Oil & Natural Gas Technology

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Quarterly Research Performance Progress Report (July - September 2013)

Verification of capillary pressure functions and relative permeability equations for gas production

Submitted by:
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National Energy Technology Laboratory

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Office of Fossil Energy

SUMMARY

Task 1.0 Project Management and Planning
Done

Task 2.0 Pore Network Generation
In progress

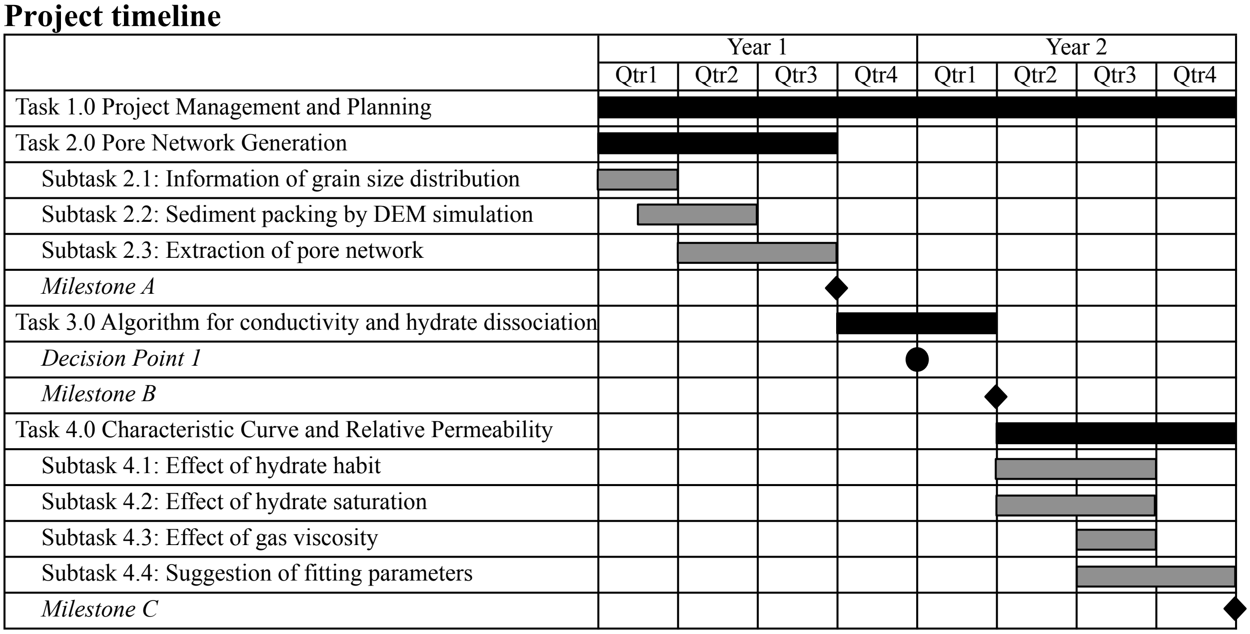
Subtask 2.1 Information of relevant information of in-situ hydrate-bearing sediments
Done

Subtask 2.2 Generation of sediment packing using Discrete Element Model (DEM)
Done

Subtask 2.3 Extraction of pore-network from sediment packing
Done

Task 3.0 Algorithm for conductivity and hydrate dissociation
In progress

Project timeline



In this quarterly report at the end of the first budget period, the project achievement during the whole budget period is attached as a presentation file format.

Verification of Capillary Pressure and Relative Permeability Equation for Gas Production

DE-FE0009927

Jaewon Jang
Wayne State University

Presentation Outline

Project Overview

Accomplishments

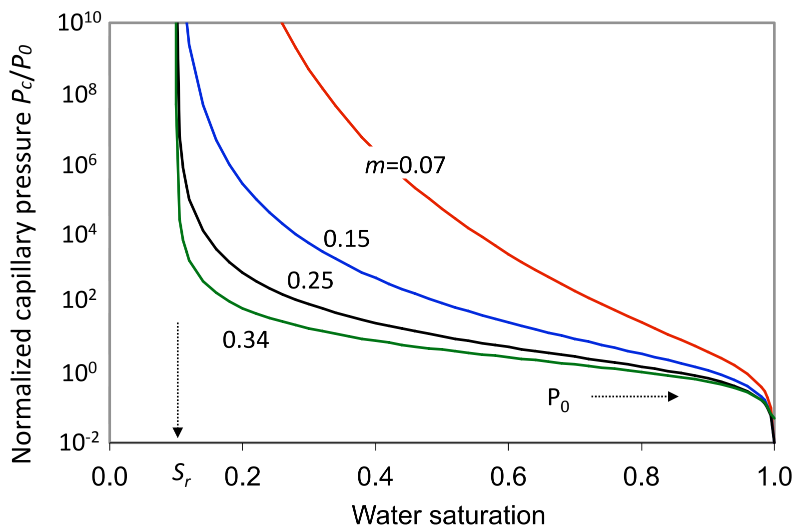
Budget / Plan for 2nd year

Presentation Outline

- Project Overview
- Accomplishments
- Budget / Plan for 2nd year

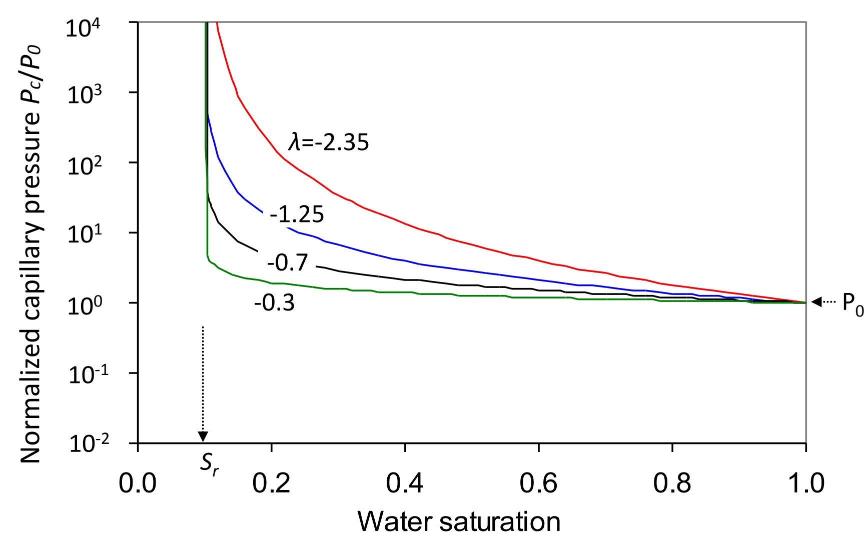
Characteristic Curve

van Genuchten (1980)



$$P_c = P_0\left[\left(\frac{S_w - S_r}{1 - S_r}\right)^{-\frac{1}{m}} - 1\right]^{1-m}$$

Corey (1954)

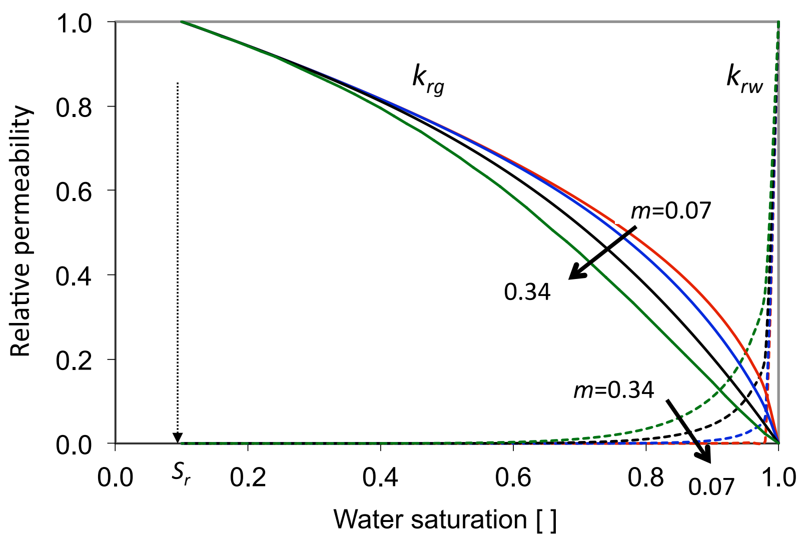


$$P_c = P_0\left(\frac{S_w - S_r}{1 - S_r}\right)^{\lambda}$$

P_c: capillary pressure, P_0: entry pressure, S_w: water saturation, S_r: residual water saturation
m-values (5521 samples): *m*=0.07 for very fine-grained soils ~ *m*=0.34 for coarse-grained soil
[Wösten et al., 1999]

Relative Permeability

van Genuchten (1980)

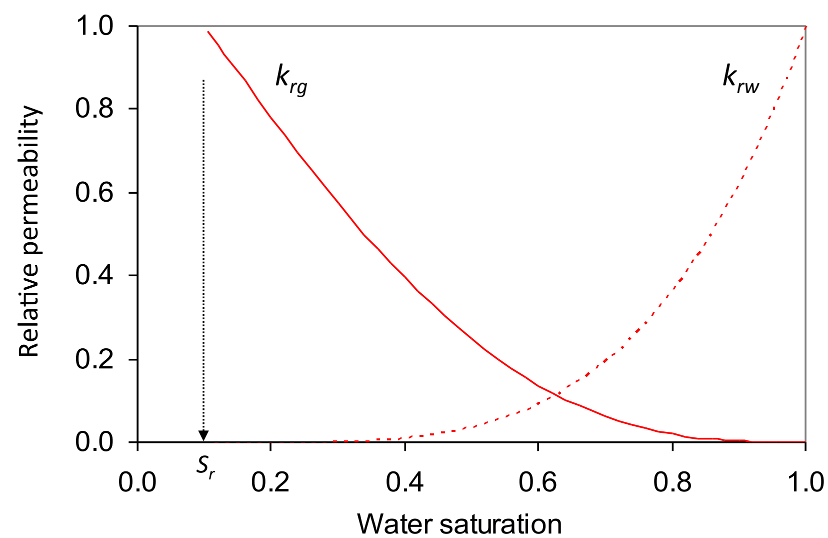


$$k_{rw} = \overline{S}^{0.5}\left[1-\left(1-\overline{S}^{1/m}\right)^m\right]^2$$

$$k_{rg} = \sqrt{1-\overline{S}}\left(1-\overline{S}^{1/m}\right)^{2m}$$

$$\overline{S} = \frac{S_w - S_{rw}}{1-S_{rw}}$$

Corey (1954)



$$k_{rw} = \overline{S}^4$$

$$k_{rg} = \left(1-\overline{S}\right)^2\left(1-\overline{S}^2\right)$$

$$\overline{S} = \frac{S_w - S_{rw}}{1-S_{rw}-S_{rg}}$$

Parameters used in Hydrate Simulation

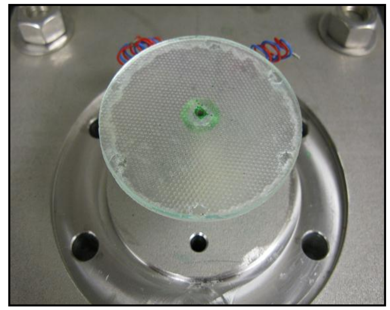
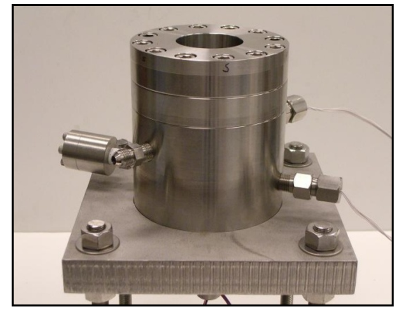
Model	Equation	Factors used in hydrate bearing sediment study					References
		Relative saturation $\overline{S}$	S_{rg}	S_{rw}	P_0	m or λ	
Van Genuchten (1980)	$P_c = P_0\left[\overline{S}^{-\frac{1}{m}} - 1\right]^{1-m}$	$\overline{S} = \frac{S_w - S_{rw}}{S_{mxw} - S_{rw}}$	-	0.14	-	0.46	Gamwo and Liu (2010)
			-	-	0.1MPa	0.45	Moridis and Reagan (2007[a]) Moridis and Reagan (2007[b])
			-	0.19	2kPa	0.45	Moridis and Sloan (2007)
			-	-	0.1MPa	0.45	Moridis et al. (2009)
			-	-	5kPa	0.77	Moridis et al. (2010) Reagan et al. (2010)
			-	0.19	2kPa	0.45	Reagan and Moridis (2008)
			-	-	2kPa	0.45	Rutqvist and Moridis (2007)
		$\overline{S} = \frac{S_w - S_{rw}}{1 - S_{rg} - S_{rw}}$	0.5	0.3 0.2	1kPa	0.45	Hong and Pooladi-Darvish (2003) Uddin et al. (2008)
Corey (1954)	$P_c = P_0\overline{S}^{\lambda}$	$\overline{S} = \frac{S_w - S_{rw}}{1 - S_{rw}}$	-	-	-	- 0.5	Corey (1954)
			-	-	-	- 0.65	Liang et al. (2010)
		$\overline{S} = \frac{S_w - S_{rw}}{1 - S_{rg} - S_{rw}}$	0.1	0.1	5kPa	- 0.25	Konno et al. (2010)

