The Study and Application of the Connectivity of the Carbonate Reservoirs in Tarim Basin*

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Introduction

The fracture-cavity carbonate reservoir with heterogenic oil deposit in the reservoir space (Zhou, 2000; Jin, 2005; and Zhang, 2001), mainly large-cave secondary dissolution pores, featured with multiple existence of fracture-cave systems, pressure systems and seepage elements (Zhang, 2000), is acknowledged for the high success rate drilling operations on it, and also plagued by the low yield of high-efficient well and the complicated of oil/gas production. The high-efficient exploration of the fracture-cavity reservoir relies on the identification of the reservoir's connectivity.

Although production dynamic data such as tracer detection or stratum pressure transient analyses or interference well testing analyses have been well adopted to analyze the inter-well communication by Chinese researchers on the Tahe Oilfield and Lunnan Oilfield (Hu and Yang, 2005; Yi et al., 2011; Deng et al., 2003; Yang, 2004; Zhang et al., 2006; Yan et al., 2008; Zhang, 2006; and Wang et al., 2010), the application of such methods are still confined to intensively explored regions with abundant drilling data, for their performance is unsatisfying in carbonate reservoirs by early and middle stages of exploration.

By introducing in the case of the Tabei YM2 area, this paper presents a series of methods and techniques of reservoir connectivity analysis with static description, dynamic verification and iterative adjustment, combining the disciplines of geology, geophysical prospecting and oil reservoir. By such techniques, researchers are able to analyze the geophysical response characters of the fracture-cavity carbonate reservoir, among which they may designate seismic the cavity and fracture blocks, and then they may conduct grid computing on different seismic bodies, and figure out the connectivity between different seismic bodies by examining the contacts between lattices after gridding. Afterwards they may introduce in the production dynamic characters to perform iterative adjustment on the thresholds of seismic attributes, in order to determine the connectivity border of the reservoir, and to make predictions on the connectivity of the whole fracture-cavity reservoir.

Characters of Reservoirs in the YM2 Region

The YM2 Region is situated in the South Yingmaili Low Uplift of the Tabei Uplift in the Tarim Basin, an inherited structure created by repeated Hercynian and Indosinian foldings, which appears as a large domelike anticline on the Ordovician limestone roof.

The oil reservoirs in this region are typical fracture-cavity ones, existing in the form of fractures-pores and fractures-caves, mainly developing in the upper parts of the Yijianfang Formation and Yingshan Formation of the Ordovician stratum, on which 60% of drilled wells have suffered blow-out and fluid loss while drilling. The formation and development of the reservoirs are mainly subject to discordant karstification, tectonization, and sedimentation, among which sedimentation established the basis of the reservoir with the vital assistance of karstification. Tectonization is crucial to the later-stage transformation of the reservoir, especially the hydrothermal karstification along the later-stage fault-fractures that is the key to the formation of the favorable reservoirs.

As shown in Figure 1, the high-steep tension strike slip faults were developed in the early-Hercynian and late-Indosinian strata under the effect of regional tectonic behavior. Products of later-stage hydrothermal behavior like siliceous lumps and diabase blocks are founded in the multiple coring wells, which show the evidence of corrosion as the result of late-stage hydrothermal fluid moving along the early-stage faults and fractures, where the reservoirs in the form of fracture-pores and fracture-caves were created by corrosion of different scales, which provided favorable spaces for oil and gas concentration.

According to the researches of Researcher Xia Riyuan (Riyuan, 2006) and other scholars, a single fracture-cavity is formed by the main cave section, the corroded inter-cave crush belt, the corroded crush belt on the collapsed roof, the effected roof crush belt, the corroded sidewall crush belt, the corroded bottom crush belt, and two or more of such fracture-cavities may join into a larger reservoir by communications between fractures, as shown in Figure 2. Current explorations on drilled wells in the research area have shown high production of wells on large reservoirs with well-communicated fractures and cavities, which epitomized the importance of reservoir communication analysis.

Techniques, Methods, and Applications of Reservoir Connectivity Analysis

A series of techniques and methods of reservoir connectivity analysis on the above mentioned highly-heterogenic fracture-cavity carbonate reservoir with static description, dynamic verification, and iterative adjustment, combining the disciplines of geology, geophysical prospecting, and oil reservoir is shown in Figure 3.

In order to select sensitive attributes and effective methods for reservoir categorization and prediction, static description is carried out firstly according to the geological model of the reservoir, as well as seismic response analysis and forward modeling, and static division of the reservoir is also completed by multiple-attribute integration and connectivity analysis. Then the thresholds of seismic attributes and parameters are further adjusted by verification against dynamic production data on basis of static carving, and repeatedly iterated to determine the boundary of the reservoir. Such boundary may be introduced in quantitative carving of the volume of the fracture-cavity reservoir, which lays the basis for reservoir evaluation.

