The Steam Chamber Study of Thermal Recovery Heavy Oil Reservoir Based on Temperature Monitoring Data, Time-Lapse Seismic and Reservoir Simulation Result*

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Abstract

As the viscosity of heavy oil is very sensitive to temperature, thermal recovery technology is still widely used as an effective method in the world until now. The temperature and pressure and their distribution are significant symbols to judge whether the thermal recovery is successful. As an important dynamic monitoring method, wellbore temperature observation system provides long-term, accurate temperature monitoring data. The measurement objects of temperature observation wells are geothermal gradient and local temperature anomaly. When a well is producing or injecting, the original temperature field will be changed, then the temperature curves can accurately reflect these changes. Time-lapse seismic data use the difference between monitor survey and baseline survey to characterize reservoir changes. Reservoir numerical simulation can depict the distribution and variation of reservoir fluid. Based on the temperature monitoring data from distributed fiber sensors, time-lapse seismic data, and reservoir numerical simulation result, this paper uses a heavy oil reservoir in China as example to discuss the following issues: analyze the reason of the temperature difference between inside and outside tube for different production phase and present the proposal for how to use the temperature data reasonably; use the characteristics of the saturated-steam and the shape of temperature curve to determine the building-time of the steam chamber; analyze steam chamber fronts in lateral and the changing process of steam chamber; calculate the speed of steam chamber overlapping; and comprehensively use all of these to differentiate the physical interlayers from reservoir, predict the distribution of remaining oil, and guide the field operation.

Introduction

Thermal recovery technology, also called reducing oil viscosity production technology (including steam stimulation, steam flooding and SAGD drilling, etc.) is the most basic recovery method for heavy oil. It is important to determine spatial distribution of reservoir properties (including reservoir rock and fluid, and their changes vs. time). The success of a thermal recovery project depends on whether real-time reservoir performance information can be obtained. There is no a kind of economical and accurate method to do this, but the purpose can be achieved or partly achieved through the integrated analysis and use of these methods.

Currently, temperature monitoring, reservoir numerical simulation and seismic monitoring are three main methods used to study reservoir performance. Fiber optic has been widely used for many purposes in the oil and gas industry since 1970 (Luigi Saputelli et al., 1999). There are many examples for fiber optic temperate sensing in the oil industry (Tor K. Kragas et al., 2002). Permanent borehole temperature distribution profile is obtained from fiber optic cable. A laser bean is sent through the fiber cable with distributed temperature profile information. The time-lapse data is critical for predicting fluids front moment. During production, changes in reservoir's fluid saturation, pressure, and temperature result in changes in density and seismic velocity (D.H. Johnston, 2000). It is observed in the lab that a large velocity change can occur in oil-bearing reservoir if the oil is replaced by steam (Nur et al., 1984). For this reason, time-lapse seismic is used as monitoring tool widely. Accurate steam chamber configuration can be obtained from high-precision 3D seismic data. However, with only seismic data, it is difficult to differentiate the influence of geological sedimentation or small-size fracture from the steam injection (Yun Ling et al., 2010). At the end of 1996, the application of numerical simulation for thermal heavy oil recovery operations using steam assisted gravity drainage (SAGD) was investigated. Both the "spreading steam chamber" and the "rising steam chamber" were simulated (Chow et al., 1996). With the development of reservoir numerical model for thermal recovery, reservoir simulation has been employed widely in the study of reservoir fluid behavior and the interpretation of the laboratory results (Egermann et al., 2001). It should be pointed out that the results of numerical simulation are well point matching, so the spatial distribution and changes of reservoir fluid are still the forecast results. More accurate distribution of reservoir fluids can be obtained by integrated study of temperature monitoring data from distributed fiber sensors, time-lapse seismic data, and reservoir numerical simulation result.

Background

The oil-bearing area of the SAGD pilot project is 0.15 km^2, the geological reserves are 249×10^4t, with top, edge and bottom water and buried at a depth between 530-640m. The oil-bearing thickness of the reservoir is 120-150m, and the barrier inside the reservoir is pure mudstone. There are only physical interlays in the reservoir, and the thickness is 0.2-2m. Physical interlays have certain inhibition effects on oil and gas migration, but have no shelter effect. Average porosity is 36.3% and average permeability is 5.54μm^2. At 50 °C, the viscosity of gas-free crude oil is 232,000 mPa.S, the crude oil belongs to super heavy oil. There are five well groups in the pilot area; they produced by the combination of vertical and horizontal wells, with vertical wells injecting and horizontal wells producing (Figure 1). The vertical and horizontal wells in the pilot were placed into production from 2000 to 2003 using cycle steam stimulation (CSS) to extract heavy oil. The total amount of injection gas is 41.06×10^4t, cumulative oil production is 31.21×10^4t, cumulative water production is 38.89×10^4t, cumulative oil/gas ratio is 0.76, cumulative water recovery ratio is 95%, the ratio of cumulative injected gas with cumulative oil is 1.71, and the recovery percent of reserve is 12.53% in CSS period. In February 2005, the production was transferred into a SAGD pilot test. The average period of CSS is 7.6 cycles for vertical wells, and two cycles for horizontal wells (Figure 1d). Based on the analysis of monitoring data and the producing characteristic, it is sure that from March 2006 until the present is the formation and development stage of the steam chamber.

After the production was transferred from CSS to SAGD pilot stage, improved monitoring systems were established for the reservoir, and six temperature observation wells were deployed. The temperature monitoring system use the well distributed optical fiber. Six temperature observation wells began to monitor well temperature continuously on March 2006. In February 2009 and February 2011, two high-density 3D seismic surveys were acquired respectively in the pilot area (Figure 1c). In addition, thermal numerical simulation was employed for the reservoir in the pilot area by CMG.