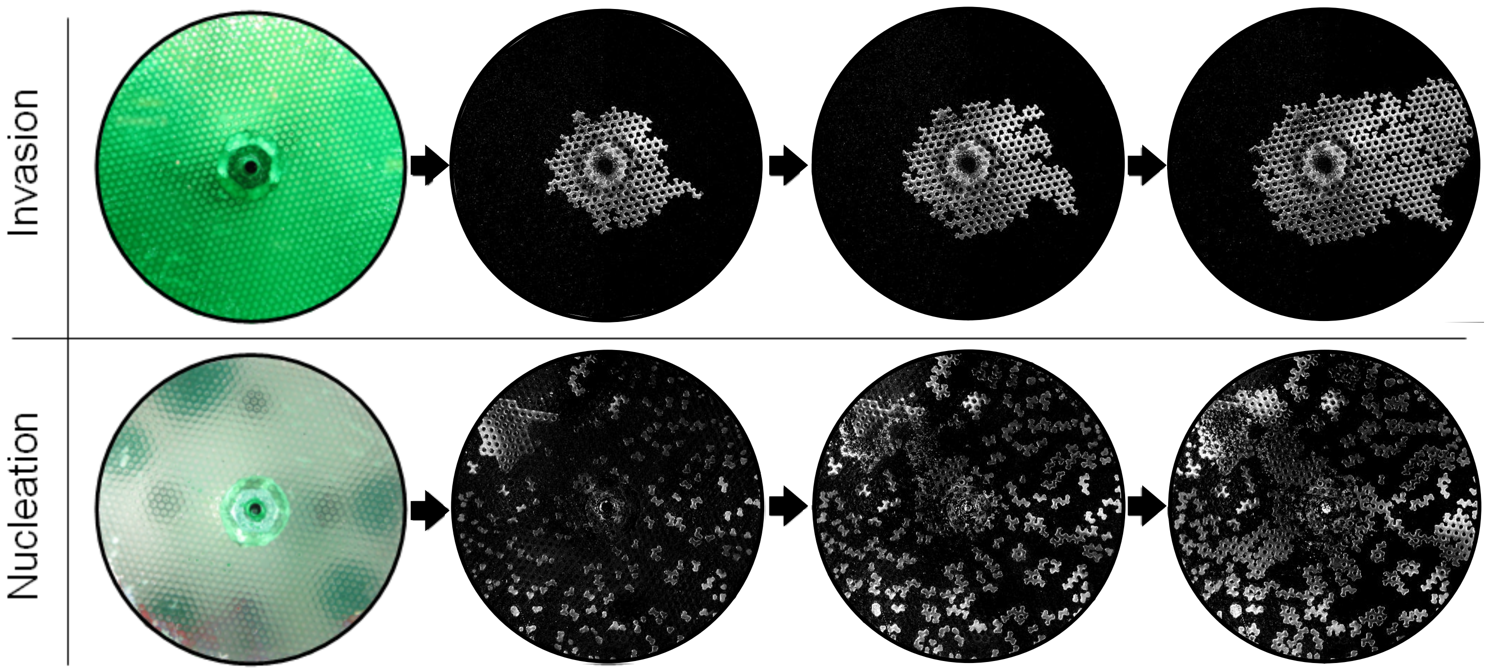
Parameters used in Hydrate Simulation

	Equation	Factors used in published hydrate bearing sediment studies			References
		S_{rw}	S_{rg}	m	
van Genuchten	$k_{rw} = \bar{S}^{0.5}\left[1-\left(1-\bar{S}^{1/m}\right)^m\right]^2$ $k_{rg} = \sqrt{1-\bar{S}}\left(1-\bar{S}^{1/m}\right)^{2m}$	0.3	0.05	0.45	Hong and Pooladi-Davish (2003)
		0.2	0.05	0.45	Uddin et al. (2008)
		0.1	-	0.45	Moridis (1998)
		-	-	0.386	Hong and Pooladi-Darvish (2005)
Corey (1954)	$k_{rw} = \bar{S}^4$ $k_{rg} = \left(1-\bar{S}\right)^2\left(1-\bar{S}^2\right)$				Nazridoust and Ahmadi (2007) Tonnet and Herri (2009)

	Equation	n_w	n_g	S_{rw}	S_{rg}	References
(modified) Stone (1970)	$k_{rw} = \left(\frac{S_w - S_{rw}}{1 - S_{rw}}\right)^{n_w}$ $k_{rg} = \left(\frac{S_g - S_{rg}}{1 - S_{rg}}\right)^{n_g}$ or $k_{rg} = \left(\frac{S_g - S_{rg}}{1 - S_{rw}}\right)^{n_g}$	3.0	3.0	0.15	0.05	Gamwo and Liu (2010)
		4.0	4.0	0.20	0.02	Reagan and Moridis (2008)
		3.0	3.0	0.25	0.02	Moridis and Kowalsky (2005) Moridis et al. (2007)
		3.6	3.6	0.25	0.02	Moridis and Reagan (2007[a])
		3.6	3.6	0.25	0.02	Moridis and Reagan (2007[b])
		4.0	4.0	0.20	0.02	Moridis and Sloan (2007)
		4.0 3.6	4.0 3.6	0.20 0.25	0.02 0.02	Rutqvist and Moridis (2007)
		4.0	4.0	0.20	0.02	Reagan and Moridis (2008) Rutqvist and Moridis (2009)
		3.6	3.6	0.25	0.02	Moridis et al. (2009)
		4.5	3.2	0.24	0	Anderson et al. (2011) Kurihara et al. (2010)
		4.5 -	- 3.2	0.25 0	- 0	Kurihara et al. (2010)
	$k_{rw} = \left(\frac{S_w - S_{rw}}{1 - S_{rg} - S_{rw}}\right)^{n_w}$ $k_{rg} = \left(\frac{S_g - S_{rg}}{1 - S_{rg} - S_{rw}}\right)^{n_g}$	-	3.0 or 4.0	0.12	-	Gupta (2007)
		3.0	2.0	0.10	0.10	Konno et al. (2010)
		0.2	0.4	-	-	Liang et al. (2010)

Preliminary Study – Invasion vs. Nucleation



Objectives

To verify and validate the use of *capillary pressure functions* and *relative permeability equations* embedded into hydrate numerical simulator

How ?

By providing fitting parameters and modifying/developing these functions and equations if necessary for better simulation of gas and water flow during gas production from gas hydrate

