A Case Study of Upscaling Extra-Fine Coalbed Methane Geological Model

Lijiang Duan(✉), Zhaohui Xia, and Liangchao Qu

Asia-Pacific Department, PetroChina Research Institute of Petroleum Exploration & Development, Beijing, China
{duanlj,xiazhui,quliangchao}@petrochina.com.cn

Abstract. Extra-fine geological model of the coalbed methane (CBM) field is not suitable for being adopted directly as a simulation model, and upscaling work is necessary. The main challenge of upscaling is to preserve important reservoir heterogeneities and flow characteristics of fine model, meanwhile ensure reasonable cell count. In study area, an extra-fine coal reservoir model was built, and 125 plies in 20 sublayers of six coal members were identified with an average single coal thickness of 0.46 m. Up-gridding was conducted from coal-member level to sublayer level and finally to coal-ply level. Various ways were adopted to estimate the results at each coarsening step. The optimal-layer-grouping scheme was achieved by conducting only 20 plus up-gridding trials. The results show that compared with ply model, active cell count was reduced by 85.28%, and average production error was less than 3%. Some of the plies cannot be merged with adjacent plies indicating significant heterogeneity. Hierarchical up-gridding was used, which saves more layer-grouping trials. Six ways were adopted to analyse the up-gridding results, enabling the final layer-grouping scheme is optimal. This paper should therefore be of interest to reservoir engineers facing a complex geo-model of CBM reservoir.

Keywords: Upscale · Geological model · Coalbed methane · Surat basin

This paper was prepared for the presentation at the 2018 International Field Exploration and Development Conference in Xi'an, China, September 18–20 2018.

J. Lin (ed.), *Proceedings of the International Field Exploration and Development Conference 2018*, Springer Series in Geomechanics and Geoengineering, https://doi.org/10.1007/978-981-13-7127-1_46

1 Introduction

Geological model built by geologist tends to be extra-fine to describe depositional cycles and internal architecture of the reservoir. However, this model cannot be used directly by reservoir engineer for production history matching and performance forecasting due to computationally expensive. Therefore, upscaling work is necessary. The main challenge of upscaling is to preserve important reservoir heterogeneities and flow characteristics of fine model, meanwhile ensure reasonable cell count.

Upscaling process can be divided into two steps: (1) determining the manner of grouping fine cells to preserve inherent reservoir heterogeneity (this is called up-gridding) and (2) reassigning reservoir properties of coarse cells using optimal property upscaling method to capture flow characteristics.

In literatures, there are two major up-gridding methods: variance-based method and simulation-based method. The former method group cells having similar sweep efficiencies [1] or velocities [2] or pressure profiles [3] or effective permeabilities [4] through variance calculating of fine geo-model. It has the advantage of being fast. However, it is hard to ensure the complex fluid flow features in fine model could be accurately represented in coarse model. The latter method is directly based on the comparison of simulation results between fine and coarse models at each coarsening step [5]. It gives accurate results but too time-consuming to upscale extra-fine and complex geo-models. Coalbed methane (CBM) reservoir is more complex compared with conventional reservoir, and it is difficult to select representative parameters for calculating to describe reservoir flow features. Therefore, simulation-based method was used in this paper, but new measures were adopted to make the up-gridding process faster.

For the property upscaling methods, more argues exist about permeability. After comparing the simulation results of various permeability upscaling methods, flow-based upscaling was recommended by Allan et al. [6] and Ma et al. [7]. Volume-weighted averaging method was used by King et al. [2], Hosseini and Kelkar [3] and Zhou and King [8]. Shehata et al. [9] found the optimal permeability upscaling method varies along with different scenarios, such as depletion process and water injection process. For making the simulation results of coarse model closer to that of fine model, different permeability upscaling techniques were investigated in this paper before up-gridding process.

2 Fine Model of CBM Reservoir

The example is from a gas field in Surat Basin, Australia. Coals in this gas field belong to Walloon subgroup of Jurassic, which are further divided into six coal measures (Kogan, Macalister, Wambo, Argyle, Upper Taroom and Condamine) from shallower to deeper. The relatively stable alluvial flood plain allows river channels to freely migrate and disturbs coal swamp development. The Walloon subgroup is characterized by carbonaceous mudstone, siltstone, minor sandstone and coal. The coal seams are generally thin and inter-bedded with siltstone and sandstone. By identifying depositional cycles and building isochronic stratigraphy frames, 20 sublayers were divided for these six coal members. And, 125 plies were further identified by conducting single coal-ply correlation, which were described in detail in Table 1.

