# Controls of Tectonics on both Sedimentary Sequences and Petroleum Systems in Tarim Basin, Northwest China

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**Abstract:** Various orders of sequences were recognized in the Tarim Basin from unconformities. Three mega-sequence groups, six mega-sequences, sixteen super-sequences and forty-two sequences were determined from the Sinian to the Quaternary. The mega-sequences and super-sequences were in accordance with the locally tectonic events occurring in both the north and the south margins of the Tarim plate. The global sea level changes only worked to control formations in the tectonically stable periods or in the low order sequences. The sequences had close relationship to the source rocks, reservoirs and cap rocks, and the tectonic events determined the migration, accumulation, and preservation of the hydrocarbon. The three mega-sequence group cycles, including the early cycle-the Sinian-middle Devonian, the middle cycle-the upper Devonian-Triassic, and the late cycle-the Jurassic-Quaternary, corresponded to three reservoir formation cycles. So, it can be concluded that the local tectonic events controlled both the sequences and the distribution of oil and gas in the Tarim Basin.

**Key words:** Sequence stratigraphy, tectonics, petroleum geology

## 1. Introduction

As a branch of geoscience, sequence stratigraphy has been accepted widely due to its high correctness in forecasting the distribution of oil-generating layers, reservoirs, and cap rocks. On the other hand, various orders of sequences reflect various orders of tectonic events. This is of significance for the research of the earth rhythm (Wang, 1997).

Based on the concept of stratigraphic sequence (Sloss, 1949). Vail, *et al.* (1977) put forward the concept of seismic stratigraphy, and emphasized global sea level changes to be the main controlling factors for the formations of sequences. The systematic concept of the sequence stratigraphy was developed by further research. The global tectonic movements, the global sea level changes, the depositions and the climate changes were considered to be main controlling factors on sequence formations, and high order sequences were mainly related to the plate movements. However, there are some disagreements on the concept of the sequence stratigraphy, for example, whether the sequences are of global comparability and what the main controlling factors are.

The research on the sequences of the Tarim Basin has got great achievements recently with the petroleum exploration in the basin (Jia, *et al.*, 1995; Xu, *et al.*, 1997). Based on the seismic data, the sequences are delineated in the Tarim Basin, and the controlling factors of the sequences and their relations to oil and gas are discussed in this paper.

## 2. Tectonic settings

The Tarim Basin is located in the northwest China. It is surrounded by mountains such as the Tianshan fold system to its north, the Kunlun fold system to its south, and the Altun fold system to its southeast (Fig. 1). It underwent a long history from the Sinian to the Quaternary, and covers 560,000 km$^2$ of area. The sedimentary succession in the basin consists of Sinian-Lower Permian marine and marine-terrestrial alternating sediments and Upper Permian-Quaternary terrestrial sediments with a total thickness of 15,000 m. The basement of the Tarim Basin is pre-Sinian metamorphic rocks. The basin can be further subdivided into seven first-order structural belts with trend E-W.

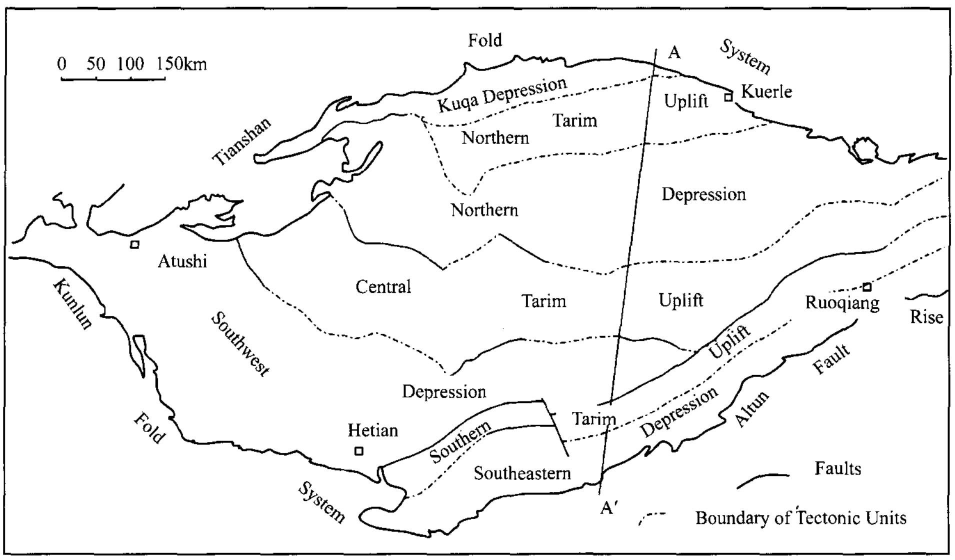
In terms of the plate tectonics, the Tarim Basin is a part of the Tarim-Sino Korea plate, or a separate plate existing in the Neoproterozoic, called the Tarim plate (Jia, *et al.*, 1995; Jiang, *et al.*, 1992; Xiao, *et al.*, 1992). The northeast of the Tarim plate was the Siberia plate, the northwest the Kazakhstan plate, and the south the Qiangtang plate, the Lasa plate, and the Indian plate (Fig. 2). The evolution of the Tarim Basin was closely related to the actions in the tectonic zones surrounding it, and the unconformities in the basin show a complicated history (Fig. 1).

