A Review of Formation Mechanism Study on Reservoirs with Tilted Oil-water Contacts

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Abstract: The distribution characteristics of the oil-water contact are the basis for the reservoir exploration and development and reserves evaluation. The reservoir with a tilted oil-water contact has a unique formation mechanism, and the understanding of its distribution and formation mechanism will directly affect the evaluations for the reservoir type, well deployment, selection of well pattern and type, determination of test section, and reserves evaluation. Based on the analysis of reservoir characteristics, petrophysical properties and geological structure in 40 reservoirs worldwide with tilted oil-water contacts, the progress of the research on the formation mechanisms of titled oil-water contacts is summarized in terms of the hydrodynamic conditions, reservoir heterogeneity, neotectonic movement and oil-gas exploitation. According to the formation mechanism of tilted oil-water contacts and the needs of exploration research, different aspects of research methods are summarized and classified, such as the calculation of equipotential surfaces for oil and water in the formation, analysis of formation pressure and analysis of reservoir physical properties and so on. Based upon statistical analysis, it is suggested that the degree of the inclination of the oil-water contact be divided based on the dip of oil-water contact (Dip_{TOWC}). The tilted oil-water contact is divided into three categories: large dip ($Dip_{TOWC} \geq 55$ m/km), medium dip (4 m/km $\leq Dip_{TOWC} < 55$ m/km), and small dip ($Dip_{TOWC} < 4$ m/km). The classification and evaluation method can be combined with structure amplitude and reservoir property. The formation mechanism of domestic and international reservoirs with tilted oil-water contacts are summarized in this paper, which have important significance in guiding the exploration and development of the oilfield with tilted oil-water contacts, reserves evaluation, and well deployment.

Key words: tilted oil-water contact, hydrodynamic force, reservoir heterogeneity, capillary pressure, neotectonic movement

1 Introduction

The position of the oil-water contact (OWC) in a field or prospect is one of the most important factors in estimating reserves and the determination of this contact is widely studied for petroleum accumulation, exploration and exploitation, and reserves evaluation. The classic theory for oil-water distribution is that they are controlled by the density differences, with oil always being at the top of the reservoir and water lies at the bottom or edge of the reservoir. The oil-water contact under hydrostatic pressure is ideally horizontal with a uniform depth and is in parallel with the tectonic stress line (He Gengsheng, 1994; Zhang Houfu, 1999); but in the actual underground reservoirs, the oil-water distribution pattern is more complicated than the classic distribution theory. The oil-water contact in the same reservoir presents the phenomenon of height difference; for instance, the Sarvak reservoir in South Azadegan Oilfield, Iran, has a sharply up tilted and elevated oil-water contact with a maximum height difference of nearly 300 m (Du Yang et al., 2015). This tilted phenomenon of oil-water contact is found worldwide (Fig. 1, Table 1), such as two classic examples in the USA, the Wheat oilfield (Adams, 1936; Nie Changmou, 2005) and the Frannie oilfield (Hubbert, 1953). Many reservoirs with a tilted oil-water contact can be found in the transition zone from the Iranian Zagros foremountain basin to the Arabian platform, such as the Yada oilfield (Xu Dejun et al., 2010), the Ula, Gyda and Tambar oilfields (O'Connor et al., 2011), and the Majoon oilfield and the Missan oilfield in Iraq et al.. In China, there are

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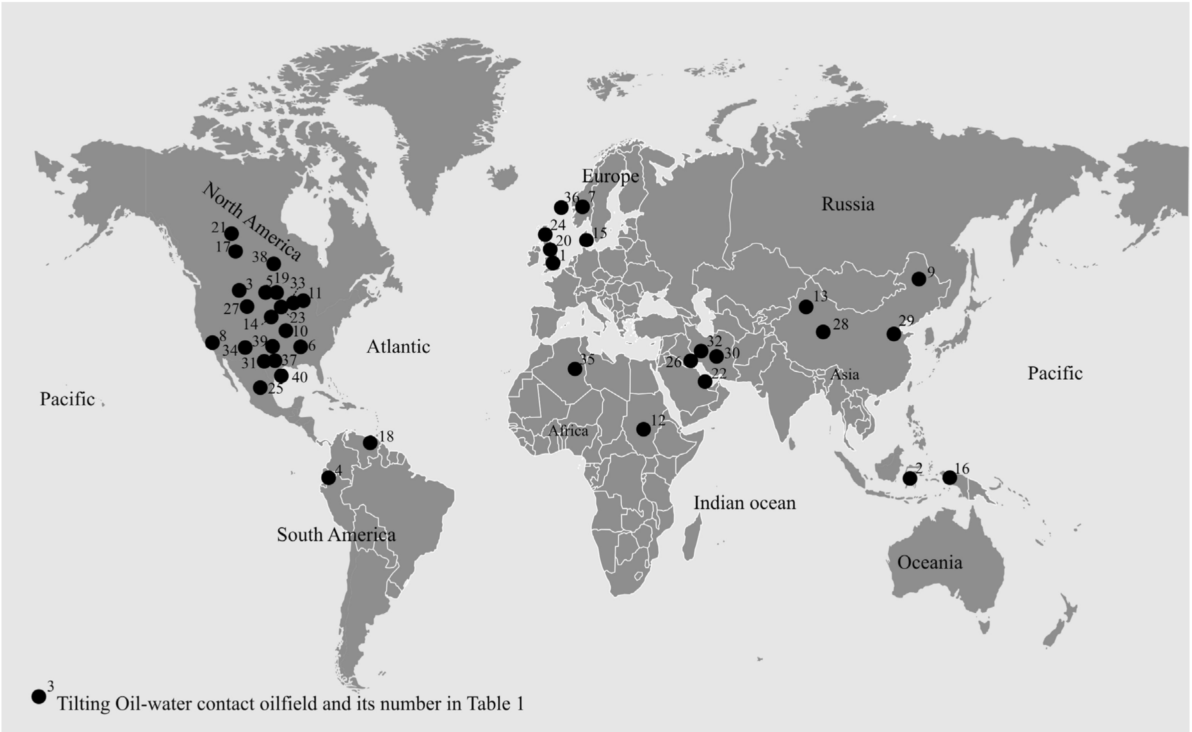

