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Ellipse evolving common reflection point velocity analysis and its application to oil and gas detection

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Abstract

An ellipse evolving common reflection point (CRP) is an innovative stack method. Under some velocity distribution, we can obtain a real zero-offset section by projecting seismic signals to isochrones along an elliptic trajectory. This paper introduces this method and its velocity analysis. By theoretical model and real seismic data processing, the ellipse evolving CRP velocity analysis more accurately estimates the CRP stack velocity of a complex geology section. The method also more clearly detects an interval velocity anomaly. It is a valuable method of reservoir prediction and oil and gas detection.

Keywords: ellipse evolving, common reflection point, velocity analysis, oil and gas detection, common midpoint

1. Introduction

It is well known that velocity is one of the most important factors in seismic data processing and interpretation. Conventional velocity analysis is based on the hyperbolic normal moveout (NMO) equation $\left(t^2(x) = t^2(0) + x^2/v_{\mathrm{NMO}}^2\right)$ (Yilmaz 2001). Its limitation is that the hyperbolic equation is rigorously correct only for homogeneous, isotropic and horizontal media. The hypothesis is too simple to conform to the actual conditions (Radovich and Levin 1982, Hake 1984, Tsvankin and Thomen 1994).

Since the conventional velocity analysis is inconsistent, geophysicists all over the world have been studying detailed velocity characteristics of various media conditions. They have presented some new and pertinent velocity analysis methods, for example velocity analysis using non-hyperbolic moveout in transversely isotropic media (Alkhalifah 1997), velocity analysis by long-offset seismic data (Carrion 1988), three parameters' velocity analysis (Lehmann and Houba 1985), four parameters' velocity analysis (Li and Yuan 2003, Yuan 2001), quartic-order velocity analysis (Guo *et al* 2003) and so on.

Every velocity analysis stated above has its own practicability and applicability. To reach the desired result, we should adopt a suitable method or a combination of different methods according to the data in question. It is noticeable that all methods above are based on common midpoint (CMP) theory. They are developments and improvements of conventional CMP velocity analysis. In the CMP method, stack velocity is relevant to dip while migration velocity is not. Generally speaking, stack velocity cannot be used as migration velocity.

Comparing with velocity analysis methods mentioned above, an ellipse evolving common reflection point (CRP) is innovative. It throws away the concepts of conventional CMP trace gathering and NMO.

The foundational theory of the ellipse evolving CRP is ray theory. Kondrashkov deduced an ellipse evolving CRP stack equation using Kirchhoff's diffraction integral and contact transformation (Kondrashkov 1977, Kondrashkov and Aniskovich 1998). For homogeneous media, the equation is consistent with the dip moveout (DMO) equation (Hale 1984, Derigovski and Rocca 1981). However, differing from the DMO equation, it includes velocity. Using this method, we

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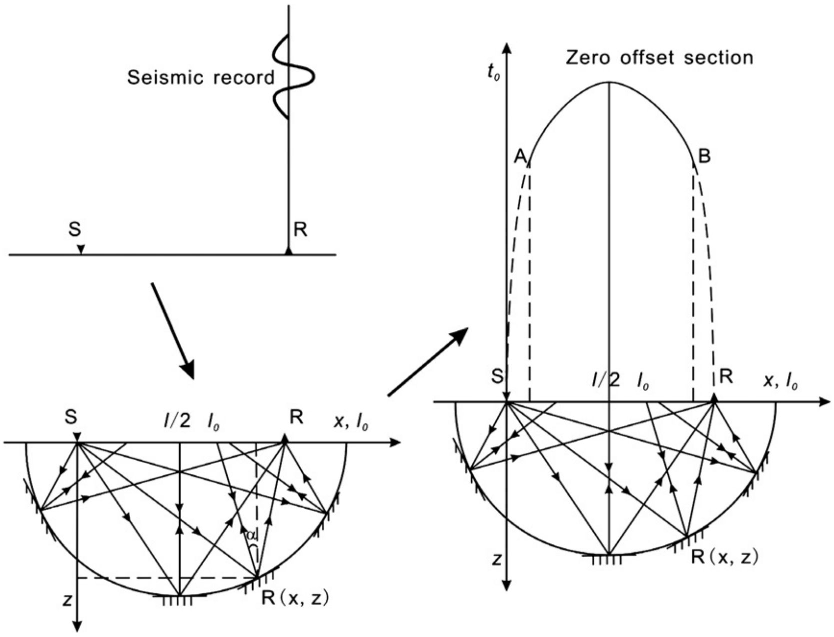


Figure 1. Scheme of the ellipse evolving CRP.