Static Seismic Description of Reservoir

Seismic response analysis on feature points in the research area has shown the existence of beads-shaped strong reflections, flake-shaped strong reflections, and irregular seismic reflections in its karst reservoirs. The scale, structure and position of the reservoir are the key factors of its seismic response. Current researches suggest that the beads-shaped reflection is corresponding to high-efficiency fracture-cavity reservoirs with large caves and fractures, where blow-out and drilling-fluid loss may be incurred in drilling courses, but the production performance is always satisfying. While the weak irregular reflections and flake-shaped reflections with great amplitude always indicate the existence of small-scale fracture-hole reservoirs, where blow-out and the loss of drilling fluid are scarce in the course of drilling.

Each seismic response corresponds to a particular reservoir, thus the category of the reservoir can be predicted by forward modeling and sensitive-attribute designation, as shown in Figure 4.

When different seismic attributes are designated to corresponding reservoir categories, the seismic scale of the reservoir is established by attributing the interpretations of well-logging results to corresponding seismic attributes, in order to determine the thresholds of such attributes.

By adopting the connectivity analyzing techniques (which is based on the analysis of inter-lattice contracts in the fusion grid), the static connectivity of the fracture-cavity reservoir is determined, and the boundary of different reservoirs are also clearly shown in 3-D, as presented in Figure 5.

Determine Reservoir Boundary by Dynamic Verification and Iterative Adjustment

There are disconformities between static reservoir connectivity and the dynamic production data due to the rough initial threshold of seismic attributes limited by the seismic resolution and interpretation accuracy of well logging, which has been demonstrated by numerous drillings. Thus such thresholds shall be adjusted by dynamic data iteration.

Among various dynamic production data, the well-testing data (from parse well testing, non-shut-in well testing and numerical well testing, etc.) is mostly used for dynamic production (Wu et al., 2006; Xiao et al., 2012a; Xiao et al., 2012b).

Case Application

The case of well region YG2 in the YM2 area is cited to illustrate the way to figure out the connectivity of the reservoir by integrated analysis of the dynamic and static data, in order to determine the boundary of the reservoir.

There are three wells in well region YG2, i.e. YG-2, YG2-1C, and YG2-2, among which YG2 is 930 m from YG2-2, and 1010 m from YG2-

1C, as shown in Figure 6. The analysis of the production characters, especially the changes of pressure, suggests that there is no interference among these wells. Their corresponding reservoirs are not interconnected, while the reservoir boundary of well YG2 should be further confirmed through other ways.

The seismic prediction of the reservoir reflects the combination of the Well YG2's reservoir's fractures and cavities, as shown in the plane and section view of the Figure 7, of two large cavities connected by fractures coming through.

The interpreting model of variable wellbore storage + radial compound reservoir + circular boundary was selected on basis of the oil reservoir geologic model of Well YG2 to interpret the well testing result of Well YG2, as shown in Table 1.

Calculations have shown the distance of the inner zone of the reservoir as 474 m, and that of the outer zone as 1080 m, among which the former is very close to the maximum boundary distance of the reservoir, according to the well testing theory. Such calculations are introduced in to confine the thresholds of seismic attributes, and by such confinement the thresholds are adjusted, with the result shown in Figure 8. After iterative adjustment, the interpreted result of well logging matched very well with the reservoir prediction and fracture-cavity carving, which further confirmed the connectivity and boundary of the reservoir.

By such methods the boundary of the reservoir in the YM2 area was divided and advanced evaluation of the reservoir was also made that provided crucial elements for oil reserve evaluation and high-efficiency deployment of wells.

Conclusions

1. Seismic response analysis under the guidance of reservoir geologic model is the basis of reservoir prediction. The selection of sensitive attributes and methods is the key to the static description of the reservoir.

2. Well testing is the major data of dynamic production description, the model of which should be jointly evaluated with the seismic prediction model of the reservoir.

3. Reservoir connectivity analysis by the technical combination of static description, dynamic verification, and iterative adjustment is highly applicable for the detailed description of the carbonate reservoir.

4. Meanwhile, as the key and long-term subject of carbonate reservoir research, reservoir connectivity analysis is calling for the constant technological improvement of seismic data gathering, processing, reservoir prediction, fracture identification and dynamic data readout to keep closer to the fact.