Steam Chamber Study

Analysis of the monitoring thermal data

Six temperature observation wells were deployed in the SAGD pilot area. The completion for the observation wells were accomplished by using annular tube with outside diameter 139.7mm banding with the hollow sucker rod, which outside diameter is 40mm. After completion, the fiber was placed into the inner bore of the hollow sucker rod. The advantage of the well distributed optical fiber technology include: (1) long-term temperature monitoring of the down hole at high pressure and high temperature condition; (2) No thermal hysteresis effect, no cable stretch, no instrument movement, and no depth discrepancy of conventional logging; (3) the fiber need not to move back-and-forth in the detection area, have no effect on the state of thermal equilibrium in the well. The six temperature observation wells began monitoring well temperature continuously in March 2006. On March 2, 2007, December 18, 2007, May 21, 2008, and August 15, 2008, simultaneous temperature measurement on the six temperature observation wells were performed inside and outside the annular tube (Figure 2). In the formation stage of the steam chamber, the temperature between the oil-bearing region being heated and the upper part of oil-bearing layers is significantly different. The heat conduction coefficient of the annular tube and the medium inside the tube is also significantly different. The annular tube conduct heat energy along longitudinal direction, it causes the difference of the thermometric data inside and outside the tube. The max difference of the data inside and outside the tube is 15 °C. With the increase of steam injection, the anomaly of the reservoir temperature decreased, and the thermometric data inside and outside the tube tends to coincide. On the heat-connection stage, steam flooding stage and steam chamber formation stage, the thermometric data outside the tube is much more reliable. On the extending stage of the steam chamber, the two thermometric data could both reflect the variation of the reservoir temperature.

The formation of steam chamber and its extension direction

Temperature observation well can provide accurate, real-time steam chamber information of well point. The main purpose of the observation well system is to monitor the changes of reservoir temperature and pressure, and thus judge the development status of steam chamber. When the temperature curve is like finger, clock or funnel, the steam chamber has not formed. The increase of temperature is mainly caused by heat conduction. When the temperature curve is like box, the steam chamber has formed already. According to the nature of the saturated steam, the pressure inside the steam chamber is equal. Therefore, the temperature of saturated steam is equal in different height inside steam chamber. According to the analysis of production characteristics and monitoring data, it makes up for the underground deficit and steam flooding between May 2005 and March 2006.The injection steam during this period was to make up for the underground deficit caused by the steam stimulation. The oil production of horizontal well mainly came from steam flooding process. Figure 3a is the temperature curve from outside tube of well gg5. The well gg5 is between the steam injector 56-158 and horizontal oil producer GP12 (Figure 3b). Comparing the temperature curve of February and May in 2006, its basic shape changes from finger to box. The temperature and the height of corresponding maximum temperature both increased. This means the steam injected by 56-158 well expands to the direction of well gg5. The steam chamber had not formed before February 2006, and the temperature rise is mainly caused by heat conduction. The temperature curve is similar and both box like in May and June in 2006 and this means the steam chamber had formed in this period and expanded in horizontal and vertical direction. The temperature in different height inside the box has little difference, and the main reason for this is that the reservoir near well gg5 develops physical intercalations. The well gg4 is between steam injector 56-158 and horizontal oil producer GP12 (Figure 3b). Comparing temperature curve of the well gg4 and well gg5 in the same period, we find that the curve of well gg4 is already box type. The maximum temperature raises little but the height increased greatly. In each observation time, the measured temperature and the height of well gg4 are both greater than those of well gg5. This means the steam injected by 56-158 well expands more in the well gg4 direction than in the well gg5 direction. The steam chamber extends homogeneously near the gg4 well.

Numerical simulation is the main technology for the quantitative study of reservoir fluid dynamic. Solve the mathematic model describing the reservoir seepage problems, which is composed of different equations including Darcy's Law equation, material balance equation, the equation of state, energy conservation equation, the corresponding boundary conditions and initial conditions. The real-time spatial distribution of reservoir fluid is obtained after matching the simulation results with the actual production performance repeatedly. However, the accuracy of this method depends on the accuracy of static reservoir description and the input parameters such as the density of fluid and the compressibility of Rock. Even so, we simulate the SAGD production performance by STARS software of CMG. The simulation area is 370m×600m, including five horizontal wells and 40 vertical wells with the spacing 70m. Geological models apply logging interpretation data, which is eight points per meter for all vertical wells and implements macro constraints with the seismic. Based on the full application of various lab experiments and monitoring data, the geological model and production parameters are adjusted properly through history matching. Then the reasonable simulation results are obtained. Figure 4a shows the temperature distribution of top Ng reservoir in the pilot area through the simulation computation, Figure 4b is the temperature profile along with well gg4 and well gg5. The temperature distribution results obtained through numerical simulation also indicate, both in profiles and maps, the temperature near the well gg5 is lower than that near well gg5 , and high temperature distribution is continuous.

The height of the steam chamber and the steam overlapping speed

Test area is a top water reservoir, monitoring the height of the steam chamber can prevent the top water from invading the reservoir. The temperature curves from October 10, 2006 to July 13, 2008 have obvious box characteristic, and the height of the box is increasing. These mean the steam chamber continuously expands vertically because of the steam overlapping. The maximum location in temperature curves indicates the height of steam chamber. By comparing the changes of maximum temperature in different time, the steam overlapping speed can be calculated. Through calculating the changes of maximum temperature from June 2006 to February 2007 of well gg6, the steam overlapping speed is 0.39 meters per month in the steam chamber forming stage. The velocity increases to 12.5 meters per month after the chamber formed from May 2008 to January 2009. Then, the speed decreases to 0.13 meters per month (Figure 5).

Seismic technology uses the geophysical differences of underground reservoir or the differences of geological research goal to study the target characteristics through seismic imaging the target body. In addition to using the 3D seismic data to study the static reservoir structure and sedimentary characteristics, it also can make use of the difference of seismic data in different periods to dynamically study the variation of reservoir fluid, temperature and pressure. This project applies the 4D seismic method to study the changes of reservoir development characteristics, the two stages seismic acquired between two years' intervals, respectively in February 2009 and February 2011.On the basis of strict consistent acquisition and consistent 4D seismic processing, the relatively high quality time-lapse seismic data is obtained.