Table 1. Zone division of coal reservoir

Coal member	Sublayer name	Sublayer number	Ply name	Ply number
Kogan	K1	2	K1 ~ K3	3
	K2		K4 ~ K6	3
Macalister	M3	3	M3-1 ~ M3-6	6
	M2		M2-1 ~ M2-8	8
	M1		M1-1 ~ M2-8	8
Wambo	W4	4	W4-1 ~ W4-5	5
	W3		W3-1 ~ W3-9	9
	W2		W2-1 ~ W2-6	6
	W1		W1-1 ~ W1-8	8
Argyle	A4	4	A4-1 ~ A4-9	9
	A3		A3-1 ~ A3-8	8
	A2		A2-1 ~ A2-8	8
	A1		A1-1 ~ A1-6	6
Upper Taroom	UT4	4	UT4-1 ~ UT4-6	6
	UT3		UT3-1 ~ UT3-6	6
	UT2		UT2-1 ~ UT2-7	7
	UT1		UT1-1 ~ UT1-5	5
Condamine	C3	3	C3-1 ~ C3-6	6
	C2		C2-1 ~ C2-4	4
	C1		C1-1 ~ C1-4	4

For capturing the complexity and heterogeneity of coal sediment, an extra-fine geological model with 125 plies (also named as ply-based model) was built. The model size is 2,824,173 cells (119 × 99 × 257) in total. The cells are 100 m in width and length. Considering the total 58 m thickness for 125 coal plies, the average coal thickness is 0.46 m which is stratigraphic.

Due to the lateral discontinuous and relatively thin coal seams, vertical wells are optimal for development. For estimating the production performance of existing wells and find opportunity for infill wells, this extra-fine geo-model was built. The dynamic model was built with gas content, permeability, Langmuir volume, and Langmuir pressure from the correlations of actual measured data, and other parameters, such as relative permeability, porosity, sorption time and compressibility, from basin-wide analogue, rules-of-thumb or educated guesses. To reduce the number of active cell counts for minimizing the simulation runtime, some cells were deactivated, including Kogan coal measure (no perforation), inter-burden and over-burden.

Through adjusting reservoir parameters, satisfactory matching results were achieved for both gas and water production on field level, as described by green line in Fig. 1. However, a runtime of 43.52 h was needed and unacceptable for the following

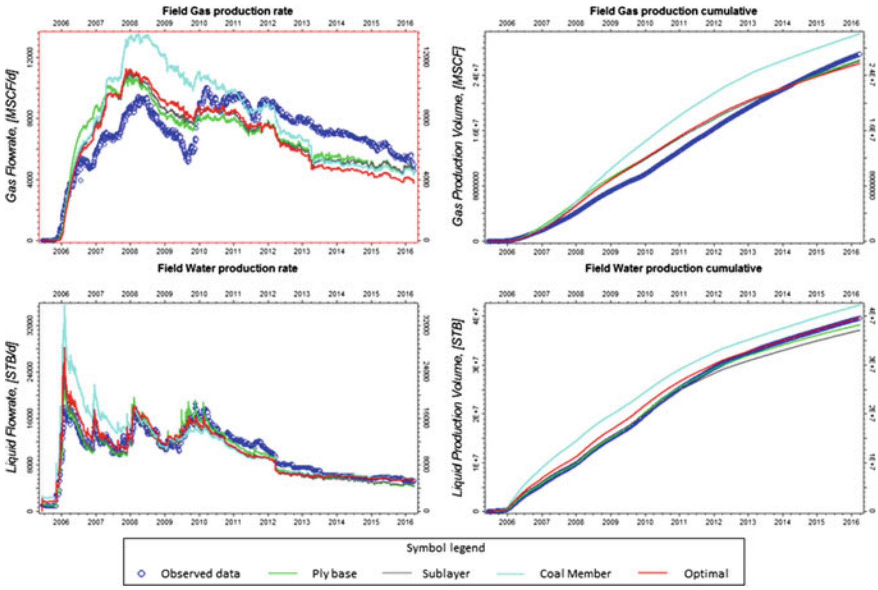

Fig. 1. Comparison of observed production and simulated production on ply, sublayer, coal-member levels and optimal model

individual well history matching work. In this case, the upscaling was necessary to reduce simulation time.

3 Determination of Permeability Upscaling Technique

In this paper, single-phase upscaling approach was adopted. In other words, relative permeability of the fine model was used directly in the simulation of coarse model. Five reservoir parameters (i.e. gas content, gas saturation, net-to-gross (NTG), porosity and permeability) were upscaled. The former four parameters are scalar quantity, so volume-weighted arithmetic averaging technique was recommended by most researchers [9, 10]. Permeability is a vector quantity, and more argues exist about the best upscaling technique. Therefore, seven upscaling techniques in Petrel™ were investigated, and the detailed items were listed in Table 2.