## 3. Plate tectonic evolution

During the evolution of the Tarim Basin from the Sinian to the Quaternary, complicated plate tectonic actions occurred both in the north and in the south margins of the Tarim Plate.

In the Sinian, the intra-continental rifting occurred in both the south and the north boundary of the Tarim plate (Jiang, *et al.*, 1992; Xiao, *et al.*, 1992; Jia, *et al.*, 1995; Li, *et al.*, 1996; Zhai, *et al.*, 2002) (Fig. 3). Subsequently in the Cambrian and early Ordovician, oceanic crusts and passive continental boundaries formed in the two boundaries. In the middle and late Ordovician, the previous passive boundaries turned to be active with subduction. From the Silurian to the middle Devonian collision occurred between the Kunlun-Qidam plate and the Tarim plate, leading the ocean between the two plates to close. The north boundary was still to be active with the west part of the boundary being a passive margin. At this time, the south boundary of the Tarim plate accomplished a tectonic cycle from rifting to closing. This stage can be called Sinian-Middle Devonian tectonic cycle, consisting of two secondary cycles of the Sinian-Ordovician rifting and Silurian-Middle Devonian closing.

In the late Devonian-Carboniferous, the north of the Tarim Basin was the remnant south Tianshan ocean, and the south of it was a passive margin connecting to the Paleo-Tethys. At the end of the Permian, the north Tianshan-Junggar Ocean closed, making the Tarim plate part of the Eurasia plate. At the same time, the south of the Tarim plate changed from a passive margin into an active margin with volcanic arcs. The Tarim Basin was located at the back of the arcs, being a backarc intra-continental rift basin. Collisions occurred between the Tianshuihai terrain and the Tarim plate, and between the Qiangtang terrain and the Eurasia plate in the early Triassic and at the end of the Triassic, respectively (Hendrix, *et al.*, 1992; Graham, *et al.*, 1993; Pan, *et al.*, 1997). The compression related to the collisions led the south of the Tarim Basin to be eroded so Triassic sediments are missing. This stage can be called the late Devonian-Triassic tectonic cycle.



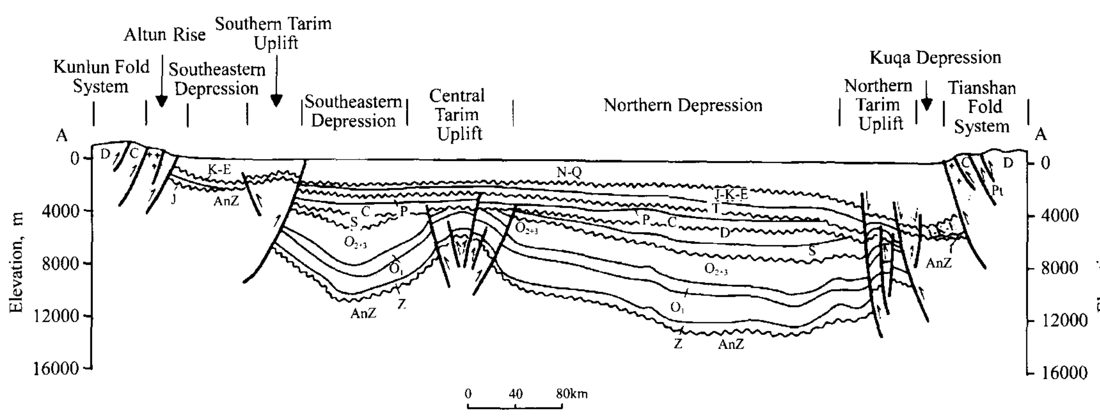




Fig. 1 Tectonic units (a) and a typical cross-section (b) of Tarim Basin

γ 2-Granite; Referencing to Table 1 for the implications of the formations

In the Jurassic, the Tethys ocean plate subducted beneath the Qiangtang plate with a low velocity. The Tarim Basin was apart away from the active continental margin. The Lasa collision (140-125 Ma) made the Lasa plate attach to the Qiangtang plate. This collision was weak and the related volcanic actions and deformations were weak, having a little effect on tectonics regionally. In the late Cretaceous, collision occurred between the Kexisitan plate and the Lasa plate at the southwest (Hendrix, *et al.*, 1992; Graham, *et al.*, 1993), causing local erosion. After the Qiangtang collision, although the other two collisions happened, the tectonic regimes of the Tarim Basin were not changed obviously because their low tectonic intensities. With the Himalayan collision in the middle-late Cenozoic (45Ma), the Indian plate attached to the Euroasia plate, and the Tethys ocean closed. This collision caused an extensive north-south compression, and changed the tectonic regime of the Tarim Basin. The far-reaching stress associated with the collision affected the evolution of the Tarim Basin.

