Structural characteristics and petroliferous features of Tarim Basin

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Abstract **Using the modern tectonic geology theories and methods such as the plate tectonic analysis, the paleo-structure analysis, the structural-lithofacies analysis, and the fault related fold and petroleum system, and combining with the seismic data, well drilling data and the circumferential field geology, study on the structural characteristics and petroleum prospect in the Tarim Basin has been carried out. Results show that the Tarim Basin is a large superimposition and combination basin with continental crustal basement, composed of a Paleozoic craton and Meso-Cenozoic foreland basins. The characteristics of the basin are: the kernel part of the basin is the marine facies Paleozoic craton, superimposed 4 continental facies foreland basins. Though the scale of the paleozoic craton of the Tarim Basin is relatively small, the structure is steady. The petroleum prospect of the Paleozoic craton is: multiphase pool-generation and accumulation controlled by ancient uplift. The Meso-Cenozoic foreland basins in the Tarim Basin, which are distributed on the cratonic circumference and are a long-term subsidence, turned into rejuvenated foreland basins after the Meso-Cenozoic period. The petroleum prospects are: coal-bed generating hydrocarbon, abundant natural gas, pool-generation in later and recent periods, the oil and gas distribution controlled by the foreland thrust belt. The structural characteristics of Tarim provide it with a superimposition and combination petroleum system of multiple resources, multiple reservoirs and multiphase pool-generation. The oil and gas exploration prospect covers two large fields: the Paleozoic craton and the Meso-Cenozoic foreland thrust belt.**

Keywords: Tarim, superimposition and combination basin, craton, foreland basin, superimposition and combination petroleum system.

The Tarim Basin is located in the south of Xinjiang Uygur Autonomous Region, covering an area of 5.6×10^5 km^2. It is abundant of oil and gas sources, and has complicated geological conditions. The characteristics there are different from the basins in eastern China, and other major petroliferous basins abroad. In the past years, in order to study characteristics of the petroliferous basins, researches on the properties of the basin, its tectonic evolution, petroleum geology, etc, have been conducted by many geologists, structural geologists and petroleum geologists[1—11]. But before the 1980s, the understanding of the geology and the exploration prospect of the basin was neither deep nor systematic, due to the limitation of the data concerned. Especially, the structural research is almost blank, and most of the knowledge was from speculation. The regional reflecting seism in the early 1980s, the large-scale petroleum exploration in the late 1980s, and the acquirement of quantities of first-hand seismic and well drilling data made the Tarim Basin a dissected model in the mid-west China. The Tarim Basin is a superimposition and combination basin composed of small cratonic and foreland basins (thrust belt). That is to say, the Tarim Basin is a large superimposition and combination basin composed of Paleozoic cratons and Meso-Cenozoic foreland basins, and the complicated petroliferous features have been discovered by Jia [12—14] et al. The kernel part of the basin is the Paleozoic marine facies craton, a superimposed 4 Meso-Cenozoic continental facies foreland basins: Kuqa, Awati, the Southwest Tarim Basin and the Southeast Tarim Basin. These factors determine that the oil and gas distribution is controlled by the Paleozoic craton and the Meso-Cenozoic foreland thrust belt, and provide the basin with the characteristics of an superimposition and combination petroleum system of multiple sources, multiple reserviors, and multiphase pool-generation. All these determine that the Paleozoic craton and the Meso-Cenozoic foreland thrust belt are two large fields involved in oil and gas prospecting and exploration in the Tarim Basin.

1 Structural characteristics of Paleozoic craton

(i) Basin with an ancient continental crustal basement

Before the 1990s, the knowledge about the basement of the Tarim Basin was acquired in light of the circumferential outcrop and the gravity and magnetic survey data. Due to the complexity of the circumferential structures and the basement structures of the Tarim Basin, the indirect speculation and interpretation of those structures with terrestrial physical field data may lead to multiple solution and uncertainty, therefore the understanding of the basement of the basin was not completely uniform[11]. In the early-middle 1990s, based on the research of the bathymetric profile sections of three south-to-north natural seismic transformed waves running through the whole basin in the north, middle and west parts, in combination with the geophysical analysis of the inversion of the gravity and magnetic data, the regional gravity field, the terrestrial heat flow, the lithosphere thermal structure, etc., authors discovered the ancient continental crustal basement and the basement structure of the Tarim Basin (fig. 1). Most part of the crustal structure is divided into three strata. The upper crust is granitoidite, the middle is granodiorite and the lower is featured with the component of andesite basalt.

The possible components of the crustal basement in the southeast corner of the Tarim Bain are garnet and granulite. The characteristics of the lateral unevenness of

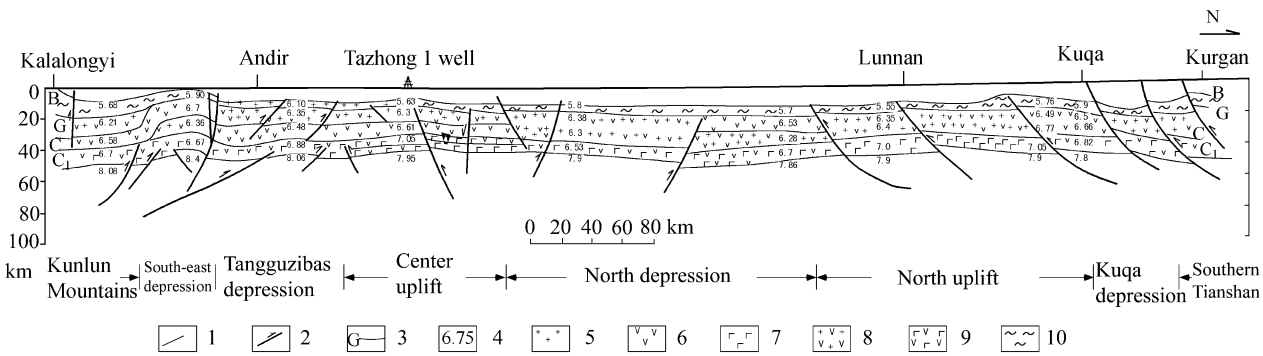

Fig. 1. Lithosphere structure and matter components of the South Tarim-Middle Tarim-Kuqa in the Tarim Basin (middle bathymetric line). 1, Speculative interface or fracture; 2, fracture; 3, transformed wave interface; 4, the velocity of longitudinal wave; 5, granitic rock; 6, intermediate rock; 7, basic rock; 8, acid rock and intermediate rock; 9, intermediate rock, basic rock; 10, metamorphics.

the crust are very distinct. The major possible component of the upper crust to the south of its middle bathymetric line and at the west bathymetric line is crystal granite, and the major components to the north of the middle bathymetric line and at the east bathymetric line are metamorphics series; the stratigraphic structures and the thickness of the middle and the lower crust are closely related, that is, the corresponding lower crust under the thicker middle crust is relatively thin, whereas, the corresponding middle crust above the thicker lower crust is relatively thin. All these determine the properties of the large superimposition and combination basin of the Tarim Basin with a bathymetric geophysical foundation[14, 15].