We only focus on vertical up-gridding in this paper and keep the areal cells same as in fine geo-model. Ply-based model was up-gridded to both sublayer and coal-member levels, and the corresponding simulation results were indicated by grey line and deep-sky-blue line, respectively (Fig. 1). During this process, flow-based harmonic averaging technique was used for permeability upscaling. It was found that the sublayer-based model has closer match results compared with that of ply-based model and the runtime is also reasonable (6.4 h). Hence, it was selected as the basis for the following permeability upscaling technique testing. Seven coarse models were created and four parameters were defined to analyse the simulation results: simulation runtime ratio,

Table 2. Detailed information of seven permeability upscaling techniques and corresponding simulation results

Sampling method	Averaging method	Runtime ratio (%)	Cum gas error (%)	Cum water error (%)	Average production error (%)
Flow-based	Harmonic average (HA)	14.71	−0.57	−2.91	1.74
	Finite difference (FD)	15.26	−0.57	−2.91	1.74
Directional average	Arithmetic-harmonic (AH)	15.09	−1.03	−3.22	2.12
	Harmonic-arithmetic (HA)	15.73	−1.03	−3.22	2.12
	Cardwell-Parsons (CP)	15.64	−1.03	−3.22	2.12
Volume weighted	Arithmetic (A)	16.23	−0.54	−2.95	1.75
	Harmonic (H)	15.90	−0.56	−3.00	1.78

cumulative gas error, cumulative water error and average production error. Runtime ratio means the ratio of simulation runtime of coarse model and fine model. Cumulative gas and water errors were calculated by using Eq. (1).

$$\text{error} = \frac{X_{\text{c}} - X_{\text{f}}}{X_{\text{f}}} \quad (1)$$

where X_{c} is cumulative gas or water production of coarse model, MSCF or STB; X_{f} is cumulative gas or water production of fine model, MSCF or STB.

By calculating the absolute value of cumulative gas and water errors and then averaging them, the average production error was attained.

As shown in Table 2 and Fig. 2, by contrast to directional averaging technique, flow-based and volume-weighted averaging techniques have less average production errors. Flow-based harmonic averaging technique has the least runtime ratio and average production error among seven upscaling techniques. So, it was selected for the following up-gridding work.

4 Procedure of Up-Gridding

Up-gridding was usually proceeded by iterating layers one by one [4], which needs more layer-grouping trials, and hence more computational time. In this paper, a new approach considering deposition cycles was proposed. In other words, up-gridding was conducted from coal-member level to sublayer level and finally to ply level.

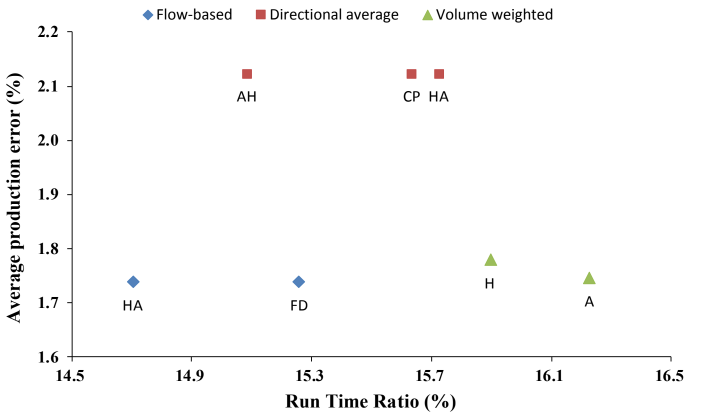

Fig. 2. Simulation results of different permeability upscaling techniques

4.1 Up-Gridding on Coal-Member Level

The sublayer-based model has a reasonable runtime and close matching results compared with that of ply-based model. Therefore, it was set as the basis for the following up-gridding work. The aim of up-gridding on coal-member level is to fast determine the layers with strong heterogeneity.

Five coal members (i.e. Macalister, Wambo, Argyle, Upper Taroom and Condamine) were investigated excepting Kogan for no perforation. Though up-gridding workflow was described in Fig. 3, an example of Macalister coal member was used to explain it in detail.