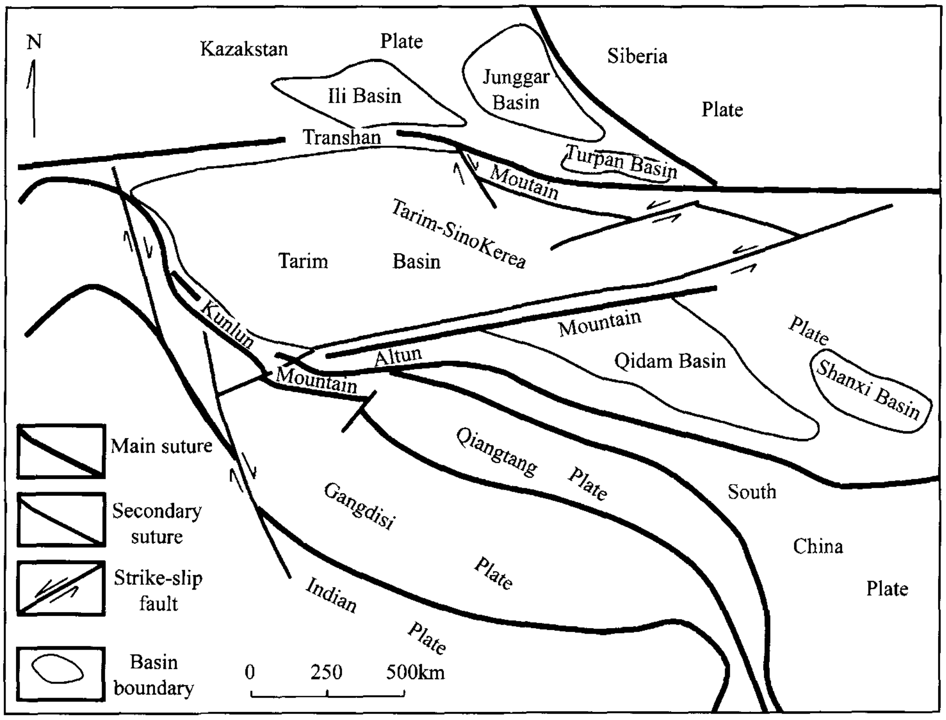



Fig. 2 Sketch map of geotectonic setting of the Tarim Basin (After Tang, 1996)

## 4. Sequences in the Tarim Basin

### 4.1 Principles of the sequence division

Based on the types, ranges and erosions of the unconformities shown on the seismic profiles (Fig. 1), and the periodic changes of paleo-water depths shown by the basin fills, the strata of the Tarim Basin can be divided into three orders of sequences. The fills can be divided into six mega-sequences, sixteen super-sequences, and forty-two sequences (Table 1). Three mega-sequence groups can be recognized, including the lower group-the Sinian-middle Devonian, the middle group-the upper Devonian-Triassic, and the upper group-the Jurassic-Quaternary.

### 4.2 Characteristics of the super-sequences

1) Super-sequences $I_1$ and $I_2$: the Sinian. The Sinian is the first set of sediments since the formation of the basement of the Tarim Basin. The lower Sinian is distributed locally in the northeast of the basin. It has three sequences and its rocks are terrestrial clastic rocks and marine moraine conglomerates. The upper Sinian distributed widely in the basin with a thickness of 400-1000 m, including seashore-shallow sea clastic rock, siliceous dolomite, dolomite, dolomite milestone and interbedded volcanic rock and moraine.

2) Super-sequence $I_3$-the Cambrian: The lower Cambrian includes three sequences with a total thickness of 200-600 m. The rocks were gulf and wide-sea shelf sandstones and mudstones in the west of the basin, and deep-sea siliceous sandstones and carbonates in the east of the basin. The middle, together with the upper Cambrian, assembled one sequence. The rocks of it were tableland carbonate and clastic rock with a thickness of 500-1200 m in the west of the basin, and bathymetric-deep sea siliceous sandstones and mudstone with a thickness of 200-600 m in the east of the basin. There were evaporites in the middle Cambrian in the east of the basin.