Fig. 1. Global examples of tilted oil-water contact reservoirs and their distribution.

also several reservoirs with a tilted oil-water contact, such as the Shanbei oilfield in Yumen (Huo Yonglu, 1989; Wang Zhixin and Zhang Yiwei, 2000), the Changyuan oilfield in Daqing, and the 'Donghe Sandstones' reservoirs in Tarim Basin, Sinkiang, western of China.

Many geologists have plenty of research on the characteristics of development, distribution, and formation mechanisms of a tilted oil-water contact, domestic and overseas, such as: In 1917, Beal gave the first detailed discussion of tilted fluid contacts in a field and their possible origin. Lee and Payne (1944) discussed the causes of tilted fluid contacts in the McLouth field, Kansas, USA. In the terms of fluid contacts tilted by hydrodynamic, Russell (1951) established a relationship among the tilt direction, angle, and head changes in the water-progress; in 1953, Hubbert published "Entrapment of petroleum under hydrodynamic conditions", in which he proposed the concept of underground fluid potential, established the corresponding calculation formula, determined the direction of oil, water, and gas movements based on the distribution of fluid potential, and interpreted the oil-gas migration and aggregation. Hubbert's theory was compelling in revealing the numerous evidences for the tilted oil-water contact under hydrodynamic conditions, and is applied for mechanism studies on reservoirs with tilted oil-water contacts in the North Sea oilfield, Norway (Dennis et al., 1998), Fula oilfield, Norway (Nie Changmou, 2005), etc. However, the influences of various factors on the tilt of the oil-water contact are numerous, such as hydrodynamics, reservoir heterogeneity and neotectonic movement, etc., and each oilfield has its unique geological conditions, reservoir lithology, characteristics of structural trap, hydrodynamic conditions, etc., creating vast differences in the characteristics and formation mechanism of tilted oil-water contacts. Currently, the cause for tilted oil-water contacts in some areas also lack a clear explanation, and many are controversial, such as the high angle tilted contact in the Middle East oilfields (Du Yang et al., 2015). In recent years, with the deep development of oilfields, the tilt of the oil-water contact caused by water injection has occurred (Dahlberg, 1995; Nie Changmou, 2005), such as the tilted oil-water contact in the Cairo oilfield is up to 28 m/km, formed only after 12 years of exploitation, while the inclination angle of the oil-water contact in this oilfield continues to develop (Nie Changmou, 2005).

Understand the characteristics and formation mechanism of tilted oil-water contacts within reservoirs is important for well deployment, selection of well pattern and types, determination of test section, reservoir reserves evaluation and rolling development, etc. For example, in the Valhall oilfield, located in central North Sea of the northwestern European continent, two wells were respectively drilled in the flank of the northwest and southeast anticlines in 1973. The oil-water contact was considered horizontal and the initial oil bearing area was delineated. In 1994, another well was drilled in the saddle of the two anticlines with a daily output of 2,000 bbl. After re-evaluation, it was realized that this reservoir has a

