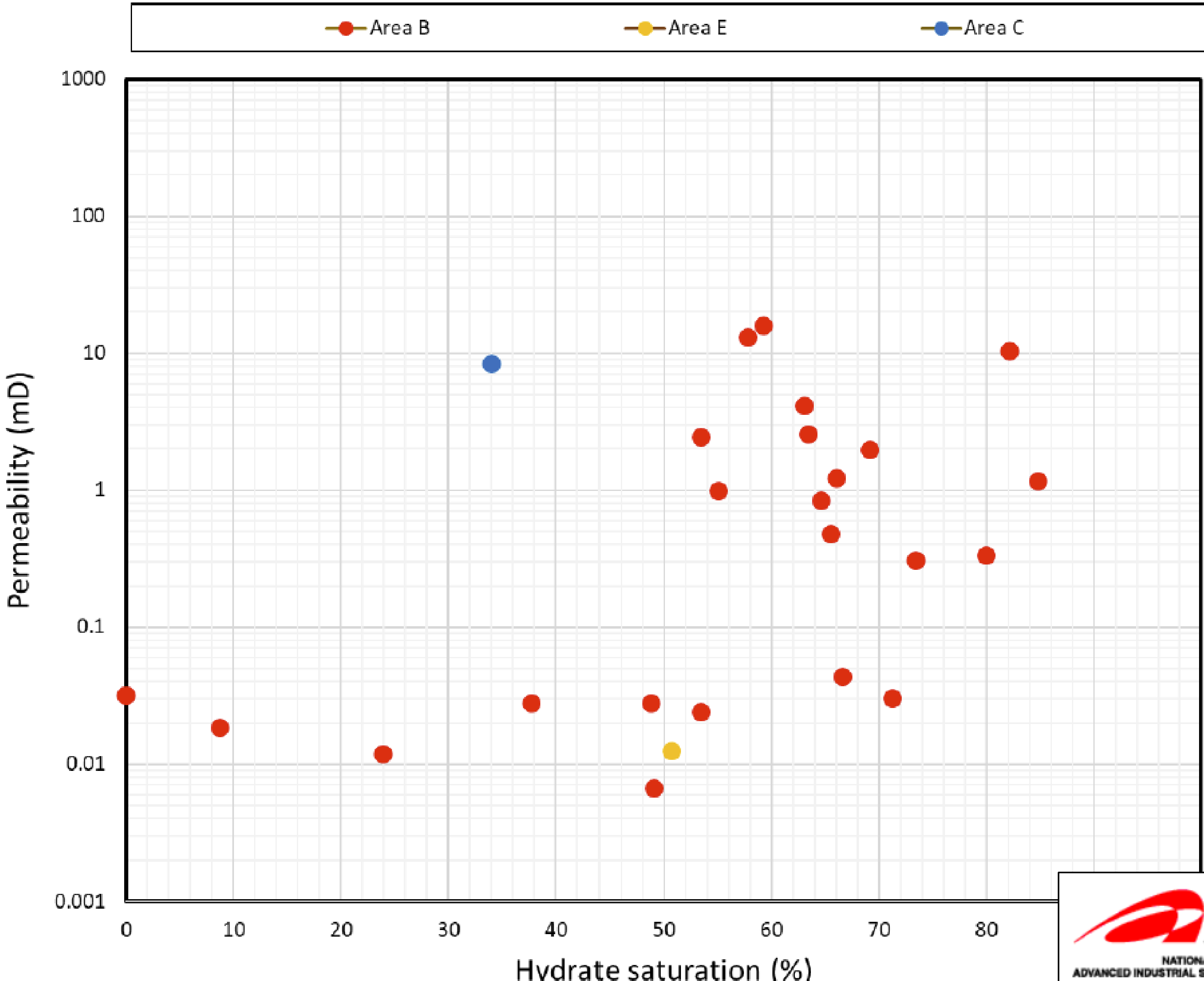
***MDT/NMR test and log analysis (<1.0 mD)***