Impact and Benefit – how will the outcome benefit industry/others

The research outcome will be incorporated into existing numerical simulator to

(1) predict more accurate production rate of methane and water,

(2) facilitate the selection for hydrate reservoirs for economic development

(3) reduce expenses to perform in-situ testing to calibrate numerical simulator

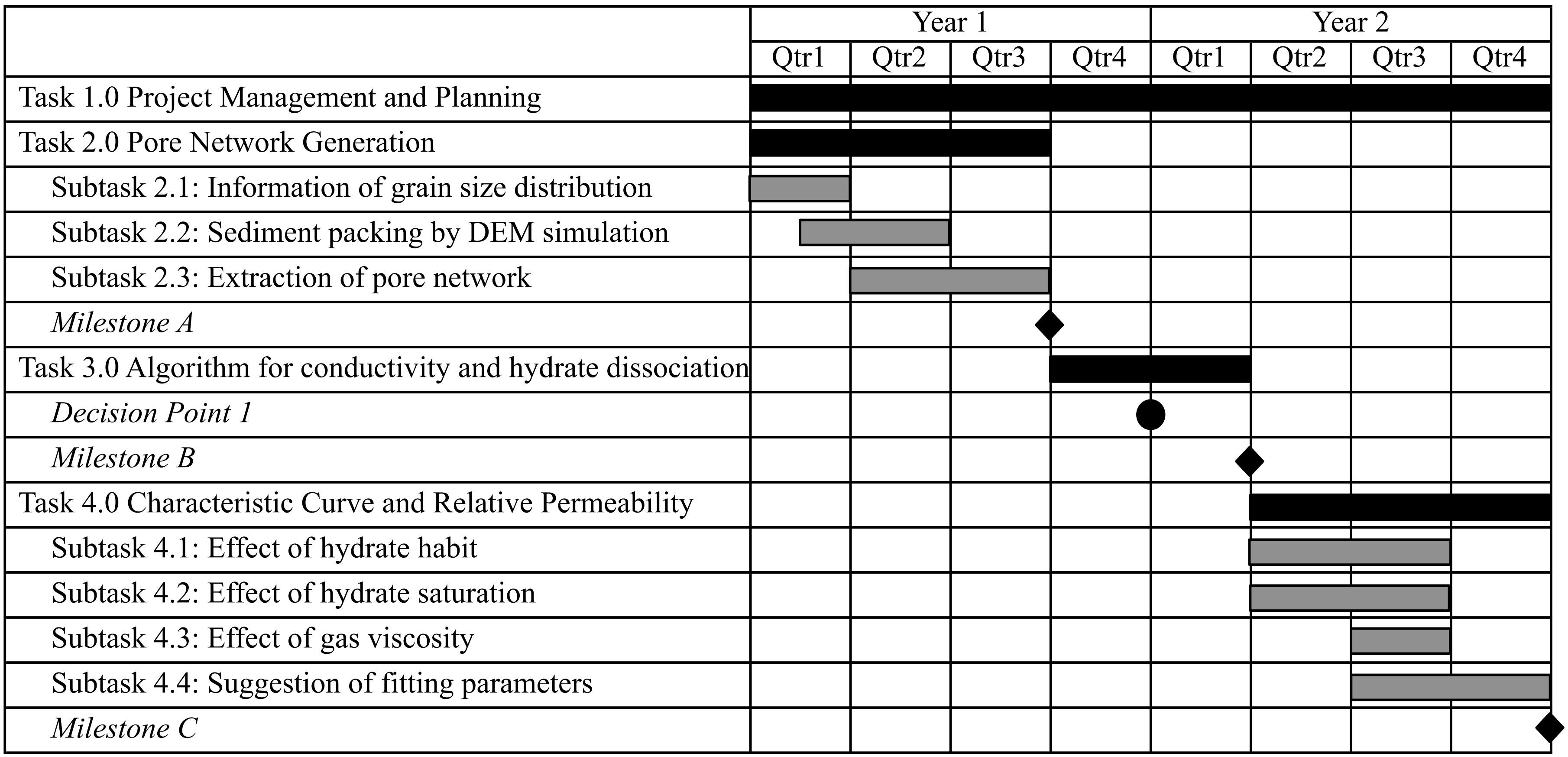
Presentation Outline

Project Overview

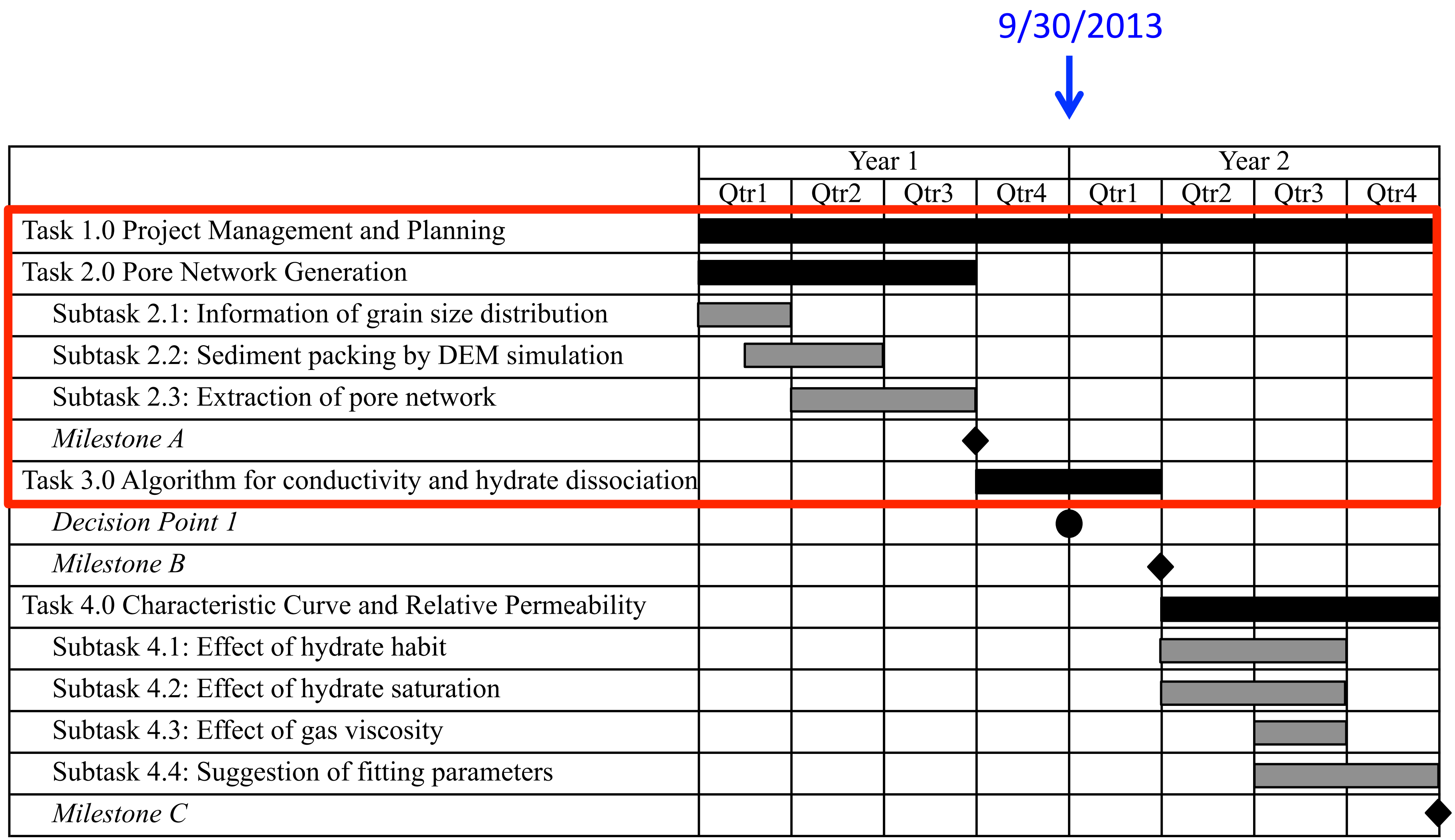
Accomplishments

Budget / Plan for 2nd year

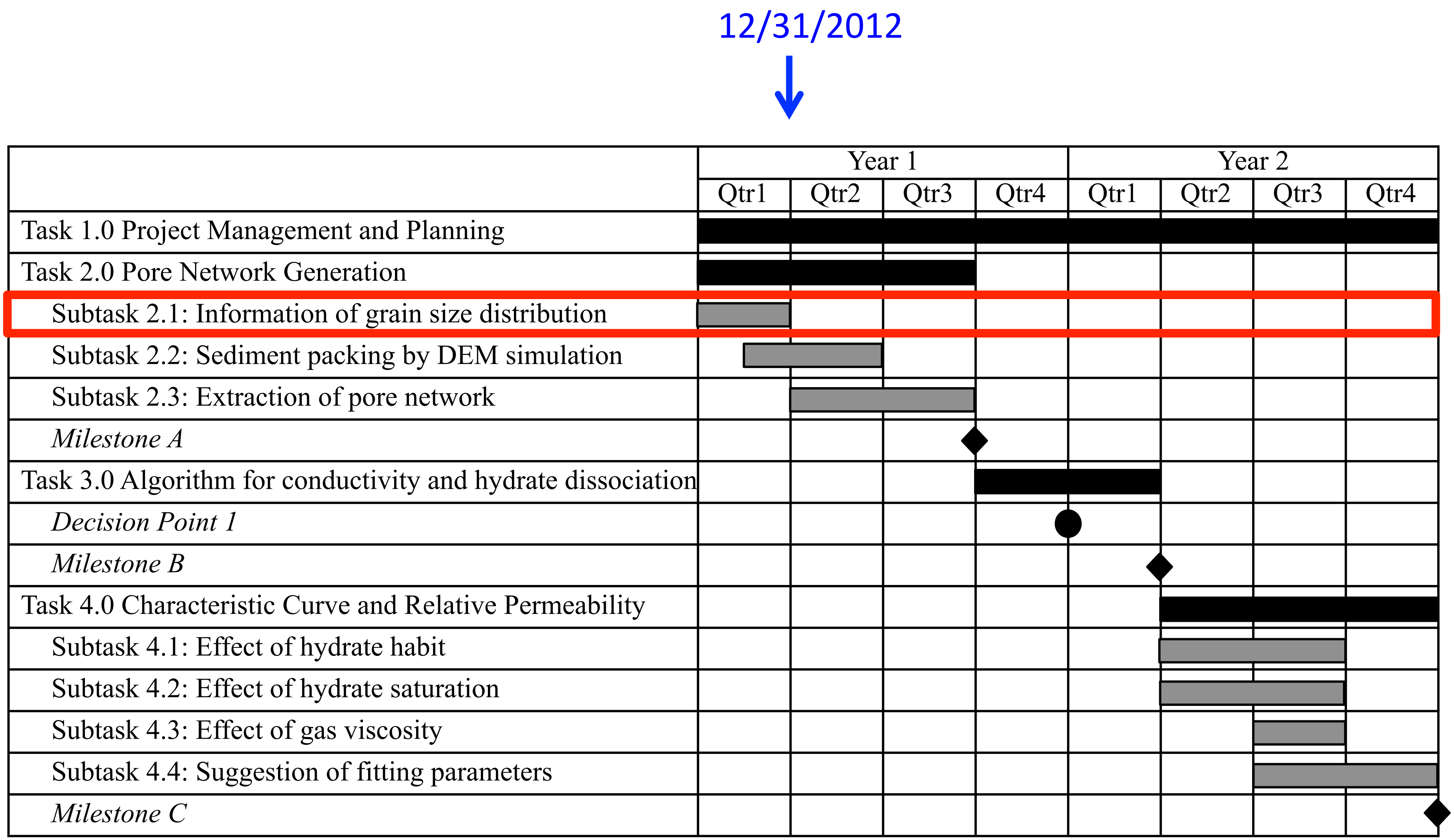
Project Schedule



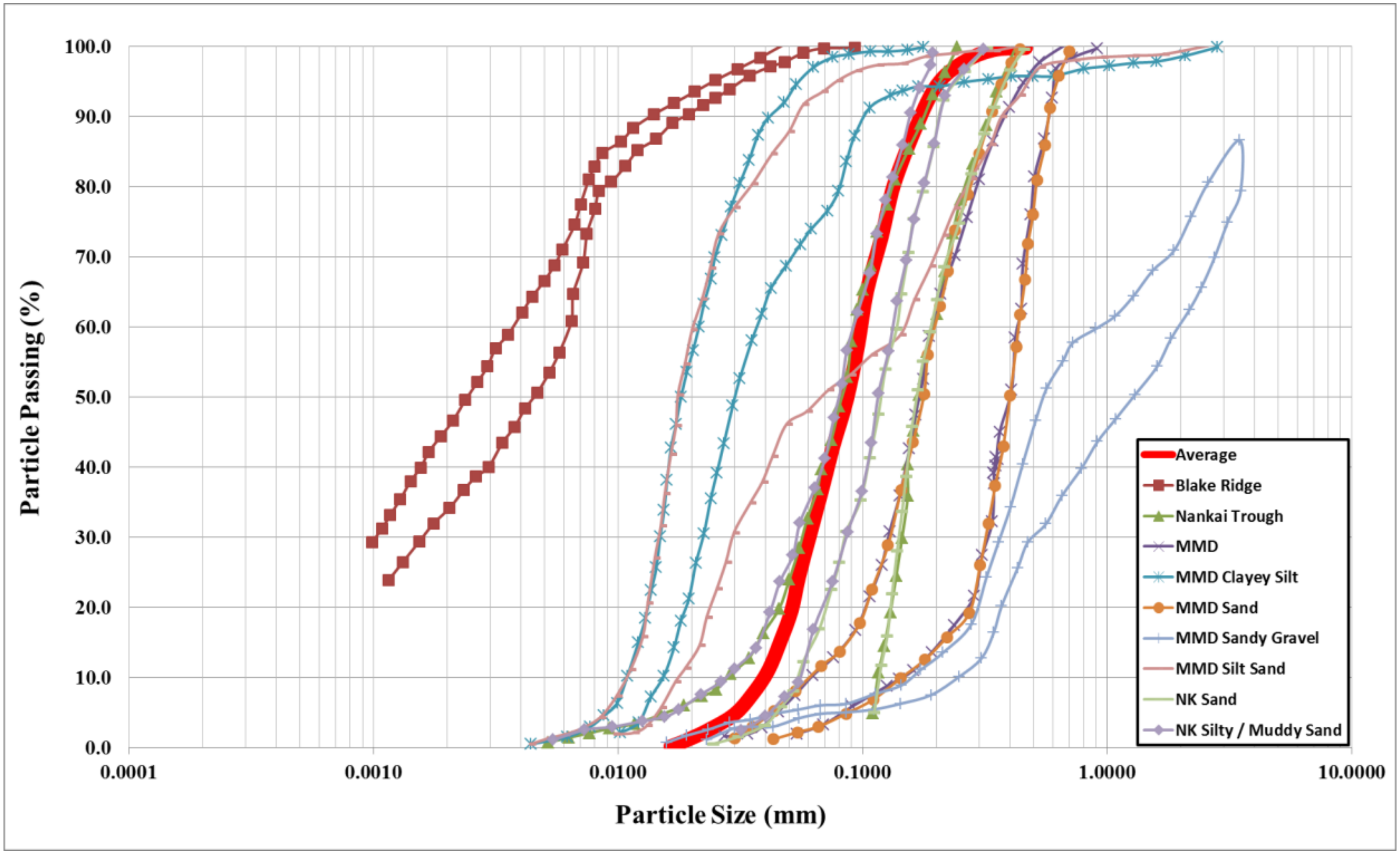
Tasks done during 1st year



Information of in-situ HBS

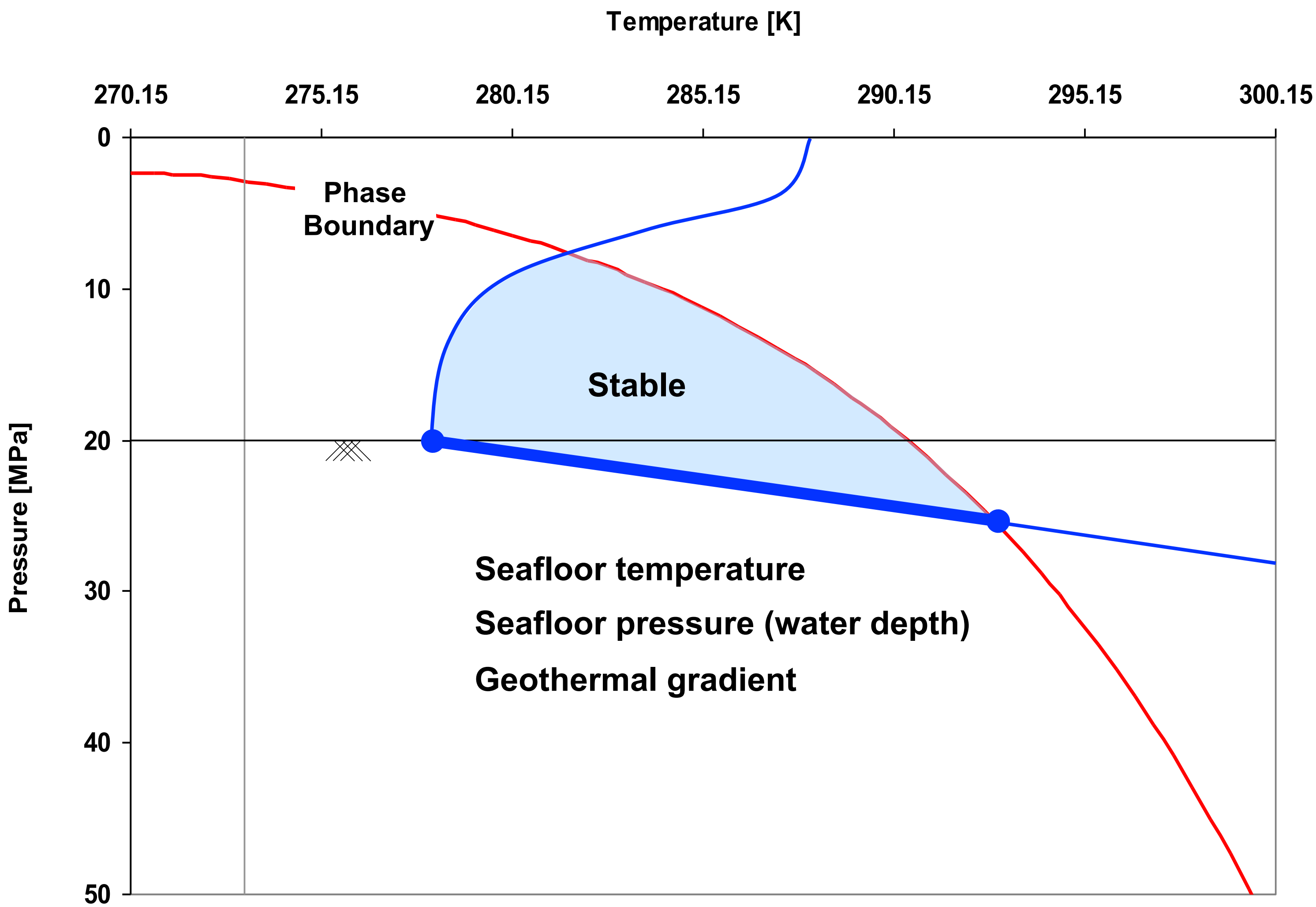


Grain Size Distribution

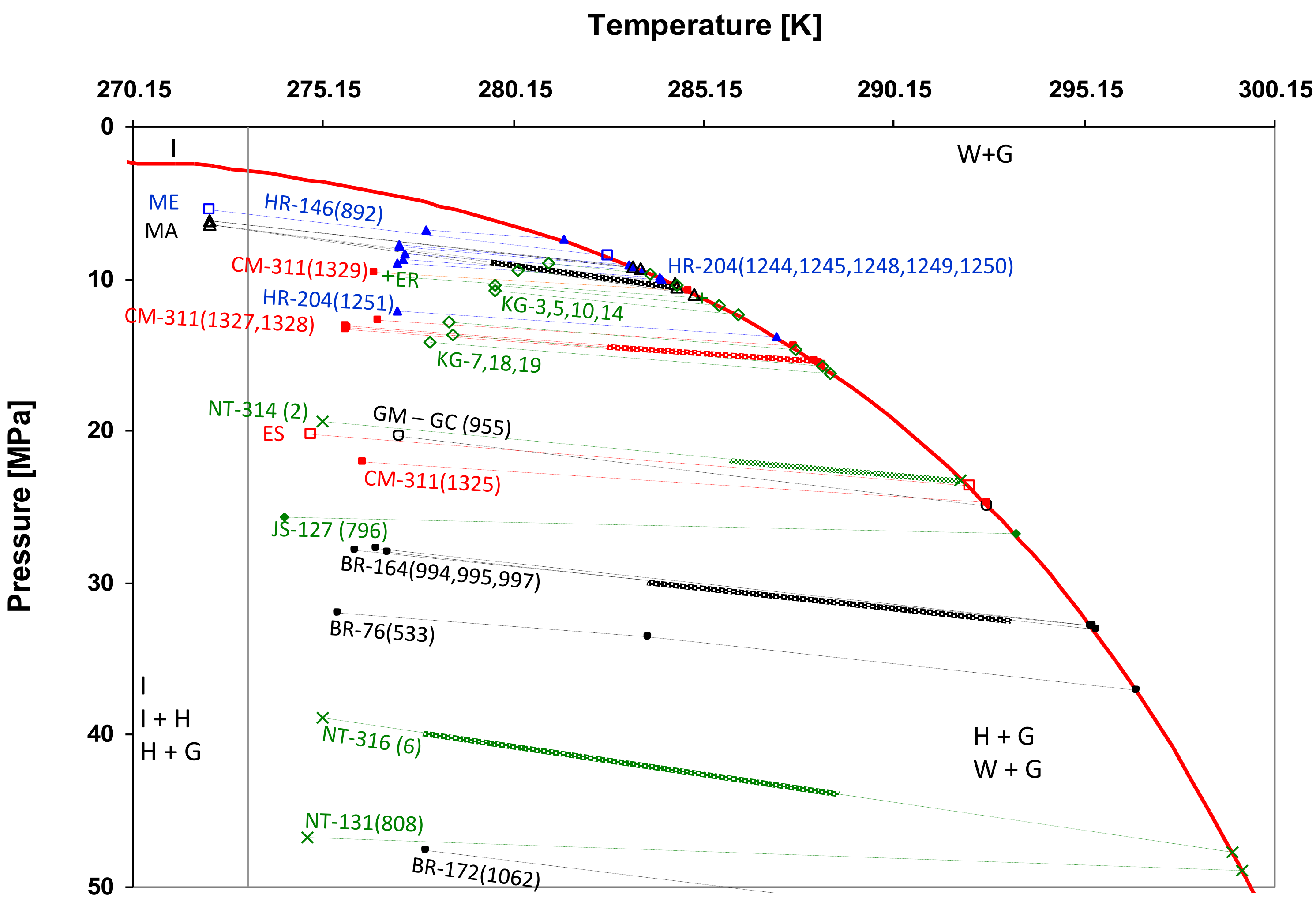


Data from Soga et al. (2007), Masui et al. (2006), Jenner et al. (1999), Paull et al. (2000), Tan (2004)