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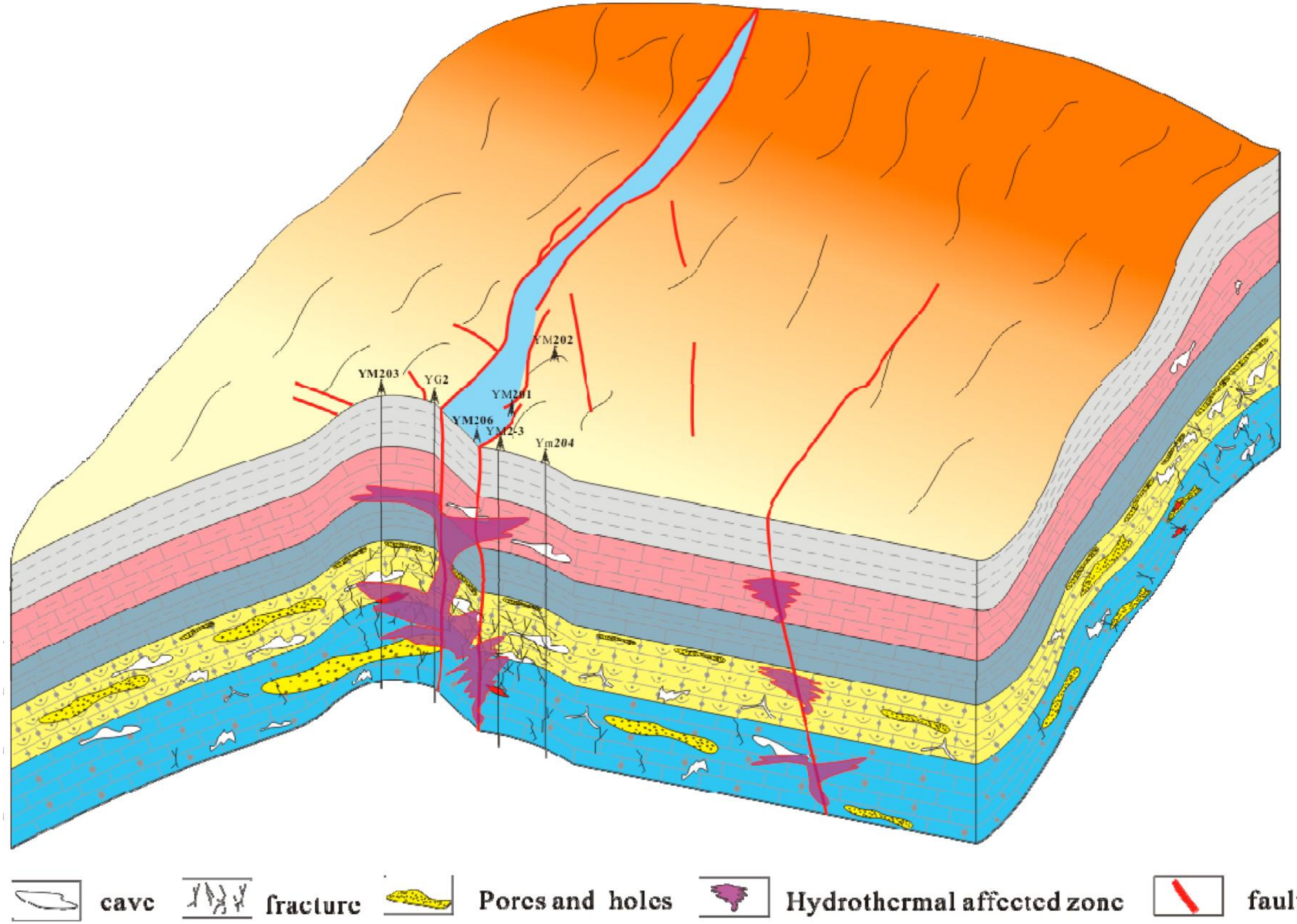


Figure 1. 3-D Geologic Map of Ordovician Reservoirs in YM2 Well Block.