***PCATS***

GEO TEK CORING

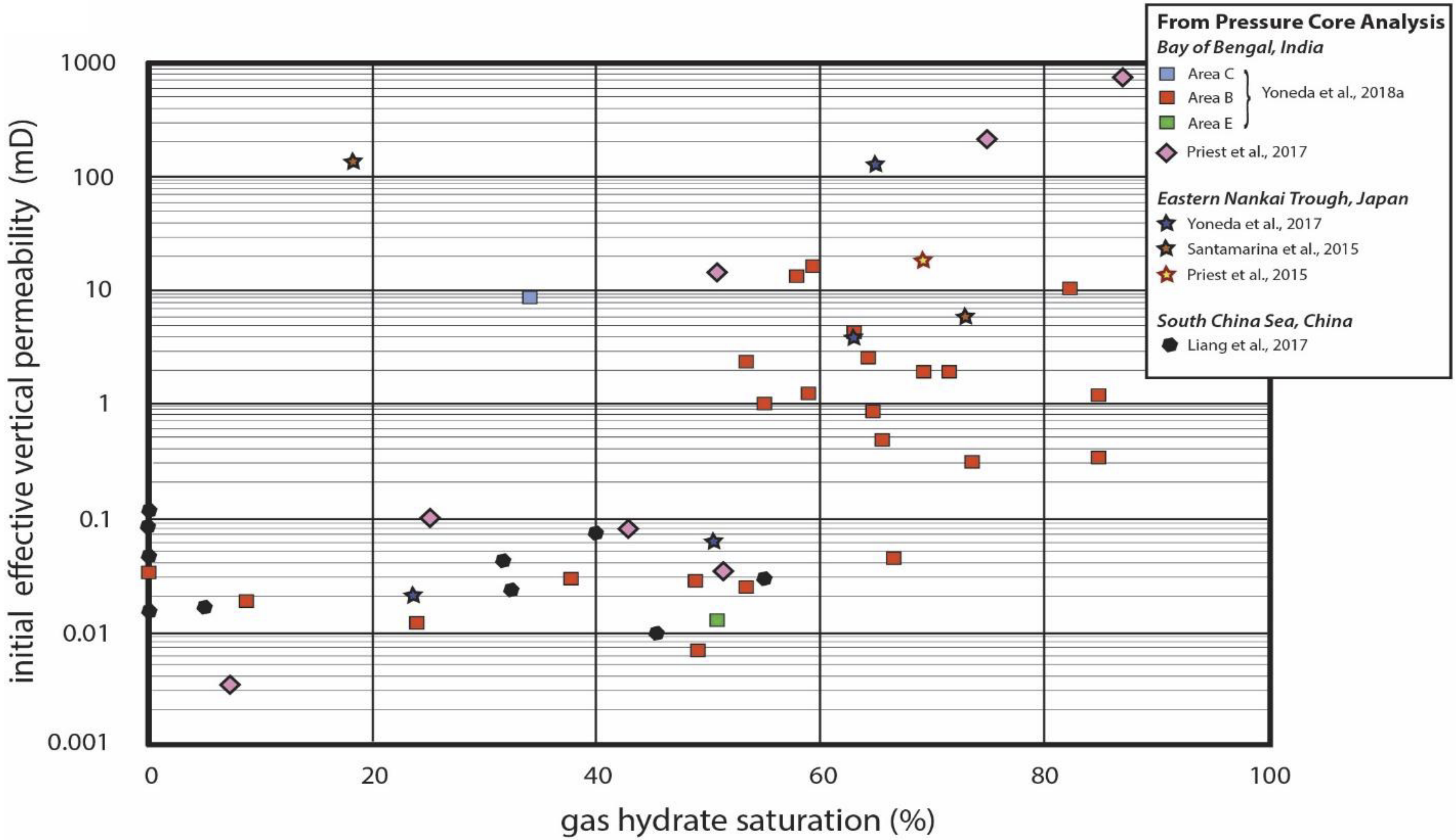
# NGHP-02 Pressure Core Analysis

## *Initial