

# Sedimentary facies and sequence stratigraphy of the Silurian at Tabei uplift, Tarim Basin, China

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Received: 15 September 2015 / Accepted: 16 June 2016 / Published online: 27 June 2016  
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**Abstract** Sequence stratigraphy division and comparison of the Silurian in Tarim Basin were a hot research field in oil industry and academia. However, basic geological problems limited the exploration needed for further research. In this paper, 21 lithofacies and 5 facies associations were identified based on the grain size of sediments, sedimentary characteristics, and bioturbation conditions: (1) fluvial-dominant delta front facies association; (2) tidal flat facies association; (3) tidal channel facies association; (4) offshore-transition facies association; (5) shoreface facies association. The seismic, outcrops, and logging data were involved to divide the Silurian (including upper Ordovician Tierkeawati Fm.) at Tabei uplift into five sedimentary sequences. SQ1 (Tierkeawati Fm.) is mainly characterized by tidal flat facies association, while delta front facies association locally develops; SQ2 (the lower Kepingtage Fm.) generally consists of offshore-transition facies association; SQ3 (the upper Kepingtage Fm.) is mainly characterized by shoreface and delta front facies association. For SQ4 (Tataaiertage Fm.), the transgressive system tract (TST) is dominated by shoreface facies association, while the fluvial-dominant delta facies association widely develops in highstand system tract (HST). SQ5 (Yimugantawu Fm.) is mainly

characterized by tidal flat facies association. From SQ1 to SQ2, an overall sea level transgressive process is shown, while an overall sea level regressive process is found from SQ2 to SQ5. The results are consistent with the progradation and regression trends of large regions reflected by sequence framework pattern. As to SQ3 sequence, TST and HST sandstones are the main reservoir intervals in the Silurian. Hercynian movement led to the strong uplift and extensive erosion in the Silurian at Tabei and Tazhong uplift, and is favorable to the formation of strata erosion unconformable traps.

**Keywords** Facies associations · Lithofacies · Sequence stratigraphy · Tabei uplift

## Introduction

Silurian is characterized by widespread marine sandstone at the Tarim Basin. In recent two decades, Silurian turned into a hot area in oil industry and academia for their significant petroleum resources potential. The sedimentary environments were changed from the Cambrian-Ordovician marine carbonate to the basin-wide distribution of the Silurian-Devonian marine clastic deposits. More increasing attention was attracted by the widely distributed Silurian sandstone containing asphalt in the last decades (Liu et al. 2001; Zhang et al. 2002; Song and Wu 2004; Liu et al 2011).

Analysis of sequence stratigraphic framework and internal depositional system was an effective method to reveal the distribution of favorable reservoir and trap development (Posamentier and Allen 1993; Van Wagoner 1995; Posamentier and Allen 1999; Posamentier 2000; Catuneanu 2006; Steven et al 2008; Helland-Hansen and Hampson 2009; Lin 2009). Sequence stratigraphic division and comparison of the Silurian in Tarim Basin were a hot research field in oil

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industry and academia with a lot of studies (Gu 1996; Zhu et al. 2002; Zhao et al. 2003; Liu et al. 2004; Zhu et al. 2005; Guo and Hong 2007; Shi et al. 2007; Zhang and Zhang 2008).

There are a lot of kinds of sequence stratigraphy classification scheme and controversial arguments for the sedimentary system in Silurian. Some scholars claimed that tidal flat system was dominated in Tazhong area, whereas shoreface sediments done in Tabei area (Gu 1996; Zhang et al. 2004). Other scholars identified fluvial delta system in Tazhong, Tabei, and Tadong areas (Jia et al. 2006). Differences such as tectonic activities, sea level changes, palaeogeomorphology, and provenance system led to complex sedimentary facies distribution, which brought great difficulty in reservoir prediction. Currently, oil reservoirs are mainly found in Tazhong area, while few drillings with industrial oil flow were discovered in Tabei area. Therefore, most of previous studies focused in Tazhong area without systematic research in Tabei area.

This study is aimed to analyze and explain the lithofacies types and sedimentary facies in Silurian at Tabei uplift in detail. The cores, logging data, and outcrops are comprehensively applied as well as seismic data. The key stratigraphic boundary surface was identified to divide sequence stratigraphy. In addition, the distribution and evolution of sedimentary facies was analyzed within sequence stratigraphic framework. In addition, the detailed sedimentary facies interpretation and sequence stratigraphic comparison with combination of multi-disciplinary and various methods are performed. An effective analysis and forecasting tools will be provided for reservoir prediction during oil and gas exploration and development process.

## Geological background

Between the Tianshan Mountains (northern) and the Kunlun Mountains (southern), the Tarim Basin is edged by the Altun fault zone as the eastern with an area of 560,000 km<sup>2</sup>. The Tarim Basin is divided into multiple structural units with different evolutionary history (Jia 1997). Such structural units mainly include Kuqa depression belt, Tabei uplift belt, northern depression zone, central uplift belt, southwestern tower depression belt, southeast uplift belt, and so on (Jia 1997). The complex tectonics and stratum structure were demonstrated by the difference of tectonic and sedimentary evolution history in these structural units (Fig. 1).

Tarim Basin has been varied from the stage of Ordovician extensional basins to the stage of Silurian-Devonian intracratonic compression basins (Su et al. 2015). The type of depositional system changed from the carbonate rocks sediment in Ordovician to clastic sediment in Silurian-Devonian. Tectonic uplift quickly shallow the basin with intense erosion during the late Ordovician. Ancient tectonic geomorphology pattern in late tectonic deformation made a profound impact on paleogeographic pattern in the early Silurian (Liu et al. 2010). There is a

steep slope in northern and eastern margin of the basin, whereas relatively moderate in southern or southeastern with thin deposition. A broad stratigraphic thinning or pinch belt was formed along such ancient band with relatively slow slope as Tazhong uplift north slope. For the north depression belt, it showed a NEE distribution and the eastern end, the western edge with shallow sea, or bathyal in early Silurian. Along the southwestern edge, there is turbidite clastic deposition from deep sea basin. The southeast slope belt of Tabei uplift developed clastic coastal and fluvial delta system (Lin et al. 2011).

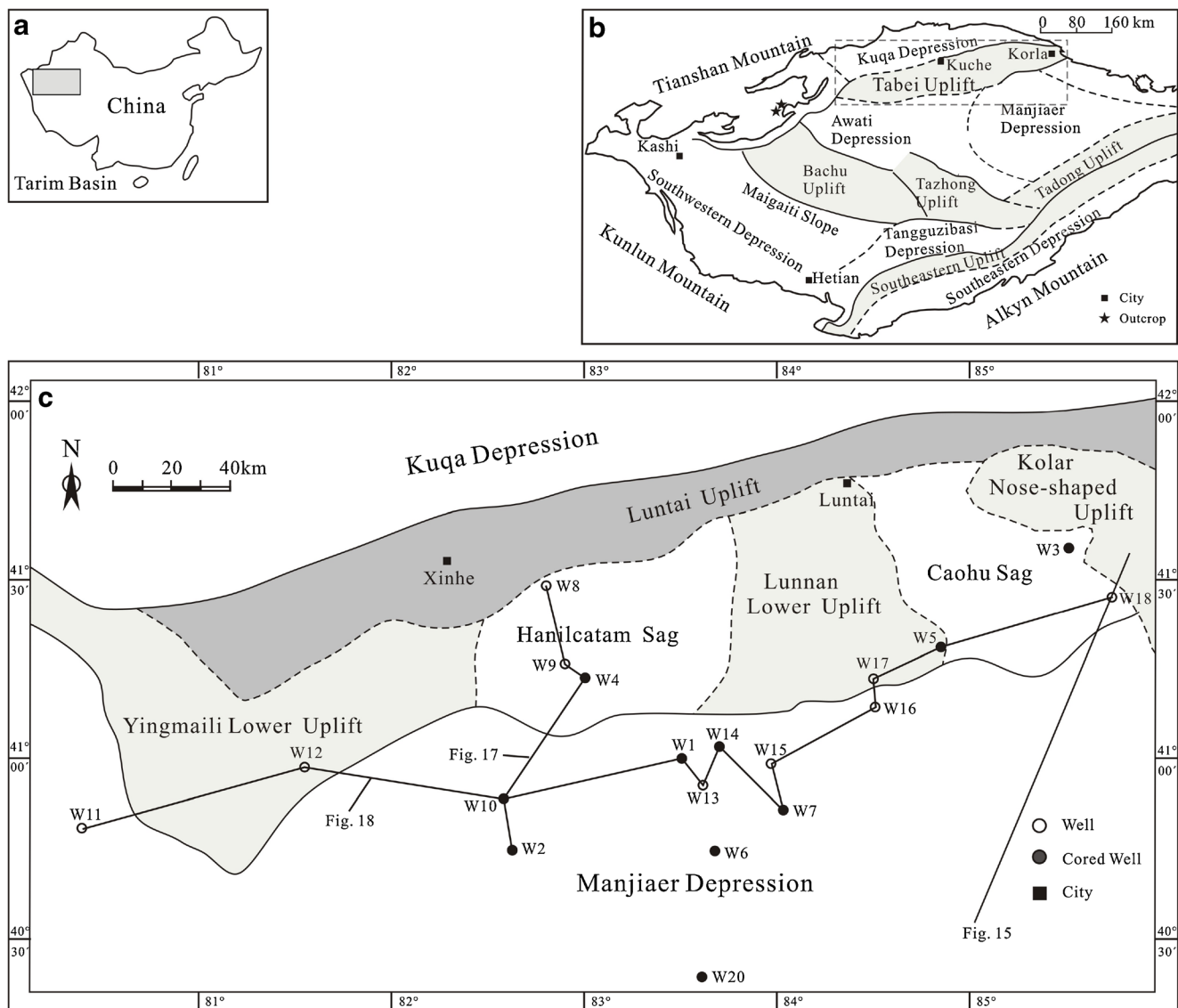
Influenced by tectonic movements in late Caledonian and Hercynian, the Silurian strata in Tarim Basin is incomplete. The Silurian is mainly distributed in northern depression, Tanggubazi depression, Keping uplift, and Kuruktag uplift. In previous studies, a lot of studies have been performed to the attribution of the Silurian and comparison of regional stratigraphy, and various classifications have been proposed (Zhou et al. 1990; Zhang and Wang 1995; Rong et al. 2003). In this study, it involved the proposal determined in 2004, at Beijing seminar for Tarim Basin Silurian. The Silurian is divided into three groups from below: Kepingtage, Tataaiertage, and Yimugantawu formations. The previous lower Kepingtage Fm. was classified as Ordovician Tierenkeawati Fm. (Fig. 2). In addition, the Ordovician Tierenkeawati Fm. and Silurian strata were both included in this study for research.

Located between Kuche Depression and the Northern Depression of Tarim Basin, the Tabei uplift is one of the most important hydrocarbon accumulation zones (Jia 1997; Cai 2005; Zhou et al. 2007; Liu et al. 2011). The Tabei uplift extends about 410 km in the E-W direction and about 90 km in the N-S direction. In this study, it mainly focused on the central area from the Yingmaili low uplift (west) to the Caohu sag (east) (Fig. 1).

With well-to-seismic calibration using synthetic seismograms, top of the Silurian boundary is an unconformable surface. From north to south, the Silurian strata below the surface are Tierenkeawati Fm., middle Kepingtage Fm., upper Kepingtage Fm., Tataaiertage Fm., and Yimugantawu Fm. Stratigraphic distribution range extends larger at the same time. Much intense erosion in northern part was reflected by the fact that the northern is narrower whereas the southern is wider. Meanwhile, from the current residual stratigraphic distribution, in the central and eastern of the research area, the strata outcrops expressed as from old to new when sequentially from north to south (Fig. 3). These features were characterized in Yingmaili low uplift areas at the same time. These regions are favorable for forming unconformity traps.

