Controls of Reservoir and Cap Rock on Gas Hydrate Formation*

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Abstract

Review of previous gas hydrate studies indicates that the formation and occurrence of gas hydrate is controlled by the factors of sea bottom temperature, geothermal gradient, availability of gas and water, gas chemistry, pore-water salinity, gas and water migration pathways and the presence of reservoir rocks and seals and so on. This paper proposes that what controlled the formation of gas hydrate in the gas hydrate stability zone (GHSZ) are two core factors: gas concentration (Cg) and gas molecular migration velocity (Vg). Only when Cg is big enough and Vg is small enough, can gas hydrate take shape. We illustrate this with a C-V function: y=f(Cg, Vg), when y is in some particular value, gas hydrate will form. On the other hand, Cg is mainly controlled by the reservoir and Vg is mainly controlled by the cap rock. Moreover, the seal ability of the cap rock can be expressed as a function: y=f(H, Φ, K, Z). H, Φ, K, and Z stand for the thickness, porosity, permeability and grain size of the cap rock, respectively. Based on this theory, this paper illustrates the relationship between sediment and Cg, Vg from qualitatively to quantitatively. Especially it will discuss the influences of the four factors controlling the seal abilities of cap rock for Vg from qualitatively to quantitatively. Thereby, we conclude that the different thicknesses, porosities, permeabilities and grain sizes of cap rock and different combinations of reservoir and cap rock, which mainly contributes to the formation of gas hydrate and how they influence the thickness of GHSZ.

Objectives

It is well known that a very huge volume of natural gas is stored in gas hydrates (Table 1), but the data experts estimated varies greatly. According to the data, the amount of the worlds' gas resources for the permafrost hydrates is from 14 to 34,000 trillion cubic meters and the amount for marine hydrates is from 3,100 to 7,600,000 trillion cubic meters. Why does the data vary so largely? The reality is that relatively little is know about the geological control on gas hydrate distribution (Collett, 2004; Collett, 2009), so the estimated volume of the gas hydrate bearing sediments, which is a main factor in the estimates, is very uncertain.

Could any kind of sediments in the gas hydrate stability zone (GHSZ) form gas hydrates? On the other hand, which kinds of sediment are the best for gas hydrate accumulation? It is obvious that not all the sediments in the gas hydrate stability zone (GHSZ) could accumulate gas hydrates. Different kinds of sediments should play different roles in gas hydrate formation and accumulation. In addition, it is indispensable that there should be abundant gas and water supply to form gas hydrate. Recently, the petroleum system approach was used in gas hydrate estimates by some experts and the sand sediments are best viewed by them (Max et al, 2006; Collett et al, 2010; Johnson, 2011).

On the other hand, gas hydrate exploration is mainly based on geophysical method at present. In addition, the bottom-simulating reflectors (BSR) are the identification marks. There are relatively no theories on gas hydrate geological exploration. Therefore, in detail scale, which area and which kind of sediments are the best targets and which should we drill first in the future are not well known.

Based on the above understanding, this paper discusses where could the gas hydrate preferentially form and accumulate and gives a relatively detailed predication of gas hydrate formation in different sediment columns. In addition, this paper will attempt to apply the theories of sedimentology and sequence stratigraphy to gas hydrate exploration.

The Basic Theory

1. Microscopic view on P-T condition

It is well known that gas hydrates form in the conditions of low temperature and high pressure. From a microscopic view of physics, the temperature is determined by the average molecules' kinetic energy. In addition, the pressure could control the number of gas molecules in per unit volume: this would determine how many gas molecules could contact with the water molecules. From a microscopic view, if more gas molecules could contact with the water molecules, the gas molecules could be captured by the water molecules more easily and gas hydrates would be easier and more rapid to form (Figure 1).

We know at a given pressure, the temperature should be low enough to form gas hydrates. This could be interpreted as that when the number of the gas molecules, which contact with water molecules is certain, the average gas and water molecules' kinetic energy should be low enough. Only in this condition, water molecules could capture gas molecules and form gas hydrates (Figure 1).

On the other hand, at a given temperature, the pressure should be high enough to form gas hydrates. This could be interpreted as that when the average gas molecules' kinetic energy is certain, the number of the gas molecules, which contact with water molecules should be big enough. Only in this condition, water molecules could capture gas molecules and form gas hydrates (Figure 1).

Furthermore, as the gas hydrate formation is exothermic (Kono et al, 2002), the temperature of the environment will be increased when gas hydrates formed. Therefore, the temperature should be adjusted to low enough to go on forming gas hydrates and this process should be slow. That means the formation of gas hydrates should be a slow process.

2. C-V controls on gas hydrate formation

The formation and occurrence of gas hydrates are controlled by many factors, such as sea bottom temperature, geothermal gradient, availability of gas and water, gas chemistry, pore-water salinity, gas and water migration pathways and the presence of reservoir rocks and seals (Collett, 1995; Maclennan and Jones, 2006). Under the appropriate temperature and pressure (which is called GHSZ), if there are abundant gas and water supply, gas hydrates could take shape. Therefore, this paper proposes that in the GHSZ, what controlled the formation of gas hydrates are two core factors: gas concentration (Cg) and gas molecular migration velocity (Vg). Only when Cg is big enough and less than a value could gas hydrates form. Another important factor is Vg. At a given gas concentration, only when Vg is less than a value, could gas molecules be captured by the structured water and form gas hydrates (Figure 2). This could be illustrated with a C-V function: y=f (Cg, Vg), when y is in some particular value, gas hydrates will form.

From Figure 2 we can conclude that there are two gas concentration limits for gas hydrate formation, the values could be expressed as Cgmin and Cgmax. Only when gas concentration is greater than Cgmin and less than Cgmax could gas hydrates form. Moreover, to form gas hydrates, the gas molecular migration velocity should be less than a value at a given gas concentration. On the other hand, there may be a gas molecular migration velocity limit, which can be expressed as Vgmax, only when Vg is less than this value, could gas hydrates form (Figure 2). In addition, Vgmax should be related to Cgmax.

3. Discussion on dynamic accumulation system for gas hydrates

As illustrated in Figure 3, the dynamic accumulation system for gas hydrates is made up of source rock, reservoir rock and cap rock. The gases are transferred to the reservoir rock from the source rock, and it is expressed as Cgi. Cgi is mainly determined by the generative gas ability of the source rock. On the contrary, the gas will leak from the cap rock, and it is expressed as Cgo. Cgo is mainly determined by the seal ability of the cap rock.

In order to form gas hydrates, the gas concentration in the reservoir should be greater than Cgmin. Whether the gases can be accumulated in the reservoir is determined by the relationships of Cgi and Cgo. When Cgi is greater than Cgo, the gases in the reservoir could be accumulated more and more. Therefore, gas hydrates could form in the reservoir. However, when Cgi is less than Cgo, the reservoir is only a bypass for the gases. Therefore, the gases could not be accumulated in the reservoir and gas hydrates could not form.

In this dynamic accumulation system, the generative gas ability of the source rock and the seal ability of the cap rock are the most important two factors. Whether the gas hydrates could form in the reservoir is mainly determined by the relationships of Cgi and Cgo.

The Cap Rock Influences on Gas Hydrate Formation

The gas molecular migration velocity (Vg) should be mainly controlled by the seal ability of the cap rock. Moreover, the seal ability of the cap rock is mainly controlled by the thickness, porosity, permeability and grain size of the cap rock. So the seal ability of the cap rock can be expressed as a function: $y=f(H, \Phi, K, Z)$. H, Φ, K, and Z stand for the thickness, porosity, permeability and grain size of the cap rock, respectively.

