A Reservoir Characterization Case Study Based on the Structural and Depositional Isochronous Framework*

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Abstract

The reservoir static modeling (RSM) is one of the key points and foundation for the reservoir engineers further to understand the beds and enhance reservoir recovery, which is also the pursuing goal of the geophysicists. However, RSM is confronted with great challenges in practical application caused by complexity of geological genesis and diversity of geophysical data, and it is well known that one of the most critical problems is the integration of the spatial resolution of seismic data and the high vertical resolution of well logging data in reservoir model building. Through years of research, a new RSM method based on the structural and isochronous stratigraphic frameworks was put forward. And three key techniques are involved such as the followings: the first is based on seismic and well logging data with the shared lateral and vertical resolution to establish the Isochronous structural framework; the second is based on sequence stratigraphic theory with the support of seismic and well logging data to establish depositional isochronous stratigraphic frameworks; the third is the reservoir static interpolating modeling technology with the constraints of the structural and depositional isochronous stratigraphic frameworks, and based on the interpolating result, the single sand-body interpretation technology is also introduced, which is a way to dynamically replay isochronous time slice and then to interpret the sand bodies. It has been successfully applied to a thin sand-shale interlayer reservoir located at the lower wall of overthrusting fault in the northwestern edge of Zhungar basin in western China, which has been verified by the oil and gas development information of the oil field. It also has solved the heterogeneity problem of the sand reservoir with high water cut in the later stage of the oil and gas development.

Introduction

In the 1940's, one-quarter wavelength of seismic vertical resolution was defined by Rayleigh, and the definition of seismic lateral resolution (Fresnel zone) was given by Sheriff (1980) based on the definition of physical optics. Obviously, in this definition, the information provided by the seismic data is far beyond the reservoir engineers' requirements of description of reservoir with thickness between one to five meters. Therefore, geophysicists have tried their best to work on every kind of methods to improve the seismic resolution. Becquey, Lavergne and Willm (1979) put forward a method of wave impedance inversion and a method of pre-stack inversion was proposed subsequently, etc. and at the beginning, the usage of these inversion methods seems to tie geophysical workers closer to reservoir engineers, but due to multiple

solutions of the inversion methods with many assumptions, the inversion in practical application is still confronted with challenges. Therefore, Aziz and Nur (1986) began the study of comprehensive reservoir static modeling by integrated utilization of rock physics, logging and 3D seismic information. Vail, Mitchum and Thompson (1977) and Vail (1988) had proposed the concept of sequence stratigraphy respectively. What more would people want are to use the comprehensive information to obtain more accurate RSM results, to further help the reservoir engineers find remaining oil and gas, and finally reach the purpose of enhancing oil recovery.

The Geological, Geophysical, and Reservoir Development Background

The study area is located in the northwestern edge of Zhungar basin in western China with an area of 180km^2, and the reservoir is located in the lower wall of overthrust fault with the buried depth of 2,000m and a total reservoir thickness of 218 m. More than 320 wells are selected among these 2,000 wells for the following study in the area. The study area mainly developed the fan delta front subfacies, including three sedimentary cycles. For this paper, the lower two sedimentary cycles are the targets, including twenty single sand bodies, whose average thickness varies from two to five meters with strong heterogeneity (as is shown in Figure 1).

Starting in 1982, an inverted seven-spot pattern with well spacing of 350 meters was used for production of the bottom part of the reservoir. By 1984 the water saturation of the commingling intervals is as high as 84%, so most of development wells began to commingling the middle of reservoir, but now the wells both of the bottom and middle of the reservoirs have high water content with great spatial difference (as is shown in Figure 2).

In order to enhance oil recovery, a high precision 3D seismic data was acquired with wide azimuth and 12.5m by 12.5m bin size in 2009 (as is shown in Figure 3). In addition, the surface is covered by small sand dunes and many oilfield development facilities, and the spatial changes of near surface will cause great changes of excitation energy and wavelets (as is shown in Figure 4). Moreover, the differences of the excitation energy and wavelets will influence seismic imaging accuracy of the reservoir, especially the seismic interpretation ability and spatial resolution in the later stage.

Definition of Relative Spatial Seismic Resolution

Rayleigh defines vertical seismic resolution limitation of one-quarter wavelength, and Sheriff defines the lateral seismic resolution. These are useful and correct in interpretation of seismic sections. According to the resolution power of these definitions one to five meters thick sand beds could definitely not be identified in the imaged seismic section, which is usually the problem from reservoir engineers in the oil and gas development. For this reason, in this paper, a geological model with two thin fan-shaped sand bodies and a river channel was used to discuss the resolution power of the seismic data. Figure 5a and 5b show respectively the 2D vertical profile and 2D lateral profile of the geological model. In this model, the thickness of the river channel and two fan-shaped sand bodies varies from zero to 18 meters.

Figure 6a is the 2D reflection coefficient profile, and Figure 6b, Figure 6c and Figure 6d show synthetic seismic profiles with 60Hz, 35Hz and 20Hz ricker wavelet being convolved respectively. It is impossible for us to distinguish the sand bodies from three synthetic sections, while the

sand bodies can be identified in the reflection coefficient profile. That is what one-quarter wavelength of vertical seismic resolution Rayleigh defines refers.

However, how to discuss the seismic resolution in another point of view? Will it make difference? Suppose that the top or bottom of isochronous geological surface is known, and then we can extract seismic attribute along the isochronous geological surface, and observe the seismic attribute response of the sand bodies. By doing so, could we improve the seismic resolution? Figure 7a shows the 2D reflection coefficient profile, and Figure 7b, Figure 7c and Figure7d show the phase attribute slices of 60Hz, 35Hz and 20Hz synthetic seismic respectively. Comparing seismic attribute slices with the reflection coefficient slice, we can clearly see the outline of sand bodies and river channel with the dominant frequency changes, no matter how low the dominate frequency is. Based on the spatial relative changes, we are able to identify the fan-shaped sand bodies and river channel. Therefore, the author gives the definition of the "relative spatial seismic resolution" as follows: The ability to recognize the spatial distribution of geologic bodies based on the geologic interpretation of geologic bodies induced spatial and vertical variation on the seismic attributes from the isochronous slices is called relative spatial seismic resolution.

Relatively Preserved Seismic Data Processing (RPP)

In practical application, the relative spatial seismic resolution theory cannot be simply applied as the vertical resolution is defined by the predecessors. Since when there are the effects of near surface or overlying strata, the seismic image would not be able to reflect the real changes of thin interlayer beds. It is the biggest challenge for relative spatial seismic resolution. If we cannot remove the effects of the near surface, it is just like putting a hand before the projector, and we cannot see the movie image except the hand's shadow. Therefore, to apply relative spatial seismic resolution theory into the seismic data interpretation and identify thin interlayer beds, it is very important and necessary to use the wide azimuth or full azimuth acquisition design to avoid the influence of the near surface (as is shown in Figure 8a), and it also necessary to apply RPP work flow to remove the effect of the near surface (as is shown in Figure 8b). RPP workflow is shown in Figure 8c, and the key technologies including time-frequency domain spherical divergence and near surface absorption attenuation compensation (Ling Yun and Gao Jun, 2005) and shot and receiver gathers statistical wavelet de-convolution, and the processing QC technologies (Ling Yun, Gao Jun etc., 2002, 2004).

Shown in Figure 9 are the QC plots of the RPP results. Figure 9a, Figure 9b, Figure 9c and Figure 9d are the source energy QC, amplitude spectrum, shot gathers and the seismic wavelet QC of the processed result respectively. Compared with the corresponding QC plots of the raw data shown in Figure 4, the differences in the source energy, frequency and wavelet are removed after RPP.

In order to further monitor the result of RPP, the isochronous stratigraphic depositional interface is introduced as a quality control tool. According to the geological sedimentary theory and seismic wave impedance interface theory, it is well known that the stable wave impedance interface can only developed with large geological event, namely with continuous reflection event. When the seismic attribute is extract along the continuous and stable reflection events. It should be response to the geological bodies with certain geological characteristics and spatially stable. Therefore, we can choose such layer as the reservoir top or the layer near the top of the reservoir, which meet the above conditions as isochronous stratigraphic depositional interface, and then along that surface to extract the seismic attribute and monitor RPP.

Figure 10 and Figure 11 are the seismic amplitude and waveform clustering attributes extracted along the isochronous stratigraphic depositional interface from legacy processed and the newly RPP processed results respectively. The seismic attributes slices from legacy processed result show irregular spatial variation without practical geological means, while with the help of RPP technology, the attributes slice of newly processed result is stable spatially with the characters of the alluvial fan deposit. In order to verify the result of RPP, the geological statistics of the well facies and single sand thickness is shown in Figure 12b. In addition, comparing Figure 12b with Figure 11, we can see the seismic attributes extracted from RPP result is well matched with the geological statistics' interpretation conclusion. In addition, it shows that RPP is very important to preserve the reservoir's geophysical information, and at the same time, it is the base of the seismic geological interpretation by use of the relative spatial seismic resolution idea.

