NUPRI Research in Reservoir Engineering & Production Technology

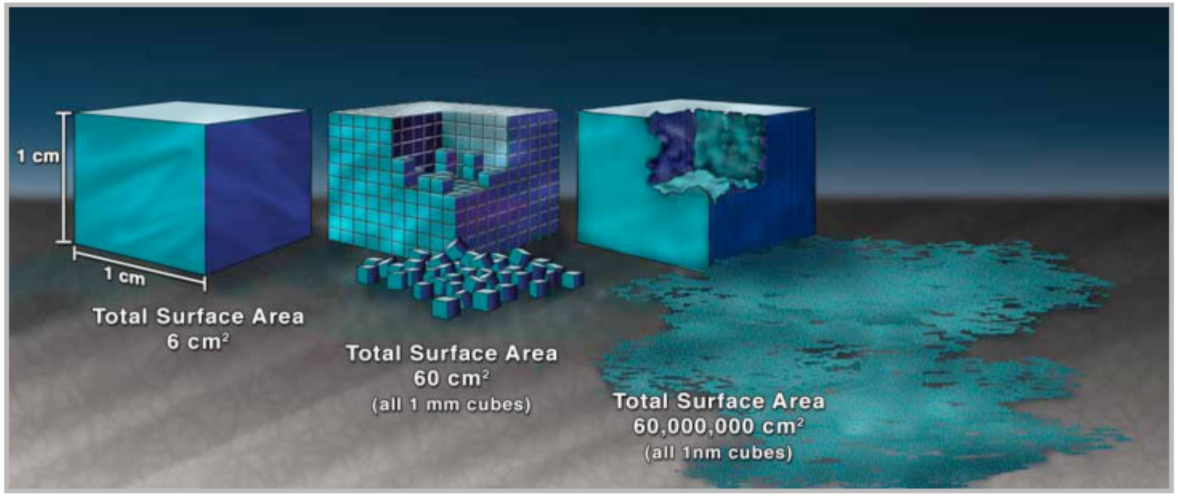
Prof Lau Hon Chung

NUS
National University
of Singapore

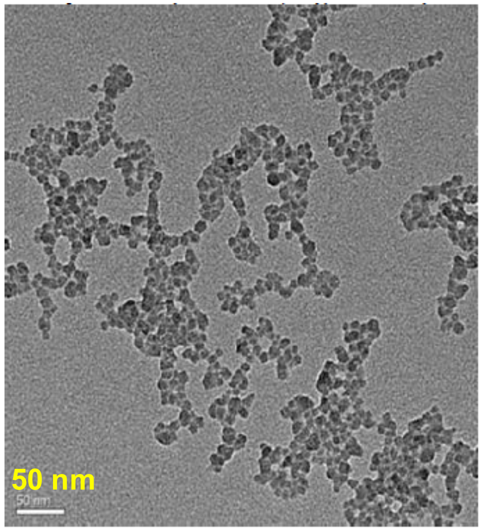
Outline

- Nanotechnology
- Smart wells
- Unconventional Resources

Introduction to Nanotechnology



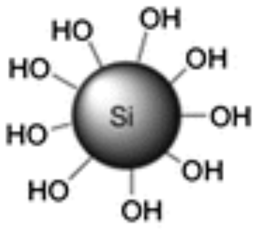
Increase in surface area provided by nanostructured materials



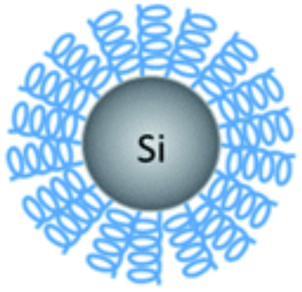
TEM of colloidal nanoparticles

- As materials shrink to nanoscale, they have properties different from bulk material due to (1) quantum effects, and (2) very large surface-to-volume ratio.
- Quantum effects: Size dependent properties at nanoscale: melting point, fluorescence, electrical conductivity, magnetic property.
- Very large surface-to-volume ratio leads to enhanced chemical reactivity.

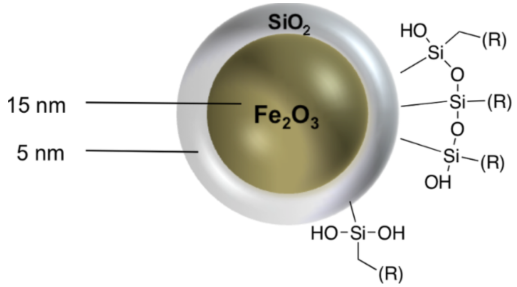
Nanoparticles for Oilfield Applications



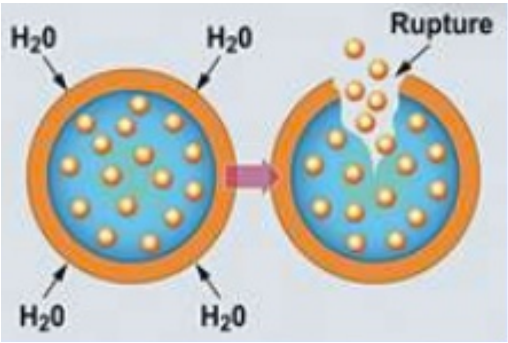
Bare silica NP
(EOR, stimulation)



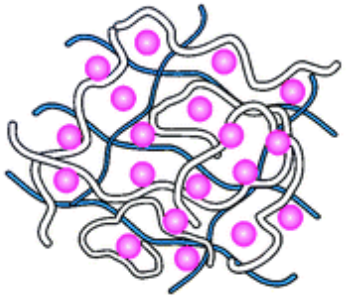
Functionalized NP
(EOR, stimulation)



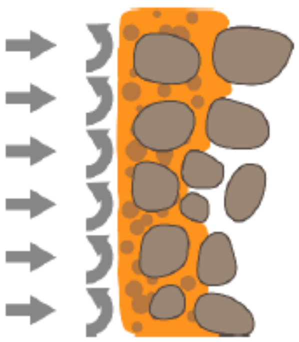
Magnetic NP
(produced water treatment)



Nano encapsulation
(delayed breaker)

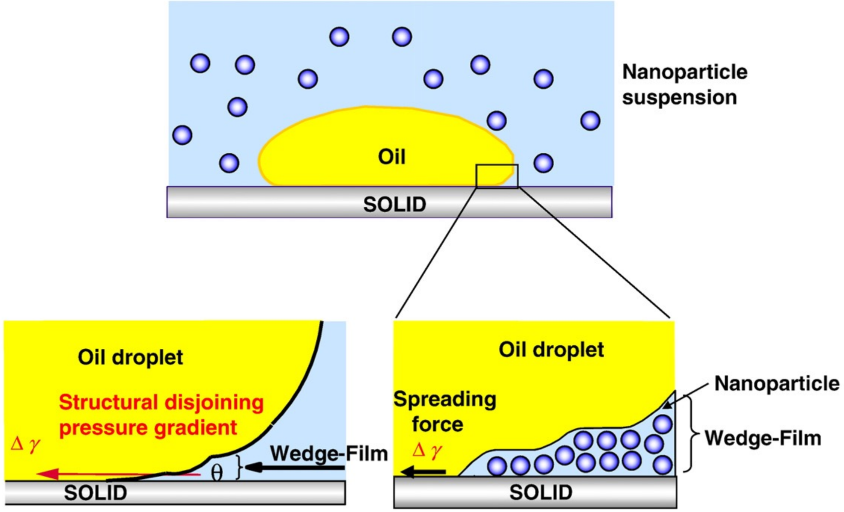


Polymer–NP interaction
(polymer strengthening)

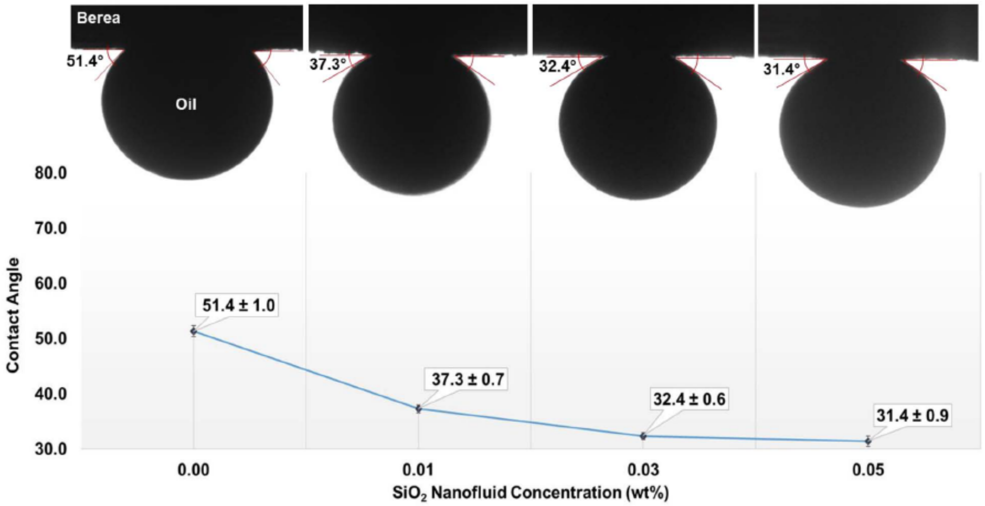


Nano filtercake (drilling through unstable zones)

Wettability Alteration by Nanoparticles



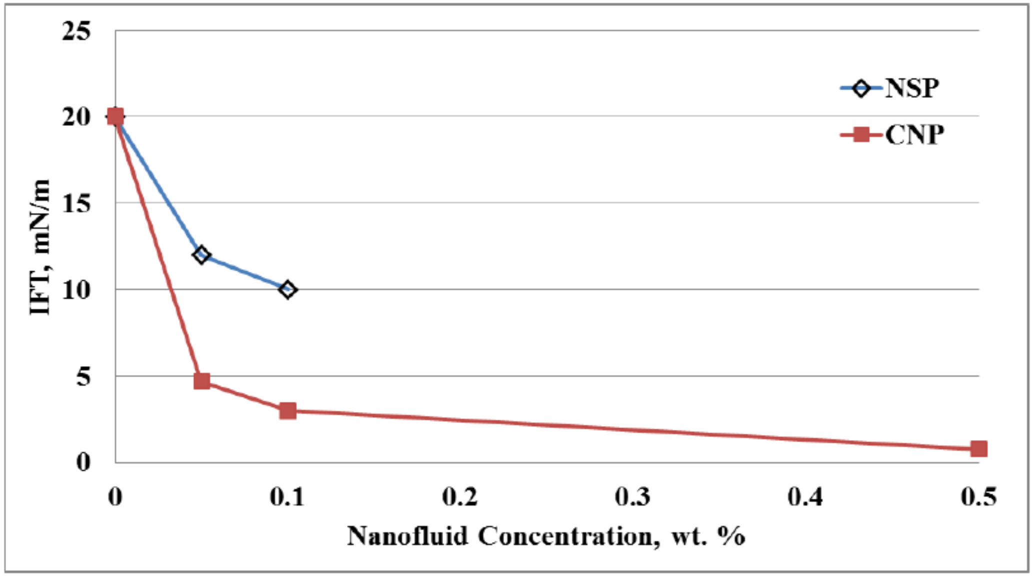
Spreading of nanoparticle fluid due to structural disjoining pressure gradient, Wasan et al. (2011)

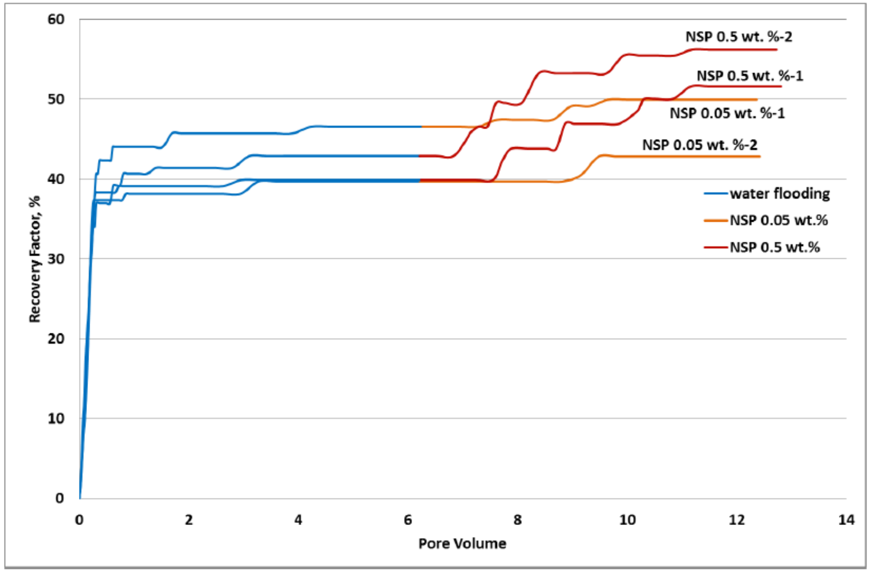


Change in oil-silica contact angle as a function of nanoparticle concentration, Otega et al. (2016)

- **Spreading force increases with decreasing particle size and increasing particle concentration.**

Interfacial Tension Reduction & Increased Oil Recovery by Nanoparticles





Reduction in oil-water IFT due to nanoparticles (Li 2016)

Enhanced oil recovery by nanoparticles (Li 2016)

Applications

- **Enhancing water injection**
  - ✓ Inject nanoparticles to make reservoir more oil-wet

- **EOR in tight rock**
  - ✓ Inject nanoparticles to make reservoir more water-wet

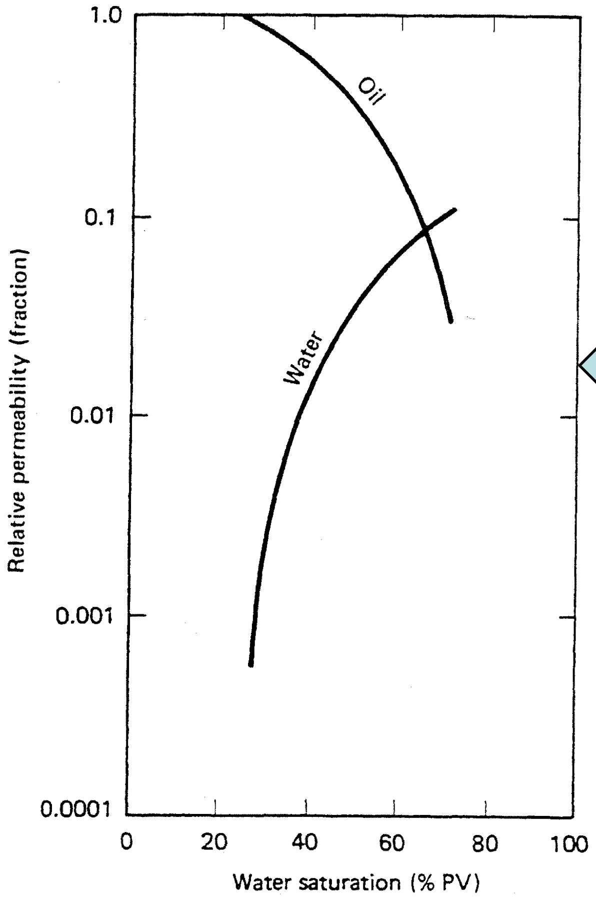
- **Near wellbore stimulation**
  - ✓ Remove paraffin / asphaltenes using nanoparticle stimulation

- **Profile control**
  - ✓ Adjust nanoparticle size vis-à-vis pore size to facilitate pore blockage

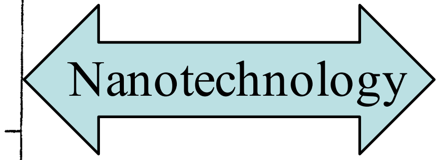
- **Mobility control**
  - ✓ Increasing water-phase viscosity using nanoparticles

- **Can nanotechnology replace or enhance low-salinity waterflooding?**
  - ✓ Similarity – Both rely on altering rock wettability
  - ✓ Difference – LSF works only on certain types of reservoirs (high salinity, clay, polar oils). Nanofluid flooding may be tailored for reservoir condition.

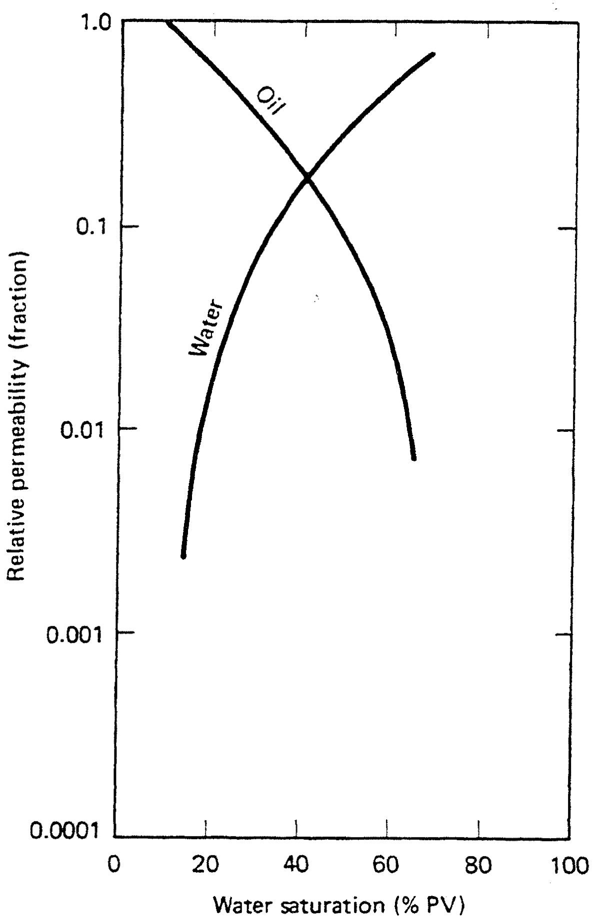
Can nanotechnology be used to alter relative perm?