Effective Permeability*



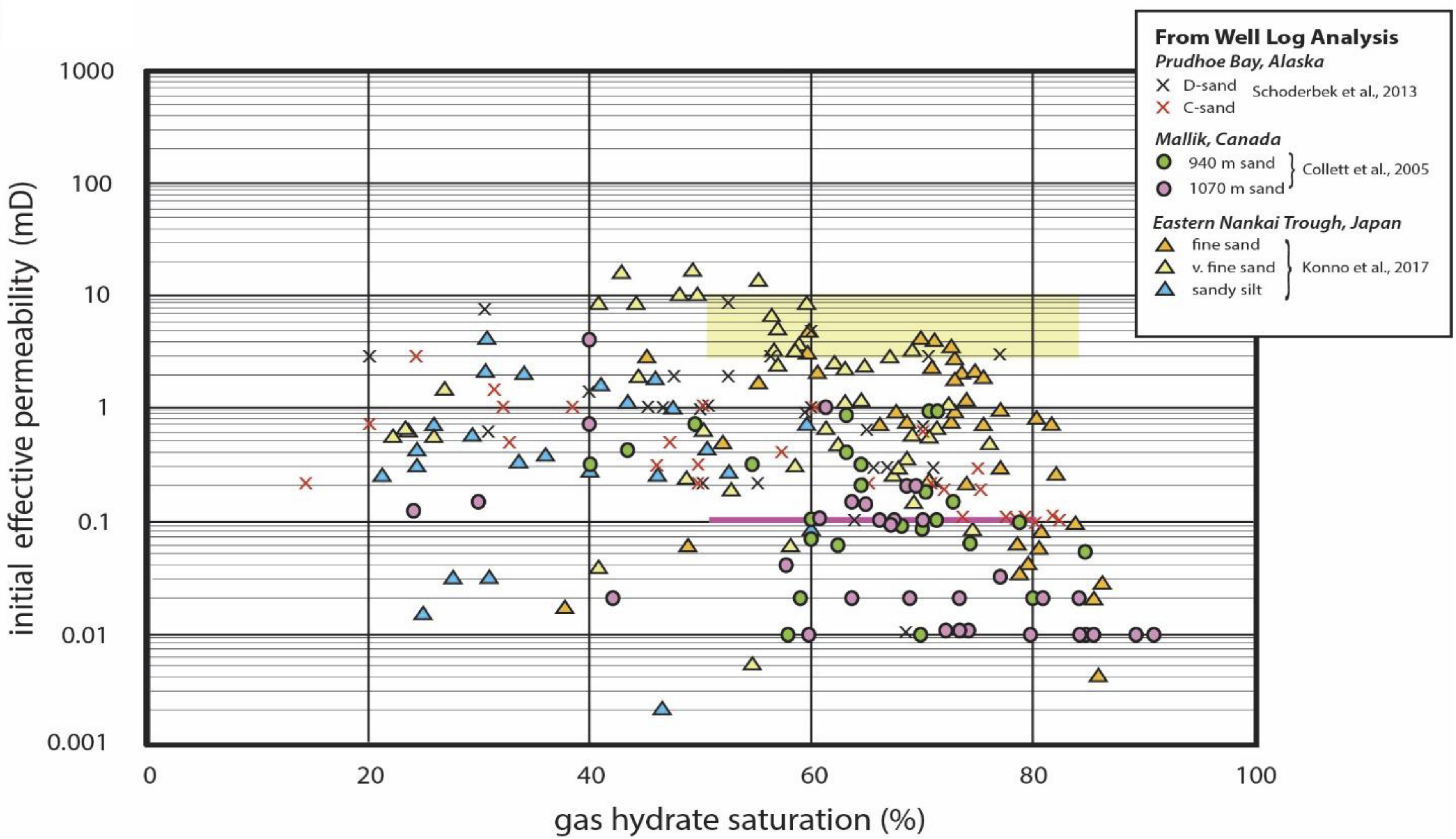
# Published Vertical Initial Effective Permeabilities