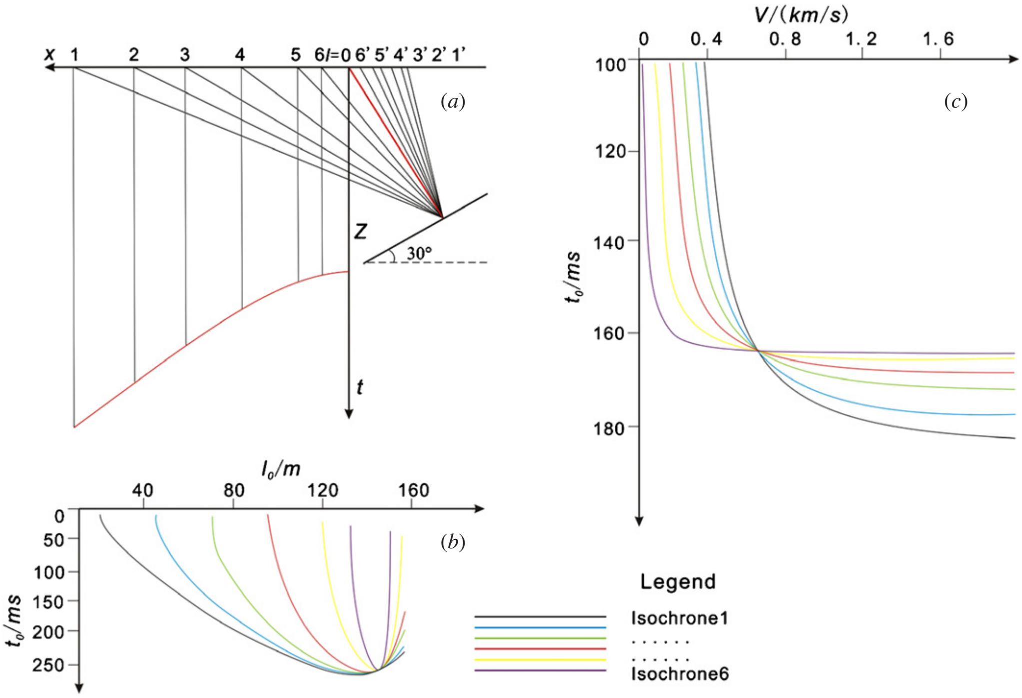


Figure 2. Velocity estimation and common tangent point of isochrones in heterogeneous media. (*a*) CRP ray image and time–distance curves in heterogeneous media; (*b*) six ellipse evolving CRP transformation isochrones contact at one point and (*c*) six ellipse evolving CRP transformation velocity curves intersect at one point.

can estimate only one correct CRP stack velocity of various dipping reflectors from a common shot point gather. The estimated velocity is not relevant to the shapes of reflectors. It can be used in migration. For heterogeneous media, the method introduces two parameters (taking transverse changes of velocity into account). So we can estimate a high precision velocity field and obtain more exact stack imaging of reflectors and diffraction points.