1. The thickness of cap rock influences on gas hydrate formation

As illustrated in Figure 4, the different thicknesses of the cap rocks are shown. It is presumed that the reservoirs, gas supplies and the grain sizes of the cap rocks are all the same in Figure 4. Only the thicknesses of the cap rocks are different. Because the seal ability of the cap rock become stronger with its thickness increased, so the seal ability of the cap rock in Figure 4C should be the strongest and Figure 4A should be the weakest. That means the gas leak in Figure 4C is the slowest and Figure 4A is the fastest. On the other hand, the gas molecular migration velocity (Vg) in the reservoir is mainly determined by the seal ability of the cap rock. Therefore, Vg in Figure 4C is the smallest and Vg in Figure 4A is the biggest. In addition, the gas concentration in Figure 4C will preferentially reach to the gas concentration limit for gas hydrate formation. Therefore, refer to the C-V control theory on gas hydrate formation, which was discussed before. Figure 4C is the best for gas hydrate accumulation. So in some instances, maybe where the cap rock is thickest, it should be the best area for gas hydrate formation and accumulation, especially when the generative gas ability of the source rock is very limited, this should be the truth.

2. The grain size of cap rock influences on gas hydrate formation

The seal ability of the cap rock is related to cap rock grain size. The grain size would mainly influence the porosity (Φ) and permeability (K). The porosity and permeability are in proportion with the grain size increase in most situations without considering the cementation and overpressure. So here, only the grain size is discussed, and the porosity and permeability are omitted in this paper.

As illustrated in Figure 5, the different grain sizes of the cap rocks are shown. The other factors such as gas supplies, reservoirs and the thicknesses of the cap rocks are all the same in Figure 5. Without considering the cementation and overpressure, the seal ability of the cap rock should be in inverse proportion to the grain size. Therefore, the seal ability of the cap rock in Figure 5A should be the strongest and Figure 5C should be the weakest. That means the gas leak in Figure 5A is the slowest and Figure 5C is the fastest. Therefore, Vg in Figure 5A is the smallest and Figure 5C is the biggest. In addition, the gas concentration in Figure 5A will preferentially reach to the gas concentration limit for gas hydrate formation. Therefore, refer to the C-V control theory on gas hydrate formation, which was discussed before. Figure 5A is the best for gas hydrate accumulation.

Therefore, in actual geological settings, if the qualities of the reservoirs, the thickness of the cap rocks and the gas supplies are similar, maybe where the grain size is the finest, it should be the best place for gas hydrate accumulation. With regard to the porosity and permeability, they have negative effect on the seal ability of the cap rock. Therefore, they have similar influences on gas hydrate formation as the grain size of the cap rock.

The Reservoir Influences on Gas Hydrate Formation

1. The reservoir influences on gas hydrate formation

The gas concentration should be mainly controlled by the reservoir. If the quality of the reservoir is better, it will have greater porosity and permeability. Therefore, the gases can be accumulated more rapidly and the gas concentration should be bigger. It was pointed out that the temperature for gas hydrate formation in the smaller grain size sediments is lower than the bigger grain size sediments

(Hovland, 1997). This also indicates that if the qualities of the reservoirs are better, the gas hydrates will be more easily and preferentially formed.

As illustrated in Figure 6, the qualities of the cap rocks are all the same, only the qualities of the reservoirs are different. The reservoir in Figure 6C should be the best one for gas hydrate formation and accumulation, because it has the largest grain size. In addition, the gas migration velocity should be the slowest in the reservoir of Figure 6C. If the gas supplies are all the same, the gas concentration should be accumulated most rapidly in Figure 6C. Therefore, refer to the C-V control theory on gas hydrate formation, which was discussed before. Figure 6C is the best for gas hydrate accumulation.

2. The combination of reservoir and cap rock influences on gas hydrate formation

The seal ability of the cap rock for the gas should not be determined only by the cap rock. It is well known that whether a rock can be the cap rock is relative. That means whether one rock can be the cap rock is related to the reservoir rock. So strictly speaking, the seal ability of the cap rock for the gas should be determined by the combination of the reservoir and the cap rock.

As illustrated in Figure 7, different combinations of reservoirs and cap rocks are shown. The qualities of the cap rocks become worse with the grain size increasing. On the other hand, the qualities of the reservoirs become better with the grain size increasing. Therefore, Figure 7A has the best cap rock and the worst reservoir; Figure 7C has the worst cap rock and the best reservoir. Considering the combinations of reservoirs and cap rocks, maybe the seal abilities of the cap rocks for the gas are all the same in Figure 7. Therefore, Figure 7 examples may play almost the same role for gas hydrate formation. In the actual geological settings, the combinations of the sedimentary facies mainly control the combinations of reservoirs and cap rocks. So sedimentology should be well considered.

The Vertical Sedimentary Rhythm Influences on Gas Hydrate Formation

As illustrated in Figure 8A, the sediments are up-fining. In this kind of sediments, the upper fine sediments could act as a good cap rock and the lower coarse sediments could act as good reservoir. Therefore, the gas could be accumulated in the lower coarse sediments and form gas hydrates. In Figure 8B, the sediments are up-coarsening. In this kind of sediment, there is not a good combination of reservoir and cap rock, so the gas could not be accumulated in the sediments. Maybe it is very hard for gas hydrate formation. Up-fining sediments are good reservoirs for gas hydrate formation, but up-coarsening sediments are not good. On the other hand, the grain size change in the vertical section is related to the sedimentary facies. So sedimentology should be well considered.

As illustrated in Figure 8C, there are three reservoirs. Because the gas is going up from the lower part, the lowest reservoir will preferentially accumulate gas and form gas hydrates while the reservoir in the upper is harder to accumulate gas and form gas hydrates. However, when there are some faults or some fractures to connect the gas sources with the upper reservoir, the upper reservoir could form and accumulate gas hydrates well too.

The Trend for Gas Hydrate Formation and Micro Reservoir-Cap Systems

As illustrated in Figure 9A, there is a good reservoir and a cap rock. Because the controlling factors are very complex for gas hydrate formation in the actual geological environments, maybe the gas hydrates could firstly form near the base of the gas hydrate stability zone (BGHSZ) which was expressed as “level a”. In addition, the gas hydrate bearing sediments will act as a good cap rock for the gas. So “level a” to “level b” will have no gas come in, and it will not form gas hydrates. However, it would not be the truth in the actual sediments. Many factors could influence the GHSZ, such as sea level change, tectonic uplift and so on. So the gas hydrates will be deformed with the BGHSZ change. There is a most stable position for the free gas to accumulate: it should be “level b” which is the contact of the cap rock and the reservoir. Moreover, gas hydrates will form from the contact of the reservoir and cap rock to the down. Therefore, in the actual geological environments, the gas hydrate accumulation should approach to the most stable position. This is the trend for gas hydrate formation.

Figure 9B illustrates the heterogeneous sediments. These kinds of sediments could be considered as many micro reservoir-cap systems. The relative fine sediments could act as the cap rocks and the relative coarse sediments could act as the reservoirs. Therefore, the gas will preferentially migrate to the relative coarse sediments and accumulate in these sediments and form gas hydrates. This may be one of the reasons why the gas hydrate forms in the samples include nodules, pellets, sheets and lenses. Additionally, some experts indicated that the gas hydrates would preferentially form in the larger pores rather than the smaller pores (Hovland et al, 1997; Clennell et al, 1995; Kraemer et al, 2000; Tréhu et al, 2006).