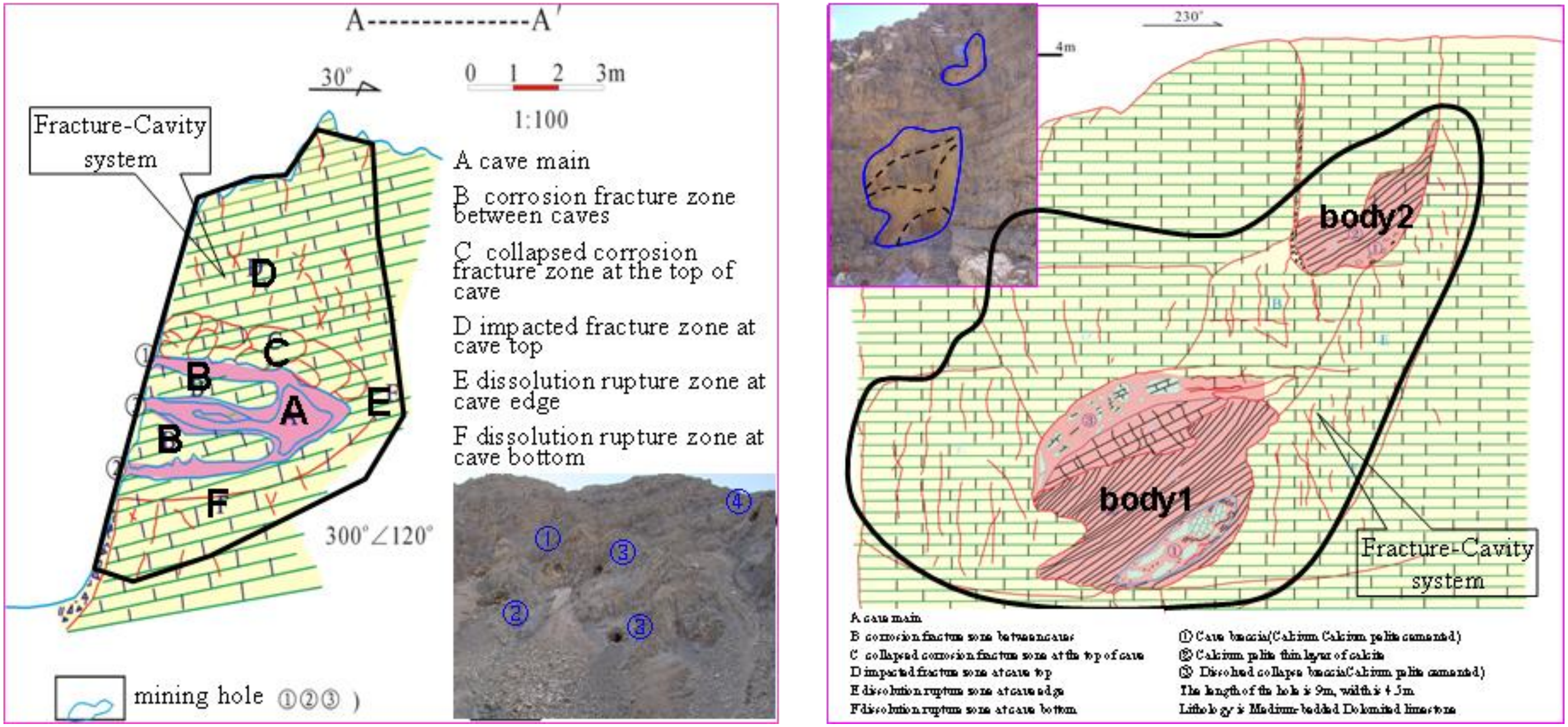


Figure 2. Fracture-Cavity Pattern (Xia Riyuan, 2006).