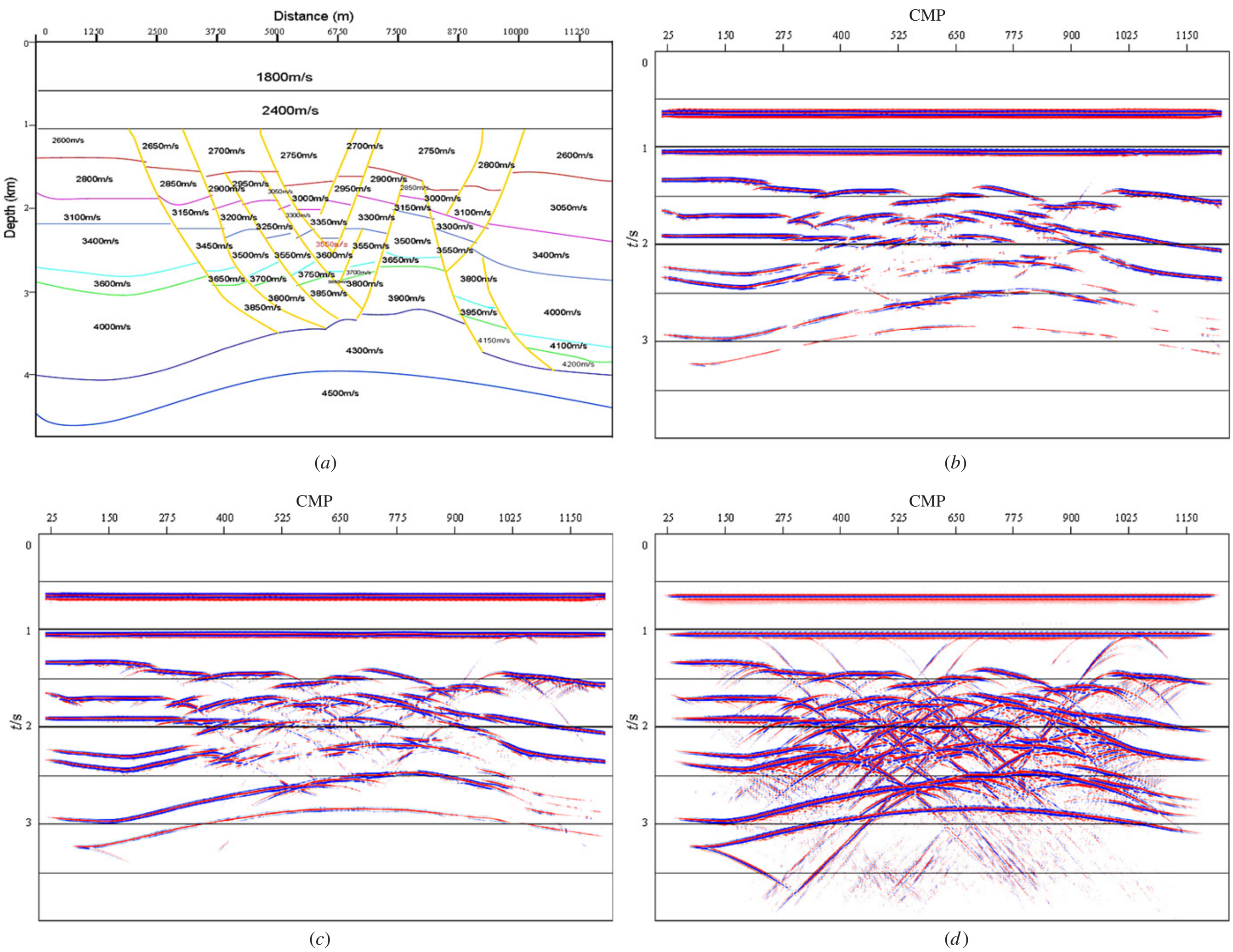


Figure 3. Processing results of a model. (*a*) Depth–velocity model, (*b*) NMO stack section, (*c*) DMO stack section, (*d*) ellipse evolving CRP stack section, (*e*) poststack time migration section based on (*b*), (*f*) poststack time migration section based on (*c*), (*g*) poststack time migration section based on (*d*) and (*h*) prestack time migration section.

2. Methodology

If we draw an elliptical surface, of which the focuses are the source point and the receiver point as shown in figure 1, the receiver response can be obtained from the reflection of any point on the elliptical surface. This is because the rays radiated from one elliptical focus and reflected by any point on the elliptical surface necessarily pass through the other elliptical focus, and their propagating distances are the same (Liu *et al* 2006).

If the velocity is true, a seismic record shoot at x_s, received at x_r and recorded at time t, can be projected to isochrones of a stack data domain (S_0). Then an elliptic arc AB is obtained in the S_0 domain. Points A and B correspond to the projections of reflection points when the down-going rays are nearly horizontal. Thus, in geometry, ellipse evolving of the seismic record is, under some velocity distribution, to evolve the seismic record along the ellipse trajectory. The elliptic arc evolved represents all possible geometric positions of the seismic record in the S_0 domain. When the records from the source–receiver pair (x_s, x_r) are evolved to intervene and stack, maximal stack energy can be formed. Then, events come into being (Kondrashkov *et al* 1998).

So, we can obtain the ellipse transformation equation from the seismic record to the zero offset section:

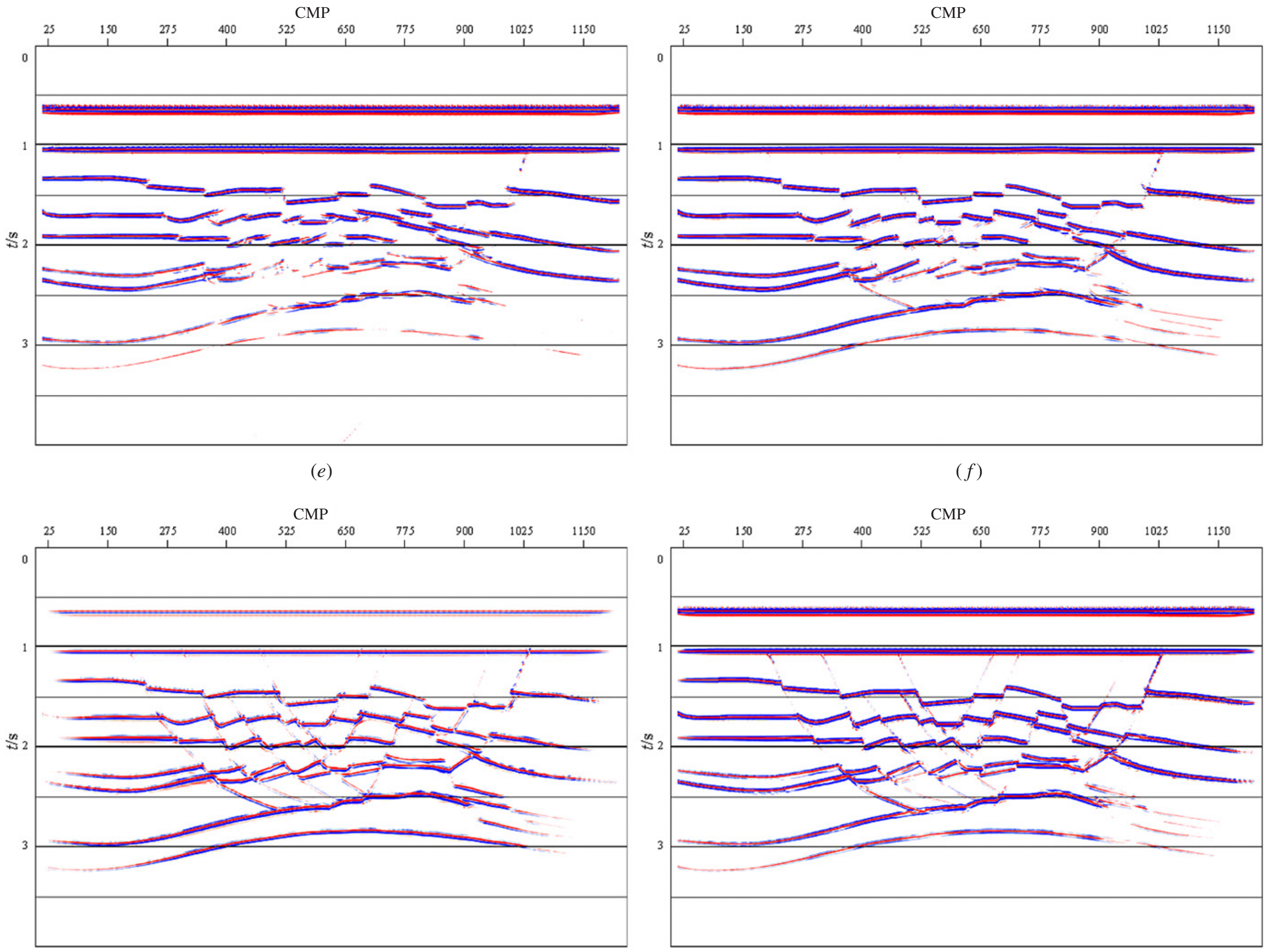
$$\frac{t_0^2}{t^2 - \frac{(x_r - x_s)^2}{v^2}} + \frac{\left(l_0 - \frac{x_r + x_s}{2}\right)^2}{\left(\frac{x_r - x_s}{2}\right)^2} = 1, \tag{1}$$

where x_s is the coordinate of the source point, x_r is the coordinate of the receiver point, t is the total travel time of up-going and down-going waves, v is the propagating velocity, l_0 is the distance between the intersection of normal and surface and source point, and t_0 is the two-way travel time going through normal.

The velocity directly participates in the formation of envelopes when the seismic record is transformed according to equation (1). Equation (1) can be rewritten as

$$v = l \Bigg/ \sqrt{t^2 - \frac{t_0^2}{2}\left(\sqrt{1 + \frac{l^2}{4R^2}} + 1\right)}, \tag{2}$$

where l is the offset and $R = (l_0 - x_s)(x_r - l_0)/(2l_0 - x_s - x_r)$.



(e) (f) (g) (h)

Figure 3. (Continued.)