Table 1 Statistics of typical tilted oil-water contact reservoirs

No.	Oilfield	Country /District	Dip_{TOWC} (°)	Dip_{TOWC} (gradient)	Tilt elevation difference (Δh)	Tilted main causes	Literature
1	Arbroath	UK	0.5	8 m/km		Hydrodynamic gradient	Dennis et al., 1998
2	Arun	Indonesia	0.7	13 m/km		Hydrodynamic gradient	Dennis et al., 1998
3	Bell Creek	America, Montana	1.3	23 m/km		Hydrodynamic gradient	Dennis et al., 1998
4	Bermajo	Equador	1.4	24 m/km		Hydrodynamic gradient	Dennis et al., 1998
5	Billings nose & Elkhom Ranch field	America, N.DAK.	0.3	5 m/km		Hydrodynamic gradient	DeMis, 1995
6	Cairo	America, Arkansas	1.7	28 m/km		Oil exploration of neighboring oilfield	Dahlberg, 1995
7	Cod	Norway	1.8	32 m/km		Hydrodynamic gradient	Dennis et al., 1998
8	Coles Levee	America, California	0.5	8.5 m/km		Hydrodynamic gradient	Dahlberg, 1995
9	Daqing Oilfield	China	0.2	2.7 m/km	64 m	Capillary Pressure Sway	Li Chuanliang, 2006
10	Eagle Mesa	America, Kansas	0.6	11 m/km		Hydrodynamic gradient	Vincelette and Chittum,1981
11	Frannie	America, Wyoming	6.5	113.7 m/km		Hydrodynamic gradient	Dahlberg, 1995
12	FulaOilfield	Sudan	0.7	12 m/km	60 m	Hydrodynamic gradient	Wang Wangquan et al., 2007
13	Hadson Oilfield, Tarim Basin	China	0.3–0.6	4.0–10.0 m/km	120 m	Unstable reservoir- neotectonic movement	Jiang Tongwen et al., 2008; Sun Longde et al., 2008
14	Hugoton	America, Kansas	0.6	11 m/km		Hydrodynamic gradient	Dennis et al., 1998
15	Kraka and Dan	Denmark	0.8	14 m/km		Hydrodynamic gradient	Dennis et al., 1998
16	Lagifu-Hedinia	P.N. Guine	5.7	100 m/km		Hydrodynamic gradient	Dennis et al., 1998
17	Leduc Woodbend	Canada, Alberta	0.6	11 m/km	160 m	Hydrodynamic gradient	Dahlberg, 1995
18	Maracaibo	Venezuela	11.3	200 m/km		Hydrodynamic gradient	Dennis et al., 1998
19	Mission Canyon	America,N.Dakota	0.3	5 m/km		Hydrodynamic gradient	Dennis et al., 1998
20	Montrose	UK	0.3	5.5 m/km		Hydrodynamic gradient	Dennis et al., 1998
21	Norman Wells	Canada	3.1	55 m/km		Hydrodynamic gradient	Dennis et al., 1998
22	North Dome	Qatar	0.2	3.5 m/km		Hydrodynamic gradient	Dennis et al., 1998
23	Northwest Lake Creek	America, Wyoming	2.7	47 m/km		Hydrodynamic gradient	Dahlberg, 1995
24	Pierce	UK	5.1	89 m/km		Hydrodynamic gradient	Dennis et al., 1998
25	Poza Rica	Mexico	1.5	27 m/km		Hydrodynamic gradient	Dennis et al., 1998
26	Rumaila Oilfield	Iraq	0.06	1 m/km	10.5 m	Hydrodynamic gradient	Zhou Jiasheng et al., 2016
27	Sage Creek, Lake Creek etc.	America, Wyoming	8.5	150 m/km		Hydrodynamic gradient	Dennis et al., 1998
28	Shanbei Oilfield	China	0.19–0.24	3.3–4.2 m/km	38–135 m	Reservoir heterogeneity	WangZhixin and Zhang Yiwei, 2000
29	Shengli Oilfield	China			25 m	Under the influence of the heterogeneity of reservoirs, structural trend, crude oil property etc.	Yan Ke and Zhao Hongbing, 2013
30	Siri	Iran	0.7	12 m/km		Hydrodynamic gradient	Dennis et al., 1998
31	Slaughter	America, Texas	0.1	2.5 m/km		Hydrodynamic gradient	Dennis et al., 1998
32	South AzadeganOilfield	Iran	0.3	4.3 m/km	260 m	Unstable reservoir- neotectonic movement	Du Yang et al., 2015
33	South Glenrock	America, Wyoming	5.4	95 m/km		Hydrodynamic gradient	Dahlberg, 1995
34	South KermitDevonian field	America, New Mexico	1.7	28 m/km	72 m	Hydrodynamic gradient	McNeal, 1965
35	Tin Fouyé-Tabankort Devonian oil field	Algerian	1.2	20 m/km	200 m	Hydrodynamic gradient	Chiarelli, 1978
36	Valhall/Hod field	Central North Sea	0.9	15 m/km		Hydrodynamic gradient	Dennis et al., 1998
37	Wasson	America, Texas	0.4	6.5 m/km		Hydrodynamic gradient	Dennis et al., 1998
38	Weyburn	Canada, SK	0.6	10 m/km		Hydrodynamic gradient	Dennis et al., 1998
39	Wheat	America, West Texas	0.6	10 m/km	30 m	Hydrodynamic gradient	Dahlberg, 1995
40	Wilcox	America, Gulf of Mexico	0.2	3 m/km		Hydrodynamic gradient	Dennis et al., 1998

tilted oil-water contact with an inclination angle of 0.9° (15 m/km). With a tilted oil-water contact, the oil-bearing area of this reservoir was increased by nearly 50% (Dennis et al., 1998), and thus a reservoir development plan was re-established. Therefore, to better analyze the formation mechanism of reservoirs with a tilted oil-water contact and guide exploration and development, the geological conditions, development and distribution characteristics, influence factors and formation mechanism of domestic and foreign classic reservoirs with tilted oil-water contacts was analyzed and classified in this paper, which has important significance to promote the mechanism study and guide the development of the reservoirs with tilted oil-water contact.