Figure 6 is 3D seismic difference figure between two stages, Figure 6a is a profile and slice display, Figure 6b is a 3D color filtered display. From the figure, the horizontal wells in different part of the reservoir have different steam chamber changes during two seismic surveys. The chamber has a quick development in area near the horizontal well on the left of the map. The chamber development also has big difference in other parts. Combining the temperature monitoring data with seismic results, we can know steam chamber is contiguous in the central area where four temperature testing wells is. The lateral variation of chamber is not large, but the vertical change is bigger. The SAGD process enter stable growth phase of steam chamber.

Interlayer Research

The interlayer is an important factor controlling the continental reservoir heterogeneity. That Interlayer within thick pay has a packer and blocking effect on the distribution of the fluid, therefore, has a significant impact on the reservoir production. In SAGD development process, short horizontal interlayers make a small impact on SAGD development process, but long horizontal ones will reduce production. Ng reservoir in pilot area develops thick massive gravel rock mass, and has no pure mudstone interlayer, but only physical interlayer. The thin interlayers have no obvious features on electrical logging, hard to recognize. Thick interlayers perform low resistivity, low interval transit time. Generally, resistivity is less than 20 Ω•m and transit time is less than 350μs/m (Figure 7). Such physical interlayer has inhibition on hydrocarbon migration, but has no sheltering effect.

The development mechanism of super heavy oil reservoir is that heat flow enters the reservoir to form a number of displacing mechanism, such as the reduction of viscosity, distillation, soluble content extraction, the expansion of thermal oil, hot water flooding, the reduction of residual oil saturation. These mechanisms depend on the physical properties of the rock and fluid, and their variation versus temperature and pressure.

Thermal conductivity, specific heat and thermal expansion can be used to characterize thermophysical characteristics of rocks. Thermal conductivity is a parameter characterizing the capacity of heat transmission. Specific heat means the absorbed or released caloricity when the temperature of one-gram rock increases or decreases 1°C. Thermal expansion is the result of changes in shape and volume of rock due to temperature change. The experimental results of core show that thermal conductivity, specific heat and thermal expansion parameters have obvious differences between interlayers with different lithology. Generally, mudstone interlayer has the highest specific heat, the greatest expansion coefficient, medium thermal conductivity. While the interlayer of muddy sand (gravel) rock has poor thermal conductivity, low heat absorption capacity and heat expansion capacity. In the same time, calcic or marlaceous sandstone interlayer has the fastest thermal conductivity and the lowest heat absorption.

Based on thermal property difference of different lithological interlayers, due to poor thermal conductivity, the location of physical interlayers will develop a certain block on the steam overlapping, it then affects the steam overlapping, which would appear on the well temperature-monitoring curve, then form bimodal-like structure (Figure 8). Figure 8 depicts well logging, well temperature monitoring curve and core photographs of the well temperature observation wells gg6. The logging data has low resistivity from depth 610m to 642m; meanwhile, the temperature curve corresponds to the maximum height and the return of the temperature at the same position. Clear dark gray lithological interlayer appears at this depth on the coring photos.

Conclusions

Temperature data has the advantages of long-term, real-time and stability, but it is the well point monitoring information. Time-lapse seismic data has the advantage of wide lateral distribution. The spatial variation of reservoir can be explained through two different time seismic characterizations, but unable to obtain real-time monitoring information; although numerical simulation can obtain both space and real-time information of the spatial distribution of reservoir fluid, numerical simulation can only get calculated results but not the actual observation results. Its accuracy is affected by multiple factors. In this paper, we study the shape of the steam chamber in the pilot area through the integrated use of these methods. Because various methods compensate each other, the accuracy of the steam chamber will be higher. In addition, the pilot test well group monitoring data analysis showed that the temperature curve outside the tube could reflect the temperature formation more accurately than that inside the tube at the forming phase of the steam chamber. While at the steam chamber expansion phase, with the reduction of differences between high temperature area and low temperature zone of upper reservoir, temperature difference between inside and outside of tube become little. At this time, tube temperature can be used to analysis the developmental situation and developmental speed of steam chamber. Combined with different thermal characteristics of the reservoir rock, temperature-monitoring curve can be used to analyze the position of the interlayer.