## *Marine Pressure Core Analysis*




*Boswell et al., (in press)*

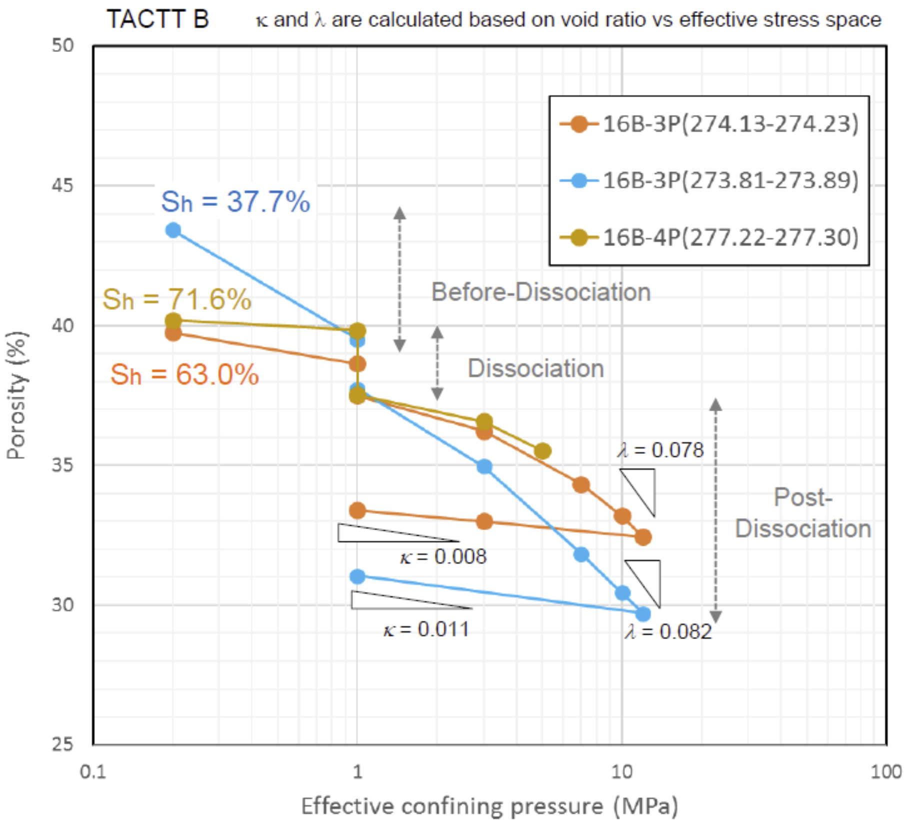
# Published Vertical Initial Effective Permeabilities
## *Marine/Permafrost NMR and MDT Analysis*