(ii) Paleozoic cratonic tectonic evolution

Impacted by the cratonic marginal plate tectonics activity in the Tarim Basin, the Paleozoic tectonic evolution had mainly gone through the following three stages:

(1) Sinian-Ordovician period: cratonic marginal aulacogene evolution. After the long period of the geologic evolution and the final consolidation in the end of the Qingbaikou period, the uniform ancient continental plate of the Tarim Basin formed, and in the Sinian it reached the structural strain relaxation stage. Under the local tensional tectonic setting, the crust-mantle began uplifting and expanding, so the ancient continental plate started splitting and subsiding, and the Tarim Basin reached the cratonic marginal aulacogene structural stage. Over this period, the Tarim Basin surrounding marginal gone through two important geologic stages, i.e. the Sinian-early Ordovician passive continental margin stage and the middle-late Ordovician active continental margin stage. The Tarim Basin consisted of the Kuman aulacogene and the west Tarim intracrationic depression[12−14, 16]. The Kuman aulacogene, located in the east of the basin, is a U-shaped aulacogene, which was arcing at the west and opened at the east, and was mainly a series of shallow sea-sub deep sea-deep sea basin facies clastic rocks and carbonate rocks. The west Tarim intracratonic depression is mainly a series of tableland facies carbonate rock deposits, and two giant subaqueous uplifting structures in Yingmali-Lunnan and Middle Tarim were developed. In the end of the Ordovician, The Kuman aulacogene closed, the center of it uplifted, and large areas in the south and north of the Tarim Basin were denudated. As a result, the central uplift and the north Tarim uplift were primarily formed.

(2) Silurian-Devonian period: cratonic marginal foreland basin evolution. During this period, both the southern and the northern margin were active continental margins. The characteristics of the northern margin were: the Silurian-early Devonian South Tianshan Oceanic Basin was expanding, and the middle-late Devonian South Tianshan Ocean was subducting to the Middle Tianshan land block, etc. As for the southern margin of the basin, the arc-land collision occurred between the Middle Kunlun Island and the continental plate of Tarim, which resulted in the formation of the North Kunlun marginal foreland basin, featuring the huge marine facies flysch and continental molasse facies deposits of the foredeep deposits nearby the subducting zone. In the intracratonic-Devonian period, the basin was an intracratonic depression, which was a series of littoral facies-neritic marine basin facies deposits. In the Devonian period, the basin was evolved into the Tarim intracratonic depression and the southwest Tarim cratonic marginal foreland depression. Among them, the intracratonic depression was characterized by the successive development of the central uplift and the north Tarim uplift. In the end of the Devonian, intensive tectonic deformations occurred, and the south Tarim thrust belt, the central strike-slip uplift belt and the north foreland uplift belt were developed and denudated intensively[14, 17].

(3) Carboniferous-Permian period: cratonic marginal depression and intracratonic rift basin evolution. The southern margin of the basin was the passive continental margin in the Carboniferous-early stage of the early Per-

mian; it was the active continental margin during the period of the late stage of the early Permian-late Permian, when the Tethys Sea subducting northward to the Tarim continental plate, and the island arc volcanic activity, the early Permian accretionary subduction complex and the late stage of the early Permian intracontinental volcanic activity in the basin were formed. The northern margin of the Tarim Basin was the active continental margin, appearing to be the oblique collision between the Tarim continental plate and the Middle Tianshan land block, the scissor-form consume of the South Tianshan oceanic basin from east to west and the formation of the ancient Tianshan orogenic belt. Inside the basin were the cratonic marginal depression, rift and the intracratonic depression basin. The igneous activity of the intracratonic rift of the Tarim Basin in the early Permian period mainly appeared to be the eruption of the basalt-mild acidic tuff during the late stage of the early Permian period and the intrusion of the basic rock on large scale under the fluvial facies-shore shallow lacustrine facieses depositional setting. According to the study of the volcanic rock age and the rock geochemistry, the usual age of the volcanic rocks such as the basalt, intrusive rock, etc. is 259—292 Ma, and the geochemical property of them is the high Titanium content. Comparatively, these volcanic rocks are abundant in light rare earth, and are characterized as the continental rift volcanic rocks[14,18—21]. During the late stage of the early Permian period, the tectonic deformation was intensive, and it was characterized as the mass uplift and denudation in the northeast of the Tarim Basin (areas to the east of the Alaer-Manxi 1-the front line of Qiemo), and also featured the development of the northern thrust-strike-slip belt[22,23].

(iii) Characteristics of the Paleozoic cratonic tectonic deformation

(1) Gentle strata, stable kernel part and intensive border deformation. The Paleozoic craton of the Tarim Basin is characterized similarly to the other large cratons abroad, that is, the structure is gentle, all strata from Sinian to Quaternary are developed, the resource rock, reservoirs and regional seal rock are widely distributed and are abundant in number. In addition, the kernel part of the Paleozoic craton of the Tarim Basin is stable, and the border part has been deformed intensively. At the same time, the Meso-Cenozoic foreland tectonic deformation was superimposed.

(2) Fluctuate crustal activity with multi-phase unconformity interface. The research shows that the crustal activity of the Tarim Basin is mainly fluctuation. Four periods of important stratigraphic unconformity interfaces, i.e. Z/AnZ, S/AnS, C/AnC and T-P2/An(T-P2)[14] are mainly developed. They are reflected clearly by the seismic data in the circumferential outcrop area and inside the basin, and are generally conform to the evolution stages of the basin, which are of great significance to the tectonic evolution of the basin, the systematic classification of the deposits, the formation and distribution of the reservoir, and the formation and preservation of the traps and oil and gas reservoirs.