Static Modeling Study Based on the Structural and Depositional Isochronous Stratigraphic Frameworks

1. The Seismic and Logging Data Interpretation under the Structural Framework

Because logging data is with high vertical resolution, the reservoir engineers prefer to make RSM using only the log information. However, due to the lack of the spatial information for logging data, the modeling of complicated thin sand-shale interlayer beds is always with greater challenges for the modeling engineers. Therefore, people hope to take advantages of the spatial information in the seismic and the vertical information in logging data to improve the accuracy of RSM. For this reason, post-stack or pre-stack inversion methods become one of the ways to improve the accuracy of the modeling. However, due to multiple solutions of the inversion methods with many assumptions, the inversion in practical application is still confronted with great challenges. In addition, the author think if the common isochronous stratigraphic interface of seismic and log data can be obtained, it may give full play to the potential of the seismic data in spatial resolution and logging data in vertical resolution. In this study, the top and bottom surfaces of the reservoir are selected as the isochronous stratigraphic depositional surfaces, or called as the structural and depositional isochronous stratigraphic frameworks. Through the calibration of the isochronous structure framework by using the seismic and log information and the isochronous horizon interpretation, we finally got the result shown in Figure 13.

2. The Interpretation of Seismic Isochronous Depositional Frameworks Based on the Sequence Stratigraphy

From the above two isochronous stratigraphic depositional surfaces with the thickness of 208 meters between them, we know that they can meet the precision requirement in structure exploration stage. However, it is far beyond the two to five meters precision requirement in the reservoir development stage. At the same time, for the reservoir of multi-cycle sedimentary, it is not enough only to use the top and bottom surfaces to restrain logging information to make the static reservoir modeling. So it is necessary for us to obtain the sub-isochronous stratigraphic depositional framework inside reservoir, and then to use these new sub-isochronous surfaces to do the integrated static reservoir modeling with seismic and well-logging data.

However, for vertical seismic resolution, it is hard to distinguish the internal isochronous surface of deposition inside reservoir. Therefore, with the constraint of the reservoir structural frameworks shown in Figure 14a, we got the following result with three sedimentary cycles shown in Figure 14b, by using the sequence stratigraphic 3D seismic auto-tracking software. According to auto-tracking result matched with the logging interpretation, the lower two of the three sedimentary cycles are selected as the so-called isochronous depositional surfaces shown in Figure

14c. Moreover, it is obviously non-isochronous for these so-called isochronous depositional surfaces auto-tracked by the software, so it is necessary for us to do the iterative interpretation to remedy these so-called surfaces with the calibration of the seismic and well-logging information. Finally, we got two internal isochronous depositional surfaces inside reservoir, as is shown in Figure 14c and 14d for 2D and Figure 15a for 3D.

3. Reservoir Static Modeling with Logging Data Based on the Seismic Data, Structural and Depositional Isochronous Stratigraphic Frameworks

Although we have obtained the structural and isochronous sub-surfaces inside reservoir and solved the problems of the spatial information integration of seismic and logging data under the frameworks, we still cannot solve the problem to recognize as many as 20 sand bodies inside reservoir. Therefore, the author puts forward "a reservoir static modeling method based on the structural and depositional isochronous stratigraphic frameworks", which is based on structural and depositional isochronous framework, to choose appropriate grid subdivision with the support of sand and shale cross plot as is shown in Figure 15b, and to obtained the final properties results of RSM. In addition, Figure 15c and Figure 15d shown as the porosity and the permeability of the modeling results with seismic section.

Generally speaking, the above results of RSM has quite a high precision, but with the buried depth of 2,000 m and the block-overthrusting of thrust fault, people often raise questions of the seismic imaging and seismic interpretation accuracy as follows: whether can the structural and depositional isochronous frameworks meet the accuracy of the thickness of two to three meters? Can we ensure the frameworks isochronous? Obviously, it is only relatively isochronic for the interpreted structural and depositional isochronous frameworks, but not absolutely, and it is difficult to meet the accuracy of the thickness of two to three meters with complicated structure and large buried depth. However, in practice only the interpretation of two to five meter single sand body can effectively solve the problems of interwell injection-production. Therefore, the author puts forward "single sand body interpretation method based on RSM attribute slice", namely using the continuous vertical section attributes' changes to solve sand body interpretation and anisochronous problem. Figure 16a is the RSM with the 3D and 2D displays, and Figure 16b shows the 20th slice counting from the bottom of the reservoirs. In addition, if according to the only 20th slice result, it is hard for us to figure out the relations to the northern source. However, if continuing to overlap the slices of 21th and 22th with 20th, we can see there are two north rivers according to the characteristic of sand spatial distribution. In the same way, based on that outcome, take another step and so on. Finally, we provided the interpretation of 20 single sand bodies in the lower two sedimentary cycles.

4. Reservoir Static Model Validation Based on the Developing Information

Although the reservoir static model mentioned above is relatively reasonable, before put into practice, this model still needs to be validated. This paper selects two wells in the same well pattern (well spacing 320m) to carry on the model validation. Between these two wells, well 8216 has already been flooded, while the neighboring well 8220 is still under development. From the cross-well section of the sand body static modeling between injection wells and well 8216 (Figure 17a) and the production curves of well 8216 (Figure 17b), obviously we can see that no connected sand bodies exist between wells in S4, and at the same time the inter-well also do not take the measures of reprobating, that is why well 8220 (Figure 18a) still produce oil to this day. According to the above validation and sand body interpretation, it is not difficult to get

the suggestions of the reprobating and water shutoff. Therefore, the model based on structural and depositional isochronous stratigraphic frameworks can meet the requirements of development and further direct the development of residual oil and gas.

Conclusions

This research comes to the conclusions that: 1) The seismic relative spatial resolution can break through the limitation of $1/4\lambda$, which can help us to do the macroscopical sedimentary facies interpretation and the single sand body interpretation of RSM ; 2) Based on structural and depositional isochronous frameworks with logging data constraints, we can take full advantage of the seismic lateral resolution and the logging vertical resolution to make RSM; 3) Based on the isochronous frameworks, a more accurate RSM can be established with reasonable spatial internal so-called isochronous grids and suitable interpolation methods;4) With the reservoir static model, it is necessary to use the dynamic slices' evolution to get reasonable single sand body's interpretation. Therefore, reservoir static modeling based on structural and depositional isochronous framework are practical for oil and gas development.