Typical PT Conditions of HBS

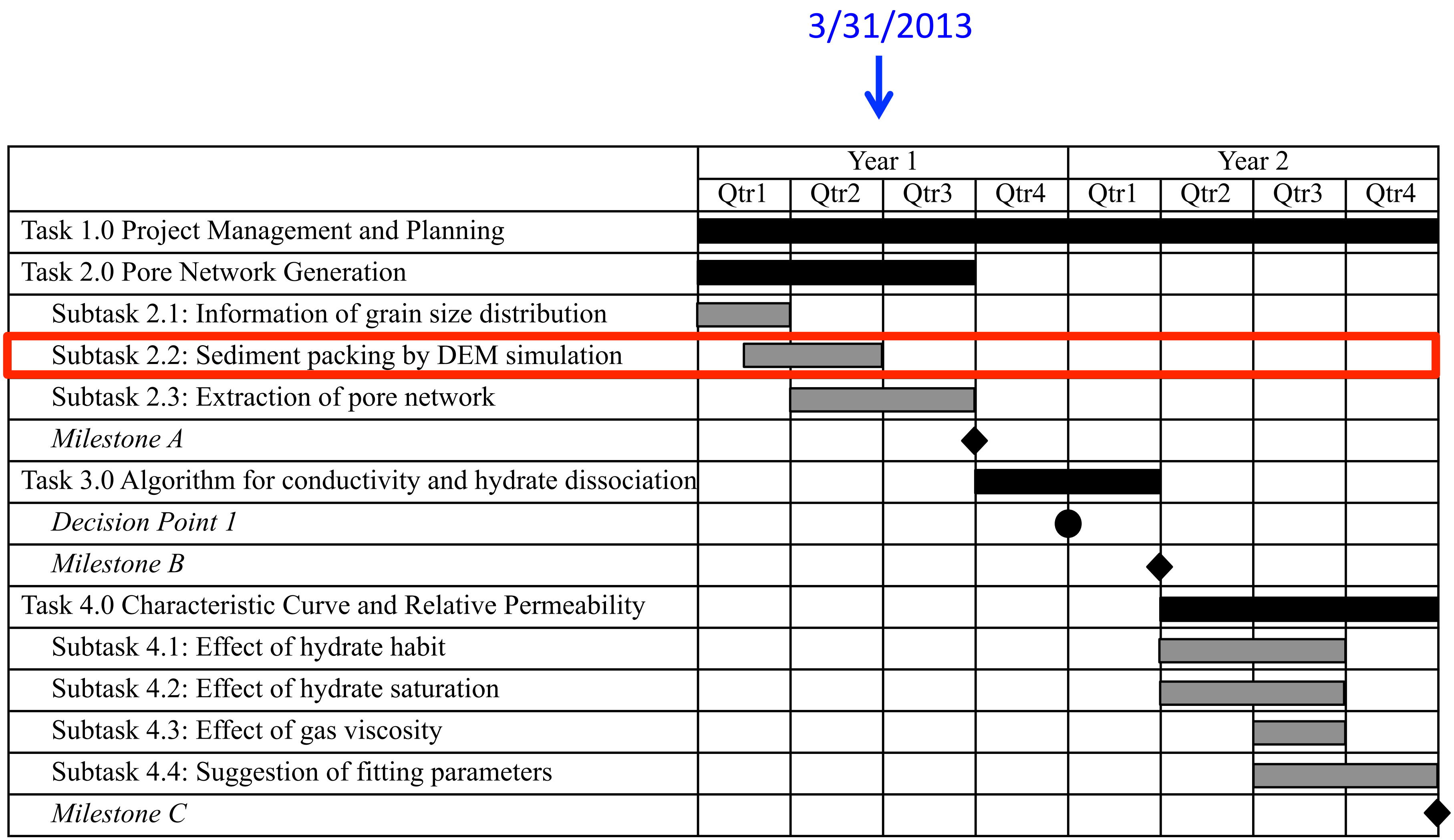


PT Conditions of HBS

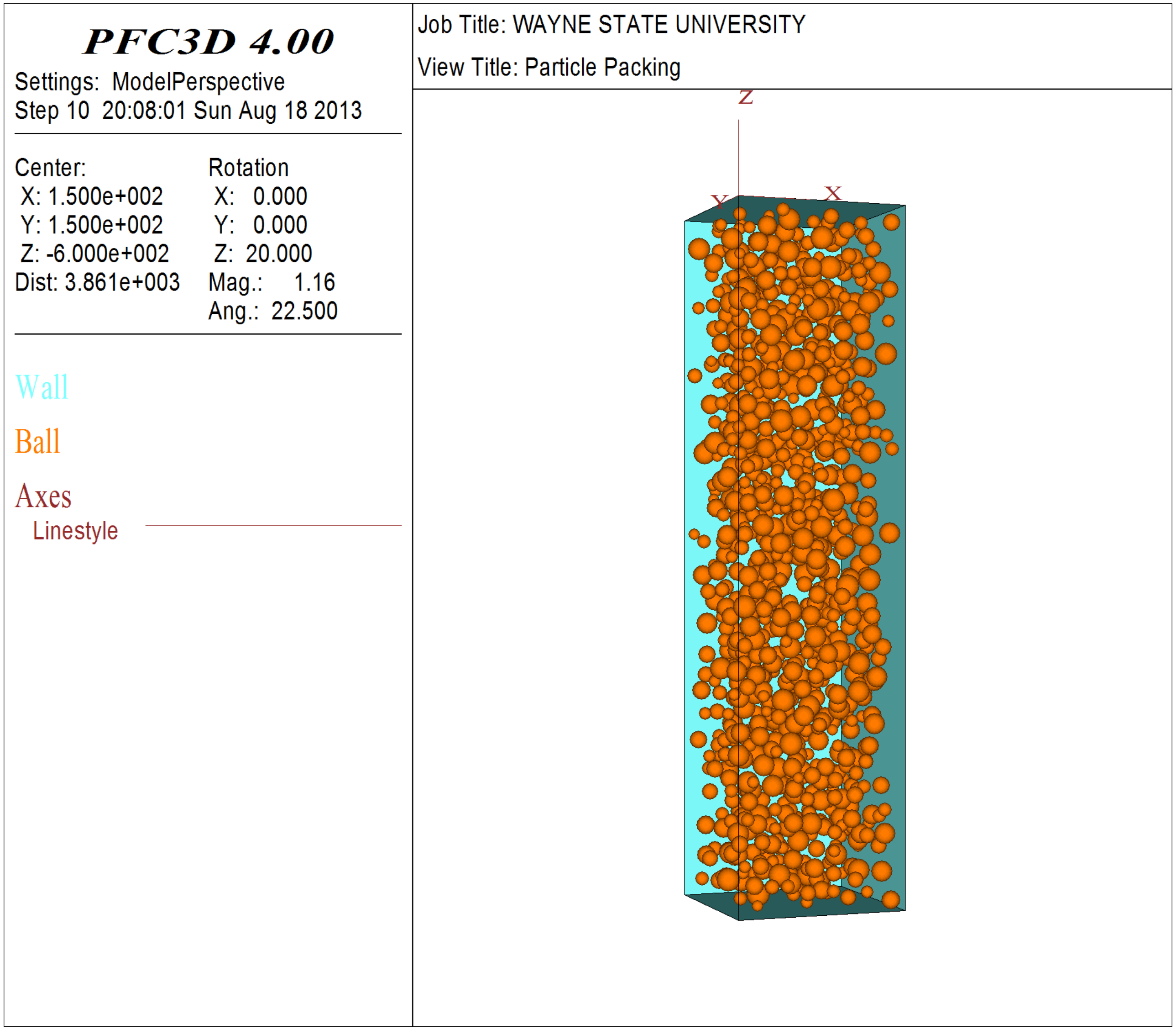


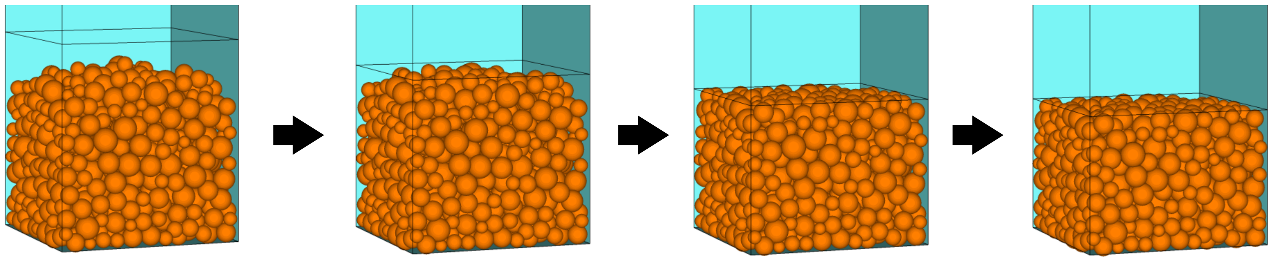
HR: Hydrate Ridge | CM: Cascadia Margin | ER: Eel River basin | GM: Gulf of Mexico | KG: Krishna-Godavari | JS: Japan Sea
NT: Nankai Trough | BR : Blake Ridge | ES: East Sea | MA: Mallik | ME: Mt. Elbert

Sediment Packing Generation

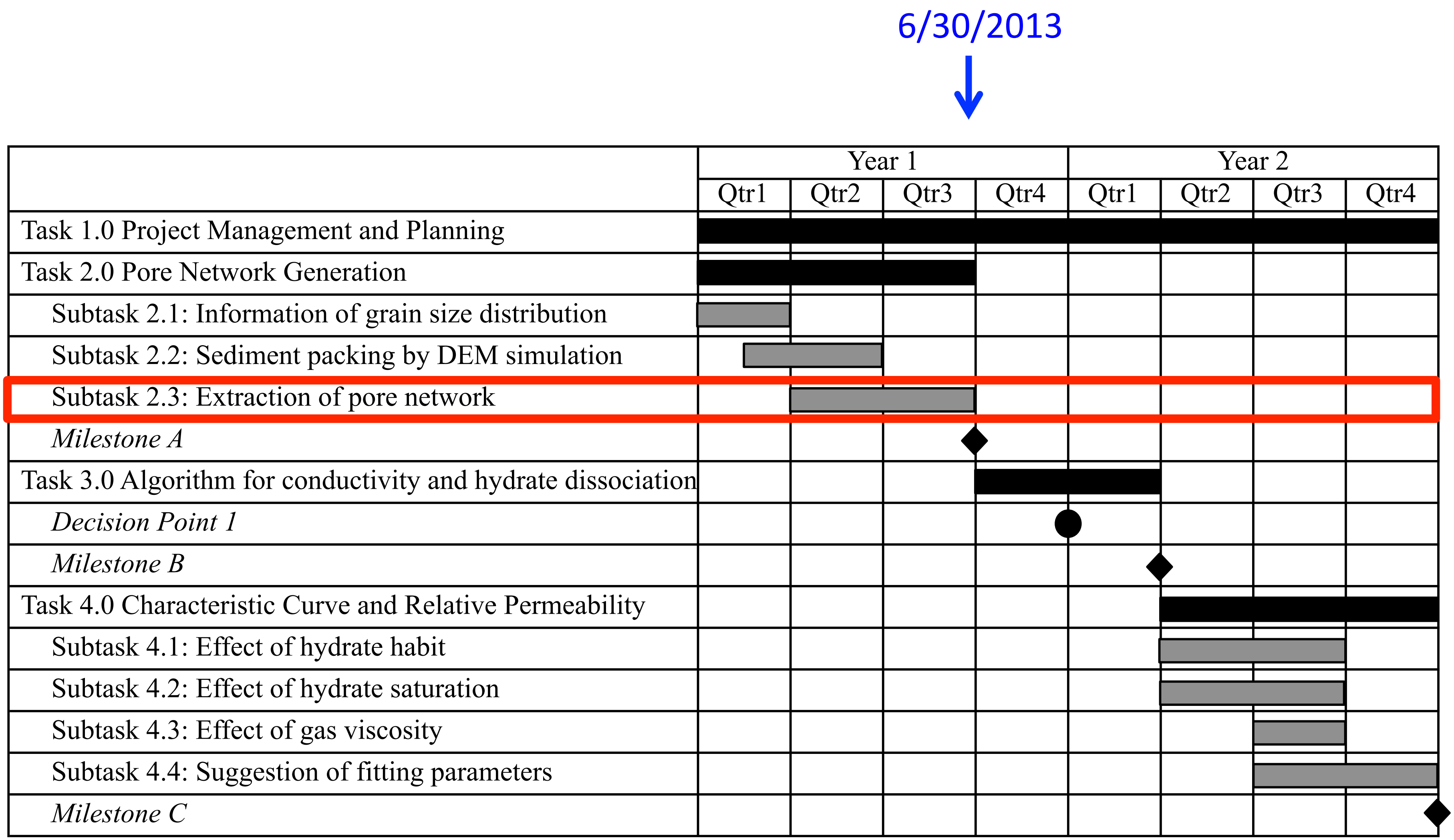


DEM


PFC3D 4.00
Settings: ModelPerspective
Step 10 20:08:01 Sun Aug 18 2013
Center:
X: 1.500e+002
Y: 1.500e+002
Z: -6.000e+002
Dist: 3.861e+003
Rotation
X: 0.000
Y: 0.000
Z: 20.000
Mag.: 1.16
Ang.: 22.500
Wall
Ball
Axes
Linestyle
Job Title: WAYNE STATE UNIVERSITY
View Title: Particle Packing
Z
Y
X



