| Test No. | $S_h$ [%] | $n$ [%] | $P$ [MPa] | $T$ [°C] | $k_{0,x}$ [$\mu m^2$] | $k_{0,y}$ [$\mu m^2$] | $k_{0,z}$ [$\mu m^2$] | $k_{e,x}$ [$\mu m^2$] | $k_{e,y}$ [$\mu m^2$] | $k_{e,z}$ [$\mu m^2$] | $k_x$ [%] | $k_y$ [%] | $k_z$ [%] | Sand Type | Formation |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 8.0 | 30.8 | 13.8 | 4.5 | 12.63 | 11.95 | 12.28 | 5.37 | 4.85 | 5.25 | 42.5 | 40.6 | 42.8 | Ottawa | Excess-gas |
| 2 | 11.6 | 38.0 | 13.8 | 12 | 33.94 | 31.10 | 39.34 | 23.38 | 9.92 | 26.03 | 68.9 | 31.9 | 66.2 | Ottawa | |
| 3 | 25.2 | 35.8 | 12.4 | 10 | 26.06 | 23.26 | 25.65 | 8.74 | 7.14 | 8.76 | 33.5 | 30.7 | 34.2 | Ottawa | |
| 4 | 39.5 | 37.4 | 10.7 | 5 | 27.28 | 28.04 | 32.14 | 1.67 | 2.31 | 2.60 | 6.1 | 8.2 | 8.1 | Ottawa | |
| 5 | 48.2 | 38.8 | 12.4 | 10 | 16.08 | 12.99 | 15.48 | 2.23 | 1.16 | 2.78 | 13.9 | 8.9 | 17.9 | Mixture | |
| 6 | 51.6 | 44.5 | 12.4 | 10 | 9.03 | 8.66 | 9.14 | 0.37 | 0.21 | 0.23 | 4.1 | 2.4 | 2.5 | F110 | |
| 7 | 57.2 | 36.6 | 13.8 | 6.5 | 46.64 | 47.05 | 43.99 | 1.40 | 2.29 | 1.89 | 3.0 | 4.9 | 4.3 | Ottawa | |
| 8 | 68.1 | 35.0 | 13.8 | 7.4 | 41.02 | 34.87 | 37.81 | 0.77 | 0 | 0 | 1.9 | 0 | 0 | Ottawa | |
| 9 | 75.0 | 36.0 | 13.8 | 6.5 | 37.55 | 37.07 | 36.68 | 0 | 0 | 0 | 0 | 0 | 0 | Ottawa | |
| 10 | 86.5 | 32.5 | 13.8 | 6.5 | 26.14 | 25.37 | 27.57 | 0 | 0 | 0 | 0 | 0 | 0 | Ottawa | |
| 11 | 41.1 | 35.8 | 12.4 | 10 | 26.06 | 23.26 | 25.65 | 2.21 | 1.21 | 2.15 | 8.5 | 5.2 | 8.4 | Ottawa | Excess-water from excess-gas |
| 12 | 51.5 | 38.8 | 12.4 | 10 | 16.08 | 12.99 | 15.48 | 1.11 | 0.51 | 1.47 | 6.9 | 3.9 | 9.5 | Mixture | |
| 13 | 55.2 | 36.6 | 14.1 | 6.5 | 46.88 | 47.20 | 44.22 | 1.14 | 1.03 | 1.14 | 2.4 | 2.2 | 2.6 | Ottawa | |
| 14 | 56.8 | 37.4 | 10.7 | 5 | 27.28 | 28.04 | 32.14 | 0.51 | 0.74 | 1.12 | 1.9 | 2.6 | 3.5 | Ottawa | |
| 15 | 75.8 | 44.5 | 12.4 | 10 | 9.03 | 8.66 | 9.14 | 0 | 0 | 0 | 0 | 0 | 0 | F110 | |
| 16 | 24.7 | 36.7 | 17.2 | 12 | 40.91 | 37.65 | 39.43 | 15.60 | 14.24 | 13.86 | 38.1 | 37.8 | 35.2 | Ottawa | Excess-water |
| 17 | 41.9 | 32.7 | 24.1 | 8.5 | 11.81 | 10.97 | 11.85 | 0.21 | 3.38 | 3.18 | 1.8 | 30.8 | 26.8 | Ottawa | |
| 18 | 43.5 | 37.4 | 10.3 | 4 | 27.28 | 28.04 | 32.14 | 2.32 | 2.01 | 2.20 | 8.5 | 7.2 | 6.8 | Ottawa | |
| 19 | 71.5 | 33.4 | 24.1 | 8.5 | 13.79 | 12.98 | 13.43 | 0 | 0 | 0.14 | 0 | 0 | 1.0 | Ottawa | |
| 20 | 71.9 | 36.7 | 24.1 | 8.5 | 42.50 | 40.32 | 42.08 | 0.23 | 0.04 | 0.08 | 0.5 | 0.1 | 0.2 | Ottawa | |
| 21 | 89.6 | 33.7 | 24.1 | 8.5 | 13.40 | 11.73 | 12.62 | 0 | 0 | 0 | 0 | 0 | 0 | Ottawa | |