## Data and methods

Seismic data, well logging, cores, and field outcrops (two sites) were comprehensively applied in this study. The seismic



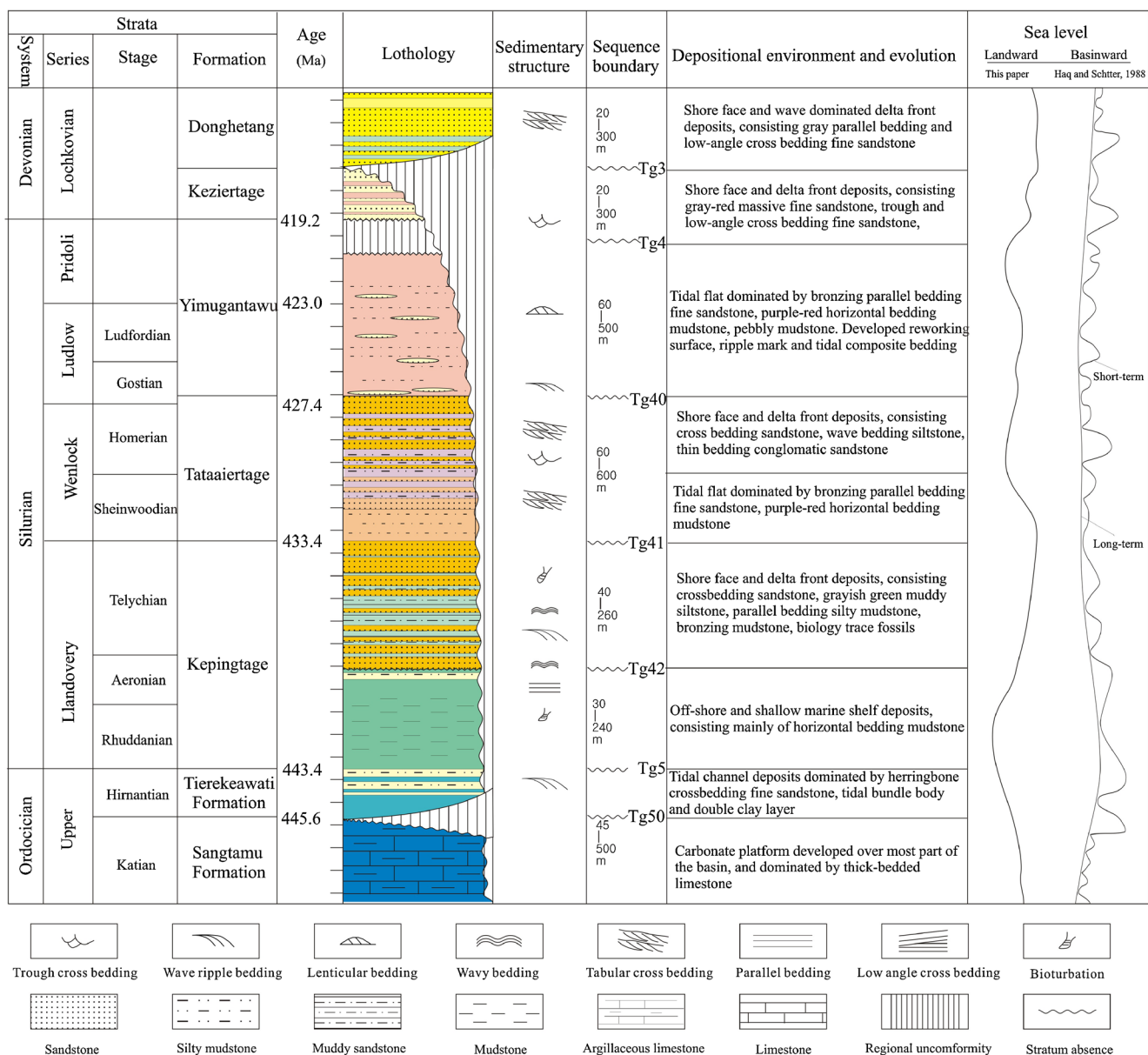
**Fig. 1** Map of the study area and the tectonic framework of the Tabei Uplift. The schematic map (b) illustrates the tectonic setting of the Tabei Uplift in the Tarim Basin (modified from Jia 1997)

data is mainly composed of 2d lines. With a vertical resolution of about 15–30 m, the frequency of 2d seismic data is higher than 35 Hz. The data of 30 drilling and logging were applied in this study. Two field profiles located in Keping area were observed as well as eight cores. The lithofacies and facies associations can be inferred from the observation of cores (80 m) and field profiles and the characteristics of logging curves that included in sedimentary facies analysis. The sedimentary facies was analyzed mainly by logging curves in well region without taking cores. The Silurian unconformable boundary surface was also identified by 2D seismic profiles. Sequence boundaries was determined and the sequence stratigraphic framework was established by tracing and comparison combined with logging data and contacting relation on cores. Then, the vertical evolution of internal sedimentary facies was analyzed as well as its distribution.

## Results and discussions

### Facies associations and depositional environments

Based on the grain size of sediments, sedimentary characteristics, and bioturbation conditions, 21 lithofacies and 5 facies associations were identified in this study (Table 1). They consisted of 11 sandstone dominant facies, 6 siltstone dominant facies, 1 interbedded sandstone and mudstone facies, and 3 mudstone dominant facies. Based on their sedimentary characteristics, hydrodynamic regimes were interpreted, which provided insights into the related depositional processes (Walker 1984; Galloway and Hobday 1996; Reading 1996). The descriptions and interpretations are summarized as following (Table 1). The facies codes used in this paper is modified from previous studies (Miall 1978; Postma 1990).



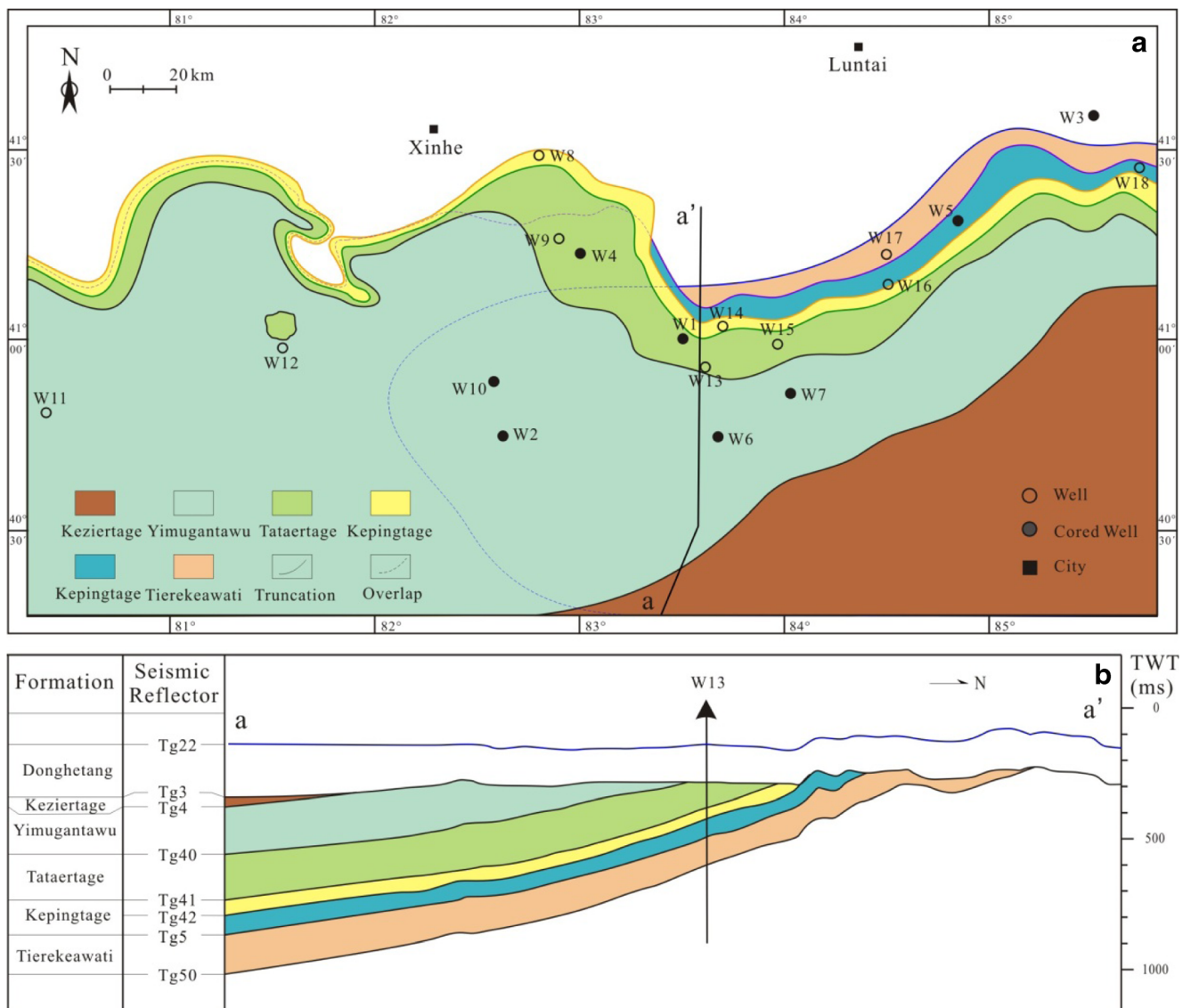
**Fig. 2** Depositional evolution of Ordovician-Silurian strata in Tabei uplift. The Upper Ordovician-Silurian is consists of six major unconformities (sequence boundaries). The relative sea-level curve

variation is appeared based on the borehole logging data in the areas. Note the comparison with the sea-level onlap curve of Haq and Schutter (2008)

*Fluvial-dominant delta front facies association*

**Description** At the Dawangou outcrop, thickness of the delta front facies association reaches around 40–80 m in Kepingtage and Tataaiertage formations. It consists of massive sandstone, trough cross-bedded sandstone, tabular cross-bedded sandstone, soft deformation structure sandstone, waves ripple bedded sandstone, wavy bedded sandstone, parallel bedded sandstone, bioturbation structure siltstone, horizontal bedded siltstone, interbedded siltstone, and mudstone. The facies association generally turned to be coarse from bottom to top in Dawangou outcrop (Fig. 4a). At the bottom, there is interbedded mudstone and siltstone and the thickness

of siltstone (5–10 cm) with horizontal bedding, wavy cross-bedding, and bioturbation increased upwardly (Fig. 4b, c). In the middle, it is composite of parallel bedded fine sandstone, tabular cross-bedded fine sandstone, and waves rippled bedded fine sandstone. In the upper part, it mainly consists of massive sandstone, trough cross-bedded sandstones, and tabular cross-bedded sandstone (Fig. 4d). The massive mudstone is observed with the thickness of about 10–20 cm in internal sandstone. Clay layers, mud drape, and soft-sediment deformation structures are also observed within sandstones (Fig. 4e). The upper sandstone bodies abruptly contacted with lower mudstone or sandstones are composed of stacked and upwardly fining sequences. The delta front facies association



**Fig. 3** The filling sequence of Silurian sediment in Tabei uplift. **a** Silurian strata distribution in Tabei uplift; **b** the strata architecture of the Silurian based on the seismic profile interpretation across the Tabei uplift (see **a** for location of the profile)

appears to be coarsening-upward funnel in Gr logging curves (Fig. 5a, d). As to cores, there is silty mudstone with bioturbation at the bottom part, and cross-bedded fine sandstone in the center with more internal scouring phenomenon (Fig. 5b–f). In the upper part, cross-bedded fine sandstone and massive fine sandstone with mudstone rip-up clasts eroded the lower fine sandstone (Fig. 5g, h).

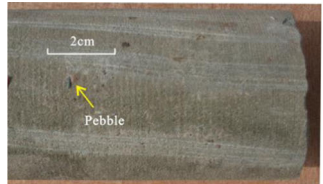
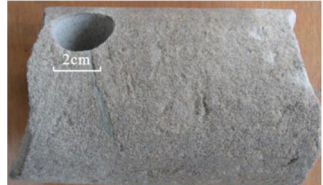

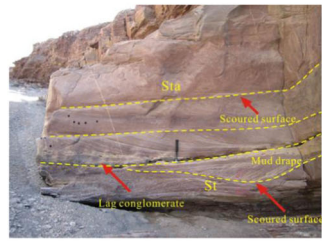
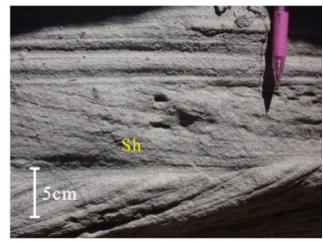
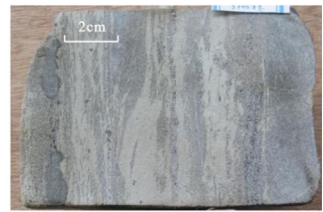

**Interpretation** The upwardly coarsening facies association is interpreted as delta front sediment. At the bottom, delta front distal sand bar deposition is indicated by interbedded mudstone and wavy bedded and bioturbation siltstone (Coleman and Prior 1982). Delta front proximal bar deposition is indicated by upward parallel bedding fine sandstone, wavy bedded fine sandstone, tabular cross-bedded fine sandstone, and

waves rippled bedded fine sandstone. Cross-bedded fine sandstone represents sediment in delta front underwater distributary channel, of which upper part upwardly fining and eroded underlying strata (Tye and Coleman 1989). The soft deformation structure in delta sandstone commonly indicated the injection of high-density flow (Tanner and Lucas 2010; Jamrozny and Weckwerth 2013). There are clay layers, mud drape, and soft-sediment deformation structures in trough cross-bedded sandstone indicating the influence of tidal effects (Johnson and Baldwin 1996).