Pore-Network Extraction



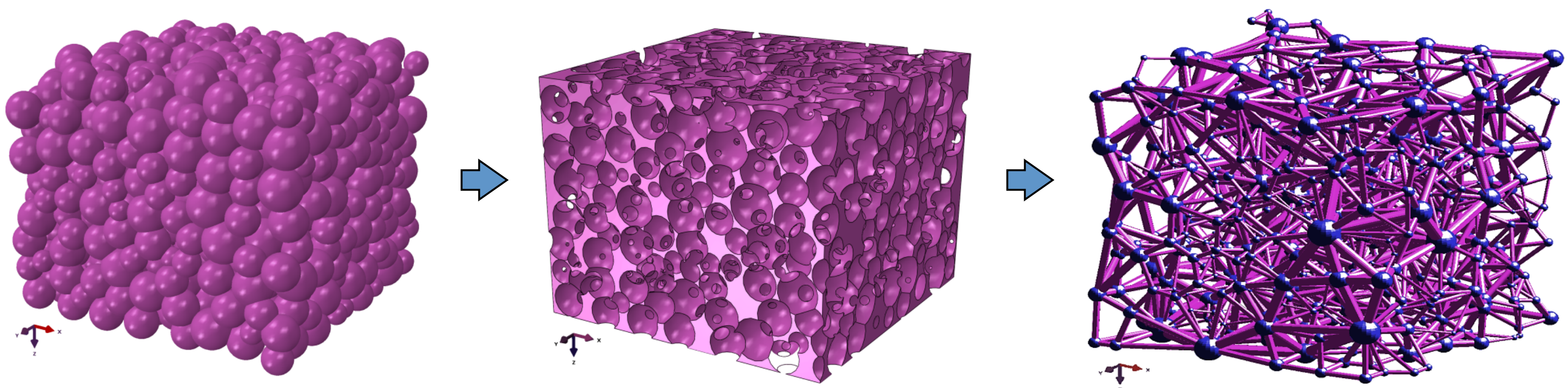
Algorithms for Pore Network Extraction

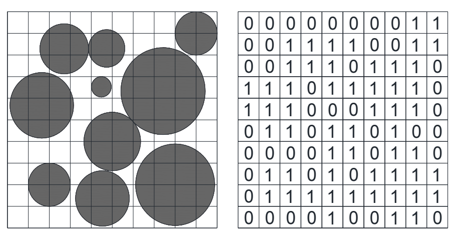
Method	Description	References
Multi-Orientation Scanning	• Algorithm using multi-orientated plates scanning along the pore channels to detect pore bodies and pore throats. Overlapping plates during the scanning from different directions give indications of local minimal which defines the throats. • Difficult in locating pore bodies. • The concept used to find the hydraulic radius along the pore space skeleton predefined using thinning algorithms.	Zhao et al. (1994) Baldwin et al. (1996) Liang et al. (2000)
Medial Axis Algorithms	• Transform the pore space into a medial axis that is the reduced representation of the pore space acting as a topological skeleton roughly running along the middle of pore channels. • Pore space partitioning can be validated along the skeleton to decide the pore throats by local minima along branches and pore bodies at the nodes.	Lindquist et al. (1996) Lindquist& Venkatarangan, (1999) Sheppard et al. (2005) Shin et al. (2005) Prodanovic et al. (2006)
Voronoi Diagram	• Possible to extract pore networks using the Voronoi diagram if grain centers are known. • An ultimate dilation to tessellate the pore space using Voronoi polyhedron. • The voxels that have neighboring voxels from four or more different grains can be regarded as the pores of the network. • The edges of the polyhedron consist of voxels that have neighboring voxels from three different grains defined the links between pores. Pore networks extracted from these methods have been proved successful in pore-scale simulation.	Bryant and Blunt (1992) Bryant et al. (1993a&b) Bryant and Raikes (1995) Øren et al. (1998) Øren and Bakke (2002&2003)
Maximal Ball Theory	• The maximal ball algorithm starts from each voxel in the pore space to find the **largest inscribed spheres** that just touch the grain or the boundary. • Then those included in other spheres are viewed as inclusions and removed; the rest are called maximal balls and describe the pore space without redundancy. • Locally the **largest maximal balls identify pores** while the **smallest balls between pores are throats**. The maximal balls were used in Silin's work (2003, 2006) only to find dimensionless capillary pressures rather than to extract a pore network from the image. • This method extended to study the pore space of sandstone and carbonate samples. Starting from the same point of finding maximal balls at each voxel, Al-Kharusi and Blunt developed a more comprehensive set of criteria to determine the maximal ball hierarchy. In Silin et al.'s work, only two types of relationship are defined, *masters* and *slaves*, which is the bigger and smaller balls respectively compared to their neighbors. **Al-Kharusi and Blunt added a new relationship, the *cluster* to accommodate the adjacent maximal balls of similar size**. This resolved the problems of ambiguity caused by the identical balls that are not trivial after transforming the pore space to maximal balls from voxels.	Silin et al. (2003& 2006) Al-Kharusi and Blunt (2007)

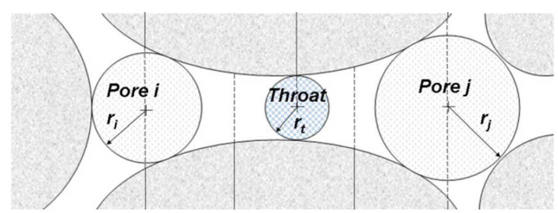
Pore Network Extraction

Network model extraction from sediment packing

Sediment packing **Pore space** **Network model**

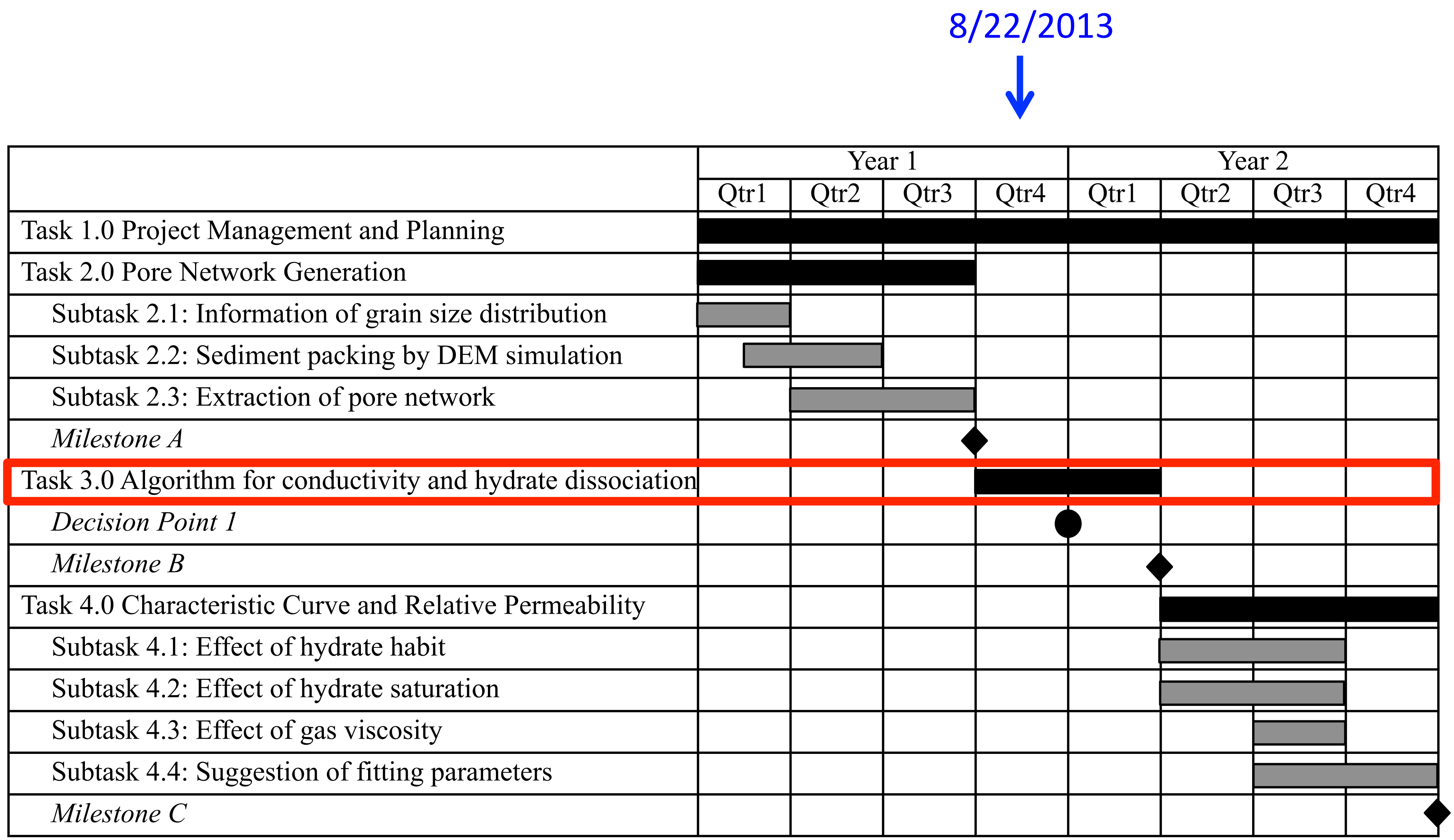




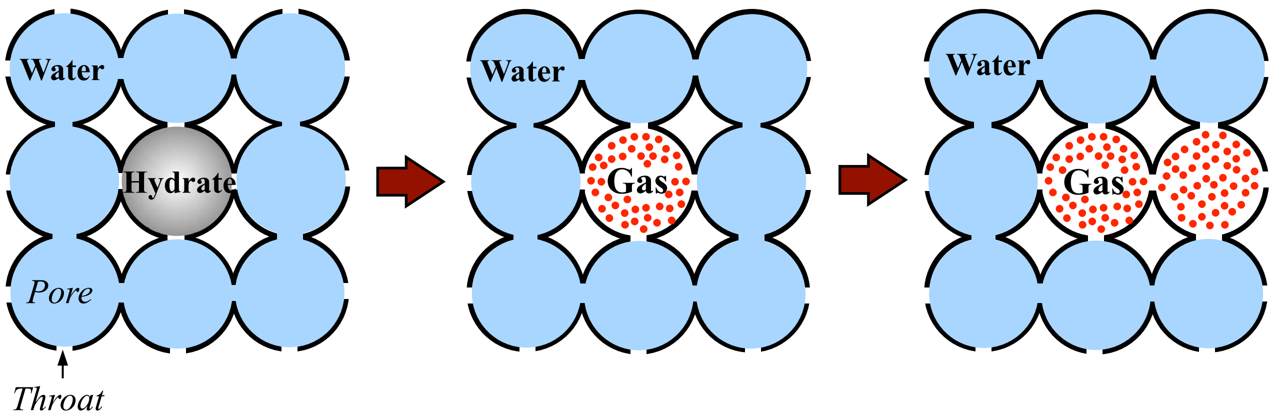


Maximal ball algorithm

Conductivity and Hydrate Dissociation

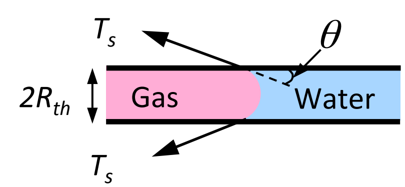


Algorithm Details – Gas Expansion



Modified *Peng-Robinson* $$P_g = \frac{RT_g}{V_g - b} - \frac{a}{V_g\left(V_g + b\right) + b\left(V_g - b\right)}$$

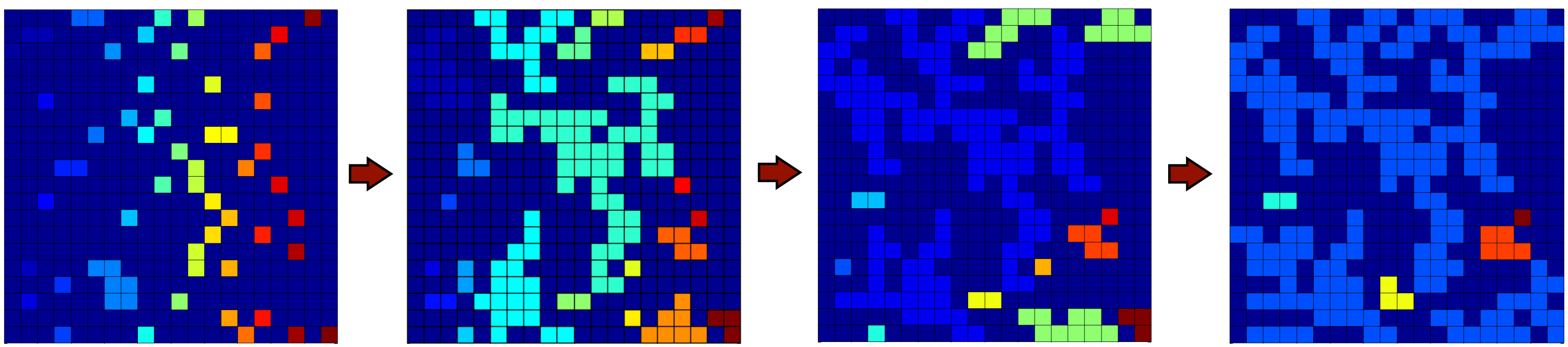
Capillary pressure $$P_c = \frac{2T_s\cos(\theta)}{R_{th}}$$



Gas expansion $$P_g > P_w + P_c$$

Algorithm Details – Gas Cluster/Percolation

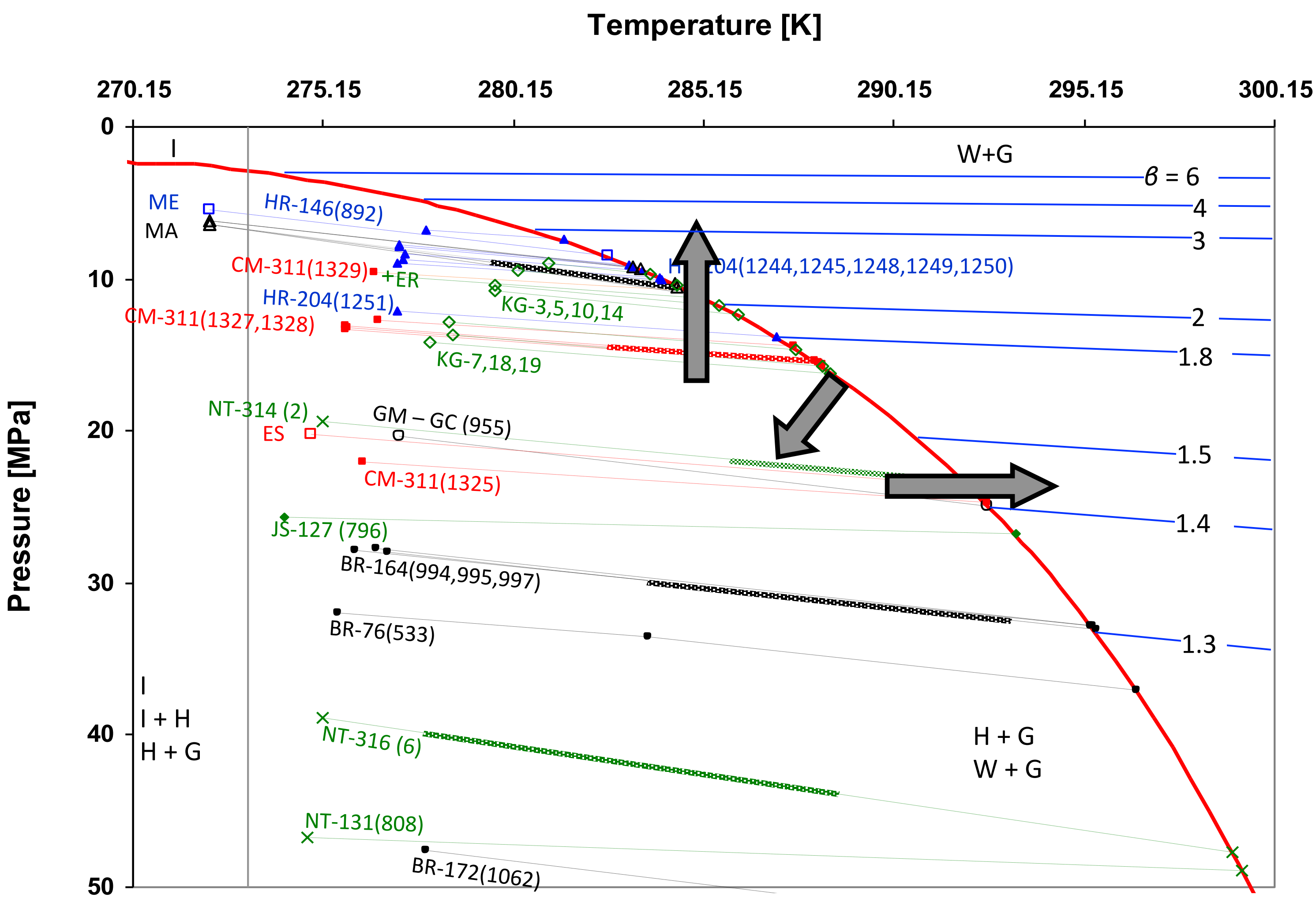
Hydrate distribution S_h=0.14 | Volume expansion β=4 S_g=0.39, E=0 | Volume expansion β=6 S_g=0.55, E=0 | Volume expansion β=8 S_g=0.63, E=0.32