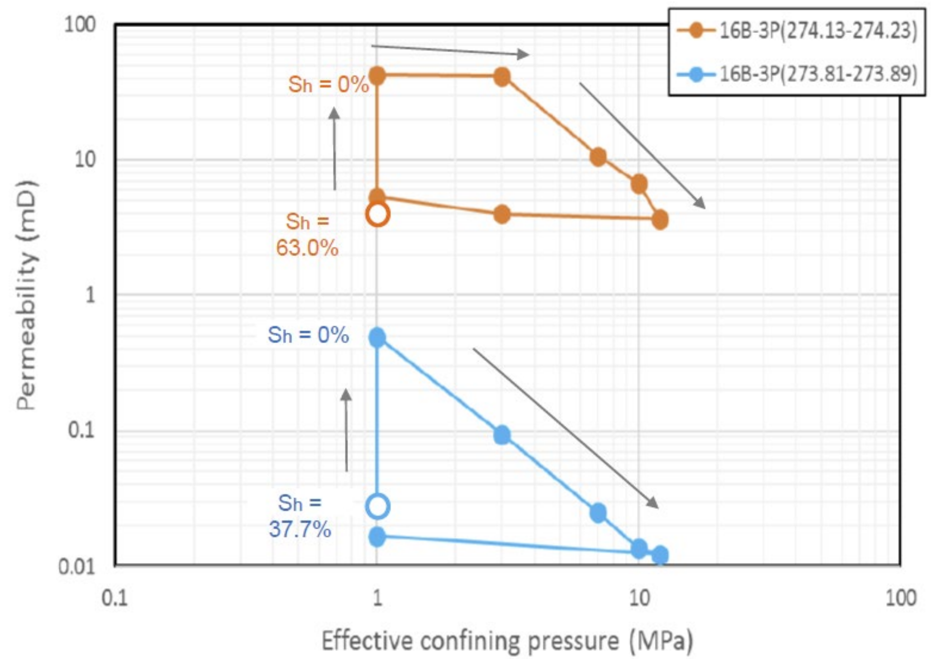



*Boswell et al., (in press)*

# Site NGHP-02-16 Pressure Core Analysis

## *Dissociation loading tests*

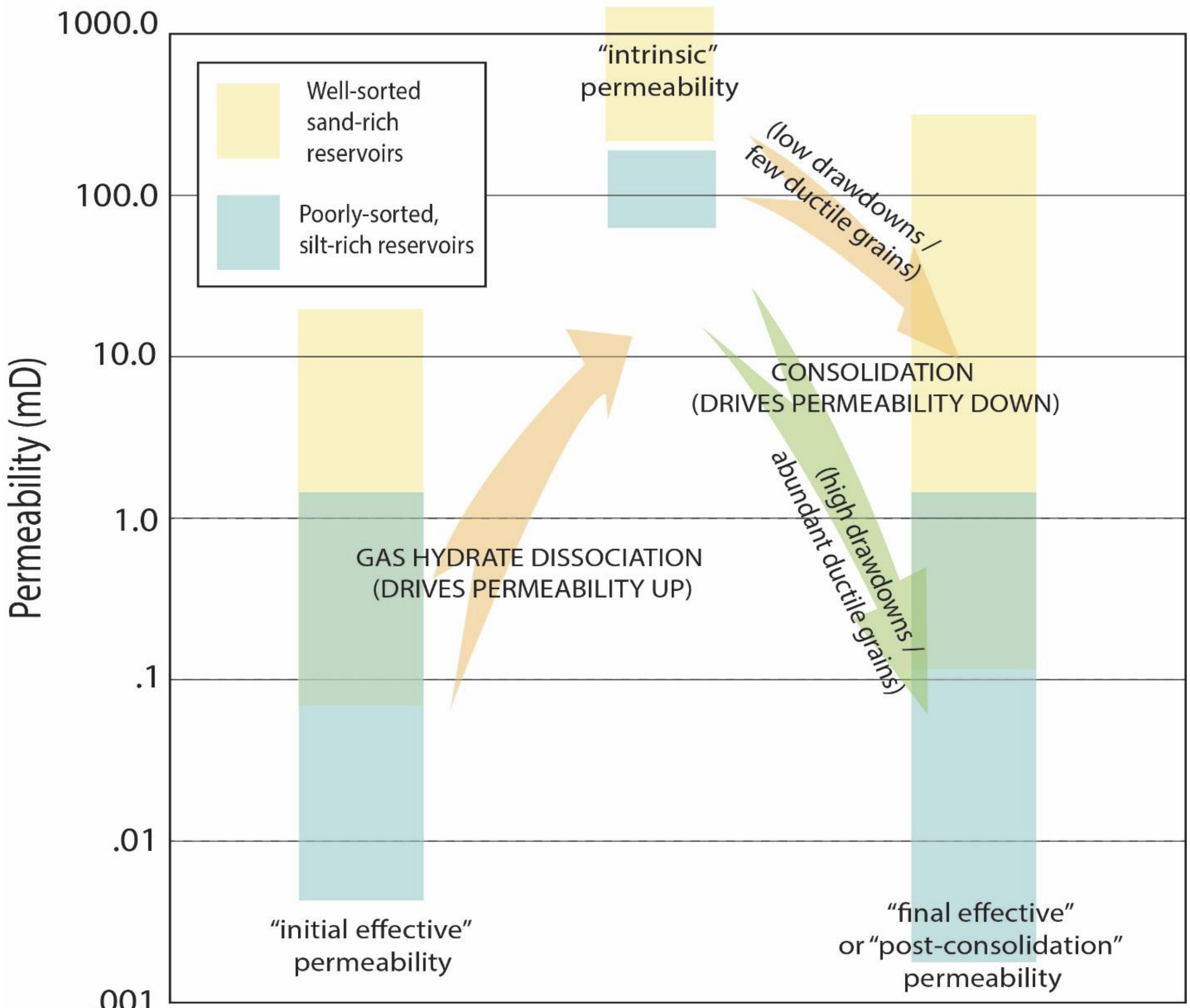



***Consolidation behavior after dissociation will first return to, then