Research Article

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Utilizing microresistivity image logs to recognize conglomeratic channel architectural elements of Baikouquan Formation in slope of Mahu Sag

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Abstract: Geological outcrop is usually the first-hand evidence to cognize the probable geometry, lateral extent, and other properties of conglomeratic channels. If there is no exposure of formation, however, it is hard to recognize elaborate architectural elements just based on poor coverage cores and low-resolution conventional logs vertically. In order to understand vertical distributions of conglomeratic channel architectural elements in the Lower Triassic Baikouquan Formation in southern slope of Mahu Sag, ultrahigh-resolution microresistivity image logs are used to recognize elements under the concept of conglomeratic channel architectures in this article. The microresistivity images were calibrated with cores in different grain-sizes and sedimentary structures. According to microresistivity image fabric, subaerial channel-fills consisted of granules to cobbles; subaqueous channel-fills were composed of well-sorted sandstones to granules. Subaerial channel-margins comprised sandstones to pebbles; subaqueous channel-margins were granules and sandstones. Bypass drapes, deposited from the tail of bypassing flows, were commonly eroded by overlying channel-fills. Convergent drapes, accumulated on top surfaces of channel-margins, preserved well without reworking. Overbank drapes, formed outside the channel, were thick-bedded. Combined with dipmeter pattern of microresistivity image log, six channel story sets were recognized depending on abrupt changes in dip azimuths. In each channel story set, per unit thickness of mud drapes ranged from 0.1 to 0.6 m. Mud drapes in channel story set 1 could be correlated horizontally. In channel story sets 3, 4, and 5, thickness of mud drapes ranged from 0.05 to 2.59 m and averaged at 0.59 m, and channel conglomerates and mud drapes alternated frequently. These understandings would provide important insights on the production potential of petroleum.

Keywords: microresistivity image log, conglomeratic channel, architectural element, mud drape, Baikouquan Formation, Mahu Sag

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1 Introduction

Conglomeratic channels are main deposits in the fluvial depositional systems in fan or fan-delta [1–3]. In oil-field developments of channelized conglomerate reservoirs, architectural elements are thought to have an important impact on recovery efficiency [1–4]. Due to the three-dimensional characteristics of gravelly geologic body, the rapid lateral facies variations, and the associated heterogeneities at different scales, the characterization of conglomeratic channel architectural elements is often highly difficult [5,6]. Related research studies have tended to focus more on the characterization and distribution of heterogeneities within the component gravelly bodies comprising the main channels. However, in fluvial systems dominated by aggradation, fine-grain deposits also play a key role in the stratigraphic succession, and provide significant insights into channel stacking and distances to the main channels [7–11]. These fine-grains, defined as mud drape, are relatively thin and laterally extensive sheet of mud deposited at slack water over a surface formed by ripple marks, sand-waves, the side of a riverine or turbidite bar in a channel, etc. [8].

In Mahu Sag, northwestern Junggar Basin, one billion tons of petroleum reservoirs have been discovered in the Lower Triassic Baikouquan Formation since 2010 [12–15]. Deposited in fluvial depositional system of fan-delta in shallow lake, conglomerates are the dominated sediments of the formation, and conglomeratic intervals are commonly draped by thin siltstones and mudstones [16–18].

No exposure of outcrops and poor coverage of cores, the elaborate conglomeratic channel architectural elements, including mud drapes, could be reflected in conventional wireline logs. Microresistivity image logs obtain the massive resistivities of borehole sidewalls and yield ultrahigh-resolution (5 mm) vertical image of the wellbore [19–24]. Combined with dipmeter pattern, the microresistivity image offers elaborate geological data which compares favorably with obtainable information from real rocks. It is useful evidence to interpret sedimentary facies, architectures, stratigraphy, and paleoenvironments [25–28]. In order to understand the high-resolution vertical stratigraphic characteristics of conglomeratic channel, in this article, microresistivity image fabric and dipmeter are used to recognize channel element, and quantify thickness of mud drapes under the concept of channel story set [29]. Vertical stacked features of architectural elements in conglomeratic channel are further discussed. Microresistivity image logs are introduced into the channel elements, which would contribute to uncover the conglomeratic channel architectural element features in petroleum development and production of Baikouquan Formation.

2 Geological setting and stratigraphy

2.1 Geological background

Mahu Sag, located in northwestern margin of the Junggar Basin, is one of the most important hydrocarbon generation depressions of China (Figure 1a and b) [12–15]. During Early Triassic, gravels were transported from provenance Zaire Mountains into shallow water of Mahu Lake. Near fault zones, gravels were transported by gravity, and the dominated transportation force is tractive current in subaerial braided river and subaqueous distributary channel on the simple structure and low gradient of slope zones. As a result, large-scale coarse-grained fluvial fan-delta systems were developed to form the Lower Triassic Baikouquan Formation around the paleoslope of sag [16–18]. On southern slope, succession of Karamay Fan-delta depositional system is the research area of this article (Figure 1c).

2.2 Stratigraphic characteristics

Sandwiched between Permian Upper Urho and Middle Triassic Karamay Formation, thickness of the Lower Triassic Baikouquan Formation is ~100 m. In stratigraphy, Baikouquan Formation is abbreviated as T_1b, and divided into T_1b_1, T_1b_2, and T_1b_3 members upward (Figure 2a). Dominated lithologies of T_1b_1 are gray-black conglomerates involving grain-size ranging from boulder to granule, remaining section is just brown siltstones and mudstones, scarcely sandstones. Mud drapes are developed in different thicknesses vertically (Figure 2b). T_1b_2, ~50 m thick, consists of thick interbeds of gray conglomerates and brown mudstones. Thin gray sandstones and granules are imbedded in meters-thick gray or brown mudstones in T_1b_3. In Baikouquan Formation, grain-sizes decrease and thicknesses of mudstones increase gradually upward, which indicates that paleo-level of Mahu Lake increased and fan-delta retrograded toward the basin margin gradually during the Early Triassic [30,31]. Roughly, thickness of mud drapes that were imbedded in conglomerates ranged from 1.5 to 4 m according to the lithology of mud log (Figure 2a). Elaborated vertical mud drapes could be reflected in mud and conventional logs.

3 Data sets and methodology

3.1 Data sets

Conventional comprehensive log programs were completed in most of the wells, which includes gamma ray, self-potential, borehole diameter, resistivity, neutron, sonic and density data (Figure 2a). For the low-quantity cores and low-resolution conventional logs, stratigraphic characteristics cannot be uncovered well. Being different from conventional open-hole logs, microresistivity image log possesses absolute advantages in geological research: (1) ultrahigh-resolution image is sufficient to detect very thin events and sequences visually and (2) dipmeter pattern is possible to determine beddings and significations of sedimentary textural and structural features [21–24]. Eight wells were run by microresistivity image logging tools (Figure 1c): one well, MH016, was logged by Extended-Range MicroImager of Halliburton; and other seven wells were run by Fullbore Formation MicroImager of Schlumberger. Standard procedures were operated to convert resistivity values into 256-grayscale conductivity images normalized in 1 m window, which dynamically enhances the lithological changes and highlights bedding surfaces [16,23]. In some wells, minority cores were taken, which is correlated with microresistivity images.