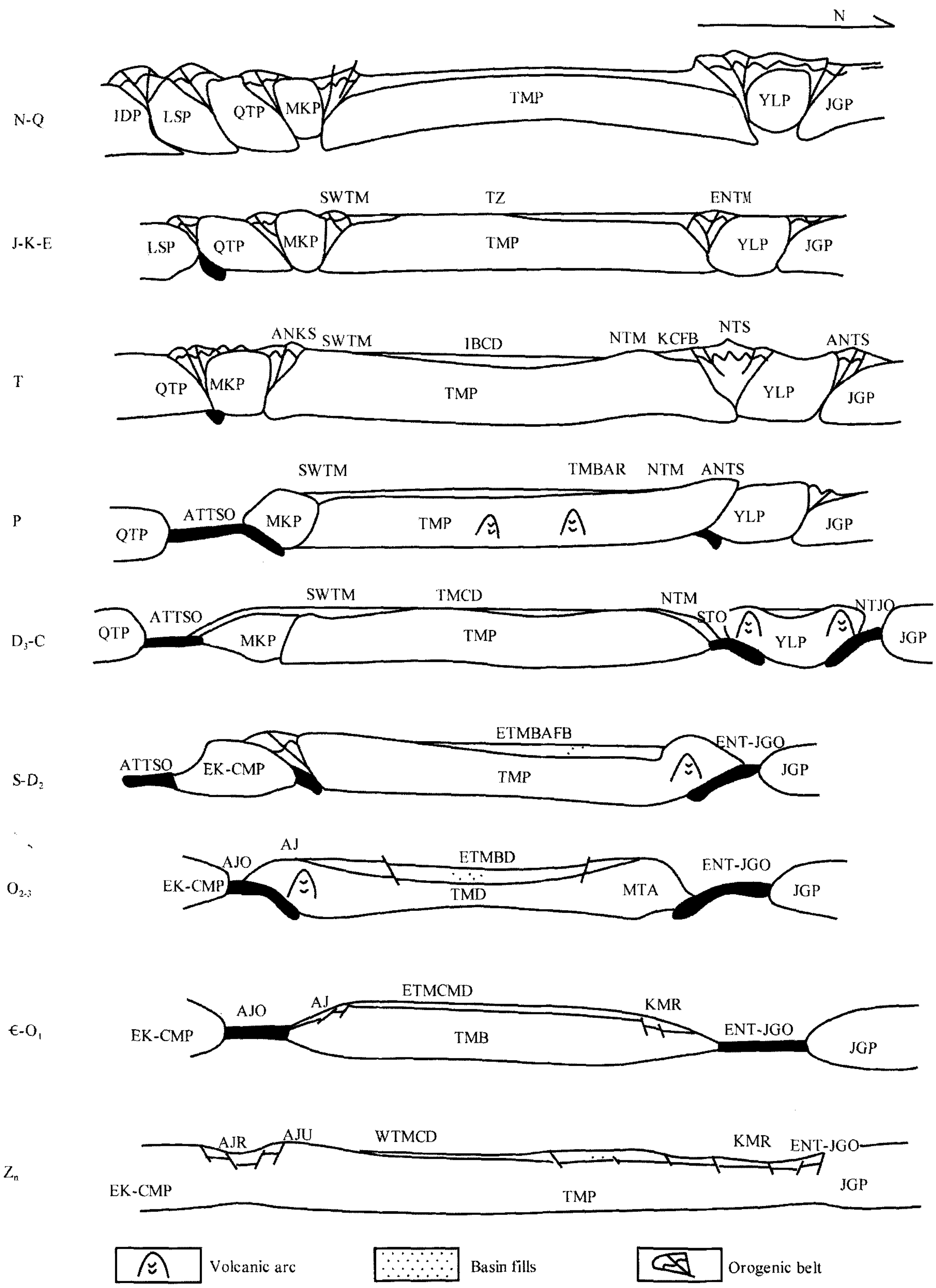



Fig. 3 Sketch map of the evolution of the Tarim Plate and its adjacent area

Notes: AJ: Altun; AJO: Altun Ocean; AJR: Altun Rift; AJU: Altun Uplift; ANKS: Paleo-north Kunlun Mountain; ANTS: Paleo-northern Tianshan; ATTSO: Paleo-Tethys Ocean; EK-CMP: East Kunlun-Qaidam Plate; ENT-JGO: Northeast Tianshan-Junggar Ocean; ETMBAFD: East Tarim Back-arc Foreland Basin; ETMCMD: Eastern Tarim Continental Marginal Basin; IDP: Indian Plate; JGP: Junggar Plate; KCFB: Kuqa Foreland Basin; KMR: Kuman Rift; LSP: Lasa Plate; MKP: Middle Kunlun Plate; NTM: Northern Tarim Basin; QTP: Qiangtang Plate; STO: South Tianshan Ocean; SWTM: Southwestern Tarim Basin; TMCD: Tarim Intra-cratonic Depression; TMP: Tarim Plate; TZ: Central Tarim Basin; WTMCD: West Tarim Intra-cratonic Depression; YLP: Yili Plate. Not to scale