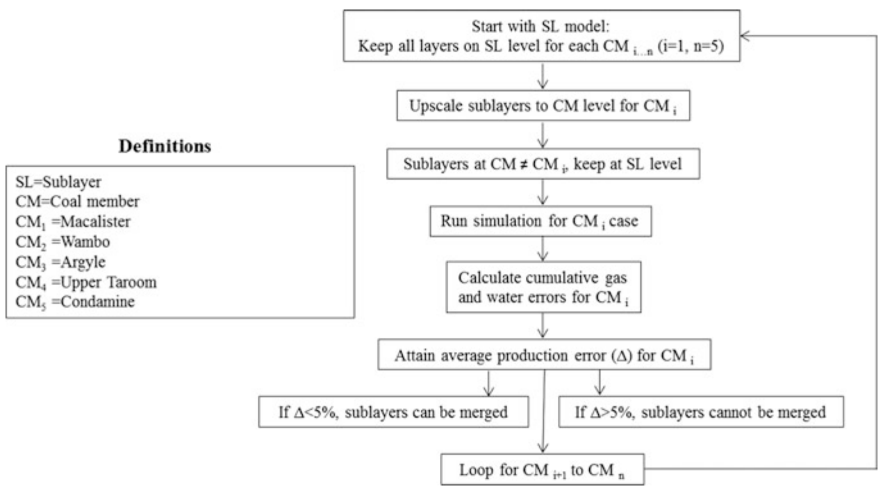

Fig. 3. Up-gridding workflow on coal-member level

(1) Upscale all three sublayers (M3, M2 and M1) to coal-member level, and keep the sublayers in other coal members unchanged.
(2) Upscale properties and then create a simulation case.
(3) Calculate cumulative gas and water errors.
(4) Attain the average production error (Δ).
(5) Judge whether all these three sublayers can be merged together by comparing Δ with the threshold value of 5%.
(6) Repeat this procedure for the other four coal members.

Five simulation runs were performed and the results are summarized in Table 3. It indicated that if all the sublayers in any of the four coal measures (i.e. Macalister, Wambo, Argyle and Condamine) were merged together, the simulated cumulative gas and water production of the coarse model are both lower than that of ply-based model, and the average production error are all less than 4%. But different phenomena were observed when merging all sublayers in Upper Taroom coal measure, and the simulated cumulative gas and water production of the coarse model are both higher compared with the corresponding values of ply-based model. The average production error is 5.02%, which is higher than the tolerance of engineering errors (5%), indicating that a major heterogeneity in fine model was homogenized. Therefore, the four sublayers in Upper Taroom coal measure (UT1, UT2, UT3 and UT4) cannot be merged.

Table 3. Comparisons of different up-gridding results on coal-member level

	Active cell	Active cell ratio (%)	Runtime ratio (%)	Cum gas error (%)	Cum water error (%)	Average production error (%)
Fine model	839,294					
Case 1	175,805	20.95	13.76	−1.79	−2.25	2.02
Case 2	164,351	19.58	12.39	−3.20	−0.05	1.63
Case 3	164,332	19.58	15.85	−4.42	−0.31	2.06
Case 4	164,332	19.58	11.72	7.59	2.46	5.02
Case 5	175,321	20.89	13.81	−5.38	−2.07	3.72

4.2 Up-Gridding on Sublayer Level

Since the four sublayers in Upper Taroom coal measure cannot be merged together, several simulation cases were created to test whether the sublayer can be merged with adjacent sublayers individually, and the workflow was described in Fig. 4.

Keeping all layers in Upper Taroom coal measure on sublayer level and others on coal-member level, a new simulation case (UT_o) was created and the cumulative production error (Δ) was calculated. This case was set as the basis for the following up-gridding work on sublayer level. Further merging UT1 and UT2 to create a simulation

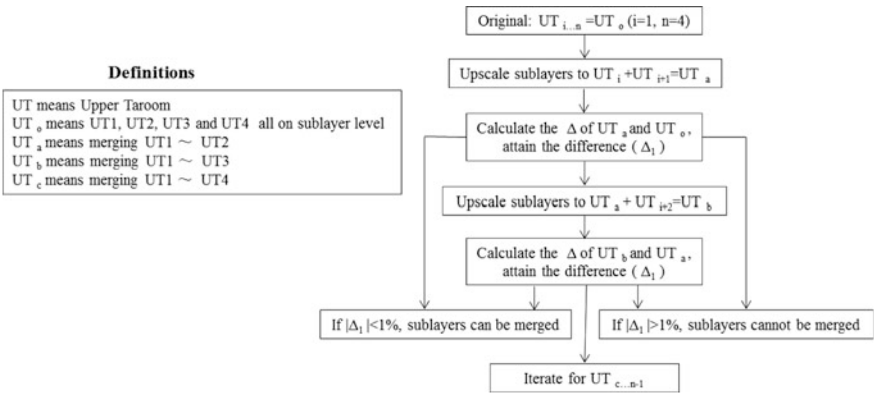

Fig. 4. Up-gridding workflow on sublayer level

case (UT_a), the Δ value of UT_a was calculated, and then the Δ values' difference of UT_a and UT_o (named as Δ_1) was attained. A judgment was conducted based on the comparison of the absolute value of Δ_1 and threshold value of 1% to identify whether these two sublayers can be merged. If Δ_1 is less than 1%, UT1 and UT2 can be merged. Otherwise, these two sublayers cannot be merged. Then, UT3 was merged with UT1 + UT2 to create a new simulation case (UT_b), and same method was used to identify if these three sublayers could be merged together. The final step was to test whether UT4 can be merged with UT1 + UT2 + UT3.