3.2 Conglomeratic channel elements

In fan-delta plain and front, for example, sediments are mainly transported and accumulated in channels which

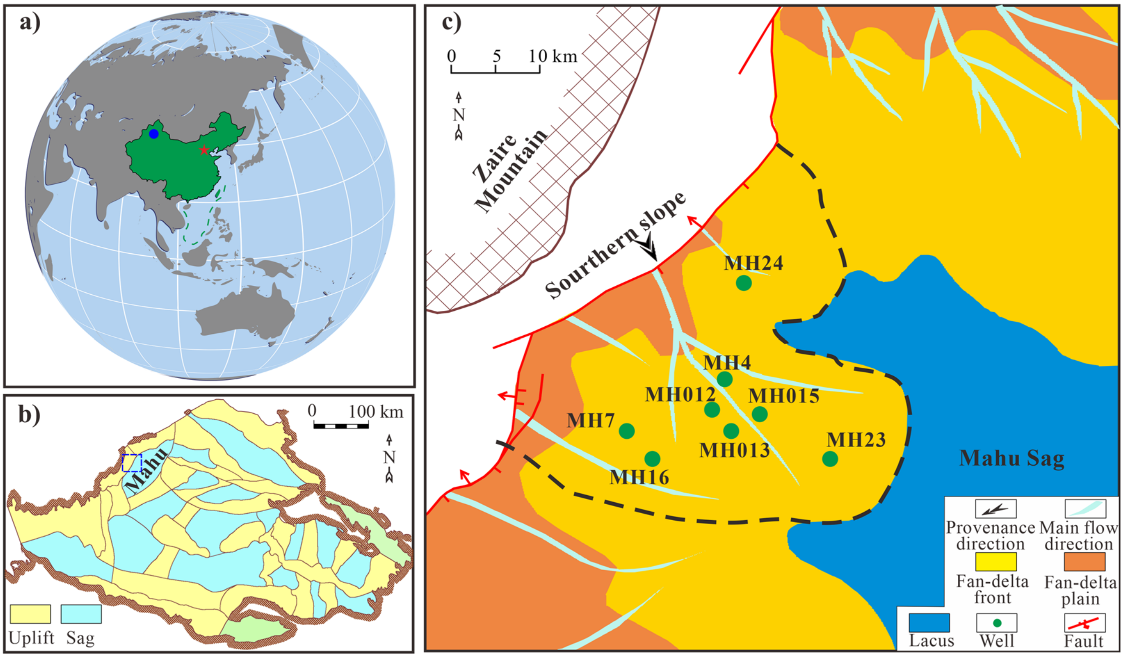

Figure 1: Geologic setting of the Lower Triassic Baikouquan Formation in southern slope of Mahu Sag, Junggar Basin. (a) Map of China. The Junggar Basin located in northwestern China, indicated by blue dot. (b) Tectonic map of the Junggar Basin. Research region is in the southern slope of Mahu Sag, northwestern margin of Junggar Basin, indicated by blue rectangle. (c) Sedimentary background of Baikouquan Formation (modified from ref. [16]). Fan-delta was dominated by deposits on the paleoslope of sag.

are dominated by complex deposits. These deposits could be informally divided into multiple hierarchical scales: (1) channel story, involving a set of conformable beds/bedsets bounded by based erosional surface; (2) channel story set, containing a set of channel stories bounded by based erosional surface; and (3) channel complex, comprising multiple channel story sets bounded by based erosional surface.

Classification scheme of conglomeratic channel architectural elements is optimized by Barton et al, including subaerial and subaqueous channel-fill, remnant channel-margin, convergent drapes, bypass drapes, and overbank drapes (Figure 3) [29]. As a dominated element, channel-fills are composed of aggradational gravels. Remnant channel-margins are controlled by successive lateral-accretion events with channel-fill developments, such as point-bar in braided or meandering river [4,32]. Lithology of convergent, bypass, and overbank drapes are mud and silt; however, they are formed in different environments. Convergent drapes are low-flow mudstone units accumulated on the top surfaces of channel-margins during the channel-fill phase. Bypass drapes are preferentially deposited from the tail of bypassing flows, prior to the main phase of channel-filling [7,29]. Mud and silt in overbank are deposited outside the channel and are common in channel overbank and levee [4,32].

4 Elements in microresistivity image

4.1 Calibration microresistivity images with cores

For the conductivity differences of various rocks, lithologies and stratifications are easily distinguished in two-dimensional visualized microresistivity image fabric. The gravels are elaborate “mottled” in microresistivity images. The spots within different gray values suggest the approximate gravelly grains: the bigger the spots, the coarser the gravels (Figure 4a–c) [16,33–36]. The images of sands are homogeneous brown yellow color (Figure 4d). Silty and muddy intervals are in low resistivity. Correspondingly, microresistivity images of both are homogeneous brown-dark or dark color (Figure 4e and f). The common sedimentary structures in conglomeratic channel of the Baikouquan Formation include cross-bedding, massive-bedding, and scour-and-fill structure. Cross-beddings are sinusoids with some dips and inclinations interpreted from the dip log patterns of microresistivity image logs (Figure 5a). Massive-beddings are disorganized in the images (Figure 4a–c). Scour-and-fill structures are erosive lithological interface with overlying spots and underlying dark massiveness (Figure 5b).