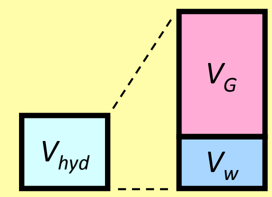
- **Gas expands by displacing water.**
- **Water drains as long as it percolates.**
- **Percolation**

R_{th} = 0.5·min(R_{pore1},R_{pore2}), log-normal distribution of R_{pore}, Three-dimensional pore network: 15x15x15 pores
Assumption: Either water or hydrate occupies entirely one pore (Water and hydrate does not coexist in one pore)

Algorithm Details - Volume Expansion



Fluid expansion



Expansion factor

$$\beta = \frac{V_W + V_G}{V_{hyd}}$$

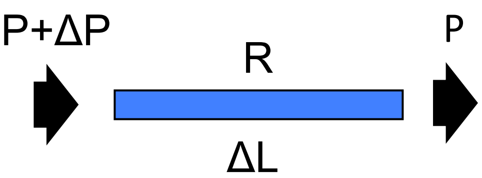
Under 1bar, 0°C

β = 171

HR: Hydrate Ridge	**CM: Cascadia Margin**	**ER: Eel River basin**	**GM: Gulf of Mexico**	**KG: Krishna-Godavari**	**JS: Japan Sea**
NT: Nankai Trough	**BR : Blake Ridge**	**ES: East Sea**	**MA: Mallik**	**ME: Mt. Elbert**	

Algorithm Details – Conductivity Calculation

Poiseuille's Eq.



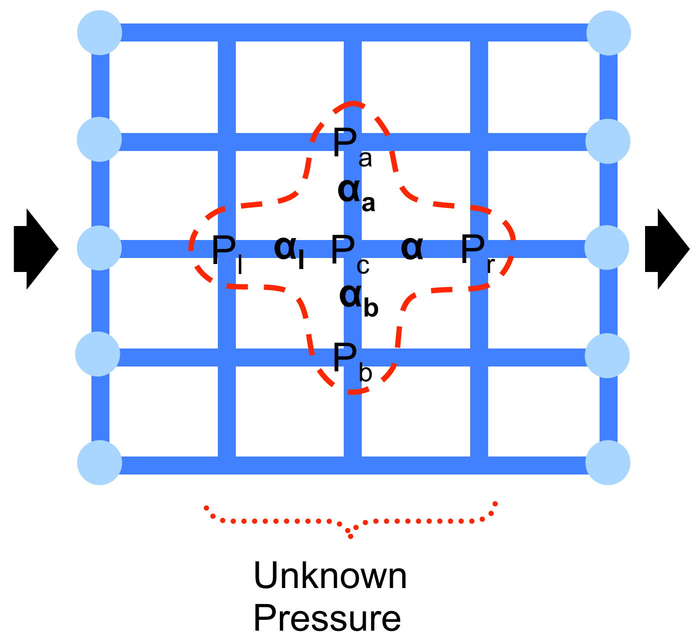
$$Q = \frac{\pi R^4}{8 \eta \Delta L} \Delta P \qquad \left(\alpha = \frac{\pi R^4}{8 \eta \Delta L} \right)$$

Mass Balance at Nodes

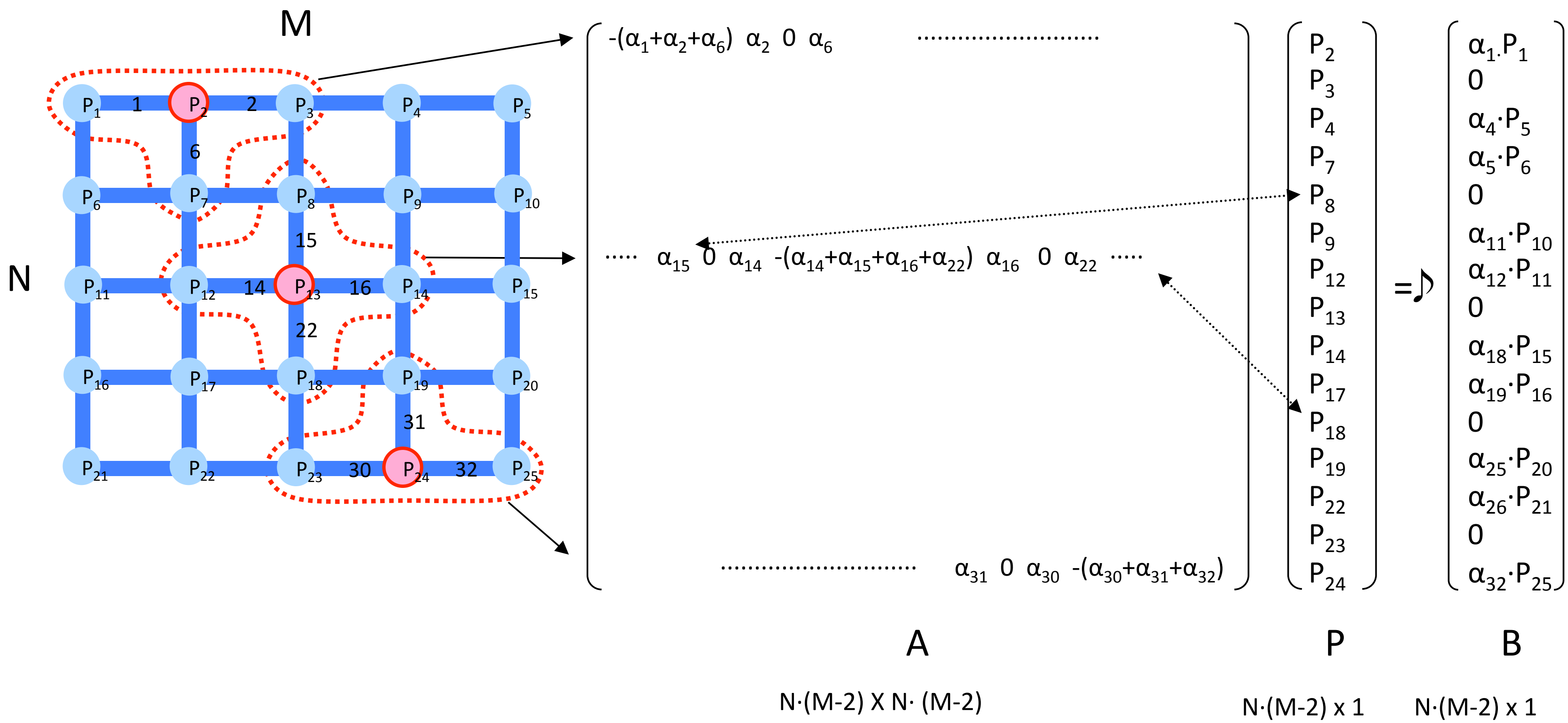
$$0 = \sum q_c$$

$$0 = \alpha_a (P_a - P_c) + \alpha_l (P_l - P_c) + \alpha_r (P_r - P_c) + \alpha_b (P_b - P_c)$$

$$0 = \alpha_a P_a + \alpha_l P_l - (\alpha_a + \alpha_l + \alpha_r + \alpha_b) P_c + \alpha_r P_r + \alpha_b P_b$$



Algorithm Details – Conductivity Calculation



System of Equations

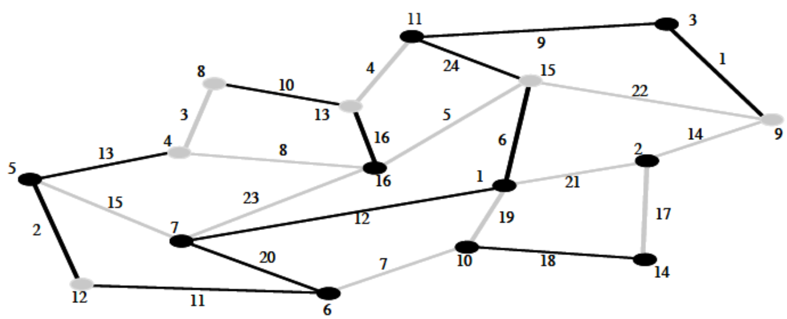
$$\underline{\underline{A}}\ \underline{P} = \underline{B} \quad \text{then} \quad \underline{P} = \underline{\underline{A}}^{-1}\,\underline{B}$$

A : matrix of tube conductivity of each elements

P : vector containing unknown *P* at each nodes

B : vector dependent on *P* at inlet and outlet

Algorithm Details – Information Matrix

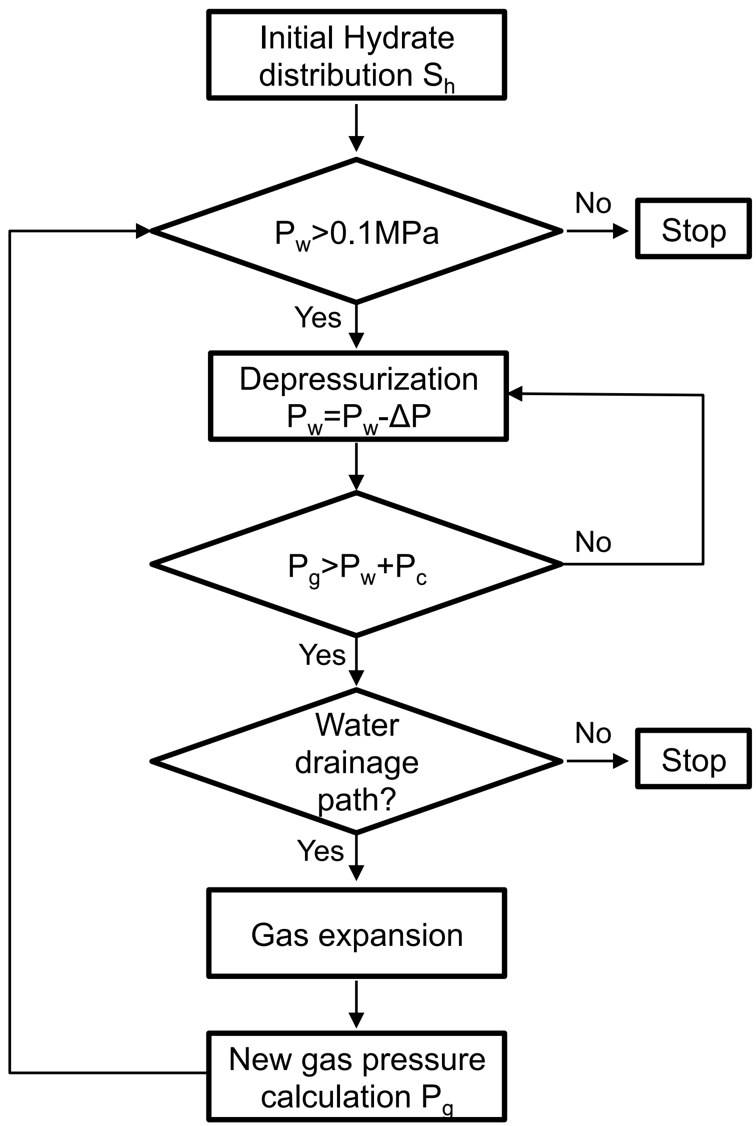


$$\text{Node} = \left|\begin{matrix} 1 \\ 2 \\ 3 \\ 4 \\ 5 \\ 6 \\ 7 \\ 8 \\ 9 \\ 10 \\ 11 \\ 12 \\ 13 \\ 14 \\ 15 \\ 16 \end{matrix}\right| \quad \text{NodeS} = \left|\begin{matrix} 1 \\ 1 \\ 1 \\ 0 \\ 1 \\ 1 \\ 1 \\ 0 \\ 0 \\ 1 \\ 1 \\ 0 \\ 0 \\ 1 \\ 0 \\ 1 \end{matrix}\right| \quad \boxed{\text{NodeNext}} = \left|\begin{matrix} 7 & 15 & 2 & 10 \\ 1 & 9 & 14 & 0 \\ 11 & 9 & 0 & 0 \\ 8 & 16 & 5 & 0 \\ 4 & 7 & 12 & 0 \\ 12 & 7 & 10 & 0 \\ 5 & 16 & 1 & 6 \\ 13 & 4 & 0 & 0 \\ 15 & 3 & 2 & 0 \\ 6 & 1 & 14 & 0 \\ 13 & 3 & 15 & 0 \\ 5 & 6 & 0 & 0 \\ 8 & 11 & 16 & 0 \\ 2 & 10 & 0 & 0 \\ 16 & 11 & 9 & 1 \\ 4 & 13 & 15 & 7 \end{matrix}\right|$$

