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Seismic Sedimentology Interpretation Method of Meandering Fluvial Reservoir: From Model to Real Data

Tao Zhang[1], **Xianguo Zhang***[2], **Chengyan Lin**[2], **Jingfeng Yu**[3], **Shouxiu Zhang**[4]
1. *College of Earth Science and Engineering*, *Shandong University of Science and Technology*, *Qingdao* 266590, *China*
2. *School of Geosciences*, *China University of Petroleum*, *Qingdao* 266580, *China*
3. *Exploration and Development Research Institute*, *Xinjiang Oilfield Company*, *Karamay* 834000, *China*
4. *Dongxin Oil Production Plant*, *Shengli Oilfield Company*, *Dongying* 257000, *China*

ABSTRACT: Reservoir architecture of meandering river deposition is complex and traditional seismic facies interpretation method cannot characterize it when layer thickness is under seismic vertical resolution. In this study, a seismic sedimentology interpretation method and workflow for point bar characterization is built. Firstly, the influences of seismic frequency and sandstone thickness on seismic reflection are analyzed by outcrop detection with ground penetrating radar (GPR) and seismic forward modeling. It is found that (1) sandstone thickness can influence seismic reflection of point bar architecture. With the increasing of sandstone thickness from 1/4 wavelength (λ) to λ/2, seismic reflection geometries various from ambiguous reflection, "V" type reflection to "X" type reflection; (2) seismic frequency can influence reservoirs' seismic reflection geometry. Seismic events follow inclined lateral aggradation surfaces, which is isochronic depositional boundaries, in high frequency seismic data while the events extend along lithologic surfaces, which are level, in low frequency data. Secondly, strata slice interpretation method for thin layer depositional characterization is discussed with seismic forward modeling. Lastly, a method and workflow based on the above study is built which includes seismic frequency analysis, 90° phasing, stratal slicing and integrated interpretation of slice and seismic profile. This method is used in real data study in Tiger shoal, the Gulf of Mexico. Two episodes of meandering fluvial deposition is recognized in the study layer. Sandstone of the lower unit, which is formed in low base level stage, distributes limited. Sandstone distribution dimension and channel sinuosity become larger in the upper layer, which is high base level deposition.

KEY WORDS: point bar, reservoir architecture, seismic sedimentology, stratal slice.

0 INTRODUCTION

Meandering river is one of the major deposition types in nonmarine reservoirs. Study of meandering fluvial deposition can be dated back to the beginning of the 20th century (Yang, 1971; Langbein and Leopold, 1966; Leopold and Wolman, 1960; Eakin, 1910; Jefferson, 1902). Miall developed the theory and method of reservoir architecture and built a hierarchic characterization method of fluvial architecture (Miall, 2002, 1988, 1985). In recent years, reservoir architecture and depositional model of meandering rivers were studied a lot both in outcrops and in reservoirs (Ma et al., 2008a, b; Wu S H et al., 2008; Wu Y Y et al., 2008; Yue et al., 2007; Xue, 1991). In meandering fluvial reservoirs, sandstone connectivity, reservoir architecture of point bars and fluid flow in reservoirs are all very complex. They can influence oil development and remaining oil distribution (Miall, 2006; Yue, 2006).

Seismic slice provides a useful tool for sedimentology interpretation of fluvial reservoirs (Maynard et al., 2010; Hart, 2008; Wood, 2004; Carter, 2003; Posamentier and Kolla, 2003; Miall, 2002; Posamentier, 2001). There are three types of seismic slices including time slice, horizontal slice and stratal slice. Stratal slice is proved to be the most geological one among the three types and it has been widely used in sedimentology study in recent years (Dong et al., 2008; Zeng and Hentz, 2004; Posamentier and Kolla, 2003; Posamentier et al., 2000, 1996; Peyton et al., 1998; Zeng et al., 1998a, b).

In seismic interpretation of meandering fluvial reservoirs, there are two important issues: What control seismic reflection of point bars and how to characterize reservoir architectures of thin beds under seismic vertical resolution? Seismic facies, which was developed in 1970's, has played a very important role in seismic interpretation (Vail and Mitchum, 1977), but it is mainly on petroleum exploration scale and takes reservoir architecture as the only factor that controls seismic facies. In this study, influences of seismic frequency and sand thickness on seismic reflection in meandering fluvial reservoirs are analyzed with seismic forward modeling, GPR detection of outcrops and real data study. The application of stratal slice in seismic sedimentology interpretation is analyzed with model

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*Corresponding author: zhangxianguo@upc.edu.cn

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data. Then method for seismic sedimentology interpretation on petroleum development scale, which is to characterize reservoir architecture of point bars, is proposed and practiced in real data from the Gulf of Mexico.

