

Seismic Sedimentology Research in Qingshankou Formation of Southern Songliao Basin*

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Abstract

Seismic data contains abundant subsurface geological information. The ever-accelerated development of seismic exploration technologies involving collection, processing and interpretation has promoted its investigative area from technological interpretation to sedimentary and reservoir study. A series of technological advancements relevant to sedimentology directly leads to a new discipline - seismic sedimentology. In an attempt to identify the 3D geometric shape, inner structure and deposition process of sedimentary units, seismic sedimentology is the basis of comprehensive response to the depositional environmental model established by high-resolution seismic data, outcrops, drilling and core data. The establishment of more 3D construction of an explicit sedimentary unit is the key goal of seismic sedimentology.

There are considerable differences between seismic sedimentology and traditional seismic stratigraphy, as well as sequence stratigraphy. The traditional seismic stratigraphy primarily employs the lateral characterization of seismic data to describe seismic attributes, while it rarely takes into account the vertical characterization in relation to the depositional geomorphology and model. Sequence stratigraphy follows the ideology of seismic stratigraphy and integrates that of sedimentology.

However, its main advantage is limited to the study of establishment of regional strata framework and large scale sedimentary system distribution. The seismic sedimentology not only has the advantage of sequence stratigraphy, it also integrates the geological data, well logging data and several seismic interpretation and processing technologies to obtain the in-depth application of seismic data (attribute cubes and slices). As a consequence, the sufficient and abundant understanding involving strata, lithology of geological units, depositional process, depositional characterization and seismic attributes can be gained.

Being an east-trending slope, the Haituozi area of southern Songliao Basin crosses the western slope and central sag. The eastern area contains the Baicheng fluvial system, the southeastern part the Tongyu fluvial system and Baokang fluvial system. Exploration activities

show that the Qing3 Formation has a favorable hydrocarbon display. This sandstone formation proves to bear favorable oil and gas accumulation as several wells have obtained industrial petroleum flow.

However, the single sandstone layer of the Qing3 Formation is thin as a result of alternating sandstone and mud sedimentary succession. Due to multiple source systems, the sandstone changes dramatically in lateral directions. The complex geological units lead to the minor difference of seismic reflection between sandstone and mud. The traditional seismic stratigraphy and sequence stratigraphy technology could not fulfill the goal of facies interpretation and identification of sandstone distribution with the aid of seismic reflection characterization. Therefore, these technologies could not meet the demands of exploration and development in this area. Aiming at this problem, this paper adopted the application of seismic sedimentology analysis technology to conduct the sandstone distribution and micro-facies study, which serves to be the necessary basis for the high-resolution exploration.

Identification of Sequence Stratigraphic Framework and Isochronous Depositional Surface

The strata slicing technology is a core technology of seismic sedimentology study. Different from traditional time slicing and horizontal slicing, the strata slicing is formed based on a series of horizons interpolated proportionally between two isochronous geological surfaces being as top and bottom. Considering the depositional rate change to the horizontal distribution, strata slicing technology is more similar to the isochronous geological surface than the other two (Hongliu et al., 1998). However, due to the dramatic lateral reservoir change of continental facies, the target horizons are usually discontinuous and weak reflections. It is hard to pick isochronous depositional surfaces and the confirmation of that has been the puzzle of seismic sedimentary study. As a result, this paper attempts to identify the isochronous depositional surface by integrating high-resolution sequence stratigraphic analysis.

According to the strata unconformity, its corresponding order and characterization reflected by lithofacies, well logging facies, seismic facies and paleontology combination, the Qingsankou Formation is subdivided into three long-term cycles (Sqn1, Sqn2, Sqn3, equivalent to three-order sequence). These cycles correspond to the Qing1 Member, Qing2 Member and Qing3 Member. Each long period cycle has an obvious characterization in seismic profiles, lithofacies and well logging facies.