(a) Water wet



What is needed?



(b) Oil wet

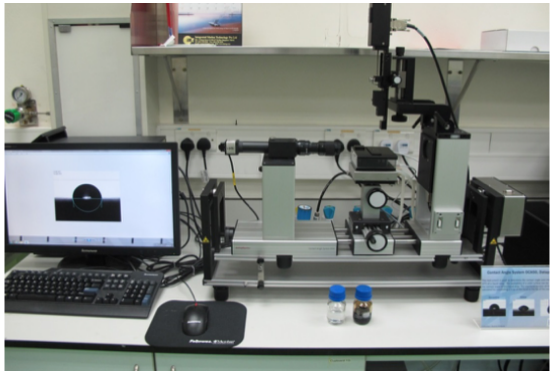
Fundamental Understanding of Factors & their Interactions Affecting Oil Recovery by Nanoparticles

Nanoparticle property	Rock Property	Oil Property	Brine Property	Flow Property
Size	Grain size	Viscosity	Salinity	Flow rate
Concentration	Clay content	Density	Hardness	Injected PV
Hydrophobicity	Perm	Interfacial tension	Temperature	Stress
	Wettability		pH	

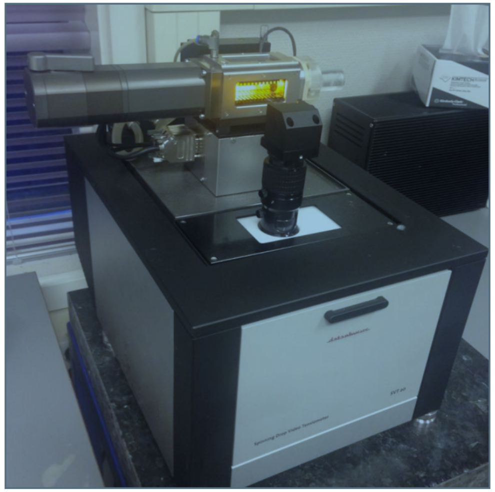
Experimental Tools – Partnership with A*STAR

Crude & Reservoir Fluid Characterization

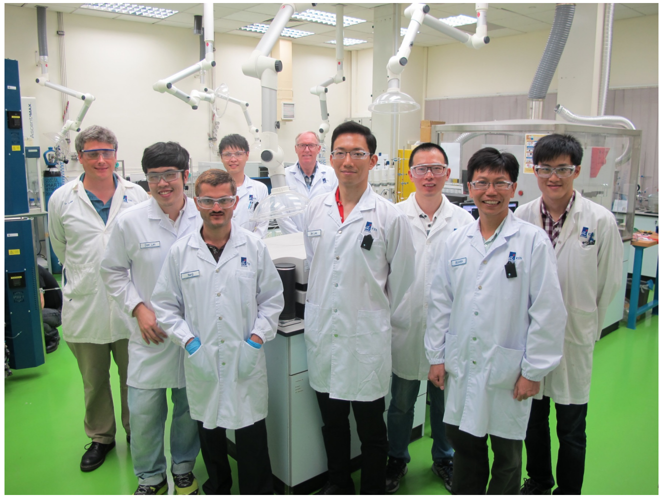
- ✓ Spinning drop tensiometer
- ✓ Contact angle meter
- ✓ Chromatography
- ✓ SARA
- ✓ Chemical analysis



Contact angle meter



Spinning drop tensiometer



A*Star research team

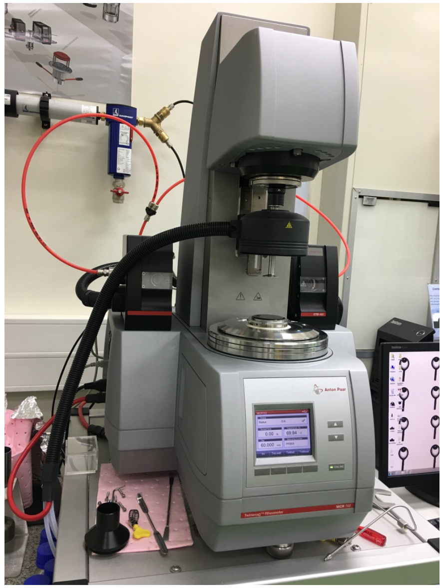
Experimental Tools – Partnership with A*STAR

Rheometer

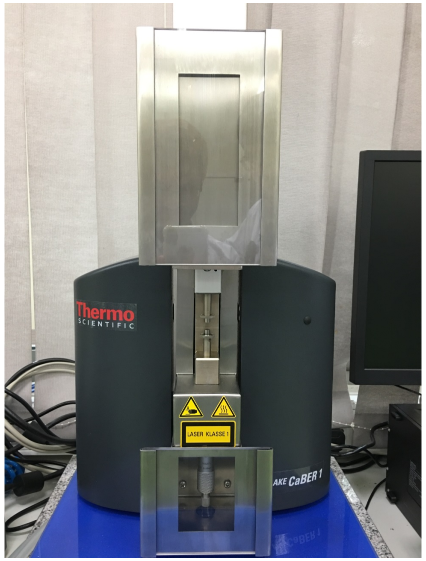
- ✓ HPHT rheometer
- ✓ Extensional rheometer

Flow Visualization and Imaging

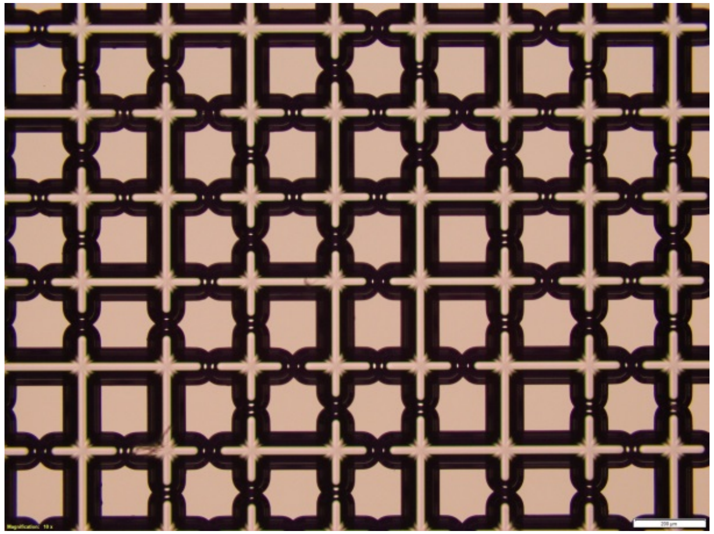
- ✓ Mico flow model
- ✓ Micro-CT



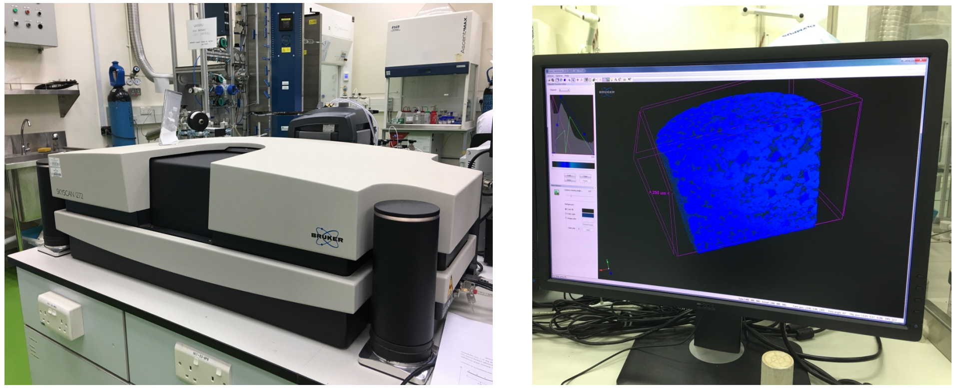
HPHT rheometer



Extensional rheometer



Glass micro flow model

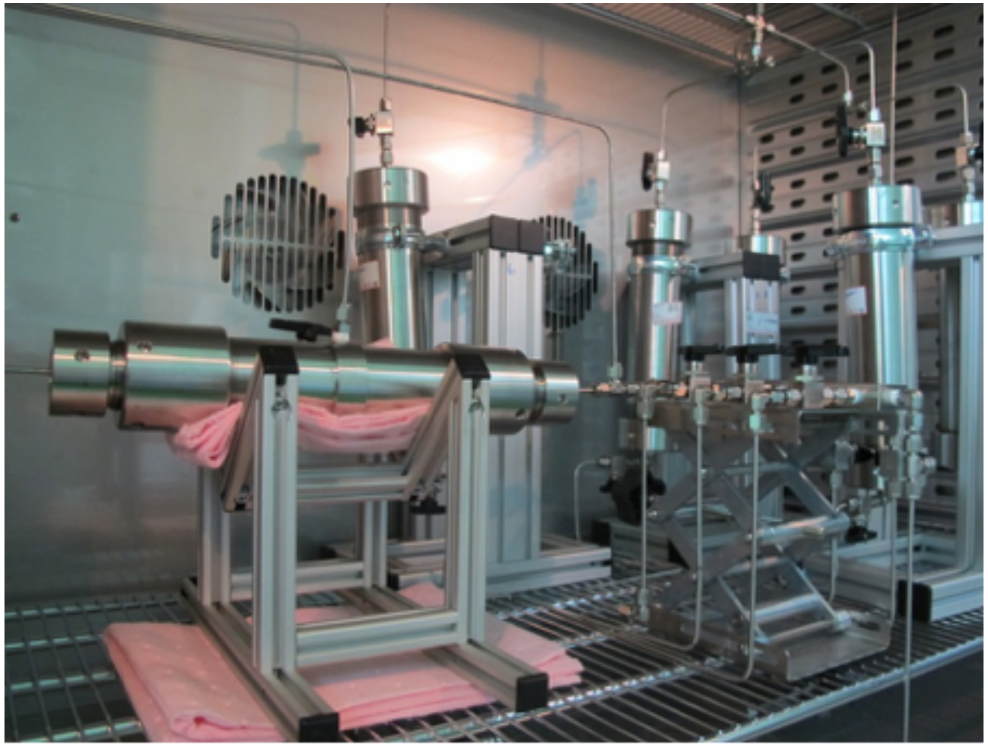


Micro-CT

Experimental Tools – Partnership with A*STAR

Coreflooding

✓ LPHT (30 bar, 80^{o}C)
✓ HPHT (700 bar, 130^{o}C)



LPHT coreflooding apparatus

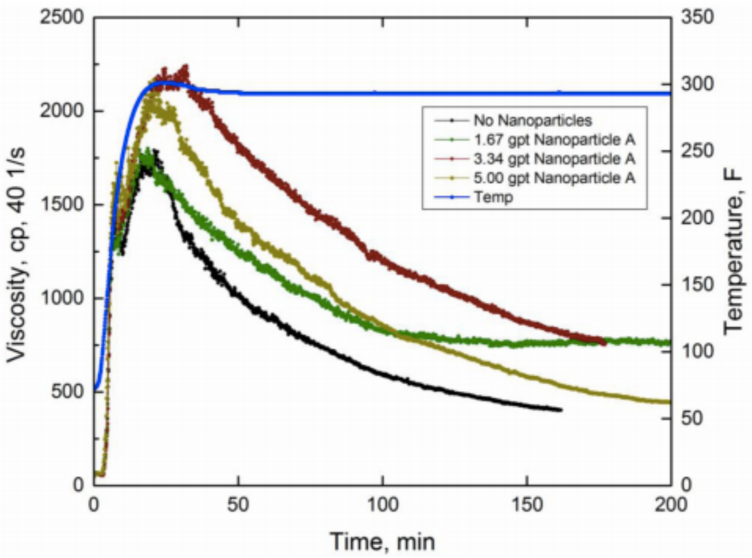
HPHT coreflooding apparatus with X-ray capability

Research Methodology

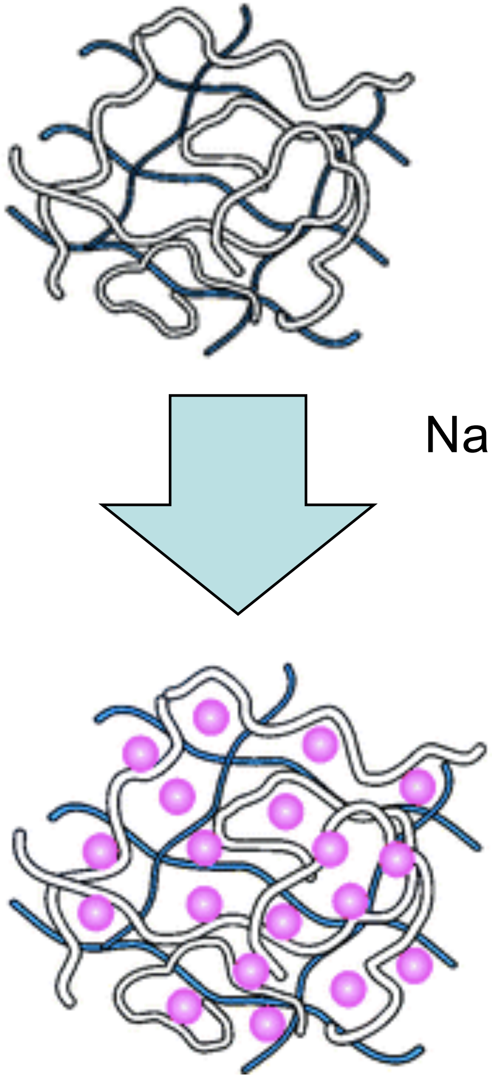
Field samples
Crude, brine, rock analyses
Corefloods
History matching to get rel perm & cap pressure
Upscaling and forecast
Pilot design

Oil & service company input
Lab experiment
Lab experiment
Reservoir simulation
Reservoir simulation
Oil & service company input

Can nanoparticles stabilize polymer for high-temp, high-salinity application?