follow, the original normal consolidation curve for the hydrate-free host sediment.***

AIST
NATIONAL INSTITUTE OF ADVANCED INDUSTRIAL SCIENCE AND TECHNOLOGY (AIST)

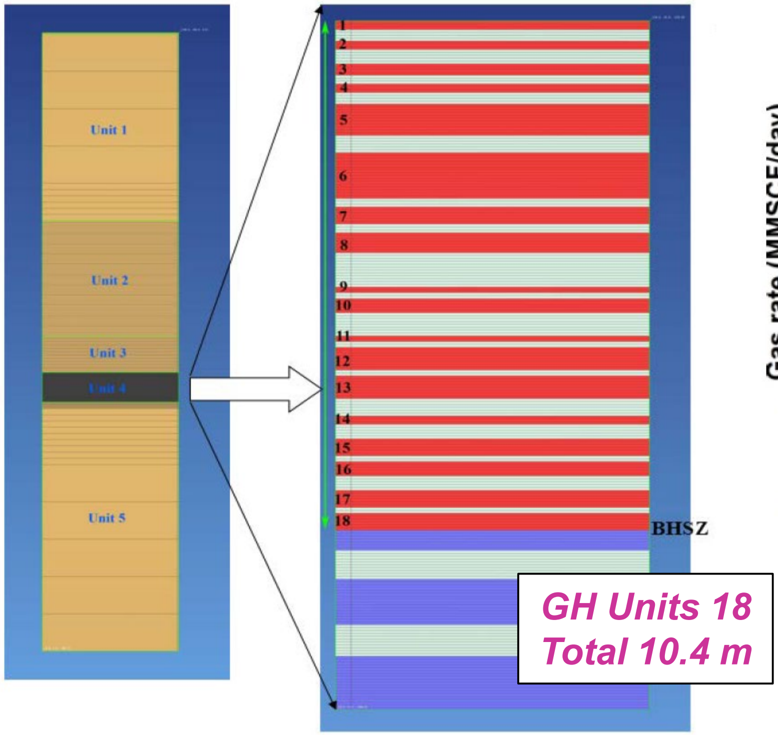
# Effective Permeability Changes During Production