The evident onlap and erosional truncation marks can be seen in seismic profiles ([Figure 1](#)). When it comes to the well logging curve, the sequence surface lies between the curve of upward coarsening cycle representing progradation and the curve of upward fining cycle representing retrogradation or aggradation, which also dictates that the base level descends to the lowest point and then ascends gradually. The three long-term cycles above are composed of eight middle-term cycles ([Table 1](#)). Each intact middle-term cycle consists of a simple upward fining cycle in which the lithology thins upwardly and the SP curve shows jagged bell-like shape, and simple upward coarsening cycle in which the lithology thickens upwardly and the SP curve shows jagged funnel-like shape. The middle-term cycle was originated within the lake level change cycle of four-order.

In [Figure 1](#), three dotted lines (red, blue, yellow) correspond to the maximum flooding surface of middle-term cycle including Qn3d, Qn3sh, and Qn3x. These maximum flooding surfaces are stable isochronous depositional surfaces and have relatively stable wave-shape characterization, reflection amplitude and phase feature. Also, they can be picked within the study area and the contact relationship of these strata is conformable. Obviously, these surfaces could meet the demands of top and bottom surface of strata slicing. Though the sequence surface of long-term cycle can be traced, a series of interpolated horizons are not isochronous enough due to the evident erosional truncation and overlap. Consequently, it could not serve to be the top and bottom surface of strata slicing.

Strata Slicing Method

Since the 1990's, a large number of investigations prove that seismic geomorphology (extract amplitude information along the isochronous depositional surface) imaging can objectively delineate distribution scale of the depositional system within the seismic survey. This kind of seismic slicing is named strata slicing, which has been the key technology of seismic sedimentology study currently (Lu et al., 2008; Brown et al., 1981).

Color Inversion

Lu et al., 2008 and Brown et al., 1981, point out that rather than a sandstone surface, the seismic events of a reflection record is tracing the reflection coefficient. Also, it holds that only acoustic impedance profile or integration seismic trace can be utilized to pick a sandstone formation. Hence, the traditional seismic data has to be processed first, which not only consumes huge amounts of time, but the inversion method based on model still has two problems: 1) the establishment of initial acoustic impedance model depends largely on experience, which may lead to multiple outcomes, and 2) the correct coefficient of synthetic record and seismic record is always not uniform, and the result may rely too much on the model. Color inversion relies less on the initial model, which ensures the credibility of outcome and makes it more interpretable. As a result, the color inversion was employed in this study

Strata Slicing

With the analysis of high-resolution sequence stratigraphy, stable reflections corresponding to the maximum flooding surfaces of Qn3d, Qn3sh and Qn3x are regarded as reference standard horizons. 30 slices have been made within 120 ms in time thickness. [Figure 2](#) shows strata slicing between 84 ms and 104 ms. The value of the figure matches up with the lithology well. For example, the high value area (red-yellow) represents sandstone beneficiation zone. The middle value area (green) represents only thin sandstone development, while the low value area (blue) represents mudstone. The change of color serves to represent the variation of sandstone in space. [Figure 3](#) is a well-correlation profile of w53-w58-w33-w27 and the sand unit is corresponds to strata slicing of 104 ms. The w53 and w33 are located in the red-yellow area of strata slicing, namely sandstone beneficiation zone. The SP curves show that w53 and w33 develop thick sandstone layers. Wells w58 and w27 are located in the blue-green area of strata slicing, namely the mudstone beneficiation zone. The SP curves show that w58 and w27 primarily develop mudstone with thin sandstone.

[Figure 2A](#) corresponds to the ascending hemi-cycle of the upper Qing3 sequence. The whole area is full of low acoustic impedance (blue) value. The sandstone body is primarily distributed in the western study area. The SP section shows that the lithology is thick mudstone with a bit of thin siltstone.

[Figure 2B](#) corresponds to the descending hemi-cycle of the upper Qing3 sequence. A large area of high acoustic impedance (red) value occurs. The SP curve indicates the beneficiation of sandstone layer. For example, the GR curves of w53 and w33 are box-like shaped with a large thickness. The north-northwest sandstone bodies comprise a huge stripped-like fluvial system. The single water channel extends 33 km of straight-line distance, 1100 m wide and 800 km² in area.