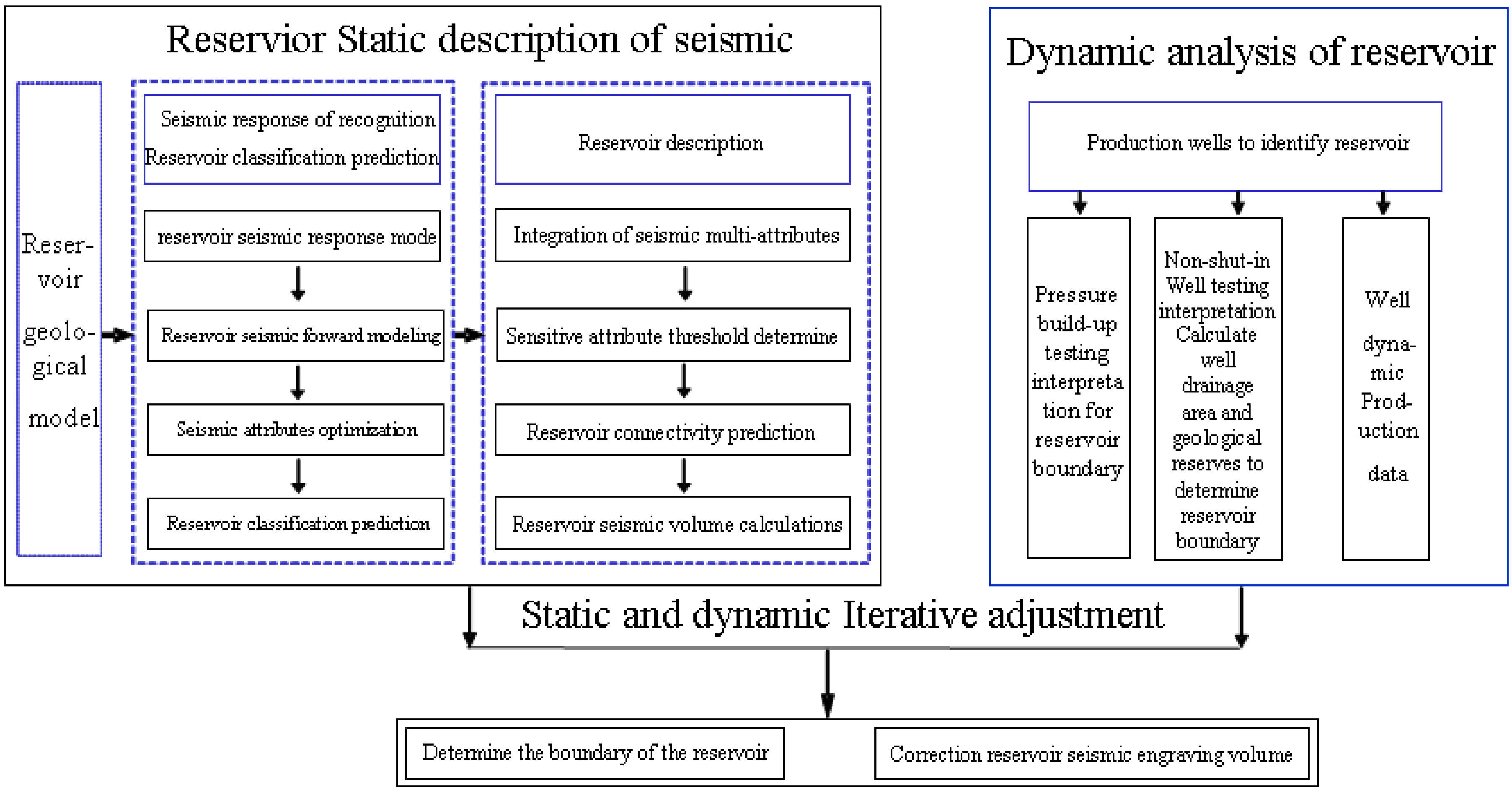


Figure 3. Technical Processes of Reservoir Connectivity Analysis.

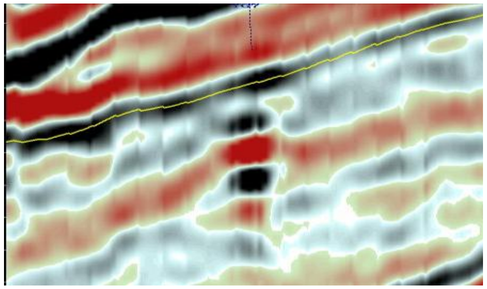
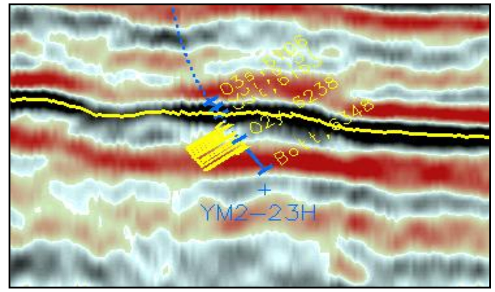
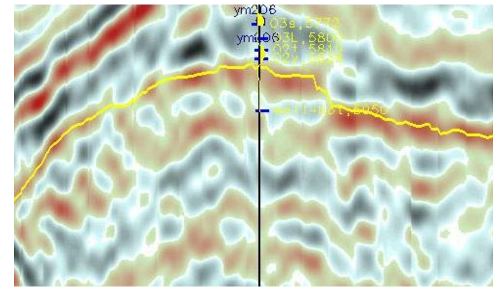
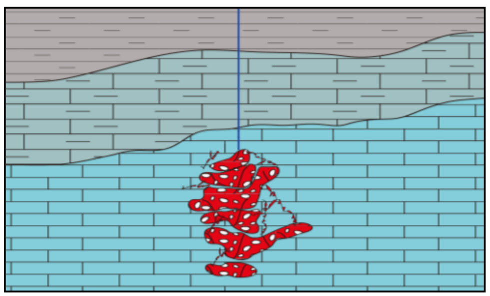
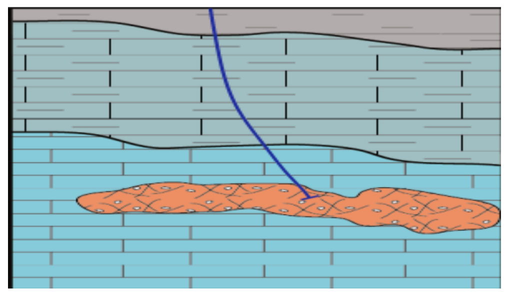
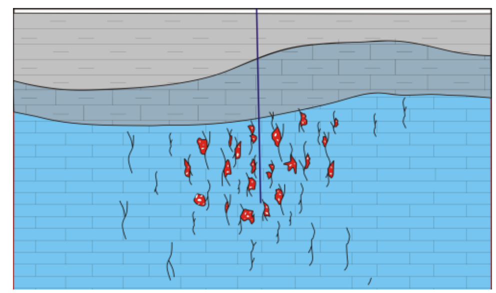
	Seismic reflection characteristics		
	bead-shaped reflection	flake-shaped reflection	weak irregular reflection
Seismic profile characteristics			
	Pen-like	flake-shaped	weak irregular
Reflection structure	two peaks one trough，Multiple peaks multiple troughs	trough amplitude is strong and continuous	weak irregular
Planar features	Punctate	flake-shaped	flake-shaped、weak irregular
Reservoir geological model			
Reservoir types	Cave、large-scale fracture-holes	Small-scale fracture-holes	fractures、Small-scale fracture-holes
Reservoir master features	fracture zone、Burial hydrothermal karst	(Quasi-) syngenetic karst、fracture	fracuture、Burial hydrothermal karst
Reservoir prediction method	RMS	Max trough amplitude	"Ant track" fracture prediction technology or AFE、local amplitude anomaly analysis techniques

Figure 4. Geologic-Seismic Model and Predicting Methods of Carbonate Reservoirs in YM2 Region.