Apply Sequence Stratigraphy to Gas Hydrate Exploration

As discussed in the former, it is very important for gas hydrate formation and accumulation to have a good combination of reservoir and cap rock. Therefore, the lowstand systems tract (LST) is the best for gas hydrate formation and accumulation. There are many good sedimentary facies could act as good reservoirs in LST, such as slope fans, submarine fans and turbidities; and there have good cap rocks in LST too. Furthermore, the mud sediments in transgressive systems tract (TST) could act as good cap rocks for the reservoirs in LST (Figure 10).

Because there are not many good reservoirs in transgressive systems tract (TST), the TST is not a good choice for gas hydrate exploration. The deltas in the highstand systems tract (HST) could act as reservoirs (maybe not very good, because it is up-coarsening), but there are no good cap rocks in an HST. Therefore, an HST is not a very good choice for gas hydrate accumulation. Only the delta front may be a good place to accumulate gas hydrates (Figure 10).

Conclusions

The formation of gas hydrates is essentially controlled by the average molecules' kinetic energy and the number of the gas molecules which could contact with the water molecules. To form gas hydrates, the average molecules' kinetic energy should be low enough and the number of the gas molecules, which could contact with the water molecules should be big enough. As it is exothermic and gas hydrates form in low temperature, gas hydrate formation is a slow process.

In the GHSZ, the gas concentration (Cg) and the gas molecular migration velocity (Vg) may control the gas hydrate formation. In addition, it would be illustrated as y=f (Cg, Vg), only when y is in some particular value, could gas hydrates form. Moreover, these two factors are mainly controlled by the reservoir and the cap rock.

The dynamic accumulation system for gas hydrates is mainly controlled by the source rock and the cap rock. Therefore, it could also be called as Source-Cap control systems. Only when the gas concentration inputted from the source rock to the reservoir is bigger than the gas concentration leaked from the reservoir to the cap rock, could gas hydrates form in the reservoir.

The seal ability of the cap rock and the quality of the reservoir would influence the gas hydrate formation and accumulation. Gas hydrates would preferentially form and accumulate in the reservoir, which has a better quality and a better cap rock along with it when other factors are almost similar.

The up-fining sediments are better than up-coarsening sediments for gas hydrate formation and accumulation. This is because that the up-fining sediments are easier to accumulate gas than up-coarsening sediments. Furthermore, the lowest reservoir should be the best one to accumulate gas and form gas hydrates when there are no faults to connect the gas sources with the upper reservoir.

There is a most stable position for gas hydrate formation and accumulation, and the formed gas hydrates will be deformed and migrate towards this position when other factors influence the GHSZ. The heterogeneous sediments could be considered as many micro reservoir-cap systems, and gas hydrates will preferentially form and accumulate in the bigger pores.

The lowstand systems tract (LST) should the best for gas hydrate formation and accumulation, because there are good combinations of reservoirs and cap rocks in the LST. The slope fans, submarine fans and turbidities in the LST are the good choice for our future exploration.

Acknowledgements

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Amount of Gas(m^3)	Reference
In-Place Terrestrial Gas Hydrates	
1.4×10^{13}	Meyer (1981)
3.1×10^{13}	McIver (981)
5.7×10^{13}	Trofimuk et al. (1977)
7.4×10^{14}	MacDonald (1990)
3.4×10^{16}	Dobrynin et al. (1981)
In-Place Oceanic Gas Hydrates	
3.1×10^{15}	Meyer (1981)
$5\text{-}25\times10^{15}$	Trofimuk et al. (1977)
7×10^{15}	Holbrook et al. (1996)
2.1×10^{16}	MacDonald (1990)
4.6×10^{16}	Harvey and Huang (1995)
$2.6\text{-}13.9\times10^{16}$	Gornitz and Fung (1994)
7.6×10^{18}	Dobrynin et al. (1981)

Table 1. World Estimates of the Amount of Gas within Gas Hydrates

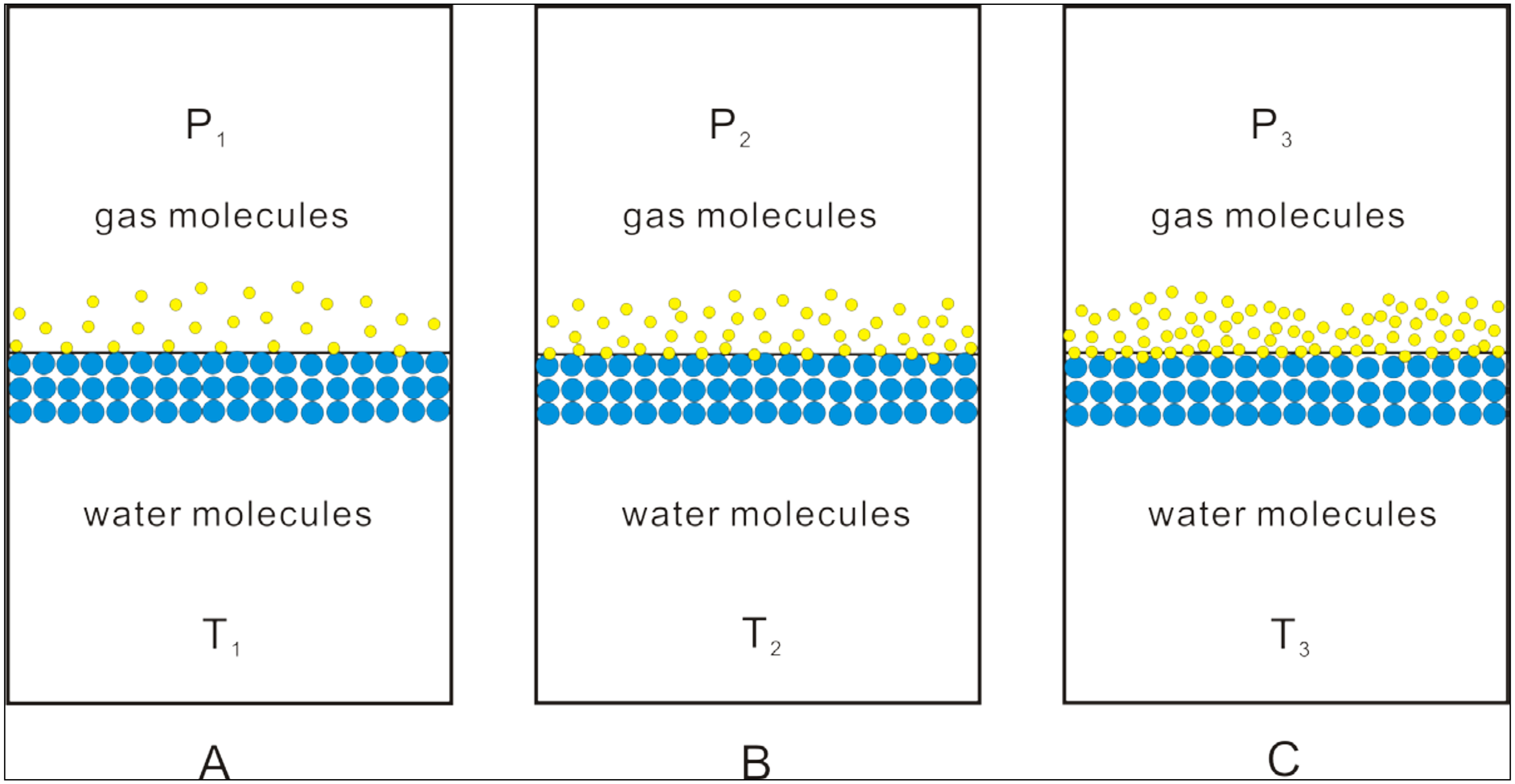

Figure 1. P-T microscopic interpretations for gas hydrate formation. With the pressure increased (P1<P2<P3), the gas molecules which could contact with water molecules become more. Therefore, at a given temperature, Figure 1C is the easiest one to form gas hydrates. On the other hand, to form gas hydrates, Figure 1A is the strictest on the temperature. That means the highest temperature which gas hydrates could form is T1<T2<T3. Because the average gas molecules' kinetic energy in Figure 1A should be the lowest to form gas hydrates.