Depositional Facies Analysis

This study shows that the huge stripped-shape water system involves a valley gravity current. Viewed from core data, the lithology is fine sandstone, siltstone and muddy siltstone. Sedimentary structure is primarily massive sandstone and deposits slump deformation structure, graded bedding, convolute bedding and the like. The C-M figure presents a stripped shape parallel to the C-M base line, which also belongs to high density gravity current deposition. The depositional sequence presents characterization of an upward coarsening cycle. The GR and SP curves show box-like and funnel-like shape with moderate range.

The deposition of stripped-shape valley gravity current can be subdivided into channel sub-facies and overflow sub-facies. Composed by shallow valley micro-facies and deep valley micro valley, the channel sub-facies is in the deepest channel of the valley and it is also the zone where coarse sediments are deposited. The deep valley micro-facies consists of massive sandstone facies, graded sandstone facies and superimposition erosional facies. Such deposition is always filled in the graben and a progradation reflection structure can be seen. The shallow valley micro-facies is primarily composed of graded bedding sandstone facies, parallel bedding sandstone facies and current bedding sandstone facies. The lithology is relatively coarse and thick.

Located in both sides of the channel facies, the overflow facies was formed by gravity currents that spilled over channel and is the typical deposition of a turbidite. The overflow facies consists of near overflow micro-facies and far overflow micro-facies. The near overflow micro-facies is primarily composed by slope deformation siltstone facies and current bedding siltstone facies and parallel bedding sandstone facies, while the far overflow micro-facies is primarily mudstone.

The formation of stripped shape valley current flow has a close relationship with paleo-tectonics and paleo-geomorphology. The study shows that the T2 graben of the early period of the Qingsankou Formation had considerable controlling effect on the formation of stripped shape valley current flow. These N-NW oriented grabens were primarily generated in the later stage of Qing2 Member. Also, the internal growth fault of Qingsankou Formation controlled partial deposition of stripped shape valley current flow. The subsiding block is thick and contains an intact sequence. The rising block was subject to the erosion and evolved into deposits compensation area. Oriented N-NW, these growth faults served a vital part in controlling the development of stripped shape current flow.

Currently, the temporary geomorphology shows that a large scale stripped shape depositional system of north to south orientation still develops, which validates evidence for the existence of huge stripped shape sandstone of the Qing3 Member.

Reservoir Forming Conditions Analysis

During the depositional period of Qing1 Member, the dark mudstone thickens from west to east in northern Haituo area. The dark mudstone exceeds 50 m in thickness in the east of w5-w10-w2 area and is viewed as a favorable petroleum layer stepping into the petroleum producing threshold. During the depositional period of Qing3 Member, the valley gravity current deposition and channel sandstone bodies primarily developed. The average porosity is more than 13% and average permeability is more than $1 \times 10^{-3} \mu\text{m}^2$. The widespread fractures play an important role in connecting petroleum source.

The oil wells w10 and w2 are primarily in the eastern fracture zone where the sandstone bodies are relatively abundant. All the oil wells except w2 are not located within the tectonic area. The traps belong to a tectonic-lithology trap type formed by pinchout of sandstone, tectonic line and faults. Apart from the eastern fracture, the sandstone of channel deposition in the mid-western area also develops well and is able to generate lithological reservoir. Also, the exploration degree of mid-western area is relative low and breakthrough in petroleum discovery is possible.

Conclusions

- 1) The high-resolution sequence stratigraphy analysis shows that the maximum flooding surface can be viewed as a feasible isochronous depositional surface, the sequence boundary of long-term cycle could not be regarded as top and bottom surface.
- 2) Based on the 3D seismic data, seismic sedimentology with the application of technology involving strata slicing seismic attribute within the isochronous framework is a feasible hydrocarbon exploration technique.
- 3) In the northern Haituo area of southern Songliao Basin, the application of seismic sedimentology efficiently delineates the distribution of a gravity current depositional system during different periods and dictates the distribution scale of favorable reservoir, such as sandstone of water channel.
- 4) The sandstone bodies of the northern Haituo area were controlled by the southwestern Baicheng fluvial system. The stripped-like sandstone bodies were primarily controlled by the T2 graben of early period of the Qingsankou Formation.
- 5) The mid-west area of northern Haituo bears favorable conditions to form lithological reservoirs.