Nanoparticles can enhance the thermal stability of X-linked HPAM at high temperature, (SPE 180402, 2016)



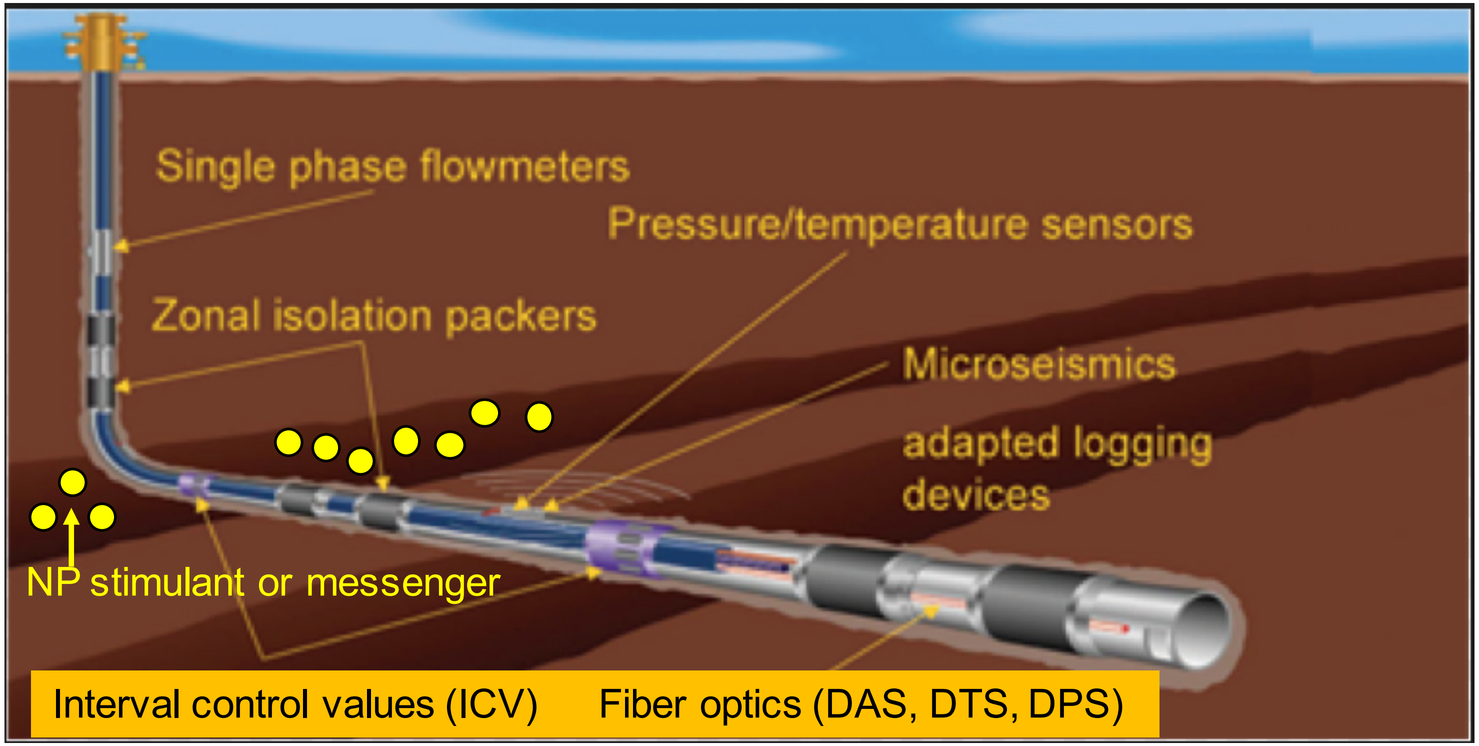
Nanoparticles

Stable at
high temp,
high salinity

Application: nano-enabled polymer (e.g. HPAM) for high-temp, high-salinity polymer flooding

Smart Wells

- **Integration of smart well technologies with nanotechnology with applications in:**
  - ✓ **In-depth reservoir stimulation (ICV+NP stimulant)**
  - ✓ **Fracture conductivity monitoring (Fiber optics + NP messenger)**



Research on Unconventional Resources

- **Shale Gas and Tight Gas**
  - ✓ Better proppant
    - ➢ *proppant for natural fractures*
  - ✓ Better fracturing fluid
    - ➢ *Non-aqueous fracturing fluid*
- **Coalbed Methane**
  - ✓ Enhanced CBM recovery by CO_2 in high-rank coal
  - ✓ Enhanced CBM recovery by thermal methods
  - ✓ Enhanced CBM recovery by nanotechnology
- **Methane Hydrates**
  - ✓ Sand control to prevent sanding up production wells
  - ✓ Geomechanics for reservoir compaction
  - ✓ CO_2 injection for enhanced gas recovery

Gas Hydrate Production in China

中国天然气水合物开发的研究

Prof Lau Hon Chung

刘汉中教授

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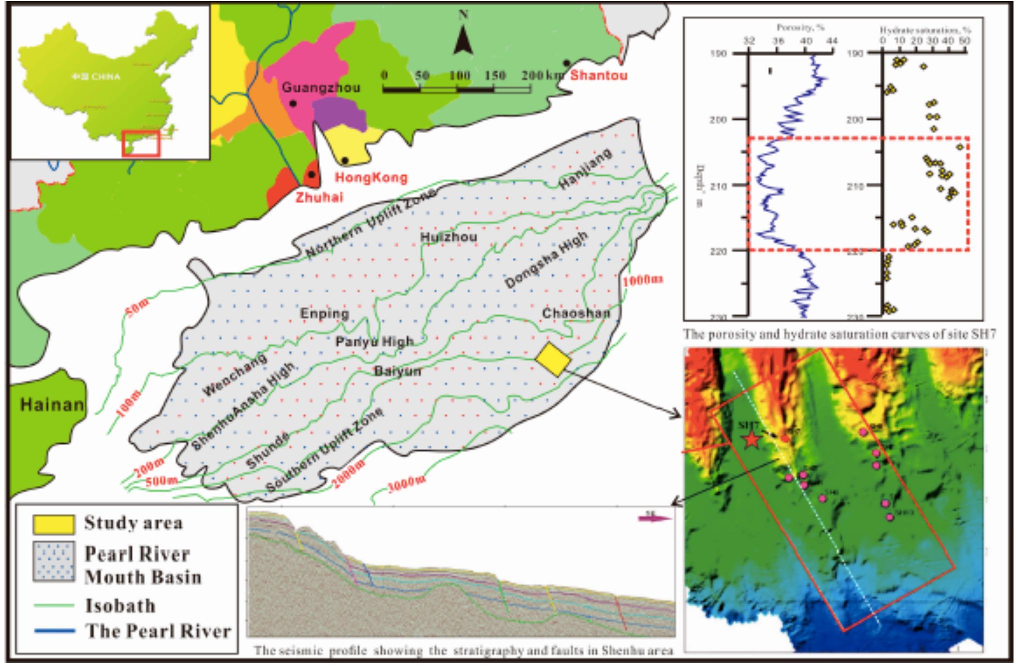
National University
of Singapore

Gas Hydrate Production in S. China Sea – 15 May 2017

- 南中国海，神狐海域
- 水深 1266m
- 海底以下 203-277m
- 连续产气 8天
- 最高产量 3.5万m^3/天
- 平均日产 1.6万m^3/天
- 累计产气超 120万m^3
- 甲烷含量达 99.5%



The porosity and hydrate saturation curves of site SH7

The seismic profile showing the stratigraphy and faults in Shenhu area

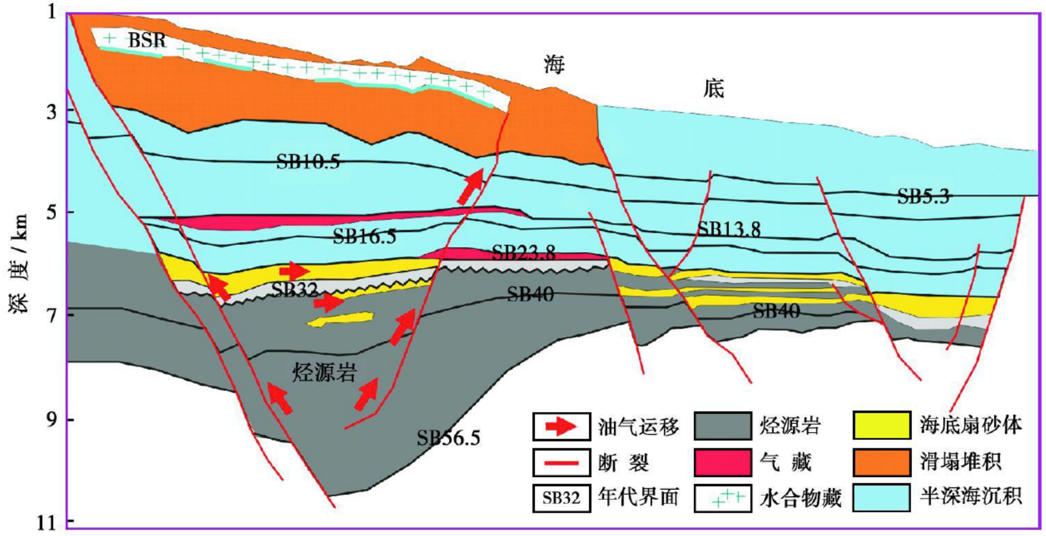
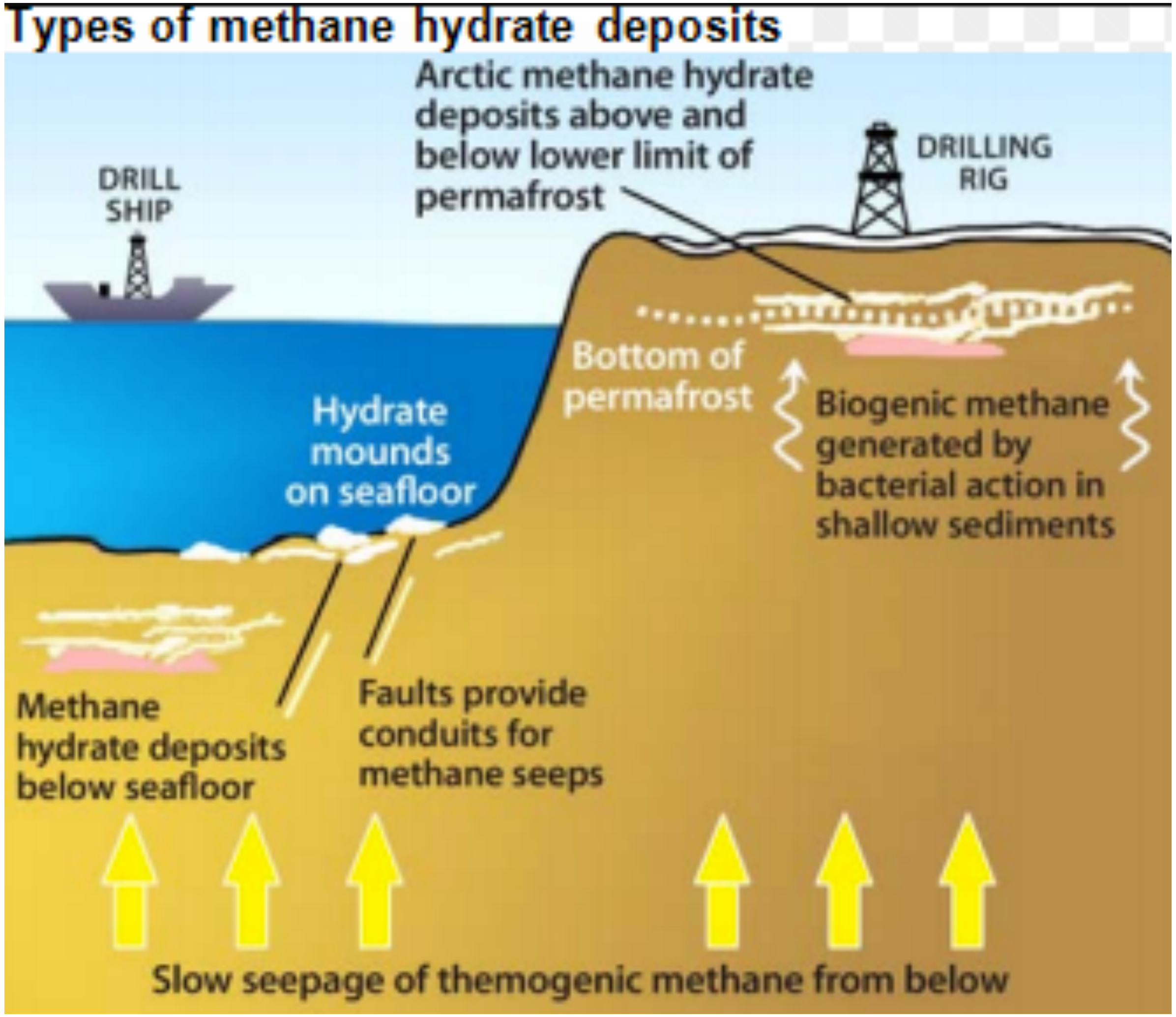
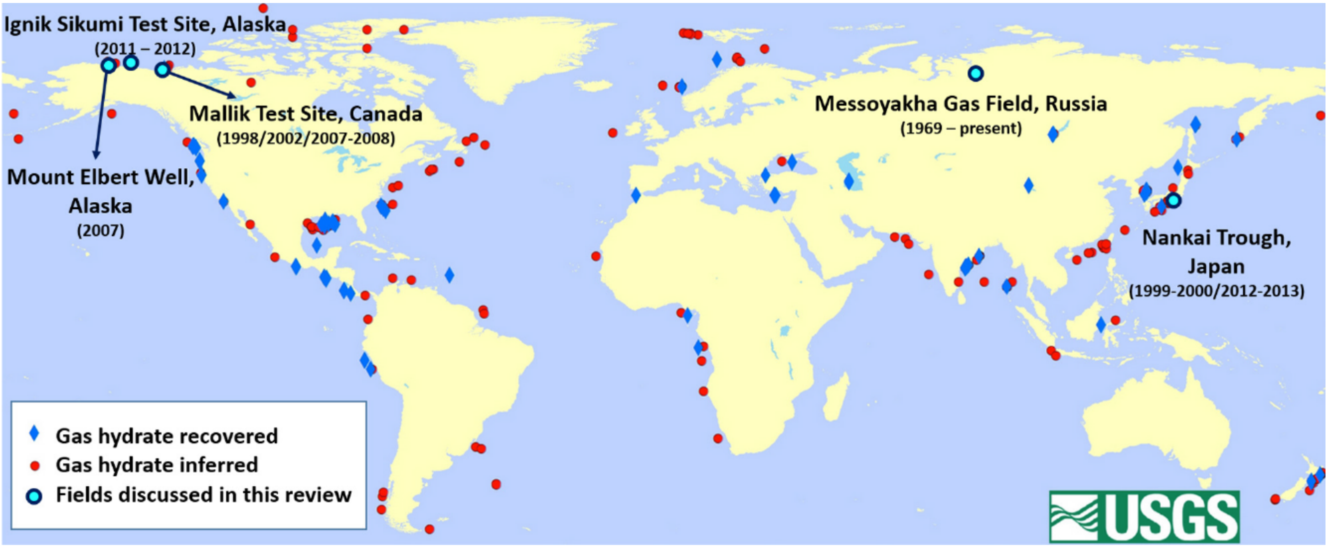


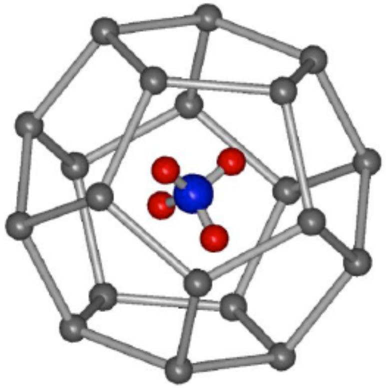
图 5　南海北部陆坡天然气—天然气水合物成藏模式

Types of Gas Hydrate – Marine & Permafrost (深水和冻土区天然气水合物)



Natural Gas Hydrates (天然气水合物)





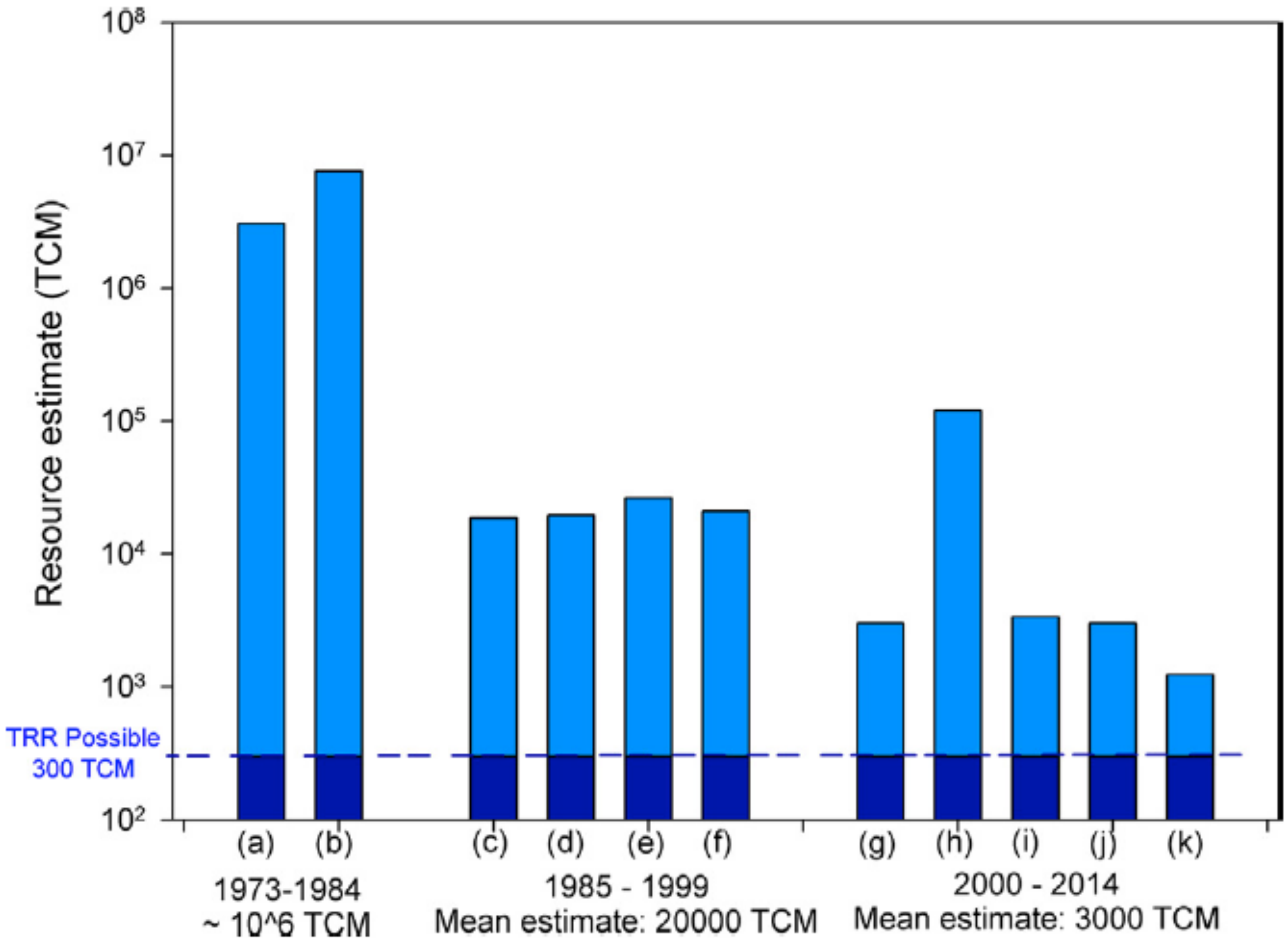
Molecular view

Naked eye view

- 1 m^3 methane hydrate contains 164 Sm^3 CH_4.
- NGH distributed worldwide
- Found in permafrost or deepwater continental margins
- Reserve estimate worldwide (ca. 300 TCM)
- Conventional gas reserve worldwide (187 TCM)
- Worldwide natural gas consumption was 3.5 TCM (2015)