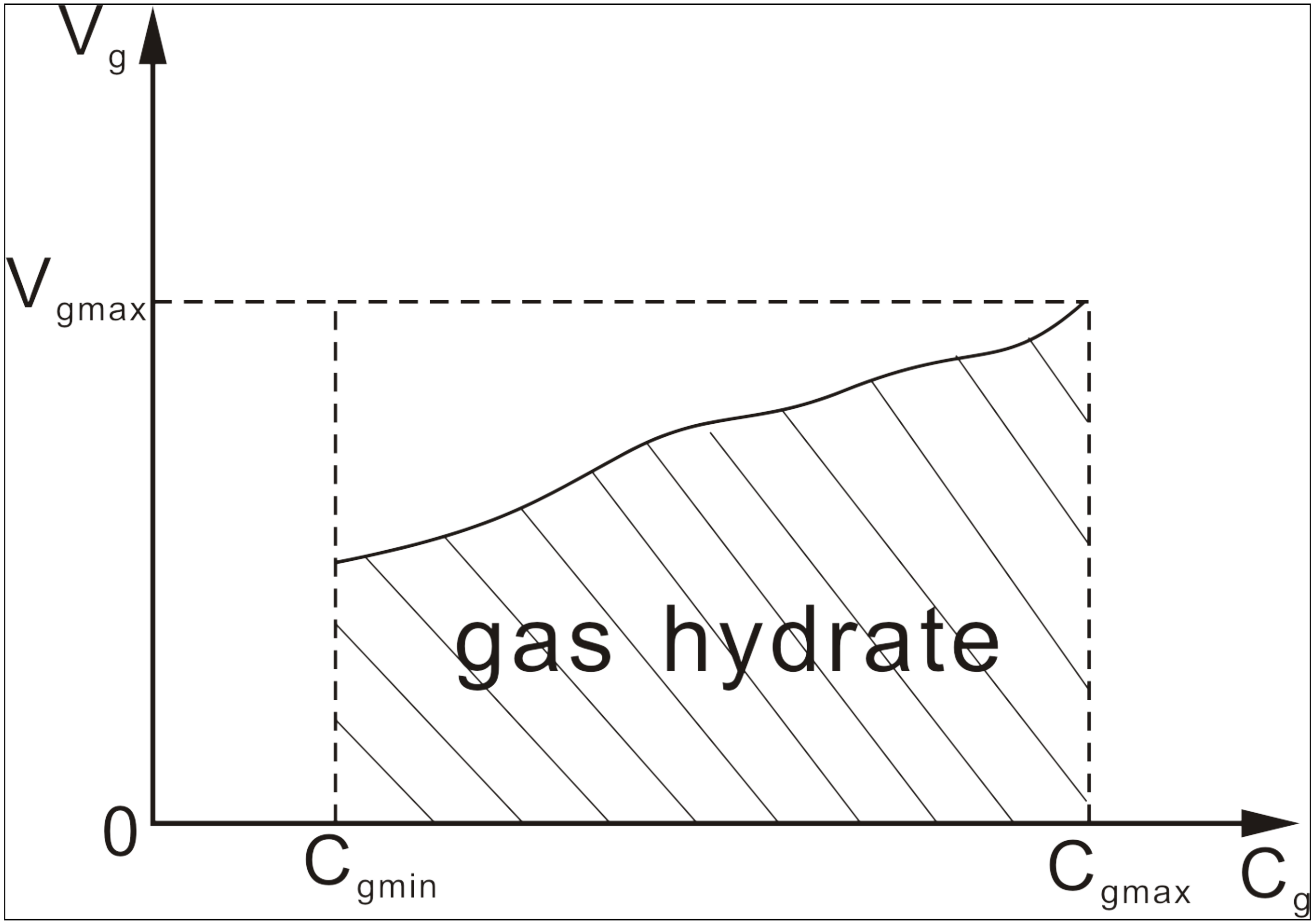

Figure 2. Gas concentration (Cg) and gas molecular migration velocity (Vg) controls on gas hydrate formation. Only when Cg is bigger than Cgmin and smaller than Cgmax and Vg is smaller than Vgmax could gas hydrates form. On the other hand, the biggest Vg for gas hydrate formation at a given gas concentration could become bigger with the Cg increase.