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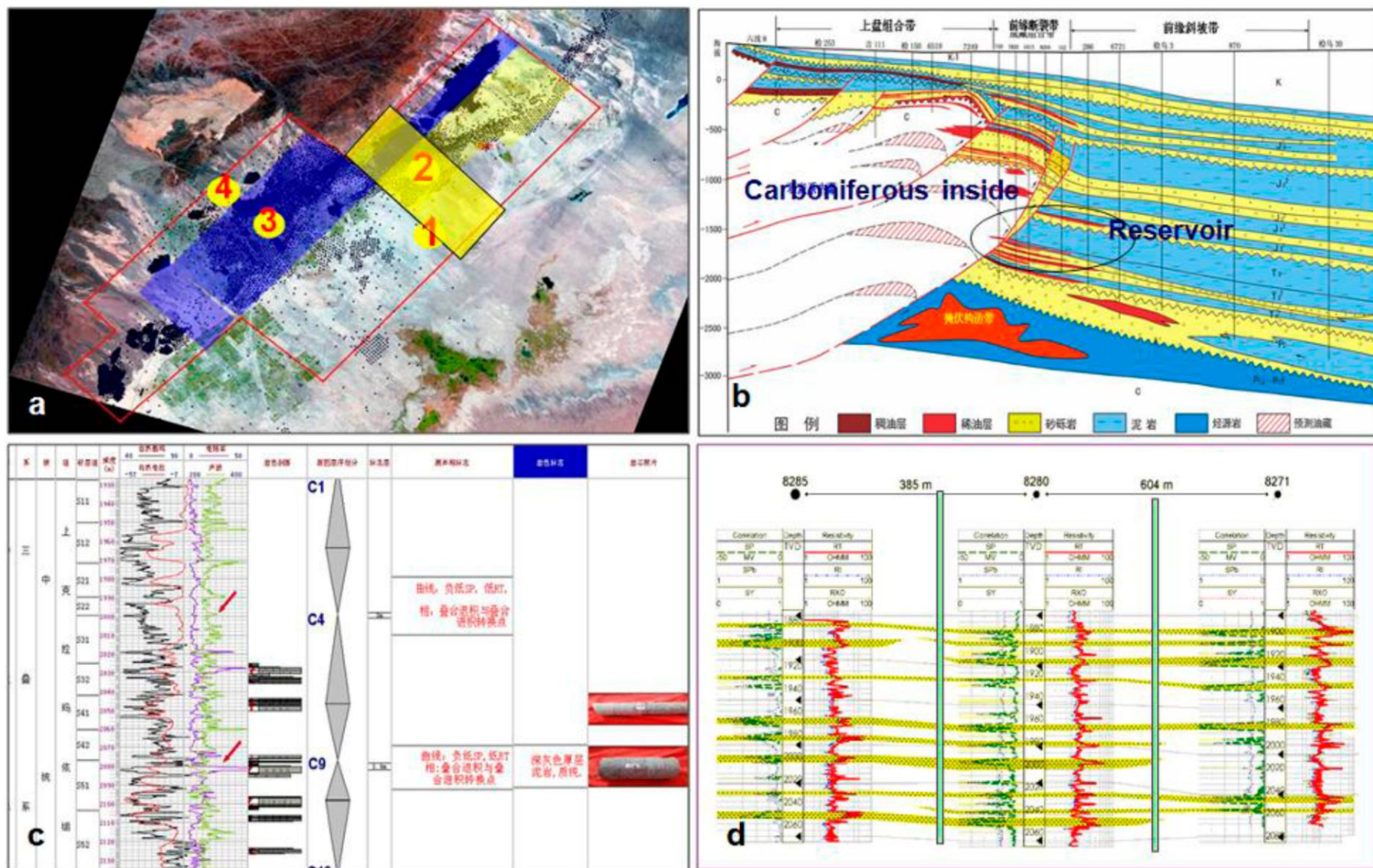
Figure 1. (a) Study area location; (b) Structure and reservoir location; (c) Log curves, sedimentary cycles and core calibration; (d) Cross-well inter-bedding sand interpretation.
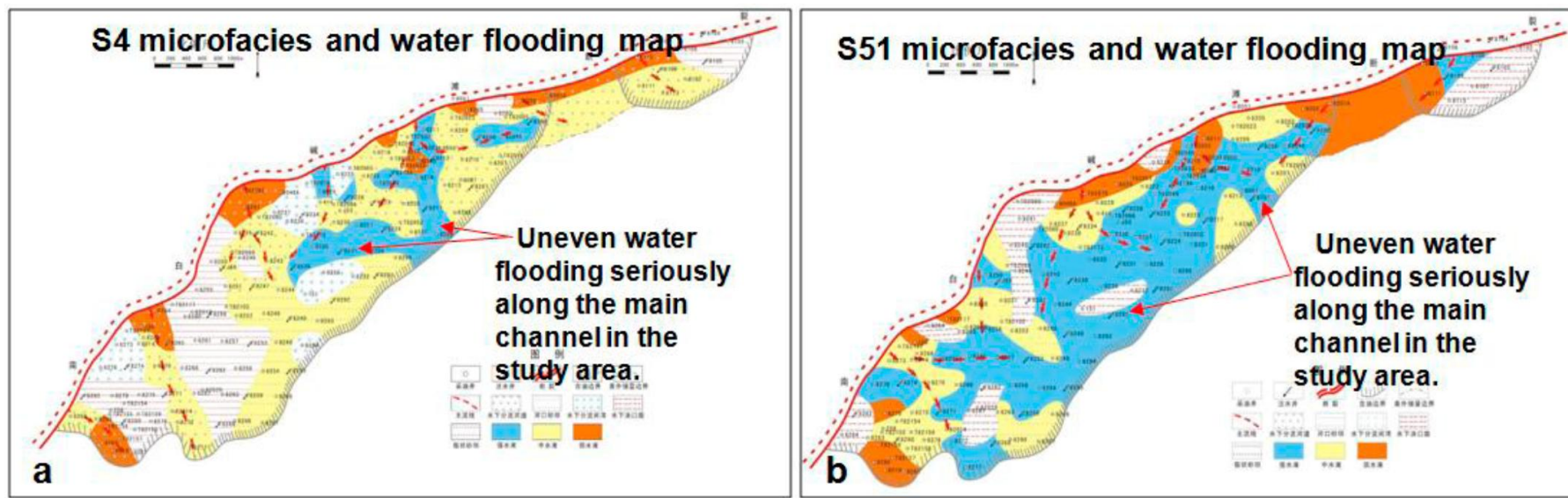
Figure 2. (a) Development status in the middle cycle of reservoir; (b) Development status in the lower cycle of reservoir.
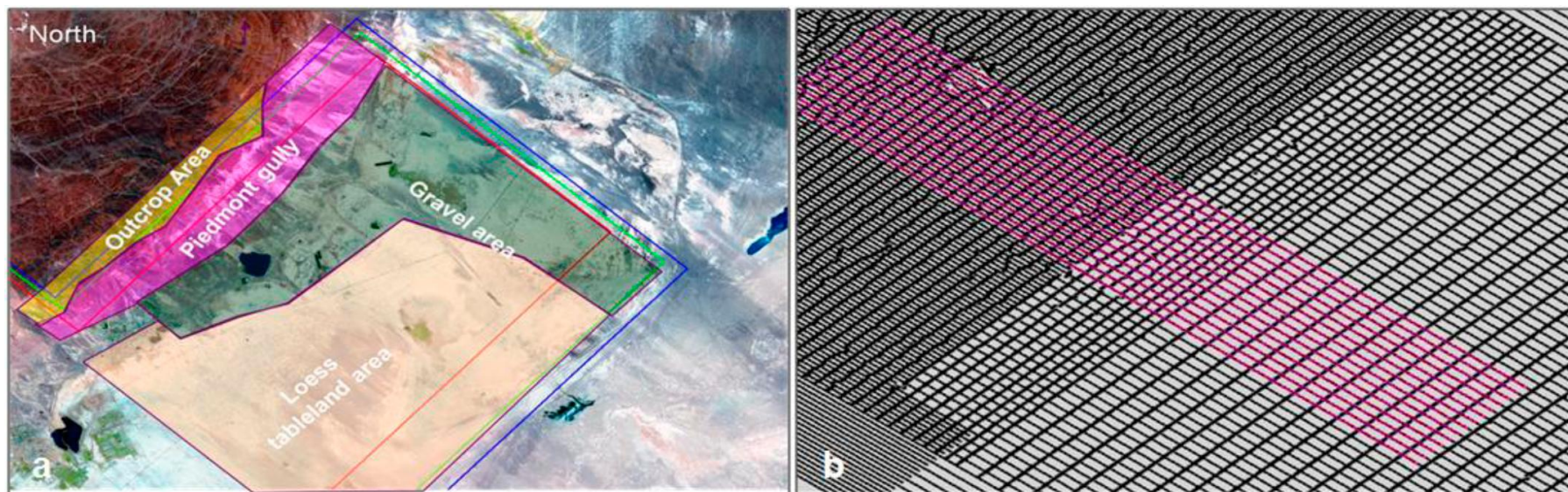
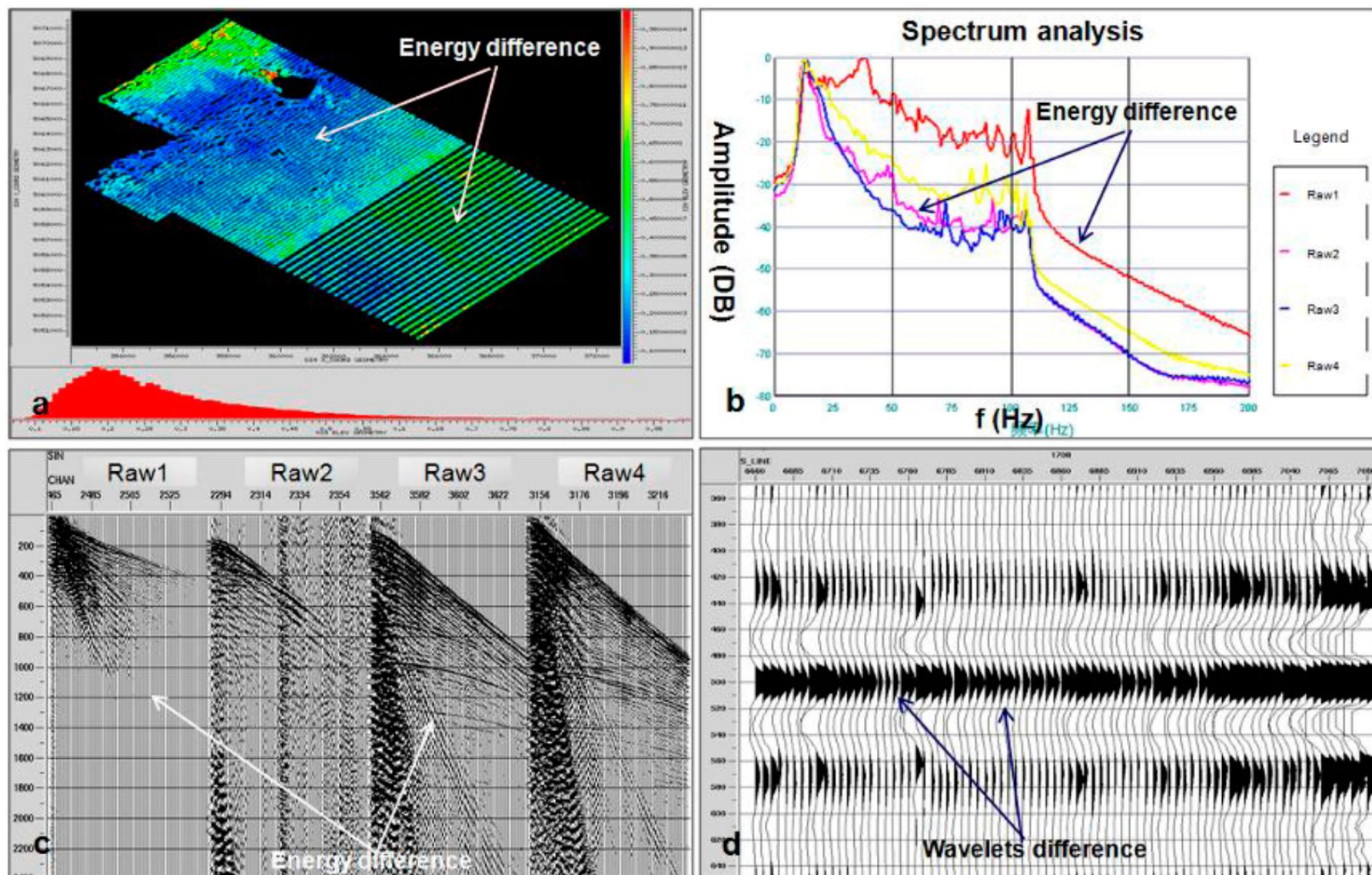Figure 3. (a) Surface features of seismic survey area; (b) Seismic geometry.