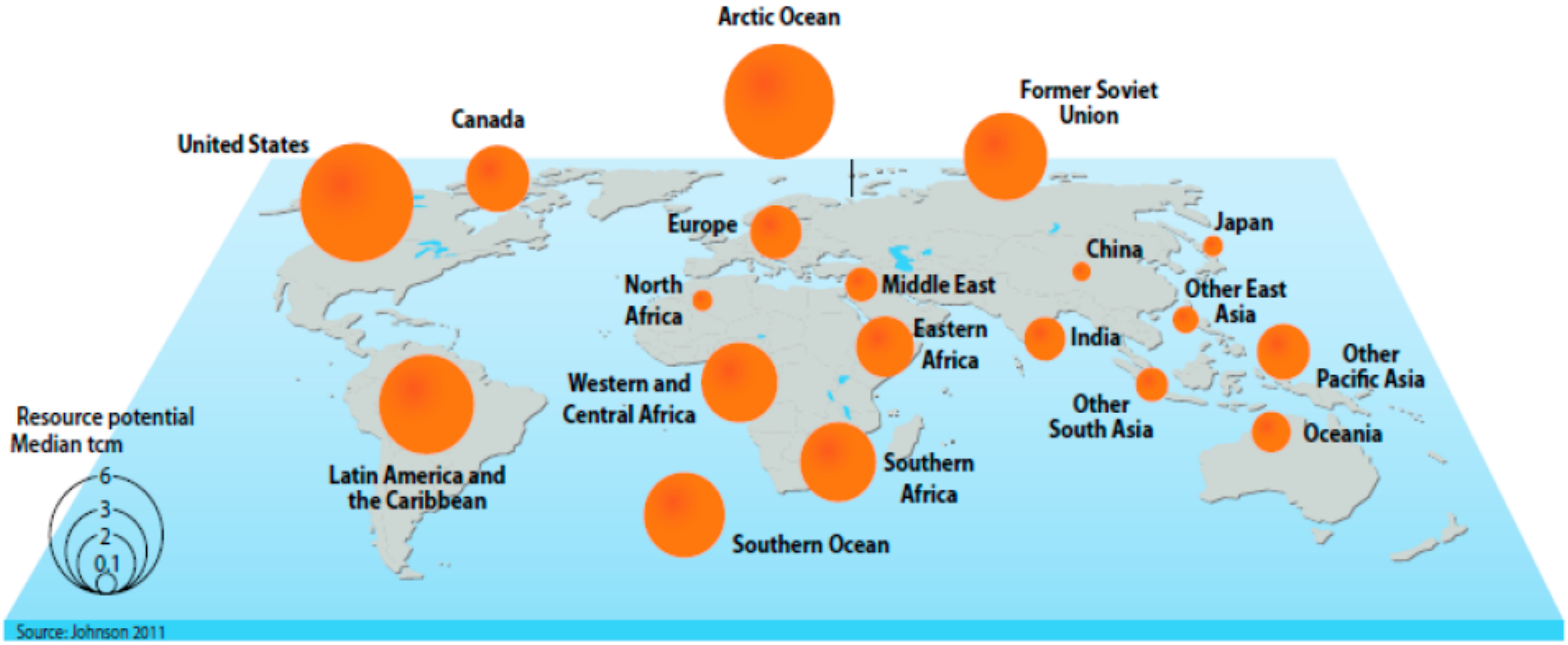
$$CH_4 + N_H H_2O \Leftrightarrow CH_4 \cdot N_H H_2O + \Delta H$$

NGH Resource Estimates (水合物资源量估计)



Zheng et al. (Applied Energy 162 (2016) 1633-1652

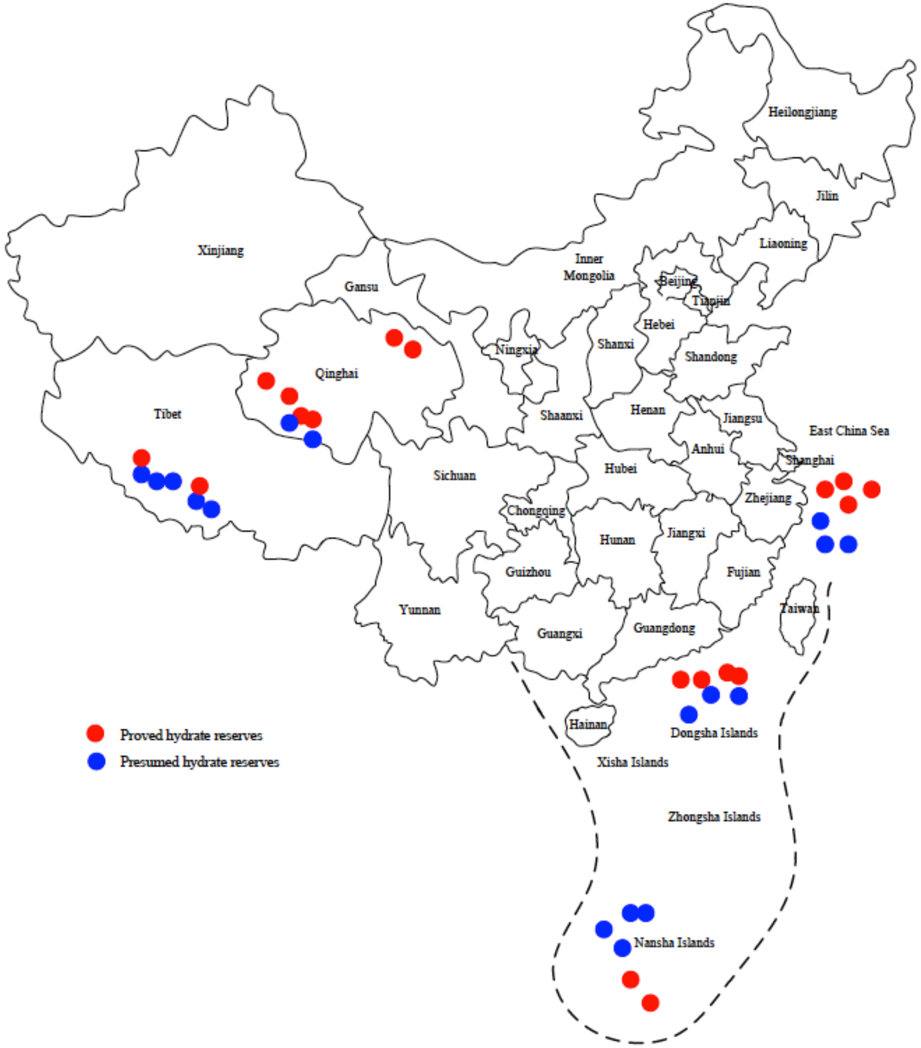
Global Natural Gas Hydrate Resource Estimate (全球天然气水合物资源量估计)

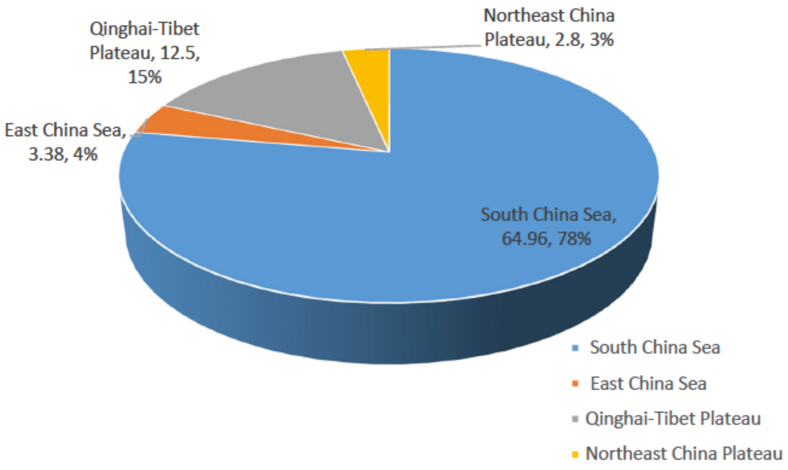


Source: Johnson 2011

Sun *et al.*, Energies (2016), 9, 714

Gas Hydrate Distribution in China (天然气水合物分布图)

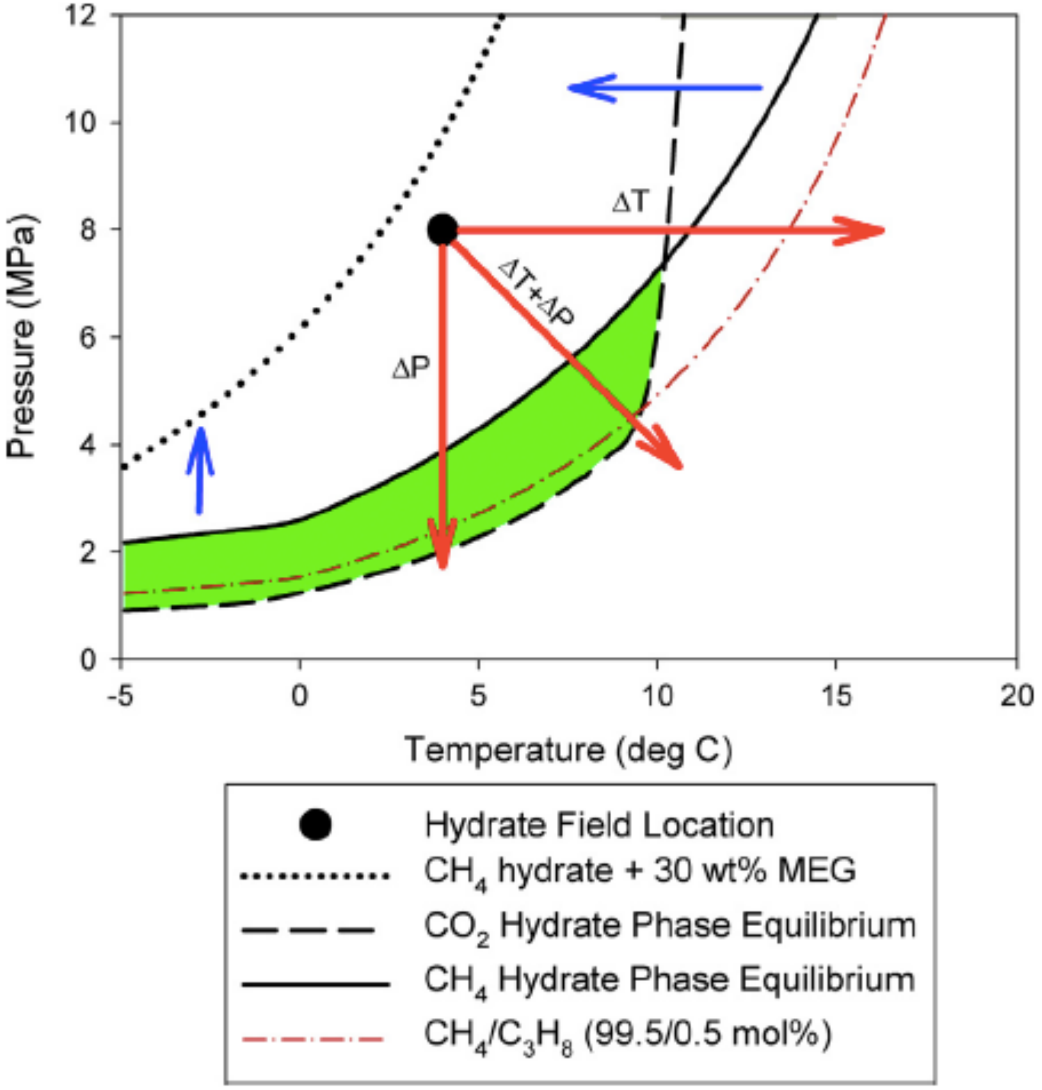




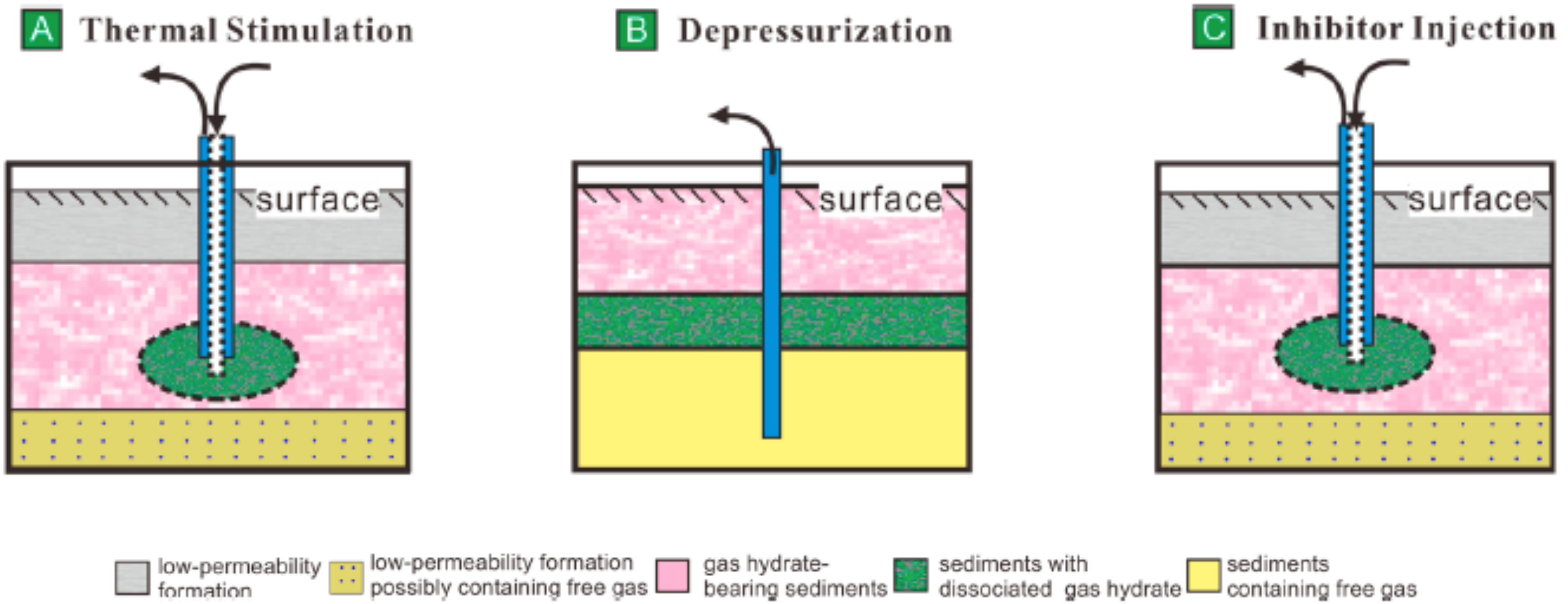
Tan *et al.*
(Sustainability
2016, 8, 520)

Methods of Gas Hydrate Production (天然气水合物开采的方法)

- **Depressurization 降压**
- **Thermal Stimulation 加热**
- **Inhibitor Injection 注入抑制剂**
- **CO_2-Exchange 二氧化碳交替**
- **Combination of above 以上组合**



Mechanism of Gas Hydrate Production
(天然气水合物采气机理)



Thermal Stimulation
加热

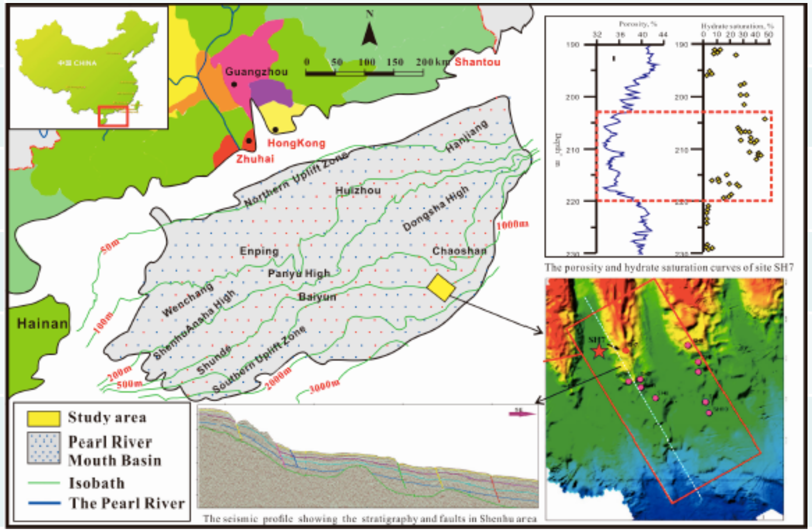
Depressuration
降压

Inhibitor / CO_2 Injection
注入抑制剂或CO_2

Reservoir Data (中国天然气水合物油藏数据)

