Abnormal high pressure in Kuqa foreland thrust belt of Tarim basin: Origin and impacts on hydrocarbon accumulation*

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Abstract Following analyses of the abnormal high pressure distribution characteristics, based on the geological characteristics, tectonic stress field and physical simulation, we investigated the formation mechanisms of abnormal high pressure and its impacts on hydrocarbon accumulation in the Kuqa foreland thrust belt. The abnormal high pressure appears at the bottom of the Paleogene and obviously exists in the Triassic and Jurassic. However, the pressure coefficient in the Triassic and Jurassic is lower than that in the Cretaceous and at the bottom of the Paleogene. Horizontally, the abnormal high pressure distribution is characterized by E-W orientation zoning. The maximum pressure coefficient lies in the Kelasu-Dongqiu-Dina tectonic zones in the center of the Kuqa foreland thrust belt and decreases away from the tectonic zones. The formation of abnormal high pressure was mainly related with the intense tectonic compression in the Early Pleistocene time, and tectonic uplifting, undercompaction and hydrocarbon generation were secondary factors contributing to abnormal high pressure. Under the rapid and intense tectonic compression in the Early Pleistocene, the rock framework firstly undertook 1/4 of the compression stress and the other was borne by the pore fluids. Due to the presence of great seal of gypsum-salt or gypsum-mudstone beds in the Paleogene, the pressure of pore fluids increased rapidly and led to the abnormal high pressure in the Kuqa foreland thrust belt. The abnormal high pressure has important impacts on hydrocarbon accumulation. It is one of the necessary conditions for formation of large oil and gas fields in the Kuqa foreland thrust belt.

Keywords: abnormal high pressure, formation mechanism, oil and gas reservoir, Kuqa foreland thrust belt, Tarim basin.

The abnormal high pressure in sedimentary basin is referred to as the pressure of strata obviously higher than hydrostatic pressure (the pressure coefficient is over 1.2)[1, 2]. There are more than 180 high pressure basins in the world. Of them, about 160 are rich in gas and oil[1, 2]. In China, the oil and gas reservoirs in over 30 areas of 10 main basins are related with high pressure[3]. Especially, in the foreland thrust belts of the basins in west China, abnormal high pressure plays an important role in hydrocarbon accumulation and distribution[1—5].

In the early 1930s, abnormal high pressure was mainly studied from the aspect of compaction. As more and more basins were found to be overpressed, particularly the breakthrough in gas and oil exploration in abnormal high pressure zones, the abnormal high pressure formation mechanism and its relation with hydrocarbon accumulation have been studied by numerous oil companies and scholars. Previous studies show that the formation mechanisms for abnormal high pressure are mainly composed of undercompaction, hydrothermal pressuring, hydrocarbon generation, dehydration of clay minerals, tectonism, temperature change and cementation of the pore space. Of them, undercompaction and hydrocarbon generation are well known[1—15].

In recent years, with the discovery of the Kela2 Gas Field and the significant breakthrough in oil and gas exploration in the thrust belts of the Kuqa, the western Sichuan Basin, and the southern Jungar Basin, research on abnormal high pressure in the foreland thrust zone of western basins becomes more and more important. The unbalanced compaction caused by rapid subsidence, hydrocarbon generation and tectonism is the possible formation mechanism of abnormal high pressure in these regions[16—24]. On the basis of geological analysis, and according to physical simulation experiment and the relationship between abnormal high pressure and tectonic stress field, it is concluded that the strong tectonic compression in the Early Pleistocene is the main reason for the formation of abnormal high pressure in Kuqa foreland

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thrust belt.