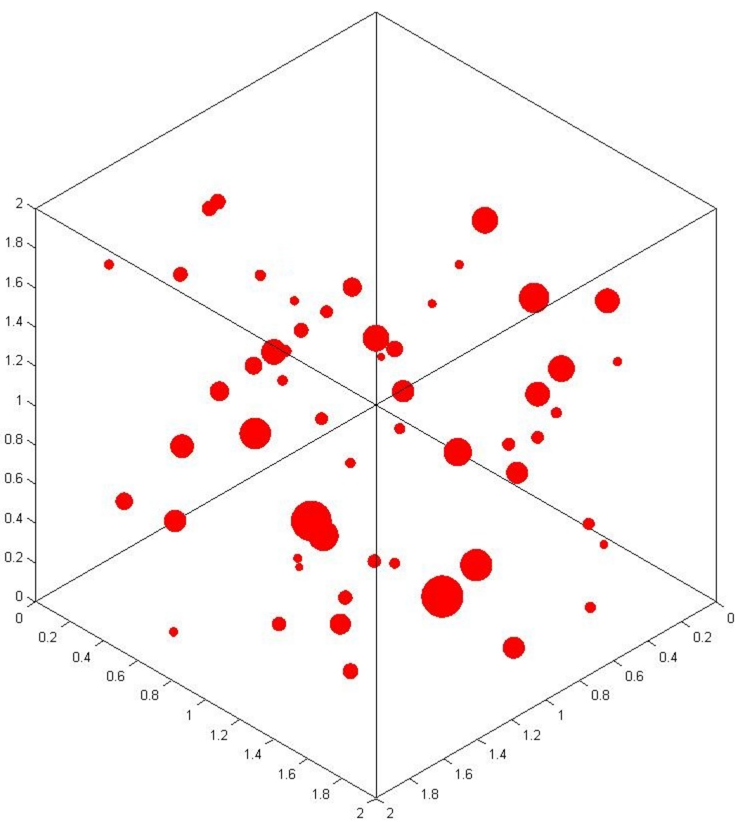
$$\text{Link} = \left|\begin{matrix} 1 \\ 2 \\ 3 \\ 4 \\ 5 \\ 6 \\ 7 \\ 8 \\ 9 \\ 10 \\ 11 \\ 12 \\ 13 \\ 14 \\ 15 \\ 16 \\ 17 \\ 18 \\ 19 \\ 20 \\ 21 \\ 22 \\ 23 \\ 24 \end{matrix}\right| \quad \text{LinkS} = \left|\begin{matrix} 1 \\ 1 \\ 0 \\ 0 \\ 0 \\ 1 \\ 0 \\ 0 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 0 \\ 0 \\ 1 \\ 0 \\ 1 \\ 0 \\ 1 \\ 0 \\ 0 \\ 0 \\ 1 \end{matrix}\right| \quad \boxed{\text{LinksOfNode}} = \left|\begin{matrix} 12 & 6 & 21 & 19 \\ 21 & 14 & 17 & 0 \\ 9 & 1 & 0 & 0 \\ 3 & 8 & 13 & 0 \\ 13 & 15 & 2 & 0 \\ 11 & 20 & 7 & 0 \\ 15 & 23 & 12 & 20 \\ 10 & 3 & 0 & 0 \\ 22 & 1 & 4 & 0 \\ 7 & 19 & 18 & 0 \\ 4 & 9 & 24 & 0 \\ 2 & 11 & 0 & 0 \\ 10 & 4 & 16 & 0 \\ 17 & 18 & 0 & 0 \\ 5 & 24 & 22 & 6 \\ 8 & 16 & 5 & 23 \end{matrix}\right|$$

Al-Futaisi and Patzek (2003)