	South China Sea (Shenhu area) 神狐海域	**Qinghai-Tibet Permafrost (Qilian Mountain)祁连山**
Ground temp, ^{o}C	NA	-1.2
Water depth, m	1235	NA
Porosity	0.38	0.35
Intrinsic perm (md)	10	69
Reservoir pressure, (MPa/psi)	15 / 2170	5.19 / 753
Reservoir temp, ^{o}C	15	5.4
Reservoir thickness, m	44	30
Reservoir depth below seafloor or ground, m	185	366
Hydrate saturation	0.25-0.48	0.25+

Hydrate Production in South China Sea
(南中国海天然气水合物开采的挑战和机遇)

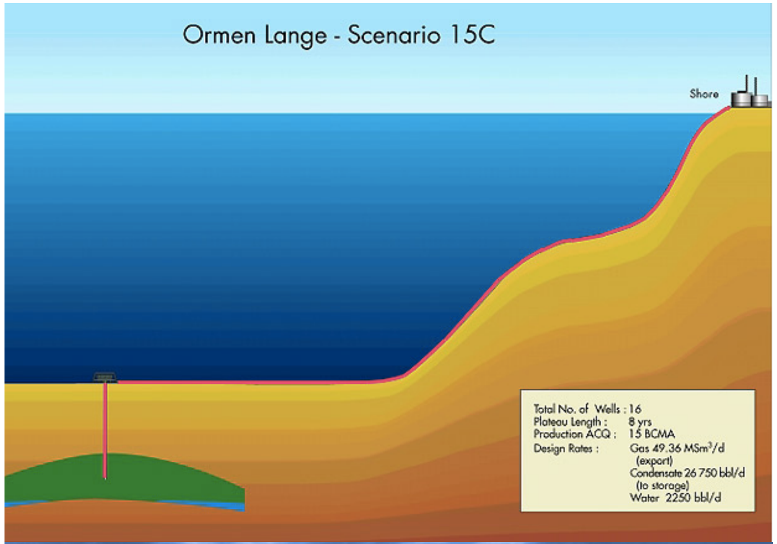
Challenges (挑战)	Opportunities (机遇)
- Costly deepwater development (300 km from land, 1,235 m water depth)	- Large resources volume ~ 78% of China's gas hydrate resource - 65 Tcm (65 billion tons of oil equiv)
- Requires TLP, subsea-to-beach or FLNG	- Ease of seismic survey
- Sand production	 The porosity and hydrate saturation curves of site SH7 The seismic profile showing the stratigraphy and faults in Shenhu area
- Seafloor subsidence	
- Water production	
- Gas pipeline to shore or FLNG	
- Will require high rate gas wells to sustain development cost	

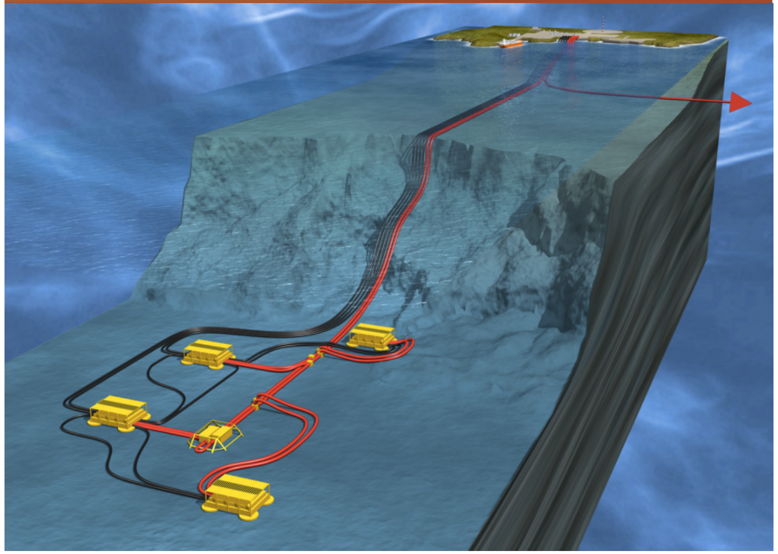
Conclusion: Due to its water depth and distance from shore, development of gas hydrate in the South China Sea will be **very expensive** and will require very high rate wells to be profitable.

Mars TLP in Gulf of Mexico

Water depth: 896 m
Distance from shore: 209 km
Oil Production: 35,000 m^3/d
Gas production: $6x10^6$ Sm^3/d
First production: 1996
Production is transported by pipeline to processing facility 89 km away
Cost: 1 billion USD

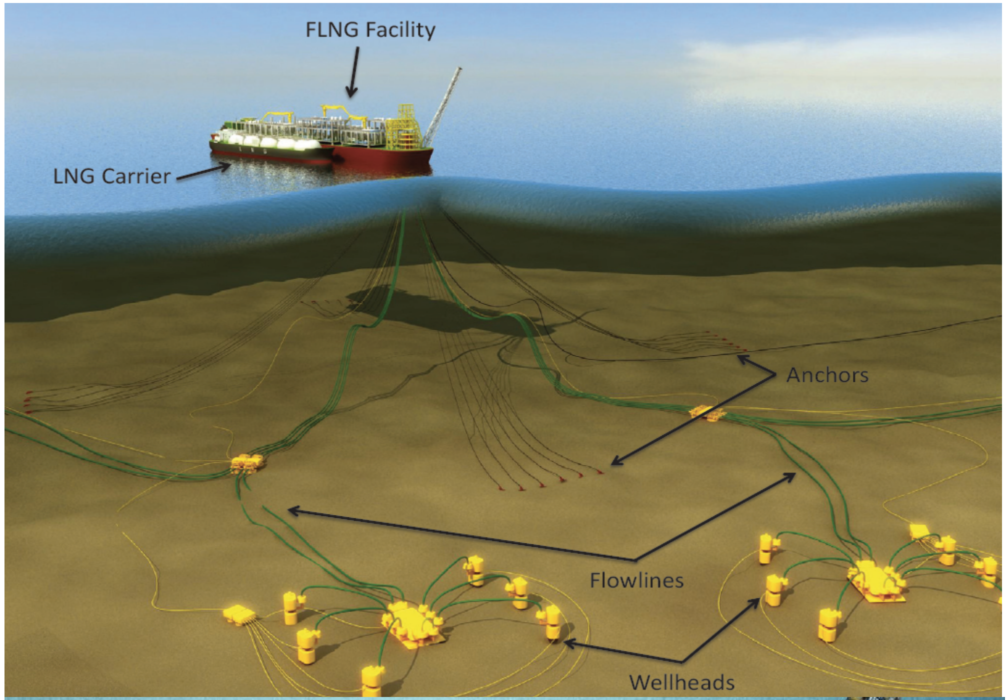
Orman Lange Subsea to Beach Development





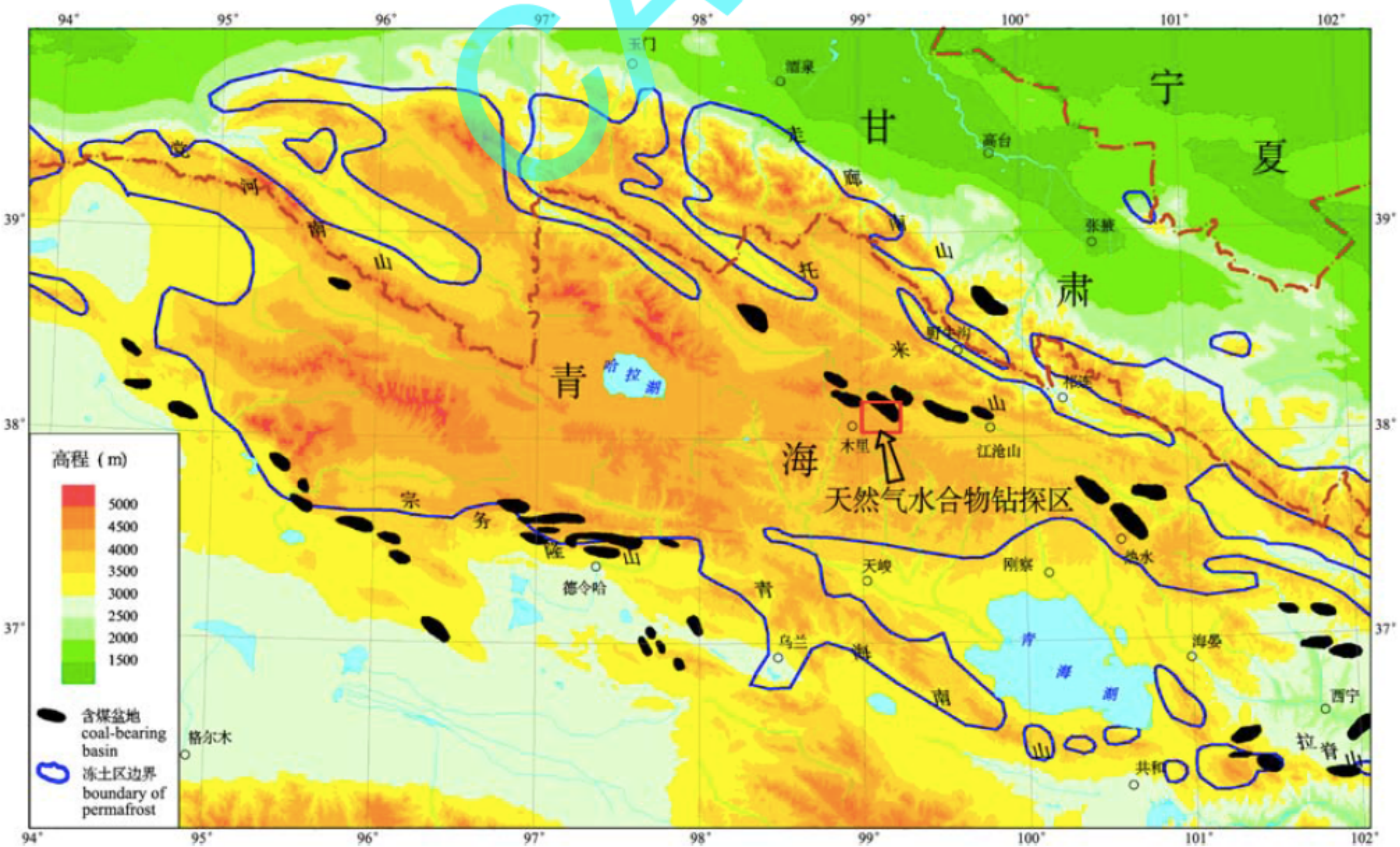
Water depth: 1100 m
Distance to shore: 120 km
24 subsea wells
Processing onshore at plant
Production: $70 x 10^6$ m^3/d
Recoverable reserve: 200 Bcm
First gas: 2007
Cost: 12 billion USD

Shell Prelude FLNG



Location: Offshore Australia
Water depth: 250m
Distance from land: 200 km
Concept: FLNG
Cost: 13 billion USD
First gas: 2018
Designed for 25 years
Production: 110,000 boe/day
Reserves: 85 Bcm

Hydrate Production in Qinghai-Tibet Plateau (青海西藏高原的天然气水合物)



Data from DK-9 hole, Qilian Mountain Permafrost

Fig. 3 Example of photos related to faults: mud and breccia in mudstone at the depths of 238.81m (left) and 402.71(right)

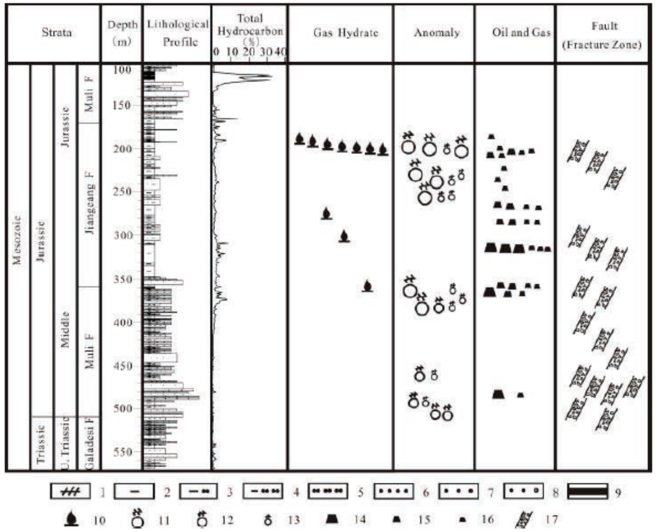


Fig. 4 Schematic distribution of gas hydrate, oil and gas, faults in DK-9

Note: 1-oil shale; 2-mudstone; 3-silty mudstone; 4-muddy siltstone; 5-siltstone; 6-fine sandstone; 7-medium sandstone; 8-pebbly coarse sandstone; 9-coal; 10-gas hydrate; 11-strongly bubbling; 12-water seepage or generally bubbling; 13-oil smell; 14-oil immersion; 15- brown precipitates; 16-strong kerosene smell; 17-fault or fracture zone

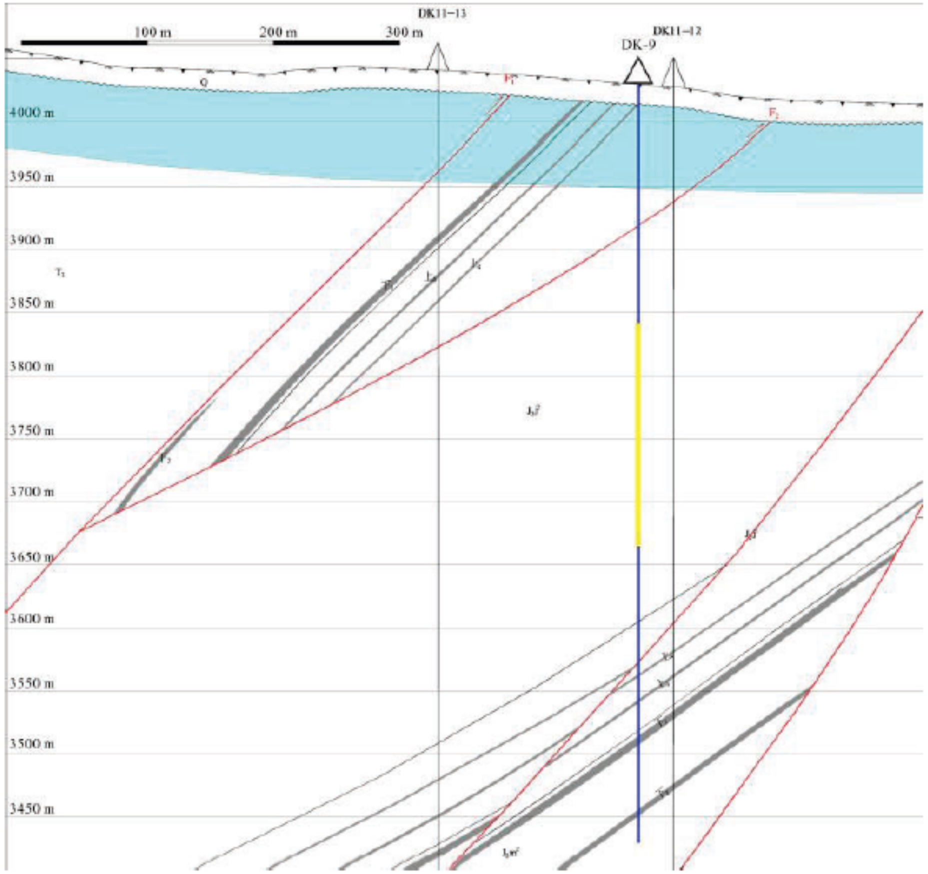


Fig. 6 Gas hydrate occurrences mainly controlled by F_2 fault in DK-9 (Base map revised from Qinghai No.105 Coal Geological Exploration Team, Xining, Qinghai, China)

Note: gas hydrate interval is marked in yellow in DK-9.

Lu *et al*. ISOPE conf. paper (2015)

Fig. 3 Abnormal indications within gas hydrate. Note: left-the lump gas hydrate and burning; middle-black heavy hydrocarbon occurs with gas hydrate; right-bubbles of slurry increasing violently near the gas hydrate stratum.