2 Definition of Reservoirs with Tilted Oil-water Contact

After oil and gas were generated from the source rock and discharged through the conductive layer, they replaced the water in the non-wetting phase. If gravity differentiation of the oil and water is effective, the formed reservoir always has an oil-water contact, or an oil-water transition zone. The classic oil-water distribution theory, as mentioned above, deems that the oil-water contact under the conditions of hydrostatic pressure is horizontal, the horizontal projection line of which is in parallel with the tectonic line, and it has a uniform depth (He Gengsheng, 1994; Zhang Houfu, 1999). But in the actual underground reservoirs, the oil-water distribution pattern is more complicated than the classic distribution theory. The oil-water contact in the same reservoir presents the phenomenon of height differences, and not necessarily a horizontal contact, but a tilted oil-water contact (abbreviated as TOWC, Hubbert, 1953; Dahlberg, 1995) and the familiar term “dipping oil-water contacts” (Nie Changmou et al., 2004; Li Chuanliang, 2009).

The tilted oil-water contact is a relatively vague concept and there is no unified definition for it at present. According to Hubbert (1953), hydrocarbon migration usually occurs in a saturated water environment; If the water is at rest, the equipotential surface of oil and gas will be horizontal and the driving force will be vertical, and this trap is one of the common ones of the anticlinal theory; If the water body is in a motion of non-vertical movement, then the equipotential surface of oil and gas will be titled downward in the direction of water flow, and the inclination angle of oil will be greater than the inclination angle of gas. With more discovery of and continued exploration research of reservoirs with tilted oil-water contacts, the geological characteristics of these reservoirs show diversification, such as structural development characteristics, slope or angle of inclination of formation, formation lithology, physical characteristics, and fluid characteristics where the reservoir located, which can lead to the tilt of the oil-water contact. The geologists’ understandings and research for a TOWC formation mechanism are not limited on the hydrodynamic conditions.

In the study of tilted oil-water contact by researchers, the inclination of the oil-water contact is described and expressed as a gradient: "m/km", "ft/mile", or dip angle of "°". For example, in the Billings nose field, the tilt of the oil-water contacts is 25 ft/mile (5.6 m/km) to the east-northeast (DeMis, 1995), or 0.3° in dip angle. The use of m/km as a unit for analyzing and describing the inclination level (Dip_{TOWC}) of a tilted oil-water contact is recommended in this paper. At present, the oil field with the largest tilted oil-water contact is in the Maracaibo Basin of Venezuela (Hubbert, 1967), and the Dip_{TOWC} is 200 m/km (Dennis, et al., 1998); in the Tensleep formation of the Sage Creek oilfield in the United States, the Dip_{TOWC} is 150 m/km (Todd, 1963); as currently reported, the reservoir with a tilted oil-water contact having the smallest dip angle is located in the Slaughter oilfield, Texas, USA, the Dip_{TOWC} of which is 2.5 m/km (Hubbert, 1967), and the North Dome oilfield in Qatar has a Dip_{TOWC} of 3.5 m/km (Hubbert, 1967). Although the angles of TOWC are usually small-mostly less than 2°, the impact across an oil field of several kilometers diameter can be highly significant (Dennis et al., 1998).

3 Characteristics of Typical Reservoirs with Tilted Oil-Water Contacts

The reservoirs with tilted oil-water contacts are quite common in the United States, the Middle East, and African regions, and they are also developed in the Daqing oilfield, Shengli Oilfield, Shanbei Oilfield of Yumen, and other places in China (Fig. 1, Table 1). Different reservoirs with tilted oil-water contacts, due to the difference of the geological conditions and formation lithology, have great differences on the inclination characteristics and formation mechanisms. Typical reservoirs with tilted oil-water contacts were selected in this paper, such as the Eagle Mesa oilfield, the Frannie oilfield of Wyoming in USA, the Valhall/Hod oilfield of the middle North Sea in Western Europe, the South Azadegan oilfield in Iran, the Changyuan oilfield of Daqing in China and the Cairo oilfield, and the characteristics of these tilted oil-water contact are discussed.

3.1 Characteristic of tilted oil-water contact reservoir in Eagle Mesa Field

The Eagle Mesa field, discovered in 1975, located on the southeast flank of the San Juan Basin. The field produces from the Jurassic, Entrada Sandstone which is a windblown deposit described as a fine to coarse grained sandstone, clean and well sorted (Campbell, 1978). Based on detailed seismic interpretation and well location control, an isolated terrain is found in the Entrada site of the Eagle Mesa field, which extends about 2.4 km from north to south and 1.6 km from east to west. According to the thickness of the Entrada sand layer exposed in the production wells, the maximum vertical relief of the Entrada high is 32 m (Fig. 2a). A tilted oil-water contact, tilting about 11 m/km to the south, has moved toward the southern of the structural trap. The southerly tilt of the oil-water contact has caused well 13-1 to be 3 m lower structurally than well 12-1 (Fig. 2b), and it need 9 m to have the same amount of net pay as the discovery well 12-1 (Vincelette and Chittum, 1981).