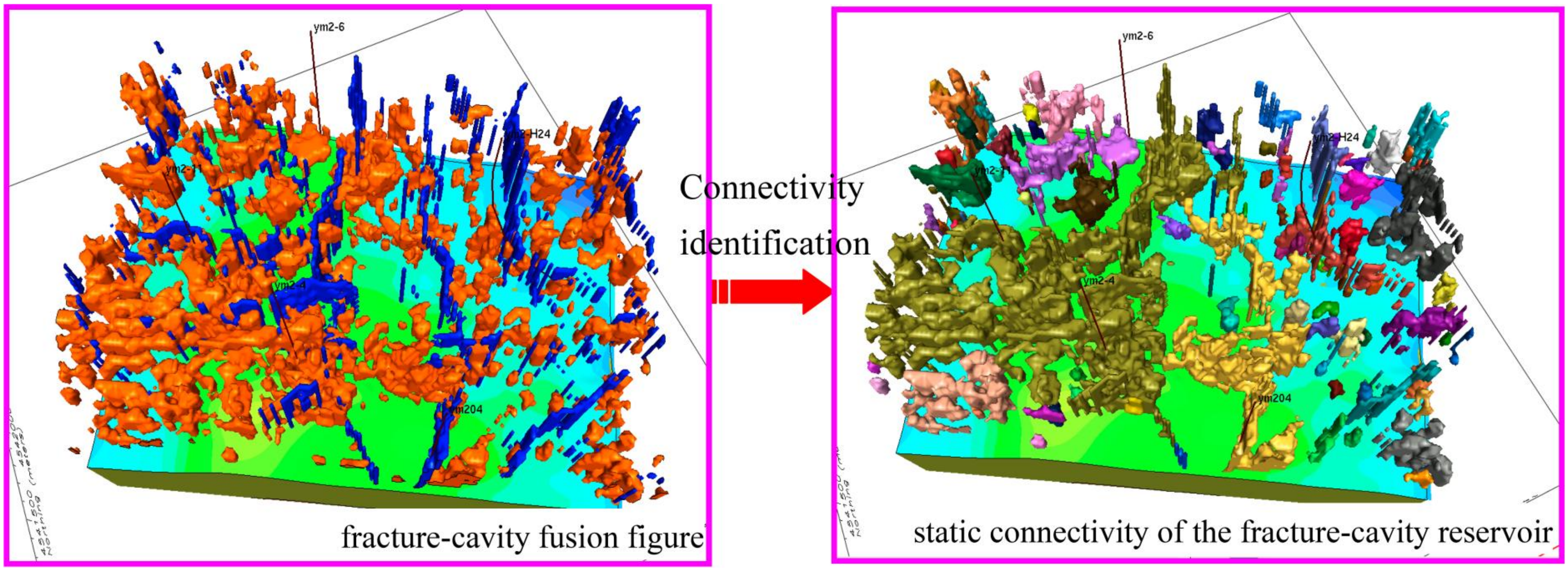


Figure 5. Principle of Seismic Static Connectivity Analysis.