1 GEOLOGICAL BACKGROUND

The study area, Tiger Shore Oil Field, is located in the Gulf of Mexico. It is geographically near the state of Louisiana, USA (Fig. 1). It is at the center of Gulf of Mexico Basin. The strata of Triassic, Jurassic, Cretaceous, Paleogene, Neogene and Quaternary are developed upward in the area (Table 1). The major oil-bearing layer is Miocene. Sedimentary system and sequence stratigraphy of Miocene have been studied a lot from 1980's (Hentz and Zeng, 2003; Galloway, 1989; Winker, 1982), but there is not so much study on Pliocene of this area. Wood (2007) made sequence stratigraphy and seismic geomorphology study of Pliocene of the whole 3D seismic survey. Her study showed that meandering fluvial depositions developed in Pliocene (Wood, 2007). But in the previous work, only the boundary of the point bar complex was mapped as a whole, reservoir architecture of the point bar complex was not interpreted.

There is little data of Pliocene because it is not oil production layer in this area. There are only wireline logs and seismic data. No drilling cores and rock analysis data is available. Seismic trace interval is 10 m and dominant frequency is about 35 Hz. The relationship between acoustic time (AC) and gamma ray (GR) in wells shows that P-wave velocity of sandstone is lower than that of mudstone in Pliocene (Fig. 2). It means sandstone has lower acoustic impedance than mudstone here. This is the base of seismic interpretation.

Table 1 Strata column of Tiger Shore (after Marin et al., 1998)

Erathem	System	Series	Chrono-zones	Geologic time
Cenozoic	Quaternary	Holocene		0.01
		Pleistocene	UPL	
			MPL	
			LPL	2.8
	Neogene	Pliocene	UP	
			LP	5.5
		Miocene	UM3	
			UM1	10.5
			MM9	
			MM7	
			MM4	18.5
			LM4	
			LM2	
			LM1	24.8
	Paleogene	Oligocene	O	38
		Eocene	E	55
		Paleocene	L	63
Mesozoic	Cretaceous		K	138
	Jurassic		U	205
	Triassic		TR	240

2 INFLUENCE FACTORS OF SEISMIC REFLECTION IN MEANDERING RIVER RESERVOIRS

Reservoir architecture is considered as the only factor that controls seismic facies in seismic stratigraphy (Sangree and Widmier, 1977; Vail and Mitchum, 1977). In this study, seismic forward modeling, outcrop detection with ground penetrating radar (GPR) and real data study are employed to reveal how seismic frequency and sandstone thickness control seismic reflection.

2.1 Seismic Frequency

Zeng and Kerans's work in carbonate platform and delta front proposed that seismic frequency controls geological meaning of seismic events (Zeng and Kerans, 2003). This is a very important and challenging new idea for seismic interpretation. But this idea was proved by numerical seismic modeling without efficient evidence from real data. Meanwhile, in meandering fluvial reservoirs, what is the geologic meaning of seismic events? How seismic frequency influences reflection events? To resolve the above problems, GPR is employed in outcrop detection to simulate seismic reflection of subsurface reservoirs.

GPR is equipment for detection of outcrop or shallow subsurface layers using high frequency electromagnetic wave. It is similar to surface seismic survey and provides geophysical reflection of geologic surfaces. Previous study has proved that GPR can be used to simulate seismic reflection in seismic interpretation study (Lee et al., 2007; Neal, 2004; Zhang et al., 2004; Tronicke et al., 2002). Fluvial outcrop of Chengshanhou Formation in Xintai-Mengyin area is chosen. Geologic profiles of outcrop are described and measured firstly and then the profiles are detected with GPR. Different frequency antennas are used in the detection to study seismic frequency's influence on

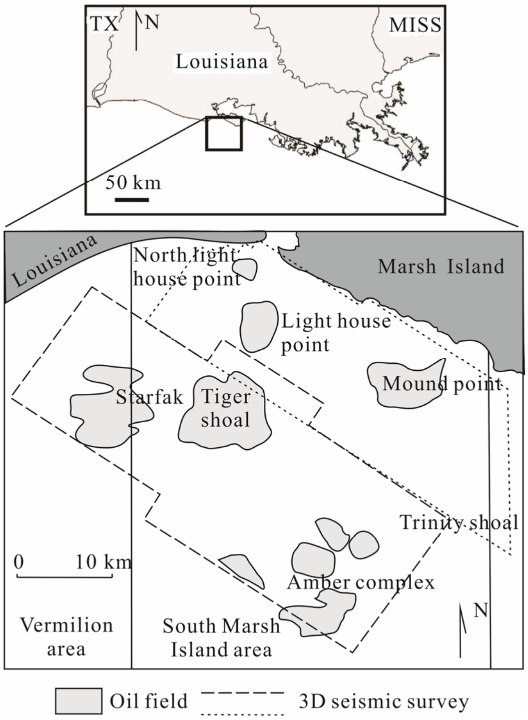

Figure 1. Geographic location of the study area (after Wood, 2007).