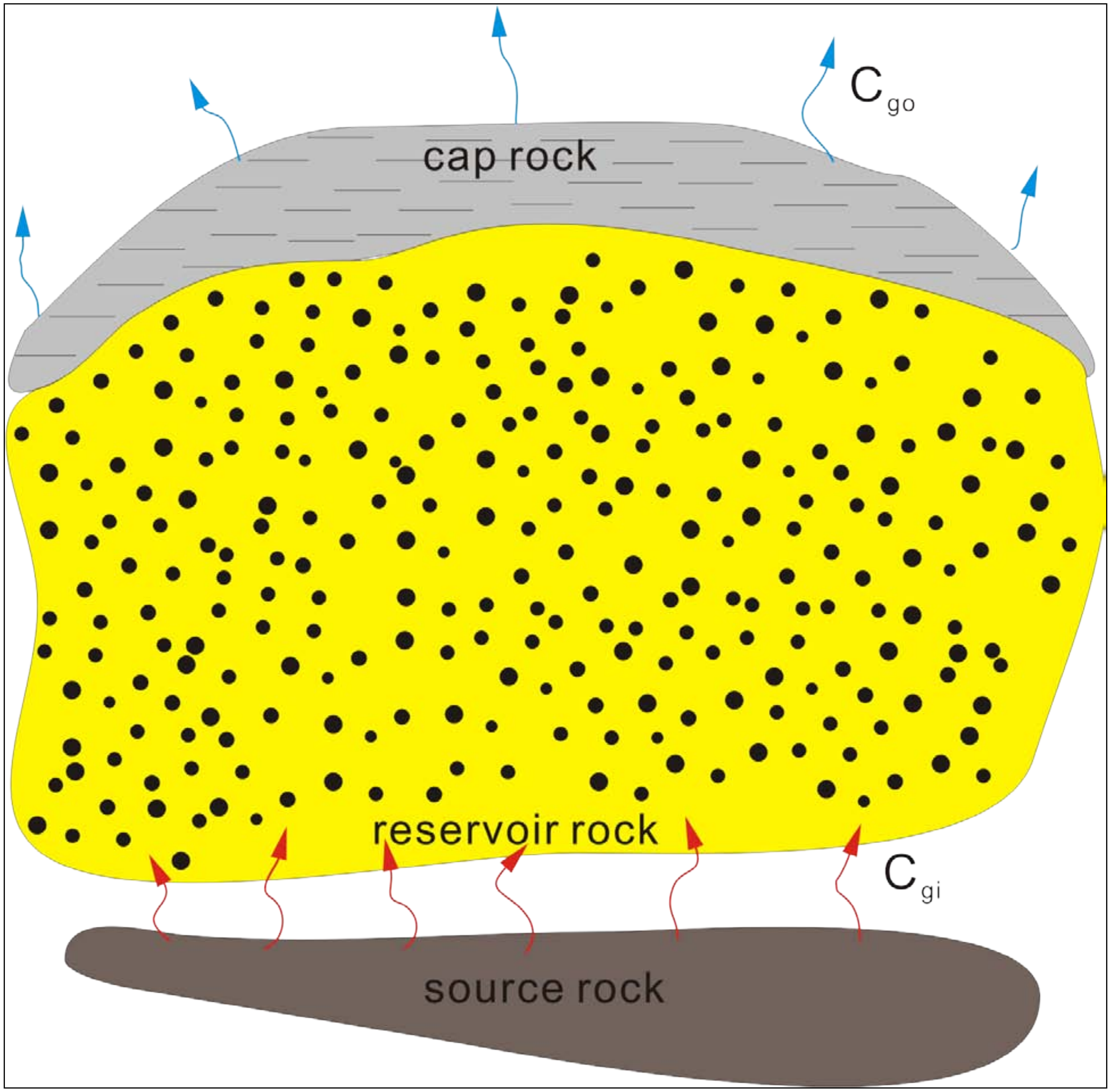

Figure 3. Source-Cap control system for gas hydrate formation. Only when Cgi is bigger than Cgo, could gases be accumulated in the reservoir and form gas hydrates.

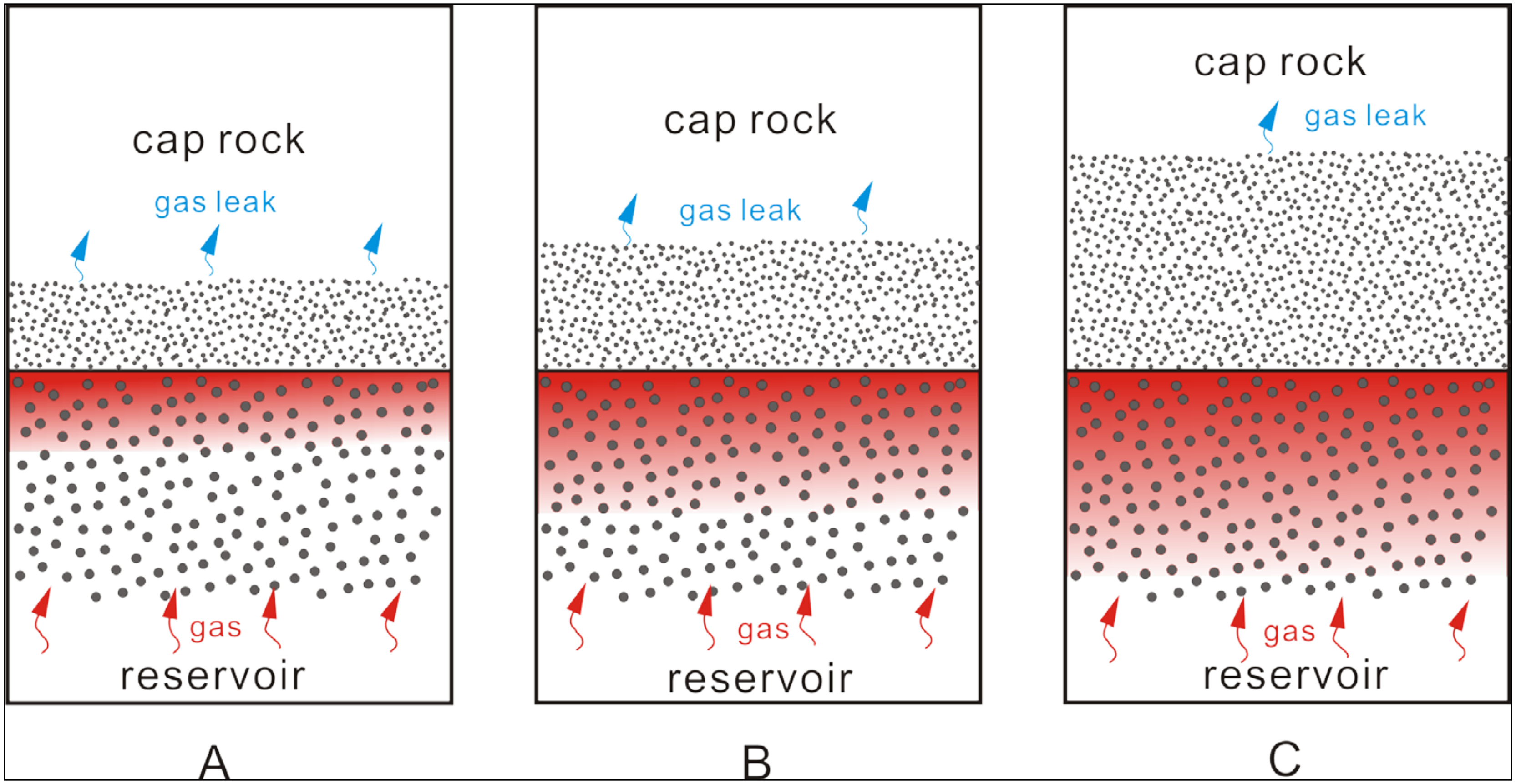

Figure 4. The thickness of the cap rock influences on gas hydrate formation. With the thickness increased, the seal ability of the cap rock will increase too. Therefore, the gas molecular migration velocity is the smallest and the gas concentration will increase most rapidly in Figure 4C. According to the C-V control theory on gas hydrate formation discussed before, Figure 4C should be the best one for gas hydrate accumulation.