**Table 1 Sequences of the Tarim Basin**

| Stratum | | | Mega-sq of North American Craton | Tarim Basin | | | Tectonic movement |
|---|---|---|---|---|---|---|---|
| Erathem | System | Series | | Mega-Sq | Super-Sq | Number of Sq | |
| Cenozoic | Quaternary | | Tejas | VI | VI | 4 | |
| | Neogene | $N_2$ | | | | | |
| | | $N_1$ | | | | | Himalayan MV. |
| | Paleogene | $E_3$ | | V | $V_3$ | 3 | |
| | | $E_2$ | | | | | |
| | | $E_1$ | | | | | End Yanshan MV. |
| Mesozoic | Cretaceous | $K_2$ | Zuni | | $V_2$ | 3 | Late Yanshan MV. |
| | | $K_1$ | | | | | Middle Yanshan MV. |
| | Jurassic | $J_3$ | | | $V_1$ | 2 | |
| | | $J_2$ | | | | | |
| | | $J_1$ | Absaroka | | | | Indosinian MV. |
| | Triassic | $T_3$ | | IV | $IV_2$ | 1 | |
| | | $T_2$ | | | $IV_1$ | 3 | |
| | | $T_1$ | | | | | End Hercynian MV. |
| Upper Paleozoic | Permian | $P_2$ | | III | $III_3$ | 1 | Late Hercynian MV. |
| | | $P_1$ | | | $III_2$ | 2 | Middle Hercynian MV. |
| | Carboniferous | $C_2$ | | | $III_1$ | 5 | |
| | | $C_1$ | Kaskaskia | | | | |
| | Devonian | $D_3$ | | | | | Early Hercynian MV. |
| | | $D_{1-2}$ | | II | $II_2$ | 1 | End Caledonian MV. |
| Lower Paleozoic | Silurian | $S_{2-3}$ | Tippecanoe | | $II_1$ | 2 | |
| | | $S_1$ | | | | | Late Caledonian MV. |
| | Ordovician | $O_{2-3}$ | | I | $I_5$ | 3 | Middle Caledonian MV. |
| | | $O_1$ | Sauk | | $I_4$ | 3 | |
| | Cambrian | $\in_3$ | | | $I_3$ | 4 | |
| | | $\in_2$ | | | | | |
| | | $\in_1$ | | | | | Early Caledonian MV. |
| | Sinian | $Z_2$ | Pre-Sauk | | $I_2$ | 2 | |
| | | $Z_1$ | | | $I_1$ | 3 | |
| | Anti-Sinian | | | | | | |

Notes: The sequence boundaries are not included in this table. Sq=Sequence. MV=Movements

3) Super-sequence $I_4$-the lower Ordovician: The lower Ordovician consisted of three sequences. The rocks were tableland limestones and dolomites with a total thickness of 600-1500 m in the west, and deep sea trough and basin graptolite shalestones, mudstones and siltstones with a total thickness of 200-600 m in the east.

4) Super-sequence $I_5$-the middle and upper Ordovician: The middle and upper Ordovician consisted of three sequences. The rocks were shallow sea shelf carbonates and clastic rocks with a total thickness of 400-1500 m in the west of the basin, and deep sea gulf-basin rhythmic sandstones and mudstones with a total thickness of 800-1300 m.

5) Super-sequence $II_1$-the Silurian: The Silurian consisted of two sequences. It is seashore-shallow sea gray-green sandstones and mudstones with a total thickness of 200-2300 m.

6) Super-sequence $II_2$-the lower and middle Devonian: The lower and middle Devonian assembled a sequence, and the rocks were seashore-shallow sea red clastic rocks with a thickness of 300-1300 m.

7) Super-sequence $III_1$-the upper Devonian-Carboniferous: The upper Devonian assembled a sequence, and the rocks are seashore-shallow sea gray-green and gray-white sandstones and mudstones with a total thickness of 100-300 m. The lower Carboniferous included two sequences, and the rocks were tableland-evaporites, tableland limestones, sandstones and gypsum mudstones with a total thickness of 600-1100 m. The upper Carboniferous assembled another sequence, and the rocks were limited tableland-wide tableland limestones, sandstones and gypsum salt with a total thickness of 200-900 m.

8) Super-sequence $III_2$-the lower Permian: The lower Permian consisted of two sequences, and the rocks were marine-terrestrial clastic rocks with basalts at the top with a total thickness of 200-1200 m.

9) Super-sequence $III_3$-the upper Permian: The upper Permian assembled a sequence, and the rocks were river-seashore-shallow sea brown sandstones and mudstone with a total thickness of 200-1400 m.

10) Super-sequence $IV_1$-the lower and middle Triassic: The lower and middle Triassic consisted of three sequences, and the rocks were river-lake gray clastic rocks with a total thickness of 200-1200 m.