(3) Main deformation with large uplift-depression structure, and successive ancient uplift. The Paleozoic marine cratonic basin structural deformation in the Tarim Basin is generally characterized with large uplift and large depression. For example, the central uplift, the north Tarim uplift and the depression in the north are all structures of large successive uplifts and depressions in the approximate direction of east-to-west formed after a long period of evolution. Meanwhile, according to the difference of the structural deformation and evolution characteristics, the uplift structures can also be divided into 5 ancient uplift and slope structures[24, 25] of 3 categories, i.e, the stable structure in the middle Tarim, the residual structure in the north Tarim, the active structure in Bachu, the residual structure in the east Tarim and the active structure in the north Tarim. Among them, the Ordovician in the middle Tarim stable ancient uplift is in its rudimentary form; the Silurian-Devonian system has been finalized, with its top denudated, and different strata of the Ordovician exposed, and the flank of the Silurian-Devonian was denudated, getting thinner and pinching out, and turned stable after the Carboniferous. The residual ancient uplift of the north Tarim was formed in the early Paleozoic, and had experienced three uplifting denudations, which happened in the end of the Devonian, the end of the Permian and the end of the Triassic. As for the residual ancient uplift, the Jurassic unconformity of the top of the ancient uplift covers the Cambrian-Ordovician and the Sinian, and the stratigraphic denudation line and the overlying pinchout line are widely distributed on the Yingmaili Slope and the Southern slope.

(4) Less faults, mainly with high angle strike-slip fault. Over the uplift part of the middle Tarim, early Carboniferous fracture system composed of the middle Tarim No.1 fracture, the central fracture, etc. are developed; the overall deformation image is a fanlike pattern which stretches out in the northwest and joins together in the southeast, and is characterized as the wrench deformation. Fracture system formed in the early Triassic period is developed in the north Tarim uplift, including many fracture belts such as the Luntai, Erbatai fracture belts, etc. and is characterized by the properties of thrust-strike-slope[18,19,22,23,26].

2 Meso-Cenozoic foreland basin structural characteristics

At the front of orogenic belts, such as the south Tianshan Mountains, the Kunlun Mountains and the Aerjin Mountain belts in the Tarim Basin, four Meso-Cenozoic rejuvenated foreland basins are developed, i.e.

the Kuqa foreland basin, the Awati foreland basin, the Southwest Tarim foreland basin and the Southeast Tarim foreland basin. These rejuvenated foreland basins formed in the frontal orogenic belt between the orogenic belt and the craton (fig. 2), and usually consist of the foreland thrust belt, the foredeep, the forebulge slope and the forebulge. These rejuvenated foreland basins have the characteristics of a halfgraben-like depression, and are recombined on the plane. They were formed through several origins: the Indian Plate and the Eurasian Plate collided and joined together in the Meso-Cenozoic, which particularly intensive in the end of the Eocene epoch, and migrated northward successively afterward; the ancient collision orogenic belts, such as the Tainshan Mountain, the Kunlun Mountains, the Aerjin Mountain, etc. uplift rapidly; the large intracontinental A-type subduction occurred in front of the mountains; the flexural deformation and fast subsidence happened to the crust.

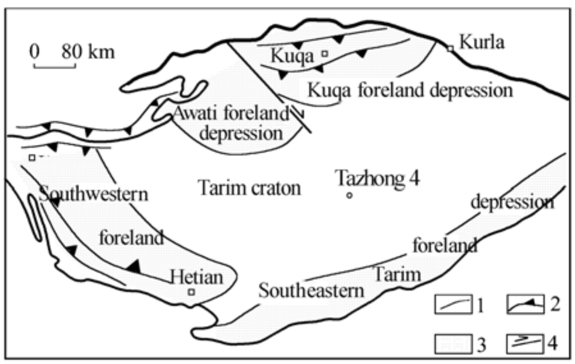

Fig. 2. Superimposition relations between distribution of Meso-Cenozoic foreland basins and cratonic in the Tarim Basin. 1, Border of basin; 2, thrust belt; 3, foreland basin; 4, fracture.

(i) Meso-Cenozoic tectonic evolution

The foreland basin developing stage in the Tarim Basin began in the Meso-Cenozoic, and the evolution was mainly controlled by the Tethys sea activities in the south margin of the basin.

(1) Triassic period: back-arc foreland basin evolution stage. The activity of main active plates in the southern margin of the Tarim plate appeared to be the intensive northward subduction of the Tethys ocean in the Triassic and the land-land collision between the Qiangtang land block and the Tarim plate in the end of the Triassic. Controlled by the compressional tecotonic setting produced by the intensive northward subduction of the ancient Tethys ocean at the southern margin of the basin, the Triassic foreland basin tectonic stage began. Within the basin are the Kuqa foreland depression, the Xinhe frontal uplift and the analogous foreland basin in the middle part of the basin. The end of the Triassic is characterized as the large area of uplift and denudation, which includes the east Tarim uplift, the west Tarim uplift and the Xinhe uplift. Among them, the east Tarim uplift, located in the east of the Tarim Basin, was formed because of the tectonic inverse happening under the Sinian-Ordovician Kuman aulacogene setting, and was also a region where the worst denudation occurred in the end of the Triassic period in the Tarim Basin, with the usual denudation thickness of 1000—4000 m[14]. These are typical characteristics of the superimposed basins.

(2) Jurassic-early Tertiary period: fault depression-depression basin evolution. After the period of the long-term compressional tectonic environment in the end of the early Permian-Triassic, the Tarim Basin entered the developing period of the fault depression structure with relaxed stress in the Jurassic-early Tertiary. In the Jurassic-Cretaceous period, the basin was an isolation fault depression-depression basin, and in early Tertiary, it was the uniform Tarim fault depression-depression basin. Of the latter, because of the enhancement of the stretching tectonic movement and the rapid subsidence in front of orogenics, the early Tertiary marine invasion of the west Tarim had extended from the later Cretaceous mountain front of the west Kunlun uplift to the Kuqa region located on the mountain front of the middle-west ancient Tianshan uplift; in the east of the Tarim Basin is mainly the fluvial facies-shore shallow lacustrine facies clastic rock deposits. In the end of the Cretaceous, the structural deformation was mainly characterized as the denudation that occurred to the west Tarim uplift.