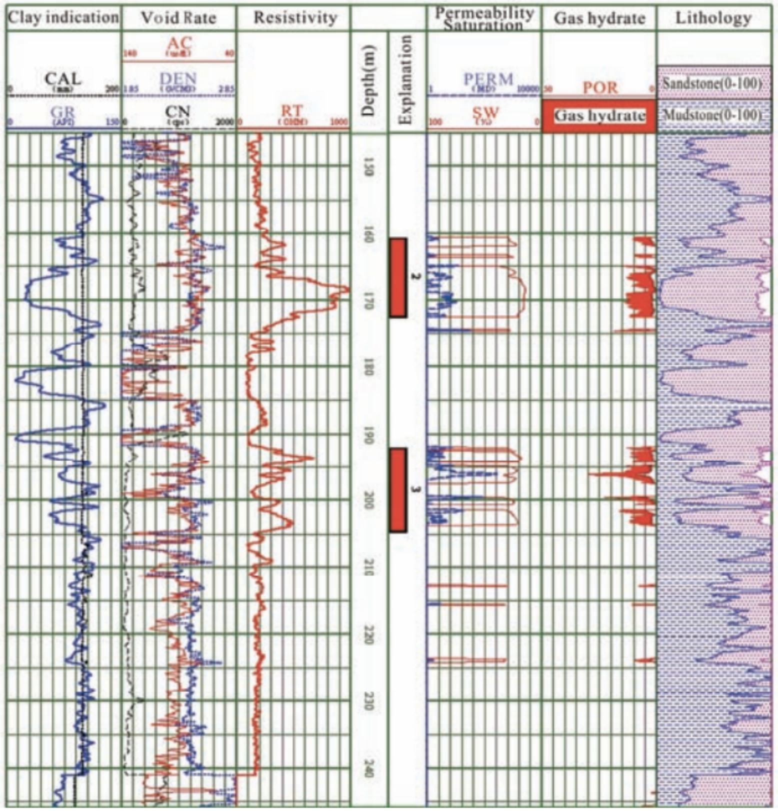


Fig. 5 Well logging explanation of gas hydrate in DK12-13 drill

Hydrate Production in Qinghai-Tibet Plateau (青海西藏高原天然气水合物开发的挑战和机遇)

Challenges (挑战)	**Opportunities (机遇)**
Difficult access: 4000-5000 m above sea level (roof of the world) 祁连山	Thick gas hydrate reservoirs (403m)
Lack of infrastructure: road, gas pipeline, oilfield equipment	Large resource volume ~ 0.12 to 240 Tcm
Temperature: -1 to -5^{o}C	Shallow formations (<400m buried depth)
Sand control	Development by vertical wells or shallow horizontal wells
Water production	
Compaction during production	

Conclusion: Developing gas hydrate in the permafrost will be much cheaper than in deepwater. Many technical issues are manageable.

Feasibility Study on Gas Hydrate Production in Qinghai-Tibet Permafrost (青海西藏高原冻土区天然气水的合物开发可行性研究)

- **Gas Hydrate Properties (天然气水合物性质)**
  - ✓ Hydrate classification: Class I-IV
  - ✓ Hydrate composition
  - ✓ Hydrate phase behavior
- **Reservoir Properties (气藏特性)**
  - ✓ Temperature and pressure
  - ✓ Intrinsic permeability, porosity
  - ✓ Hydrate, free gas, water saturation
  - ✓ In-place volumes
  - ✓ Buried depth
  - ✓ Reservoir thickness
  - ✓ Lithology
  - ✓ Rock strength
  - ✓ Relative permeabilities
  - ✓ Capillary pressure
  - ✓ Fractures
  - ✓ Pore size distribution
- **Geomechanics (地质力学)**
  - ✓ Shear failure
  - ✓ Subsidence
  - ✓ Well failure
- **Environment Impact (环境冲击)**
  - ✓ CH_4 release to environment
  - ✓ Stability of gas hydrate
  - ✓ CO_2 storage
  - ✓ Environmental footprint

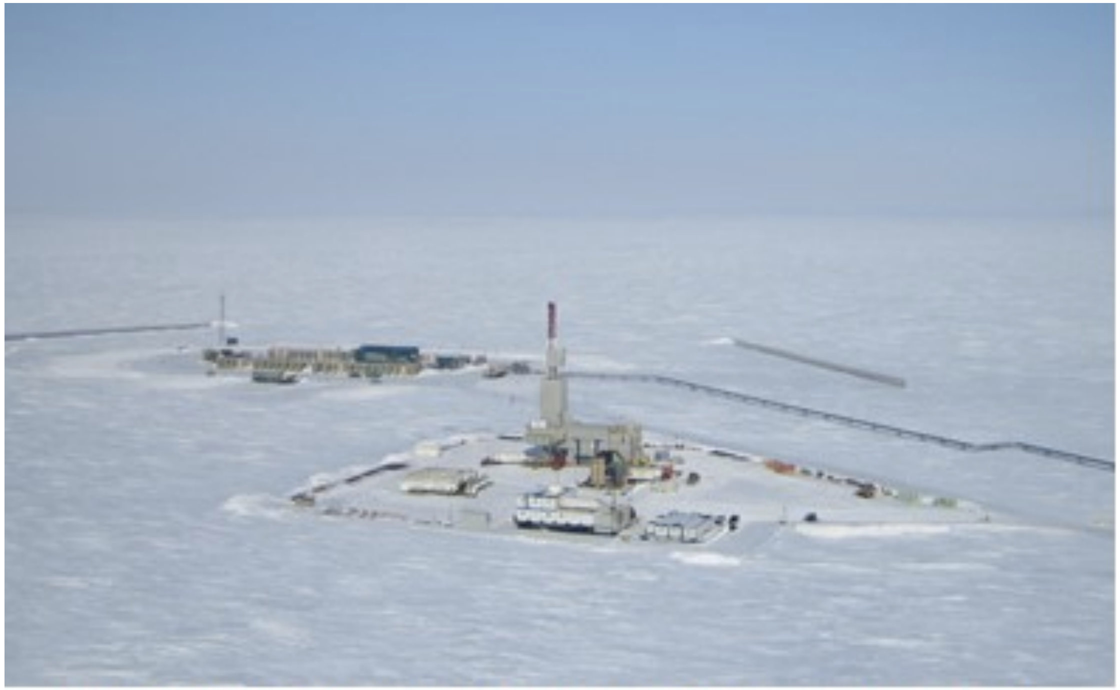
Feasibility Study on Gas Hydrate Production in Qinghai-Tibet Permafrost

- **Sand Control (防沙)**
  - ✓ Is sand control needed?
  - ✓ What type of sand control?
  - ✓ Can we produce sand to the surface and manage?
- **Well type (井型)**
  - ✓ Vertical well
  - ✓ Horizontal well (difficulty to drill extended reach in shallow reservoirs)
  - ✓ Multi-lateral (wellbore instability during drilling and production)
- **Production rate forecast (产量预测)**
  - ✓ Single well production rate
  - ✓ Fieldwide production rate
- **Recovery mechanisms (采气机理)**
  - ✓ Depressurizaton
  - ✓ Thermal Stimulation
  - ✓ Inhibitor
  - ✓ CO_2-Exchange
  - ✓ Combination
  - ✓ Software: CMG-STAR, TOUGH+HYDRATE

Key Technical Studies of Hydrate Production from the Qinghai-Tibetan Permafrost (陆相天然气水合物开采的主要技术研发)

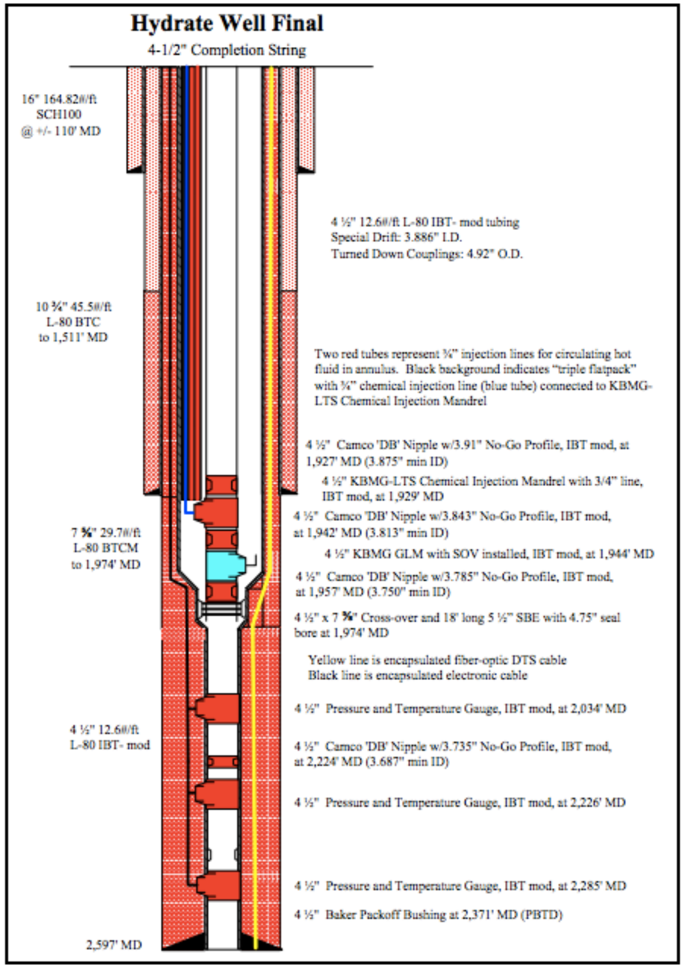
- **Geology (地质)**
  - Deposition environment
  - Reservoir continuity
  - In-place volume
  - Geo-modelling
- **Reservoir Engineering (油藏)**
  - Rock and fluid properties
  - Recovery mechanism
  - Well placement
  - Production forecast
- **Production Engineering (采气)**
  - Sand control
  - Well type
  - Well design
  - Inflow-outflow
  - Artificial lift
  - Abandonment
- **Drilling Engineering (钻井)**
  - Well trajectory
  - Drilling fluids
  - Wellbore stability
  - Casing integrity
  - Permafrost drilling
- **Facility Engineering (地面设施)**
  - Gas pipeline
  - Surface facility

Gas Hydrate Well in Alaska (2012)



Ignik Sikumi gas hydrate test site in Alaska and flared gas.

credit: NETL



Challenges and Opportunities of Coalbed Methane Development in China

中国煤层气开发的挑战和机遇

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Energy Fuels 2017, 31 4588-4602

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Challenges and Opportunities of Coalbed Methane Development in China

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ABSTRACT: Coalbed methane (CBM) resources in China have been estimated to exceed 36 Tcm. As of 2014, there were ~9300 producing CBM wells in China with an annual production of ~4.4 Bcm. To satisfy its need for energy and to transition to a low-carbon economy, China has a big need to accelerate CBM development. This paper gives an overview of the status of CBM development in China, identifies key technical challenges, and proposes solutions to overcome them. Our review of the literature has revealed that current CBM development in China faces several technical challenges. Current projects are focused on high-rank coals in the Qinshui and Ordos basins, which have major geological and engineering challenges. The former includes low permeability, subhydrostatic reservoir pressure, and a lack of understanding of the connectivity of coal seams, which leads to difficulty in sweet spot indication. The latter includes difficulty in hydraulic fracturing in vertical wells, because of the ductile nature of the coal seams in the Qinshui basin, bore hole instability and formation damage during drilling of horizontal wells. To remedy this situation, we propose a refocus on the more-abundant high-permeability low-rank coals in China and detailed coal seam characterization using current industry best practices of static and dynamic modeling of CBM reservoirs. This refocus on low-rank coal may lessen the need for hydraulic fracturing in vertical wells. For horizontal wells, research should focus on non-formation-damaging drilling fluids, incorporating geomechanics studies to reduce the risk of borehole collapse during drilling and production, and new horizontal well designs, which minimize the risk of collapse of the mother bore.

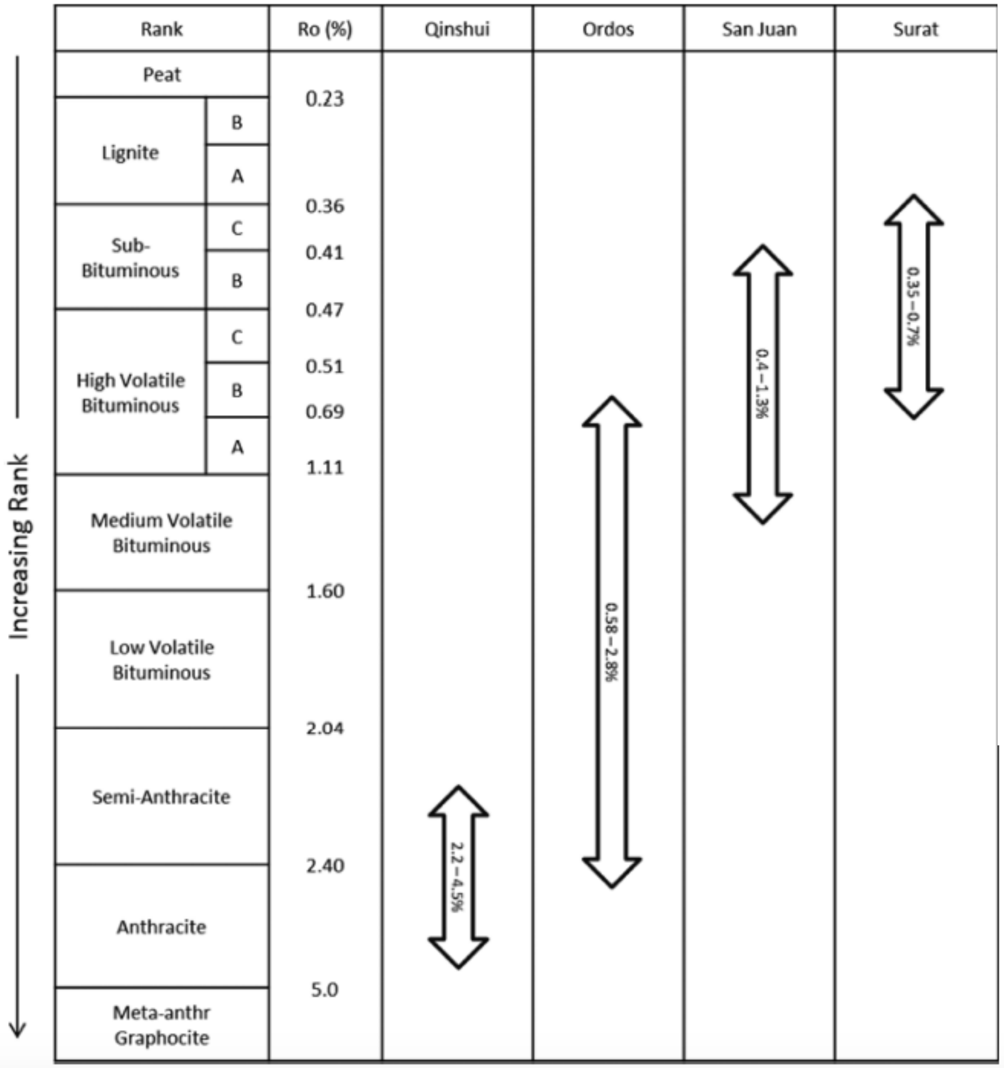
Distribution of China’s CBM Basins (中国煤层气盆地分布图)