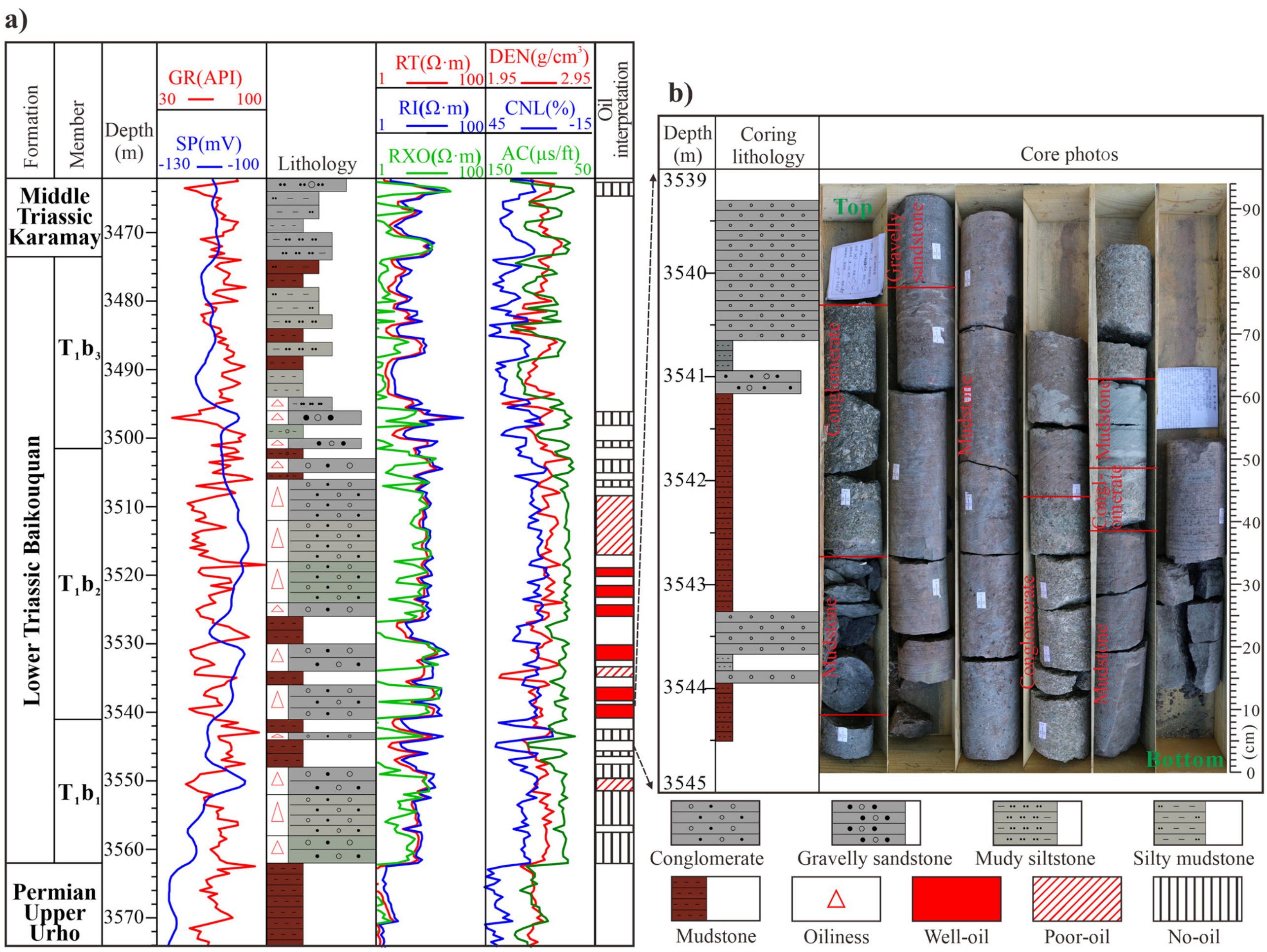

Figure 2: Stratigraphic characteristics of the Lower Triassic Baikouquan Formation in southern slope of Mahu Sag. (a) Generalized open-hole stratigraphic column of well MH015. Conventional logs: GR – natural gamma ray, SP – spontaneous potential, RT – deep investigation resistivity, RI – middle investigation resistivity, RXO – shallow investigation resistivity, DEN – compensated bulk density, CNL – compensated neutron, AC – acoustic time. (b) Core description and photos in well MH015. Note the alternation of granules and muds. Coring depth is marked in Figure 2a.

4.2 Subaerial elements

In fan-delta plain, granules to cobbles were mainly transferred by high energy traction current in braided river. In microresistivity image fabric, the channel-fill element is characterized by (1) abrupt change and irregular based interface, suggesting erosional surfaces, (2) chaotic spots within different brightness or disconnected dark stripes,

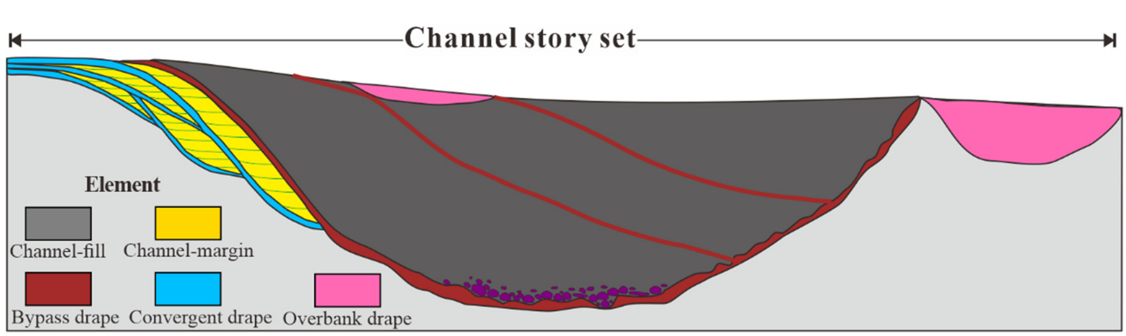

Figure 3: Schematic diagram illustrates the conglomeratic channel architectural elements (modified from ref. [29]). Note the three different mud drapes.