1 Geological setting

The Kuqa foreland thrust belt is located at the northern Tarim basin and south of the Tianshan Mountains, NW China. The belt is adjacent to the Northern Tarim uplift (Fig. 1), 45 km long and 20—60 km wide. The strata mainly consist of Mesozoic and Cenozoic sequences. The Mesozoic is generally 2000—3000 m thick with a maximum thickness of over 4000 m. It consists of sandstones and mudstones of lacustrine, swamp and fluvial facies with coal measures, carbonaceous shale and oil shale developed in the middle and lower parts. The Cenozoic is generally 3000—5000 m thick and has a maximum thickness of over 8000 m. It is composed of sandstones and mudstones of lacustrine and fluvial facies with two sets of gypsum-mudstone and gypsum-salt beds developed in the middle and lower parts. There are three sets of reservoir-seal assemblages in the Jurassic, Paleogene and Neogene.

The tectonic styles in the studied area are dominated by fold-thrusts developed during Cenozoic times. They have the characteristics of zoning in north-south orientation and vertical layering. Horizontally, there are four detachment and thrust zones and two sags, which are the monocline tectonic zone, Kelasu-Yiqikelike tectonic zones, Baicheng-Yangxia sags and Qiulitag front tectonic zone from north to south (Fig. 1). Controlled by four detachments of gypsum-mudstone beds in the Neogene Jidik formation, Paleogene gypsum-salt beds, Jurassic and Triassic coal measures and crystalline basement detachment, the vertical deformation of rock was obviously of layering, and the structures beneath and above the gypsum-salt bed are clearly unsymmetrical.

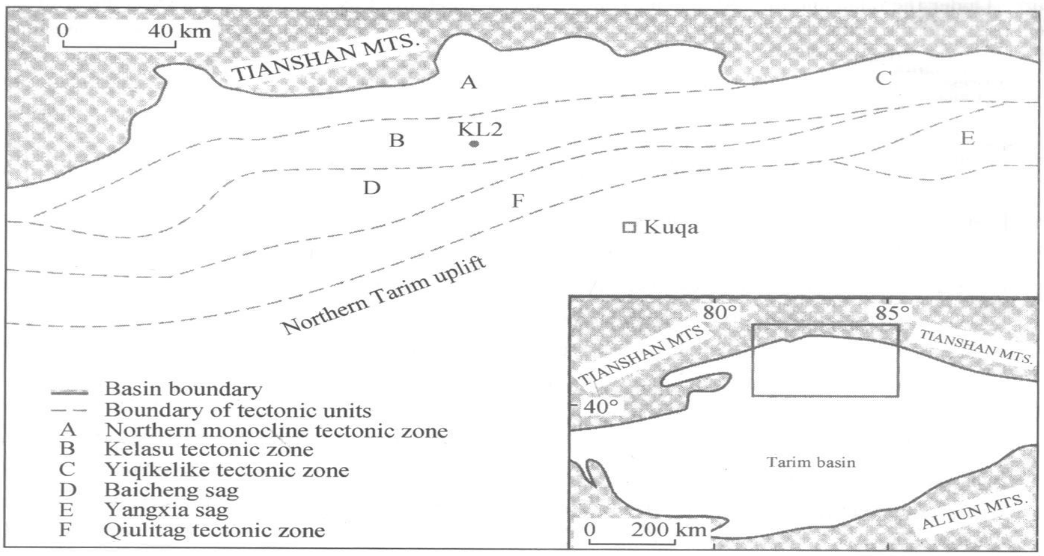

Fig. 1. The location of the Tarim basin and the studied area.