3.2 Tilted oil-water contact in Frannie oilfield of USA

The Frannie oilfield in BigHorn Basin, Wyoming, USA, is a typical reservoir with a tilted oil-water contact (Hubbert, 1953). The anticline structure in the Frannie oilfield presents the obvious asymmetric characteristics (Fig. 3). The oil-water contact at the eastern edge of the reservoir is nearly identical with the structure contour of 1400 ft (426.7 m), while the height above sea level of the oil-water contact at the western edge of the reservoir is down to 600 ft (182.9 m), indicated that the inclination to the southwest is about 113.7 m/km. Hubbert (1953) deemed that the moving direction of formation water in Tensleep was identical with the dip direction of the oilfield (Fig. 4), and the hydrodynamic condition is the main cause for the inclination of the reservoir, and the extent of the inclination is very close to the prediction, which was made only using hydrodynamic characteristics (Nie Changmou et al., 2004).

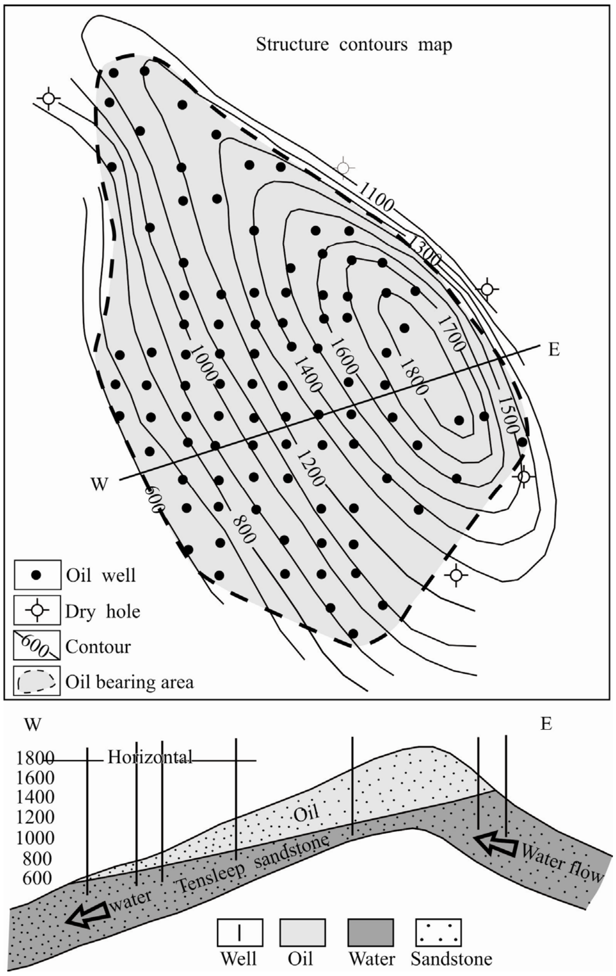

Fig. 3. Structure contour map and cross section showing the Frannie oilfield in Wyoming (modified from Hubbert, 1953; Dahlberg, 1995).

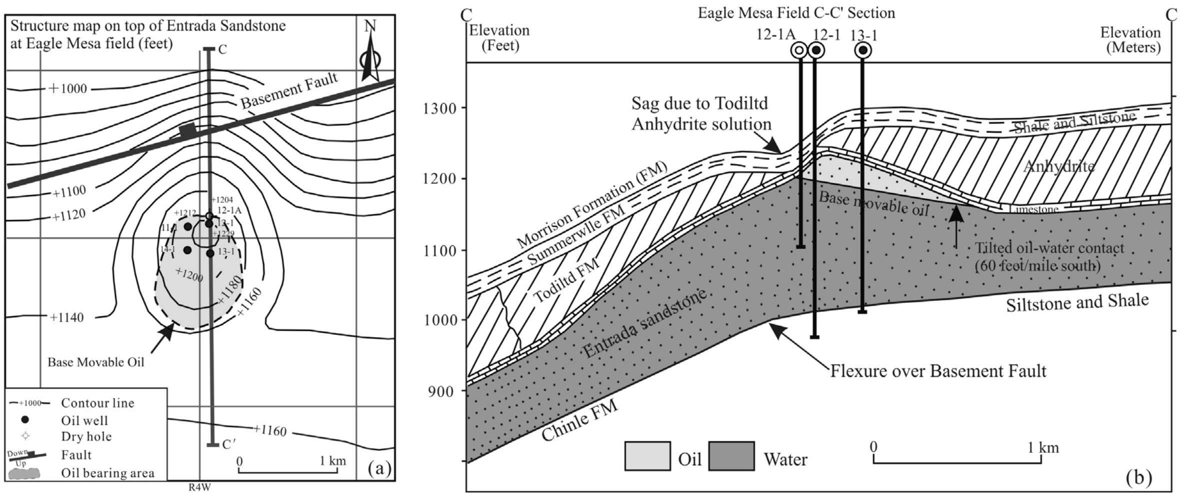

Fig. 2. Structure and cross section map on top of the Entrada Sandstone in the Eagle Mesa oilfield (after Vincelette and Chittum, 1981).