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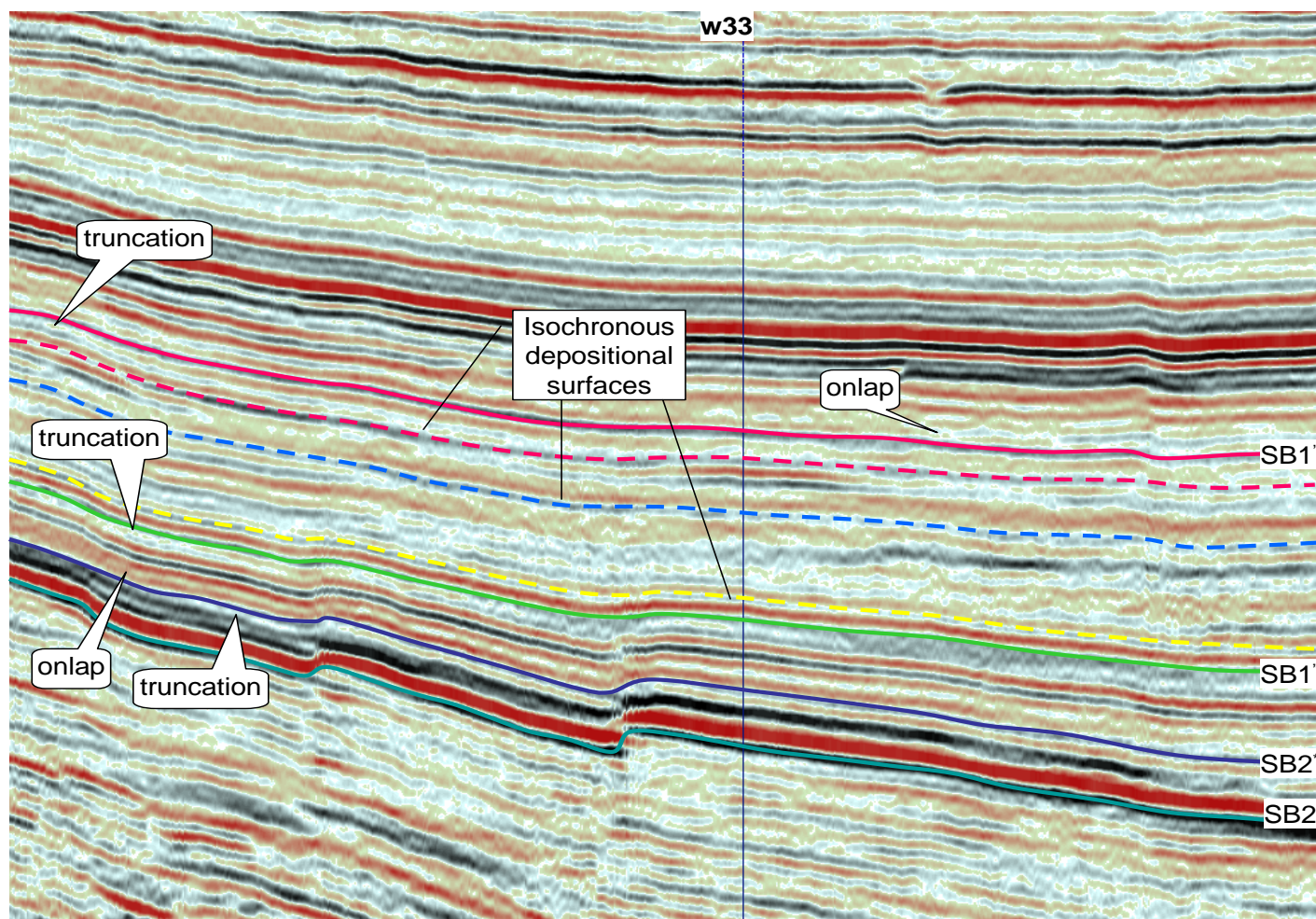


Figure 1. Seismic reflection characteristics of sequence boundaries.