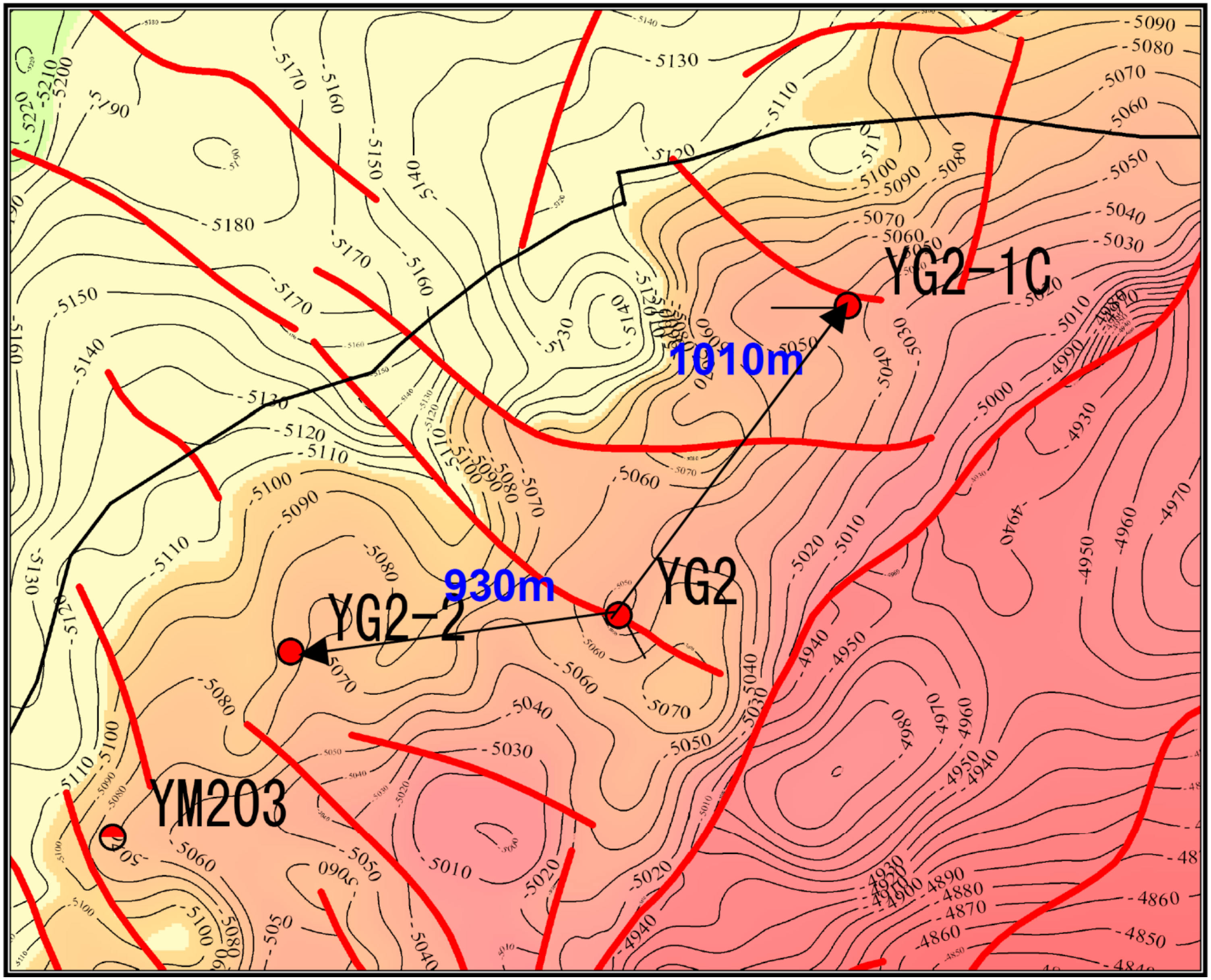


Figure 6. Regional Structure Map of Well Region YG2.