Referring to the NMO velocity estimating equation (Pusyrev 1979), we can obtain an ellipse evolving CRP velocity v_{stk} estimating equation. When $l \to 0$,

$$v_{\mathrm{stk}} = \left[\frac{1}{2}\frac{\mathrm{d}^2 t^2}{\mathrm{d}l^2}\,|_{l=0} - \frac{t_0^2}{16R^2}\right]^{-1/2}. \quad (3)$$

For heterogeneous media, we need to take the velocity difference of the down-going wave and up-going wave into account. Define the velocity ratio $\gamma = v_2/v_1$ and average velocity $\overline{v} = 2v_1v_2/(v_1+v_2)$, where v_1 is the down-going wave velocity and v_2 is the up-going wave velocity. By expanding equation (1), we can obtain the transformation equation applicable to heterogeneous media:

$$t_0 = \sqrt{(l_0-x_s)(x_r-l_0)\left[\frac{t^2(1+\gamma)^2}{(x_r-x_s)[\gamma^2(l_0-x_s)+(x_r-l_0)]}\right] - \frac{4}{\overline{v}^2}}. \quad (4)$$

The stack velocity v_{stk} of (l_0, t_0) is

$$v_{\mathrm{stk}} = \left[\frac{(1+\gamma)^2}{8\gamma}\frac{\mathrm{d}^2 t^2}{\mathrm{d}l^2}\,|_{l=0} - \frac{t_0^2}{16R^2}\right]^{-1/2}. \quad (5)$$

After introducing r and $\bar{v}$, their values can be estimated according to the maximal stack energy principle and the imaging points focus on the normal location (figure 2). Figure 2(a) shows a heterogeneous media model, where the dip of the reflector $\alpha = 30°$, down-going wave velocity is 1 and up-going wave velocity is 0.5. Figure 2(b) indicates that for all source–receiver pairs which correspond to the same reflection point, their semi-elliptic arcs which evolved in the (l_0, t_0) domain still only contact at one point. The tangent point is the image of the reflection point. Note that curves evolved are no longer standard ellipses. This is because the velocity of the up-going wave is different from that of the down-going wave. Figure 2(c) shows the velocity analysis result of the ellipse evolving CRP. All the velocity curves still only intersect at one point. The velocity at intersection is the stack velocity. It is equal to the average velocity with which the wave propagates in the media.

In the ellipse evolving CRP, the estimated velocity is a limiting effective velocity. It exactly belongs to the fixed common reflection (diffraction) point. No matter what shape the reflector is, the stack velocity is equal to the real media velocity in homogeneous media and the stack velocity is equal

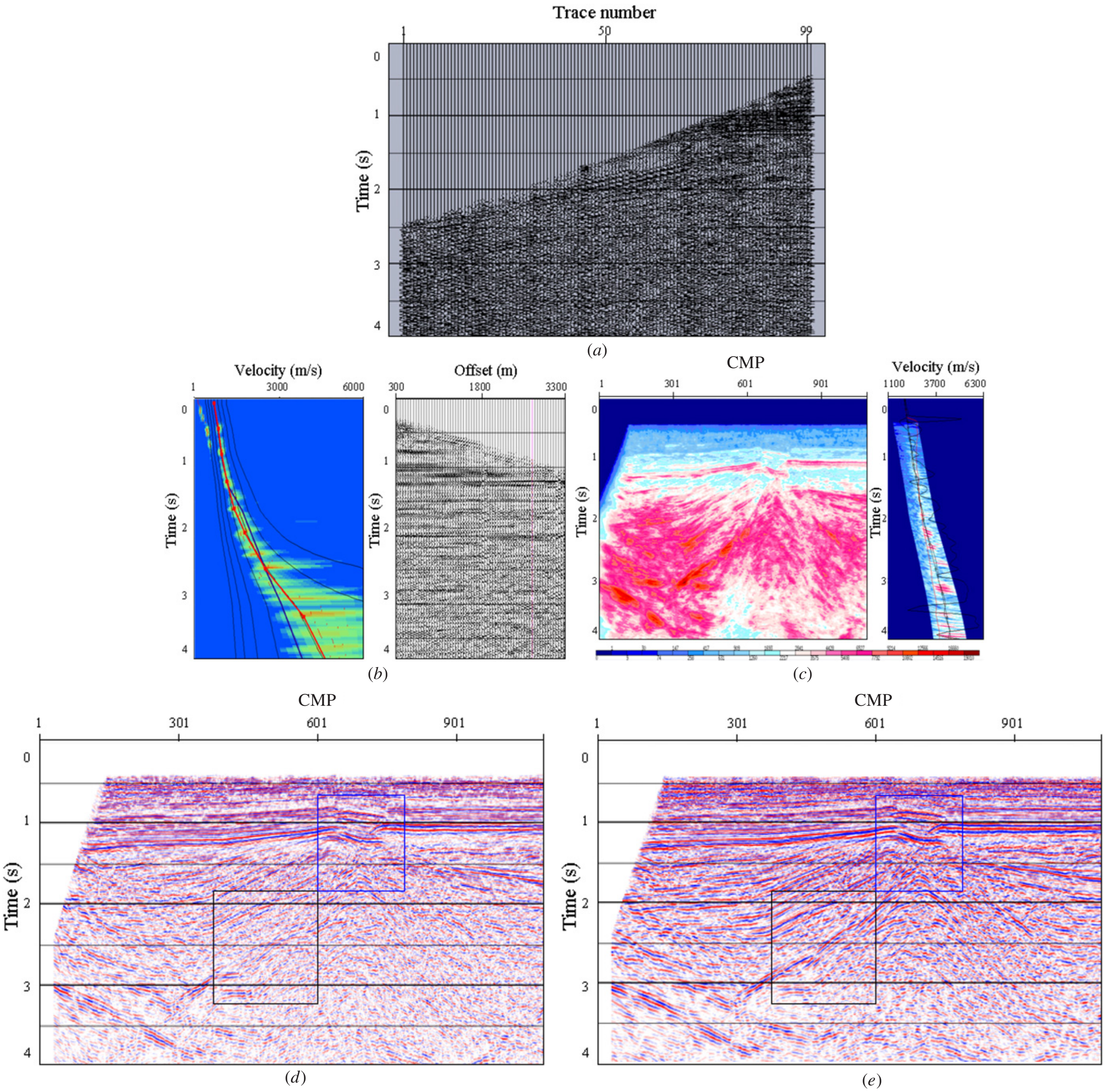
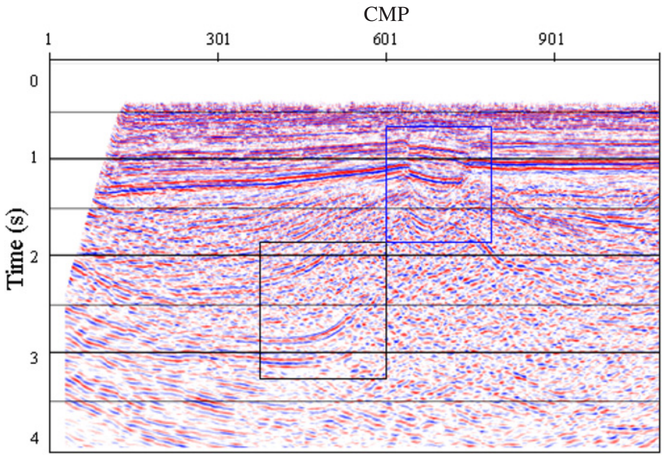