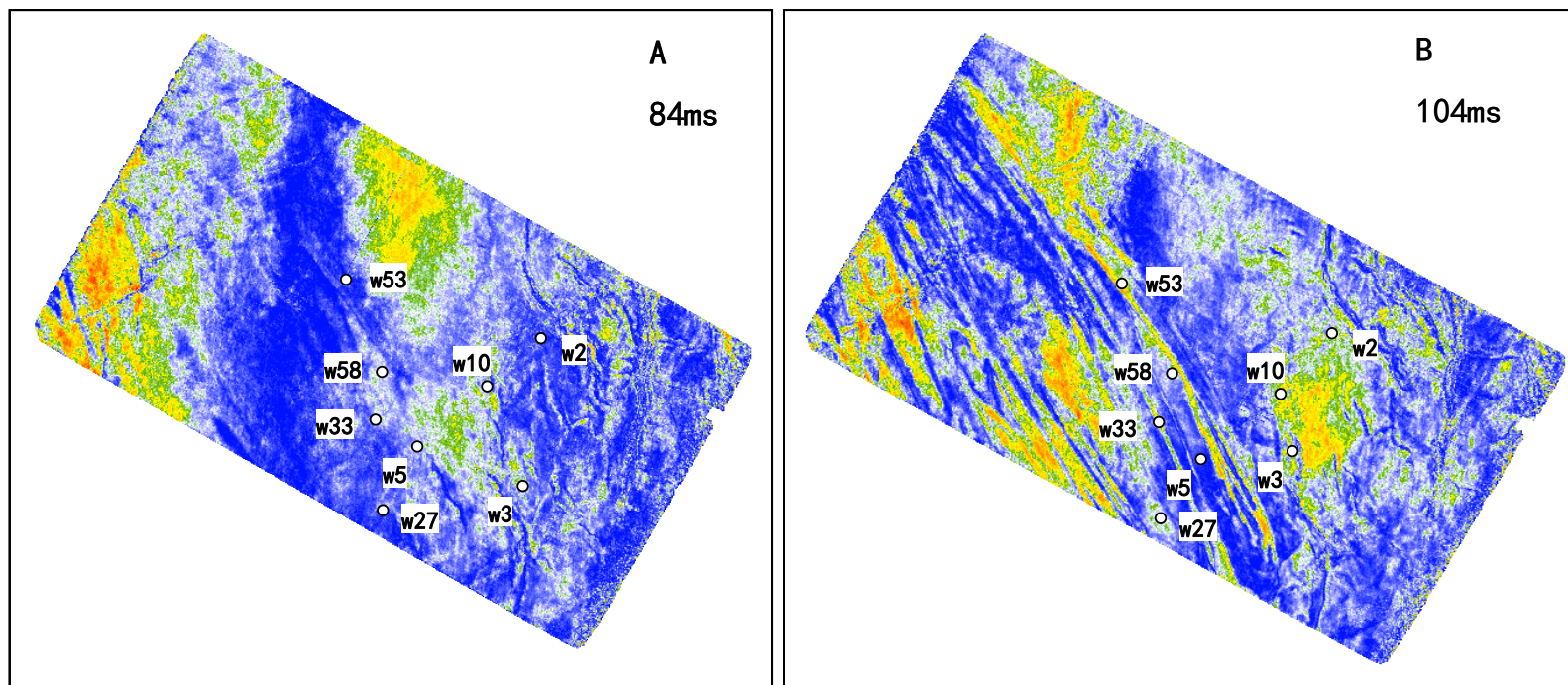


Figure 2. Typical stratal slicings.