Four simulation cases were run and the results indicated that UT1 and UT2 can be merged together but UT3 and UT4 should be kept individually according to the judgment criterion discussed above. The detailed information was listed in Table 4.

Table 4. Comparisons of different up-gridding results on sublayer level

	Active cell	Active cell ratio (%)	Runtime ratio (%)	Cum gas error (%)	Cum water error (%)	Average production error (%)	Difference of two cases (%)
Fine model	839,294						
UT_o	87,912	10.47	1.03	−2.14	4.34	3.24	
UT_a	76,923	9.17	1.01	−1.64	4.92	3.28	0.04
UT_b	65,934	7.86	0.55	2.06	7.25	4.65	1.37
UT_c	54,945	6.55	0.41	14.42	10.67	12.54	7.89

4.3 Up-Gridding on Ply Level

Since UT3 and UT4 cannot be merged with each other and with the other two sublayers in Upper Taroom coal measure, further trials were done to identify if the ply in the same sublayer can be merged with adjacent plies.

Keeping layers in UT3 and UT4 on ply level, UT1 and UT2 merged together, others on coal-member level, a new simulation case ($UT34_o$) was created. The up-gridding work on ply level was conducted following the workflow in Fig. 5. The layer-grouping sequence for the 12 plies was from shallower to deeper (i.e. from UT4-1 to UT3-6). This workflow was same as that described in Fig. 4, excepting for two differences: 1) adopting 0.1% as an identifying criteria of merging adjacent layers. 2) honouring depositional cycle constraint of sublayer during up-gridding process. After running five cases (from $UT34_a$ to $UT34_e$) to test the plies in UT4, the sixth simulation case ($UT34_f$) was created by further merging UT3-1 and UT3-2 on the base that all piles in UT4 were merged together, rather than merging the total seven plies from UT4-1 to UT3-1. Hence, ten trials were conducted.

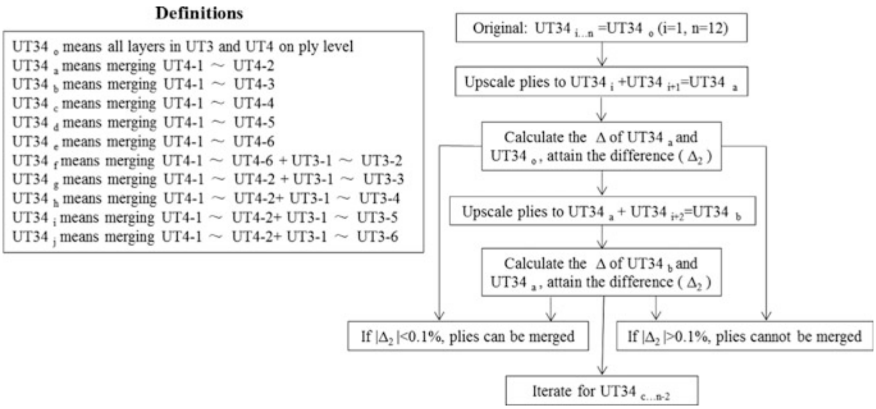

Fig. 5. Up-gridding workflow on ply level

The simulation results were described in Table 5. Based on the identifying criterion of merging adjacent plies, it revealed that UT4-1, UT4-2, UT4-3, UT4-4 can be merged together, UT4-5, UT4-6, UT3-1, UT3-3, UT3-3, UT3-4 should be kept individually, and UT3-5 and UT3-6 can be merged.

5 Results and Discussion

The final layer-grouping scheme was that layers in Kogan, Macalister, Wambo, Argyle and Condamine were on coal-member level, and layers in Upper Taroom were optimized into nine zones, as described in Table 6. A new dynamic model was built based on this scheme (named as the optimal model), and the simulation results showed that the active cell count was reduced by 85.28%, runtime was reduced by 98.78%, cumulative gas and water errors were −1.98 and 3.90%, respectively, by contrast to the ply-based model.