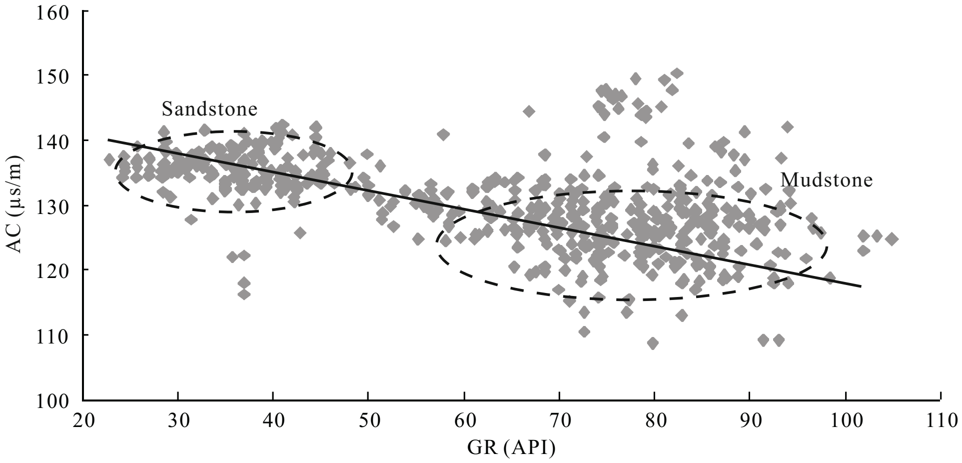

Figure 2. The relationship between AC and GR.

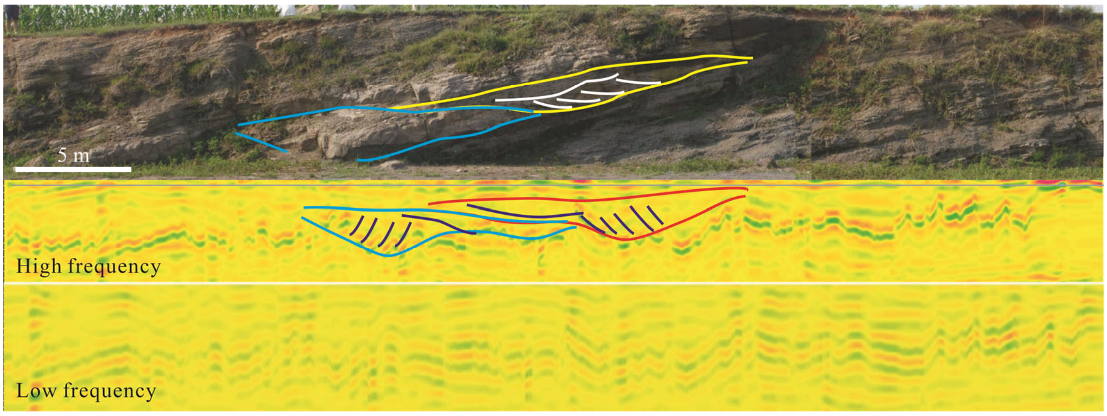

Figure 3. Outcrop profile and its GPR detection sections of different frequencies.

its reflection.

Comparing GPR profiles of different frequencies with geologic outcrop profile (Fig. 3), it can be found that: (1) in high frequency GPR data, reflection events are consistent with the lateral aggradation surfaces which are isochronic. The isochronic surfaces in outcrop can be recognized in GPR reflection profiles; (2) in low frequency GPR data, reflection events are parallel to lithologic surfaces and lateral aggradation surfaces in point bar cannot be interpreted (Fig. 3). This means GPR (or seismic) frequency can control the geological meaning of reflection events. So it is necessary to analyze seismic frequency and the geological meaning of seismic events firstly in sedimentologic interpretation of seismic data.

2.2 Sand Thickness

Because of the depositional autocyclicity, architectures of meandering fluvial reservoirs formed in different hydrodynamic circumstances are similar, but their thickness is different. Sandstone thickness is a very important factor that influences seismic reflection especially for thin layers under seismic vertical resolution. Seismic forward modeling of point bar is employed in this study to reveal the influence of sandstone thickness (Fig. 4).

2.2.1 Seismic forward modeling

A 3D point bar model is built according to the classic meandering fluvial sedimentary model. Velocities of different layers in the model are from real meandering fluvial reservoir of Pliocene, in Tiger shoal, the Gulf of Mexico. Sandstone velocity is 2 240 m/s and that of shale is 2 390 m/s. For thin bed, seismic event in 90° seismic data is proved to have lithologic meaning (Zeng and Backus, 2005a, b), so Ricker wavelet is

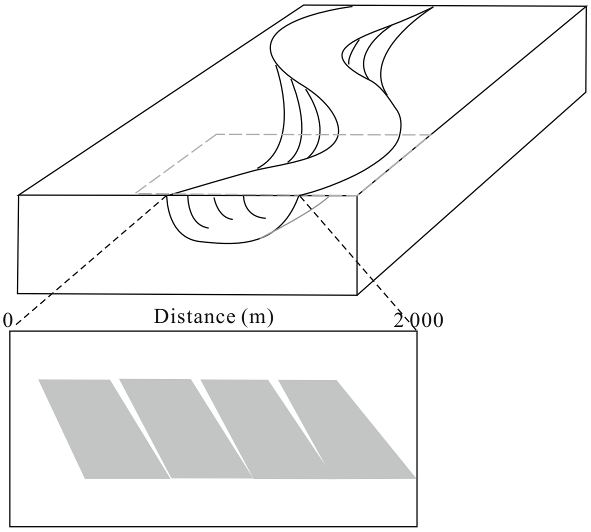

Figure 4. Geologic model of point bar for seismic forward modeling.

converted 90º as wavelet for the forward modeling. The forward modeling seismic data is a 90° one.