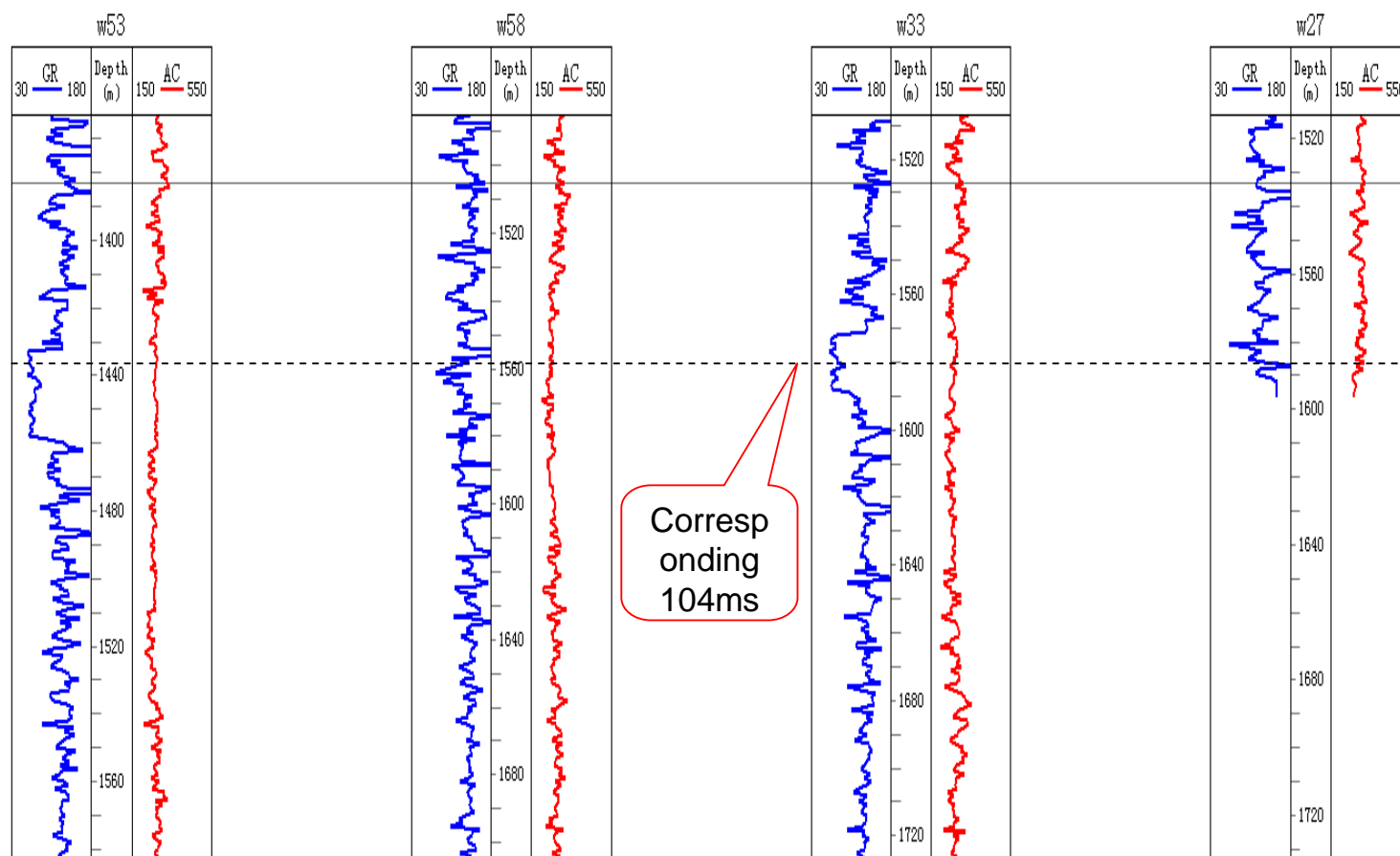


Figure 3. Well correlation section of w53-w58-w33-w27.