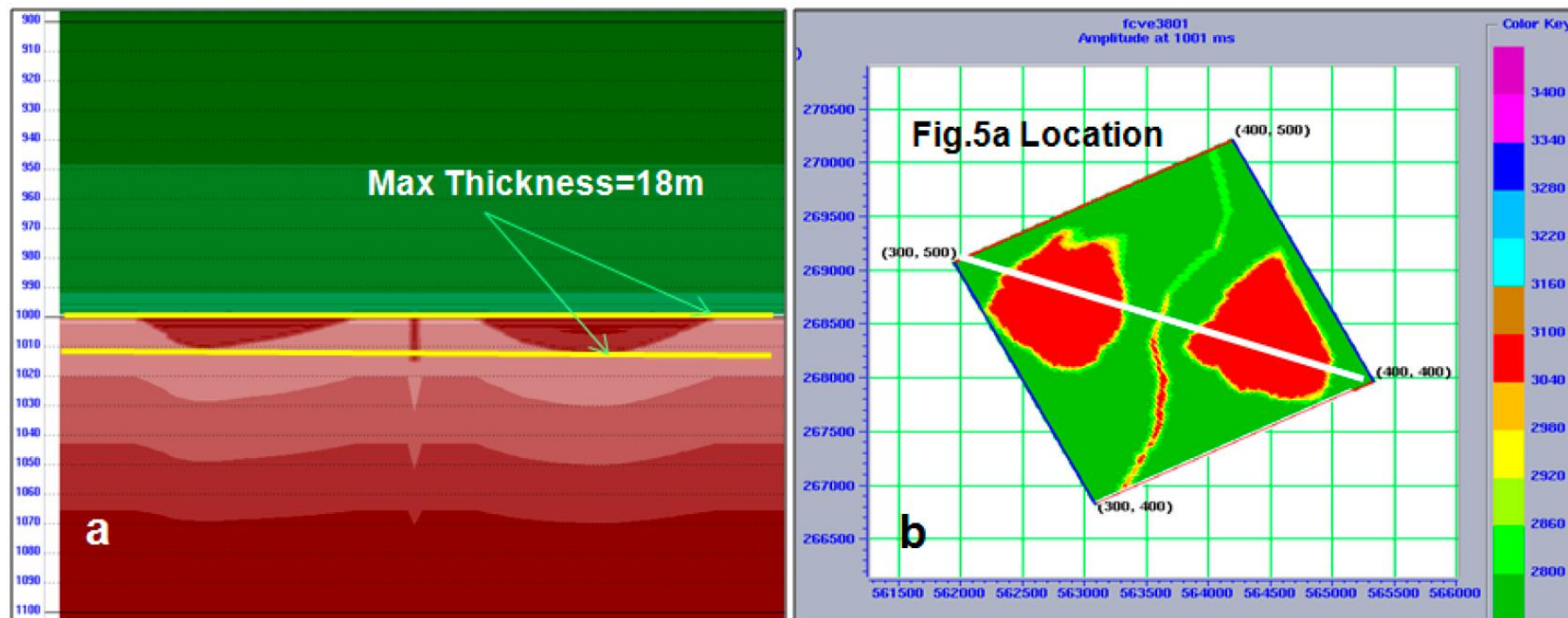Figure 4. (a) Source energy of raw shots; (b) Amplitude spectrum of raw shots; (c) Raw shots gathers; (d) Wavelets of raw shots.