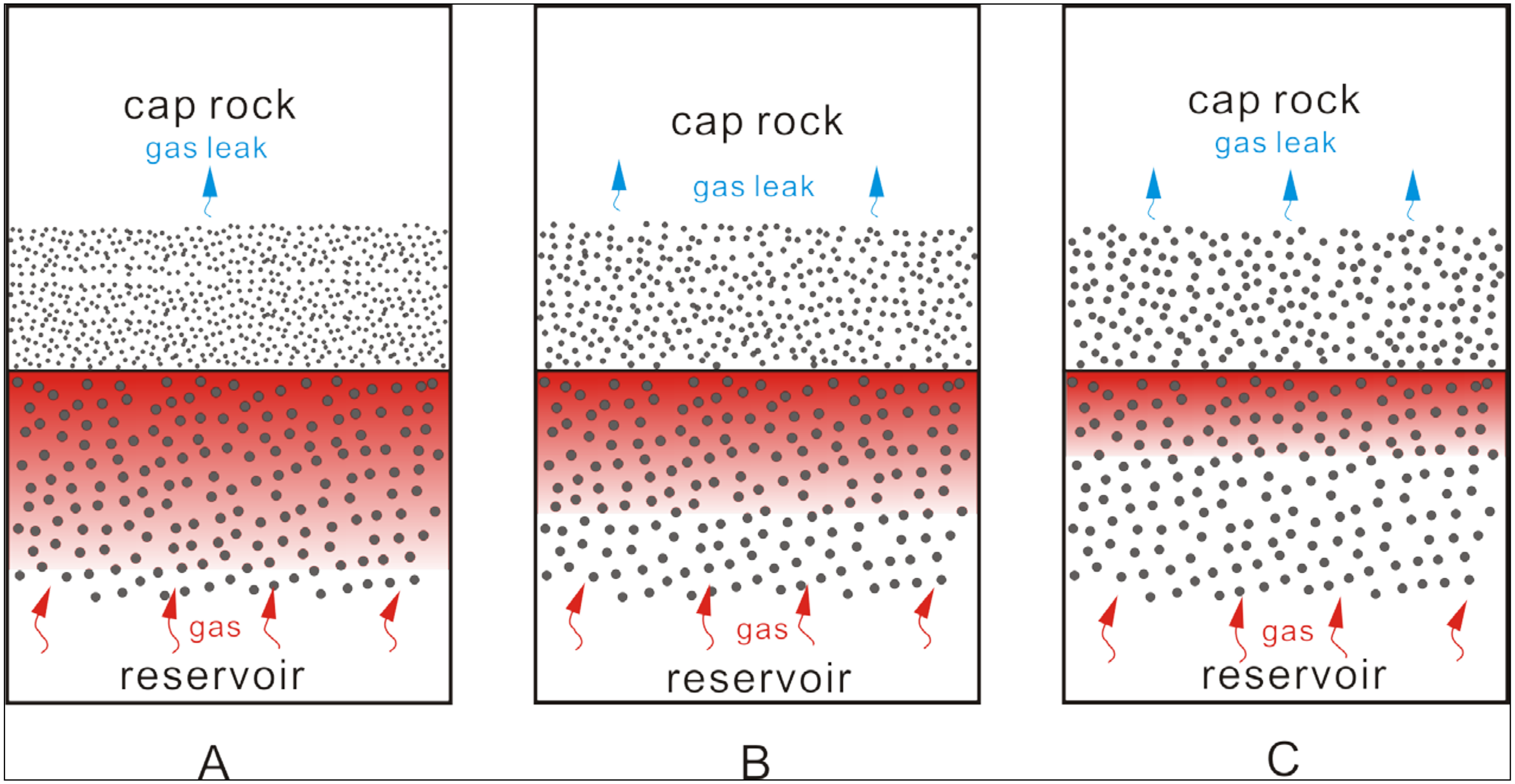

Figure 5. The grain size of the cap rock influences on gas hydrate formation. With the grain size increased, the seal ability of the cap rock will decrease. Therefore, the gas molecular migration velocity is the smallest and the gas concentration will increase most rapidly in Figure 5A. According to the C-V control theory on gas hydrate formation discussed before, the Figure 5A should be the best one for gas hydrate accumulation.

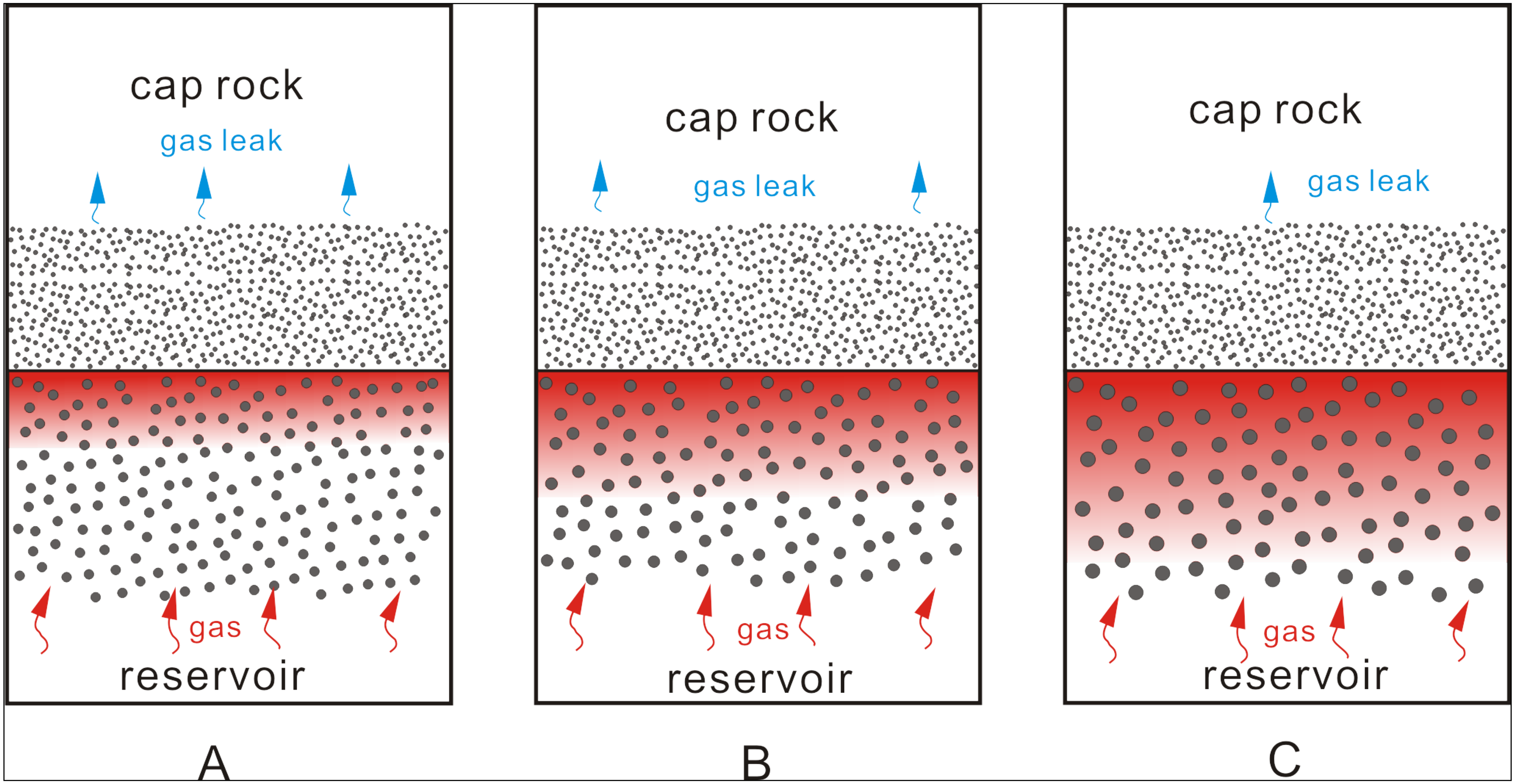

Figure 6. The reservoir influences on gas hydrate formation. With the grain size increased, the quality of the reservoir will become better. Therefore, the gas molecular migration velocity is the smallest and the gas concentration will increase most rapidly in Figure 6C. According to the C-V control theory on gas hydrate formation discussed before, the Figure 6C should be the best one for gas hydrate accumulation.