In the modeling, three models, whose thickness are respectively $\lambda/4$ (λ is seismic wavelength), $\lambda/3$ and $\lambda/2$, are built. Seismic modeling profiles are in Fig. 5. For thin layer of $\lambda/4$, reservoir architecture of point bars cannot be recognized and reflection of the whole point bar is in a single peak (the red reflection event in Fig. 5). Seismic events are horizontal and amplitude changes laterally (Fig. 5a). Architecture of point bars cannot be interpreted geologically in such a seismic profile and the horizontal amplitude changes can even be taken as noise.

With thickness increasing, seismic reflection becomes complex. In $\lambda/3$ thick model, abnormal seismic reflection of inclined lateral aggradation surfaces is obvious. But the dip direction of lateral aggradation surfaces in point bars cannot be uniquely interpreted (Fig. 5b). When point bar is thick enough, seismic reflections of its top and bottom are separated (Fig. 5c). Seismic events at the lateral aggradation surfaces are complex and their geometry like ‘X’. Dip direction of lateral aggradation surfaces cannot be interpreted. So it is hard to interpret the reservoir architecture of point bars no

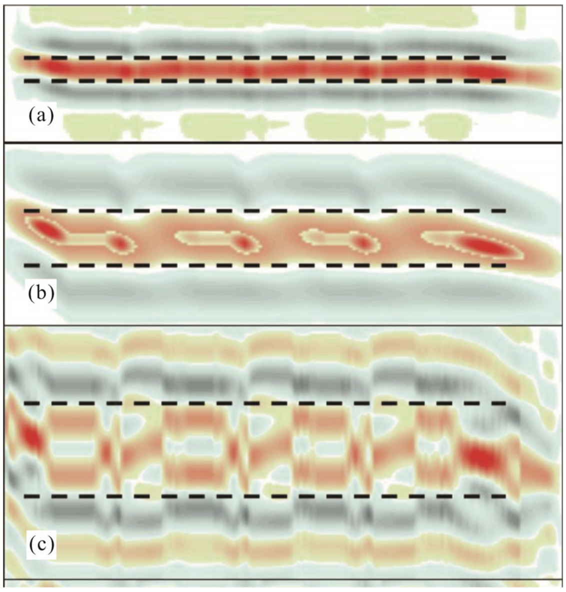

Figure 5. Seismic forward modeling of point bar with different thickness. Point bar thickness: (a) $\lambda/4$; (b) $\lambda/3$; (c) $\lambda/2$.