2 Distribution characteristics of abnormal high pressure

According to mudstone acoustic time difference logging and actual drilling data, there is obviously abnormal high pressure in the Kuqa foreland thrust belt. For example, in the Kela 2 Gas Field, the sandstones at the bottom parts of the Paleogene Kumugelimu Formation and in the Lower Cretaceous Bashijijik Formation belong to the same pressure system. Their pressure coefficients are generally 1.7—2.0. The maximum pressure coefficients are over 2.2 and the residual pressures are 30—38 MPa[19—24]. The actual drilling pressure in the middle parts of gas-bearing interval of Dina 2 well is 101.1 MPa and the pressure coefficient is 2.18. The maximum residual pressure in Dongqiu 5 well is 47.6 MPa[23]. In plane view, the pressure coefficient is distributed by E-W orientation zoning[22]. The maximum coefficient of formation pressure lies in the Tubei, Kelasu, Dongqiu and Dinan tectonic zones, where their pressure coefficients are more than 2.0 and decrease southwards and northwards. The northward decreasing rate is much greater than the southward rate, which probably resulted from intensive faulting and significant strata uplifting at the front of the Tianshan Mountains. These tectonic activities led to the rapid unloading of pressure. The pressure system is close to normal in the Northern Tarim uplift where the pressure coefficients are less than 1.3.

The abnormal high pressure distribution is closely related with gypsum-salt and gypsum-mudstone beds in the Paleogene. If there were no thick gypsum-salt or gypsum-mudstone beds, no abnormal high pressure would exist. Generally, if the thickness of gypsum-salt or gypsum-mudstone beds is over 400—500 m, there is possibly abnormal high pressure underneath this place, but not *vice versa*. Besides huge gypsum-salt or gypsum-mudstone beds, the abnormal high pressure distribution is also controlled by structural position. The good sealing property of gypsum-salt or gypsum-mudstone beds in the Paleogene is the necessary condition for the formation of abnormal high pressure.

Vertically, the formation pressure is normal above the Paleogene gypsum-salt or gypsum-mudstone beds where the pressure coefficient is less than 1.2. The abnormal high pressure begins to appear at the bottom of the Paleogene. When the pressure coefficient reaches its maximum, it will decrease gradually with depth. However, the pressure remains the same (Fig.2), which means the bottom parts of the Paleogene and the Cretaceous belong to the same pressure system[19]. Because of several non-permeable layers in the Paleogene and Cretaceous, the pressure is unevenly changed and has division properties within the abnormal high pressure system of reservoirs. The abnormal high pressure also exists in the Jurassic and Triassic where the abnormal high pressure appears in the Paleogene and Cretaceous. There are a few actual drilling data for pressure in the Jurassic and Triassic. According to a few pieces of actually measured data of pressure at several drilling wells, such as Yinan 2, Yinan 4 and Yishen 4 in the south of Yiqikelik tectonic zone, the pressure coefficients are usually 1.6—1.8, with the maximum over 1.9, which is lower than that at the bottom parts of the Paleogene and the Cretaceous.

3 Mechanism of abnormal high pressure

The possible mechanisms of abnormal high pressure in the Kuqa foreland thrust belt are mainly undercompaction, hydrocarbon generation, and tectonic

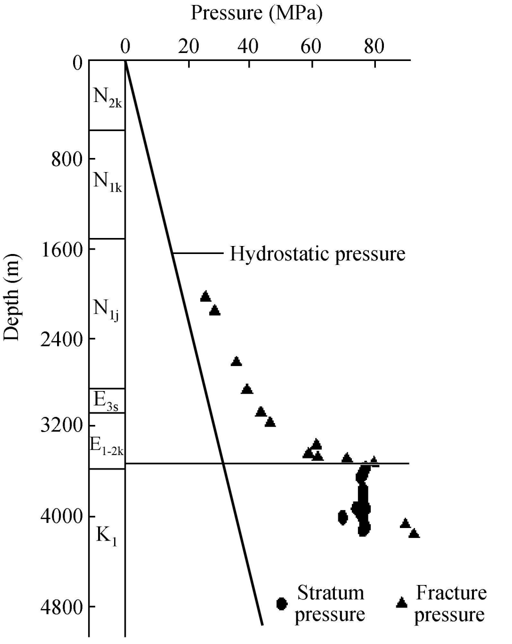

Fig. 2. The distribution of actual formation pressure and fracture pressures of stratum in Kela 2 well.