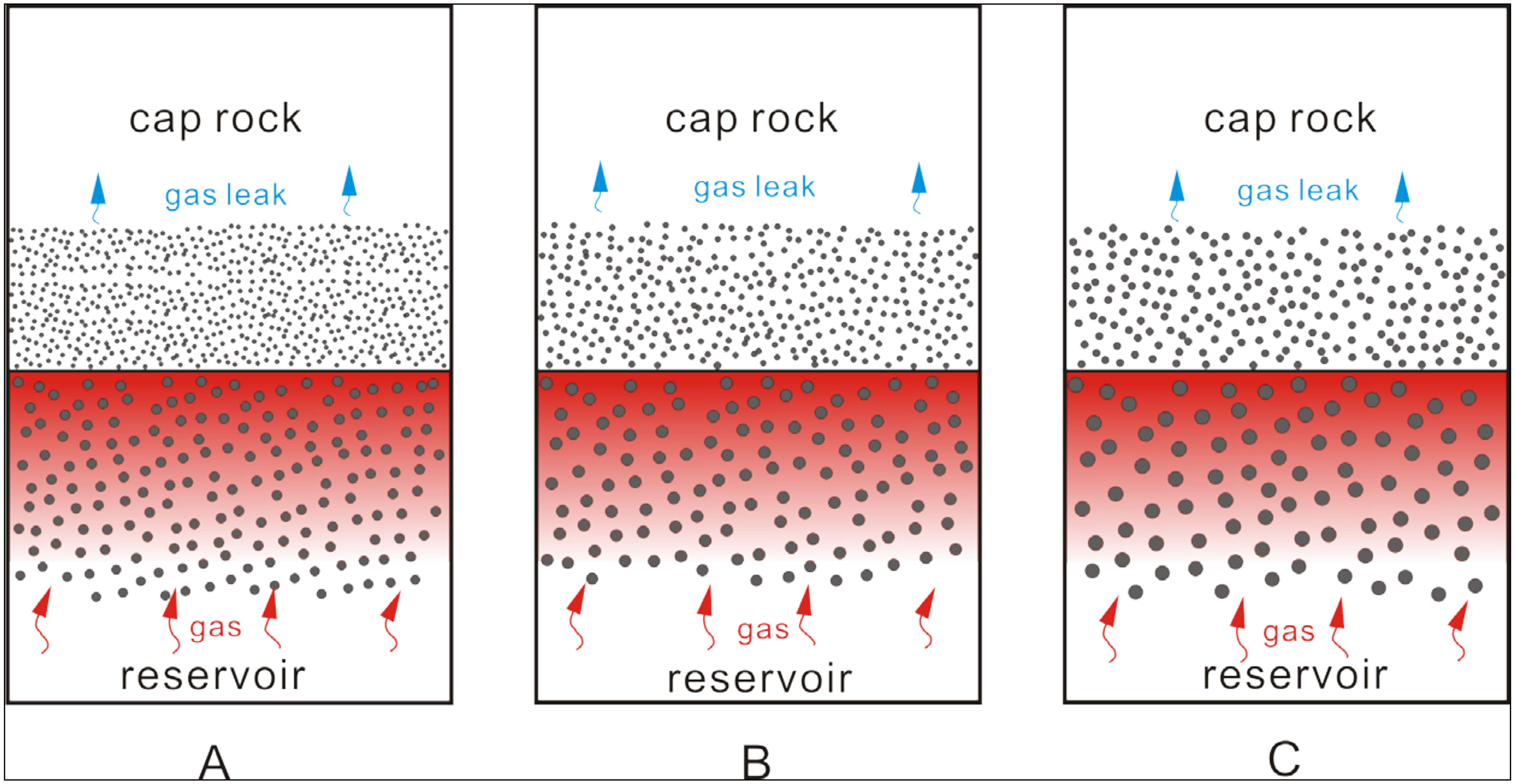

Figure 7. The combination of reservoir and cap rock influences on gas hydrate formation. The seal ability of the cap rock is not controlled only by the cap rock, but is controlled by the combination of the cap rock and the reservoir. Therefore, Figure 7A, B and C may play the same role for gas hydrate formation and accumulation.

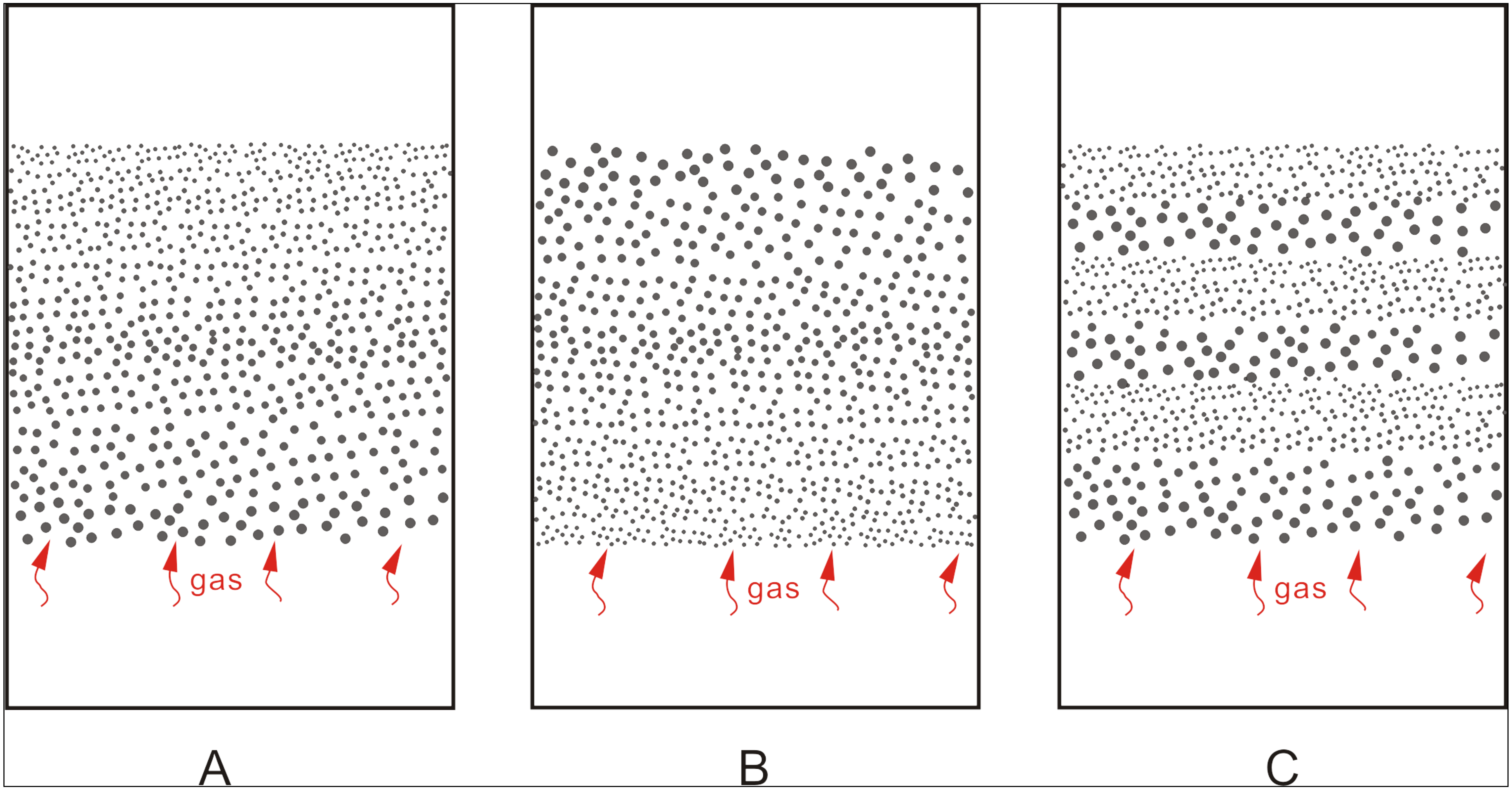

Figure 8. The vertical sedimentary rhythm influences on gas hydrate formation. Figure 8A illustrates up-fining sediments and it is better to accumulate gas and form gas hydrates than Figure 8B which is up-coarsening. The lowest reservoir in Figure 8C should be the best reservoir to accumulate gas and form gas hydrates when there are no faults or fractures to connect the gas sources with the upper reservoir.