(a), Structure map on top of the Entrada Sandstone; (b), Structural cross section CC' through Eagle Mesa oilfield. Location of cross section is shown on (a).

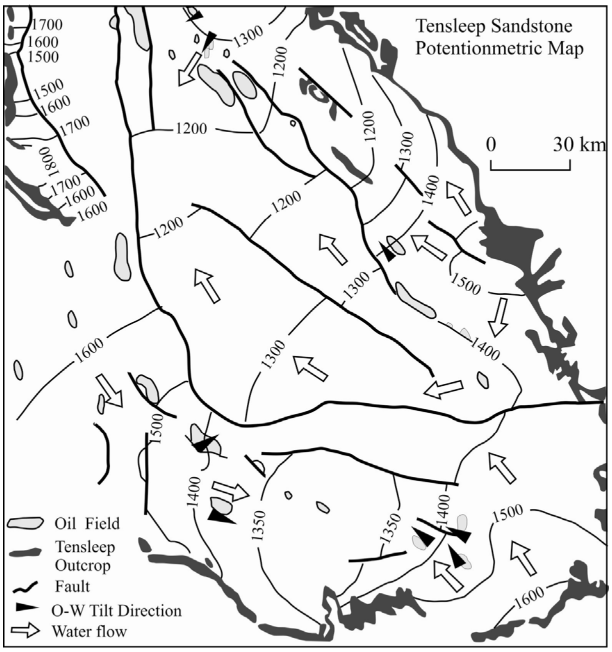

Fig. 4. Potentiometric map for the Tensleep Sandstone in the Big Horn Basin in Wyoming, demonstrating the correlation between potentiometric gradients and related titled oil-water contacts in associated pools (after Dahlberg, 1995).

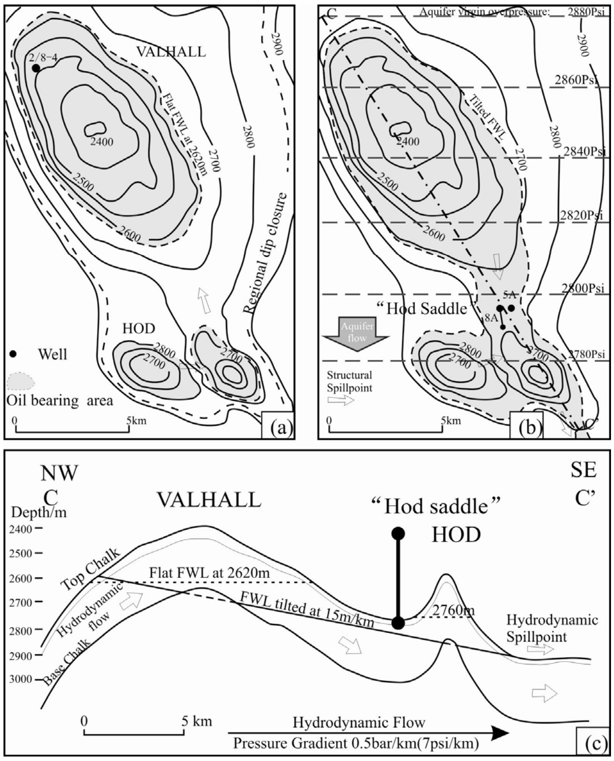

Fig. 5. Structural depth and field outline map of the Valhall oilfield (after Dennis et al., 1998).

3.3 Tilted oil-water contacts in the North Sea

The Valhall/Hod Field is located in the center of Graben, the south of the North Sea, Norway. Exploration wells were drilled in 1975 at 2 / 8-6 and began production in 1982 (Barkved et al., 2003). The Valhall Field tectonic trends NW-SE, and covers an area of more than of 60,000 acres.

The Valhall/Hod field has three tectonic highs, Valhall, West Hod and East Hod, initially were considered as three separate pools. However, in 1994, oil was found in the relatively low saddle in the proven hydrocarbon accumulation (Fig. 5). The area was considered a stratigraphic trap before drilling (Campbell and Gravdal, 1995), but according to drilling, the formation was found to be in pressure contact with the southern Hod field, and a different theory was needed to explain the trap. Thus, a hydrodynamic model was used to explain the hydrocarbon accumulation (Fig. 5), with the OWC tending to the south, similar to the trends in the Danish sector described by Megson (1992), Thomasen and Jacobsen (1994). The implications of this model for Valhall/Hod's additional stockpile of crude oil reserves are significant, although the recoverability of this oil also depend on identifying the high-quality fractured chalk reservoir above the TOWC (Dennis et al., 1998).