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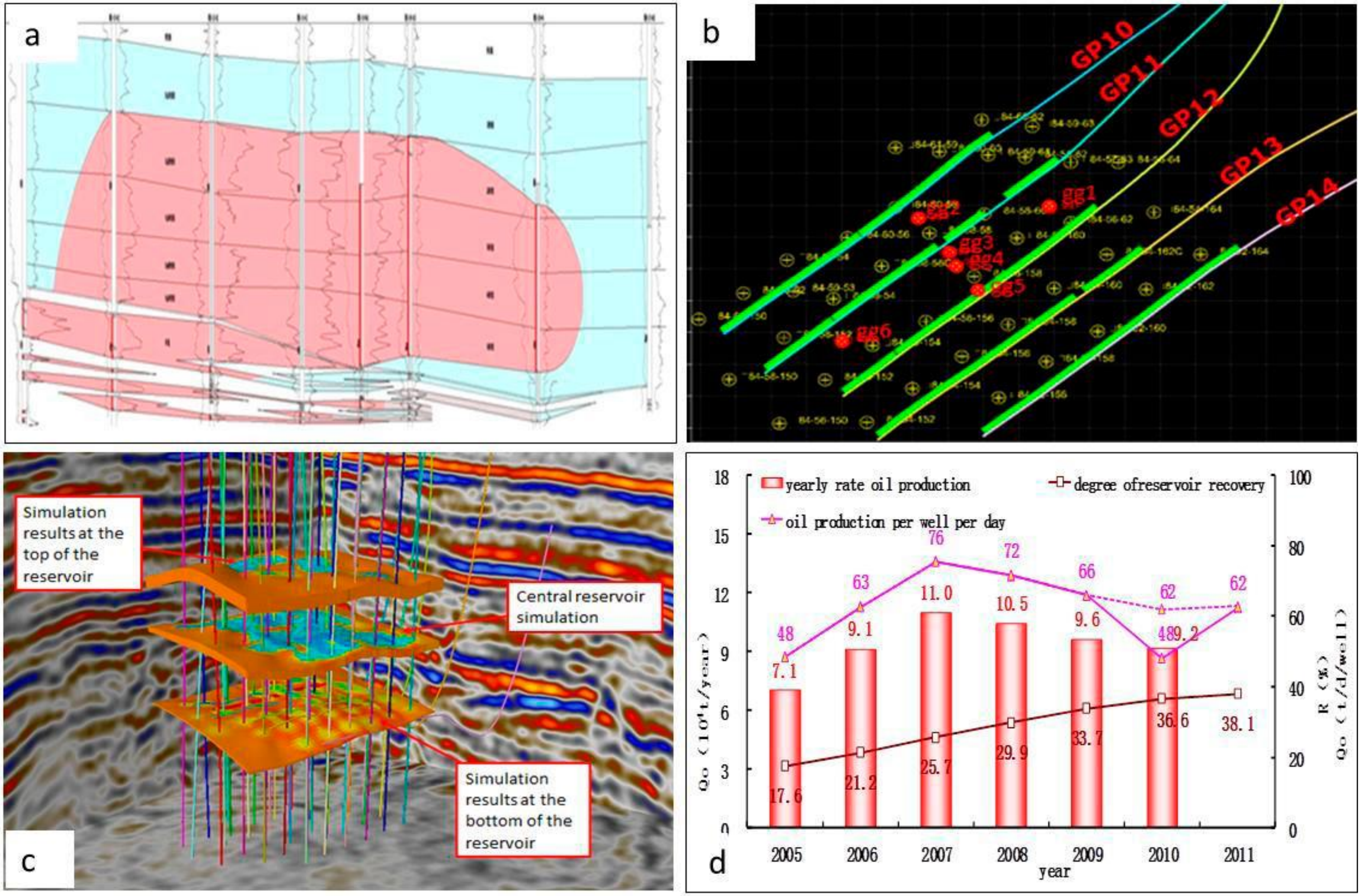

Figure 1. a) Ng profile of the reservoir; b) well location map of the SAGD pilot area; c) diagram of seismic and reservoir numerical simulation; d) synthesis mining curve of the SAGD pilot area.

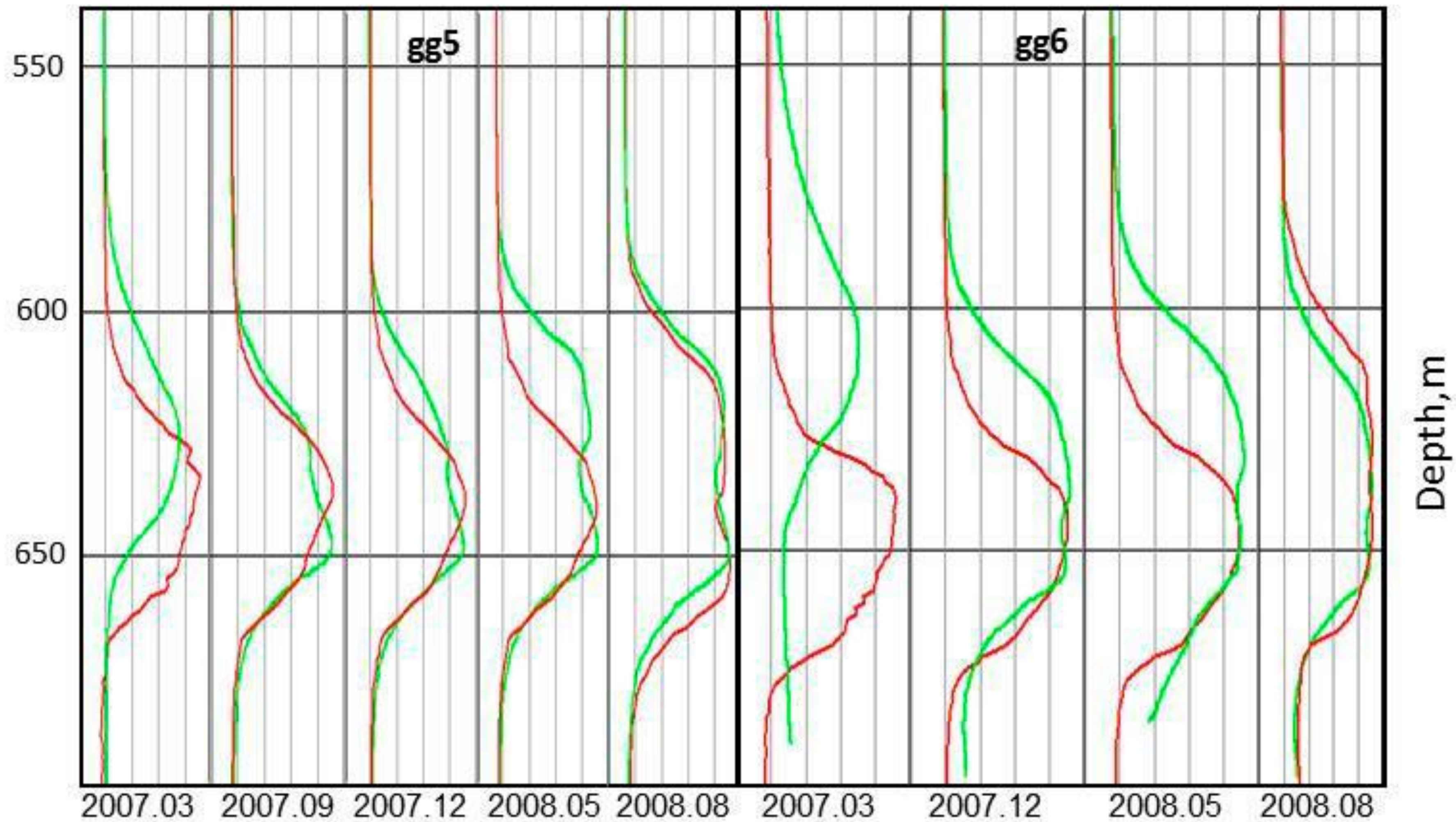

Figure 2. Contrast diagram of temperature curve inside (green) and outside (red) the tube.