(3) Later Tertiary-Quaternary period: combination rejuvenated foreland basin[14,27]. During this period, the dominant tectonic movements are: the Indian plate and the Eurasia continental plate began colliding and joining together in the end of the Eocene epoch, and migrating northward constantly; complete collision and joining together began at the end of the Tertiary-early Pleistocene. While affected by the intensive compressional tectonic stress field, the large intracontinental A-shaped subduction was generated in front of the surrounding orogenics of the Tarim Basin, therefore, many rejuvenated foreland basins formed, i.e. Kuqa, Awati, southwest Tarim, southeast Tarim foreland basins. At the end of the Tertiary-Quaternary, the intensive structural deformation occurred in the basin, and the main characteristics were the foreland thrust belt and the strike-slip structural deformation.

(ii) Characteristics of structural deformation in Meso-Cenozoic

During late Tertiary-Quaternary, the finished collision between the Indian plate and the Eurasia continental plate in the south part of the Tarim Basin (Xinjiang Geologic Bureau, 1993[16]), and the intensive structural deformation occurred to the Tarim rejuvenated foreland basin. Generally, the major movement was the horizontal nap, accompanied by the intensive strike-slip. On the one hand, due to the tremendous horizontal compressional stress caused by the collision, the surrounding mountain systems were uplifted sharply and overthrust inward the basin. As a result, several thrust belts of complicated fault and folding deformation formed in front of the Kunlun and the south Tianshan Mountains. The structures were distributed in rows, and the intensity of the deformation decreased from the orogeny to the basin. On the other hand, due to the impact of the Aerjin strike-slip fault activities, the strike-slip in the southeast Tarim was intensive, and was characterized as structures related to the large scale of strike-slip movements[27].

(1) Kuqa regenerated foreland thrust belt. The Kuqa rejuvenated foreland thrust belt is located in front of the Tianshan Mountains in the north Tarim Basin, and is mainly the Meso-Cenozoic complicated step thrust fault composed of the faulted flat-fault ramp and fault related folds. This structural belt is related to three detachment planes, i.e. the top of the Mesozoic basement, the Triassic-Jurassic coal bed and the Lower Tertiary gypsum-salts bed. Also, the structural belt can be divided into several minor belts from north to south, which are the northern marginal thrust-monoclinal belt, the Kelasu-Yiqikelike anticlinal belt, the Baicheng depression, the Qiulitage anticlinal structural belt and the Yingmai 7-Tiergen tension structural belt[28]. Among them, the structural deformation characteristics of the deep layer and the shallow layer of the main body of the thrust belt are not consistent. The deeper layer is usually the fault bend fold or the duplex thrust structure. The shallow layer is the fault propagation fold. The time sequence of the deformation of the structural belt is from the late Tertiary Jidike period to the Kuqa period. These structuaral belts are key targets of the oil and gas prospecting and exploration.

(2) Souhwest Tarim rejuvenatetd foreland thrust belt. The southwest Tarim rejuvenated foreland thrust belt, located in front of the Kunlun Mountains in the southwest part of the Tarim Basin, is divided into several tectonic belts according to the structural deformation. These structural belts, are arc structural belts in the northern margin of the Pamir, the Qimugen structural belt, the Kekeya-Sangzhu structural belt and the Piyaman-Hetian structural belt in turn from west to east. The inconsistent deformation is involved in the Qimugen structural belt and the Kekeya-Sangzhu structural belt. The deep layers (the Paleozoic and the Mesozoic) are complicated imbrication structural; the top plane fault is the Lower Tertiary substrate gypsum mudstone bed; the footwall fault is the Paleozoic (Cambrian) bottom bed. The shallow bed (Cenozoic) is the passive ascending arc structure formed by the stacking of the deep rock beds.

(3) Rejuvenated foreland thrust in Keping-west sector of south margin of south Tianshan Mountains. Keping-the west sector of the south margin of south Tianshan Mountains refers to the region to the west of Akesu. This thrust belt is a complex structural deformation belt slipping along the bottom bed of the Paleozoic, with the Paleozoic basal plane as the detachment plane. The frontal area of deformations has different beds from the shallow bed to the deep bed. The shallow bed is a detachment fold of the Tertiary bottom, while the deep is the basement involved deformation, and the whole belt is a reverse sequence deformation thrust belt, which is divided into 6 structural belts from south to north, i.e. Kashi, Atushi, Kangsu-Kaerguole, Aqike, Bayinbuluti-Kalajun Akecheyi-Bakesugaite, etc.

(4) Intensive strike-slip activity. During the late Tertiary-Quaternary, due to the collision of the Indian plate and the Eurasia continental plate, and influenced by the movements of NEE left-lateral strike-slip fracture systems of the East Kunlun-Aerjinshan Mountain, the giant NEE left-lateral strike-slip structural system developed in the southeast margin of the Tarim Basin at the same time when the rejuvenated foreland thrust belt, which was mentioned above, occurred to the basin. Among them, the Minfeng depression, rhombic-shaped, may belong to the pull basin of the Aerjin left-lateral strike-slip fault system. The thickness of the Miocene, Pliocene-Pleistocene deposits is larger than 4000 m. In addition, movements related to the strike-slip activity, such as the en echelon fracture, fold, etc. also developed.

3 Petroliferous features and exploration prospect

The structural characteristics of a superimposition between the Paleozoic craton and the Meso-Cenozoic foreland basin, and the multi-phase evolution and structural deformation, determined that the petroliferous features are characterized by the properties of a superimposition and combination petroleum system, including multiple resources, multiple reservior and multiphase poolgeneration. It is also determined by the factors mentioned above that two prospecting and exploration fields are the Paleozoic craton and the Meso-Cenozoic foreland thrust belt.