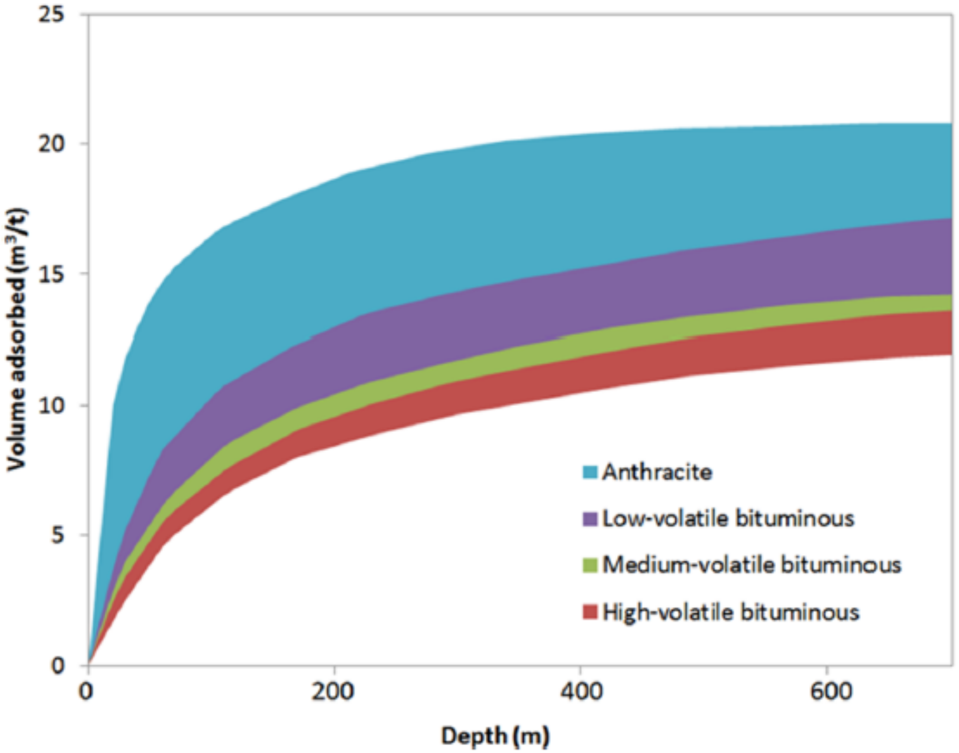
🟥 High rank 21% 高煤阶

🟨 Medium rank 39% 中煤阶

🟦 Low rank 40% 低煤阶

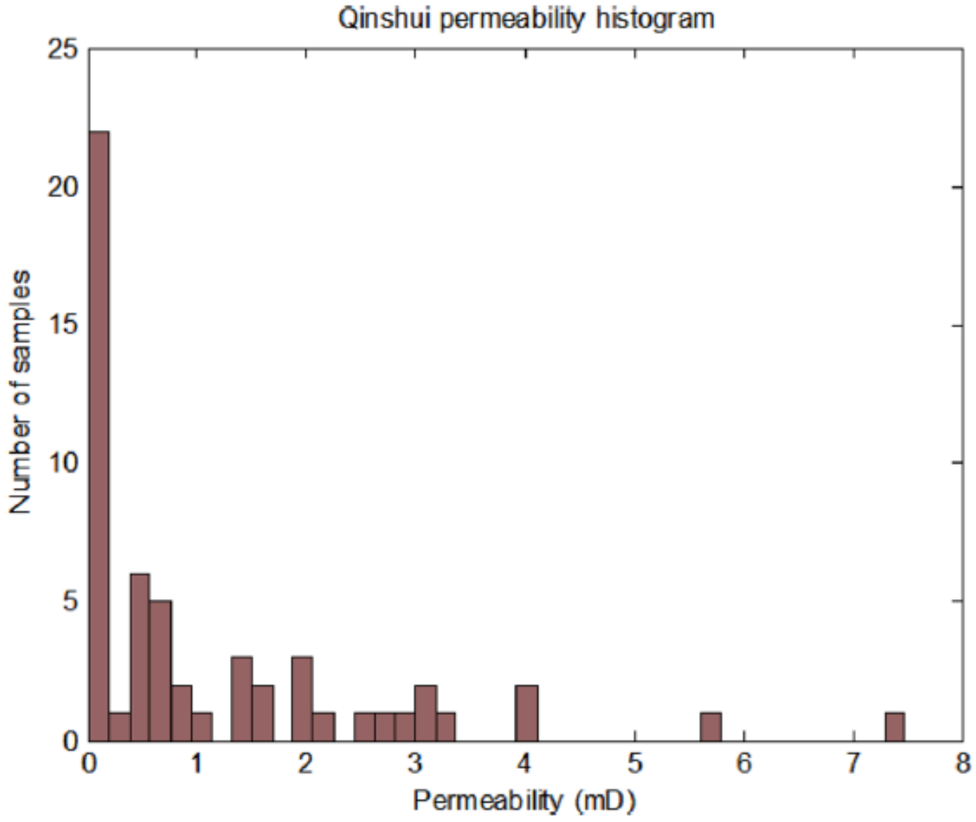
Comparison of Coal Rank (煤阶与吸附量的关系)

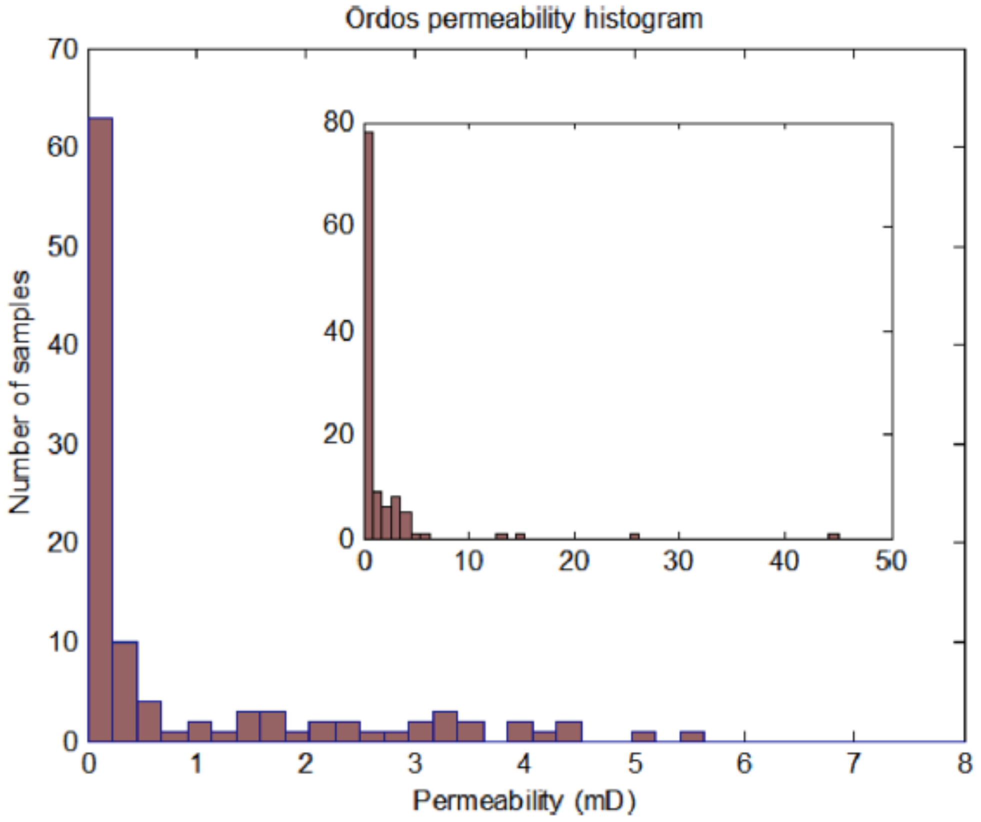




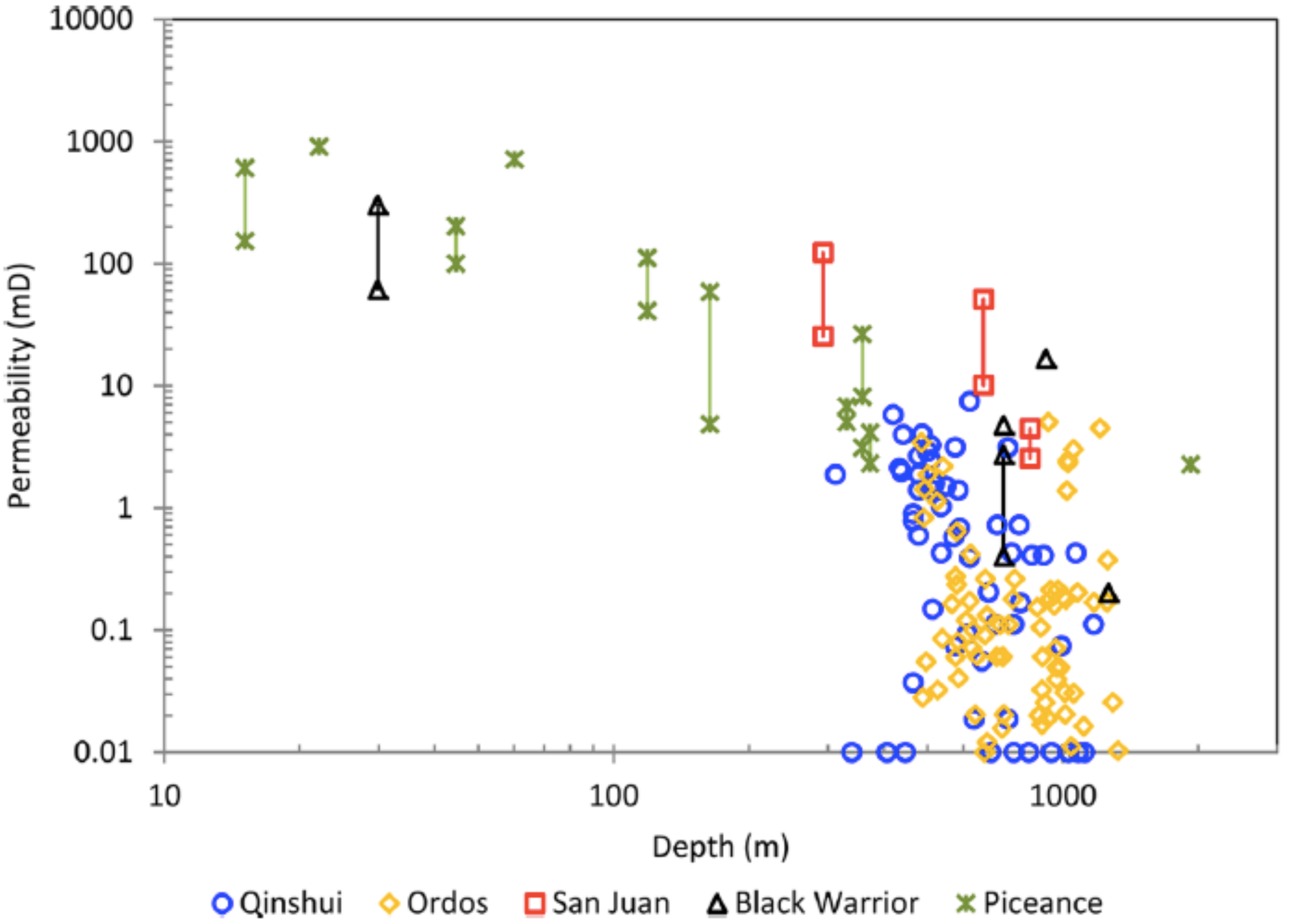
Relationship between rank, depth and adsorptive capacity

Histograms of Coal Perm in Qinshui & Ordos Basins (沁水与鄂尔多斯盆地煤层渗透率的直方图)

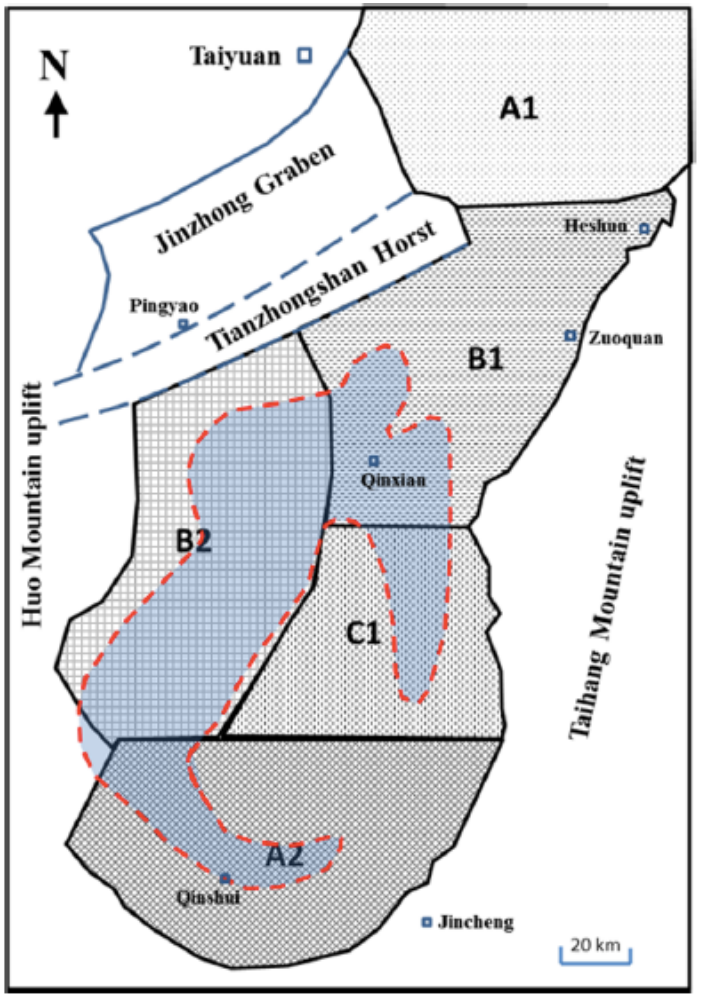


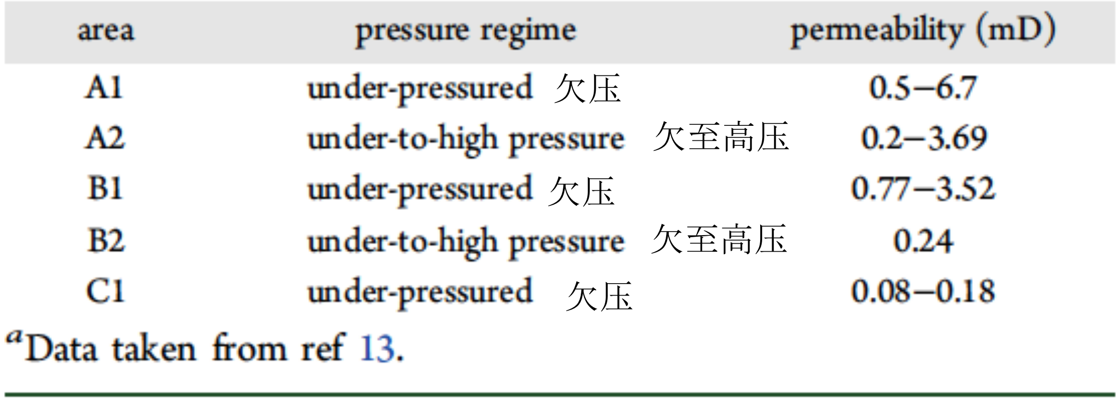


Perm-depth Comparison for CBM Basins
(各煤层气盆地渗透率与埋深的比较)



Pressure Regime & Perm in Five Areas of Qinhsui Basin (沁水盆地五区气藏压力图)



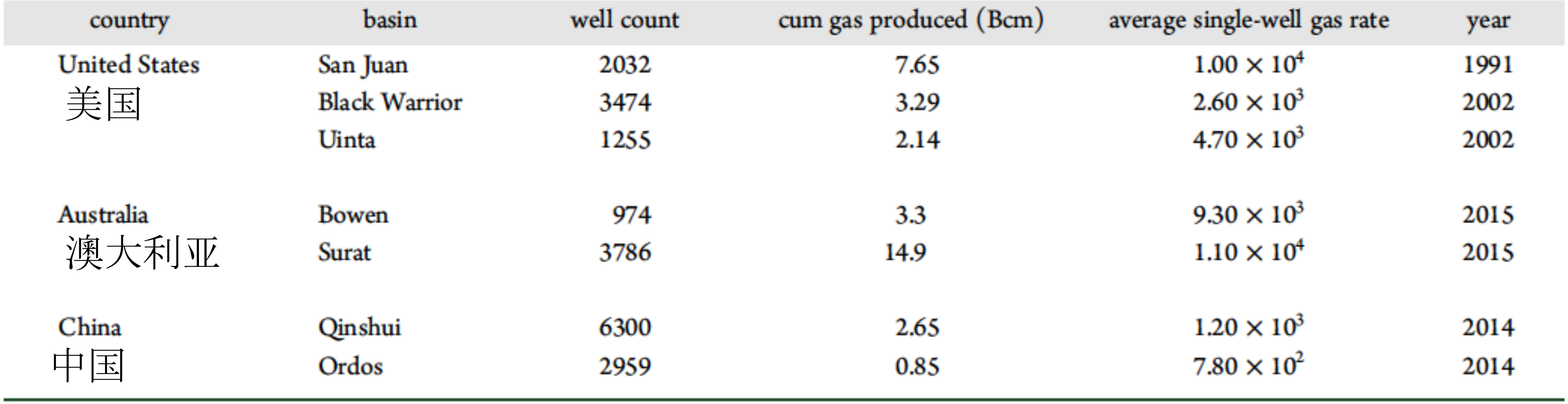


area	pressure regime	permeability (mD)
A1	under-pressured 欠压	0.5–6.7
A2	under-to-high pressure 欠至高压	0.2–3.69
B1	under-pressured 欠压	0.77–3.52
B2	under-to-high pressure 欠至高压	0.24
C1	under-pressured 欠压	0.08–0.18

[a] Data taken from ref 13.