When putting the simulation results of the optimal model, sublayer level model and coal-member level model together, it was found that coal-member level model has the

Table 5. Comparisons of ten up-gridding cases' results on ply level

	Active cell	Active cell ratio (%)	Runtime ratio (%)	Cum gas error (%)	Cum water error (%)	Average production error (%)	Difference of two cases (%)
Fine model	839,294						
$UT34_o$	150,499	17.93	1.72	−2.94	3.09	3.01	
$UT34_a$	141,378	16.84	1.52	−2.75	3.27	3.01	0.00
$UT34_b$	132,227	15.75	1.40	−2.29	3.56	2.92	−0.08
$UT34_c$	122,677	14.62	1.19	−2.10	3.85	2.97	0.05
$UT34_d$	114,042	13.59	1.10	−1.30	4.03	2.66	−0.31
$UT34_e$	105,844	12.61	1.03	−1.68	4.34	3.01	0.35
$UT34_f$	80,601	9.60	0.78	−4.77	2.90	3.84	0.83
$UT34_g$	79,899	9.52	0.78	−1.56	4.97	3.27	−0.57
$UT34_h$	77,224	9.20	0.78	−0.88	6.07	3.47	0.21
$UT34_i$	76,927	9.17	1.22	0.08	6.62	3.35	−0.12
$UT34_j$	76,923	9.17	1.01	−1.64	4.92	3.28	−0.07

Table 6. Comparison of layer-grouping schemes

Original zone division	Final zone division
Kogan	Kogan
Macalister	Macalister
Wambo	Wambo
Argyle	Argyle
Upper Taroom	UT4-1 ~ UT4-4
	UT4-5
	UT4-6
	UT3-1
	UT3-2
	UT3-3
	UT3-4
	UT3-5 ~ UT3-6
	UT1 + UT2
Condamine	Condamine

biggest average production error, indicating significant loss of heterogeneity and flow characteristics of fine model. Compared with the sublayer level model, the optimal model reduced the simulation runtime ratio by more than a factor of 10 from 14.71 to 1.22%, and introduced no more than 2% error in average cumulative production (Fig. 1 and Table 7). This is a very good result which provides us with the foundation required for the following individual well history matching work.

Table 7. Comparisons of different up-gridding results on ply, sublayer, coal-member levels and optimal model

	Active cell	Active cell ratio (%)	Runtime ratio (%)	Cum gas error (%)	Cum water error (%)	Average production error (%)
Fine model	839,294					
Sublayer	197,296	23.51	14.71	−0.57	−2.93	1.75
Coal member	54,945	6.55	0.41	14.42	10.67	12.54
Optimal	123,535	14.72	1.22	−1.98	3.90	2.94

After putting all the up-gridding simulation results together, it was found that as active cell ratio decreased, runtime ratio deceased and the trend can be described by an exponent formula (Fig. 6). With decreasing active cell ratio, cumulative water error increased linearly, and most error values are positive. There is no obvious relationship between cumulative gas error and active cell ratio, and most error values are negative. In other words, layers up-gridding tended to overestimate water production and underestimate gas production for CBM reservoir (Figs. 7 and 8).

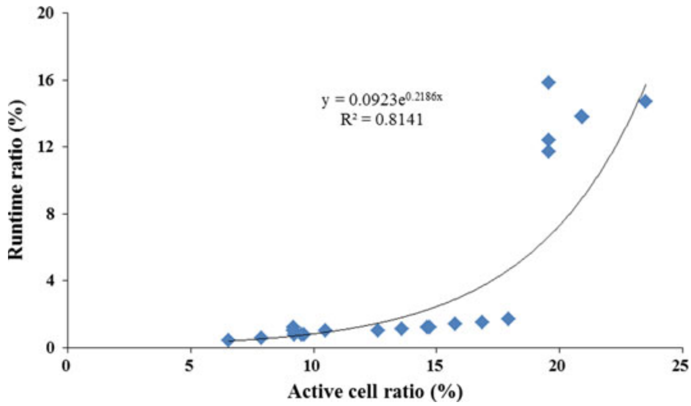

Fig. 6. Plot of runtime ratio versus active cell ratio

Layer up-gridding inevitably combines coal and non-coal, which overestimate the lateral continuity of coal. An example from six coal plies of UT4 sublayer can be used to illustrate this issue. As indicated in Fig. 9, the coal was only distributed in part of study area with thickness varying from 0 to 3.03 m. And the average thickness is 0.6 m. After combining these six plies together, the distribution of coal covers all the study area with the thickness varying from 0 to 8.48 m, as shown in Fig. 10. And the average thickness is 2.8 m. The comparison of cell thickness distribution in fine and