uplift and compression[16—24]. Among them, tectonic compression is considered to be the principal factor by numerous studies[18—22]. Under the strong tectonic compression in the Neogene and Early Pleistocene, there were intense uplifting and significant erosion along with the further thrusting and folding, which resulted in erosion of over 2000 m in the Neogene Kuqa formation. In theory, if the formation pressure was not changed following uplifting and erosion, the hydrostatic pressure in the stratum over 6000 m of burial depths in the geological period could be turned into present-day abnormal high pressure. If taking the factors of temperature reduction, rock pore volume change and formation water change into consideration, which were accompanied with uplifting, the pressure after uplifting and erosion is not high but static or even tends to be lower[20—22]. Therefore, the influence of tectonic uplifting on abnormal high pressure formation is considered to be less significant.

The undercompaction and hydrocarbon generation are also the possible factors for abnormal high pressure formation[23,24]. However, these mechanisms are not supported by the actual geological data. Firstly, there are no abundant oil and gas in all of the strata or structures with abnormal high pressure. Secondly, the Triassic coal bearing strata and the Jurassic lacustrine mudstone are the main hydrocarbon source rocks, but the known pressure coefficients in these strata are lower than those at the bottom parts of the

Paleogene and the Cretaceous. Thus, there are many doubts for the hydrocarbon generation mechanism. In addition, according to the microscopic observation of cements and diagenesis in the Cretaceous system, there were obvious recrystallization and replacement of cements at the late diagenetic stage. It means that the abnormal high pressure was formed late and undercompaction did not cause the abnormal high pressure[17].

After ruling out the possible mechanisms of undercompaction, hydrocarbon generation and tectonic uplifting, the horizontal tectonic compression is the main factor for formation of abnormal high pressure in the Kuqa foreland thrust belt. The formation of the abnormal high pressure is related with intensity of tectonic compression, such as strain and stress magnitude. Through the statistical analysis of abnormal high pressure, folding intensity and compression ratio from the Mesozoic sequences, the residual pressure is linearly related to the extent of closeness of traps and the compression ratio. Wang concluded that the tectonic compression was the main factor for the increase of pore fluid pressure[23].

According to studies of the relationship between tectonic stress field and abnormal high pressure, it is known that there is a good correlation between them. Firstly, in view of the formation time of abnormal high pressure and evolvement of tectonic stress field, the abnormal high pressure was formed during the intense compression periods. Using the estimation from rock memorial information measured by acoustic emission[25], the mean maximum effective stress values were 28.8 MPa in the Jurassic (208—135 Ma), 41.1 MPa in the Cretaceous (135—65 Ma), 58.5 MPa in the Paleogene (65—23.3 Ma), 63.3 MPa in the Neogene (23.3—2.6 Ma), and 76.4 MPa in the Early Pleistocene (2.6—0.78 Ma). The mean maximum effective stress values of the Cretaceous reservoirs in the Early Pleistocene were 80.9 MPa. They indicate that the compression intensity became stronger and stronger since Jurassic time, and the intensity reached its peak in the Early Pleistocene. The Early Pleistocene was the main period both for abnormal high pressure formation and for rock deformation. Analyses of 4 balanced cross sections indicate that the shortening ratio was 77%—80% during this period.

From abnormal high pressure and regional tectonic position[25], it can be seen that the abnormal high pressure has good corresponding relations with the severe rock deformation and stress concentration zones. Horizontally, the maximum pressure coefficient is mainly distributed at the Tubei-Kelasu-Dongqiu-Dinan tectonic zones where the rocks were severely deformed in strong tectonic stress field. The pressure system at the Northern Tarim uplift is close to normal due to the weak tectonic compression. Vertically, the bottom parts of the Paleogene and the Cretaceous, where the largest pressure coefficient and residual pressure exist, are also the stress concentrative intervals (Fig. 3).