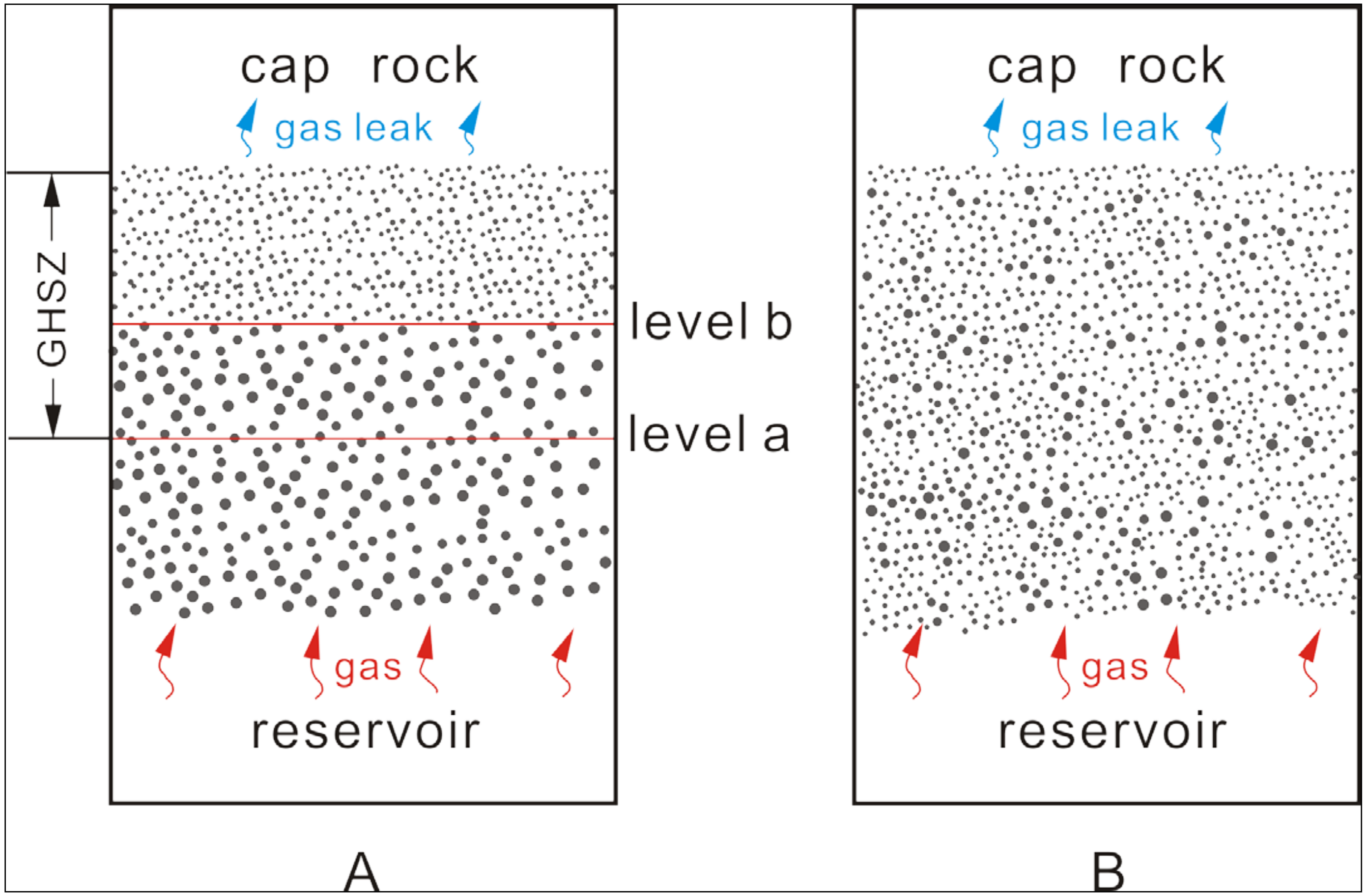

Figure 9. The trend for gas hydrate formation and micro reservoir-cap systems. Maybe the gas hydrates could form firstly near the BGHSZ (level a) in Figure 9A, but many factors will make the BGHSZ change and the gas hydrates will be deformed to approach to "level b". So "level b" is the most stable position. Figure 9B are heterogeneous sediments, this kind of sediments could be considered as many micro reservoir-cap systems in it. In addition, the gas hydrates will preferentially accumulate in the relative coarse sediments.

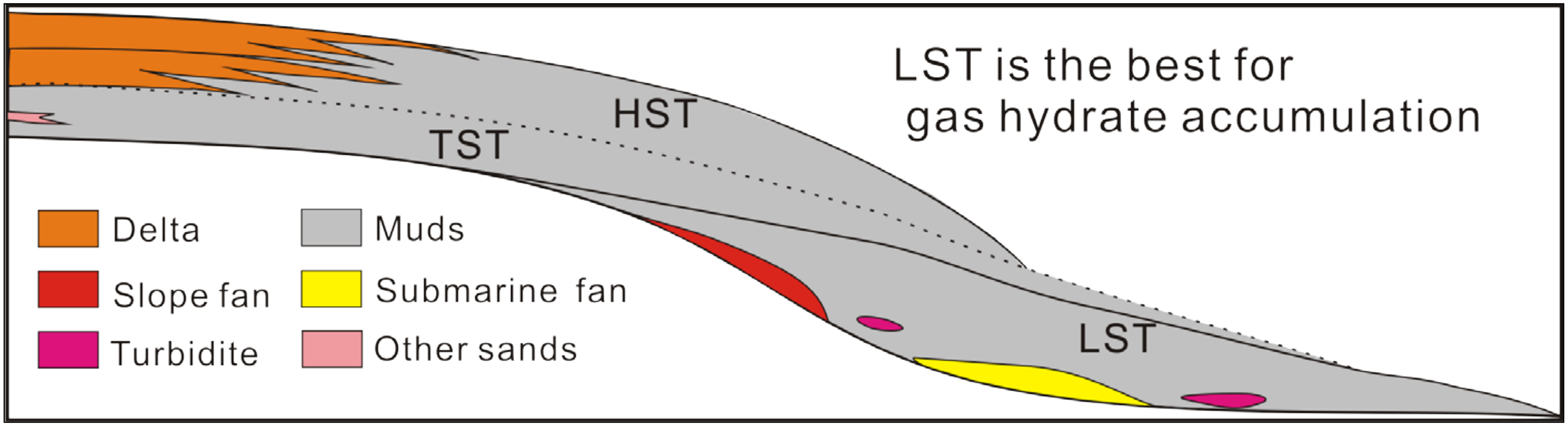

Figure 10. Apply sequence stratigraphy to gas hydrate exploration. There are good reservoirs and cap rocks in LST, poor reservoirs in TST and good reservoirs but bad cap rocks in HST. Therefore, slope fans, submarine fans and turbidities in LST are the best for gas hydrate formation and accumulation.