Figure 5. (a) Vertical section of fan shaped sand bodies and river channel; (b) Horizontal slice of fan-shaped sand bodies and river channel.
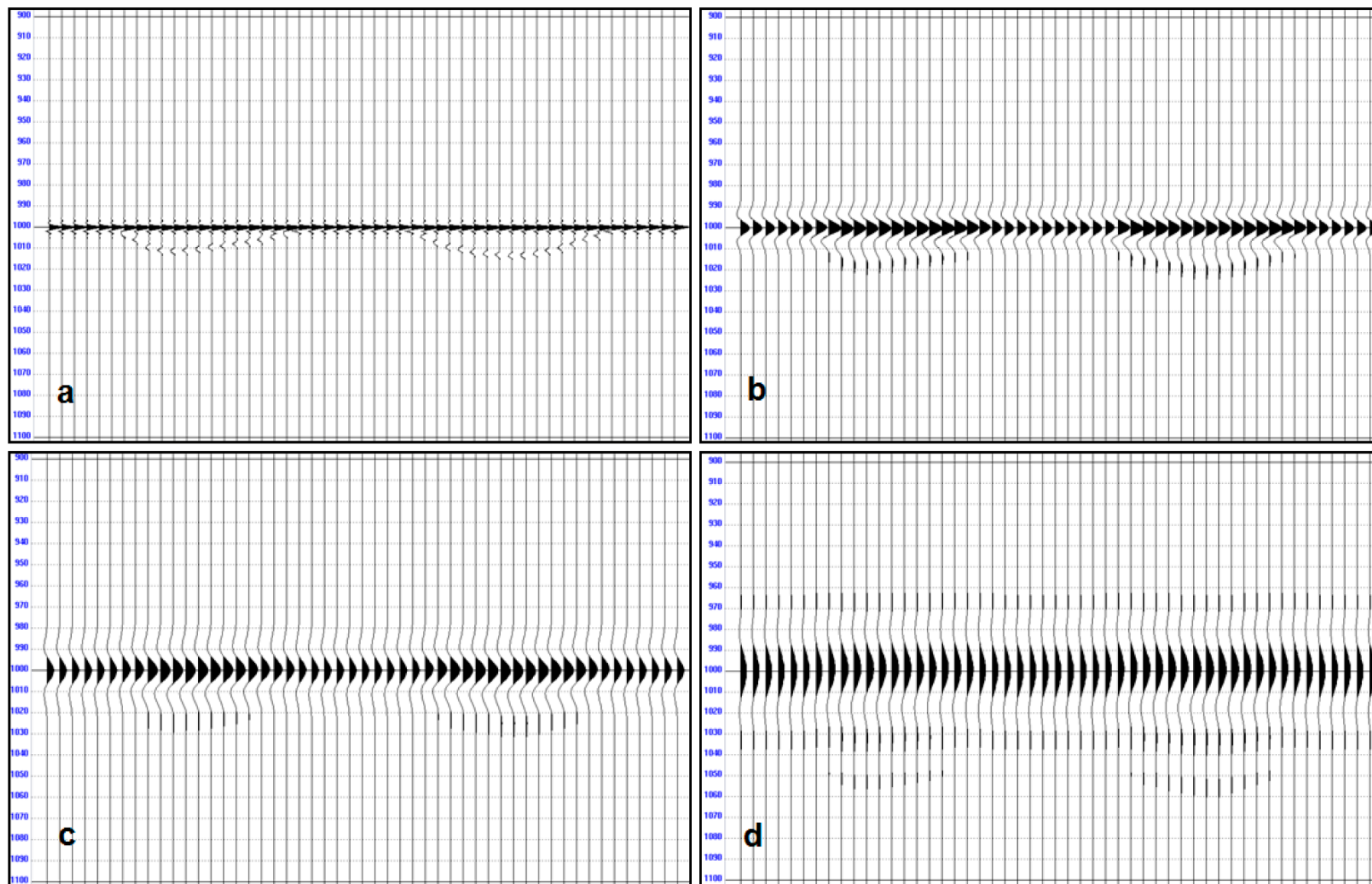
Figure 6. (a) Reflection coefficient; (b) 60Hz synthetic; (c) 35Hz synthetic; (d) 20Hz synthetic.
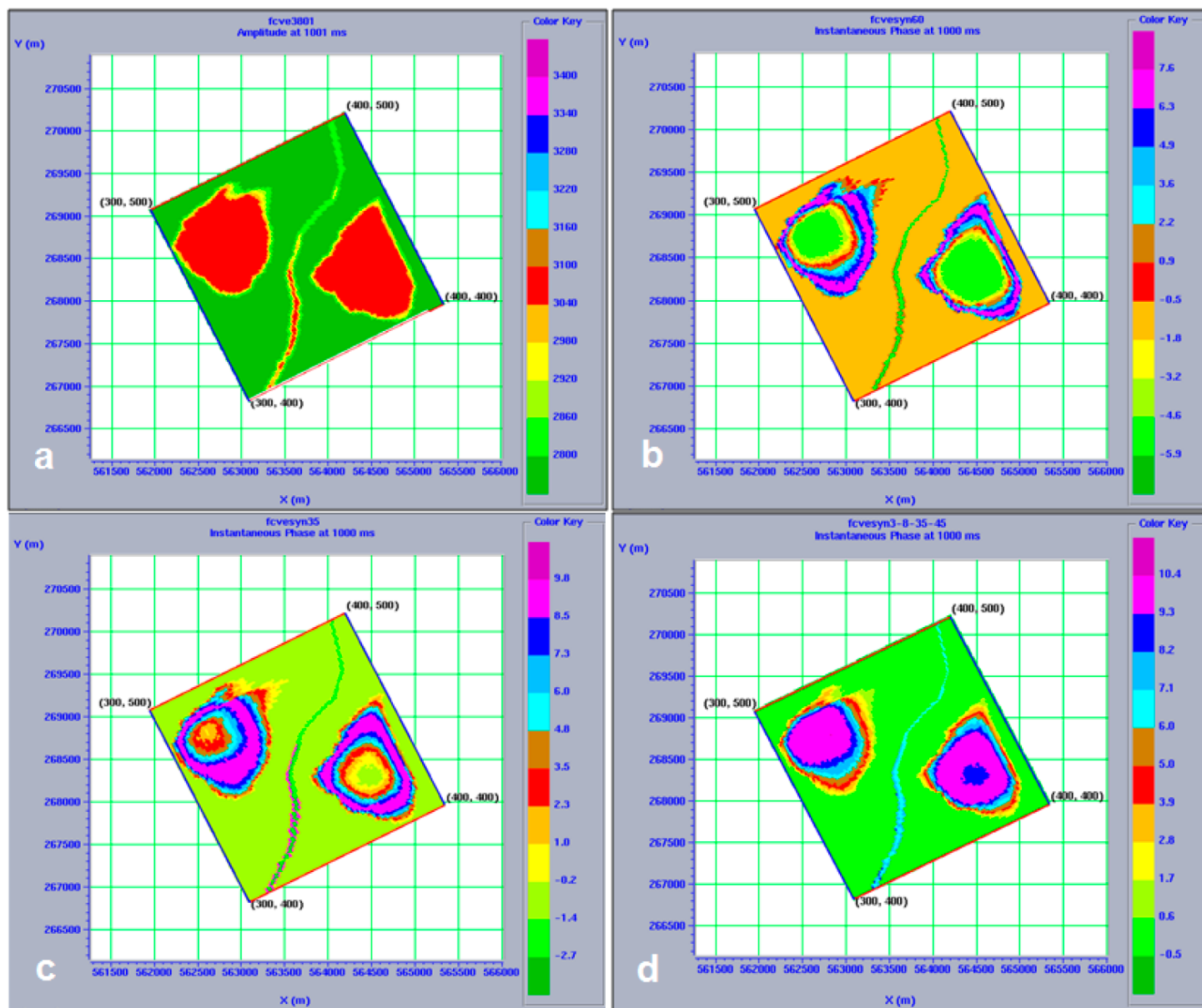
Figure 7. (a) Velocity slice; (b) 60Hz phase slice; (c) 35Hz phase slice; (d) 20Hz phase slice.
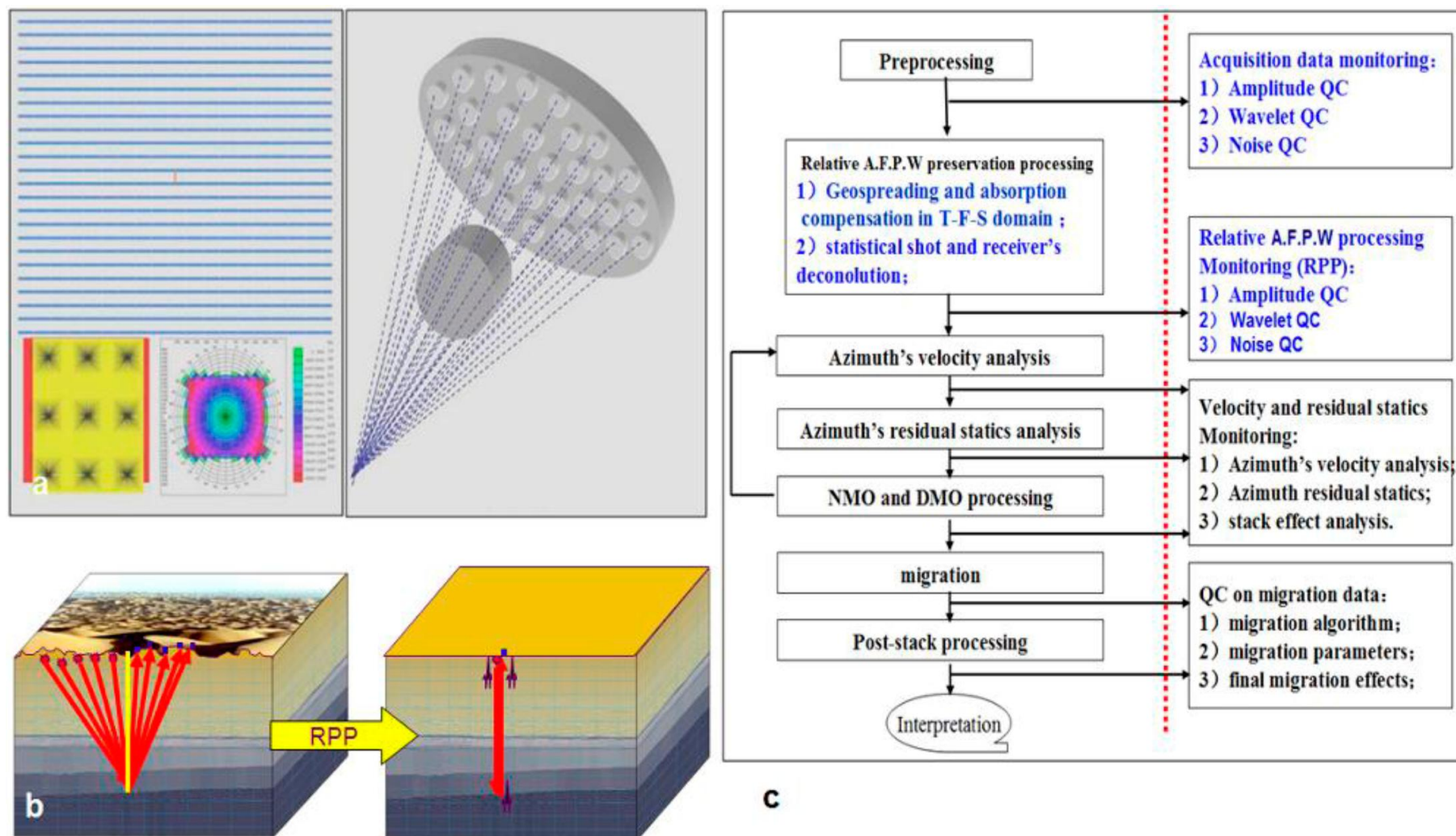