11) Super-sequence IV2-the upper Triassic: The upper Triassic is a sequence, and the rocks were shallow lake-river clastic rock with interbedded coal layers with a total thickness of 100-500 m. This supper sequence distributed mainly in the inner basin.

12) Supper-sequence $V_1$-the Jurassic: The Jurassic consisted of two sequences, and the rocks were lake-river-flood plain sandstones and mudstones with interbedded coals with a total thickness of 200-1500 m. This supper sequence distributed mainly around the margins of the basin.

13) Super-sequence $V_2$- the Cretaceous: The Cretaceous consisted of three sequences, and the rocks were river-shallow lake red sandstones and mudstones with a total thickness of 200-2000m. The upper Cretaceous is almost totally missing in the basin.

14) Super-sequence $V_3$-the Paleogene: The Paleogene consisted of three sequences, and the rocks were terrestrial red clastic rocks with a total thickness of 200-1800 m. Gulf and lagoon sedimentation occurred both in the northwest and in the southwest of the basin.

15) Super-sequence VI-the Neogene and Quaternary: This supper sequence consisted of three sequences, and the rocks were river and intermittent lake clastic rocks with a total thickness of 200-6000 m.

In the lower mega-sequence group, the Sinian-middle Devonian, the Sinian was the low-stand tract system, the Cambrian-lower Ordovician the transgressive tract system, and the middle-Ordovician-middle Devonian the high-stand tract system. In the middle mega-sequence group, the upper Devonian-Triassic, the upper Devonian was the low stand tract system, the Carboniferous the transgressive tract system, and the Permian-Triassic the high stand tract system. In the upper mega-sequence group, the Jurassic-Quaternary, the Jurassic was the lower stand tract system, the Cretaceous-Paleogene the transgressive tract system, and the Neogene-Quaternary the high stand tract system. Each of the lower order sequences can be divided into lower stand tract system, transgressive tract system, and high stand tract system.

## 5. Controls of tectonics on sequences

The sequence stratigraphy of the Tarim Basin shows that the factors controlling the sequences occurred periodically. The boundaries of the various order sequences in the Tarim Basin were not in agreement with the global sea level changes (Sloss, 1963), instead in sound agreement with the local tectonic regime changes.

Generally, the Phanerozoic can be divided into two mega-sequence groups, one of which is the Cambrian-lower Carboniferous, and the other is the upper Carboniferous-Quaternary (Vail, *et al.*, 1977). The two groups refer to the two highest order cycles of the sea level changes in the Phanerozoic, with time intervals of 200-350 Ma each. On the contrast, three mega-sequence groups can be determined in the Tarim Basin, which were the lower Sinian-middle Devonian, the middle upper Devonian-Triassic, and the upper Jurassic-Quaternary. Each of the three mega-sequence groups consisted of the low-stand tract system, the transgressive tract system, and the high-stand tract system, each showing a full period of sea level change. The three mega-sequence groups correspond to the three tectonic evolutionary stages, each of which consists of three tectonic regimes, the early extension, the middle rift, and the late compression. It is can be concluded that the factors controlling the mega-sequence groups are the tectonic actions of the north and south boundaries of the Tarim Basin. In each mega-sequence group, the lowstand and highstand tract systems are controlled by the tectonic events occurring in the south and north margins of the Tarim Basin, and the transgressive tract system was controlled by the global sea level changes.

The boundaries of the six mega-sequences were not in accordance with the global mega-sequence boundaries but in accordance with the tectonic cycles of the north and south margins of the Tarim plate. Mega-sequence I, the Sinian- Ordovician corresponds to the primary opening and closing of the paleo-Xinjiang-craton; Mega-sequence II, the Silurian-middle Devonian to the initial closure after the primary opening; Mega-sequence III, the upper Devonian-Permian, to the second closure after the primary opening; Mega-sequence IV, the Triassic, to the Qiangtang collision; Mega-sequence V, the Jurassic-Paleogene, to the Lasa-Kexisitan collision and Mega-sequence VI, the Neogene-Quaternary to the Himalayan collision. These showed that the local tectonic actions controlled the mega-sequence. Within each of the six mega-sequences, global sea level changes controlled the transgressive tract systems. For the sixteen super-sequences, although the boundaries were in sound correspondence to the tectonic events occurred in the south and north margins of the Tarim Basin, the number of the boundaries, which were corresponding to the global sea level changes such as the super-sequences I4, II1 and V3, increased. This showed that the controls of the global sea level changes on the lower order sequences increased.

The sequences of the Tarim Basin were mainly controlled by local tectonic actions. The controls of the global sea level changes on the sequences showed two aspects. One is that they played an important role in the sequences forming in the stable tectonic stages such as in a passive continental margin or a craton, for example, the sedimentations of the Cambrian-Lower Ordovician and Carboniferous. The other aspect is that they controlled some low order sequences.