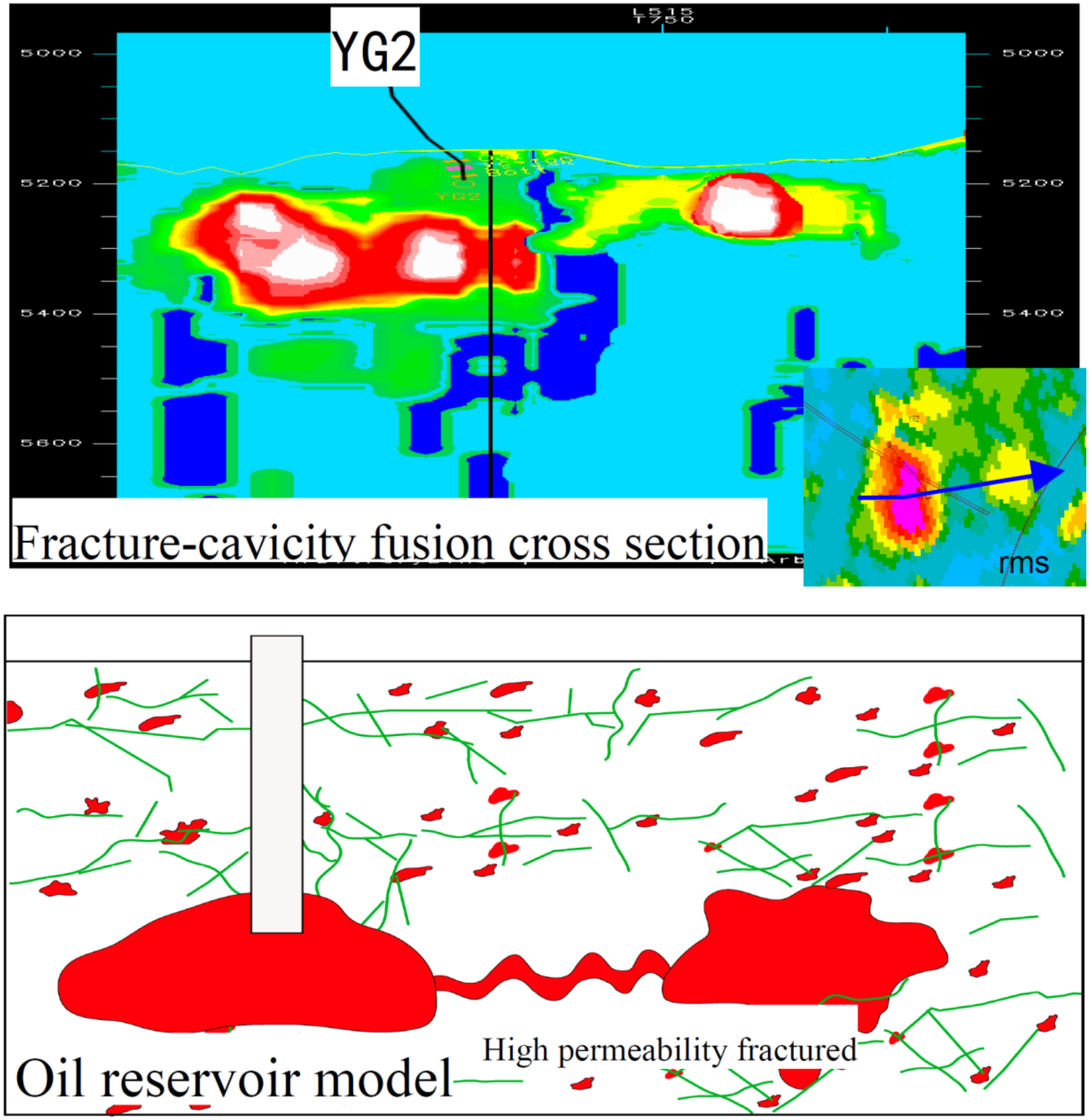


Figure 7. Reservoir Prediction Section and Oil Reservoir Model Section in Well YG2.

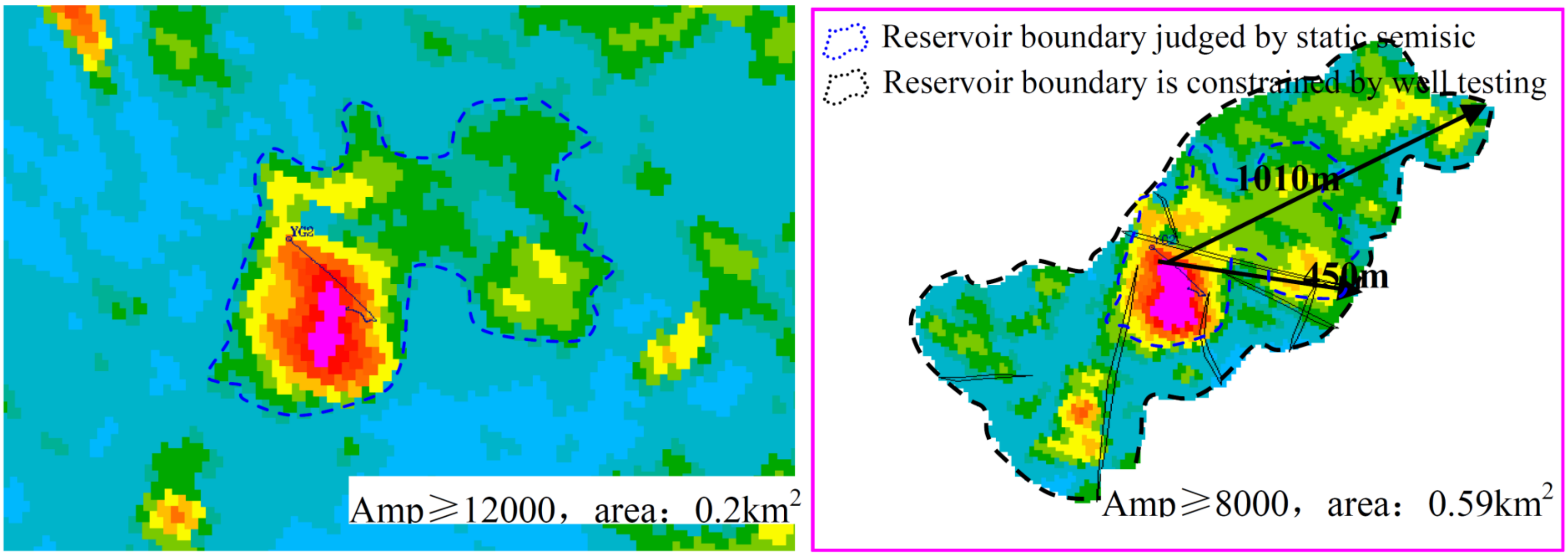


Figure 8. Comparison of Reservoir Boundaries of Well YG2 before and after Threshold Confinement.

interpreting model	wellbore storage + radial compound reservoir + circular boundary	
Parameters	Unit	numerical value
formation coefficient of the inner zone (Kh1)	10^{-3}μm2.m	88400
Effective permeability of the inner zone (K1)	10^{-3}μm2	4420
formation coefficient of the outer zone(Kh2)	10^{-3}μm2.m	875
Effective permeability of the outer zone (K2)	10^{-3}μm2	44
Mobility ratio(Kh/μ) 1/2	Dimensionless	101
Distance of inner zone	m	474
Distance of outer zone	m	1080
Mechanical skin factor(S_W)	Dimensionless	-5.08
Wellbore storage coefficient(C)	m^3/MPa	8.98
Fitting formation pressure(P_i)	MPa	62.50

Table 1. Interpretation of Well Testing Result of Well YG2.