Figure 8. (a) Wide or full azimuth seismological observation systems; (b) The surface differences before and after RPP; (c) Key techniques of RPP work flow.
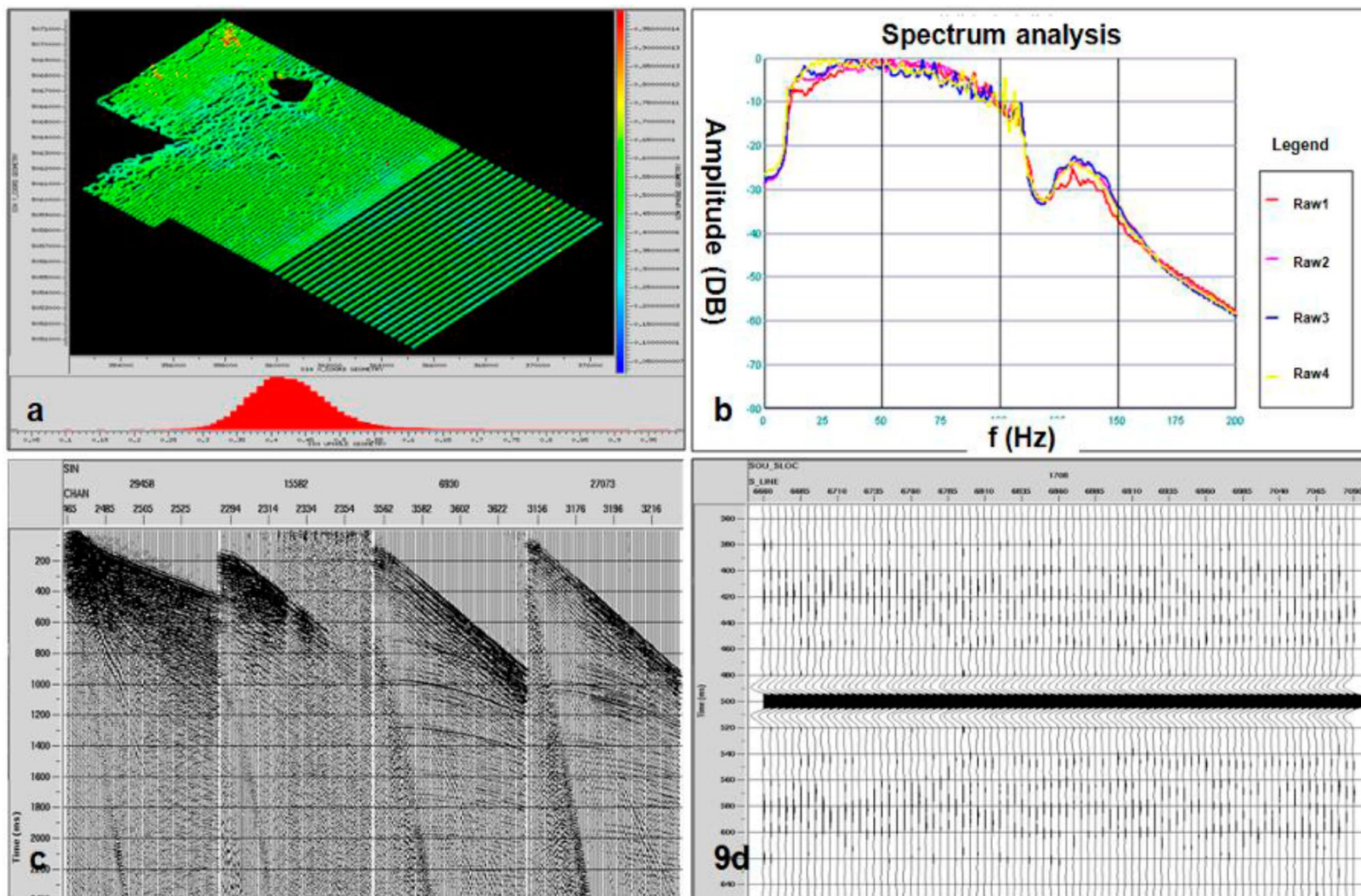
Figure 9. (a) Shot energy QC after RPP; (b) Amplitude spectrum after RPP; (c) Shot gathers after RPP; (d) Wavelets QC after RPP
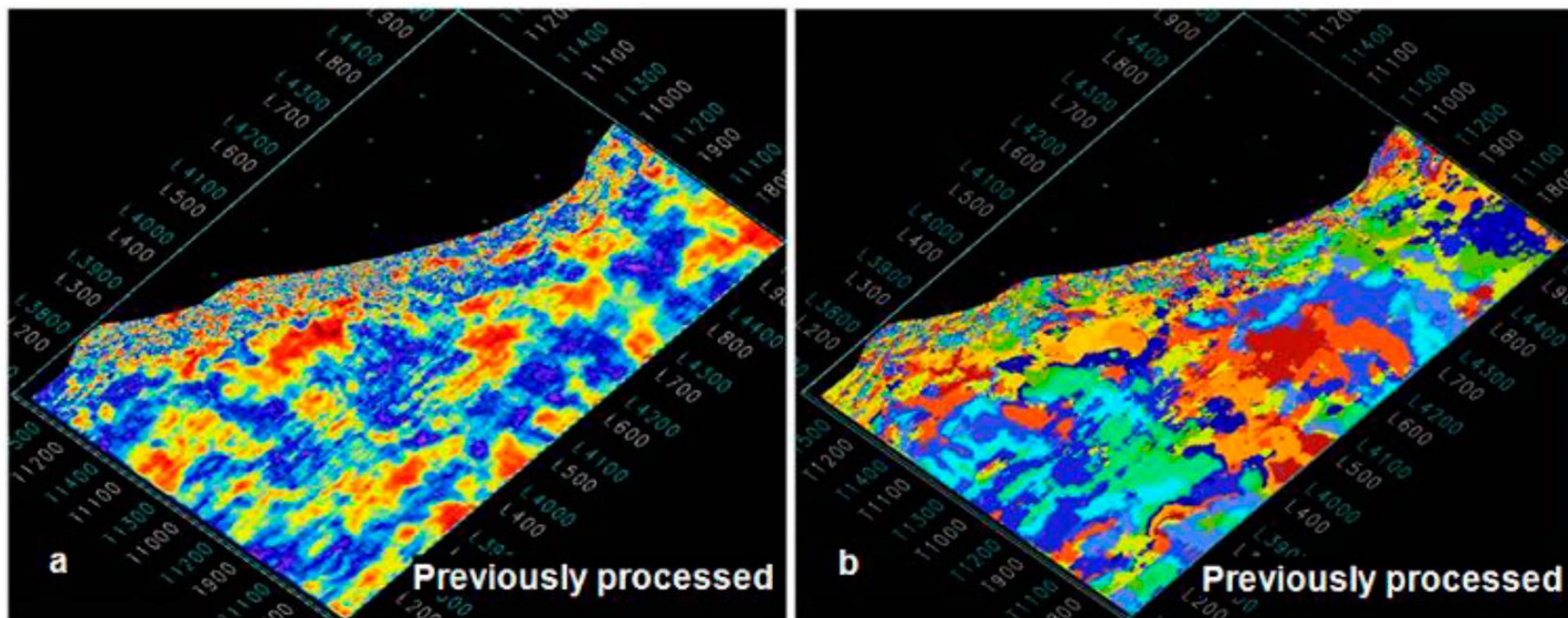
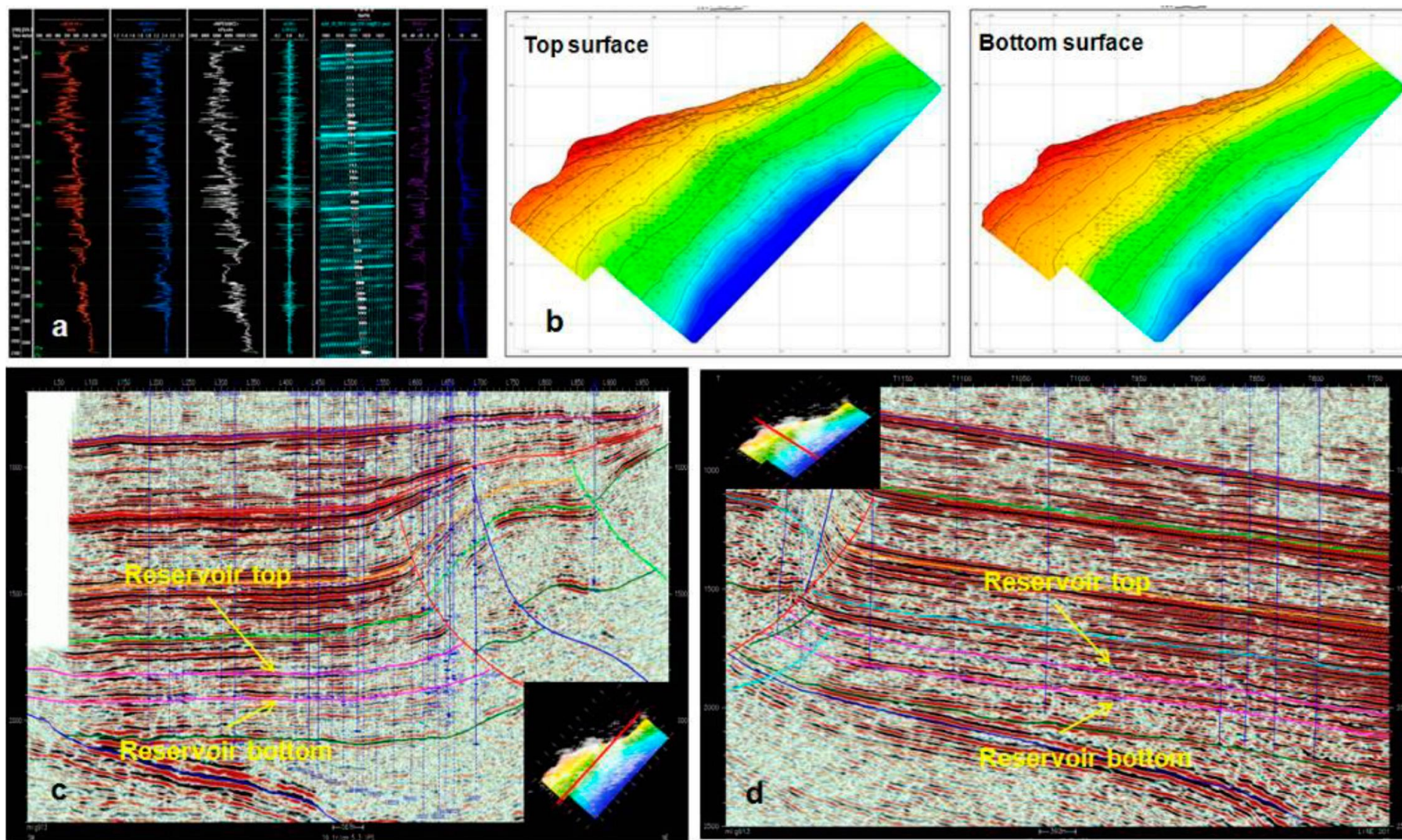Figure 10. (a) Amplitude attribute slice; (b) Waveform clustering attribute slice of the legacy processed result.