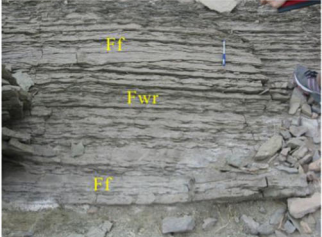
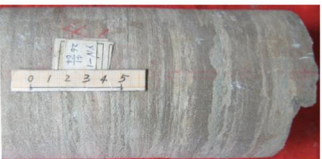
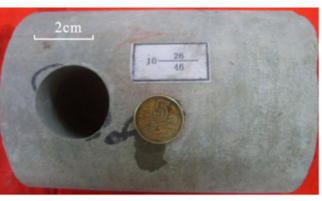


*Tidal flat facies association*

**Description** At the Dawangou and Sishichang outcrops, the thickness of tidal flat facies association reaches 80–200 m in

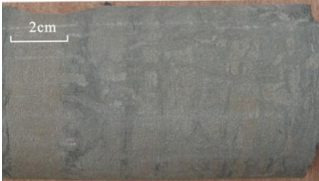

**Table 1** Classification of lithofacies. Facies codes are modified from previous studies (Miall 1978; Postma 1990)

Number	Code	Lithofacies name	Characterizes	Interpretation	Photographs
Sandstone dominant facies					
1	Spe	Pebbly sandstone	A few centimeters to meters thick, fine to very coarse sands with pebbles	A high energy deposits	
2	Sm	Massive fine sandstone	A few centimeters to meters thick, massive, structure less, well sorting sands	A high flow regime and fast deposit environment, and well sorting, sediments are not easy to present the bedding	
3	Sta	Tabular cross bedded fine- medium sandstone	Tens of centimeters thick, fine to medium sands, well-sorted with planar cross bedded	Migration of bars and dunes, lower flow regime deposits	
4	St	Trough cross-bedded fine sandstone	Tens of centimeters thick, well to very well sorted, trough cross bedded (set thickness: 6-20 cm) fine sandstone with abundant, well developed mudstone rip-up clasts and reactivation surfaces. Bases of sets are scoured and locally feature mudstone rip-up clasts	Migration of 3D dunes, indicated by cross-bedding. with mud drapes and reactivation surfaces indicate lower energy fluctuating current strength and suspension settling of mud during slack water	
5	Sh	Herringbone cross-bedded fine-medium sandstone	Tens of centimeters thick, fine to medium sands with Herringbone cross bedding, clay layers are locally present.	A bidirectional flow, typically in tidal environment	
6	Sw	Wave ripple bedded fine sandstone	A few centimeters to meters thick, well to very well sorted, ripple cross bedding fine sandstones. . Mud rip-up clasts along laminae are well developed.	A high energy deposits, lower flow regime deposits affected by wave, typically in deltas, and shallow marine area	
7	Scc	Cross-bedded fine sandstone with clay layers	Tens of centimeters to meters thick, Fine, moderately to well sorted sands with cross-bedding. double clay layers are locally present.	Typically in tidal environment	

**Table 1** (continued)

8	Sp	Parallel bedded fine sandstone	A few centimeters to meters thick, fine-grained sands with parallel or cross bedding A few centimeters to meters thick, well sorting fine grained sands to medium grained sands with low angle cross stratification sand, sometimes sands base contain carbon or coarse sands or granules and arrayed to low angle cross stratification	A upper flow regime deposits, could be formed by storm or wave, or planar bed flow (lower and upper flow regime)	
9	SI	Low angle cross-bedded fine sandstone	Tens of centimeters thick, fine to medium sands with convolute bedding	A wave or storm effect dominate environment	
10	Sb	Bioturbated fine sandstone	Fine, moderately to well sorted sandstone, bioturbated with diverse, well-developed vertical and sub-horizontal burrows.	The degree of bioturbation and ichnofossils present indicate a fully shoreface, subtidal environment	
Siltstone dominant facies					
12	Fh	Horizontal bedded siltstone	Tens of centimeters thick, fine to medium sands with convolute bedding	High deposition rate, allows the sediments to pack loosely, typically in deltas, and shallow marine area	
13	Ff	Flaser bedded siltstone	A few centimeters to meters thick, very well sorted, flaser bedded silts	A low energy environment, silts grain size dominate and deposition from suspension	
14	Fwr	Wavy ripple bedded siltstones	Thin beds of ripple bedded sandstone with mud drapes or flaser bedded sandstone-siltstone locally present. Symmetrical ripple marks are locally present	A high energy environment, mud in filled sand ripples, typically in tidal environment	
15	Fw	Wavy bedded siltstone	A few centimeters to meters thick, mud and sand deposits are equal, Symmetrical ripple marks are locally present	Wavy and lenticular bedding indicate alternating higher energy and lower energy conditions	
16	Fm	Massive siltstone	A few centimeters to meters thick, massive, structureless, well sorting silt sands	Wavy bedding indicates alternating higher energy and lower energy conditions. Typically in tidal environment	
17	Fb	Bioturbated siltstone	A few centimeters to meters thick, silts with irregular relict lamination	A low energy environment, sediments deposition from suspension and a little bio activity	

**Table 1** (continued)

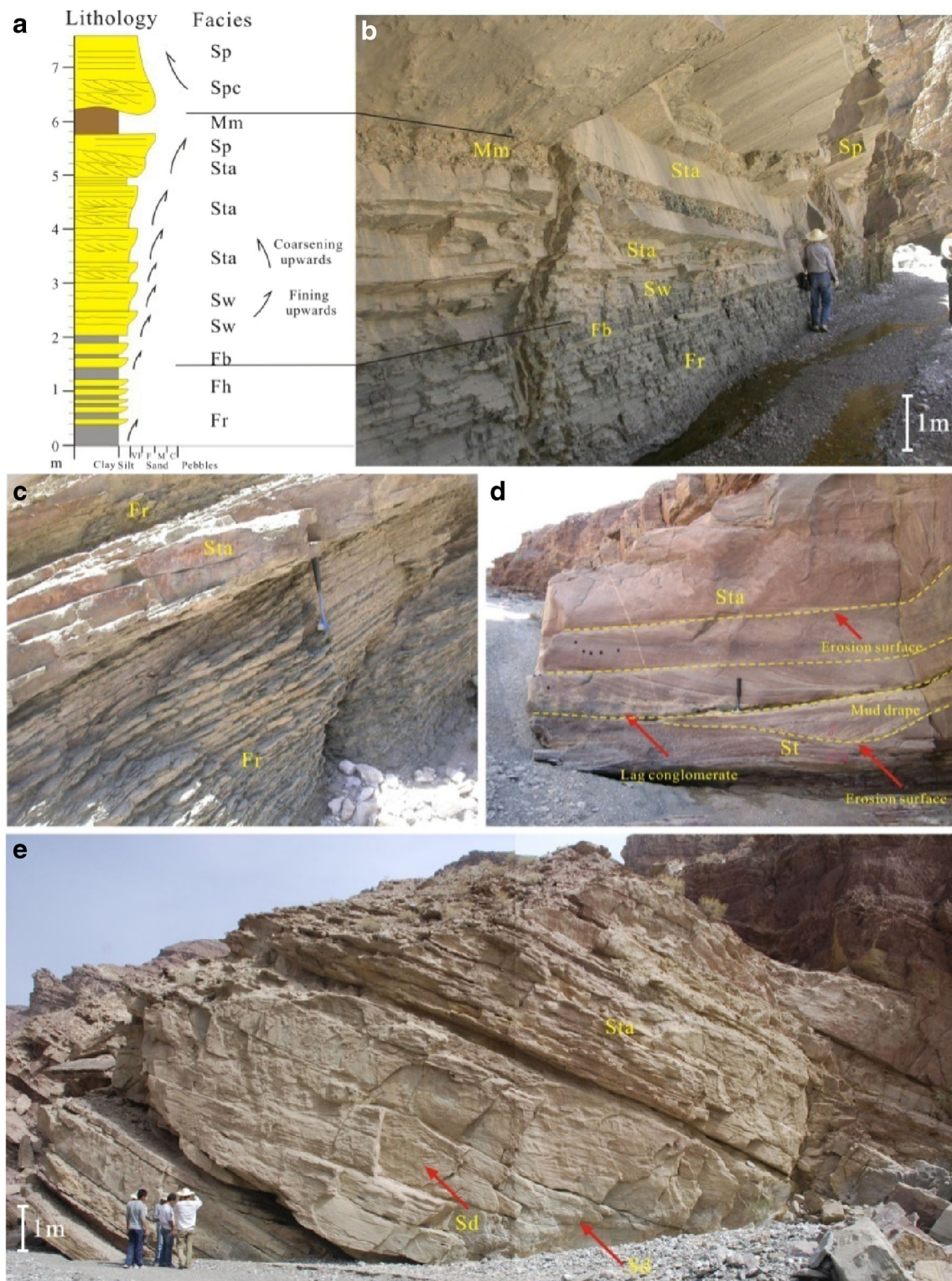
Interbedded sandstone and mudstone facies					
18	Fr	Rhythmic siltstone and mudstone interbeds	A few centimeters to meters thick, thin layer sand and mud interbeds, present wavy, flaser, lenticular bedding or ripple bedding, sometimes with slightly bioturbation	A alternation condition of suspension deposits and low to middle, flow regime, like tidal effect or distal delta front	
Mudstone dominant facies					
19	Mm	Massive mudstone	A few centimeters to meters thick, structureless massive muds	A low energy environment, approximate grain size deposition from suspension	
20	Mb	Bioturbated silty mudstone	Vertical burrows generally well developed and overprint primary structures. Locally very thin to thin beds of laminated fine sandstone	A low energy environment, after bedded or massive muds deposition, and strong bioturbation induced irregular lamination, Sandier intervals reflect intermittent higher energy conditions	
21	Mc	Composite bedded silty mudstone	A few centimeters to meters thick, mainly wave bedding	A low energy environment, like tidal flat or distal delta front	

Kepingtage, Tataaiertage, and Yimugantawu formations. It consists of massive and horizontal bedded mudstone, rhythmic bedded mudstone and siltstone, flaser bedded, lenticular bedded, wavy bedded siltstone, and parallel bedded fine sandstone with visible bioturbation structures and ripples. Both upwardly coarsening and fining successions are found in this facies association. The mudstone dominant sedimentary unit is generally composed of reddish-brown thick massive mudstone with the thickness up to 50 m (Fig. 6a, b) and thin horizontal bedded and wavy bedded siltstone (Fig. 6c). The thickness of sandstone dominant sedimentary unit reached up to 10–30 m, which is composed of flaser bedded, lenticular bedded, wavy bedded siltstone, rhythmic bedded mudstone and siltstone, and parallel bedded fine sandstone (Fig. 6d–f). Muddy and sandy sedimentary units are generally repeated in vertical (Fig. 6c, f). It was commonly eroded by trough cross-bedded sandstones, tabular cross-bedded sandstones, and herringbone cross-bedded sandstones. For the cores, brown

mudstone and gray fine sandstones are found as well as interbedded siltstone and mudstone with rhythmic bedding (Fig. 7a, b). The reactivation surface and mudstone rip-up clasts is well developed in sandstone. At the same time, flaser bedding, lenticular bedding, and wavy bedding are developed as well as water current ripples with more rounded peaks and valleys and mud cracks structure (Fig. 7c–g).

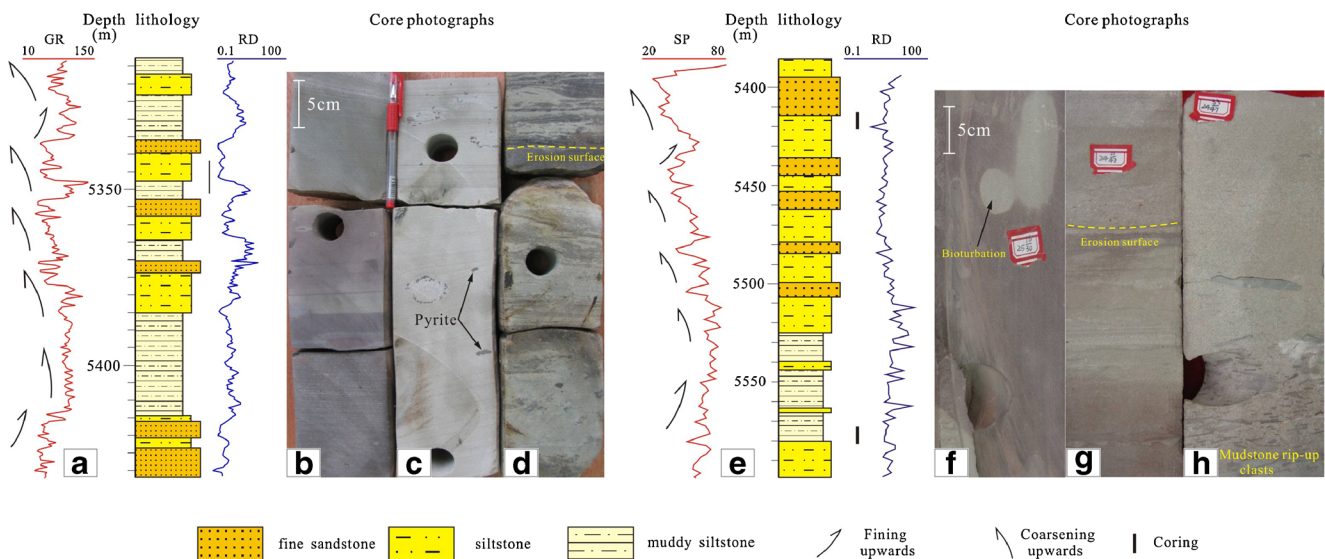
**Interpretation** This facie association is generally abruptly contacted with lower tidal channel facies or delta front facies. The sedimentary structures are dominated by tidal bedding and mudstone rip-up clasts along sandstone layers, suggesting tidal influence for this facies association (Chakrabarti 2005; Dalrymple and Choi 2007; Tovaglieri and George 2014). The preserved thickness of tidal flat depositional sequence is relatively large. The internal developed tidal channel indicated estuarine sediments under the condition of medium-large tidal range (Terwindt 1988).





**Fig. 4** Fluvial-dominant delta front facies association in Dawangou outcrop. **a** The upwardly coarsening facies association with massive mudstone, rhythmic siltstone and mudstone, bioturbated siltstone, tabular cross-bedded fine sandstone, and parallel bedded fine sandstone, Kepingtage Fm. **b, c** The upwardly coarsening facies association with rhythmic siltstone and tabular cross-bedded fine sandstone, Kepingtage

Fm. **d** Trough cross-bedded fine stone with internal scouring phenomenon; the cross-bedded conglomeratic fine sandstone eroded the underlying fine sandstone, Tataaiertage Fm. **e** Deformation structure fine sandstone, the deformed beds are typically 50–100 cm in thickness; some deformed beds are overlain by parallel bedded or tabular cross-bedded fine sandstone, Kepingtage Fm.