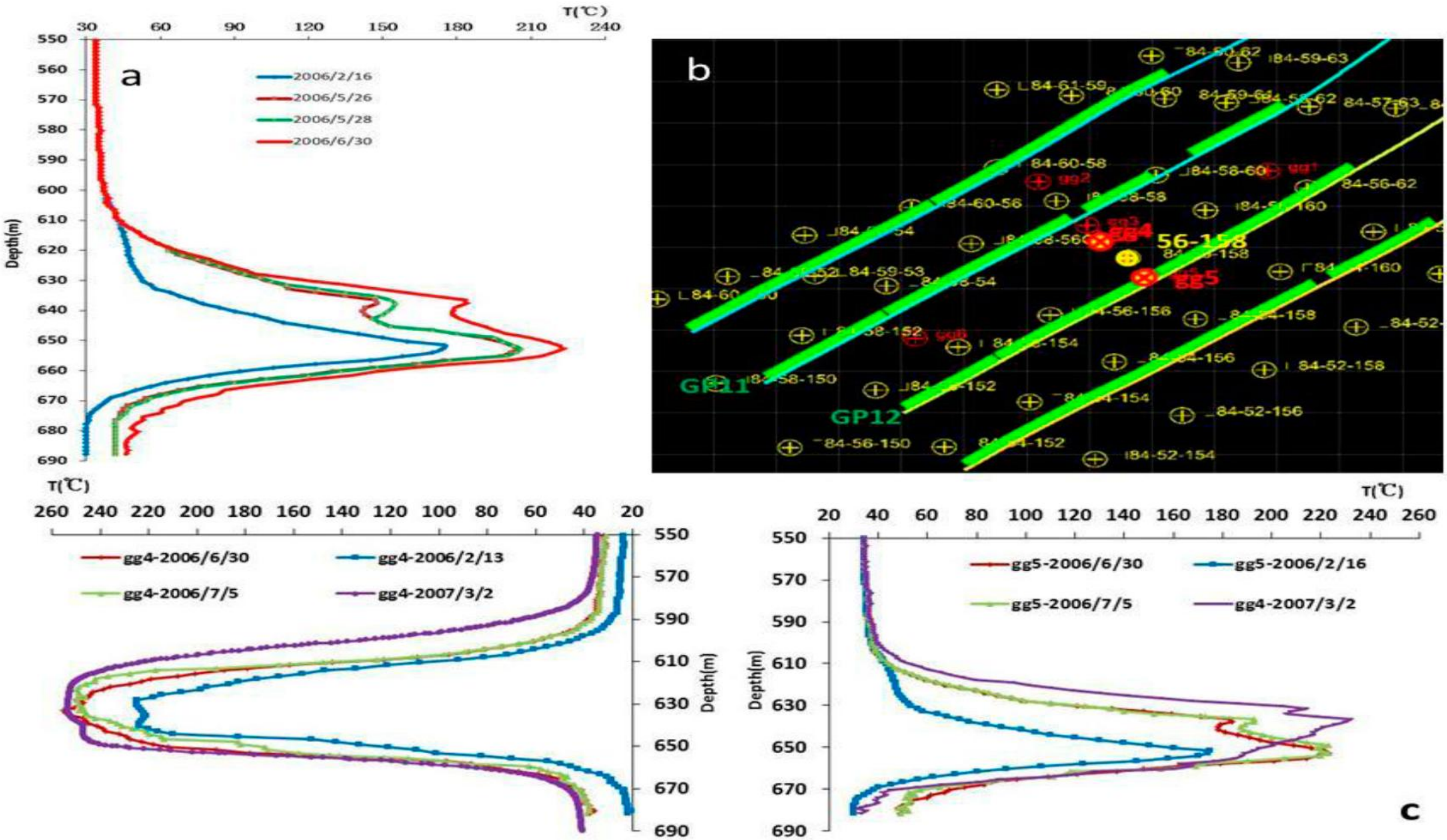

Figure 3. Temperature monitoring curve of gg4 and gg5.