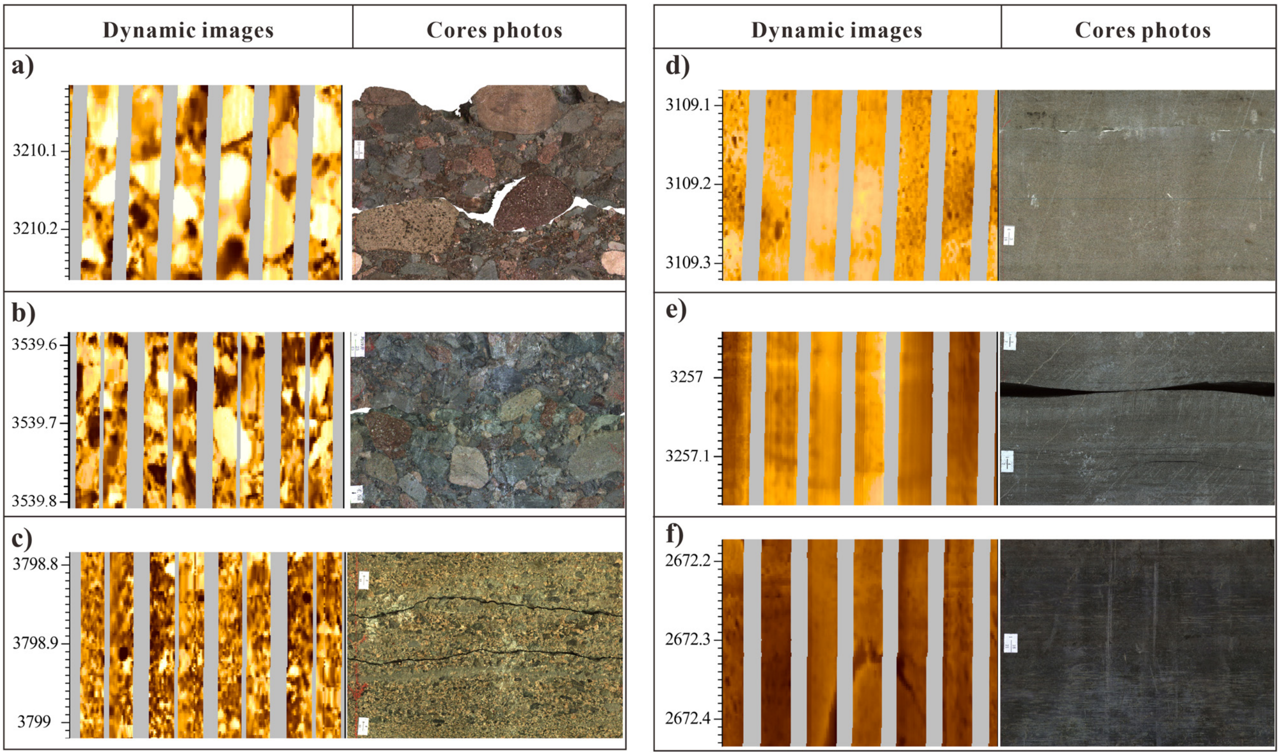

Figure 4: Microresistivity images and core photographs of grain-size (modified from ref. [16]). (a) Cobbles are big spots in microresistivity images. (b) Pebbles are medium spots in microresistivity images. (c) Granules are small spots in microresistivity images. (d) Sandstone is brown yellow in microresistivity images. (e) Siltstones are brown-dark color in microresistivity images. (f) Mudstones are dark color in microresistivity images.

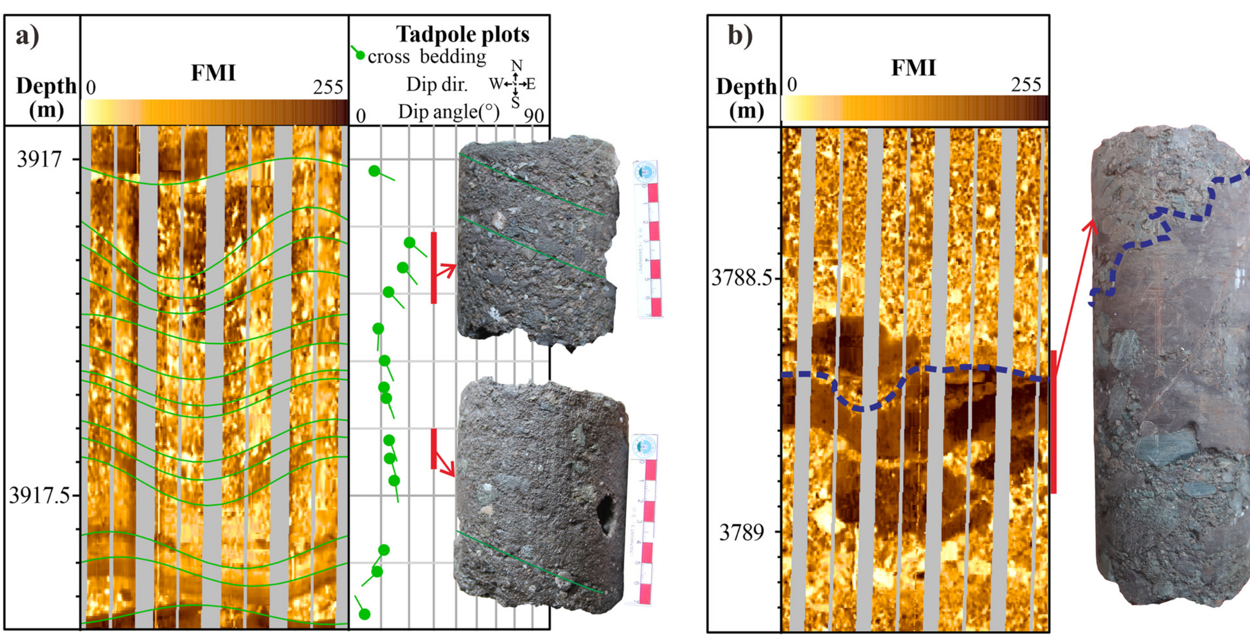

Figure 5: Microresistivity images and core photographs of sedimentary structures (modified from ref. [16]). (a) Cross-beddings in granules. The microresistivity images show sinusoids with some dips and inclinations. (b) Scour-and-fill structures and mudstone-clasts. The microresistivity images show erosive lithological interface.

implying based lag deposits, (3) decrease in spots' diameter upward, indicating normally graded conglomerates, and (4) decrease in dips and constant azimuths of dips upward, representing aggradational deposition in the axis of channel. Bypass drapes, suggested by dark block in microresistivity image fabric, were eroded by overlying channel conglomerates to form top irregular erosional surfaces and lag deposits during erosion and downcutting in channel-fill phase (Figure 6a). The erosional bypass drapes were called "channel-base drapes" as well [29]. In strong erosion, channel conglomerates would interfinger with channel-base drapes. Channel-margin consists of normally graded granules to sandstones in weak cross-bedding. Convergent drapes are characterized by flat contact with underling and overlying channel-margin conglomerates. In interstratified interval of multiple channel-margins and convergent drapes, upward bed-thinning successions of conglomerates are evident (Figure 6b). In addition, floodplain mud drapes are not found in vertical fan-delta plain in wells.

4.3 Subaqueous elements

Compared with subaerial channel-fill elements, lithologies of subaqueous channel-fill elements in fan-delta front are mainly normally graded and well-sorted granules and sandstones, no pebbles or cobbles. Their channel-base-bounding surfaces are associated with sedimentary features suggestive of significant erosion and bypass. Within channel-fill element, dip azimuths are uniform in the same coset, and the dip may be different in different cosets (Figure 7a). Subaqueous channel-margins consist of gravelly sandstones and sandstones in weak cross-bedding.