$S_h$ = Hydrate Saturation; $n$ = Porosity; $P$ = Pore Pressure; $T$ = Temperature; $k_0$ = intrinsic permeability; $k_e$ = effective permeability; $k$ = normalized permeability; Ottawa = Ottawa Sand with ~250 μm mean diameter; F110 = F110 Sand with ~120 μm mean diameter; Mixture = Specimen with a layer of Ottawa sand and a layer of F110 sand.

Excess-gas: Sand is mixed with water and packed into a column-shaped specimen. Methane pressure and temperature are adjusted to the targeted values to form methane hydrate with constant pressure gas supply. Excess-water from excess-gas: Brine is flushed through hydrate-bearing specimens formed under excess-gas condition. Excess-water: High pressure methane is introduced to water-saturated specimens, then temperature is reduced and hydrate forms with constant pressure water supply.

**Table 1**

Information of hydrate-bearing specimens used in this study.

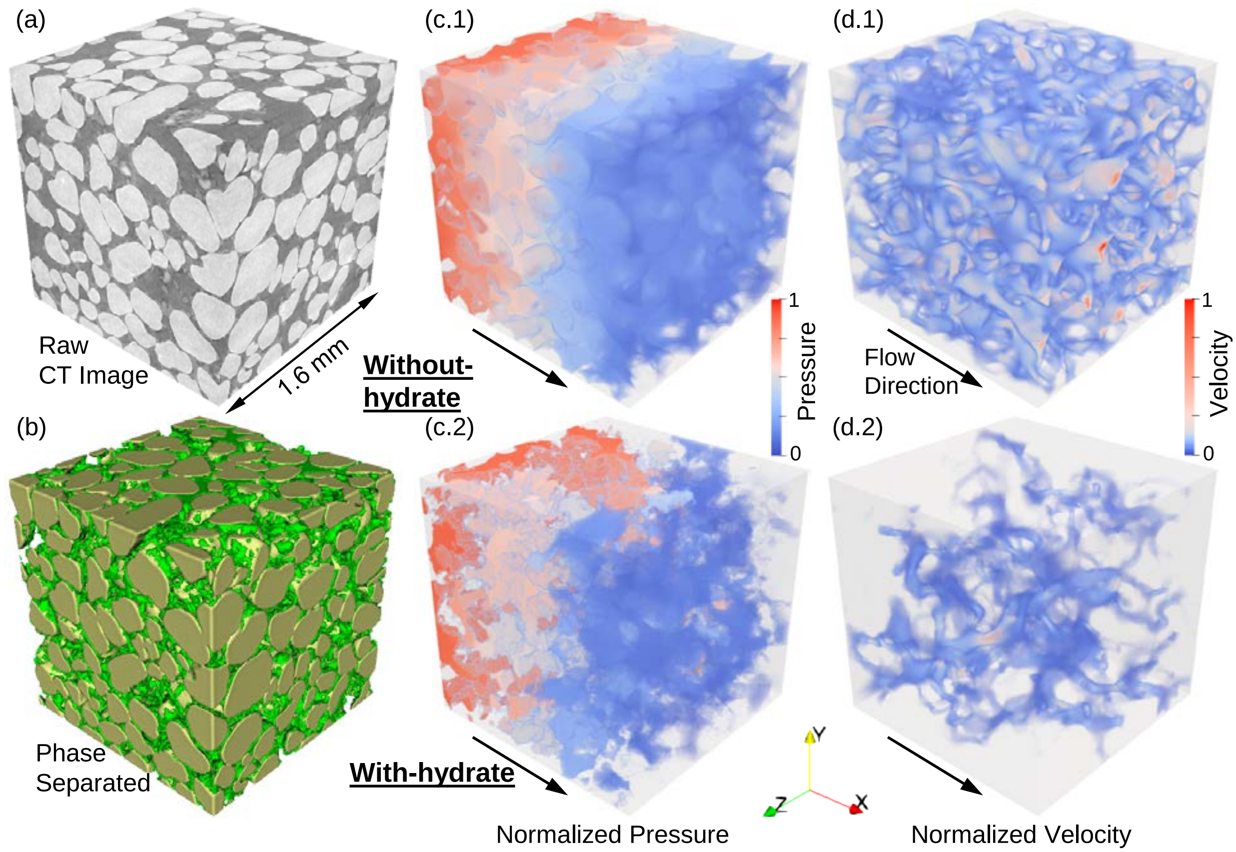


**Figure 1**

Procedure from raw CT image to pressure and velocity fields of fluid flow through specimens (Test 4, excess-gas condition, $S_h$ = 39.5%). (a) Raw 3D micro-CT image. (b) 3D pore structures after segmentation: sand particles in brown, hydrate in green, and free methane transparent. (c) Normalized pressure fields with a flow direction along the X axis. (d) Normalized velocity fields with a flow direction along the X axis. (c.1-d.1) is Without-hydrate case and (c.2-d.2) is With-hydrate case.