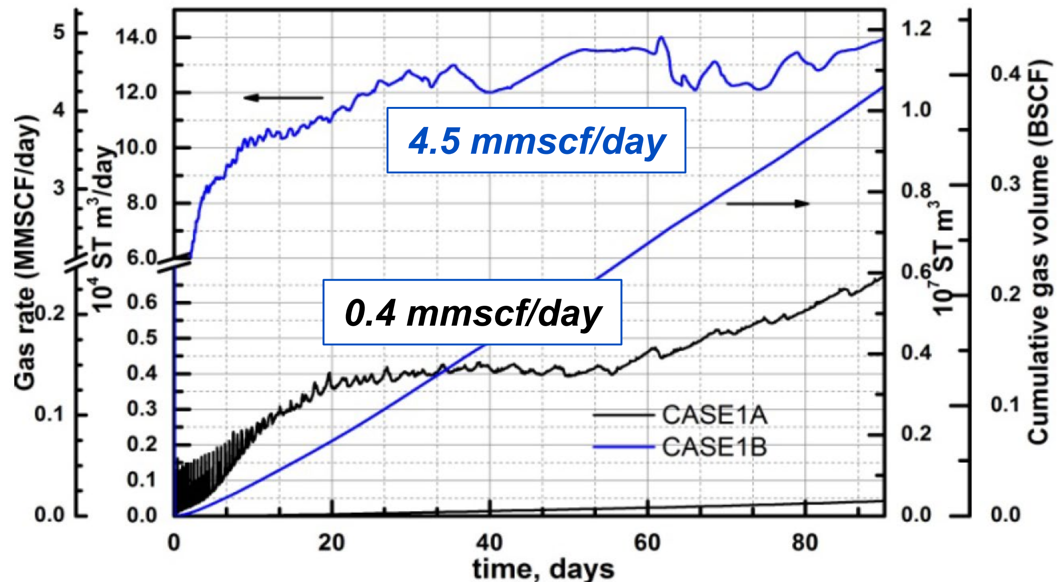


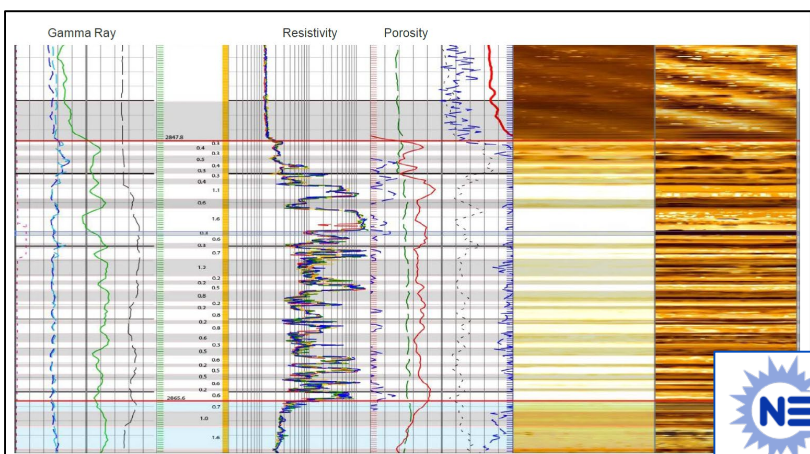

*Boswell et al., (in press)*

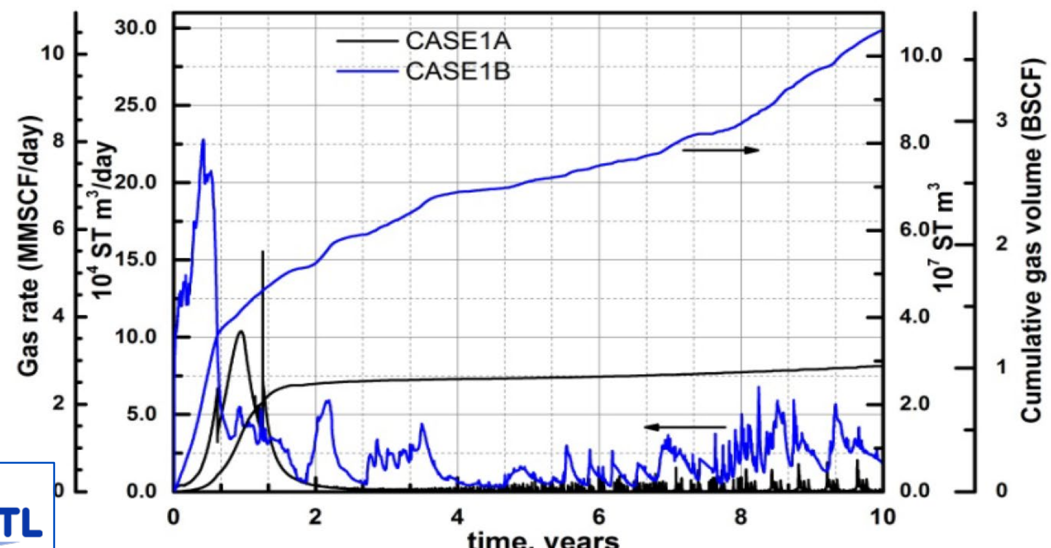
# GH Production Modeling – Permeability Uncertainty