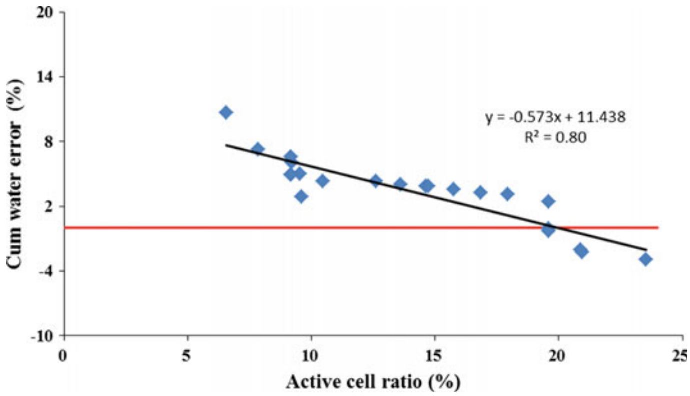

Fig. 7. Plot of cumulative water errors versus active cell ratio

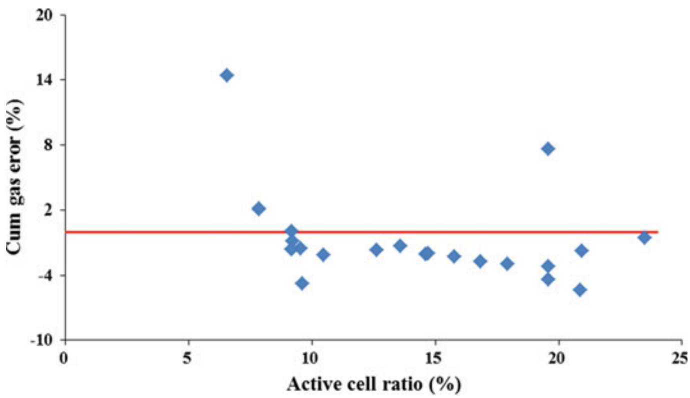

Fig. 8. Plot of cumulative water errors versus active cell ratio

coarse models was displayed by a histogram as shown in Fig. 11, and an obvious difference can be observed. In other words, the loss of heterogeneity in fine model is significant.

During layer upscaling process, the loss of reservoir heterogeneity is inevitable. Three threshold values of 5, 1 and 0.1% were adopted, respectively, at each coarsening step on coal member, sublayer and ply levels to preserve critical level of heterogeneity. Total upscaling errors are caused by homogenization and discretization, and the impact of these two factors is opposed. The dynamic response of coarse model is a complex function of reservoir and simulation parameters [10]. By contrast to conventional reservoir, most gases are adsorbed in coal reservoir, which is controlled by pressure and saturation. That is to say, CBM reservoir is more complex than conventional reservoir. So, a multi-parameter criterion in this paper was used to analyse upscaling results, enabling the final layer-grouping scheme is optimal.