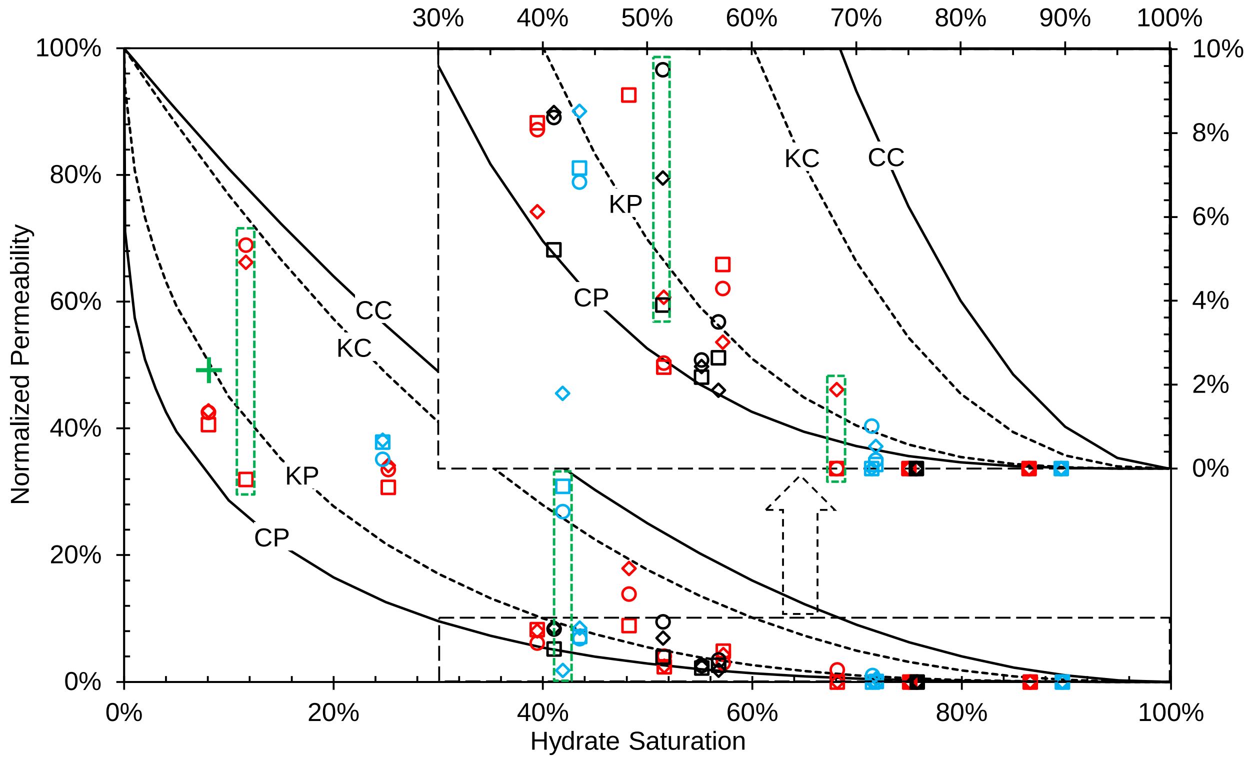


**Figure 2**

Normalized permeability from numerical simulations as a function of hydrate saturation. CC = Capillary-tube Coating, KC = Kozeny-grain Coating, KP = Kozeny-grain Pore-filling, and CP = Capillary-tube Pore-filling (Kleinberg et al., 2013). Symbols are results on conditions of excess-gas (red), excess-water from excess-gas by fluid injection (blue) and excess-water (black) as summarized in Table 1, and ◇, □ and ○ represent permeability in X, Y, and Z direction. The green + shows the result in Figure 3b. Vertical green frames highlight permeability anisotropy.

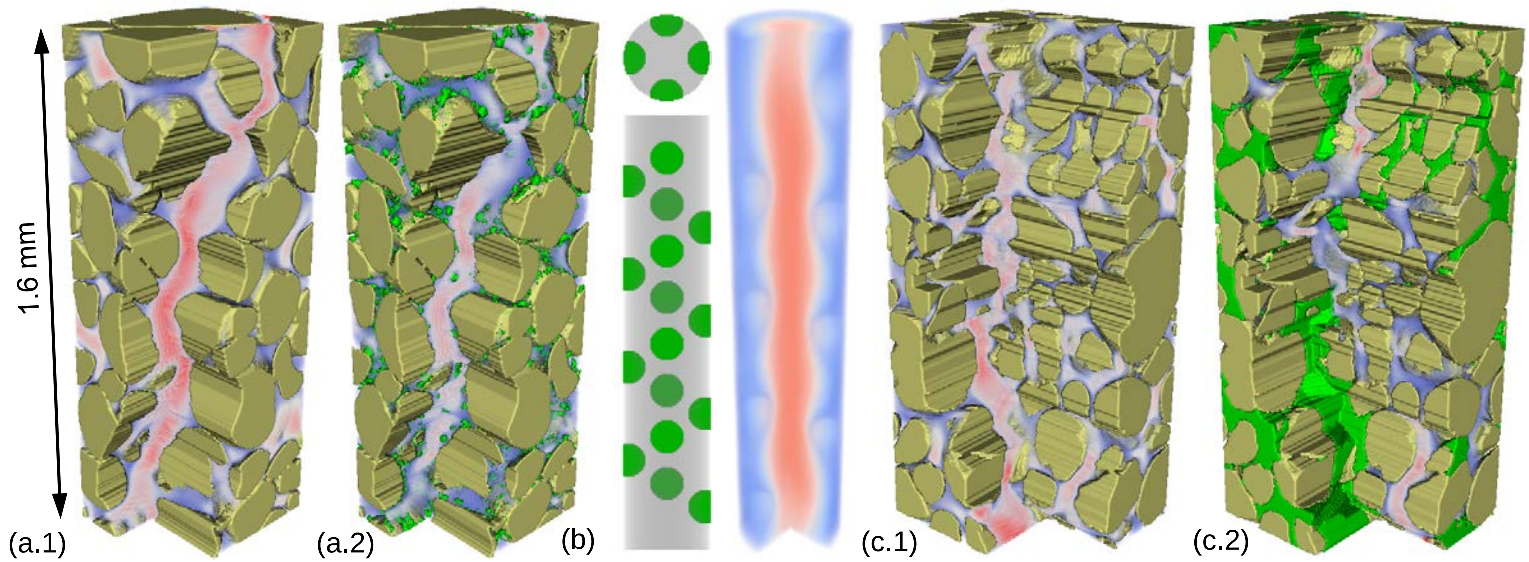


**Figure 3**

Effect of hydrate on geometry of flow path and velocity fields. (a) and (c) show the effect of actual hydrate distribution with hydrate saturation of 8.0% (Test 1) and 71.5% (Test 19). (b) presents the effect of hydrate with idealized distribution mimicking that in (a).