**Fig. 5** Log response and selected core photographs of fluvial-dominated delta front facies association in cores. **a** The overall coarsening-upward funnel in GR logging curves, upper Kepingtage Fm., W1 Well; **b** horizontal bedded siltstone with two upwardly coarsening association, 5348.4 m, upper Kepingtage Fm., W1 well; **c** parallel bedded fine sandstone and cross-bedded fine stone with pyrite concretion, 5348.0 m, upper Kepingtage Fm., W1 well; **d** the wavy cross-bedded fine sandstone with erosion surface, 5347.5 m, upper Kepingtage Fm.,

W1 well; **e** the overall coarsening-upward funnel in gr logging curves like W1 well, upper Kepingtage Fm., W19 well, located southeast of the study area; **f** bioturbation structure in siltstone, 5577.5 m, upper Kepingtage Fm., W19 well; **g** wavy bedded siltstone with erosion surface, 5412.5 m, upper Kepingtage Fm., W19 well; **h** massive fine sandstone containing mudstone rip-up clasts, 5420.2 m, upper Kepingtage Fm., W19 well

There are large amounts of trace fossils in wavy bedding, lenticular bedding, flaser bedding, and thin interbedded layers. The emergence of a large area wave mark indicates intertidal-supratidal sedimentary environment. In thin interbedded layers, the sediment of double clay layer covers the subtidal flat or tidal channel sandstone. Then it is transitioned to muddy sediments, associated with mud cracks, which indicates supratidal sediment. Due to the fluctuation of tidal, it is easy to produce mudstone rip-up clasts in tidal flat facies association, especially in the subtidal flat deposition. In addition, the development of reactivation surface is another typical feature of tidal flat system.

#### *Tidal channel facies association*

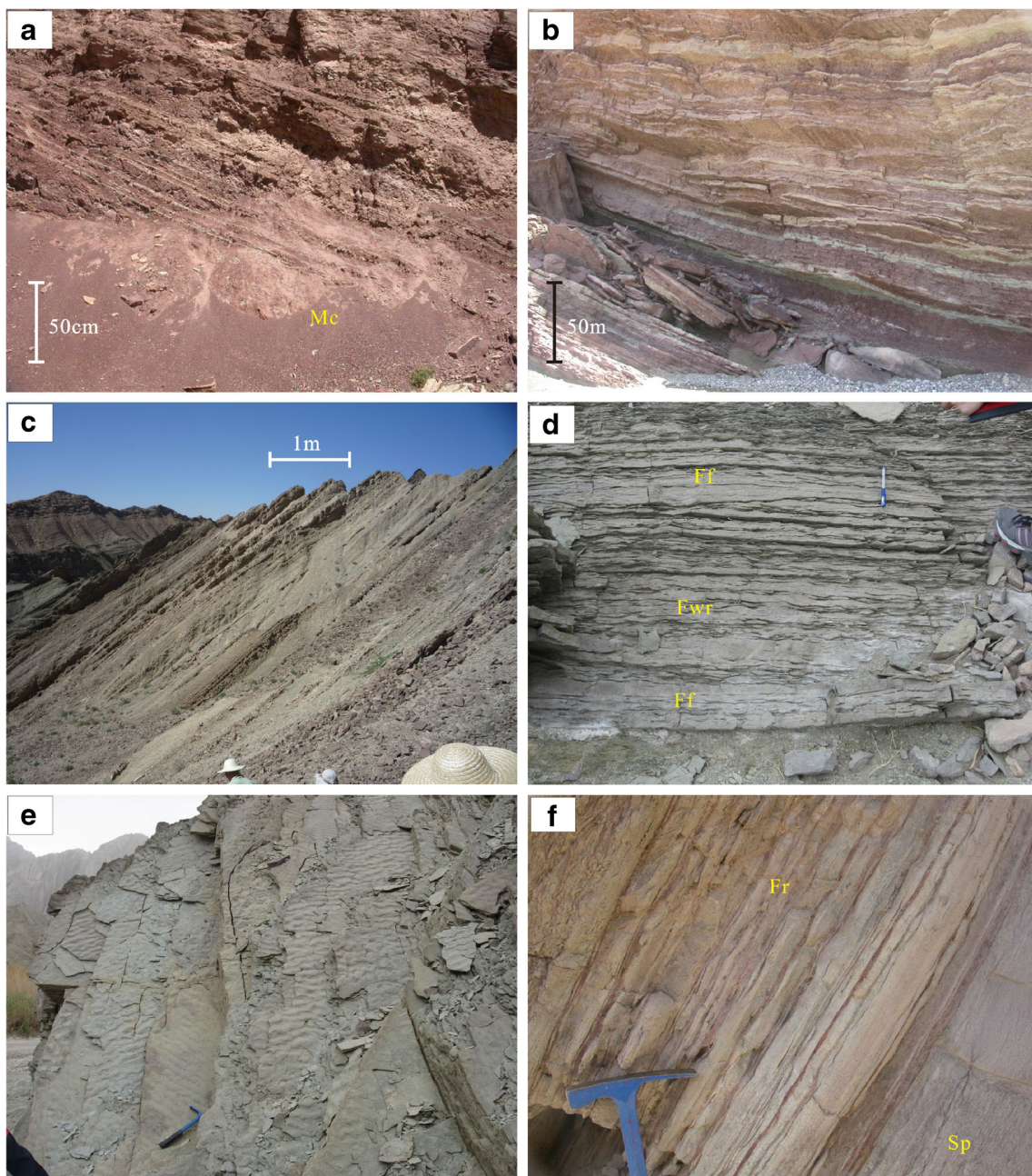
**Description** The thickness of tidal channel facies association reaches up to 2 m in Tierekeawati Fm. at Sishichang outcrop. Tidal channel facies association consists of pebbly sandstone, herringbone cross-bedded fine-medium sandstone, tabular cross-bedded fine-medium sandstone, cross-bedded sandstones, and flaser bedded sandstone. There is a scouring surface at the bottom of tidal channel facies. The large tidal bundle body sequence is composed of tabular cross-bedded fine sandstone with the clay layer and double clay layers (Fig. 8). The height of tidal bundle is about 60 cm at Sishichang outcrop (Fig. 8b, d). In upper unit, the tabular cross-bedding and parallel bedding are developed with the thickness of 20 cm. Alternately, cross-bedding and flaser bedding, herringbone

cross-bedding, and reactivation surface can be observed occasionally (Fig. 8b, d). The bioturbation and mudstone rip-up clasts distribution along the layers are also typical characteristics in this facies association. Pebbly sandstone is found in cores within tidal flat facies dominant sedimentary (Fig. 9).

**Interpretation** Erosion boundary surface and retained pebble deposits, overall upwardly fining sedimentary sequence with trough cross-bedding and tabular cross-bedding indicate a channel deposition (Bridge 2006; Dalrymple and Choi 2007; Buatois et al. 2012). The herringbone cross-bedding, tidal bundle, and clay layer indicate a strong two-way tidal flow condition (Nio and Yang 1991; Dalrymple and Choi 2007). Therefore, the facts suggest the facies association is tidal channel deposition. The tabular and trough cross-bedding reflected unidirectional flow is dominated by flood or ebb. Tidal channel deposition is gradually transitioned into sandstone and mudstone, and then interbedded with tidal flat facies association in vertical.

#### *Offshore-transition facies association*

**Description** This facies association is characterized by thick successions (30–60 m). It is mainly composed of massive mudstone or siltstone (Figs. 10a and 11) with low GR value in well log (Fig. 12). The mudstone or siltstone are of pervasively bioturbated or interbedded (Fig. 11d). Siltstone layers with the

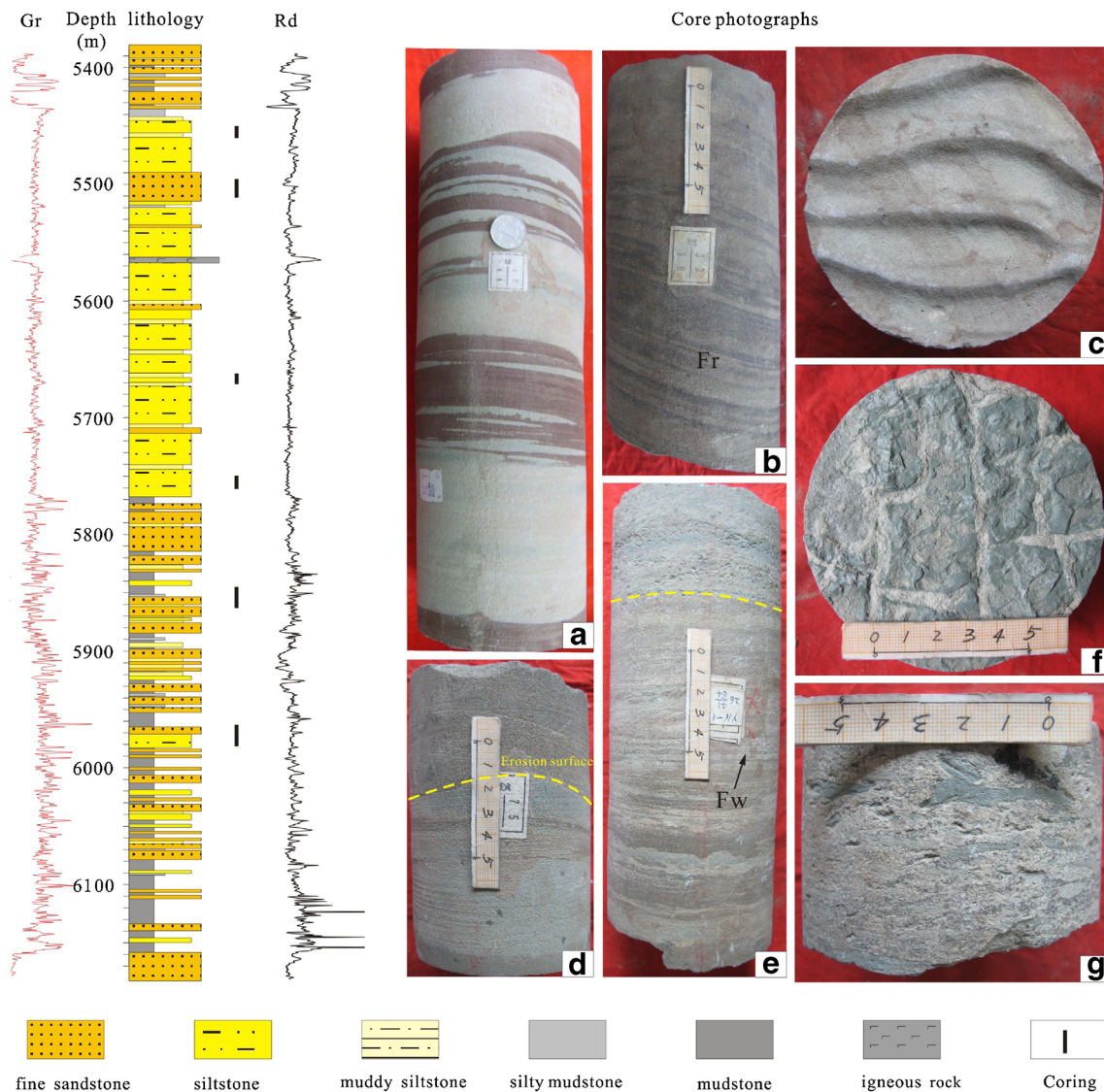


**Fig. 6** Tidal flat facies association in outcrops. **a** Thick-bedded red massive mudstone with thin-bedded green mudstone, Tataaiertage Fm., Dawangou outcrop; **b** horizontal red mudstone with thin-bedded green mudstone, Yimugantawu Fm., Dawangou outcrop; **c** muddy and sandy sedimentary units are vertically and upward repeated (a single sandstone bed is 30–50 cm thick), Tataaiertage Fm., Sishichang outcrop; **d** composite bedded siltstone, including wavy ripple bedded siltstone,

flaser bedded siltstone, and lenticular bedded siltstone, Kepingtage Fm., Sishichang outcrop; **e** ripple mark, asymmetrical shape seems to originate in the drifting of materials along the bottom of the water; Kepingtage Fm., Sishichang outcrop; **f** rhythmic siltstone and mudstone with flaser bedded siltstone, Tierekeawati Fm., Sishichang outcrop; **i** tidal bundle (is about 60 cm), Tierekeawati Fm., Sishichang outcrop

thickness of millimeter to centimeter develop horizontal bedding and wavy bedding (Fig. 11c–f). Some thin-layer wavy bedded sandstones are sharp-based with gutter cast or with convolute beddings (Fig. 11g). Offshore facies association commonly covers shoreface facies association. The facts show that a gradual upward increase in grain size, sandstone/mudstone ratio, and sandstone layer thickness into shore facies association.