## 6. Relationship of the sequences to petroleum systems

Tectonic actions controlled the sequences and the sequences in turn controlled the formations of the source rocks, reservoirs, cap rocks, and the formations of the oil pools.

### 6.1 Source rocks

Petroleum mudstone and limestone source rocks have total organic carbon of above 0.4% and 0.2%, respectively, according to our evaluation criteria. There are four sets of source rocks in the Tarim Basin, which are the Cambrian (Fig. 4), the Ordovician, the Carboniferous-Permian, and the Triassic-Jurassic (Gu, *et al.*, 1995; Li, 2001; Zhao, *et al.*, 2001).

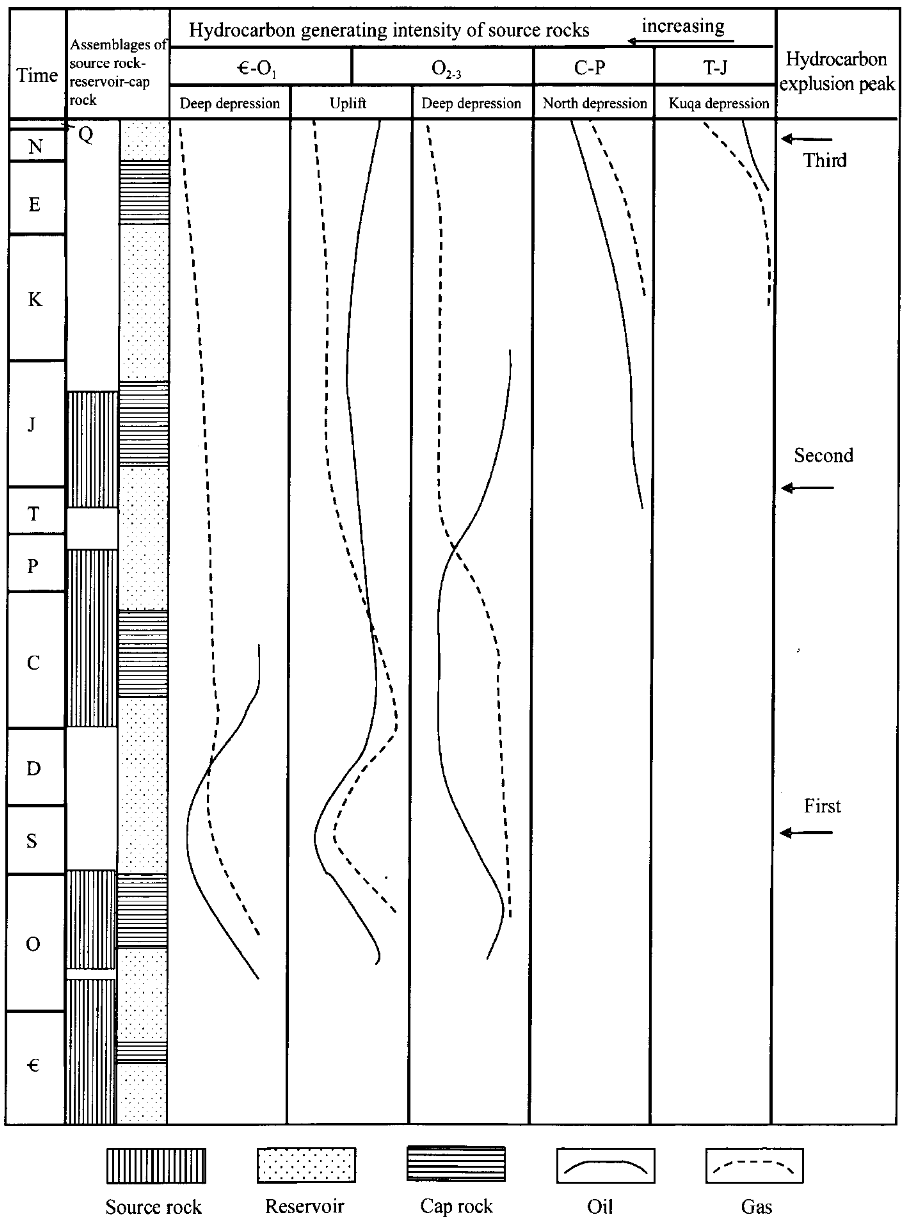



Fig. 4 Petroleum features of the Tarim Basin (Summarized based on Zhou, 1995 and Zhao, *et al.*, 2001)

The former two were marine carbonate with wide distribution, the third the marine clastic rocks with wide distribution, and the last one the terrestrial coal system with distribution mainly along the margins of Tarim Basin. Expect for the Jurassic which was a low-stand tract system, the others were corresponding to the transgressive or high-stand tract system of the three mega-sequence groups. The sets of the source rocks in the Tarim Basin determined the composite petroleum systems (Zhou, 1995; Li, *et al.*, 1996; Lu and Hu, 1998).