Figure 4. Processing results of 2D seismic data. (*a*) A common shot point gather, (*b*) DMO velocity spectrum and CMP gather after NMO, (*c*) ellipse evolving CRP stack energy section and velocity spectrum, (*d*) DMO stack section, (*e*) ellipse evolving CRP stack section, (*f*) poststack time migration section based on (*d*), (*g*) poststack time migration section based on (*e*) and (*h*) prestack time migration section.

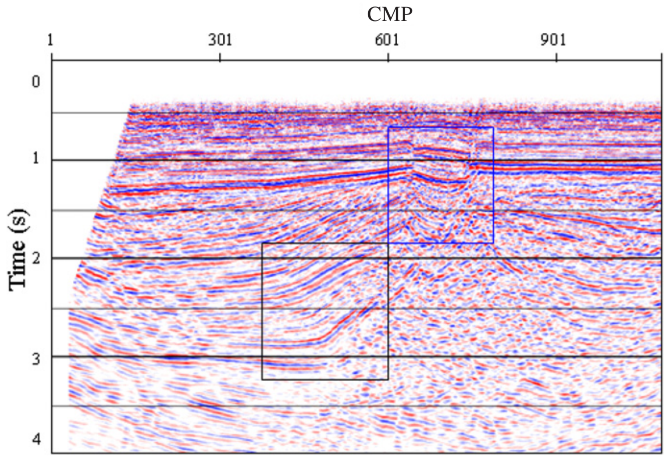
to the average velocity with which the wave propagates in heterogeneous media. Furthermore, signals can be stacked only by using the real CRP velocity.

3. Ellipse evolving CRP applied to model and real seismic data

Figure 3 shows a 2D complicated depth–velocity model and corresponding processing results. The seismic records are obtained by using forward seismic modeling. The total record time is 4 s and the sample interval is 2 ms. The maximal fold is 40. There are 1225 CMPs in the stack section, and the CMP spacing is 10 m. Figure 3(*a*) illustrates the depth–velocity model. There are very complex subsurface structures, rich faults, changeable occurrences and some minor fault planes. The velocity differences of some adjacent blocks are very small (maybe only 50 m s^{-1}). It is difficult to acutely image. Figures 3(*b*)–(*d*) are the stack sections of NMO, DMO and ellipse evolving CRP, respectively. Comparing to the NMO stack section, DMO improves the imaging of dip reflectors. However, it is worse than the ellipse evolving CRP (figure 3(*d*)). In figure 3(*d*), both diffraction and reflection