**Interpretation** A mudstone dominant depositional setting with pervasive bioturbation suggests low energy, stable conditions in an offshore-transitional environment (Johnson and Baldwin 1996; Pemberton et al. 2001; Suter 2006). During fair-weather periods, fine-grained sediments settle from suspension and bottom sediments with bioturbation. Consequently, the massive mudstone and bioturbated silty



**Fig. 7** Log response and selected core photographs of tidal flat facies association in cores. **a** Thick-bedded green massive mudstone with thin-bedded red mudstone, 5455 m, Yimugantawu Fm., W2 well; **b** rhythmic siltstone and mudstone with lenticular bedding, 5970.2 m, Tataaiertage Fm., W2 well; **c** ripple mark, 5505.3 m, Yimugantawu Fm., W2 well; **d**

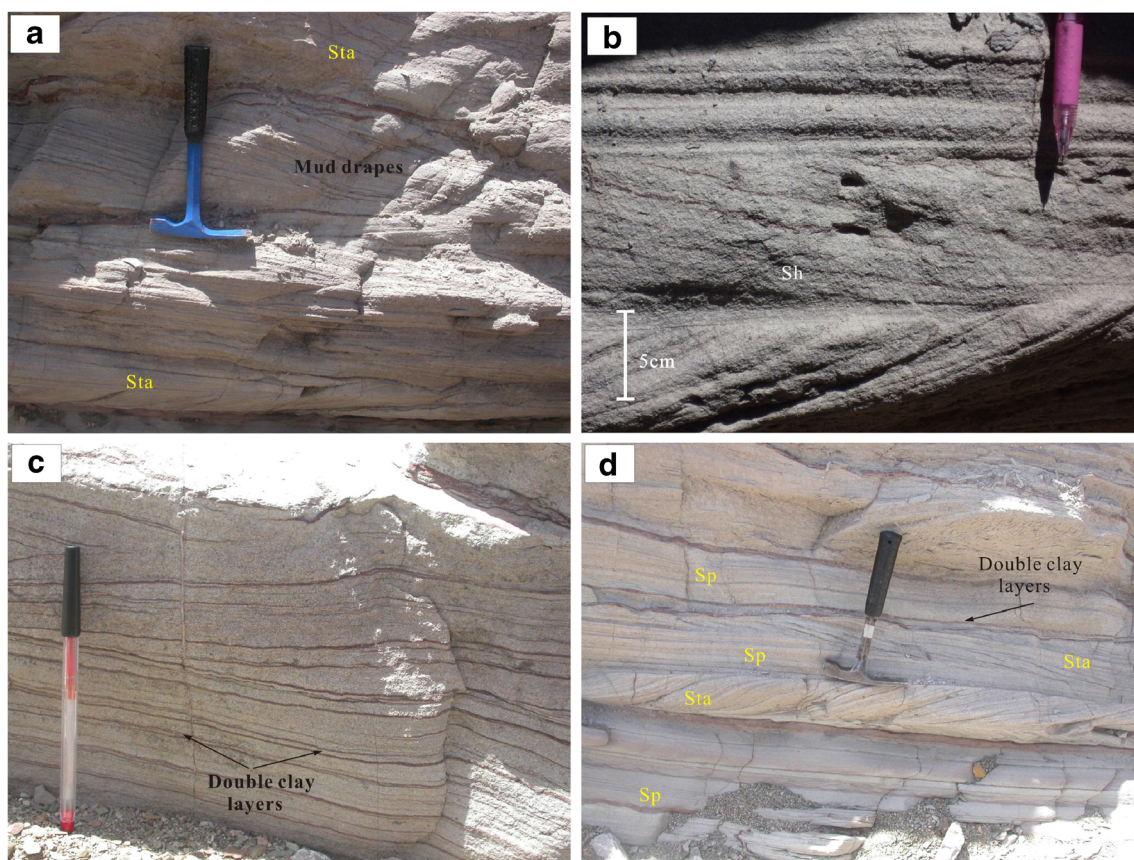
massive sandstone with erosion surface, 2850.5 m, Yimugantawu Fm., W2 well; **e** wavy bedded siltstone with erosion surface, 5861.2 m, Tataaiertage Fm., W2 well; **f** mud crack, 5857.8 m, Tataaiertage Fm., W2 well; **g** mud rip-up clasts in fine stone, 5851.7 m, Yimugantawu Fm., W2 well

mudstone are mainly found in the offshore-transition facies association. During storms, the bottom sediments are affected by oscillatory waves, shoaling waves, and storm-generated currents. Consequently, storm-generated lithofacies such as thin-layer wavy bedded sandstones with gutter cast or convolute beddings are formationed.

#### *Shoreface facies association*

**Description** The thickness of this facies association is ranged 10–50 m. It consists of parallel bedded sandstone, low-angle cross-bedded sandstone, wavy bedded sandstone, bioturbated sandstone, and thin layer mudstone (Fig. 13). The thickness of mudstone layers ranges from centimeter

to decimeter. They are normally graded, occasionally structureless, and/or containing thin parallel bedded siltstone (Fig. 13a–e). The thickness of siltstone and fine sandstone layers range from centimeter to decimeter, which are characterized by good sorting and commonly sharp-based with mudstone, and eroded by low-angle cross-bedded sandstone. The sandstone/mudstone ratio, grain size (very fine- to fine-grained sand), and the thickness of sandstone layer show an increase upwardly (Fig. 14). Erosion surface is overlaid by a sandstone dominant interval, which consists of low-angle, parallel bedding sandstone with graded mudstone rip-up clasts (Fig. 13f, g). Occasionally, reactivation surface is observed underlying massive mudstone directly (Fig. 13d).



**Fig. 8** Tidal channel facies association in outcrops. **a** Parallel bedded fine sandstone with double clay layers, Tierekeawati Fm., Sishichang outcrop; **b** herringbone cross-bedded fine-medium sandstone, Tierekeawati Fm., Sishichang outcrop; **c** parallel bedded fine sandstone with double clay

layers, Tierekeawati Fm., Sishichang outcrop; **d** tabular cross-bedded sandstone and parallel fine sandstone with clay layers, Tierekeawati Fm., Sishichang outcrop

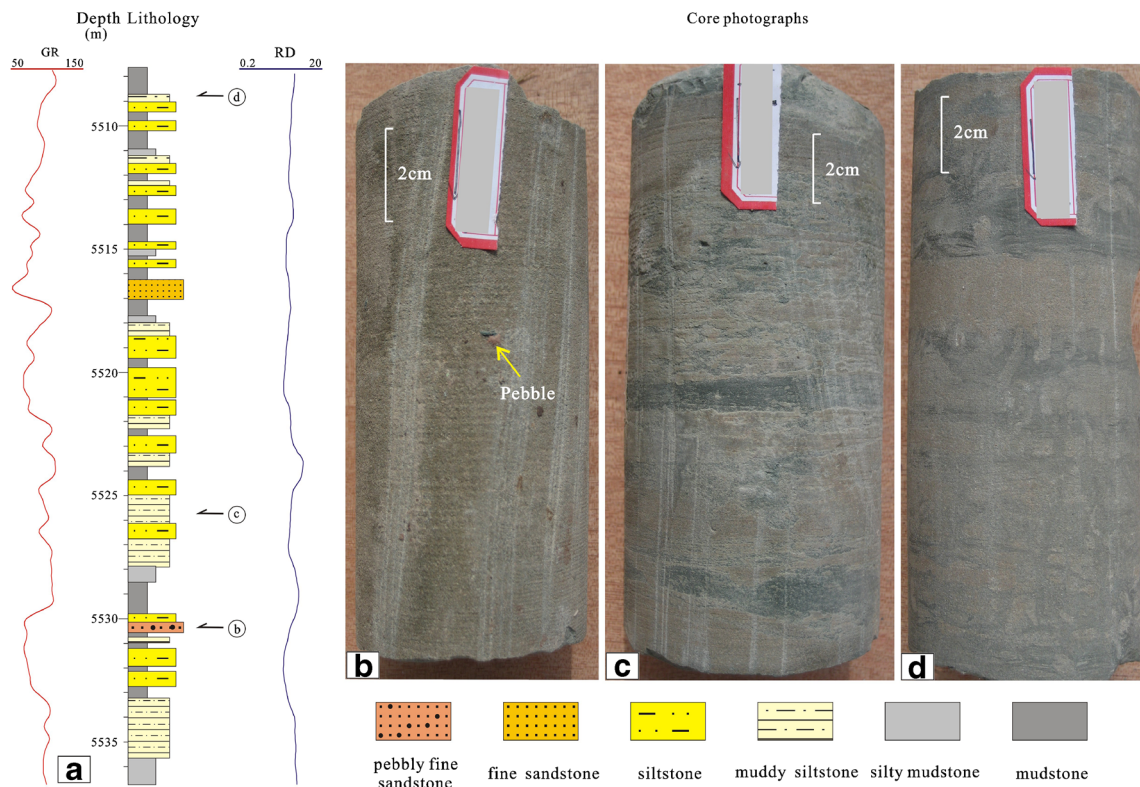
**Interpretation** Shoreface facies association records generally upward increasing depositional energies and depositional rates. It is reflected by the upward-coarsening grain size trend coupled with increasing sandstone bed thickness. The deposits of a wave-dominated shoreline were indicated based on the dominance of wave-generated facies. The periods of very rapid mud accumulation was demonstrated by the paucity of burrowing within these mudstone layers (Vakarelov et al. 2012). The sandstone with sharp-based, parallel bedded to low-angle cross-bedded sandstone represents a transgressive sand/lag deposit formed by wave ravinement and associated with a flooding process (Swift et al. 1991; Murakoshi and Masuda 1992). The top of parallel bedded sandstone and low-angle cross-bedded sandstone are swash zone deposits on beach environment. A small number of burrowing is typical in these depositional conditions (Bann et al. 2008).

### Sequence stratigraphy

Sequence stratigraphy is a genetic framework established to analyze facies relationships and stratal

architectures (Catuneanu 2009). The recognition of sequence stratigraphic surfaces contributes to an interpretation of the chronostratigraphic framework. Several sequence stratigraphic surfaces is formed during a cycle of base-level change. Two types of surfaces were recognized as time barriers (or approximate time surfaces) and time offsets (or diachronous surfaces). The low diachronous surfaces were useful for sequence stratigraphic framework established. In contrast, time offset surfaces are not suitable as bounding surfaces of sequence stratigraphic units. Generally, unconformities and their correlative conformities are applied as sequence surfaces (Mitchum et al. 1977; Haq et al. 1987; Posamentier and Vail 1988).

In this study, 6 unconformable surfaces are identified in Silurian at Tabei uplift based on 2D seismic profiles, outcrop profiles, well logging, and cores (Figs. 15, 16, 17, and 18). The six surfaces are Tierekeawati Fm. bottom surface (SB1), Kepingtage Fm. bottom surface (SB2), upper Kepingtage Fm. bottom surface (SB3), Tataaiertage Fm. bottom surface (SB4), Yimugantawu Fm. bottom surface (SB5), and

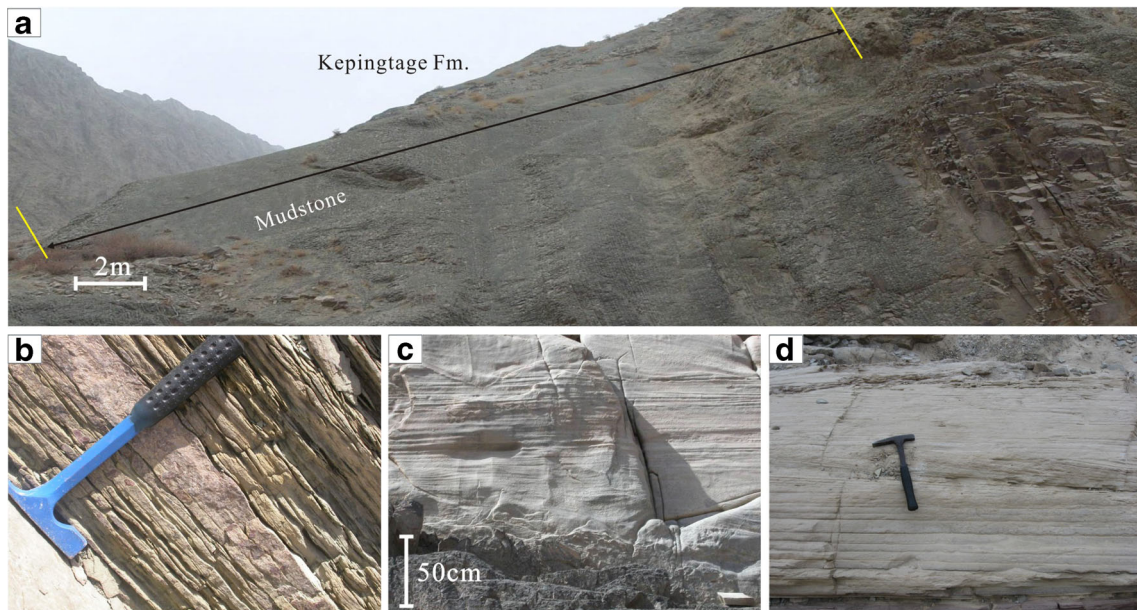


**Fig. 9** Log response and selected core photographs of tidal channel facies association in W17 well. **a** Log response and lithologic characteristic; **b** pebbly sandstone, 5530.5 m, Tierkeawati Fm. **c**

muddy siltstone interbedded thin mudstone, tidal flat facies, 5525.8 m, Tierkeawati Fm. **d** Bioturbated muddy siltstone, tidal flat facies, 5508.9 m, Tierkeawati Fm.