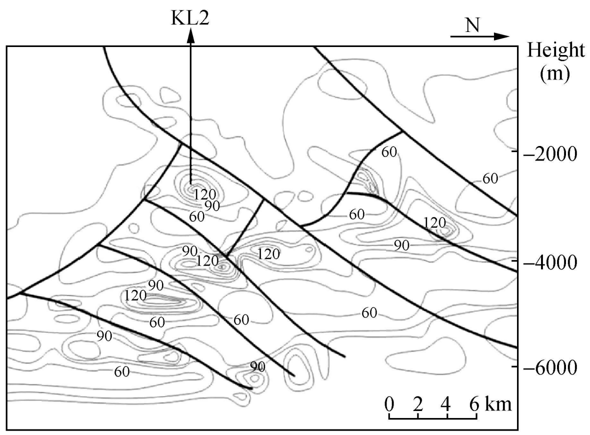

Fig. 3. The isoline of the mean stress in Kela2 structure.

According to the actual measured data of formation pressures and the corresponding tectonic stress in several drilling wells, the formation pressures and residual formation pressure linearly increase with the maximum tectonic principal stress[22]. Although the measured data at drilling wells are limited, this distribution in each drilling well is very clear and completely consistent. This shows the direct influence of horizontal tectonic compression on the abnormal high pressure formation.

4 Physical simulation experimentation

4.1 Experimental conditions

To model the mechanism of abnormal high pressure, physical simulation experimentation has been carried out. The simulation was made on the improved PVT equipment of RUSKA-2730A type which consists of a sample container with high pressure, an axis pressure loading system, a confining pressure loading system and a measure system. The rock samples are the Lower Cretaceous sandstone at the depth of 3825.7 m in Kela 2 well, which have a porosity of 12% and a permeability of $8\times 10^{-3}\ \mu m^2$.

The samples were enclosed by rubber band to approximately simulate the good sealing effect underneath the gypsum-salt or gypsum-mudstone beds of the Paleogene on reservoir. The pressure loaded by the confining pressure loading system was 62.7 MPa to approximately simulate the confining pressure caused by overlying strata. The pressure loaded by the axis pressure loading system was 10.3—67.7 MPa to approximately simulate the influence of tectonic compression stress on the change of pore fluid pressure.

4.2 Result analyses

According to the simulation experimentation data, a curve of bulk pore volume with different axis pressures was obtained at first (Fig. 4). It shows that the bulk pore volume decreased with the increasing axis pressure. The curve could be divided into two sections and the incline ratio of section I was bigger than that of section II. The decreasing rate of bulk pore volume with stress was faster at the beginning than that in the latter state. According to the curve of pore fluid pressure with different axis pressures (Fig. 5), with the axis pressure being added, the pore fluid pressure also increased. The curve could also be divided into two sections and the slope of the latter section was bigger than that of the former one. The increasing rate of pore fluid pressure with stress was faster in section II than that in section I, indicating that when the tectonic stress is added, the stress was mainly borne by rock grains and turned into rock structure stress. The stress increased by 22 MPa and the rock pore fluid pressure by about 9 MPa. That is to say, about 60% of stress was borne by the rock framework. When the tectonic stress was over 25 MPa, the stress was mainly borne by pore fluids and turned into pore fluid pressure. The stress increased by 34 MPa and the pore fluid pressure by about 26 MPa. This means that about 76% of stress was borne by pore fluids.

Because of the limit of experimental conditions, the axis pressure could not exceed 70 MPa. According to studies of tectonic stress field[25], the maximum principal stress in the Neogene could be 100—120 MPa. Under this stress status, the rock fluid pressure could reach 70—85 MPa by the section II trend of Fig. 5. It is approximately equivalent to the actual formation pressure in the studied area. Although the simulation conditions were not completely consistent with the actual geological conditions, especially micro-creep deformation mechanism of rock could not be satisfied in the experimentation fully, this simulation experimentation verified the influence of tectonic compression on pore fluid pressure. The strong horizontal tectonic compression could form abnormal high pressure in the Kuqa foreland thrust belt.