Dennis et al. (1998) describes the initial pressure differences in the Cretaceous Chalk Formation and Paleocene sandstones in the central North Sea, where both strata are continuous, permeable, and non-intermittent, so there may be relative hydrodynamic surroundings. In addition, the TOWCs were found in a number of fields in both strata, and the slope is in line with the expected pressure trend (Fig. 6).

3.4 Characteristics of the tilted oil-water contact in the Sarvak reservoir, South Azadegan oilfield, Iran

The South Azadegan oilfield (hereafter referred to as the SA oilfield) in Iran, located on the border between southwestern Iran and Iraq, lies at the west side of oil-gas accumulation area in Dezful Gulf, and is among the world's largest reserves of oilfields (Liu Hui et al., 2013; Du Yang et al., 2015). The SA oilfield is a large anticline along with the north-south long axis as a whole, about 60 km long by 20 km wide. It is divided into two relative structural highs in the south and north, with the southern one is higher than the northern, and the west wing is steep while the east wing is relatively gradual. A northwest-southeast striking fault developed locally with a small fault throw. The main oil layer of the oilfield is the Sarvak layer in Cretaceous strata (short for S layer or S reservoir). The early exploration shows that the oil-water contact of the reservoir along with the south-north main axis of the structure has the characteristics of tilting and upward lift (Du Yang et al., 2015). The reservoir profiles show that the S reservoir is uplifted from the lower S-8 layer to the

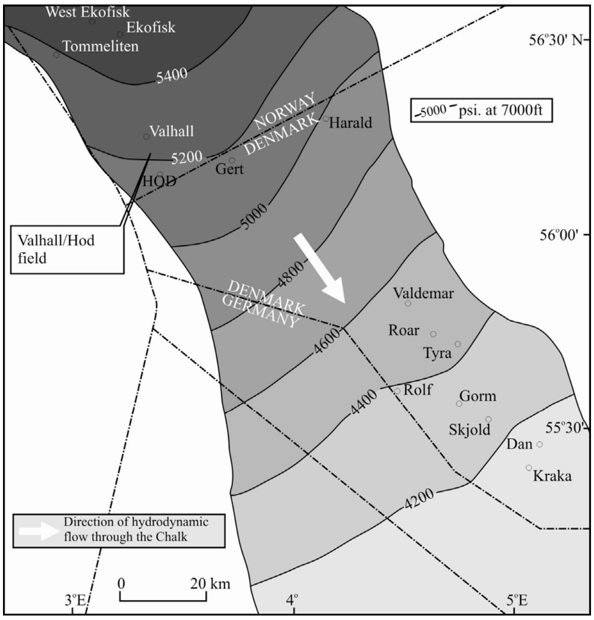

Fig. 6. Distribution of chalk overpressure in the Danish Central Graben (after Megson, 1992).

upper S-4 layer, from north to south, with a maximum height difference between two single wells of nearly 300 m (Fig. 7). Du Yang et al. (2015) considered that the ultra-late adjustment of the trap caused by the Jager Ross tectonic movement was the main reason for the tilt of the oil-water contact in this area. The ancient anticline trap reservoir was formed in the Sarvak layer of the SA Oilfield during the late Miocene, with the form of higher in the north and lower in the south and contrary to the current structure pattern. The Neogene Jager Ross orogeny caused the second change of the trap forms. The southern ancient tectonic lows are greatly raised in the mode of Seesaw and the new secondary traps formed, which evolved into the present structure pattern of two structural highs with the highs in the north and a low in south. The change of trap conditions broke the dynamic balance of the former ancient reservoir, leading to the secondary hydrocarbon migration adjusted to the south secondary high trap for the hydrocarbon fluids. The oil-water contact of this reservoir is still in the adjustment process. Currently, the drastically tilted oil-water contact shows the features of the ancient reservoir with an incomplete adjustment.

3.5 Characteristics of the tilted oil-water contact in the Changyuan oilfield, Daqing, China

The Changyuan oilfield in Daqing is located in a large anticline structure belt in the central depression of Songliao basin, which consists of seven anticline structures named Lamadian, Saertu, Xingshugang, Taipingtun, Putaohua, Gaotaizi, and Aobaota. The structures are connected through the saddles (Zhai Guangming, 1993), with the structure contour line of −1025 m as the unified trap line in Changyuan. The main oil layers are the Saertu, Putaohua and Gaotaizi formations with the characteristics of continuous and multilayer. The height of oil-water contact in each layer is basically the same, at about −1050 m. But the oil-water contact in the north-south direction of the placanticline structure shows as high in the south and low in the north, while the depth of the oil-water contact at the wings in different structure positions is also changed, for example, the west wing in the north part of the Lamadian oilfield is 4 m lower than the east wing; the west wing is 20 m higher than the east wing in both the southern part of the Xingshugang oilfield and northern part of the Taipingtun oilfield; the west wing is 35 m higher than the east wing in the Putaohua oilfield;