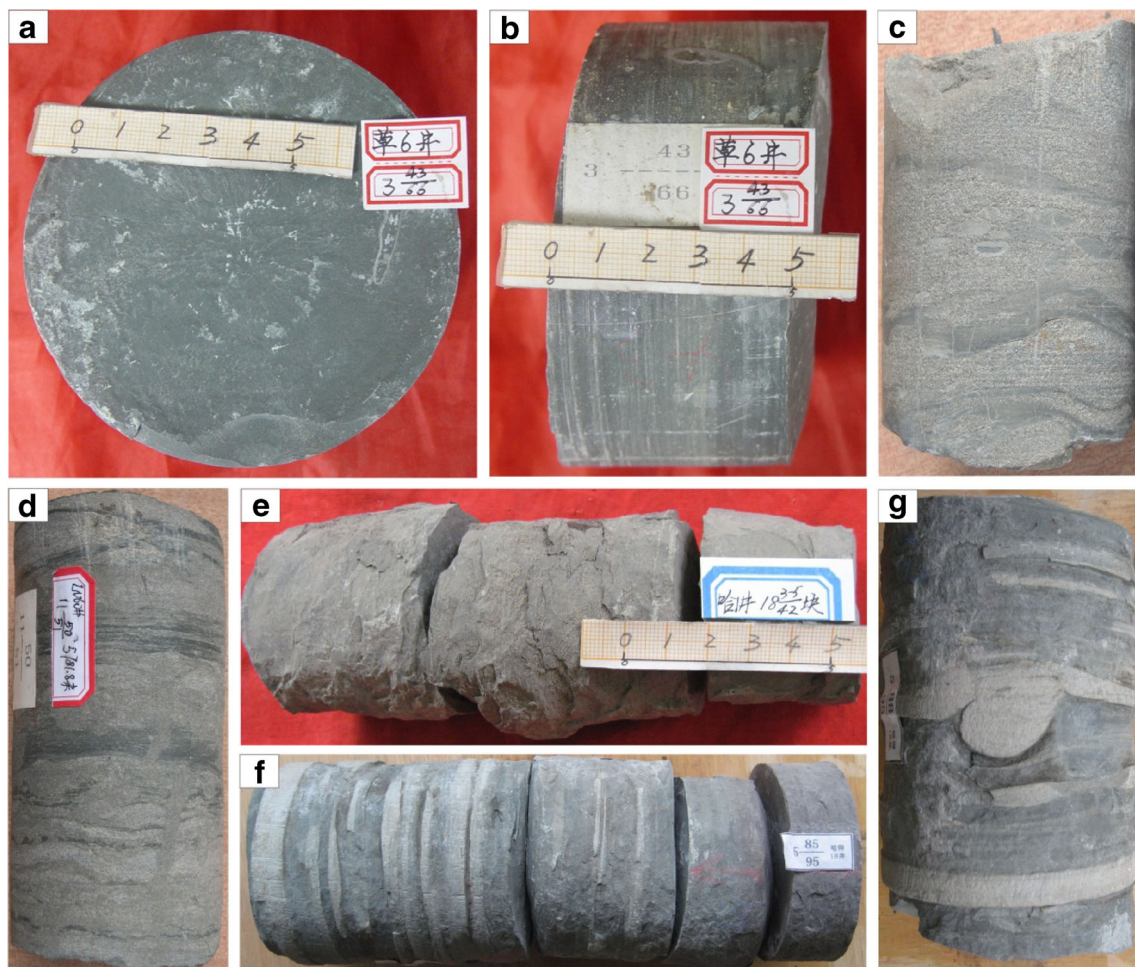
Keziertage Fm. bottom surface (SB6). Third order sequence stratigraphic units of the Silurian are defined

by the conformable boundary surfaces and their comparison is established as well.



**Fig. 10 a** Thick-bedded green massive mudstone with thin-bedded siltstone interbedded, lower Kepingtage Fm., Dawangou outcrop; **b** the stacked upward-coarsening associations with wavy bedded siltstone, low-angle cross-bedded sandstone and parallel bedded sandstone, Kepingtage

Fm., Sishichang outcrop; **c** parallel bedded sandstone with erosion surface by storm at the top of the sandstone, Kepingtage Fm., Sishichang outcrop; **d** parallel bedded sandstone and low-angle cross-bedded sandstone, Kepingtage Fm., Sishichang outcrop



**Fig. 11** Selected core photographs of tidal channel facies association. **a**, **b** Green massive mudstone, 5400.5 m, Kepingtage Fm., W3 well; **c** Wavy bedded siltstone with mud rip-up clasts, 5850.5 m, Kepingtage Fm., W5 well; **d** Bioturbated siltstone with wavy bedding, note the vertical burrows, 5781.8 m, Kepingtage Fm., W5 well; **e** massive mudstone,

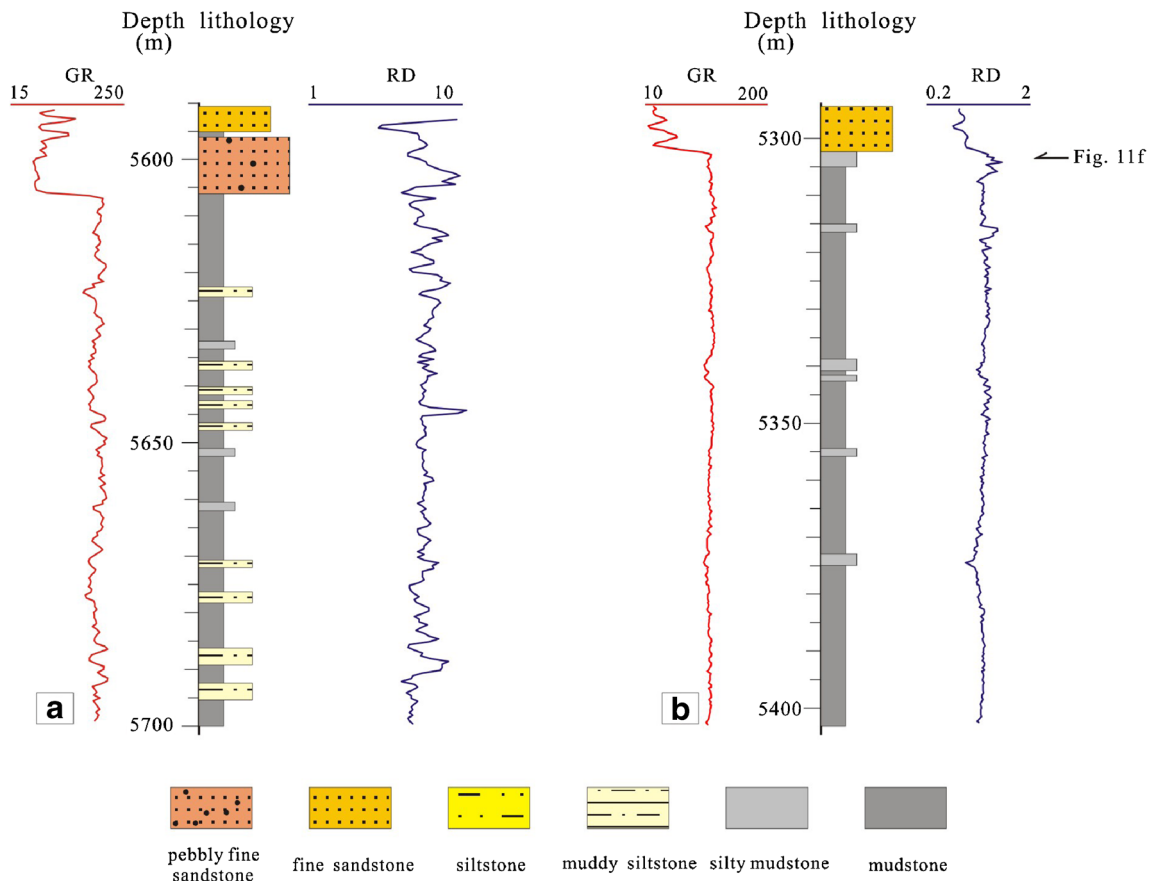
6340.4 m, Kepingtage Fm., W4 well; **f** thick-bedded mudstone with thin-bedded siltstone with horizontal bedding, 5305.4 m, Kepingtage Fm., W14 well; **g** thin-layer parallel laminae sandstones with sharp-based and gutter cast, 5305.8 m Kepingtage Fm., W14 well

### Sequence surfaces

Due to the influence of sea level variation, tectonic movement, sediment supply, and other factors, there are significant response characteristics in the second and third order sequence boundary, including outcrops, cores, well logging curve shape, seismic reflection structure, and sedimentary facies.

The bottom surface of Tierekeawati Fm. (SB1) is a significant unconformity surface with intense truncation on seismic profile (Fig. 15). On the Dawangou outcrop, there is abrupt contact between bottom conglomerate of the Tierekeawati Fm. and underlying black shale of Yingan Fm. (Fig. 16f). The bottom surface of Kepingtage Fm. (SB2) is represented by large angular unconformity or by micro-angular unconformity between the Silurian and the Ordovician in Tabei region. Above the SB2, thick gray-green mudstone, silty mudstone, and interbedded local thin argillaceous siltstone deposited (Fig. 16e). Seismic reflection characteristics of this surface

are stable with truncation and onlap (Fig. 15). The bottom surface of upper Kepingtage Fm. (SB3) is abrupt contact between gray-green fine sandstone and underlying gray-green mudstone. The overall logging curve shifts under the surface with large changes of lithofacies (Figs. 17 and 18). Seismic reflection characteristics of this surface with a certain truncation are represented by onlap above the surface (Fig. 15). The bottom surface of Tataaiertage Fm. (SB4) is a significant unconformity surface with large-scale onlap in seismic reflection which is obvious in Caohu depression of eastern Tabei region and Yihe region (Fig. 17). Medium thickness layer of gray fine sandstone, argillaceous siltstone, and gray fine-grained sandstone were generally deposited above the surface, while under the surface, gray-green fine sandstone were generally deposited (Fig. 16c). Logging curve shape abruptly changes at this unconformity surface (Fig. 18). The bottom surface of Yimugantawu Fm. (SB5) is easy to be identified with strong and stable seismic reflection. The onlap of



**Fig. 12** Log response of offshore-transition facies association in Kepingtage Fm. of W5 well (a) and W6 well (b)

Yimugantawu Fm. develops in Hudson and Caohu except in Yingmaili and Hanilcatam area. The top surface of Yimugantawu Fm. (SB6) is widely distributed with angular unconformity in the study area (Fig. 16a). In the late Silurian, affected by tectonic movement of late Caledonian, most areas suffered intense uplift and erosion at Tabei uplift, and a second order sequence surface was formed between Silurian and Devonian or Carboniferous. In the study area, the overlying strata of Yimugantawu Fm. in Hudson and Hanilcatam area are mainly the Donghetang Fm. of Devonian, whereas in Yingmaili areas is Triassic or Jurassic on the erosion belt.

### Comparisons

The system tract is the basic unit for forming the sequence stratigraphy. According to the strata configurations, the location of strata in sequence, and the boundary types, the system tract can be explained and analyzed (Catuneanu 2002). With the analysis of cores, loggings, and seismic data in Tabei area, the system tract was divided in Silurian. Each sequence consists of transgressive system tract (TST) and highstand system tract (HST), whereas SQ1 contains lowstand system

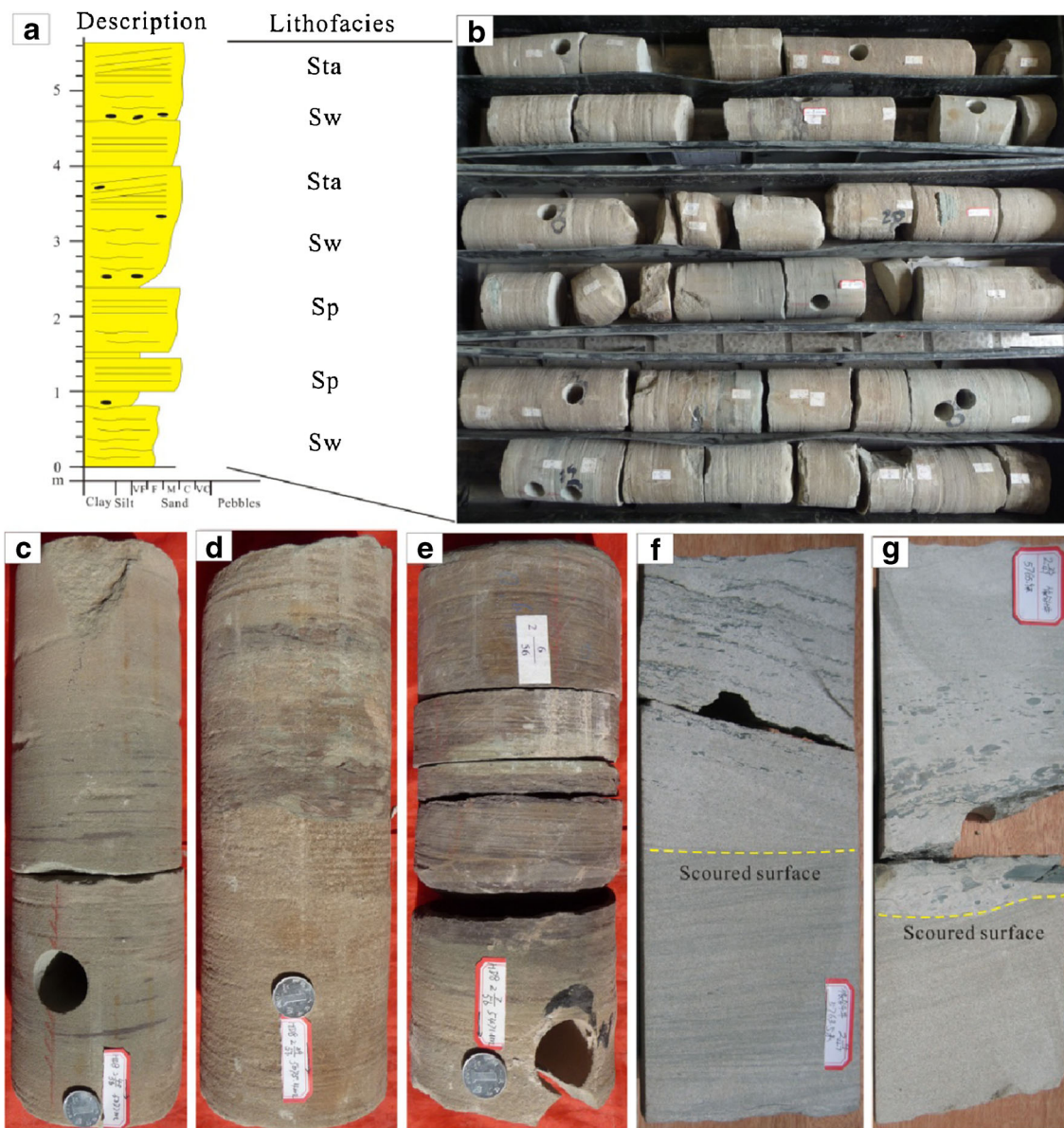
tract (LST) (Figs. 16, 17, and 18). Sedimentary model is established based on analysis of depositional system in sequence stratigraphic framework (Fig. 19).