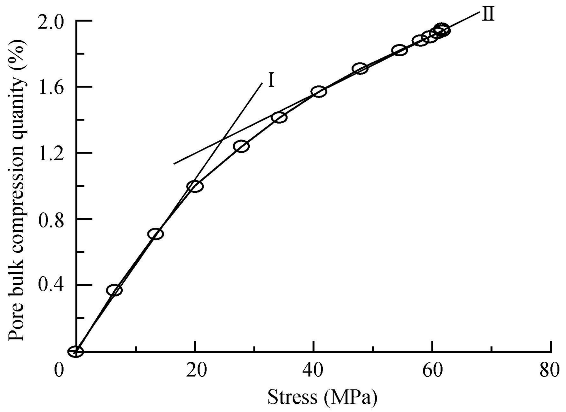

Fig. 4. The change curve of rock pore volume and stress obtained by physical simulation experiment data (Samples are sandstones from the Lower Cretaceous of Kela 2 well at 3825.7 m).

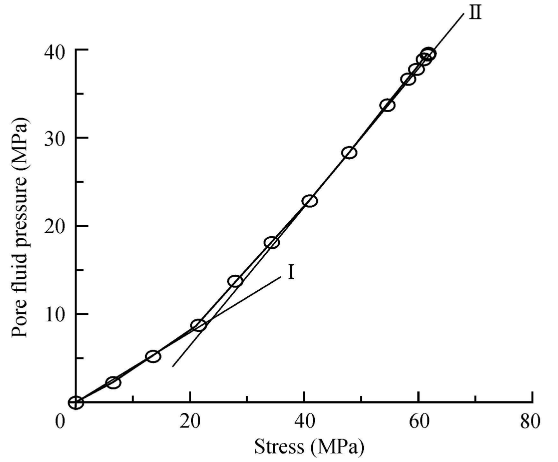

Fig. 5. The change curve of rock pore fluid pressure and stress obtained by physical simulation experiment data (Samples are sandstones from the Lower Cretaceous of Kela 2 well at 3825.7 m).

5 Mechanism of tectonism

According to the geological analyses and physical simulation experiment results, the strong horizontal tectonic compression in the Early Pleistocene is the main mechanism for abnormal high pressure formation in the Kuqa foreland thrust belt.

Based on the stress analysis of rock, the stress can be divided into two parts. One is the mean stress (σ) which causes the bulk deformation of rock ($\sigma = (\sigma_1 + \sigma_2 + \sigma_3)/3$), the other is the shear stress (τ)

which makes the shear strain of rock ($\tau_{max} = (\sigma_1 - \sigma_2)/2$). The former is the main stress resulting in abnormal high pressure[26,27]. Under the closed conditions that there is no fluid discharge, when rock is affected by tectonic stress field, some part of the tectonic stress is borne by rock framework and turns into effective stress, the other part is borne by fluid in pores and turns into pore fluid pressure. The change of rock bulk under the stress is

$$\Delta V = \frac{V(\sigma - P_p)}{K},$$

where ΔV is the change of bulk rock volume, V is the bulk rock volume, σ is the mean stress, P_P is the pore fluid pressure, and K is the elastic module of rock.

Under the stress, the change of bulk fluid volume in pores of rock is

$$\Delta V_V = \frac{nP_P V}{K_V},$$

where ΔV_V is the change of bulk pore fluid volume, n is the porosity, and K_V is the compression coefficient of pore bulk.