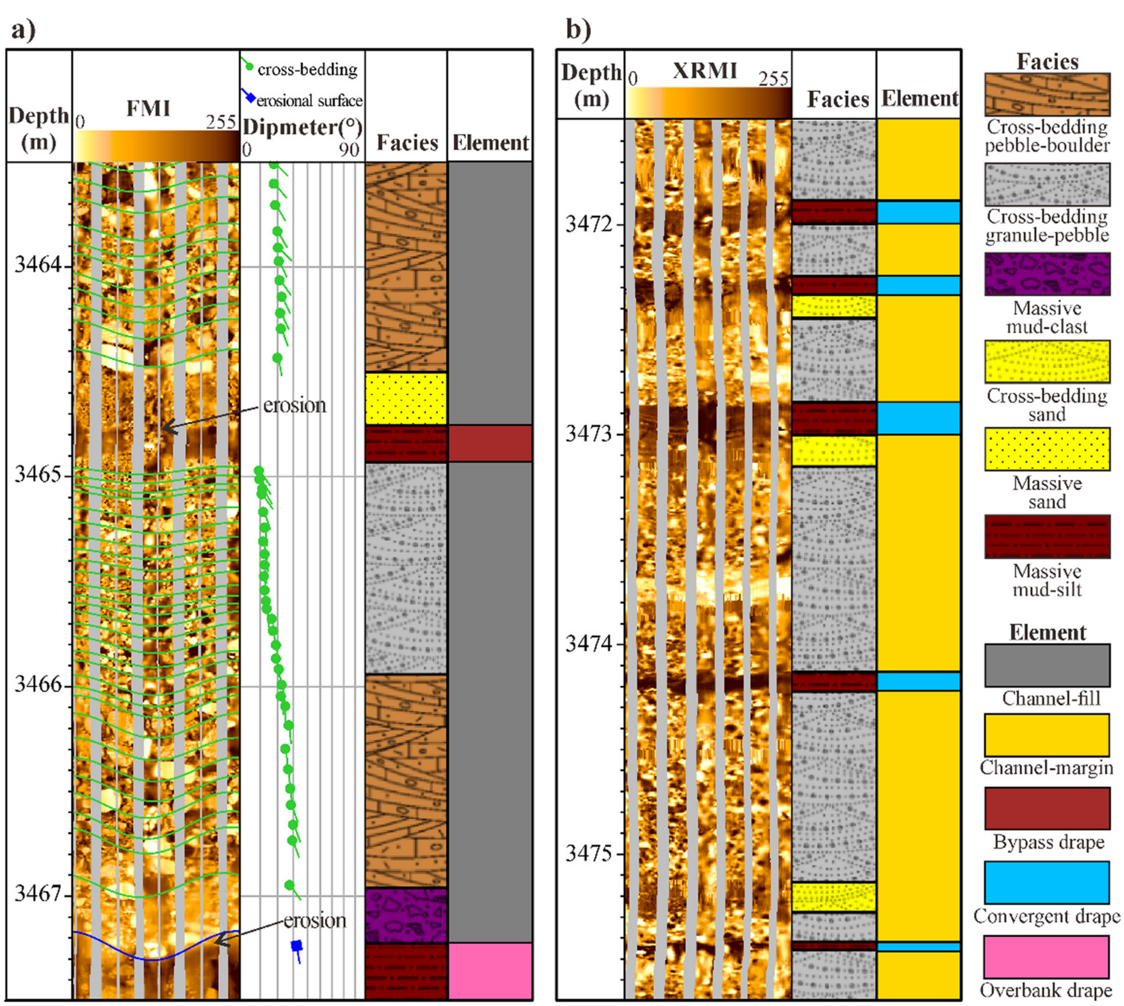

Figure 6: Microresistivity image fabric of subaerial elements. (a) Microresistivity image fabric of subaerial channel-fills and bypass drapes in well MH012. Note the based erosional surfaces and lag deposits, upward dips decrease and normally graded in channel-fills. (b) Microresistivity image fabric of subaerial channel-margins and convergent drapes in well MH16. Note the interstratified upward bed-thinning conglomerates and muds.

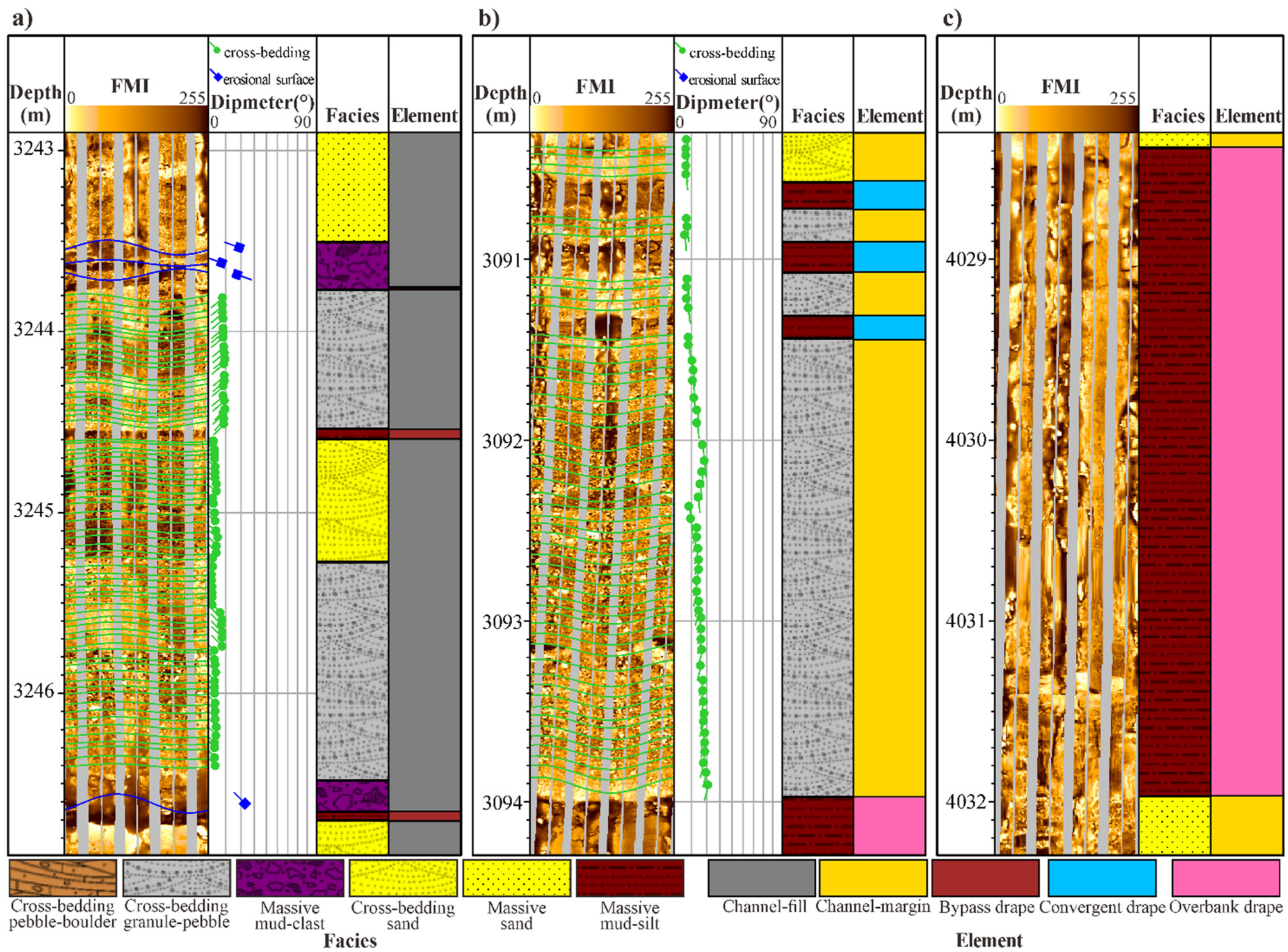

Figure 7: Microresistivity image fabric of subaqueous elements. (a) Microresistivity image fabric of subaqueous channel-fills and bypass drapes in well MH7. Note the erosional surfaces, lag deposits, and centimeter-thick drapes. (b) Microresistivity image fabric of subaqueous channel-margins and convergent drapes in well MH24. Note the interstratified upward bed-thinning sand-rich conglomerates and thin muds. (c) Microresistivity image fabric of subaqueous overbank drapes in well MH23. Note the thick mudstones.