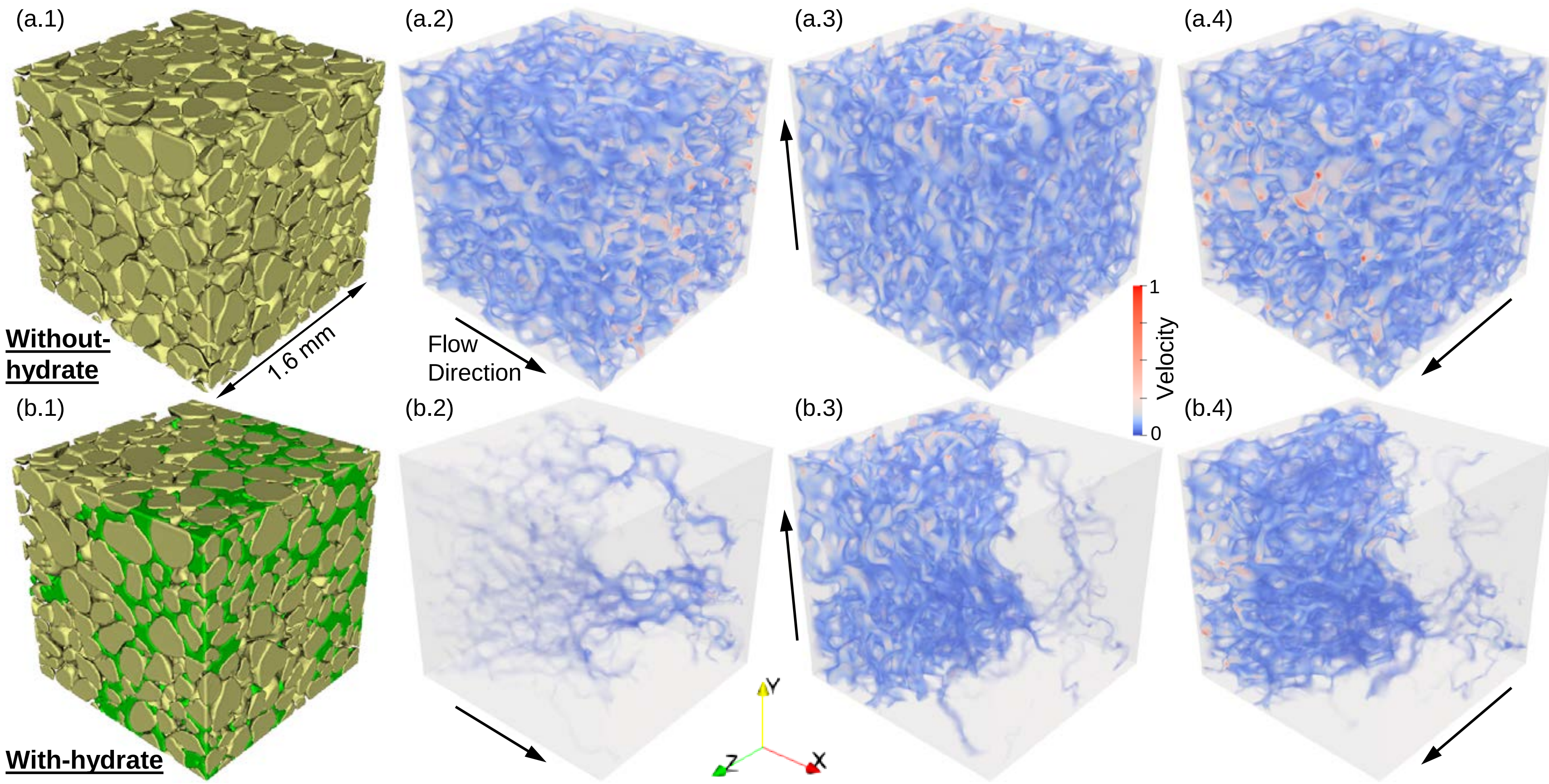


**Figure 4**

Unevenly distributed hydrate induced permeability anisotropy (Test 17, $S_h$ = 41.9%). (a-b) show Without-hydrate case and With-hydrate case. (a/b.1-a/b.4) present 3D pore structure, and flow velocity fields along X, Y and Z directions.