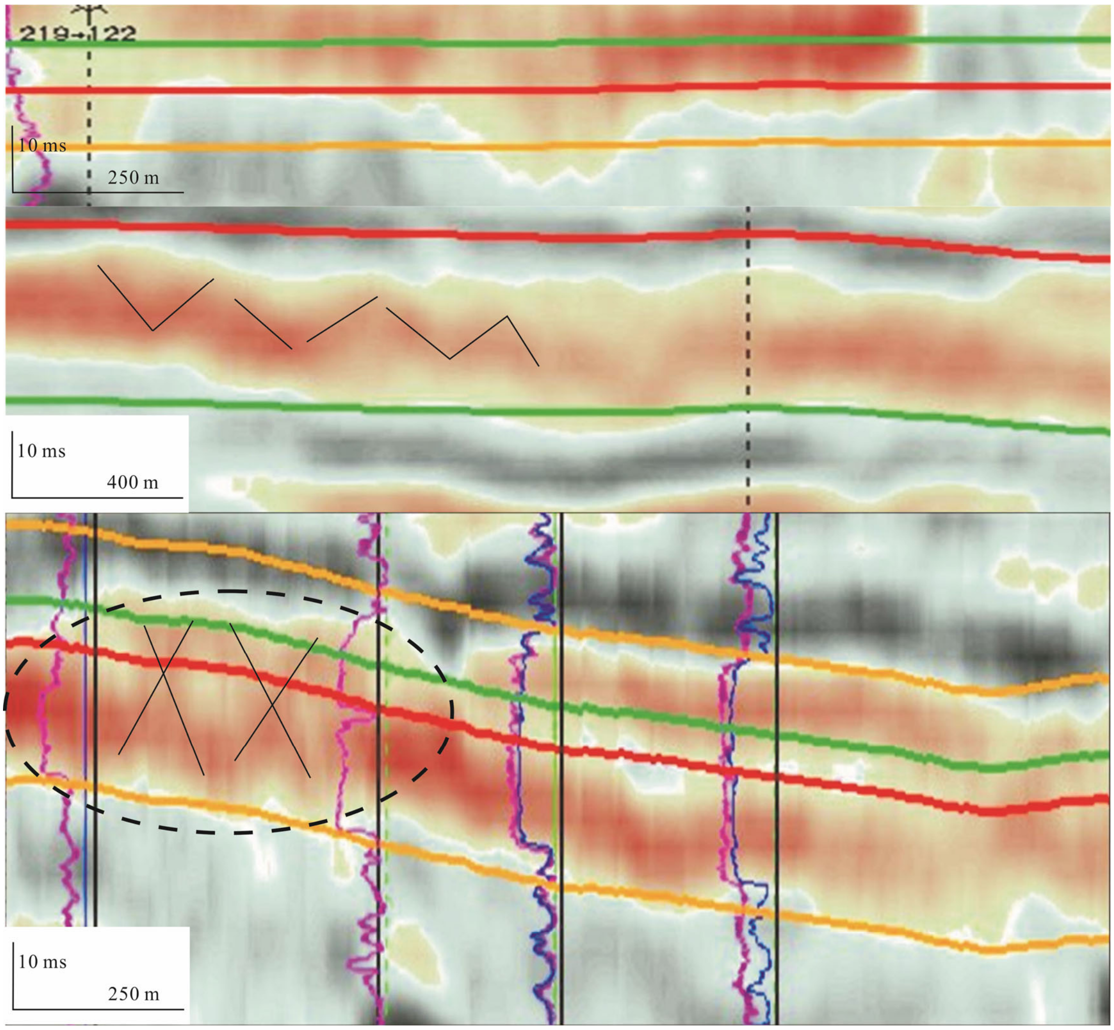

Figure 6. Seismic reflection of point bars with different thickness in real 3D data (Tiger shoal, the Gulf of Mexico).

matter what its thickness is.

2.2.2 Real data study

Real data study is made in Tiger shoal, the Gulf of Mexico. Seismic data is calibrated with well logs. The three types of seismic reflection in the above forward modeling can be observed in real seismic data (Fig. 6). The up picture in Fig. 6 is seismic reflection of point bars that is thinner than $\lambda/4$. Its seismic reflection is similar to that in Fig. 5a.

In real data study, sand body thickness is 18 m (Fig. 6b). It is about $\lambda/3$. Its seismic reflection is the "V" type. It can indicate point bar reservoir is not homogeneous but the dip direction of the lateral aggradation surfaces cannot be interpreted. With layer thickness increasing, seismic reflection changes to "X" type.

3 STRATAL SLICE INTERPRETATION METHOD: ON MODEL DATA

Outcrop detection with GPR and seismic forward modeling show that seismic reflection of point bar is very complex and it is hard to interpret its reservoir architectures. So information from seismic section is not enough to characterize the reservoir architectures. In seismic sedimentology study, strata slice is a useful tool for interpretation (Zeng and Hentz, 2004; Posamentier and Kolla, 2003; Posamentier et al., 2000; Zeng et al., 1998a, b).

There are three kinds of slices including time slice, horizontal slice and stratal slice. Time slice extends along seismic travel time while horizontal slice is parallel to a strata surface (top or bottom) which is usually called horizon in seismic interpretation software. Stratal slice is made proportionally between two isochronic reference horizons (Zeng et al., 1998a). Although stratal slicing has some limits (Qian, 2009; Zhang et al., 2007), it is still the best method of the three kinds of slices in sedimentology study of isochronic units. This has been proved theoretically and practically (Zhang, 2010; Zhang et al., 2010a, b; Zeng et al., 1998a, b).

In meandering fluvial reservoirs, architecture elements, such as interlayers between lateral aggradation units, are usually thinner than seismic vertical resolution. So it's difficult to characterize reservoir architecture of point bars only on seismic profiles. The horizontal dimension of sand body (H), thickness of single sand body which is formed in a single sedimentary episode (V), seismic vertical resolution (R_v) and horizontal resolution (R_h) follow such an equation

$$\frac{H}{R_h} \gg \frac{V}{R_v} \tag{1}$$

Equation (1) means that we can use planar information of seismic data to interpret sand body that is too thin to be recognized on seismic profiles. This can help to characterize meandering fluvial architectures. There are two key points in such an interpretation. One is depositional sand body recognition on plane and the other is the original relationship between sand bodies' planar characteristics and vertical characteristics.