## *Case 1A – Ke 0.1 md vs. Case 1B – Ke 10 md*



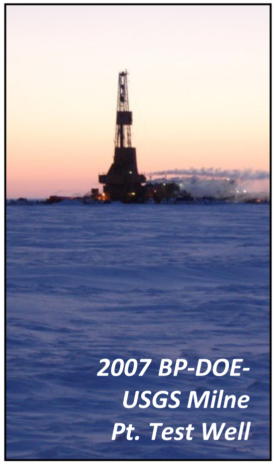



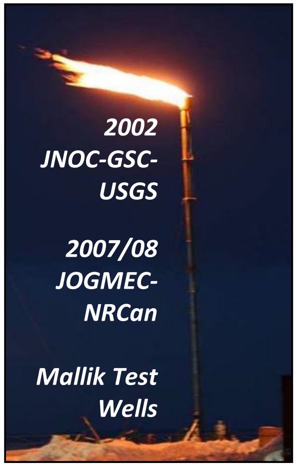



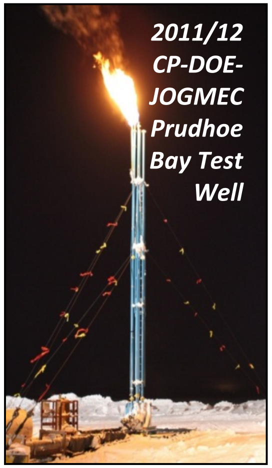
# Summary - Technical

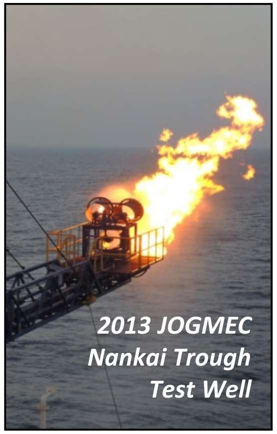
## *GH Prospecting - Characterization - Production Technology*

- **Application of Petroleum System Concept**
  - Support of gas hydrate prospecting and assessments
- **Target Resource is Substantial**
  - 40,000 tcf globally
  - 10,000 tcf US offshore (BOEM)
  - 85 tcf technical recoverable Alaska (USGS 2008)
- **Base Production Technology Demonstrated**
  - Four successful Arctic permafrost related scientific field tests, additional marine tests in China, Japan, and planned for India
  - Base technology (depressurization) identified
  - Modeled rates encouraging (up to 40 mmscf/d)
  - Recovery should be high (70-80%)
  - Long-term test required; Alaska opportunity in progressing
- **Wells Will be Challenging**
  - Cold reservoirs, low-pressure, etc.
  - Produced water & subsidence concerns
  - Environmental impact monitoring





# Summary - Challenges
## *GH Prospecting - Characterization - Production Technology*

**<u>Challenges</u>**

- In support of gas hydrate production modeling and testing efforts, continue to develop pressure coring equipment and pressure core analysis capabilities.
- <u>"Scientific"</u> production/mechanical testing designed to maximize scientific insight.
- Testing needs to include advance monitor programs to identify and assess mechanical/environmental response/impacts.
- Further development and calibration of gas hydrate production and mechanical models with results from field testing and pressure cores.
- <u>"Demonstration"</u> production/mechanical tests designed to maximize rates and establish deliverability.