Without being eroded, convergent drapes separate individual channel-margin element. Decimeters-thick channel-margins and convergent drapes are alternated to be sandstone and mud interbeds (Figure 7b). Overbank drapes deposited outside the channel levee are commonly referred to as interchannel shales (Figure 7c). Vertically, this mud drapes are meters-thick.

5 Elements in vertical formation

5.1 Channel story sets

Taken well MH015 as an example, recognition result of channel story set is shown in Figure 8 combining with dipmeter of microresistivity image logs of entire formation. Overlying beds of amalgamated granules and sandstones that display upward-decreasing dips are interpreted as channel-fills. Flat-bedded successions of thin-bedded sandstones and mudstones are interpreted as channel-margins and convergent drapes, respectively. Thick-bedded siltstones and claystones are interpreted as overbanks. Irregular abrupt fabric changes between conglomerates and mud drapes are interpreted as the position of erosional disconformities. The pattern of bedding dips within each channel story set depends on the channel-fill architecture; therefore, abrupt changes in dip azimuths mark the probable different channel story sets [29]. Based on rose diagram of dip azimuths in channel-fills and thickness of mud drapes, six channel story sets are identified in the Lower Triassic Baikouquan Formation of well MH015 (Figure 8a).

The base of channel story set 1 is indicated by 1.03 m thick chaotic-based lag conglomerates overlying Permian

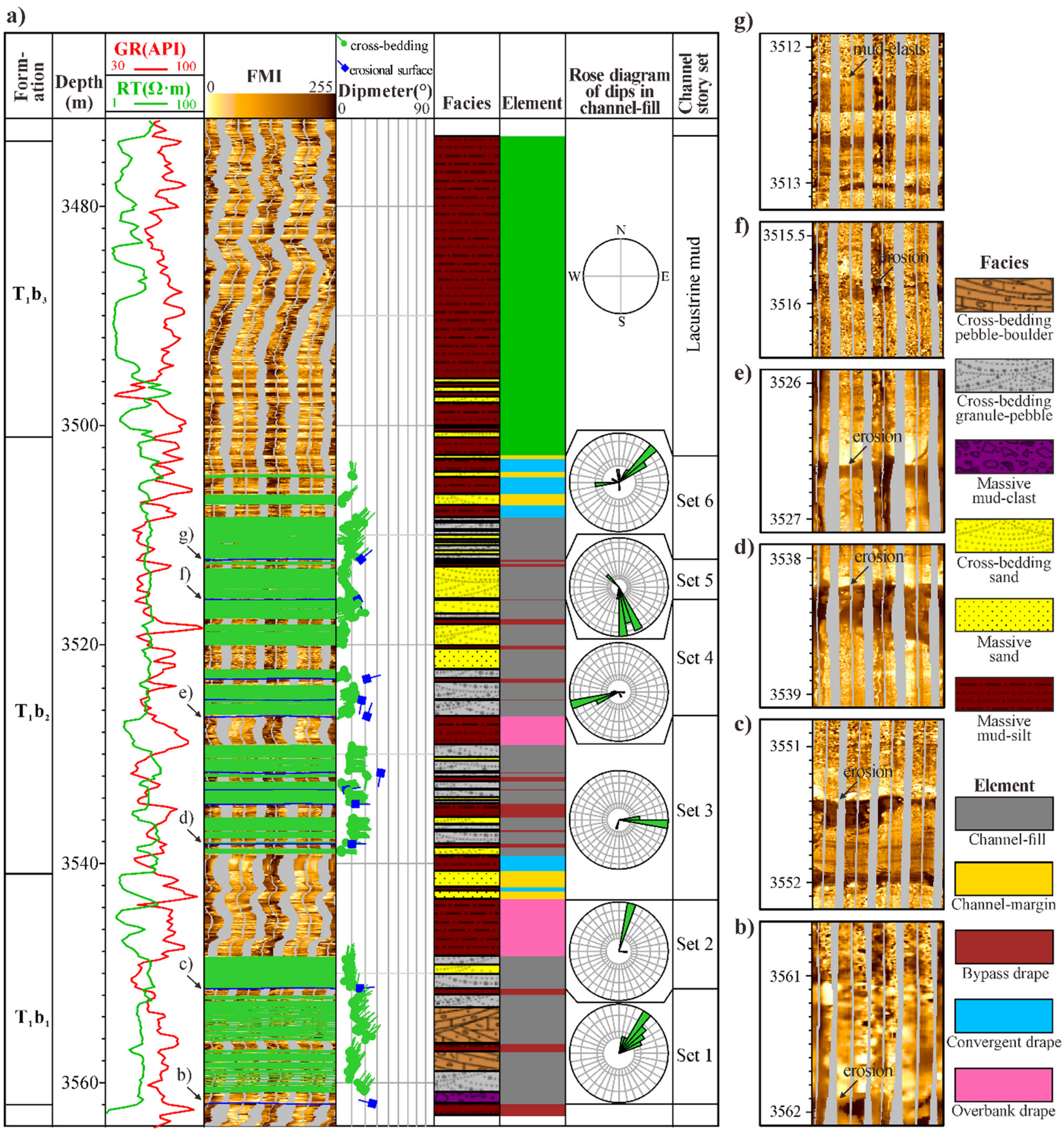

Figure 8: Recognized result of architectural elements and channel story sets in well MH015. (a) Six channel story sets are identified. Note the abrupt changes in dip azimuths between channel story sets. (b) Microresistivity image of base of channel story set 1. Note the erosional surface in 3561.9 m. (c) Microresistivity image of base of channel story set 2. Note the erosional surface in 3551.4 m. (d) Microresistivity image of base of channel-filling in channel story set 3. Note the erosional surface in 3538.2 m. (e) Microresistivity image of base of channel story set 4. Note the erosional surface in 3526.5 m. (f) Microresistivity image of base of channel story set 5. Note the chaotic-based lag mud-clasts in 3515.8 m. (g) Microresistivity image of base of channel story set 6. Note the erosional surface in 3512.2 m.