After diagenesis, the rock framework volume is compressed little. Thus, the change of rock bulk is approximately equal to that of pore bulk, namely $\Delta V \approx \Delta V_V$. Then, the relationship between pressure of pore fluid and mean stress can be expressed as $P_P \approx B\sigma$, where $B = K_V/(nK + KV)$, and B is the invert coefficient depending on seal degree and saturation. To the completely sealing and saturated terrane, the compressibility of water is much lower than that of rock framework, so $B \approx 1$, that is to say, all of the mean stress can turn into pore fluid pressure. To the dry rock or the fully open system, the compressibility of rock pore is much higher, so $B \approx 0$, that is to say, the mean stress can not turn into pore fluid pressure. To unsaturated wet rock or incompletely sealing system, $B = 0 \sim 1$, that is to say, part of mean stress can turn into pore fluid pressure. The higher saturation or sealing degree of terrane is, the bigger B is. According to the results of physical simulation experimentation and its analogy to the actual geological conditions, the invert coefficient B can be 0.76.

The impacts of tectonic compression on abnormal high pressure have become more and more recognized by numerous studies[28—34]. Under the tectonic compression, the stress transmission and bearing are limited by the actual geological conditions such as seal of cap rock, saturation, tectonic intensity, and so on. The good seal of huge gypsum-salt or gypsum-mudstone beds in the Paleogene is the essential condition for abnormal high pressure formation in the Kuqa foreland trust belt. Under the intense and rapid tectonic compression during the Early Pleistocene time, the pore volume of rocks was reduced. Because of the adequate sealing by gypsum-salt or gypsum-mudstone beds in the Paleogene, the fluids could not be squeezed out, and the majority of the tectonic compression stress was borne by pore fluids. It caused the rapid rise of pore fluid pressure and formed the abnormal high pressure in the Kuqa foreland thrust belt. According to the results of tectonic stress field analysis and its numerical simulation data, the mean stress of the Kela 2 well was over 90 MPa and could cause more than 68 MPa fluid pressures in sandstone reservoirs at the bottom parts of the Paleogene and the Cretaceous. By this way, we can deduce that more than 80% of abnormal high pressure in Kela 2 well was caused by tectonic compression. The contribution of undercompaction and hydrocarbon generation was less than 20%. Therefore, the formation process of abnormal high pressure in Kela 2 well could be divided into two stages. The mechanism of abnormal high pressure in the first stage was mainly by undercompaction, but the maximum pressure coefficients by this way were less than 1.3. The mechanism of abnormal high pressure in the second stage was mainly by tectonism, and the maximum pressure coefficients by this way were more than 2.2 (Fig. 6).

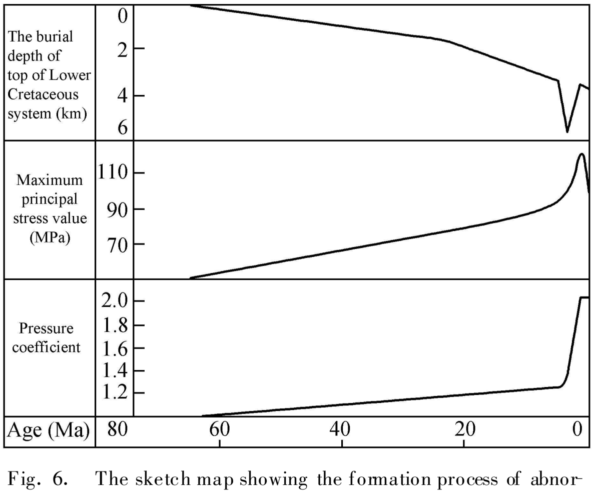

Fig. 6. The sketch map showing the formation process of abnormal high pressure in Kela 2 Gas Field.

6 Influence on oil and gas accumulation

The abnormal high pressure has quite important influences on oil and gas accumulation. Being advantageous or not, it depends on the actual geological conditions. It can not only expedite the conversion of organic materials to hydrocarbons, but also seal the diffusive phase natural gas in concentration, increase the sealing capability of cap rocks and faults, and prevent groundwater, oxygen and bacteria from destroying the entrapped oil and gas. However, when abnormal high pressure in reservoirs was formed before oil and gas charging, or was higher than that in hydrocarbon source rocks, it was very difficult to let oil and gas migrate into reservoirs and accumulate. Furthermore, abnormal high pressure can also make pressure of gas reservoirs be released off and natural gas leak out. These are the disadvantages for oil and gas accumulation[17—19].