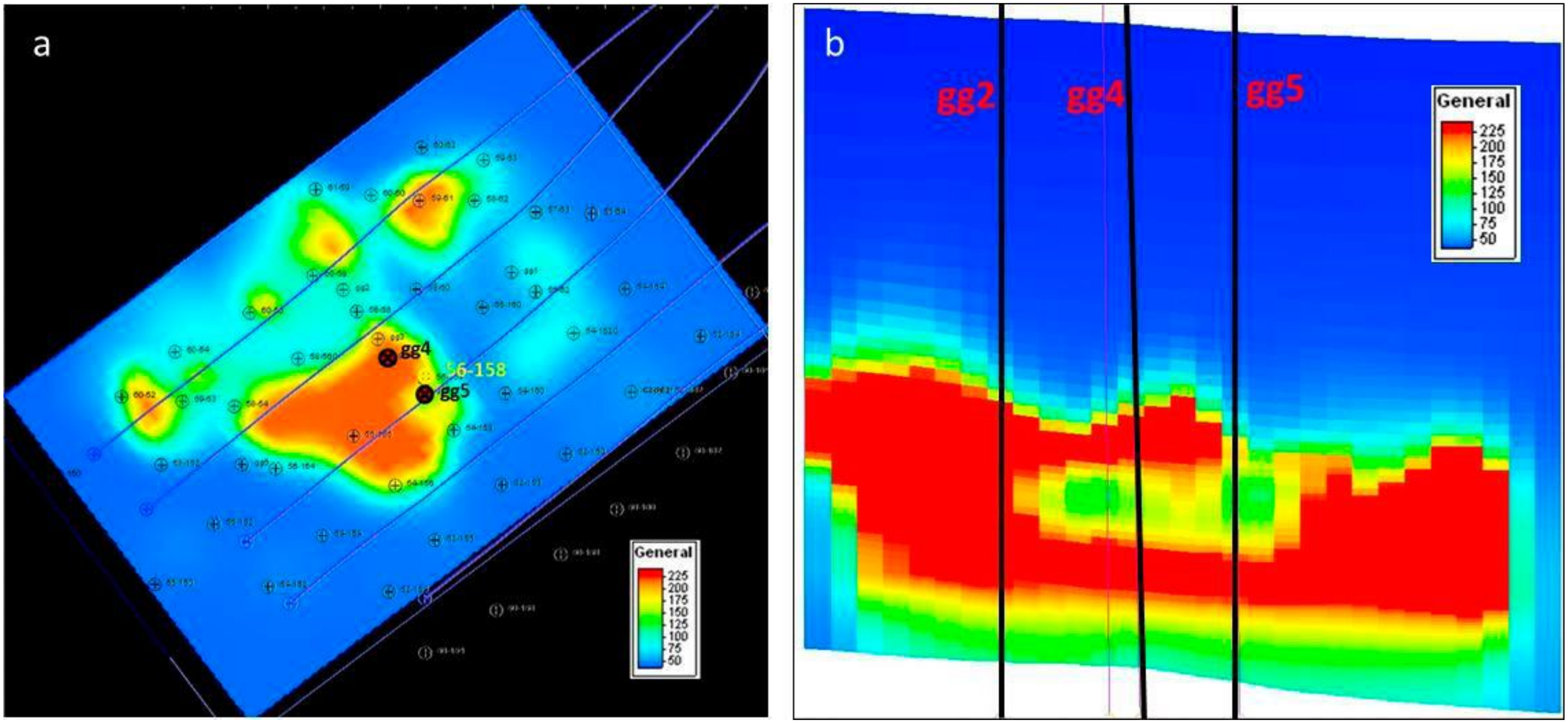

Figure 4. Temperature map of reservoir numerical simulation. a) Ng temperature distribution on top of the reservoir; b) temperature profile of gg4-gg5.

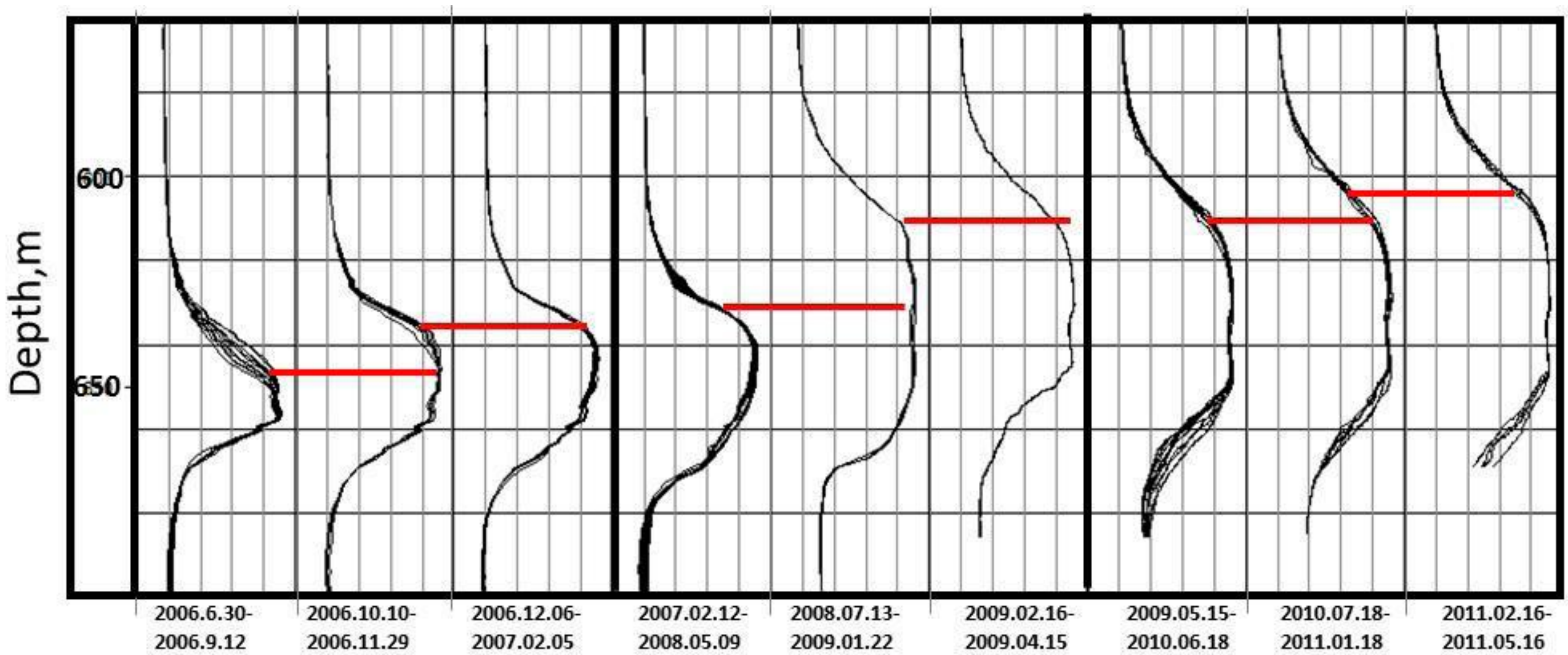

Figure 5. The temperature-time curve of gg6.