(i) Basic petroliferous features in Tarim Basin—superimposition and combination petrroleum system

(1) The superimposition and combination petrroleum system formed by the vertical superimposition and the horizontal combination between the Paleozoic and the Meso-Cenozoic petroleum system, with the characteristics of multiple resource and multiple reservior. According to the researches, 4 suits of major hydrocarbon source rocks are developed: the Cambrian-Lower Ordovician, the Mid-Upper Ordovician, the Carboniferous-Permian and the Triassic-Jurassic; 4 suits of major reservoirs are: sandstones in the bottom of the Cretaceous and the Lower Tertiary, sandstone in the Triassic-Jurassic, Donghe sandstone and bioclastic limestone in the Carboniferous, and gypsum mudstone in the Lower Tertiary. 3 suits of regional seal rocks are: gypsum mudstone in the Middle-Upper part of the Carboniferous, coal beds and mudstone in the Middle-Upper Jurassic and the gypsum mudstone in the

Lower Tertiary. 7 suits of petroleum systems are formed: 1) Manjiaer: the Cambrian-Lower Ordovician and the Middle-Upper Ordovician hydro carbon source rocks; 2) Kuqa: Triassic-Jurassic hydro carbon source rocks; 3) Southwest Tarim: the Cambrian Ordovician, the Carboniferous-Permian and the Jurassic hydrocarbon source rocks; 4) Yingjisu: the Jurassic and the Cambrian-lower Ordovician hydrocarbon source rocks; 5) Southeast Tarim: the Jurassic hydrocarbon source rocks; and 6) Awati: the Cambrian-Ordovician, the Carboni ferous-Permian and the Triassic hydrocarbon source rocks; and 7) Tangguzibasi: the Cambrian-Ordovician hydrocarbon source rocks (fig. 3). The former 4 suits of petroleum systems have been proved until now.

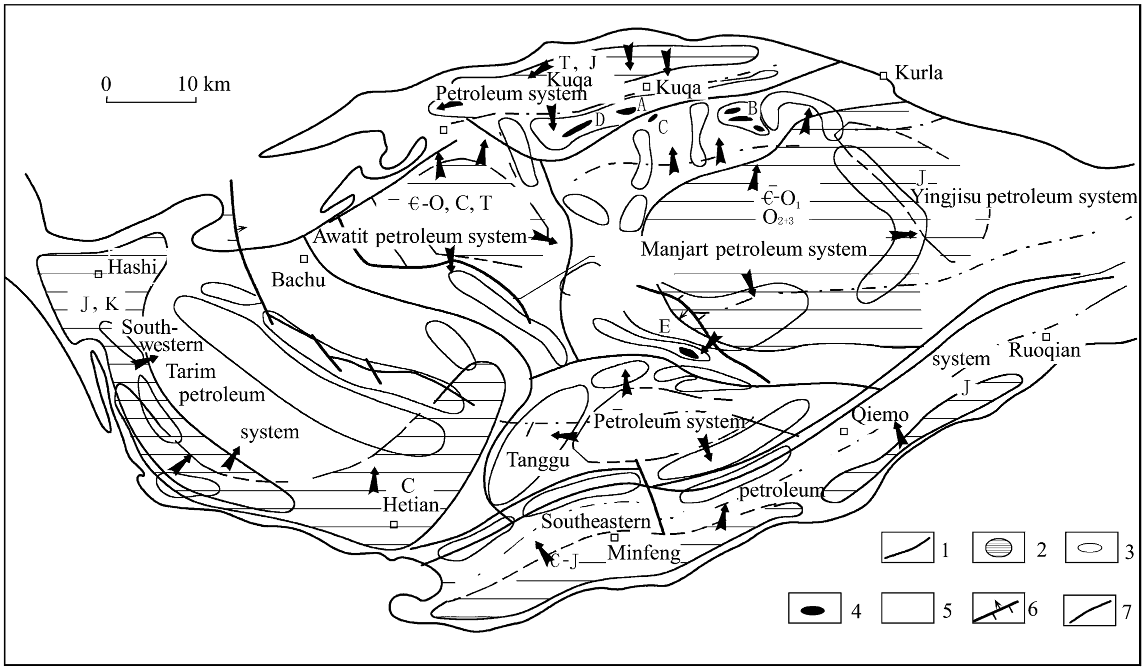

Fig. 3. Distribution of superimposition and combination petroleum systems and hydrocarbon source rocks in the Tarim Basin. 1. Border line of petroleum system; 2, hydrocarbon source rock area; 3, favorable structural belt; 4, major oil and gas field; 5, border line of struuctural unit; 6, fault; 7, borderline of basin; A, Yaha Oil and Gas Field; B, Lunnan Oil Field; C, Donghetang Oil Field; D, Yingmaili Oil and Gas Field; E, Middle Tarim 4 Oil Field.

(2) Pooling with multiphase, but mainly in late stage.

Pooling with multiphase, but mainly in late stage is another distinct characteristic of the petroliferous features of the Tarim Basin. Among the 4 suits of hydrocarbon source rocks mentioned above, the main hydrocarbon generation stages of the Cambrian-Lower Ordovician system were late Caledonian-early Hercynian, late Hercynian period and the Himalayan period, of which the former two periods generate oil mainly, and the Himalayan period generate the dry gas mainly; the Middle-Upper Ordovician hydrocarbon source rocks are in the climax generation at present; as for the Carboniferous-Lower Permian hydrocarbon source rocks, only the middle-south part of the Maigaiti slope and the southwest mountain frontal regions are in higher maturity and have certain hydrocarbon generation potential; Triassic hydrocarbon source rocks have become high-post mature in the late Tertiary Kuqa period, and the Jurassic hydrocarbon source rocks have developed into the high-post mature stage in the Quaternary Xiyu period. The superimposition distribution of these 4 suits of hydrocarbon source rocks determine the multiplephase pool-generation, i.e. the early Hercynian period, the late Hercynian period, the Himalayan period, etc. According to the following studies on the oil and gas reservoirs found, the thermal evolution history of different hydrocarbon source rocks, the regional unconformity surface of the basin and the preserving condition in the late period, the late Himalayan period is the most favorable for pool-generation. At present, most oil and gas reservoirs found in the platform-basin area and the foreland area were formed or reformed in the Himalayan period.

(3) Complicated oil and gas reservoir distribution, with Paleozoic mainly rich in oil and Meso-Cenozoic mainly rich in natural gas. There are a variety of oil and gas reservoir types, with very complicated distributions. Structural, stratigraphic, lithologic and structural-stratigraphic, structural-lithologic reservoirs all have been found in the Paleozoic, while the structural reservoirs are major in the Meso-Cenozoic system. By the end of 2000, the PetroChina Corporation had approved that the

geologic reserves for oil and natural gas in the Tarim Basin are 30751×10^4 t and 4909.98×10^8 m^3 respectively. Of them, the reserves in the Paleozoic platform-basin area are 24686×10^4 t and 888.36×10^8 m^3 respectively; the reserves in the Meso-Cenozoic foreland area are 6065×10^4 t, 4021.62×10^8 m^3 respectively. The characteristics that the Paleozoic is mainly abundant in oil and the Meso-Cenozoic is mainly abundant in natural gas, are embodied primarily. This is mainly related to the hydrocarbon rock types of Ⅰ-Ⅱ kanrogen in the Paleozoic, the hydrocarbon rock types of Ⅲ kanrogen in the Mesozoic and the high thermal evolution maturity of the foreland region.