(*f*)



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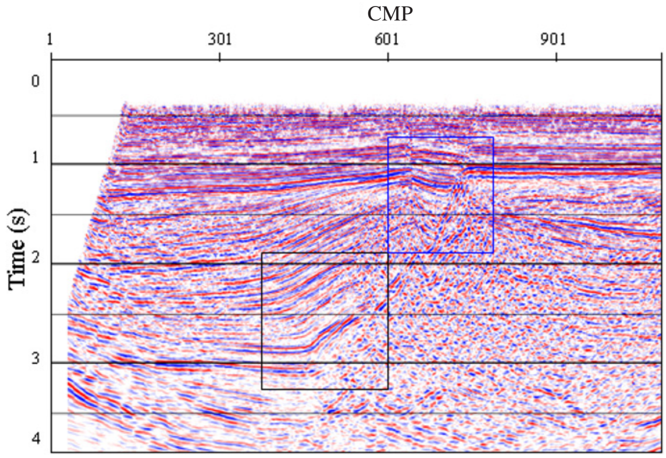

(*h*)

Figure 4. (Continued.)

signals are effectively enhanced. The enhancement of the signal is apparently embodied on its poststack time migration section. Figures 3(*e*)–(*g*) are poststack time migration sections of NMO, DMO and ellipse evolving CRP, respectively. DMO poststack time migration partly improves the imaging of fault planes. But some steeply dipping fault planes are vague and discontinuous. Ellipse evolving CRP poststack time migration greatly recovers the complex structures. Strata contact relationships are very clear. Fault planes are continuous and break points are distinct. Figure 3(*g*) can compare favourably with the prestack time migration section (figure 3(*h*)).

Figure 4 shows the processing results of real 2D seismic data. The total record time is 4 s and the sample interval is 4 ms. The maximal fold is 100. There are 1101 CMPs in the stack section, and the CMP spacing is 12.5 m. Figure 4(*a*) shows a common shot point gather. The S/N ratio is very low. We illustrate the velocity spectrum of CMP 300. Figure 4(*b*) is the DMO velocity spectrum and 4(*c*) is the ellipse evolving CRP velocity spectrum. The colour bar stands for stack energy. Figure 4(*c*) well indicates the subsurface structure frame. We cannot obtain satisfied processing effect by DMO (figures 4(*d*) and (*f*)). The imaging quality of the ellipse evolving CRP (figures 4(*e*) and (*g*)) is better than that of DMO. The fault planes are clearer. The reflection events are richer and more continuous. The S/N ratio and resolution are higher. Figure 4(*g*) is the best approximation of prestack time migration (figure 4(*h*)). It can reliably serve seismic and geology interpretation.

For the layered subsurface, we can obtain effective velocity by the ellipse evolving CRP velocity analysis. When the dip angle of strata is smaller than 60°, the velocity is approximately equal to the root mean square velocity (Kondrashkov 1977, 1998, Kondrashkov and Aniskovich 1998). So we can calculate the interval velocity by using the Dix formula. The interval velocity section can predict an interval velocity anomaly. We can improve the interval velocity precision of the object area by horizon velocity analysis. Detailed steps are as follows: (i) displaying the stack section and picking up the top horizon and bottom horizon of the object area, (ii) displaying the total root mean square velocity section and picked horizons, (iii) recalculating the root mean square velocity based on picked horizons, (iv) recalculating the interval velocity of the object area based on (iii) and the Dix formula. The new interval velocity is more precise than the old one. Then, the interval velocity anomaly of the object area can be shown if any. Figure 5 shows an example—using an interval velocity anomaly to successfully recognize lithological oil and gas pool. It is a seismic section