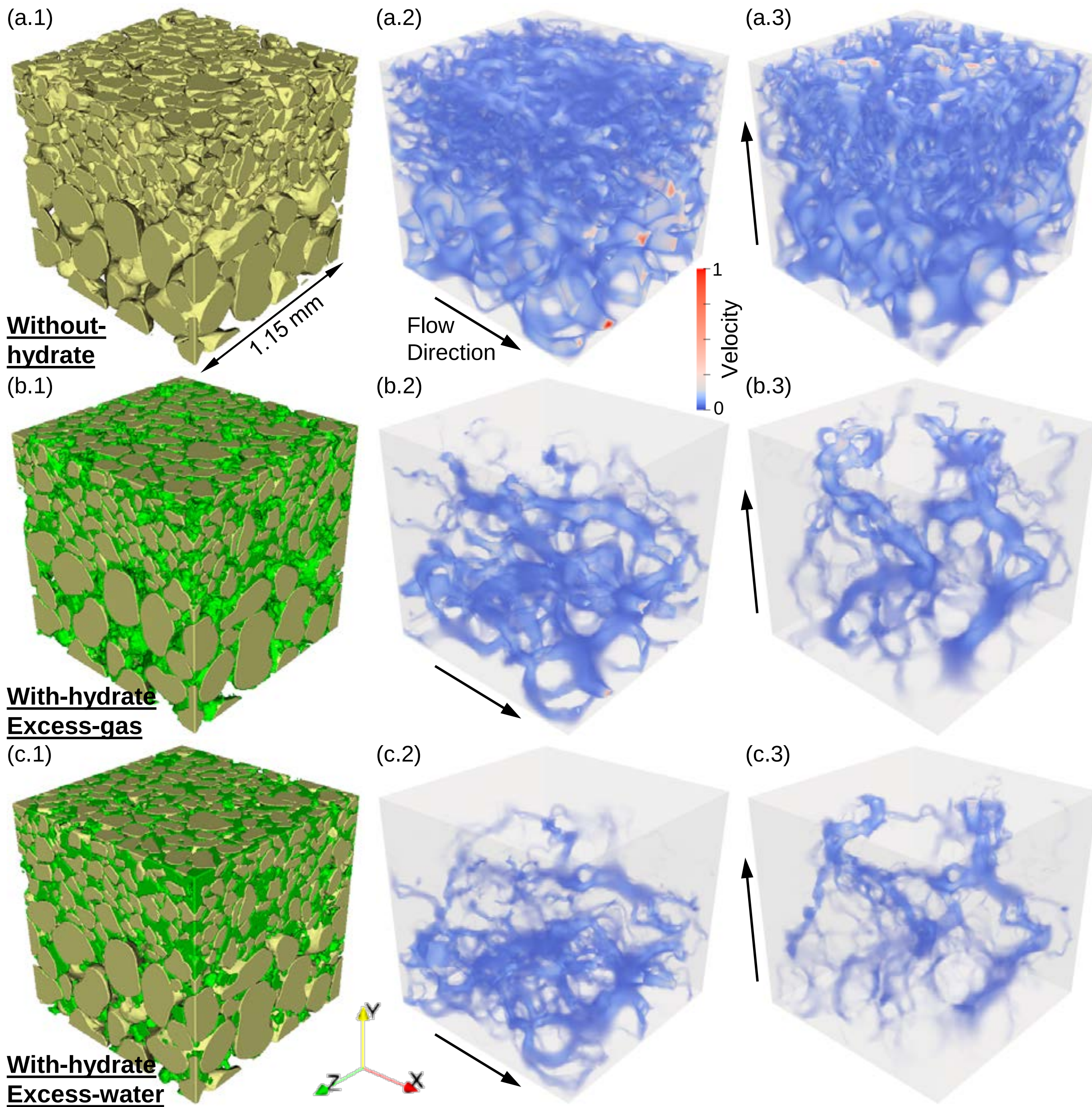


**Figure 5**

Permeability in layered systems. (a-c) show cases of Without-hydrate, With-hydrate under excess-gas condition (Tests 5, $S_h$ = 48.2%) and excess-water condition (Tests 12, $S_h$ = 51.5%). (a/b/c.1-a/b/c.3) present 3D pore structures, and flow velocity fields along X and Y directions.