(ii) Petroliferous features of the Paleozoic craton

(1) Multiple resources and multiphase pooling with widely mixed resources. Three suits of marine facies hydrocarbon source rocks of high quality, i.e. Cambrian-Lower Ordovician hydrocarbon source rocks, Mid-Upper Ordovician hydrocarbon source rocks and Carboniferous-Permian hydrocarbon source rocks, are mainly developed in the Paleozoic craton. Distinct differences present in these 3 suits of marine facies hydrocarbon source rocks in terms of distribution, organic types and thermal evolution history. Even in one hydrocarbon source rocks suit, different maturity and burial thermal evolution history occurred in different areas. The distribution of the superimposition of these 3 suits of hydrocarbon source rocks determines the 3 main pooling phases for the oil and gas reservoirs in the platform-basin area, which are the late Caledonian-early Hercynian, the late Hercynian and the Himalayan periods. Comparing the oil and gas resources, the conclusion can be drawn that most of the oil and gas reservoirs found in the Paleozoic craton are featured with mixed resources. Among them, the Lunnan and middle Tarim regions mainly have mixed oil and gas resources of the Cambrian-Lower Ordovician and Middle-Upper Ordovician hydrocarbon source rocks, and the oil and gas in Qunkuqiake region are featured with mixed Cambrian-lower Ordovician with Carboniferous. The mixed source is a distinct characteristic of the formation in the Paleozoic craton.

(2) Pooling controlled by ancient uplift. The 5 ancient uplifts of 3 categories and their slope structures found in the Tarim Paleozoic craton play a very important role in controlling the Paleozoic oil and gas accumulation. In the middle Tarim, north Tarim and Bachu uplifts, the oil and gas reservoirs found are all distributed in the ancient uplifts and their slope areas. Pooling controlled by the ancient uplift, especially of the successive ancient uplift, lies in the following three aspects. Firstly, multiple traps, such as structural traps, stratigraphic traps, lithologic traps and structural-stratigraphic traps, are developed on the ancient uplift and their slopes. These structures are favorable targeting and accumulation places for the migration of the oil and gas generated in each oil generation depression. Secondly, the development of the long-term evolution of the ancient uplift and the unconformity surfaces plays a very important role in controlling the deposition and the development of reservoirs, which indicates that the ancient uplifts are the main developing regions for Cratonic reservoirs. Thirdly, due to the intensive structural deformation of the higher part of the ancient uplift in the late period, secondary pooling were main; the lower part of the ancient uplift and their slopes, where the tectonic movement is comparatively weak, with good preserving conditions, are the favorable places for giant-medium oil and gas reservoirs.

(3) Example: pooling pattern in Lunnan Ordovician buried hills. The Lunnan Ordovician buried hill reservoirs in the north Tarim uplift reveals the pooling pattern, that is, the giant oil pooling in the early period had the experience of local damage after pooling, and had experienced the adjusting preservation and refill. Therefore, the formation of the Lunnan Ordovician buried hill oil reservoirs on the north Tarim uplift is a typical case of the oil and gas accumulation controlling by ancient uplifts (fig. 4).

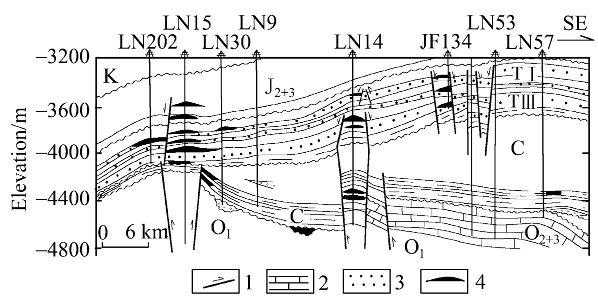

Fig. 4. Oil and gas pooling pattern in the Lunnan region. 1, Fracture; 2, gypsum-salts rock bed; 3, sandstone; 4, coal measure stratum.

The early period of the reservoir formation: after the Carboniferous deposition, the large buried hill anticlinal trap formed, with the Ordovician buried hill weathering crust as the reservoir, and the Carboniferous as the seal rocks. The Cambrian-Lower Ordovician resource rocks in the Permian period had started their climax in generating and releasing hydrocarbon, and giant oil reservoirs of their early stages had been formed by then. It is speculated that the oil-bearing areas cover the middle part and the south part of the Lunnan buried hill anticline.

The local damage period: in the end of the Permian, the buried hill anticlines were uplifted and denudated. As a result, the top “trap-door” Carboniferous seal rocks were removed; the oil, gas and water relocation was triggered;

the oil and gas in the higher part of the buried hills began escaping; at the same time, the light components in the oil reservoirs in the periclinal part of the anticlines began differentiating and escaping. Thus, the normal crude oil changed into heavy oil and thick oil gradually.

The reservoir formation period of adjusting preservation and refill: after the Triassic-Jurassic deposition, new buried hill drape anticlinal traps were formed, and the adjustment and the light components escaping in the Ordovician buried hill oil reservoir were going on. But with the "trap-door" being sealed and the higher part thick oil "enveloping" condition being formed, the Ordovician oil reservoir in the periclinal part of the anticline was preserved considerably. In the Tertiary, due to the refill with the normal crude oil from the Middle-Upper Ordovician resource rocks, and with the high maturity gas from the Cambrian-Lower Ordovician, Triassic drape anticlincal oil and gas reservoirs and normal oil and gas distributing regions in the east of the buried hill anticlinal Ordovician were formed.