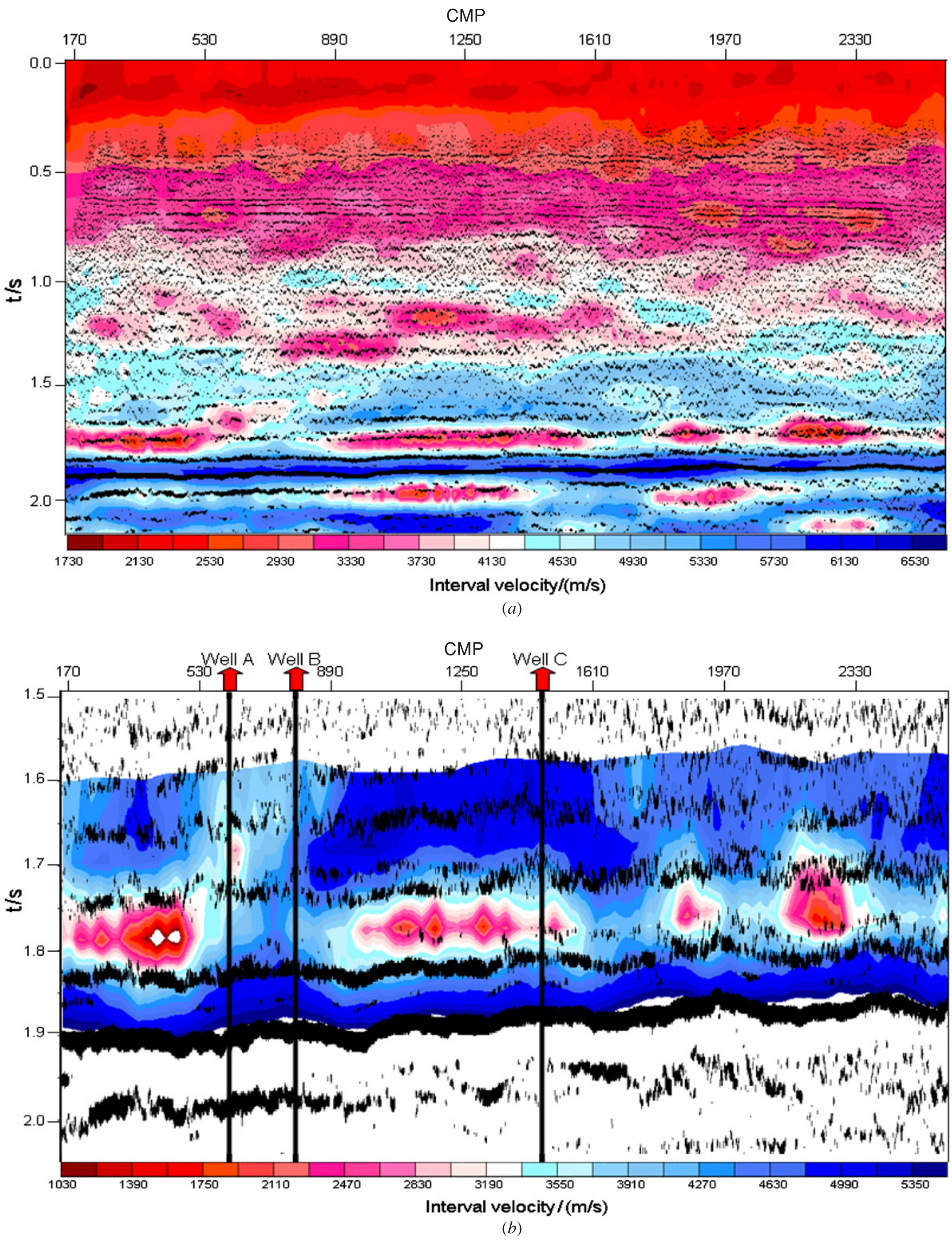

Figure 5. A seismic section passing through three wells of Western China with rich seams of gas. (*a*) Stack section and interval velocity section and (*b*) horizon velocity analysis of the object area.

passing through three wells of western China where rich seams of gas are stored. Well A outputs very little gas, well C is rich with gas, while well B is dry. The colour bar in the figure stands for the interval velocity value. The low interval velocity anomaly corresponds to the gas pool. Well A is located at the boundary of the anomaly region, well C is in the anomaly region and well B is located beyond.

4. Conclusions

Comparing with the CMP method, the ellipse evolving CRP changes not only the transformation arithmetic of seismic data, but also the velocity estimating method. Just so, it throws off the basic limitation of the CMP method in which the velocity is regarded as a stack parameter. It directly processes common shot point gather data. Its typical feature is that velocity directly participates in calculating in the process of stacking. The maximal stack energy can be obtained only by using true CRP stack velocity. In contrast, obtaining maximal stack energy means that the estimated velocity is true. The velocity estimated by the ellipse evolving CRP is limiting effective velocity. It exactly belongs to the fixed common reflection (diffraction) point. It is independent of the shapes of reflectors. It is more reasonable to establish a migration velocity field based on it.

The ellipse evolving CRP covers all the CRP trajectories. It makes use of all kinds of effective information (strong or weak, horizontal or steeply dipping, and reflection or diffraction information) to implement velocity analysis and stack. Therefore, its processing effect is surely superior to the conventional CMP method.

By using the ellipse evolving CRP velocity analysis, we can estimate not only a high precision stack velocity field, but also a more accurate interval velocity field by which we can analyse and recognize oil and gas pools more exactly. Many tests confirm that this method is a good assistant method of reservoir prediction and oil and gas detection.

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