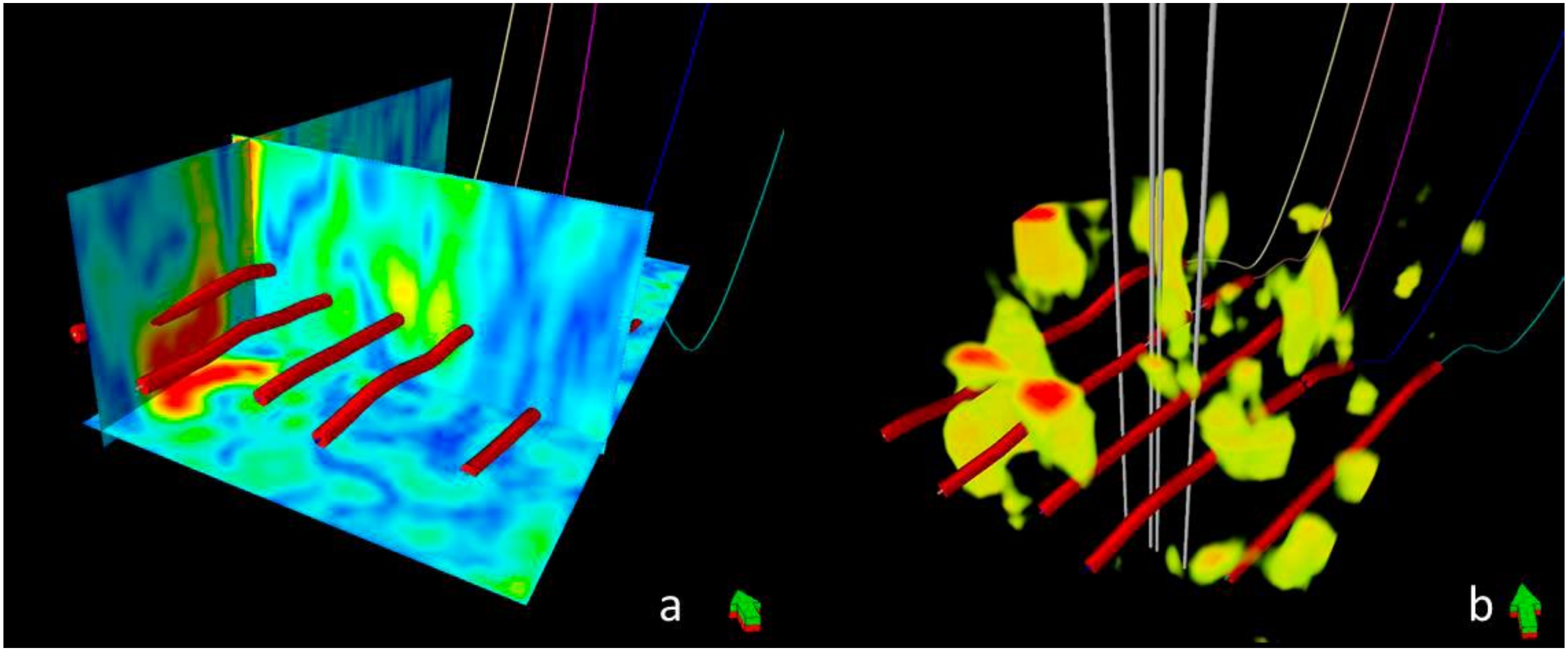

Figure 6. 3D display two stages time-lapse. a) Profile and sections diagram; b) difference body filter display.