Figure 11. (a) Amplitude attribute slice after RPP; (b) Frequency attribute slice after RPP.

Figure 12. (a) Sedimentary cycle interpretation based on well and seismic data; (b) Sand-body thickness geological statistics map based on logging data.
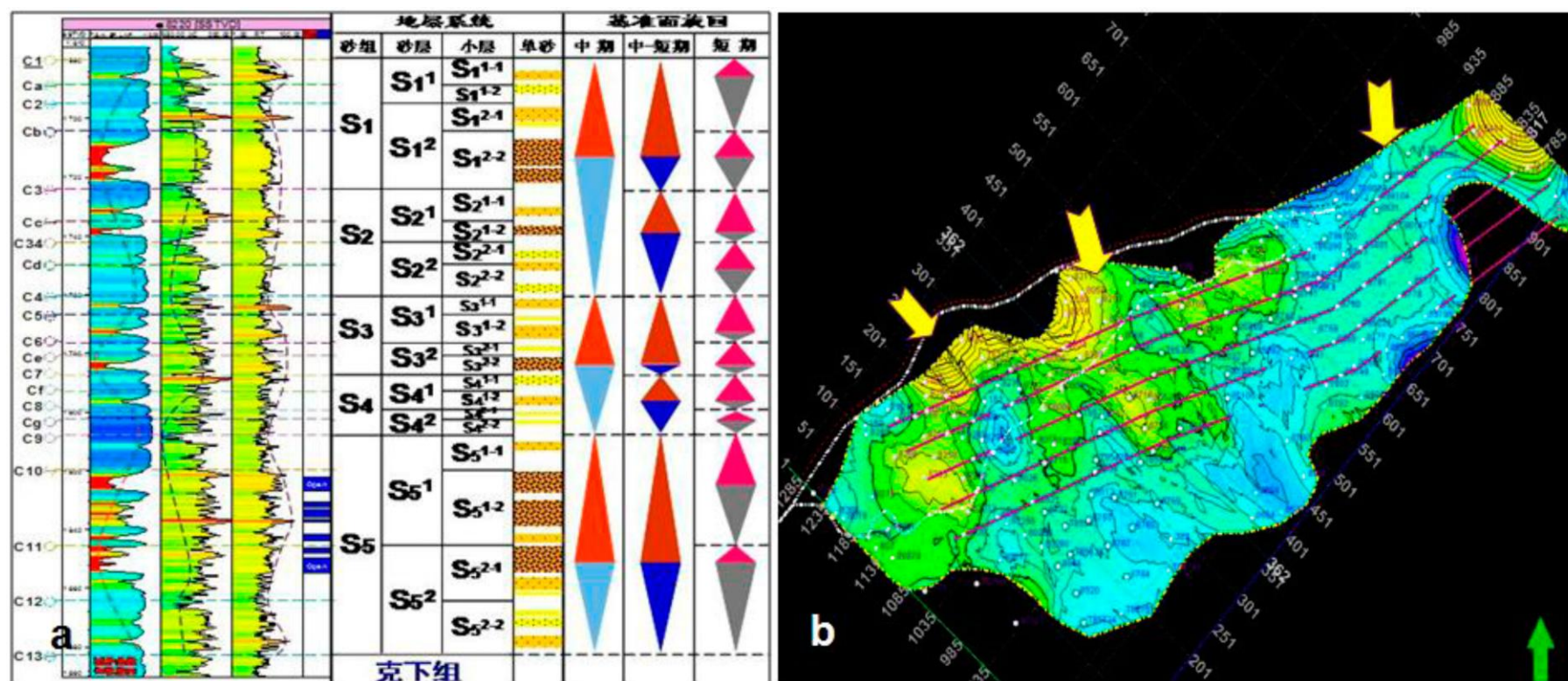
Figure 13. (a) Well logging and seismic calibration; (b) Structural to and bottom surfaces; (c) Mid-cycle seismic interpretation results of reservoir vertical to northern source; (d) Mid-cycle seismic interpretation results of reservoir parallel to northern source.
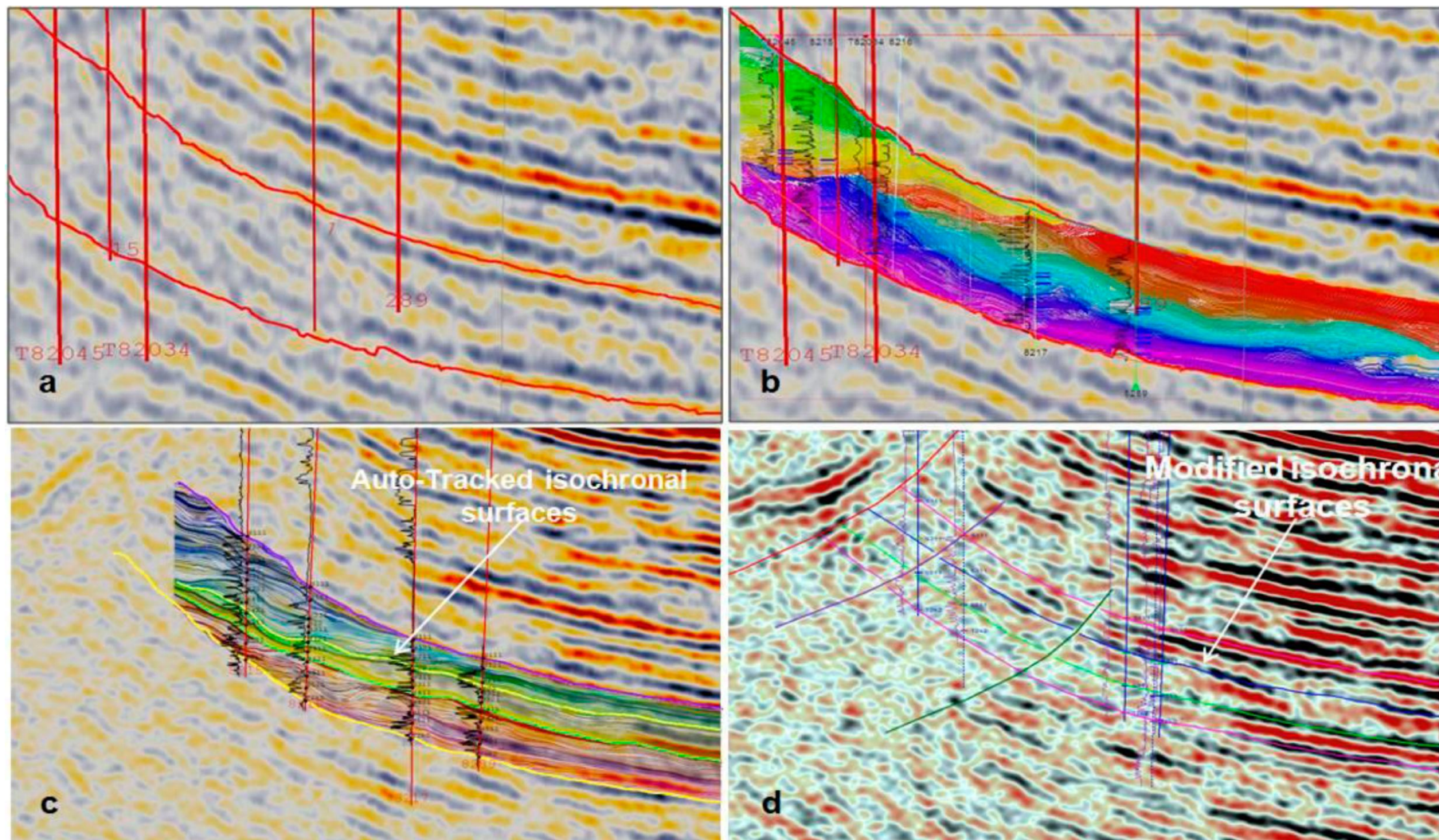
Figure 14. (a) Reservoir top and bottom interpretation; (b) 3D auto-tracked sequence interpretation; (c) Auto-picked depositional isochronal sub-surface; (d) Interpretation results based on sub-sequence, logging and seismic data.