SQ1: TST consists of mainly tidal flat facies association with multiple retrograding parasequence groups. HST is also composed of tidal flat facies association with multiple progradation-aggradation parasequence groups indicated the overall regressive sequence. The total transgressive and regressive sedimentary sequences develop well in Caohu and Hadexun area with complete sedimentary cycle (Fig. 17).

SQ2: It is large-scale transgression period of the Tarim Basin during SQ2 developed. TST is entirely composed of offshore-transition facies association with thick massive mudstone, while HST is composed of offshore-transition facies association and lower shoreface facies association with massive mudstone, thin layer horizontal bedded and wavy bedded siltstone. The stratigraphic stacking patterns are mainly aggradation and retrogradation (Figs. 17 and 18)

SQ3: From the well-tie sequence comparison profile in Tabei uplift, it is indicated that the maximum thickness of the SQ3 located in Yingmaili area. TST and HST both





**Fig. 13** Selected core photographs of shoreface facies association. **a, b** The stacked upward-coarsening associations with wavy cross-bedded fine sandstone (*Sw*), parallel bedded fine sandstone (*Sp*), and low-angle cross-bedded fine sandstone, Tataaiertage Fm., W6 well; **c** upward-coarsening associations with horizontal bedded siltstone and parallel bedded fine sandstone, 5477. 0 m, Tataaiertage Fm., W6 well; **d** parallel bedded fine sandstone with scoured surface by a upward-

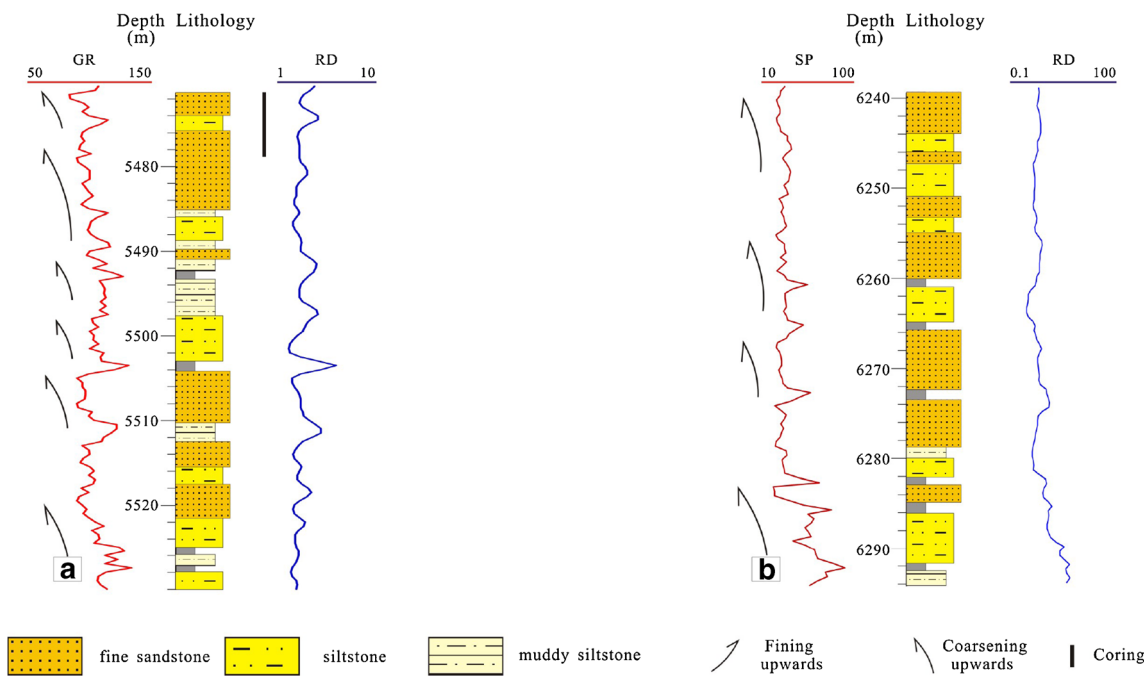
coarsening association, 5475.4 m, Tataaiertage Fm., W6 well; **e** parallel bedded fine sandstone with scoured surface 5471.1 m, Tataaiertage Fm., W6 well; **f, g** cross-bedded fine sandstone with a scoured surface, the lower sandstone low-angle cross-bedding and the upper sandstone with mudstone rip-up clasts along the lamina, 5763.5 and 5765.9 m, Tataaiertage Fm., W20 well

consist of fluvial-dominated delta front facies association and shoreface facies association with mainly fine sandstone, siltstone, and interbedded thin mudstone. Multiple retrograding stratigraphic stacking patterns are observed in TST, and aggradation and retrogradation in HST (Fig. 18).

SQ4: This sequence shows huge deposition thickness of about 330–420 m in regions, which is the maximum thickness unit in Silurian (Fig. 18). TST and HST both mainly consist of shoreface facies association with mainly fine

sandstone, siltstone, and mudstone. TST is composed of multiple upwardly fining parasequence with relatively high mudstone content showing retrogradation stacking patterns. HST consists of multiple upwardly coarsening parasequence with progradation stacking patterns. In addition, interbedded brown mudstone and gray-green fine sandstone is found indicating intermittent exposure to water during Tataaiertage Fm. deposition (Fig. 18).

SQ5: This sequence has suffered a large area of erosion in study area. The erosion is gradually increased from



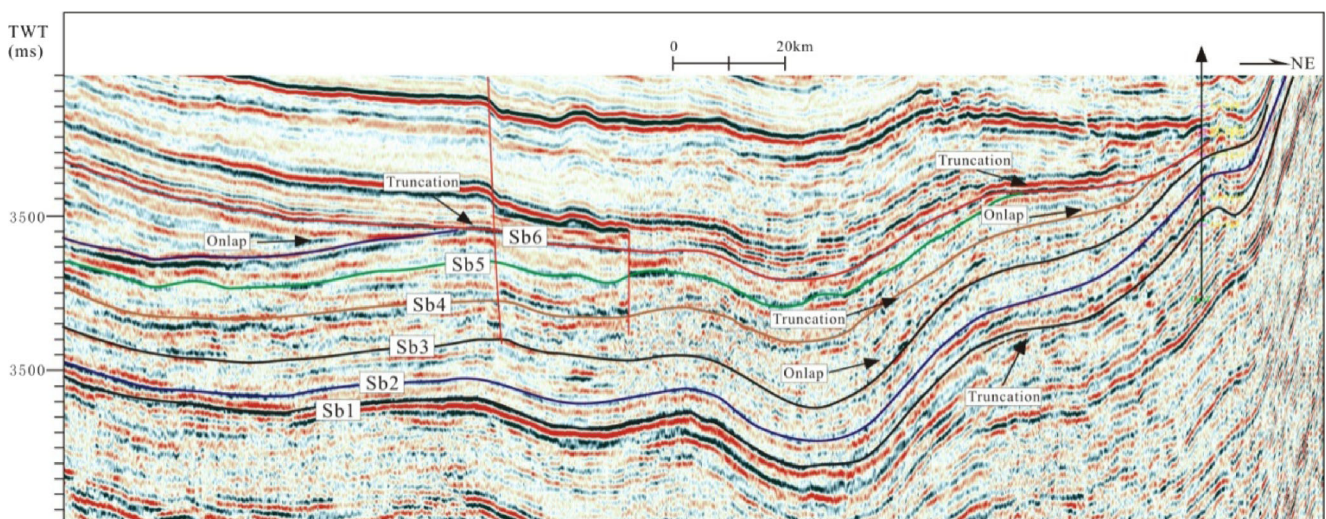
**Fig. 14** Log response of shoreface facies association in Tataaiertage Fm. of W6 well (a) and Kepingtage Fm. of W10 well (b)

southern slope to northern uplift belt (Fig. 18). The sequence is preserved well in Yuenan and Caohu area. From the comparison, it was observed that the logging characteristics in TST and HST are similar (Fig. 18). The logging response characteristics on maximum flooding surface are not visible due to the relative small variation in depositional environment. TST and HST both mainly consist of tidal flat facies association. The stacking pattern is mainly aggradation and progradation in HST, while mainly retrograding and aggradation in TST (Fig. 18).

**Controls on the development of sequences and depositional system**

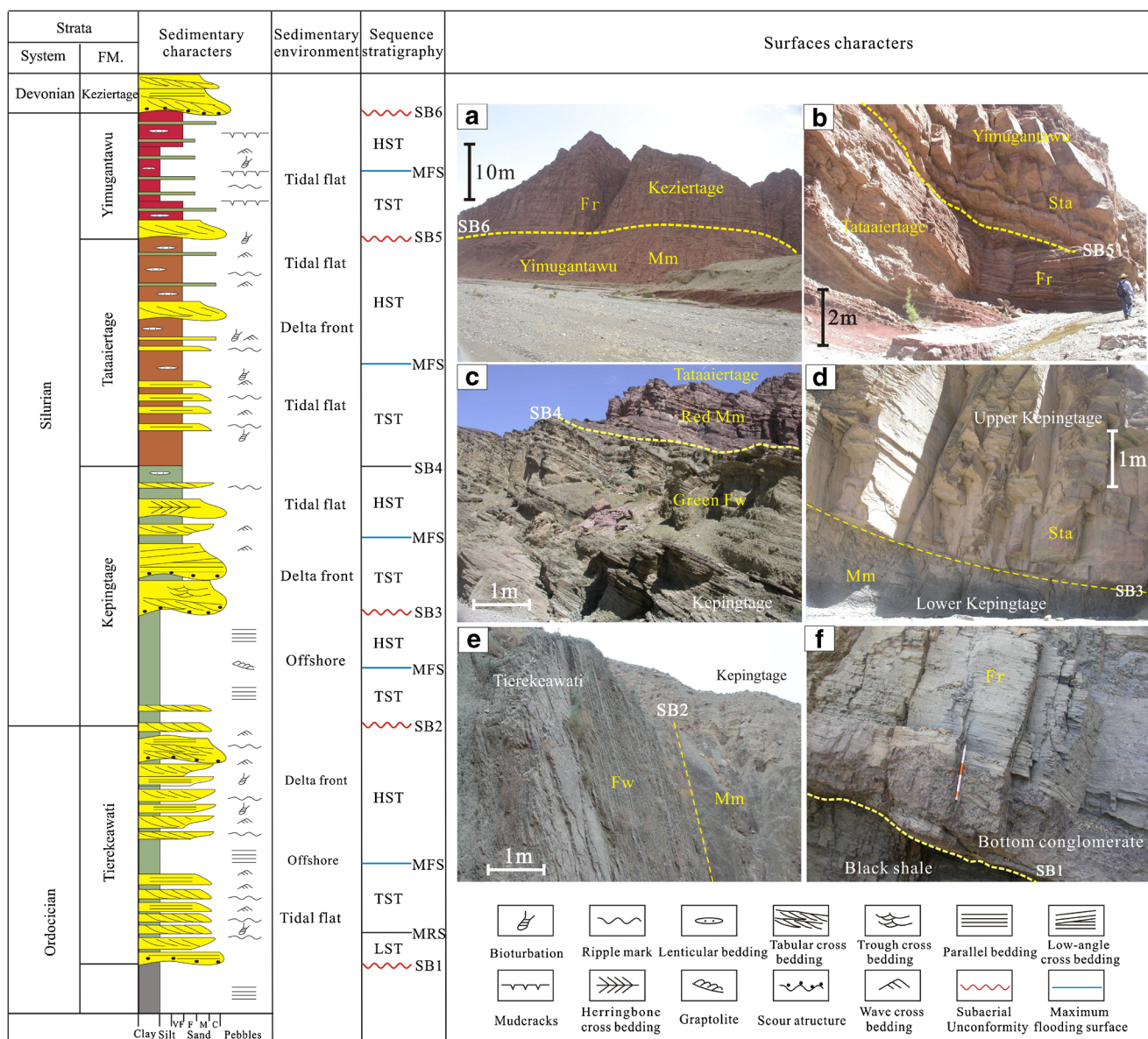
*Tectonic factors*

Tectonic movement is the key factor to control the sequence development of Silurian, whereas sequence surface SB1 and SB6 are tectonic uplift unconformity. The bottom surface of Silurian (SB1) indicates late Caledonian movement at the end of Ordovician. During the plate movement, ancient oceanic plate in the northern of the Tarim plate strongly subducted to



**Fig. 15** Seismic reflection characteristics of sequence boundary (Fig. 1c showing the location). Unconformity surface (SB1) with intense truncation; SB2 is a micro-angular unconformity; SB3 and SB4 are

large-scale onlap unconformity; SB5 corresponding reflection axis amplitude on seismic profile is strong and stable; SB6 is widely distributed angular unconformity in study area

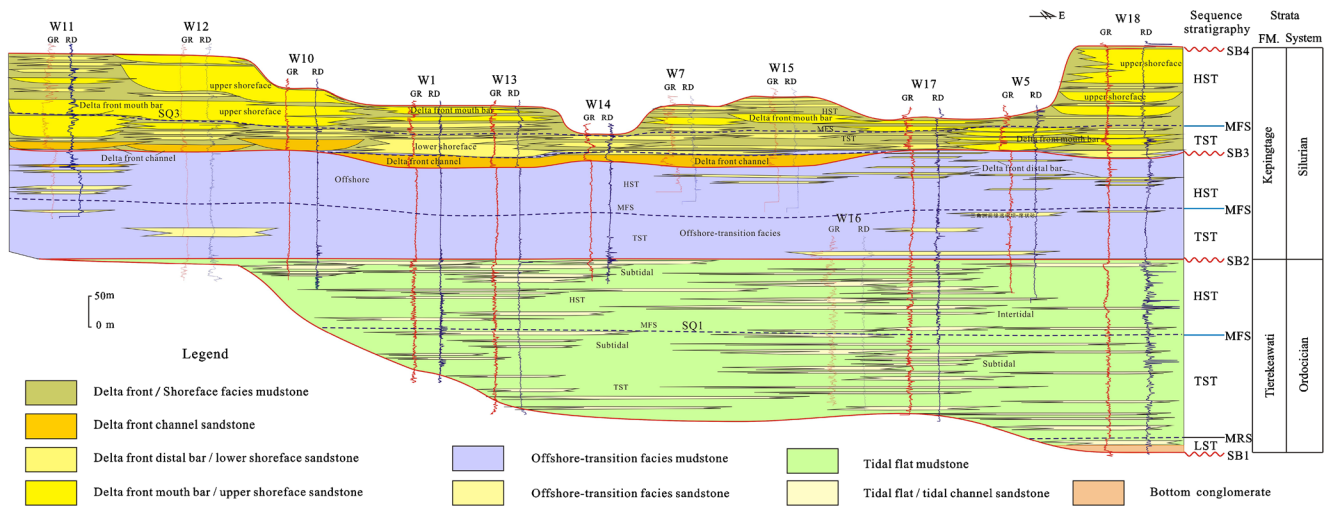


**Fig. 16** Sequence stratigraphy division and surface features in outcrops

southern Tianshan plate (Tang 1997; Wang 1999). This tectonic movement has played an important role in the formation and evolution of Tarim Basin: (i) The Sinian-Ordovician extensional basins dominated stage has transferred to Silurian-Devonian cratonic compressional basin stage; (ii) Due to the large area of uplift erosion and strong deformation within the basin, there is wide unconformable contact between the underlying strata and Ordovician Tierekeawati Fm. within and periphery of the basin; (iii) The carbonate rock sedimentation dominated type has changed to Silurian-Devonian clastic sedimentary dominated type.