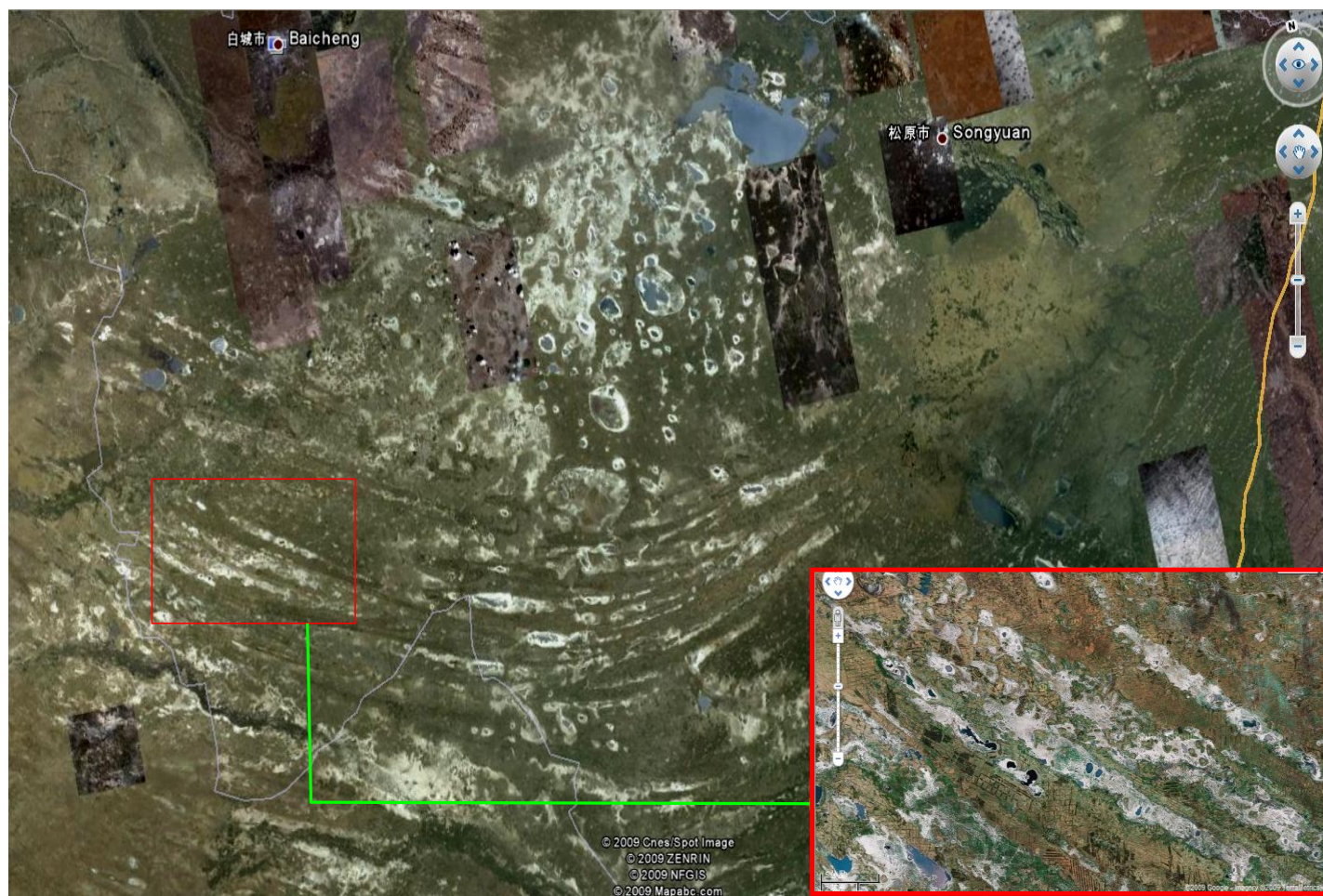


Figure 4. Current sedimentation system distribution of stripped shape in the south of Songliao Basin (according to Google photo)

Strata system		Refrection surface	Seismic characteristics of sequence surface	Three order sequence surface	Base surface cycle		High-resolution sequence stratigraphy	
formation	member				long term	Middle term	long term	Middle term
nengjiang	K ₂ n ¹							
yaojia	K ₂ y ²⁻³	T ₁	Truncation	SB1			Syao	Ysh
	K ₂ y ¹		onlap					Yx
Qingshan kou	K ₂ qn ³	T ₁ '	Truncation	SB1'			Sqn3	Qn3d
			onlap、 downcutting					Qn3sh
								Qn3zh
								Qn3x
	K ₂ qn ²	T ₁ ''	Truncation	SB1''			Sqn2	Qn2sh
	offlap、foreset		Qn2x					
K ₂ qn ¹		T ₁ [*]		SB2 [*]			Sqn1	Qn1sh
				Qn1x				
quantou	K ₂ q ⁴	T ₂	Truncation	SB2				

Table 1. The sequence column section of the middle-shallow sequence stratigraphy in the south Songliao Basin.