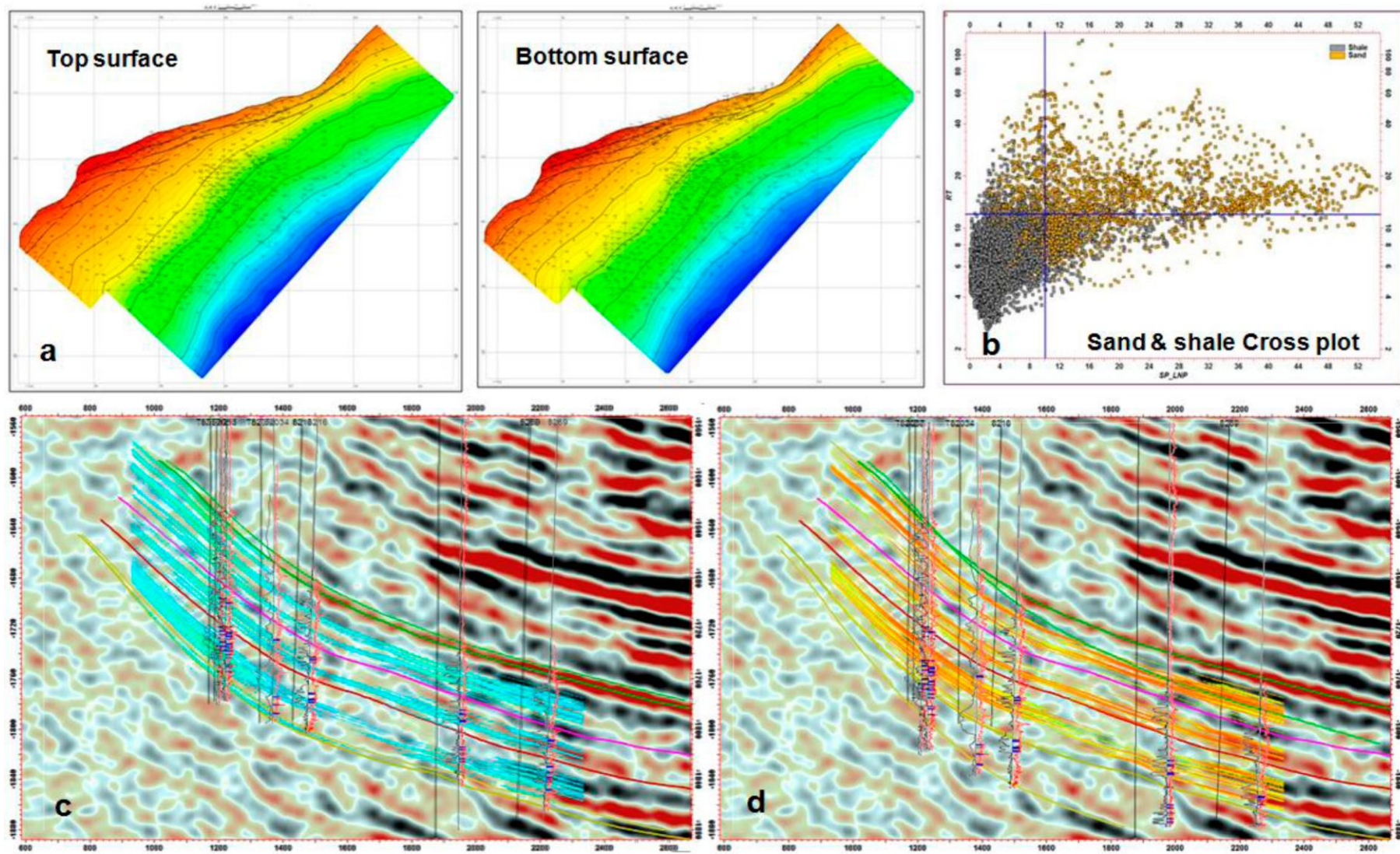
Figure 15. (a) Depositional isochronal sub-surfaces of two cycles in reservoir; (b) Sand and shale cross plot; (c) Final porosity modeling result with seismic section; (d) Final permeability modeling result with seismic section.
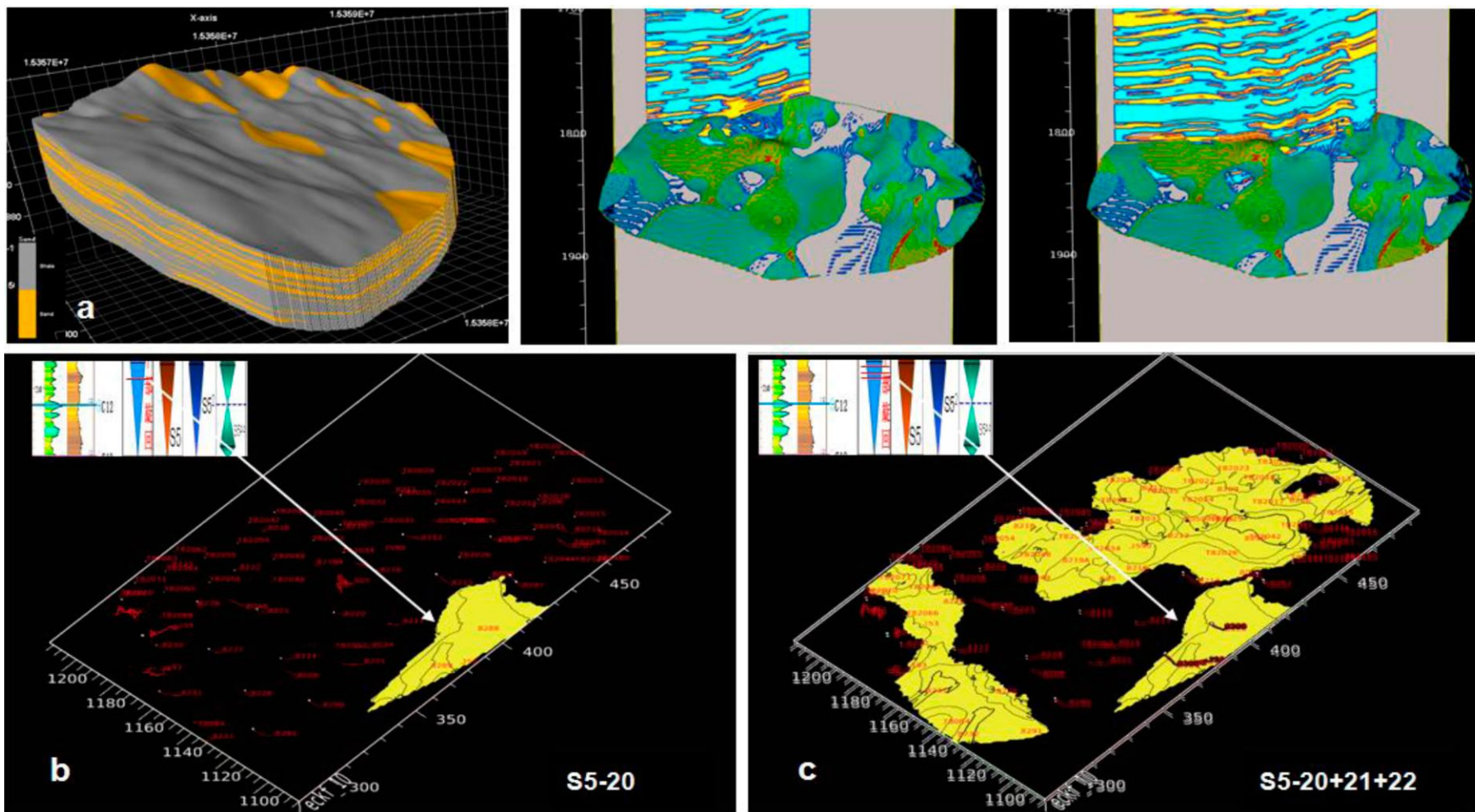
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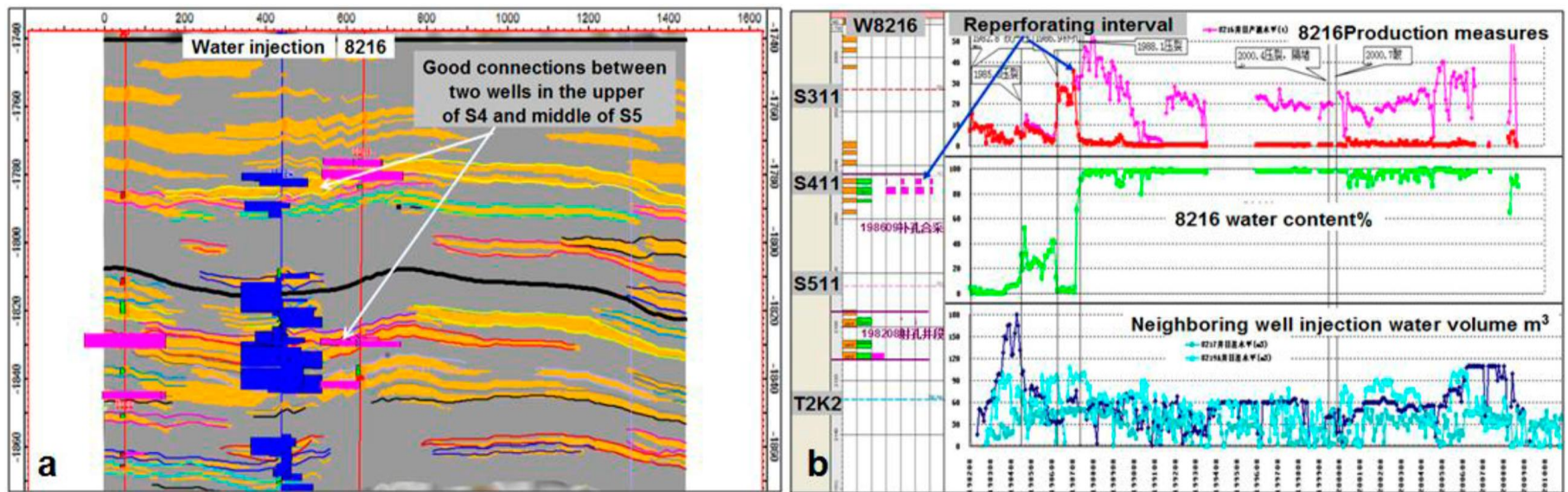
Figure 17. (a) Water injection well and W8216 with sand section; (b) Production curves of well 8216.
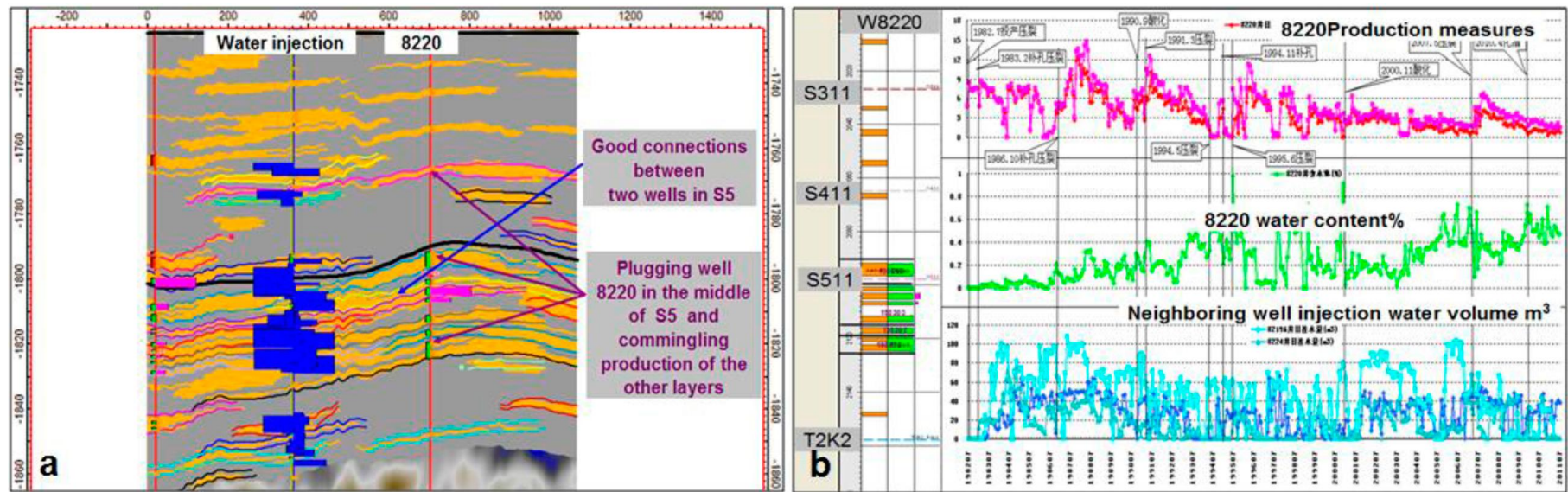
Figure 18. (a) Water injection well and W8216 with sand section; (b) Production curves of well 8216.