The above interpretation method can be proved through seismic forward modeling. In the $\lambda/4$ thick point bar model, seismic events are continuous. There is no abnormal reflection

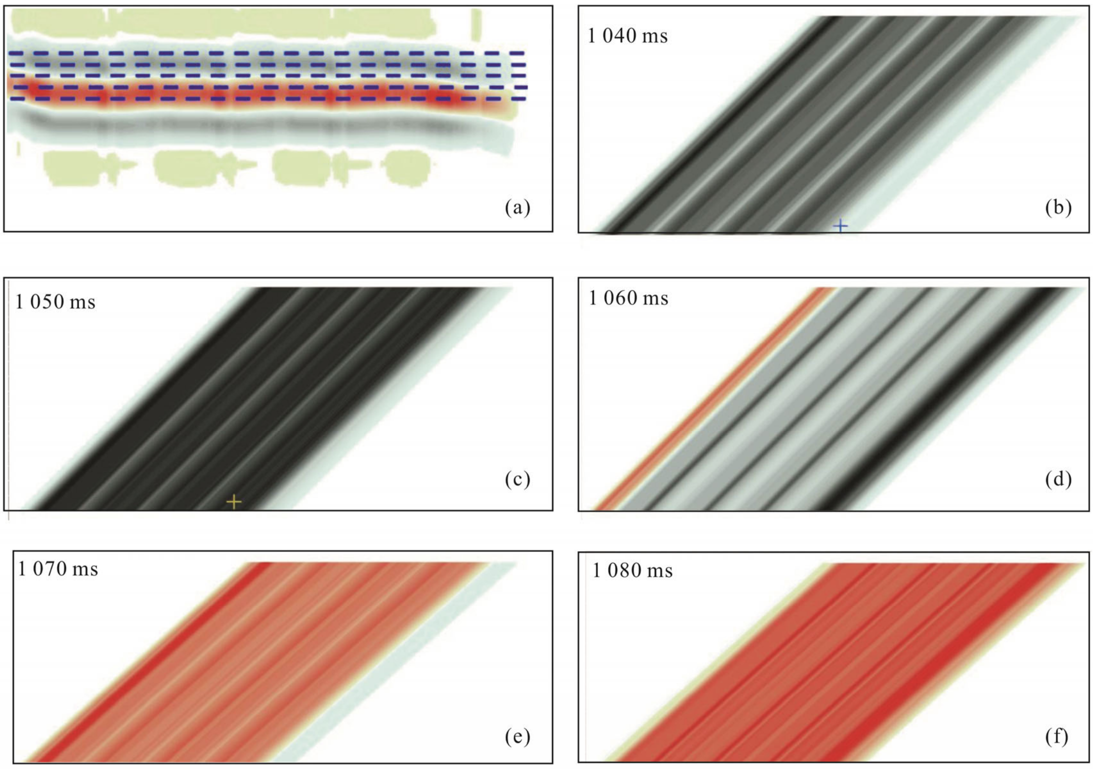

Figure 7. Seismic profile and slices of seismic forward modeling. The geologic model is in Fig. 4 and the point bar thickness in the model is $\lambda/4$. Figures (b)–(f) are respectively seismic slices at depth of 1 040–1 080 ms. Seismic slices are vertically at the blue dash lines in (a).

except for some slight amplitude changes (Fig. 7a). Architecture of point bars, such as the trend of the river on plane and the dip of the aggradation surface in vertical, cannot be recognized in seismic profiles. But reservoir architectures can be interpreted easily on seismic slices. In any seismic slice of the modeling, seismic reflections of both the river boundary and lateral aggradation units boundaries are clear (Figs. 7b–7f). It can be interpreted that there are four lateral aggradation units in the point bar complex and trend of the river is northeast. From modern deposition and outcrop study of meandering rivers, we know that the dip of lateral aggradation surfaces has a close original relationship with its planar trend and the river's planar geometry. So, lateral aggradation surfaces, which cannot be interpreted on seismic profile, can be characterized on stratal slices. With this method, a geologically reasonable and unique seismic interpretation for point bar architecture can be made.

4 METHODOLOGY

This article is the study of seismic sedimentology interpretation method and is focus on how to interpret reservoir architectures of point bar complex with seismic data. Basic geology study with wells has been made (Zhang, 2010; Wood, 2007) and is not included in this article.

Because of their influences on seismic reflection, seismic frequency and sand body thickness are analyzed firstly. Dominant seismic frequency is about 35 Hz and wavelength is about 56 m. Most single sand bodies are thinner than 14 m ($\lambda/4$). Their seismic reflection on profile is like type (a) of Fig. 5. So stratal slice is needed to characterize the reservoir architectures.

Then make 90º phasing to convert seismic data into a 90º one. As seismic forward modeling, seismic data used in real data study is a 90º one. Zeng and Backus's study proved that seismic event has lithological meaning for thin beds in 90º seismic data (Zeng and Backus, 2005a, b).

For sand bodies that are thinner than $\lambda/4$, planar position of lateral aggradation surfaces in point bars can be finely characterized on stratal slices. After planar geometry of the river and lateral aggradation surfaces' position of point bars are interpreted, dip direction of lateral aggradation surfaces can be determined with deposition model from modern deposition and outcrop study. Traditional seismic interpretation is line by line. It is in fact a 2D interpretation method for 3D data. In this study, to make a geological characterization of reservoir architecture, information from both seismic profiles and stratal slices are combined. So this is a real 3D interpretation. In such a workflow, chair display mode is a useful tool in the 3D interpretation.