mudstones disconformably (Figure 8b). Restricted by two thin bypass drapes, two subaerial NE ward-dipping channel-fills consist of granules to cobbles. The base of channel story set 2 is marked by based erosional surface, and consists of one NNE ward-dipping channel-fills and 5.20 m thick overbank drape (Figure 8c). The base of channel story set 3 is marked by two massive channel-margin sandstones and convergent mudstone interbeds. Eastward-dipping sand-rich channel-filling sequences contain based erosional indicators (Figure 8d). The channel story set 4 overlies 2.59 m thick overbank muds disconformably (Figure 8e). Five bypass drapes separate five channel-fill elements vertically. The base of channel story set 5 is suggested by 0.12 m thick chaotic-based lag mud-clasts overlying residual millimeter-thick drapes (Figure 8f). Upward-decreasing dips are evident in one dominated channel-fill. The base of channel story set 6 is indicated by complex bypass drapes formed by two 0.2 m thick mudstones (Figure 8g). NE ward-dipping 3.85 m thick channel-fill is covered by convergent drapes and channel-margins. Proved by lithology, microresistivity image, and conventional log, from 3502.78 m to the top of Baikouquan Formation, thick fine grain-size intervals containing siltstones and mudstones suggest lacustrine sediments (Figure 8a) [12–18].

5.2 Quantification of mud drapes

Based on various architectural elements in conglomeratic channels recognized in image logs, quantitative statistical assessments of mud drapes in the channel story set would be obtained in entire vertical formation. In these six channel story sets of well MH015, per unit thickness of three kinds of drapes ranges from 0.1 to 0.6 m (Figure 9). It means that conglomerates are dominated sediments. In channel story sets 3, 4, and 5, per unit count of drapes is

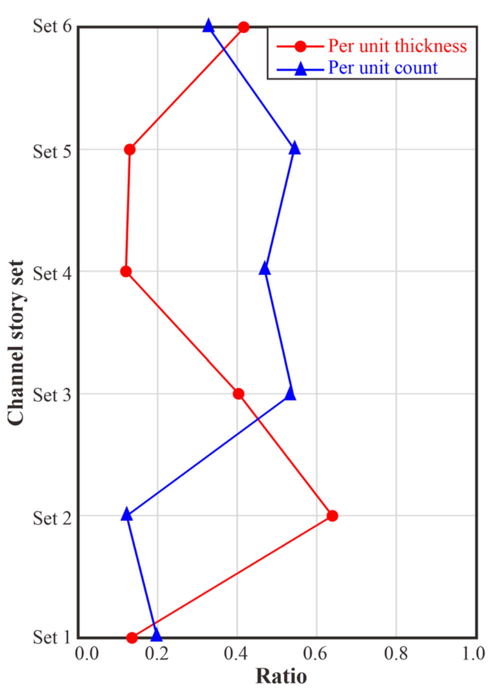

Figure 9: Per unit thickness and count of drapes in different channel story sets of well MH015.

Table 1: Facies of architectural elements identified from microresistivity images

Environment	Element	Texture and fabric	Sedimentary characteristics	Main process
Subaerial	Channel-fill	Granule to boulder, based mud-clast	Cross-bedding, massive, based erosional surface, decrease in dips upward, normally graded	High energy traction current
	Channel-margin	Sandstone to pebble	Cross-bedding, massive, similar dipmeters, upward bed-thinning	Migration of channel-fill
	Convergent drape	Mudstone to siltstone	Massive, thin-bedded	Suspension on top of channel-margin
	Bypass drape	Mudstones to siltstone	Massive, top erosional surface, thin-bedded	Suspension from tail of bypassing flows
Subaqueous	Channel-fill	Granule to sandstone	Cross-bedding, massive, based weak erosional surface, similar dips, normally graded	Middle-low energy traction current
	Channel-margin	Sandstone	Weak cross-bedding, massive, upward bed-thinning	Migration of channel-fill
	Convergent drape	Mudstone to siltstone	Massive, thin-bedded	Suspension on top of channel-margin
	Bypass drape	Mudstone to siltstone	Massive, top weak erosional surface, thin-bedded	Suspension from tail of bypassing flows
	Overbank drape	Mudstone to siltstone	Massive, thick-bedded.	Suspension outside of channel levee

~0.5, larger than that in channel story sets 1 and 2. This means that channel conglomerates and mud drapes alternate more frequently in these three channel story sets. The thickness of drapes in channel story sets 3, 4, and 5 ranges from 0.05 to 2.59 m, averages at 0.59 m, and more than 80% of drapes are less than 0.5 m thick. Proved by actual production of this research area, oiliness of well-sorted channel-fill elements in channel story sets 3, 4, and 5 are the best. These thin and frequent drapes might contribute to block petroleum molecules in conglomeratic elements effectively during hydrocarbon enrichment stage to form oil-bearing intervals [30].

6 Discussion

6.1 Summarized characteristics of elements

Differentiated features of various elements from microresistivity image fabric could be summarized as follows (Table 1): (1) subaerial channel-fills consist of granules to cobbles, and subaqueous ones are composed of well-sorted sandstones to granules; (2) subaerial channel-margins comprise sandstones to pebbles, and subaqueous ones are granules and sandstones; (3) channel-fills generally associate with based erosional surfaces and mud-clasts, and channel-margins contact with drapes in flat surfaces; (4) bypass drapes are commonly eroded by overlying channel-fills; (5) convergent drapes preserve well with no reworking; and (6) overbank drapes are thick-bedded. All these characteristics would contribute to recognize fan-delta conglomeratic sedimentary facies and architectural elements in Baikouquan Formation using microresistivity images.

6.2 Correlation in wells

Grain flow and gravity flow in conglomeratic channel are the main processes to form the fan-delta deposit which may be overlaid or draped by laminated beds of very fine grains. High-resolution vertical elements are recognized similarly in adjacent wells using microresistivity image logs. Correlating the mud drapes in near wells is