In view of distribution of the known oil and gas reservoirs, the large oil and gas reservoirs, specially the large gas reservoirs, are closely related with abnormal high pressure in the Kuqa foreland thrust belt. The formation pressure coefficients at oil and gas reservoirs are significantly larger. Due to the requirement of quite good preserved conditions for abnormal high pressure preservation, the preserved condition was generally excellent where abnormal high pressure existed. Because abundant oil and gas sources exist in the studied area, large oil and gas fields, specially large gas fields, could be formed in the tectonic traps where good preservation conditions are present. For example, the structures of Kela 2, Kela 1 and Kela 3 belong to the same tectonic zone, but the formation pressure is lower than the fracture pressure of the cap rock in Kela 2 structure (Fig.2), i.e. the Kela 2 structure had better preservation conditions. This is the key factor for formation of the large gas field of Kela 2. Kela 1 and Kela 3 structures had unfavorable preservation conditions, so it was difficult for gas to accumulate and to form a large gas field in these two structures.

The main hydrocarbon source rocks are the coal bearing strata and mudstones in the Triassic and Jurassic in the Kaqu foreland trust zones, and the main reservoir rocks are sandstones in the Lower Cretaceous and at the bottom parts of the Paleogene. These sandstones together with the gypsum-salt or gypsum-mudstone beds in the Paleogene constitute one set of reservoir-seal assemblage. The tectonic traps were principally formed at the end of Neogene, and they provided the good trapping conditions for gas and oil accumulation[35]. The peak oil and gas charging occurred mainly at the end of Neogene and Early Pleistocene. Structural traps and abnormal high pressure were finalized in the Early Pleistocene. The abnormal high pressure was mainly caused by unbalanced mechanical compaction prior to the Neogene and was only distributed in the Middle and Lower Jurassic hydrocarbon resource rocks and compartmented by mudstone beds in the Upper Jurassic and Lower Cretaceous. Under the strong horizontal tectonic compression at the end of Neogene, it formed not only structural traps, but also faults connecting hydrocarbon source rocks with reservoirs. Under the driving forces of strong tectonic stress and abnormal high pressure of hydrocarbon resource rocks, the oil and gas generated by the Middle and Lower Jurassic hydrocarbon source rocks migrated vertically and episodically along faults and accumulated to form oil and gas pools in reservoir rocks sealed by the Paleogene thick gypsum-salt or gypsum-mudstone beds. Simultaneously, intense tectonic compression led to uplifting and erosion and destroyed the balance of fluid pressure in the upper strata, which is the other factor for oil and gas migration. Furthermore, when further oil and gas charging occurred again in the Early Pleistocene, the abnormal high pressure of reservoirs at the bottom parts of the Neogene and Cretaceous systems was formed. The abnormal high pressure in reservoirs strengthened sealing capability of the cap rocks and prevented groundwater, oxygen and bacteria from destroying the entrapped oil and gas. Thus, oil and gas could be preserved to form the large fields. When the primary oil and gas reservoirs were destroyed by subsequent faulting, the re-migrating oil and gas could form secondary accumulations in the favorable positions above gypsum-salt or gypsum-mudstone beds in the Neogene.

In sum, the matching of space and time among the abnormal high pressure occurrence, traps formation and gas and oil charging is the key factor to determine the validity of formation of oil and gas reservoirs in abnormal high pressure zones[36]. The structural straps in the studied area developed early. They began to appear since the Paleogene, and were formed on large-scale at the end of the Neogene and finalized in the Early Pleistocene. Gas and oil charging and abnormal high pressure formation occurred almost at the same time, with the charging slightly earlier as indicated by the sequence of events. The good matching of the above-mentioned three factors was the necessary geological condition for forming the large-sized oil and gas fields in the Kuqa foreland thrust belt.

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