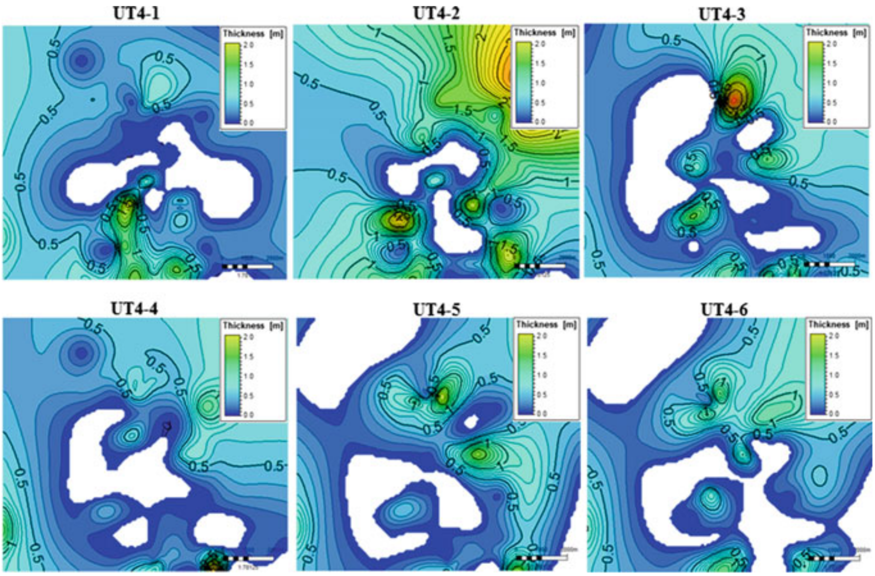

Fig. 9. Thickness maps of six coal plies in UT4

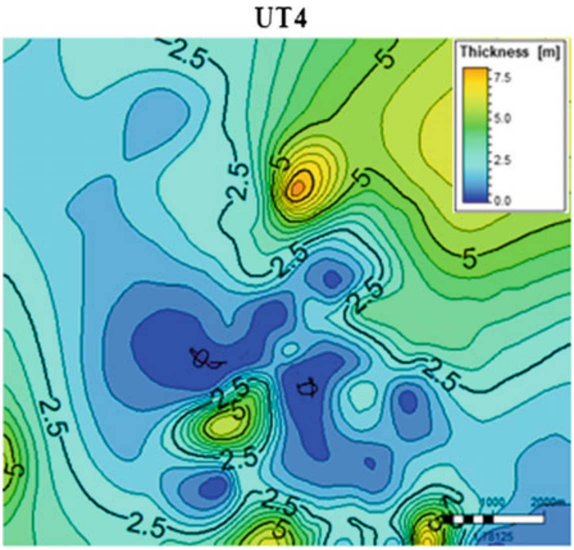

Fig. 10. Thickness map of UT4

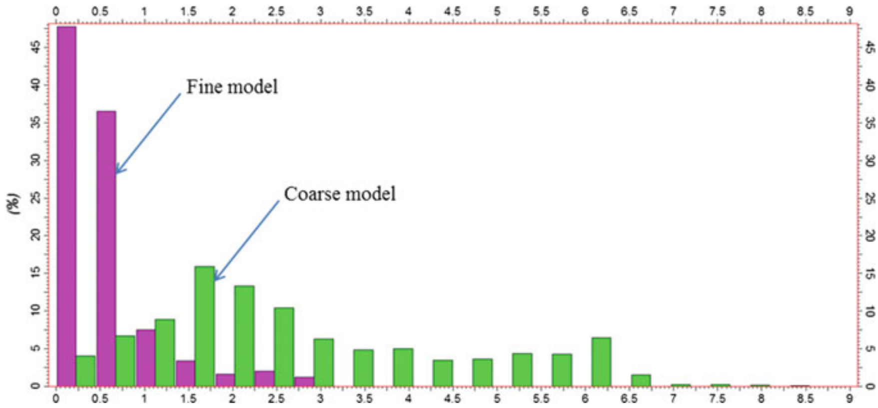

Fig. 11. Thickness histogram comparison of layers in UT4

6 Conclusions

An extra-fine CBM geological model with 125 plies was upscaled by conducting only 20 plus layer-grouping trials. Compared with fine model, the active cell count was reduced by 85.28%, runtime was reduced by 98.78%, cumulative gas and water errors were −1.98% and 3.90%, respectively. The key point of this successful work lies in that important strategies were adopted in property upscaling and up-gridding processes. Seven permeability upscaling techniques were investigated, and the flow-based harmonic averaging method was deemed as the best due to its shortest simulation runtime and least average production error. The up-gridding work was conducted in three levels (i.e. from coal-member level to sublayer level to ply level), and different layer-grouping workflows were used. Three layer-merging thresholds of 5, 1 and 0.1% were used in these three stages. Multiple measures were taken to estimate upscaling results, such as active cell ratio, cumulative gas and water errors, simulation runtime ratio, areal map and histogram, to ensure the final layer-grouping scheme is optimal.

References

1. Stern D, Dawson AG. A technique for generating reservoir simulation grids to preserve geologic heterogeneity. In: SPE 51942, presented at reservoir simulation symposium, 14–17 Feb 1999.
2. King MJ, Burn KS, Wang P, et al. Optimal coarsening of 3D reservoir models for flow simulation [A]. In: SPE 95759, presented at the annual technical conference and exhibition, 9–12 Oct 2005.
3. Hosseini SA, Kelkar M. Analytical up-gridding method to preserve dynamic flow behaviour [A]. In: SPE 116113, presented at the annual technical conference and exhibition, 21–24 Sept 2008.
4. Kelkar M, Atiq M. Up-gridding method for tight gas reservoir [A]. In: SPE 133301, presented at the annual technical conference and exhibition, 19–22 Sept 2010.

5. Suzuki K, Asada K, Yoshida K, et al. Accelerated history matching through process independent scale-up techniques in a giant carbonate reservoir [A]. In: SPE 87012, presented at the Asia Pacific conference on integrated modeling for asset management, 29–30 Mar 2004.
6. Allam FA, EI-Banbi AH, Bustami SS, et al. History match tuning through different upscaling algorithms [A]. SPE 90292, presented at the annual technical conference and exhibition, 26–29 Sept 2004.
7. Ma E, Ryzhov S, Wang Y, et al. Answering the challenge of up-scaling at 900 million-cells static model to a dynamic model—greater Burgan field, Kuwait [A]. In: SPE 164187, presented at the middle east oil and gas show and conference, 10–13 Mar 2013.
8. Zhou Y, King MJ. Improved upscaling for flow simulation of tight gas reservoir models [A]. In: SPE 147355, presented at the annual technical conference and exhibition, 30 Oct–2 Nov 2011.
9. Shehata AM, EI-Banbi AH, Sayyouh MH. Proper selection of upscaling techniques for different production processes [A]. In: SPE 150863, presented at the North Africa technical conference and exhibition, 20–22 Feb 2012.
10. Sablok R, Aziz K. Upscaling and discretization errors in reservoir simulation [A]. In: SPE 93372, presented at the reservoir simulation symposium, 31 Jan–2 Feb 2005.