5 RESULT: REAL DATA INTERPRETATION

It developed meandering fluvial deposition in Pliocene in Tiger shoal, the Gulf of Mexico. Most single sand bodies are under seismic vertical resolution ($\lambda/4$). Their seismic reflection is similar to type (a) of the modeling (Fig. 5a). Reservoir architectures of point bar complex cannot be characterized on seismic profile.

Study stratum is divided into 2 units by the interlayer. The two units are formed in different depositional stages (Zhang, 2010) and the dip angles in the dipmeter log have a sudden change at the surface between them (Fig. 8). In stratal slice interpretation of the lower unit, we can see architecture of the reservoirs including boundaries of lateral aggradation units, river boundaries and abandoned channels (Fig. 9). It is residual deposition of meandering fluvial in the early depositional stage.

Dimension of sandstone distribution in the lower unit is small. There are three main channels extending from the north to the south in the area. Area of sandstone is small and their planar distribution is like narrow belts (Fig. 9).

In the upper unit of the strata, sandstone distributes widely. The sinuosity of meandering river is larger than that in the lower unit. There develops a large point bar complex, four narrow channels and a wide river valley in the study area (Fig. 10).

It is interpreted slice by slice and the sedimentary history is revealed from the bottom to the top of the layer. So the forming of the point bar complex can be reconstructed.

6 INTERPRETATION

From the seismic interpretation, it indicated that there developed meandering fluvial depositions of two episodes in the study area.

In the early stage, channels are narrow and sandstone distribution is limited. Bank of the channels is stable. The lower unit is deposition in a low base level stage. Sedimentary base level rises with time and sandstone distribution become wider in the upper unit of the study layer.

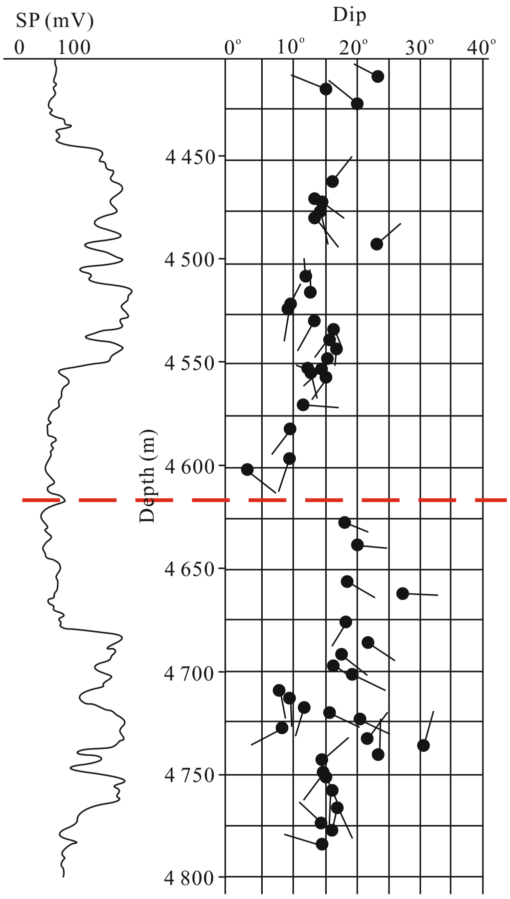

Figure 8. Dipmeter log of Well A. Red line is the surface between the upper and lower units.

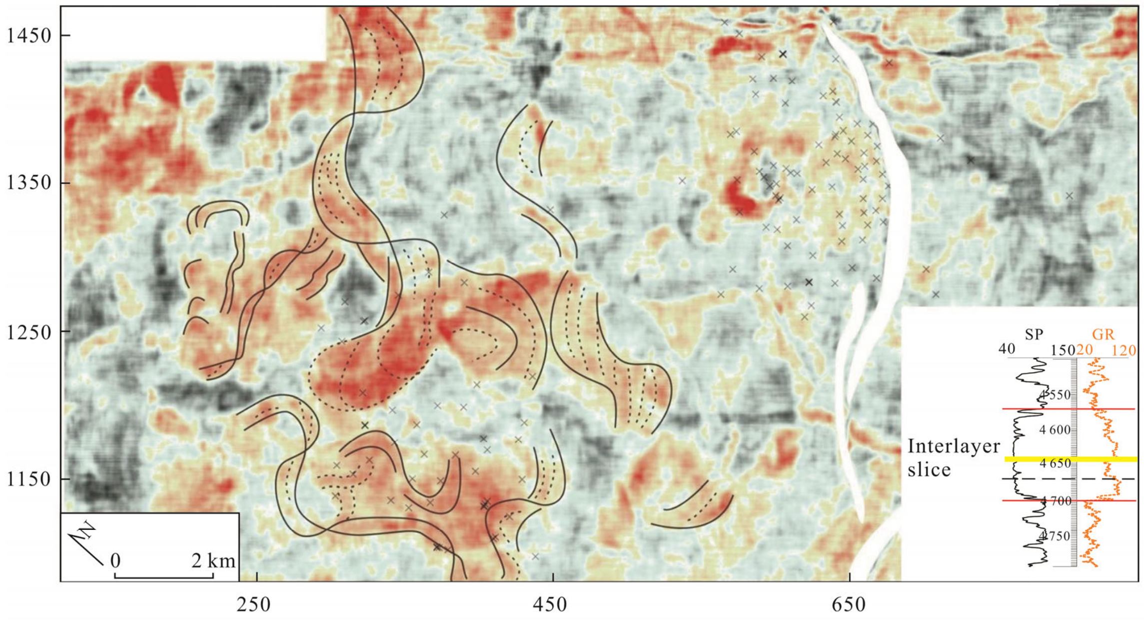

Figure 9. Slice interpretation of the lower unit of the study layer.