Algorithm Details - Flow Chart

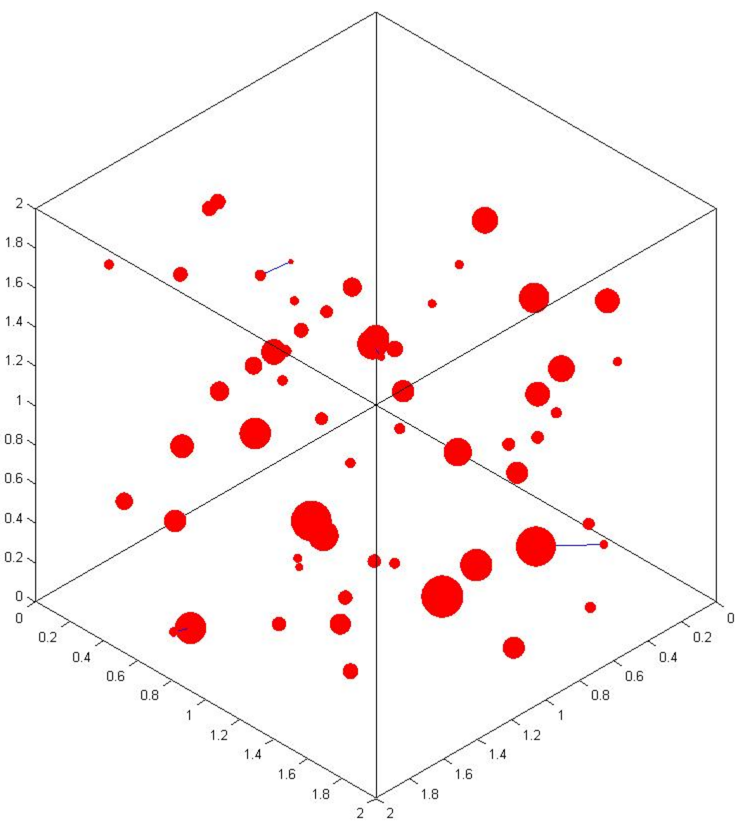


Simulation - Gas Expansion



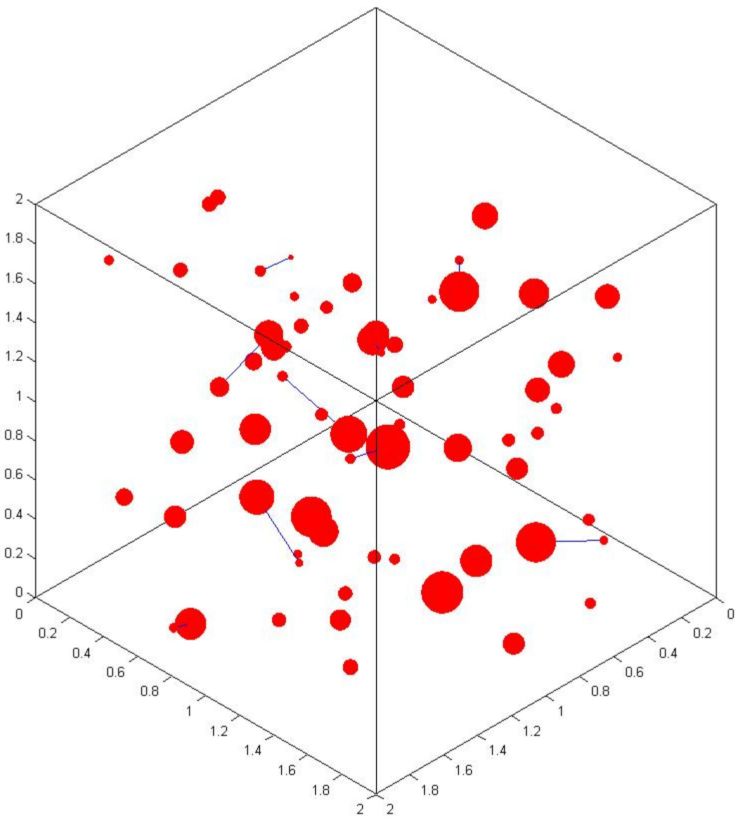
Hydrate Saturation ~10 %

Simulation - Gas Expansion



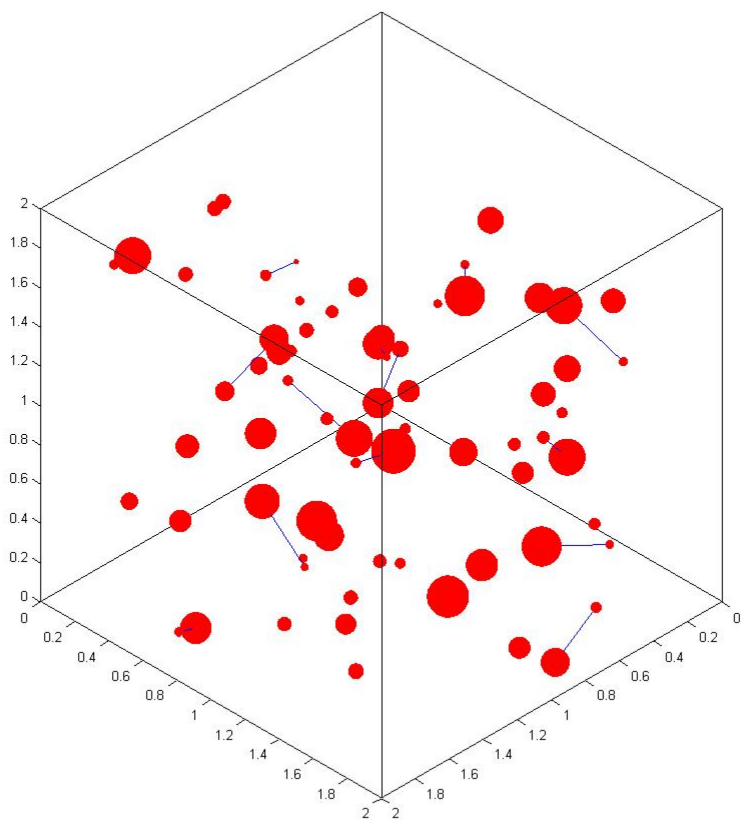
Gas Saturation 10.7 %

Simulation - Gas Expansion



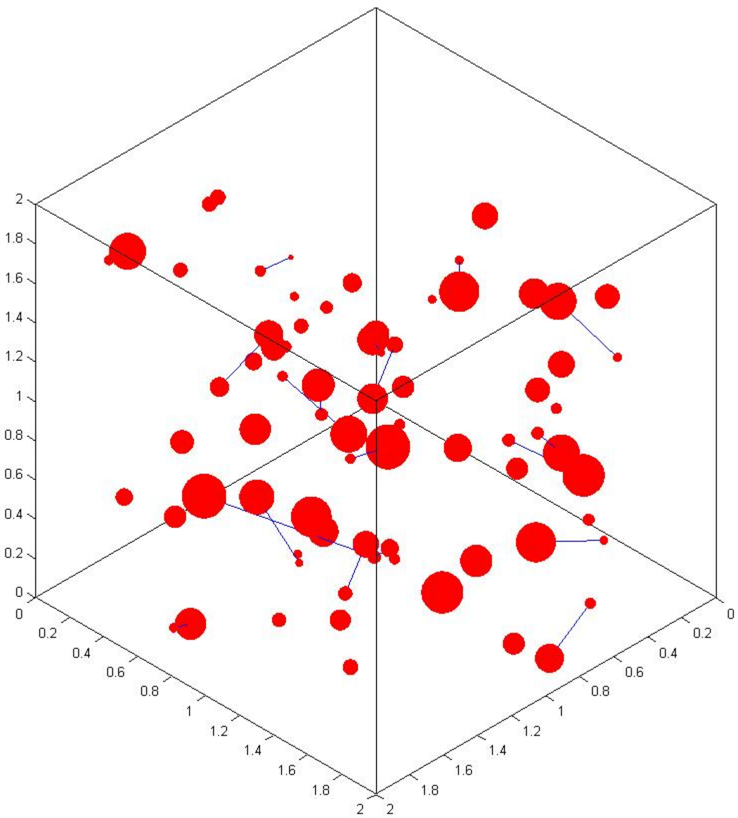
Gas Saturation 11.6 %

Simulation - Gas Expansion



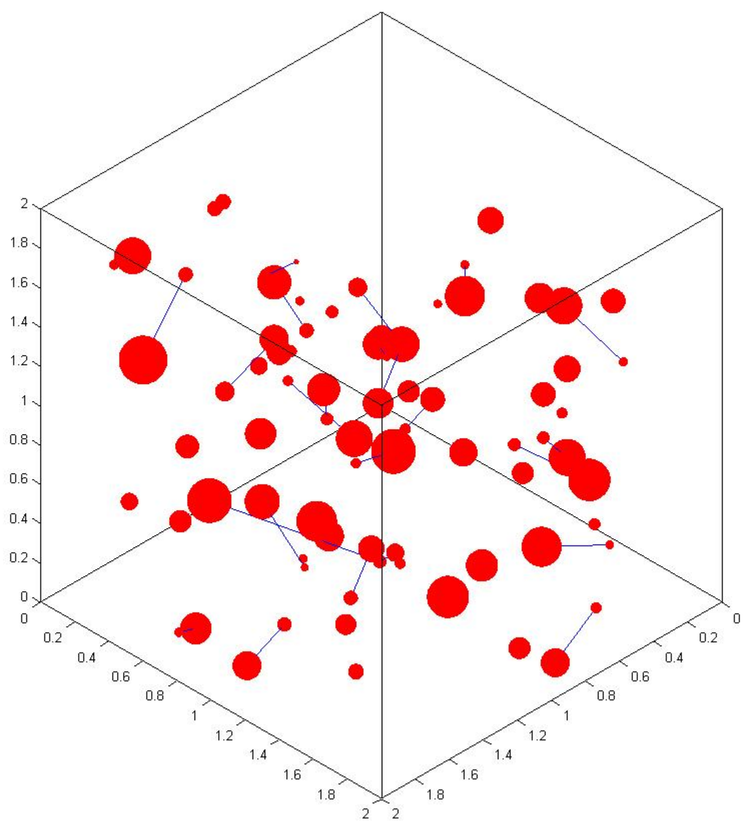
Gas Saturation 12.5%

Simulation - Gas Expansion



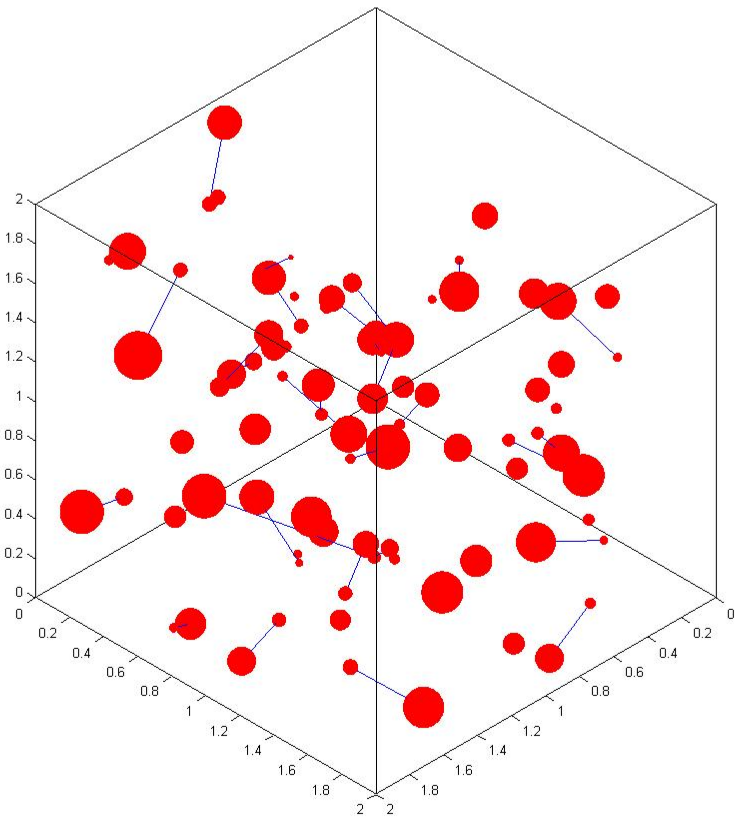
Gas Saturation 13.4%

Simulation - Gas Expansion



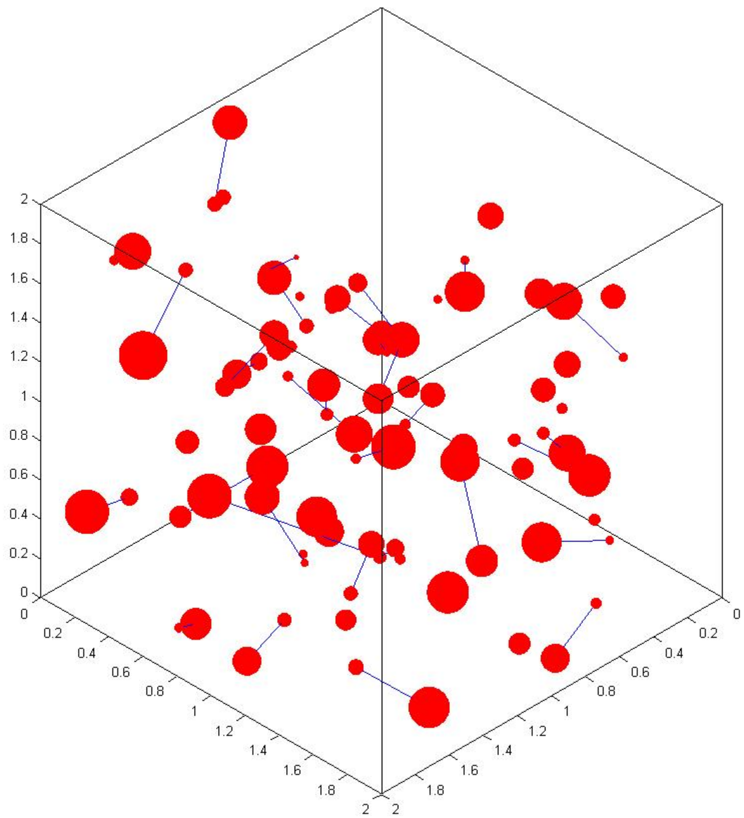
Gas Saturation 14.3%

Simulation - Gas Expansion



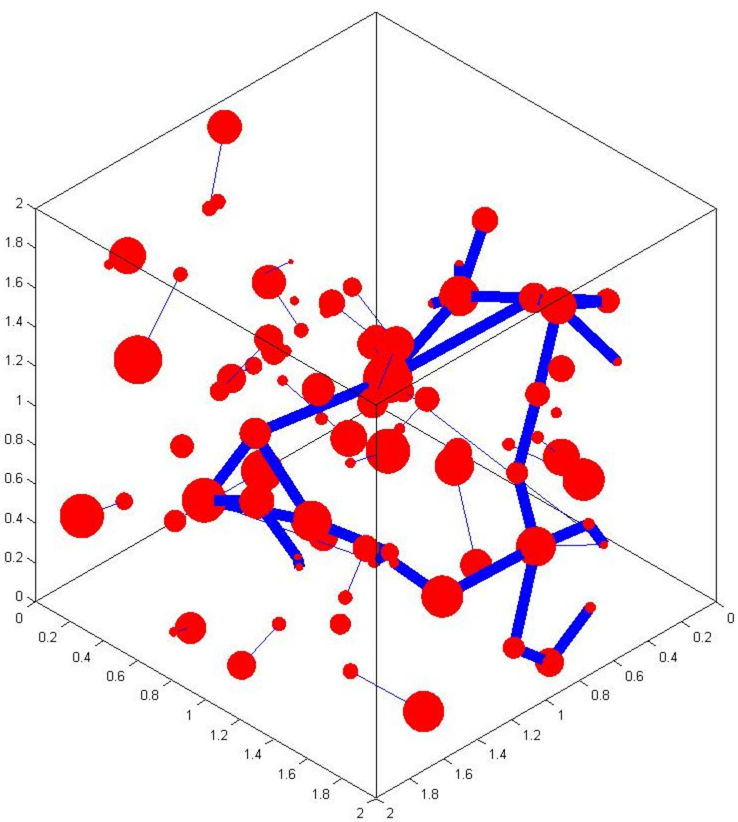
Gas Saturation 15.2%

Simulation - Gas Expansion



Gas Saturation 15.9%

Simulation - Gas Expansion / Percolation



Gas percolation 15.9%

Status of Technical Approach

Task 1.0 – Project management and planning *Completed*

Task 2.0 – Pore network generation *Completed*

- **Subtask 2.1 Compilation of relevant information of in-situ HBS**
- **Subtask 2.2 Generation of sediment packing using DEM**
- **Subtask 2.3 Pore network model extraction**

Task 3.0 – Algorithm development for gas expansion *In progress*

Task 4.0 – Studies of characteristic curve and relative permeability

- **Subtask 4.1 Effect of hydrate spatial distribution and pore size distribution**
- **Subtask 4.2 Effect of hydrate saturation**
- **Subtask 4.3 Effect of gas pressure – viscosity**
- **Subtask 4.4 Recommendation of fitting parameters**

Success Criteria at Decision Point

Decision Point	Decision Point 1 9/30/2013	
Success Criteria	• Three sets of ***grain size distribution*** curves gathered for in-situ hydrate-bearing reservoirs.	**Presented**
	• ***Particle packing*** generated by grain size distribution and in-situ effective stress.	**Presented**
	• ***Pore network model*** generated from the pore space image of particle packing.	**Presented**
	• ***Simulation algorithm*** for hydrate dissociation and gas expansion verified by the known volume of fluid expansion available in the literature.	**Presented**

Presentation Outline

Project Overview

Accomplishments

Budget / Plan for 2nd year

Budget – 1st year

Projection by 9/30/2013

Categories	Planned	Spent	Available	Comments
Salary/Fringe Benefit	38,644	21,982	16,662	GRA's fellowship at WSU
Tuition	13,500	6,750	6,750	GRA's fellowship at WSU
Software (*PFC 3D*)	13,670	13,670	0	
Travel	844	0	844	Kick-off meeting via WebEx
Total (Direct cost)	66,658	42,402	24,256	36% remaining

6 month of GRA salary
1 semester tuition

Project Team

Jaewon Jang
PI

N. Mahabadi
GRA

Task 1 – Project Management and Planning

Task 2 – Pore Network Generation

Task 3 – Algorithm Development for Gas Expansion

Task 4 – Studies of Characteristic Curve and Relative permeability

Plan for 2nd year

Task 3.0 Algorithm for Conductivity and Hydrate Dissociation

Task 4.0 Characteristic Curve and Relative Permeability

Subtask 4.1 Effect of hydrate habit

Heterogeneity of hydrate distribution and hydrate pore habit

Subtask 4.2 Effect of hydrate saturation

Hydrate saturation-vs.-parameters

Subtask 4.3 Effect of gas viscosity

Methane viscosity μ_g=<u>11.6</u> [μPa•s] at P=<u>3.2</u>MPa to μ_g=<u>20.2</u> [μPa•s] at P=<u>20.5</u>MPa under T=298K [van der Gulik et al., 1988]

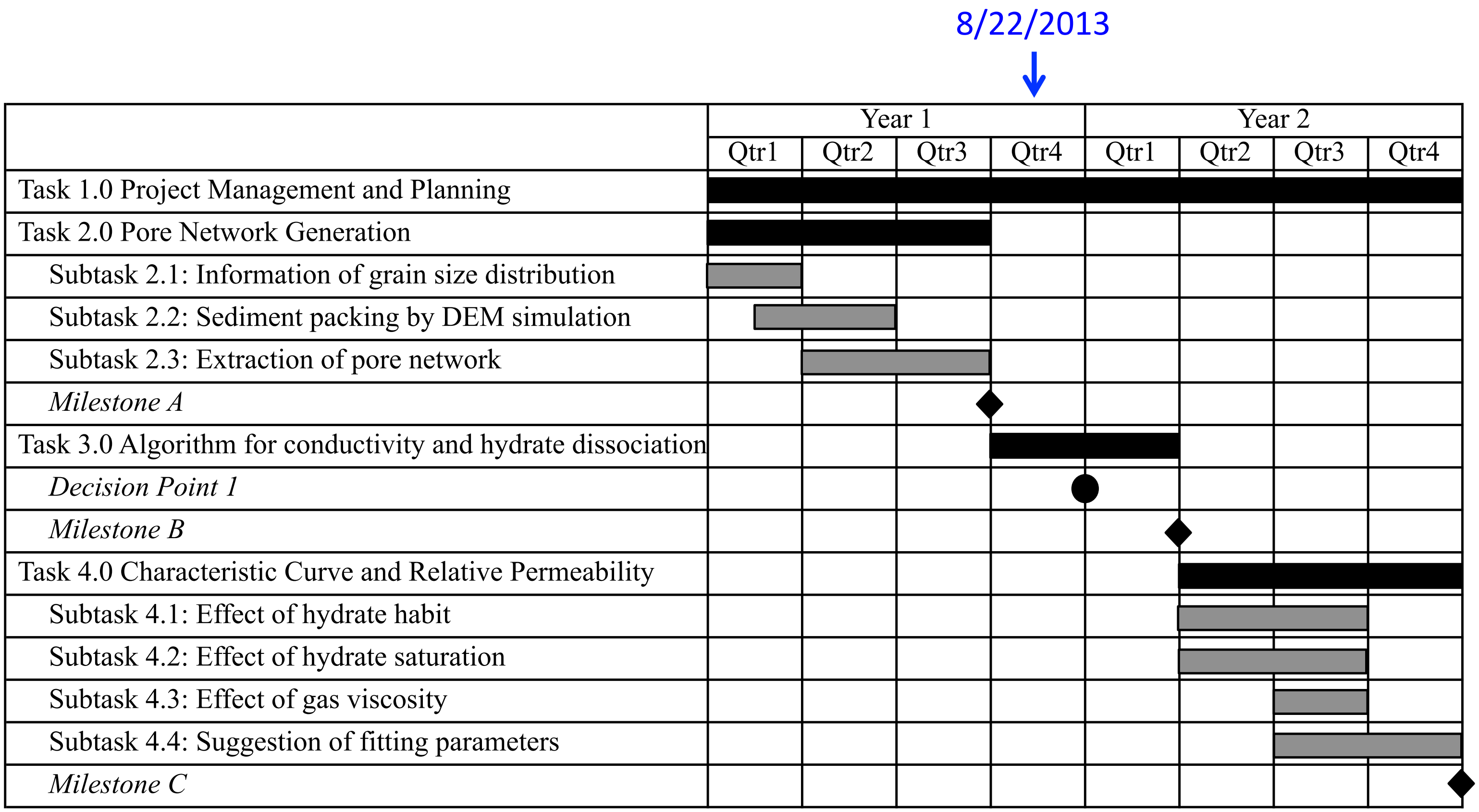
Subtask 4.4 Suggestion of fitting parameters

Additional tasks

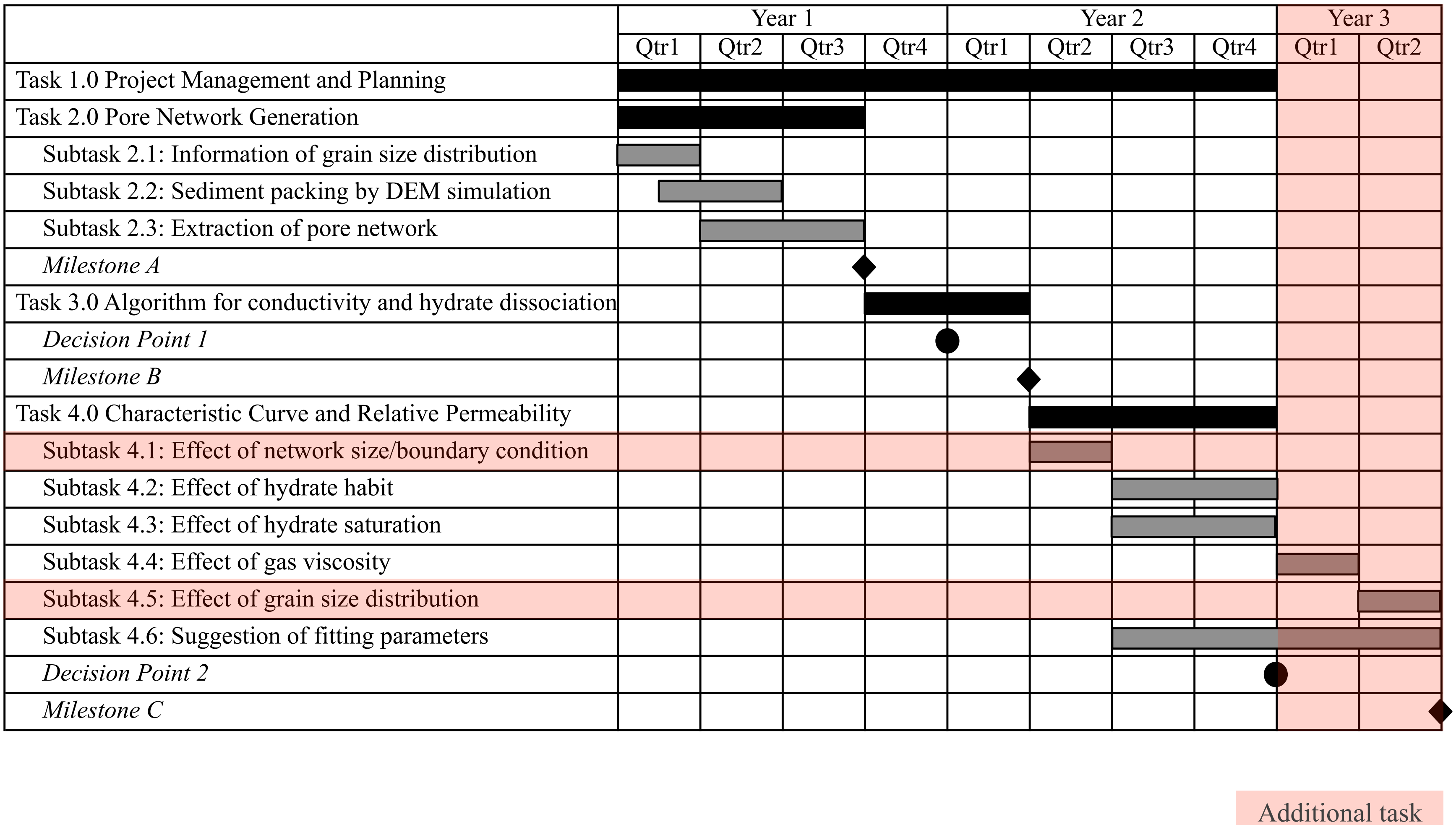
Effect of pore network model size / Boundary conditions (periodic)

Effect of grain (pore) size distribution: statistical and spatial distribution

Original Plan



Suggested Plan - Additional tasks



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