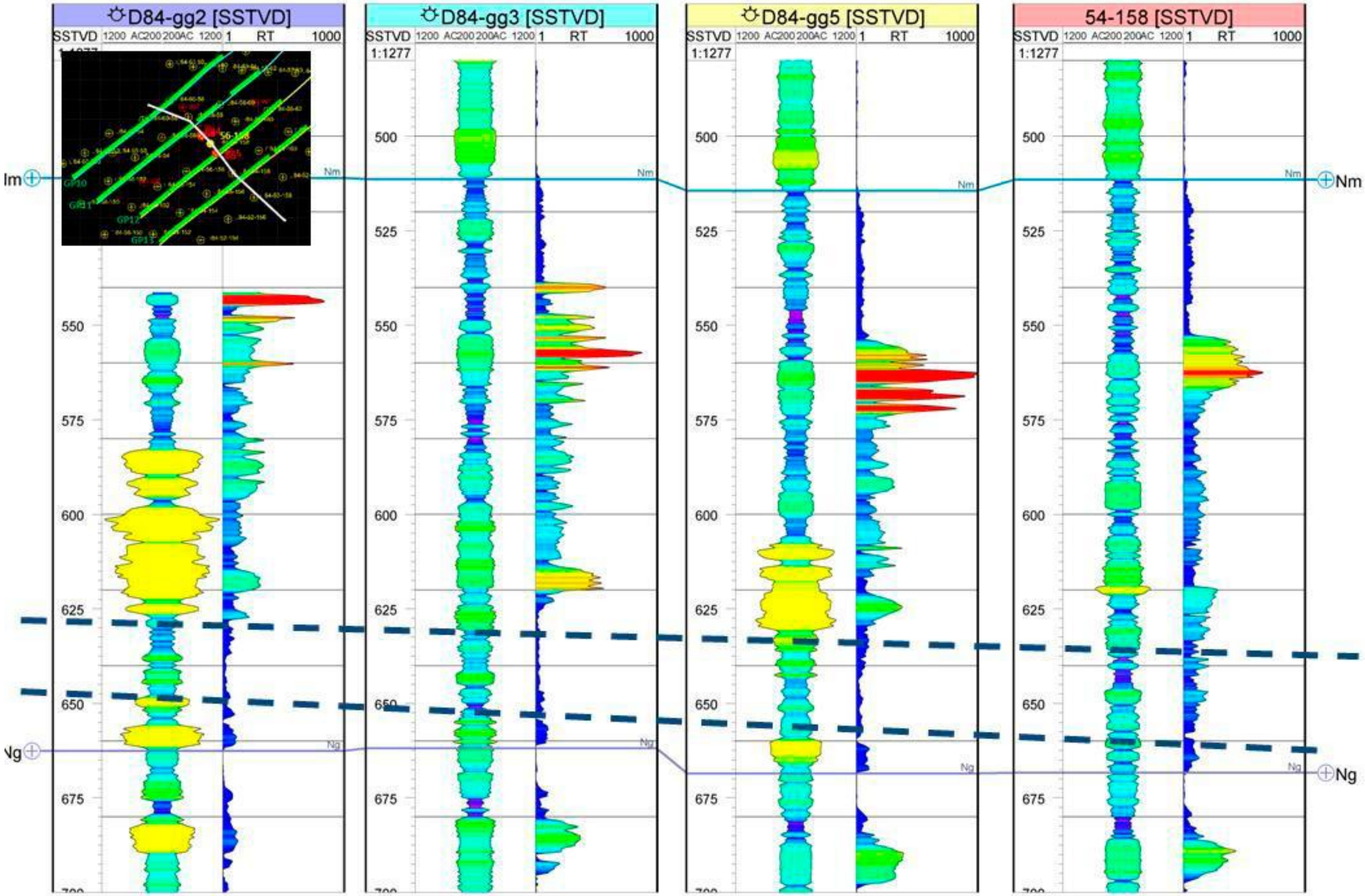

Figure 7. The distribution map of interlayer contrast of Ng formation (low physical between two blue dashed).

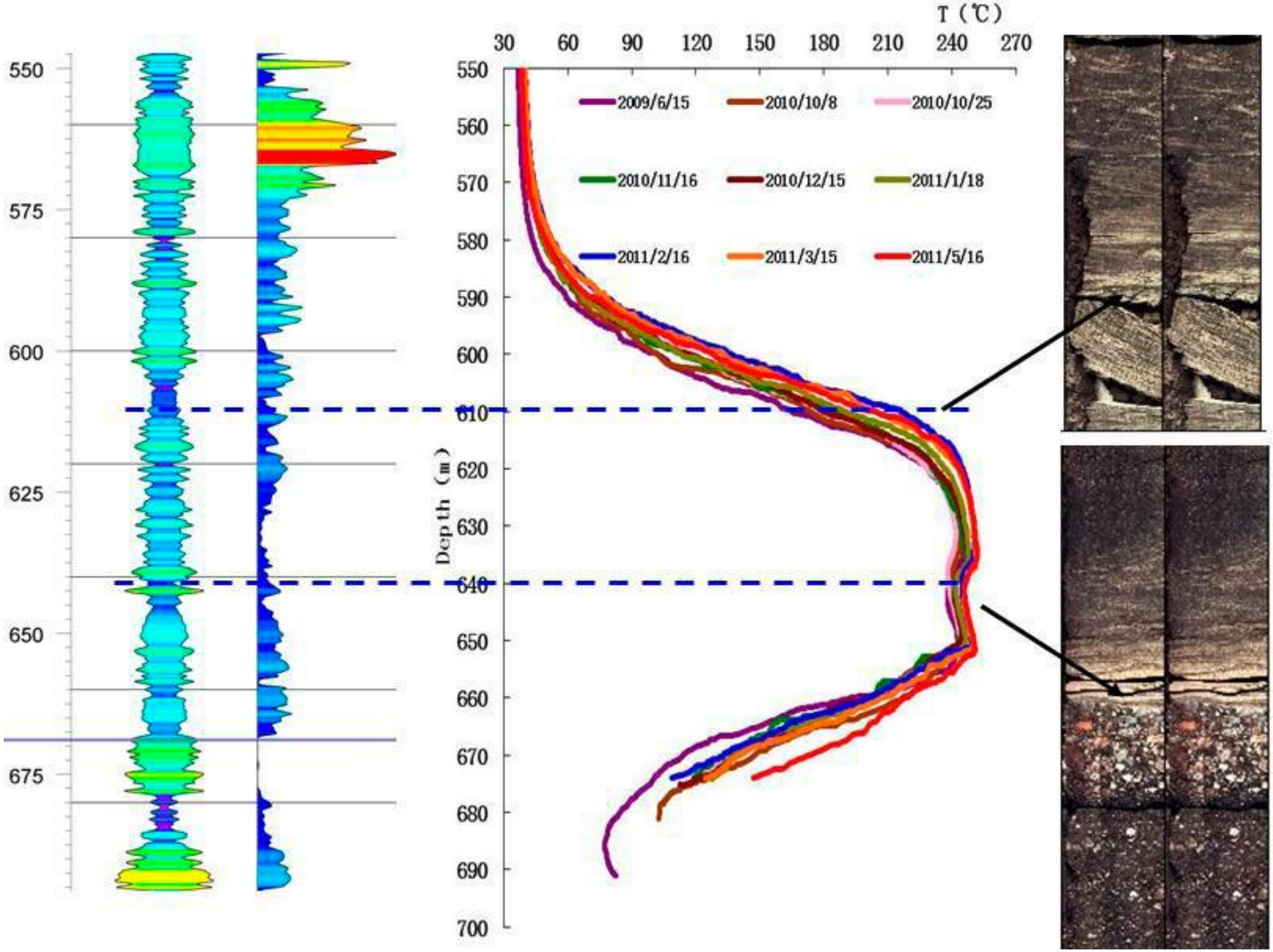

Figure 8. The comparative map of electrical measurement curve-temperature cure-coring photos of well gg6.