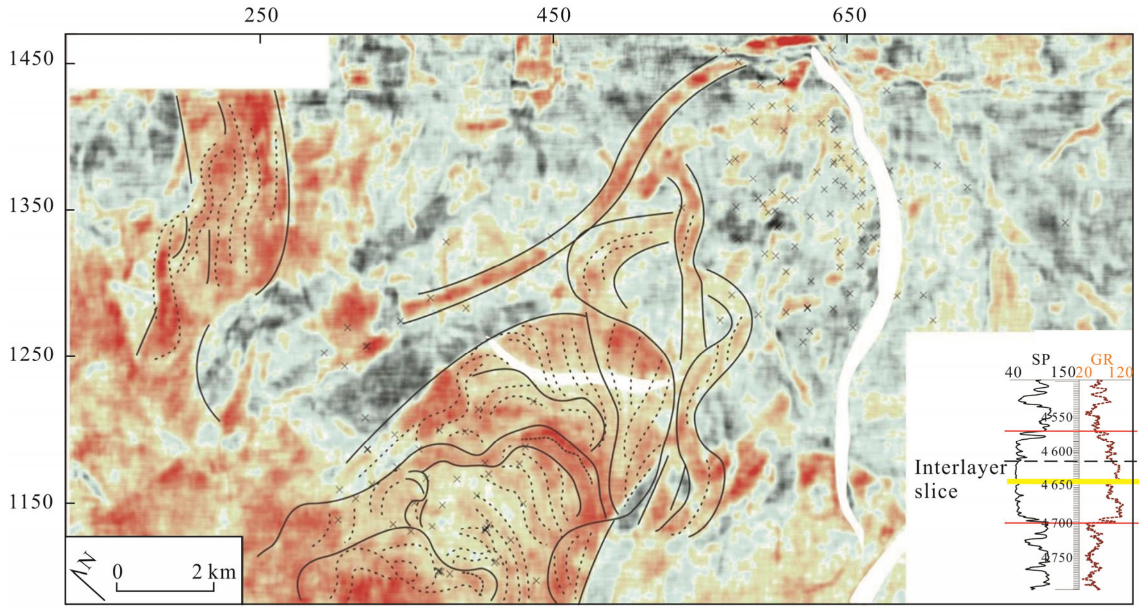

Figure 10. Slice interpretation in the upper unit of the study layer.

In the late stage, it can be observed according to the relationship of the channels that the point bar complex in the upper unit is formed in three sub-episodes. Sinuosity of the river becomes larger than that of the early stage. The interpreted point bar is residual deposition of the river. The point bar complex is incised by another channel from the north to the south. There are many residual channels and small point bars inside the river valley in the west of the study area.

It can be determined from the sandstone distribution that the hydrodynamic force of the early depositional stage is larger than that of the late stage. This can be proved by the dip angle changes in well. Dip angle of sedimentary surfaces in point bars is associated with depositional hydrodynamic force. In dipmeter logging, dip angles of the lower unit is obviously larger than that of the upper unit (Fig. 8). This means the lateral aggradation surfaces in the deposition of early stage is dipper than that of the late stage. So the hydrodynamic force in the early stage is larger.

The above geologic knowledge from seismic interpretation is in accordance with previous studies based on wells (Zhang, 2010).

7 CONCLUSION

In meandering fluvial reservoirs, seismic forward modeling and outcrop study with GPR reveal that seismic frequency and sandstone thickness can influence its seismic reflection. With layer thickness increasing from $\lambda/4$ to $\lambda/2$, there are three types of seismic reflection geometries including ambiguous reflection, “V” type reflection and “X” type reflection.

Thin layers that are under seismic vertical resolution cannot be characterized on seismic profile with traditional seismic facies interpretation method. Strata slice is an effective tool for reservoir architecture characterization. Depositional boundaries can be characterized on stratal slice even its reflection on seismic profile is ambiguous.

A method is built for seismic sedimentology interpretation of point bar architectures. Its workflow includes seismic frequency and sand thickness analysis, 90º phasing of seismic data, stratal slicing and an integrated 3D interpretation.

Two stages of meandering fluvial deposition developed in the study layer. Dimension of sandstone distribution in the early stage is smaller than that of the late stage. River sinuosity of the late stage is larger than that of the early stage. The change of sandstone distribution is the depositional response of base level rising.

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