(iii) Petroliferous features in Meso-Cenozoic foreland thrust belt

(1) Features of coal-bed generation hydrocarbon, with pooling in late stage. The hydrocarbon source rocks in the Meso-Cenozoic foreland basin are mainly lacustrine-swamp facies Triassic-Jurassic coal bed. For example, the organic carbon content in the Jurassic hydrocarbon source rocks in Kuqa is higher than 2.0%, and the organic matter types are Ⅲ and Ⅱ2 kanrogen. The carbon isotope of the natural gas found in the foreland thrust belt up to now is heavy. Especially, the usual isotope of the ethane, mainly reflecting the characteristics of resource rocks, is lower than –28‰, and is indicative of typical coal-generation gas, e.g. the $\delta^{13}C_1$ of the natural gas in the Kuqa region is –30.9‰—–38.8‰, and the $\delta^{13}C_2$ is –16.8‰—–25.7‰. In addition, with the help of the gas/source direct contrast technology, the study of the relationships between the product from the source rock thermal simulation and the carbon isotope in light hydrocarbon, such as the natural benzene and natural phenylmethane has further proved that the natural gas in the Kuqa foreland thrust belt is related to the coal source rocks.

The Meso-Cenozoic foreland thrust structures were mainly formed during the later Tertiary-Quaternary period. Up to now, all the source rocks have developed into the high-post maturity condensate gas stage and the wet-dry gas stage. The hydrocarbon generation climax is well matched with the trap forming period. In view of the match relationships between the fill of the hydrocarbon and the formation of the traps, the oil and gas reservoirs in the thrust belt are endowed with the feature of the reservoir formation in the late and recent period.

(2) Tertiary gypsum-salts seal bed controls distribution of giant-middle oil and gas fields. Besides the coal seal and mudstone seal developed in the Meso-Cenozoic foreland basin, the gypsum-salt seal rocks of better cap sealing are developed in the Tertiary. These seal beds control the distribution of the Meso-Cenozoic giant-medium oil and gas fields. For example, under the close seal bed composed of the lower Tertiary saline, gypsum-salt and gypsum-bearing mudstones, hundreds of meters thick in the middle-west part of the Kuqa depression, the giant Kela No. 2 natural gas field was found with an approved reserve of 2846×10^8 m^3; the approved natural gas and condensate reserves in the Upper Tertiary of the Dina 2 gas field in the east of the Qiulitage structural belt are 550×10^8 m^3 and 390×10^4 t respectively, with the thickness of the seal rocks, namely mudstone and gypsum-bearing mudstones, larger than 1000 m. The main seal bed of the Kekeya gas field, in the southwest Tarim, are thicker mudstone and gypsum-bearing mudstones in the Upper Tertiary Meso-Cenozoic, with the approved natural gas geologic reserves of about 300×10^2 m^3. It can be concluded that the distribution of the giant-medium gas fields in the Meso-Cenozoic is closely related to the Tertiary gypsum-salt bed.

(3) Anticline below the saline bed controls the distribution of oil and gas. The anticline developed under the saline slipped bed controls the distribution of the oil and gas field in the Meso-Cenozoic. In the Kuqa and Southwest thrust belt, large array thrust structures and all types of fault related folds were formed along the Tertiary gypsum-salt slippage rocks. Above the saline structural bed, fault propagation folds are mainly developed, with the fractures exposing to the ground surface; below the saline structural bed, passive top plane duplex structures are mainly developed, and high amplitude and large area anticlinal traps with a long axis formed widely. These anticlinal traps are distributed in rows in this region. For example, the Kela No. 2 under saline bed anticlinal trap, the Dabei No. 1 under saline bed trap and the Kekeya structure are all duplex structures under the Lower Tertiary gypsum-salt bed; the Dina No. 2 structure is an anticlinal structure under the Upper Tertiary gypsum-bearing mudstone slipped bed. All these structures are rich in oil and gas.

(4) Example——natural gas pooling pattern in Kela No. 2 gas field. The Kela No. 2 gas field, in the Kuqa depression, is a typical giant anticlinal trap, where the reservoir formation occurred in the later or recent period in the Meso-Cenozoic foreland thrust belt and the hydrocarbon generation occurred in the coal bed, with the gypsum rocks as the effective seal rocks and with oil and gas

accumulating under the gypsum bed in abundance (fig. 5). The reservoirs of the Kela No. 2 gas field are the Lower Tertiary-Cretaceous Bashijiqike Formation sandstones (interbedded with thin bed carbonate rocks) below the Lower Tertiary gypsum-salt bed. The gas resources of the Kela No. 2 reservoirs come from the Triassic-Jurassic coal bed hydrocarbon source, and the giant anticlinal trap under the Tertiary gypsum-salt bed, formed after the Kangcun Period, is the trap that controls accumulating oil and gas. The late Tertiary Kuqa period is the crucial stage for the formation of the Kela No. 2 gas field. Among them, the area and the amplitude of the anticlinal traps restrict the oil and gas richness. While the oil and gas resources are sufficient, the larger the area and the more the amplitude of the trap is, the higher the oil and gas richness will be.

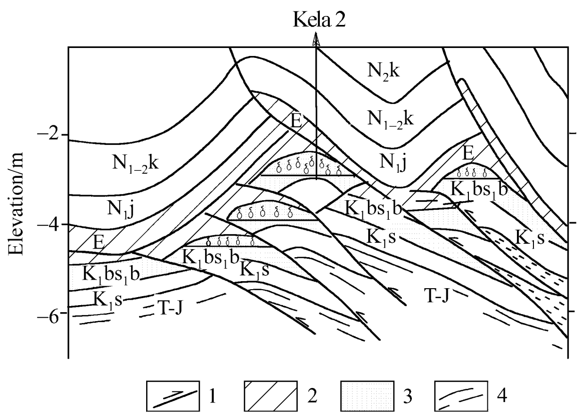

Fig. 5. Natural gas reservoir formations in Kela No. 2 gas field. 1, Fault; 2, carbonate rocks; 3, sandstone; 4, oil reservoir.

(iv) Exploration prospects in the further

(1) Oil prospecting and exploration directions. The main prospecting and exploration targets are the north Tarim uplift, the middle Tarim uplift, and their slope structures and arc belt to the west of the Manjiaer depression. In the north Tarim, the key object is the comprehensive prospecting and exploration of multiple targets bed, i.e. the Ordovician, the Carboniferous and the Triassic in Lunnan. Meanwhile, the Ordovician and Jurassic anticlinal belt in the Yingmaili structure, Halahatang and its marginal Carboniferous Donghe sandstone trap, Donhetang-Xinhe area Cambrian-Ordovician buried hills shall be evaluated again.