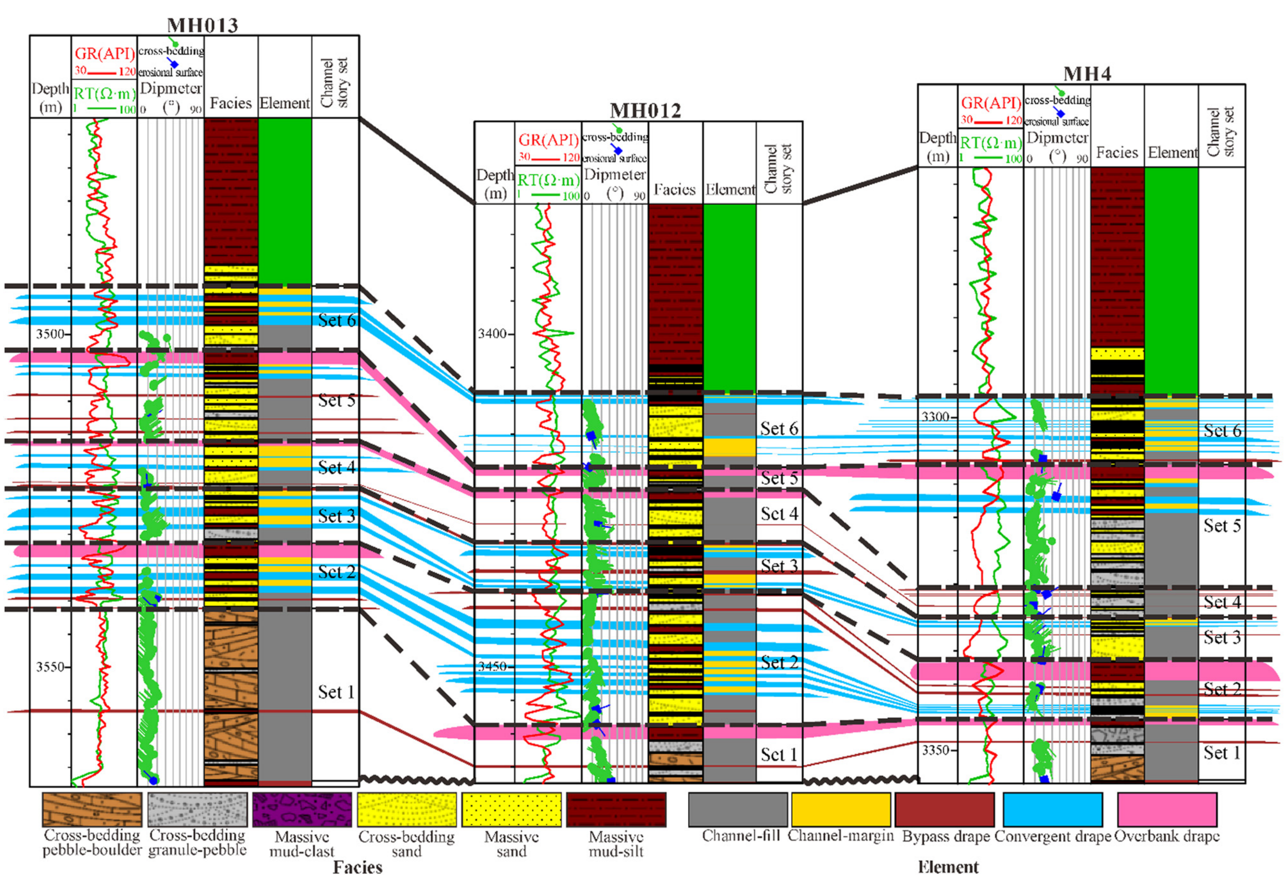

Figure 10: Mud drape correlation of wells MH4, MH012, and MH013. Well locations are marked in Figure 1.

an effective method to describe the channel architecture characteristics. Some elements could be correlated along- and/or across-stream. For example, the mud drape correlations of well MH4, MH012, and MH013 are shown in Figure 10. Channel story set 1 consists of two channel-fills and mud drapes which are correlated wells. The min and max thickness of this set are 8.65 m in well MH012 and 25.83 m in well MH013, respectively. Imbedded by channel-fills, thickness of the bypass drapes ranges from 0.07 to 0.75 m; however, they can be traced horizontally. Thickness of the convergent drapes in channel story set 2 ranges from 0.03 to 1.18 m. Accompanied with erosional surface, there is no top thick drape in well MH013, MH4, or MH012. In channel story sets 4, 5, and 6, channel-fills, channel-margins, and drapes are superimposed randomly. All drapes are recognized vertically, even though, some thin drapes are hard to be correlated horizontally [37]. According to the oil interpretation, channel-fill and channel-margin in channel story sets 2, 3, 4, and 5 are dominated by oil-bearing intervals.

In hydrocarbon reservoir, impenetrability mud drapes act as baffles and barriers of underground flow between individual reservoir elements, such as point bar, channel-fill, and foreset [38–40]. Extensive large-scale drapes fill in shelf edge canyon, hemipelagic or abyssal zone with hundreds of meters-thick. Meters-thick mud drapes blanketed in swamp, lake, floodplain, abandonment channel, side of river, tidal, or turbidite channels depositional environment are usually meso-scale [41–44]. Sparse, randomly distributed small-scale drapes are only a few millimeters or centimeters thick laminations occurring in irregular micro-topography, such as channel surface, ripple mark, or shallow scour [41,42]. In Baikouquan Formation, the upper dozens of meters-thick lacustrine is the extensive continuous large-scale drapes that cover the fan-delta deposits. It is the regional cap rocks of conglomeratic channel reservoirs. Secondarily, top meters-thick overbank drape in each channel story set is the partial meso-scale barriers for channels. Within channel story set, centimeters-thick bypass and convergent drapes are small-scale interlayers sandwiched by channel-fill and channel-margin.

7 Conclusions

In the fan-delta deposit of Lower Triassic Baikouquan Formation in southern slope of Mahu Sag, microresistivity image logs are characterized to recognize architectural elements in conglomeratic channel architectures vertically. Based on microresistivity image fabric, subaerial and subaqueous channel elements are recognized, respectively. Subaerial normally graded channel-fills consist of granules to cobbles, and subaqueous ones are composed of well-sorted sandstones to granules. Subaerial upward bed-thinning channel-margins comprise sandstones to pebbles, and subaqueous ones are granules and sandstones. Channel-fills generally associate with based erosional surfaces and mud-clasts, and channel-margins contact with drapes in flat surfaces. Bypass drapes are commonly eroded by overlying channel-fills. Convergent drapes preserve well without reworking. Overbank drapes are thick-bedded.

In vertical sense, six channel story sets are recognized depending on abrupt changes in dip azimuths from dipmeters pattern of microresistivity image logs. In these channel story sets, per unit thickness of mud drapes ranges from 0.1 to 0.6 m. In channel story sets 3, 4, and 5, channel conglomerates and mud drapes alternate more frequently than that in story sets 1 and 2. The thickness of mud drapes in these three channel story sets ranges from 0.05 to 2.59 m, averages at 0.59 m, and more than 80% of drapes are less than 0.5 m. In transverse area, thickness of the bypass drapes in channel story set 1 ranges from 0.07 to 0.75 m; however, they can be traced horizontally. Thickness of the convergent drapes in channel story set 2 ranges from 0.03 to 1.18 m. In channel story sets 4, 5, and 6, channel-fills, channel-margins, and drapes are superimposed randomly.

The upper dozens of meters-thick lacustrine in the Baikouquan Formation is the extensive continuous large-scale cap rocks that cover the fan-delta deposits. The top meters-thick overbank drape in each channel story set is the partial meso-scale barriers for channels. Within channel story set, centimeters-thick bypass and convergent drapes are small-scale interlayers sandwiched by channel-fill and channel-margin.

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