### 6.2 Assemblages of the reservoir-cap rock

There are five sets of regional cap rocks, forming five good reservoir-cap rock assemblages with the overlain reservoirs as in Table 2 and Fig. 4.

**Table 2 Assemblages of the reservoir-cap rock**

| Cap rock | Reservoir |
|---|---|
| Middle Cambrian salt-gypsum | Overlain carbonate |
| Middle-upper Ordovician mudstone | Overlain carbonate |
| Carboniferous salt-gypsum-mudstone | Upper Devonian Donghe sandstone or the buried mountains of the Ordovician and Cambrian Carbonate |
| Lower-middle Jurassic coal layer | Overlain clastic rock |
| Paleogene salt-gypsum layer` | Overlain clastic rock |

### 6.3 Periods of the reservoir formation

There were three hydrocarbon expulsion peaks in the Tarim Basin, which were the Silurian-Devonian, the Permian-Triassic, and the Cenozoic (Fig. 4). Geochemical analyses showed that there were three periods of reservoir formations, which were from the late Caledonian movement to the early Hercynian movement (from the Silurian to the Devonian), from the late Hercynian movement to the Indosinian movement (from the Permian to the Triassic), and in the Himalayan movement (the Cenozoic)( Lu, *et al.*, 1996; Lu and Hu, 1998). The periods of the reservoir formations were corresponding to the three hydrocarbon expulsion peaks, the three mega-sequence groups, and the three periods of the uplift-subsidence. *Oil/gas accumulation from the late Caledonian movement to the early Hercynian movement*: The traps were ones in the Cambrian and in the Ordovician and the Silurian anticlines. The hydrocarbons were derived from the Cambrian-Ordovician limestone source rocks in the first hydrocarbon expulsion peak (Fig. 4). Most of the accumulations formed in this cycle were destroyed by the subsequent extensive uplifting and erosion which happened at the end of the Middle Devonian.

*Oil/gas accumulation from the late Hercynian movement to the Indosinian movement*: Traps were formed mainly by the late Hercynian movements and then enhanced by Indosinian movements. They comprised fault blocks of Lower Ordovician, detached anticlines in the Ordovician and anticlines in the Upper Devonian and Carboniferous. Hydrocarbons include those generated by Cambrian source rocks, those generated by Ordovician source rocks, and those generated by Carboniferous source rocks (Fig. 4).

*Oil/gas accumulation in the Himalayan movement*: The traps consist of anticlines, faulted anticlines and fault blocks formed by Yanshanian and late Himalayan movements, and those formed by earlier tectonic movements. The hydrocarbons came mainly from the source rocks in the third hydrocarbon expulsion peak (Fig. 4). Part of the oil/gas accumulated also came from the previous trapped oil/gas, which had migrated along faults formed by the subsequent tectonic movements. The formation of the reservoirs occurred mainly in the Neogene. The reservoirs formed in this period were characterized by multi-source rocks, traps formed in several periods, reservoirs in several layers, a short period of reservoir formation, good preservation conditions, and high efficiency of reservoir formations. Oil/gas reserves in the accumulations formed in this period make up a significant proportion of the total reserves in the Tarim Basin.

Regarding the distribution of the reservoirs, the reservoirs in the central Tarim were dominated by those formed in the late Hercynian movement, and enhanced by the Himalayan movement. The reservoirs in the northern Tarim were dominated by those formed in the Cenozoic. The reservoirs around the margins of the basin were dominated by those formed in the Cenozoic, and were related to the distribution of the Paleogene salt-gypsum layers.

## 7. Conclusions

1) The strata in the Tarim Basin can be divided into three mega-sequence groups, six mega-sequences, sixteen super-sequences, and forty-two sequences, based on the unconformities of the basin. Due to the local tectonic events, the boundaries of the various order sequences were not in agreement with those of the global sequences.

2) In the various orders of sequences, the tectonic

actions occurring in both the north and the south margin of the Tarim plate were the dominant factors controlling the sequences, and the global sea level changes were secondary factors. The global sea level changes determined the sequences either in the tectonically stable periods such as passive continental margins or cratons or in the low orders of sequences.

3) Several sets of source rocks formed in the Tarim Basin, leading to composite petroleum systems. Several periods of tectonic movements and changes of the tectonic regime caused multi-periods of reservoir formations. There were three periods of reservoir formations in the Tarim Basin, which were from the late Caledonian movement to the early Hercynian movement (from the Silurian to the Devonian), from the late Hercynian movement to the Indosinian movement (from the Permian to the Triassic), and in the Himalayan movement (the Cenozoic). The three periods of the reservoir formations were corresponding to the cycles of the three mega-sequences. The reservoirs formed in the former two periods, particularly those forming in the second period, mainly distributed in the inner basin, and the reservoirs formed in the third period were mainly around the margins of the Tarim Basin.

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