The overall evaluation shall be conducted to the north part of the Manjiaer depression, and the exploration and drilling shall be conducted to the traps in the Aman transit belt-Yuenan-Hadexun area, where the Carboniferous is continuous and the scope for choice is broad. Efforts shall be made to find new zone with abundant black oil. Meanwhile, exploration and drilling evaluations shall be conducted to the Carboniferous and Triassic traps in the southeast of the Tahe region.

The main target for oil prospecting and exploration is the west part in the middle Tarim. The prospecting and exploration deployment that equal attention shall be paid to the Carboniferous Donghe sandstone and Cambrian-Ordovician carbonate rocks shall be abided by. As for the Cambrian-Ordovician carbonate rocks, the fracture belt Ⅰ and the deep large anticline are the prospecting and exploration targets, and collective developing zones for the carbonate rock reservoirs shall be detected in them. Study and evaluate the Carboniferous Donghe sandstone traps again, and try to obtain the reserves. Meanwhile, efforts shall be made to find new distribution zones of black oil in the north Kuqa monoclinal belt and the west Qiulitage belt.

(2) Natural gas exploration directions. 13 natural gas fields, such as Kela No. 2, etc. have been found in the Tarim Basin until now. Natural gas reservoirs have been found both in the thrust belt and in the platform-basin area. But the major gas fields and approved geologic reserves are distributed in the Kuqa depression, the Bachu uplift and the Southwest depression, which have constituted a crescentic natural gas accumulating belt in the west of the Basin. Therefore, these regions remain to be the main area for natural gas prospecting and exploration. In addition, it is possible that the Yingjisu depression in the East Tarim is another important gas field found after the Kuqa and Southwest Tarim.

4 Conclusions

The Tarim Basin is a giant superimposition and combination, with an ancient crustal basement, composed of the Paleozoic craton and Meso-Cenozoic foreland basins. The kernel part of the basin is the marine facies Paleozoic craton, and the superimposed four continental facies Meso-Cenozoic rejuvenated foreland basins, i.e. Kuqa, Awati, Southwest Tarim and Southeast Tarim. All these determine that the oil and gas distribution is controlled by the Paleozoic craton and the Meso-Cenozoic foreland thrust belt, and the Tarim Basin is characterized by the superimposition and combination petroleum system, i.e. multiple resources, multiple reservoirs and multiphase pool-generation.

Although the Tarim Paleozoic craton is smaller compared with the other giant cratons abroad, the kernel structure of it is much more stable, and the marginal deformation is intensive. The tectonic evolution has gone through 3 stages, i.e. the Sinian-Ordovician cratonic marginal aulacogene, the Silurian-Devonian cratonic circumferential marginal foreland basin, the Carboniferous-Permian Cratonic marginal depression and the Intracratonic rift basin. The major tectonic deformations are large uplifting and depressional structures, where 5 ancient uplifts and their slope structures of 3 categories are developed, i.e. the stable structure in the middle Tarim, the residual structure in the north Tarim, the residual structure in the east Tarim, the active structures in Bachu and the active structures in the south Tarim. The petroliferous is characterized as multiple resources (Cambrian-Lower Ordovician, Middle-Upper Ordovician and Carboniferous-Permian hydrocarbon source rocks), the multiphase pool-generation (later Caledonian-early Hercynian period, later Hercynian period, Himalayan period, etc.) and the oil and gas accumulation controlled by the ancient uplift and its slope structures.

The four rejuvenated foreland basins in the Tarim Basin, namely the Meso-Cenozoic Kuqa, Awati, southwest Tarim and southeast Tarim, distributed at the circumferential margin of the Tarim craton, have experienced the long-term subsidence and the rapid subsidence after the Meso-Cenozoic period, which resulted in the formation of intensive thrust structures. The tectonic evolution has gone through 3 stages, i.e. the Triassic back-arc foreland basin, the Jurassic-early Tertiary fault depression-depressional basin and the later Tertiary-Quaternary combination rejuvenation foreland basin. 3 rejuvenated foreland thrust belts, namely the Kuqa, the southwest Tarim and the western section of the Keping-South Tianshan southern margin, and the southeast strike-slip structural belt are developed there. The former three structures are characterized as the fault-flat-fault-ramp thrust and the fault related fold structure, and are distributed in rows and belts. The deformation intensity decreases gradually from the orogenic frontal to the basin. The petroliferous features are characterized as hydrocarbon formed in the Mesozoic coal measure, richness in natural gas, pool-generation in the late or recent period and the oil and gas distribution controlled by the foreland thrust belt.

The superimposition and combination petroleum system in Tarim Basin, was composed of the vertical superimposition and the horizontal combination between the Paleozoic and Meso-Cenozoic petroleum system. 4 suits of major hydrocarbon source rocks, 4 suits of major reservoirs, 3 suits of regional seal rocks and 7 suits of petroleum systems are developed; it is also multiphases pool-generation, with the late period as the main period; the distribution types of the oil and gas are complicated, among which the Paleozoic is mainly featured with the high richness in oil, and the Meso-Cenozoic is mainly characterized by the high richness in gas; the craton is characterized by the multiphase pool-generation, oil is controlled by the ancient uplift, etc. The foreland basin is featured with the hydrocarbon generation in the coal bed, the pool-generation in the late period, the foreland thrust controlling the gas and rich in gas, etc.

The structural characteristics determine that the two large fields, which are the Paleozoic craton and the Meso-Cenozoic foreland thrust belt, shall be included in the oil and gas prospecting and exploration. The main favorable regions for oil prospecting are: the north Tarim and middle Tarim uplifts and their slope structures and the arc belt to the west of the Manjiaer depression; the main favorable area for natural gas prospecting are: the Kuqa depression, the Bachu uplift, and the western crescentic natural gas accumulating belt constituted by the southwest Tarim depression and the east Tarim Yinjisu depression.

Acknowledgements Sincere thanks for the great helps from the Academician Guo Lingzhi of Earth Science Department of Nanjing University, Academician Qiu Zhongjian, Academician Li Desheng, Prof. Shi Baoheng and Prof. Liang Digang of the PetroChina Corporation. This work was supported by the "Oil and Gas Exploration in Tarim Basin" Project of the National Key Scientific-technological Project during the ninth "Five-Year-Plan."

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(Received August 9, 2002)