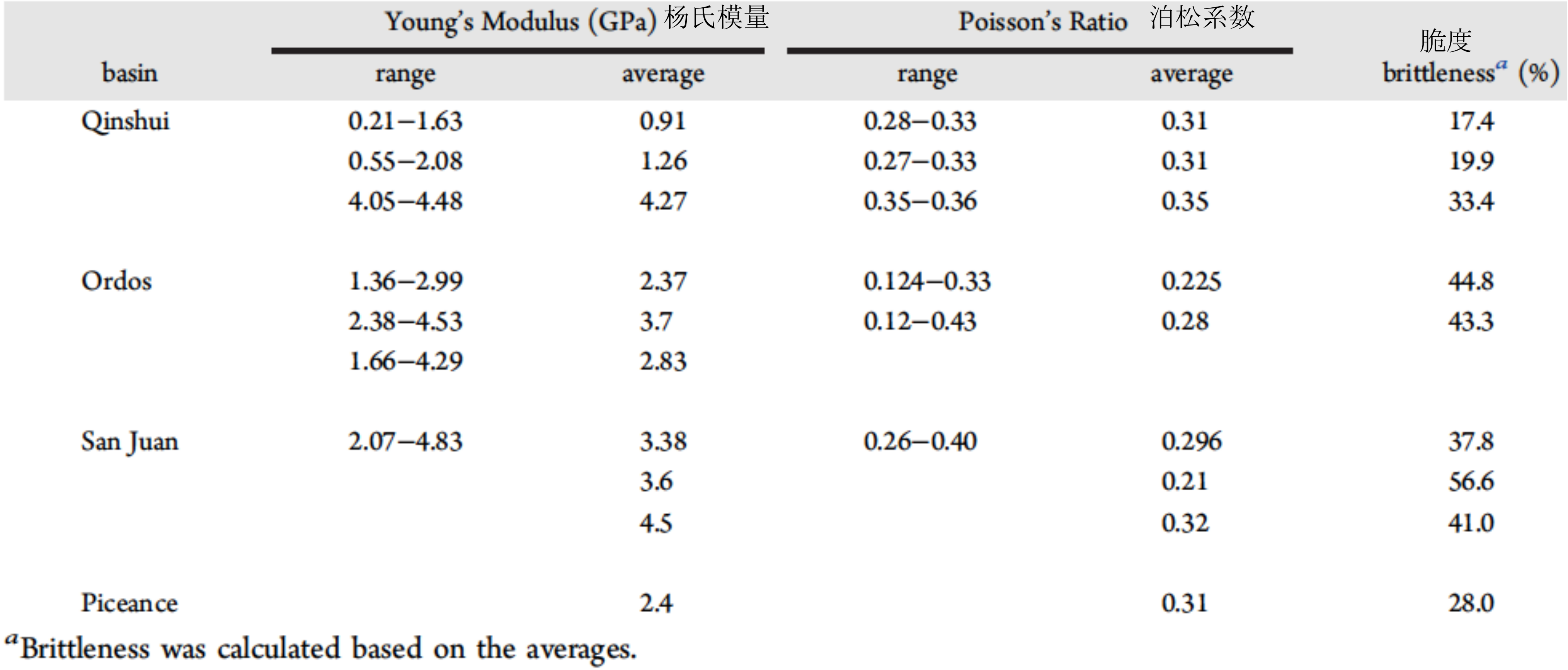
Production Rates for Various CBM Basins (各煤层气盆地产量的比较)

Sm^3/d



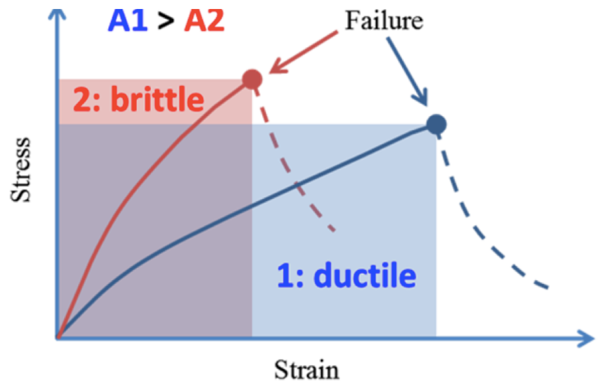
country	basin	well count	cum gas produced (Bcm)	average single-well gas rate	year
United States 美国	San Juan	2032	7.65	1.00×10^4	1991
	Black Warrior	3474	3.29	2.60×10^3	2002
	Uinta	1255	2.14	4.70×10^3	2002
Australia 澳大利亚	Bowen	974	3.3	9.30×10^3	2015
	Surat	3786	14.9	1.10×10^4	2015
China 中国	Qinshui	6300	2.65	1.20×10^3	2014
	Ordos	2959	0.85	7.80×10^2	2014

Comparison of Mechanical Properties (机械性能的比较)

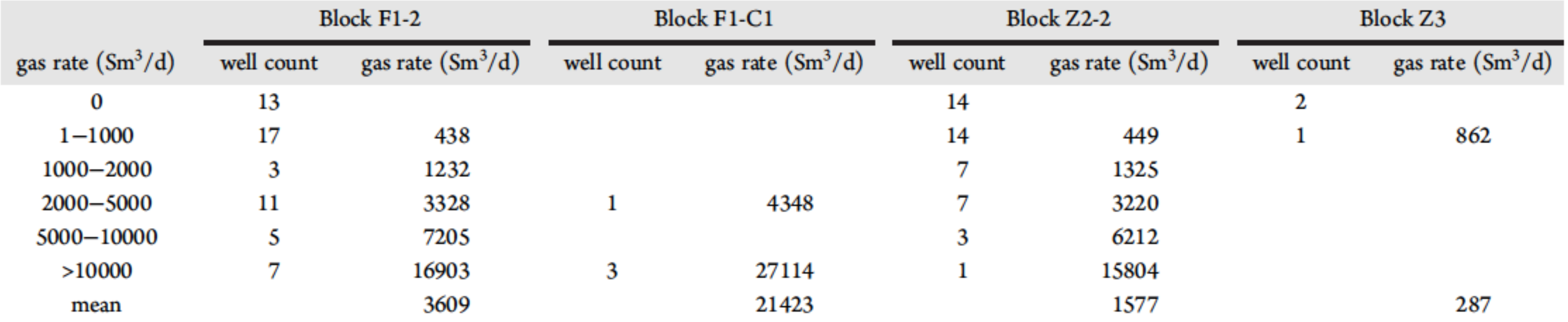


basin	Young's Modulus (GPa) 杨氏模量		Poisson's Ratio 泊松系数		脆度 brittleness[a] (%)
	range	average	range	average	
Qinshui	0.21–1.63	0.91	0.28–0.33	0.31	17.4
	0.55–2.08	1.26	0.27–0.33	0.31	19.9
	4.05–4.48	4.27	0.35–0.36	0.35	33.4
Ordos	1.36–2.99	2.37	0.124–0.33	0.225	44.8
	2.38–4.53	3.7	0.12–0.43	0.28	43.3
	1.66–4.29	2.83			
San Juan	2.07–4.83	3.38	0.26–0.40	0.296	37.8
		3.6		0.21	56.6
		4.5		0.32	41.0
Piceance		2.4		0.31	28.0

[a] Brittleness was calculated based on the averages.



Production Rates of Horizontal CBM Wells in South Qinshui Basin (南沁水盆地水平井产量)



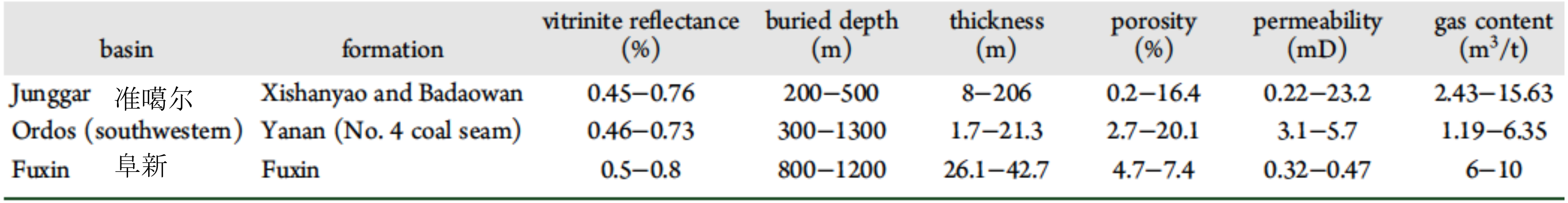
	Block F1-2		Block F1-C1		Block Z2-2		Block Z3	
gas rate (Sm^3/d)	well count	gas rate (Sm^3/d)	well count	gas rate (Sm^3/d)	well count	gas rate (Sm^3/d)	well count	gas rate (Sm^3/d)
0	13				14		2	
1–1000	17	438			14	449	1	862
1000–2000	3	1232			7	1325		
2000–5000	11	3328	1	4348	7	3220		
5000–10000	5	7205			3	6212		
>10000	7	16903	3	27114	1	15804		
mean		3609		21423		1577		287

Opportunities for Future Development (机遇)

Development of Moderate to Low-Rank Coal (中丶低煤阶开发)

1. **China has abundance low-rank coal CBM resources**
   - a) 147 Tcm, ~40% of total CBM resource (低煤阶资源量佔全国40%)
   - b) Junggar and Tu-hua basins in NW China (准噶尔和吐哈盆地)
   - c) Halaer and Erlian basins in NE China (海拉尔和二连盆地)
   - d) Ordos basin (鄂尔多斯盆地)

Properties of Low Rank Coals in China (中国低煤阶煤的特性)



basin	formation	vitrinite reflectance (%)	buried depth (m)	thickness (m)	porosity (%)	permeability (mD)	gas content (m^3/t)
Junggar 准噶尔	Xishanyao and Badaowan	0.45–0.76	200–500	8–206	0.2–16.4	0.22–23.2	2.43–15.63
Ordos (southwestern)	Yanan (No. 4 coal seam)	0.46–0.73	300–1300	1.7–21.3	2.7–20.1	3.1–5.7	1.19–6.35
Fuxin 阜新	Fuxin	0.5–0.8	800–1200	26.1–42.7	4.7–7.4	0.32–0.47	6–10

Opportunities for Future Development (机遇)

Understand Coal Connectivity through Improved Reservoir Characterization (中丶低煤阶开发)

1. **Integrated Reservoir Modeling (综合油藏模拟)**
    - a) Integrate well logs, cores, seismic, topology to calculate in-place volume
    - b) Sensitivity and uncertainty studies
    - c) Geo-model building
    - d) Single well history match
    - e) Fieldwide history matching
    - f) Well placement and production forecasting

Integrated Geo-Model Building Workflow for CBM

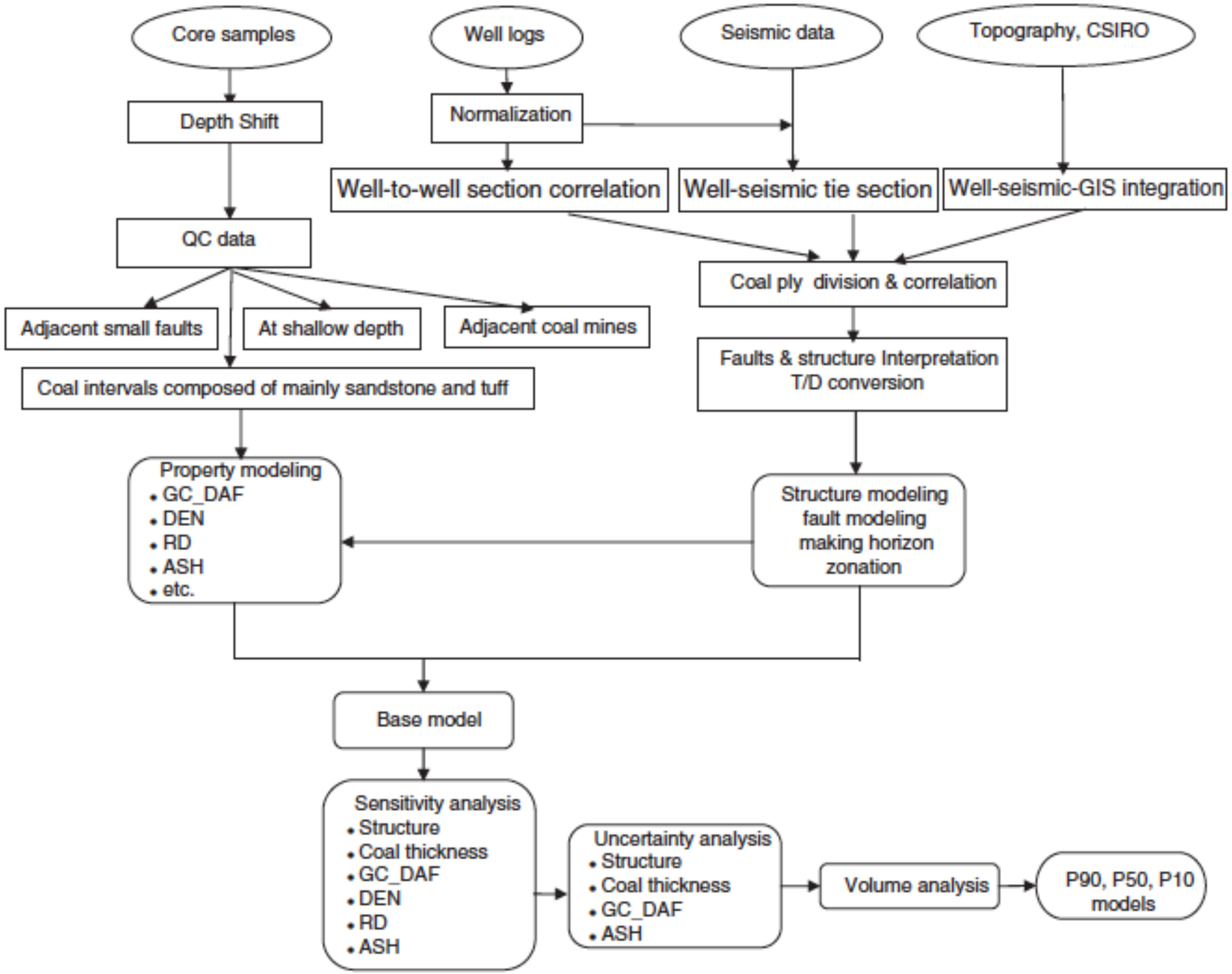


Fig. 1—An integrated geomodel-building work flow for CBM.

Zhang *et al.*, SPE Res Eval & Eng, May 2015

Opportunities for Future Development (机遇)

Engineering Studies (工程研究)

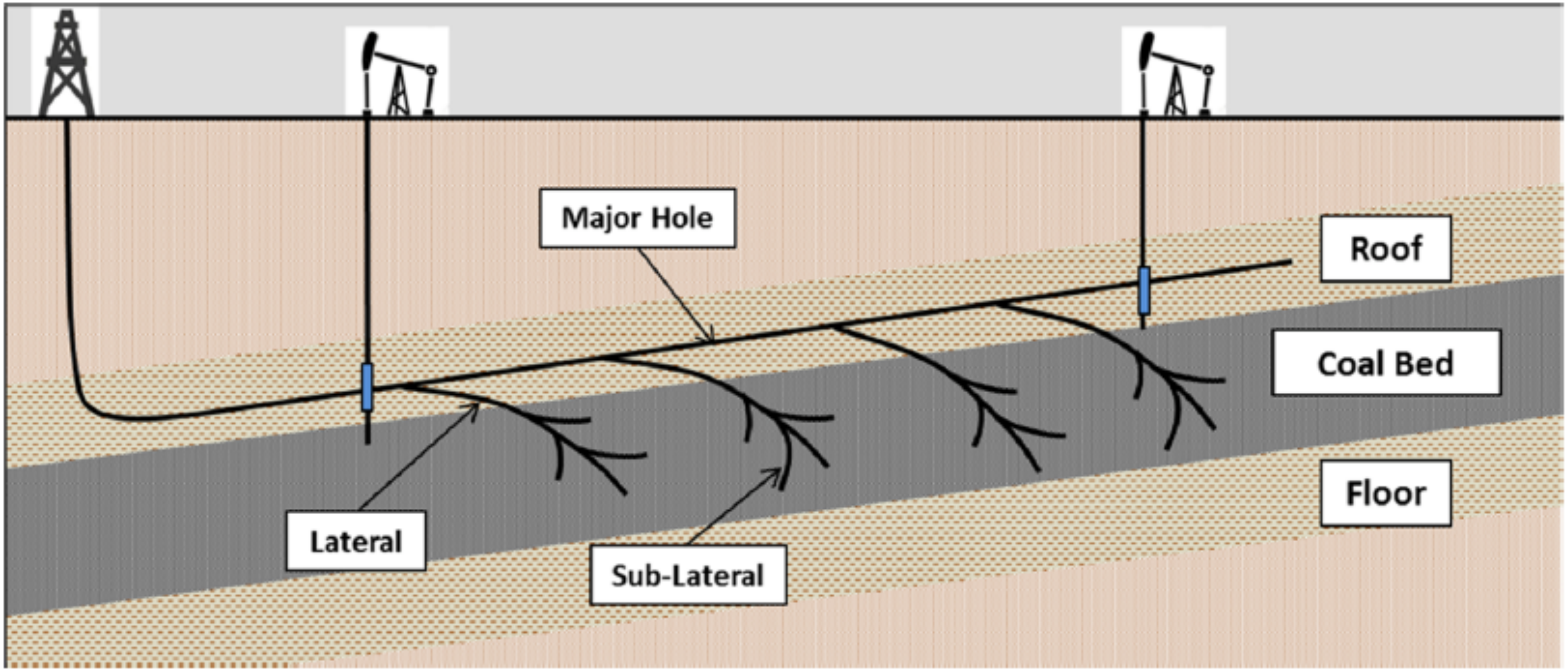
1. **Hydraulic Fracturing Design (水力压裂设计)**
   a) Determine need for hydraulic fracturing for low-rank coal in China (低煤阶煤层气开发是否需要水力压裂)
   b) Fracturing fluids: cross-linked gel vs slick water (压力液的设计: 交联凝胶或是减水)

Opportunities for Future Development (机遇)

Engineering Studies (工程研究)

1. **Horizontal well design (水平井设计)**
   a) Non-formation damaging drilling fluids (防地层损害钻井液)
   b) New well types to tackle borehole instability during drilling and production (防垮塌井型)

Tree-like Horizontal Well Design Piloted in Qinshui Basin (沁水盆地树型水平实验井)




Thank You!