SB2 surface is tectonic compression unconformity. During the development of SQ2, ancient oceanic plate in the northern of the Tarim plate margin was strongly subducted to southern Zhongtianshan plate. Tectonic extrusion was produced when

the southern margin of the Kunlun ocean plate was strongly subducted to Kunlun island arc. Internal deflection of Tarim Basin resulted the rapidly subsided of basement and the relative sea level quickly raised, forming extensive unconformity between the SQ2 and SQ1. This unconformity has been formed during global sea level rise with greatly increased water depth. There are following characteristics in this surface: (i) the shallow water deposition has been directly overlaid by deeper water deposition. Above the SB2, there is mainly dark gray, gray-green mudstone, interbedded thin layer of siltstone, and fine sandstone, which is a set of the offshore-continental facies, while under the surface, there is light gray and gray cross-bedded siltstone and fine sandstone, which is the product of tidal flat environment (Fig. 17). (ii) The strata are widely onlap towards the land. The bottom surface of SQ2



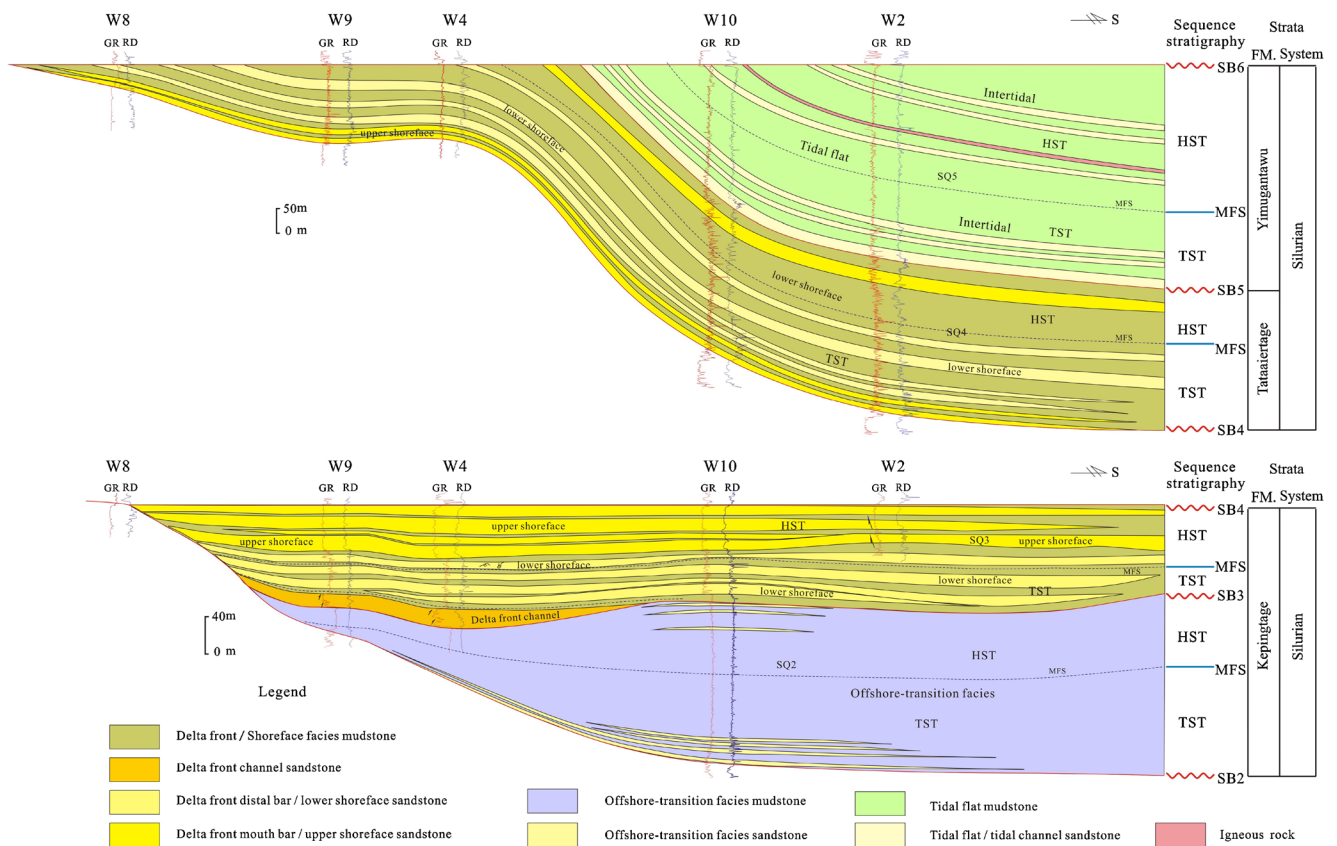
**Fig. 17** The sedimentary sequence comparison and sedimentary facies distribution in south-north section (Fig. 1c showing the location of wells)

is corresponding to Tg43 in seismic reflection, which is mainly characterized by extensively onlap (Fig. 15).

*Relative sea-level changes*

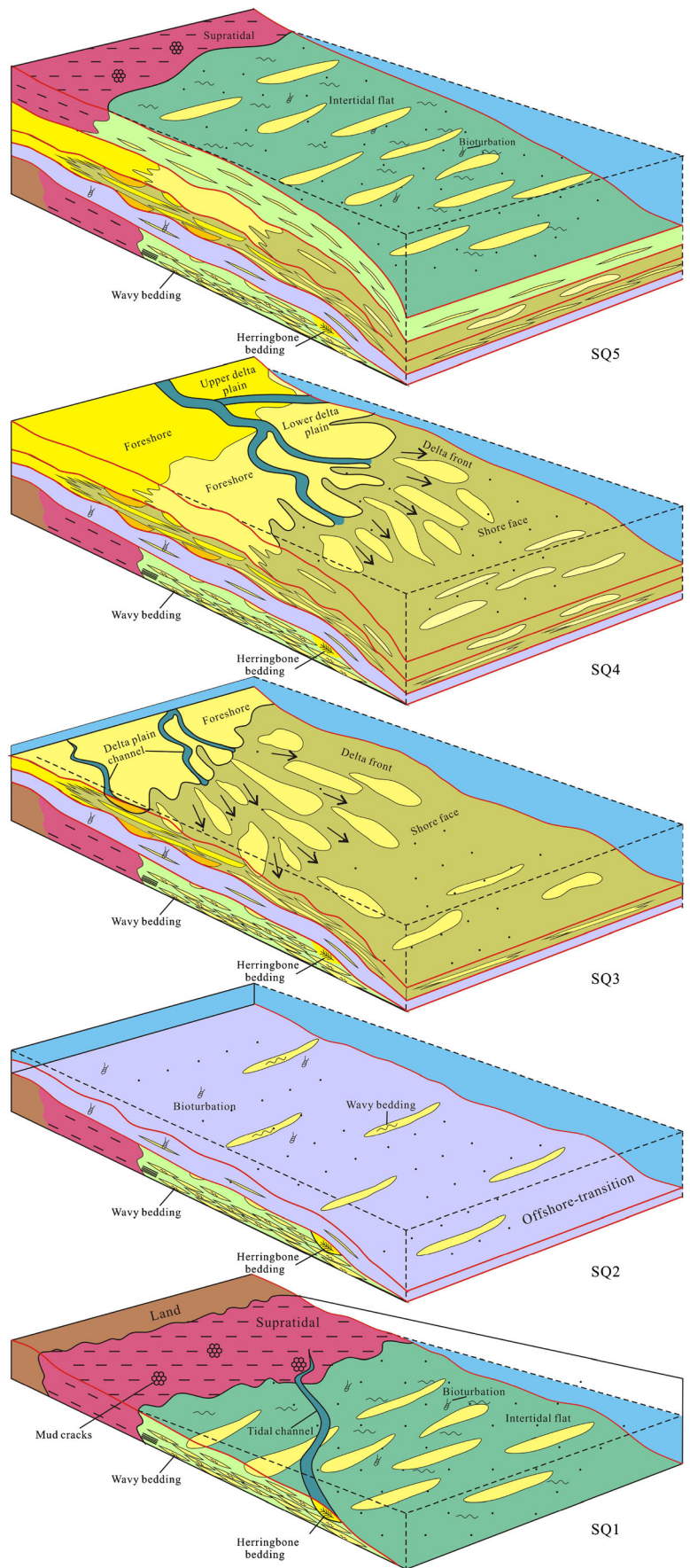
Global sea level (Global eustasy or Global sea-level) is the location of a given sea level relative to the reference point

(such as center of the earth). Therefore, global sea level is nothing to do with local factors. During the formation of Silurian, the first order cycle of global sea level is in the drop period. While, for the second order cycle of global sea level, in the early to mid-Silurian, the sea level has generally raised, while in the medium and late Silurian, the sea level has generally fallen (Vail et al. 1977). In general, from SQ1 to SQ2, an overall sea level transgressive process was showed by the



**Fig. 18** The sedimentary sequence comparison and sedimentary facies distribution in west-east section (Fig. 1c showing the location of wells)

**Fig. 19** Sedimentary model of the Silurian at Tabei uplift



sequences. From SQ2 to SQ5, an overall sea level regressive process was showed as well (Figs. 17, 18, and 19). The result is consistent with the progradation and regression of large regions, which is reflected by sequence framework pattern. It shows that, from SQ2 to SQ5 sedimentary period, the scope of basin is continuously shrunk and the sedimentation and subsidence centers continue to advance into the basin.

### Reservoir development and trap styles

With epicontinental sedimentary environment, Silurian is mainly formed in shoreface and delta system. The TST and HST of SQ3 are the main reservoir interval in the Silurian for its domination by the shoreface, tidal flat, and delta facies. The TST sandstone is generally consisting of a serial of gray sandstone, gray muddy fine sandstone, gray siltstone, and thin gray-light purple mudstone. For the HST sandstone, it mainly develops into purple sandstone, green and gray coarse sandstone, purple fine sandstone, and purple silty mudstone. During the period of maximum flooding, a serial of purple mudstone develops between TST and HST sandstone. The mudstone can be applied as the cap rock for lower sandstone, forming an effective combination of reservoir and cap. Hercynian sequential movement led to the strong uplift of basin and extensive erosion in Sulrian at Tabei and Tazhong uplift, and is favorable to the formation of strata erosion unconformable traps. The erosion unconformable belt along uplift erosion area to slope area is mainly distributed in such nose-like tectonic region as Hudson and Yingmai. Currently, all founded oil and gas reservoirs are this type of traps.

### Conclusions

- (1) Twenty one lithofacies and 5 facies associations were identified based on the grain size of sediments, sedimentary characteristics and bioturbation conditions : (1) fluvial-dominate delta front facies association; (2) tidal flat facies association; (3) tidal channel facies association; (4) offshore-transition facies association; (5) shoreface facies association.
- (2) Six unconformity surfaces are identified in Silurian at Tabei uplift and five third order sequences were classified. Sequences were composed by TST and HST, whereas only SQ1 contains LST. SQ1 is mainly characterized by tidal facies association, while delta front facies association locally develops; SQ2 mainly consists of offshore-transition facies association; SQ3 is mainly characterized by shoreface and delta front facies association. For SQ4, the TST is dominated with shoreface facies association, while the fluvial-dominate delta front facies association is widely developed in HST. SQ5 is mainly characterized by tidal flat facies association.
- (3) Silurian is mainly dominated by the shoreface and delta facies association. The TST and HST sandstone in SQ3 is the main reservoir at Tabei Uplift. Hercynian sequential movement led to the strong uplift of basin and extensive erosion in Sulrian at Tabei and Tazhong uplift, and is favorable to the formation of strata erosion unconformable traps.

**Acknowledgments** This work was supported by the National Natural Science Foundation of China (No. 41130422) and the National Key Basic Research Project (No. 2011CB201100-03). We would like to thank the Petro China Tarim Oilfield Company for data support. In addition, the comments and suggestions by the editors and reviewers were greatly appreciated.

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