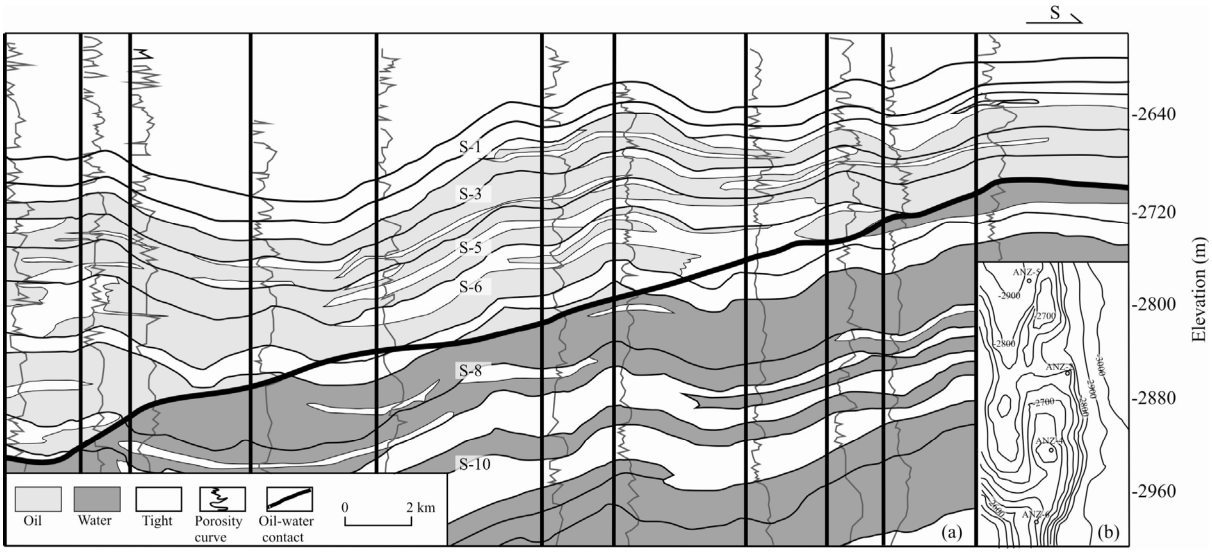

Fig. 7. The north-south reservoir section (a) and structural map of Sarvak top surface (b) of the Sarvak reservoir, South Azadegan oilfield, Iran (after Du Yang et al., 2015).

and the west wing is 20 m lower than the east wing in Aobaota oilfield (Lin Jingye et al., 2007).

Because of the oil-water contact with the characteristics of high in the south and low in the north in Changyuan oilfield of Daqing, and the great change between the west and east wings, there have been many explanations for the tilted oil-water contact, such as the heterogeneity of sedimentary reservoir, different structural positions, the direction of hydrocarbon migration, crustal stress and hydrodynamic condition factors (Xu Yunxin, 1994). Lin Jingye et al. (2007) analyzed the causes for the inclination of oil-water contact at two wings in the Changyuan oilfield of Daqing using the equilibrium principle of buoyancy and capillary force, and it is considered that the oil-water contact changed because of the reservoir physical property differences between the two sides of the structure, especially the changes of the sandstone pore radius, after the oil moved into the structural traps of Changyuan oilfield in Daqing. It is thought that the oil, gas and water in a pure structural reservoir will follow the gravitational differentiation principle. The better the reservoir physical properties in the transition zone of oil and water, the lower the oil-water contact will be. When the reservoir physical properties in the transition zone of oil and water change little, the oil-water contact is approximately similar to a plane.

3.6 Tilted oil-water contact in Cairo oilfield

The Cairo oilfield in Arkansas, USA, is a typical reservoir with a tilted oil-water contact formed during the exploitation process, which occupies a domed structure (Fig. 8), where the formation water is initially hydrostatic. Goebel (1950) suggested that the pressure gradient in the Smackover limestone in the Cairo field was historically about 0.015 lbs/sq. in./ft (49 Psi/km) due to artificially produced reasons, and that the tilt of the oil-water contact in this reservoir slopes at an angle of about 150 ft/mi (28 m/km). Assuming a difference in the specific gravity between the oil and water is 0.2, the tilt of an oil-water contact in equilibrium with a pressure gradient of 49 Psi/km was about 915 ft/mi (173 m/km) by the equation (1) put forward by Russell (1956). Since the maximum pressure gradient of the reservoir was about 360 ft/mi (68 m/km), it is clear that the oil accumulation in the Cairo anticline would be swept away before the equilibrium point was attained (Russell, 1956). It is noted that the dip level of the oil-water contact was formed in a relatively short period of 12 years (Nie Changmou et al., 2004).

$$T = 12200G / (\rho_w - \rho_o) \quad (1)$$

Where T is Tilt of fluid contact in ft/mi; G is Pressure gradient in lbs/sq. in./ft; $\rho_{w/o}$ is Density of water/oil in grams/cu. cm.

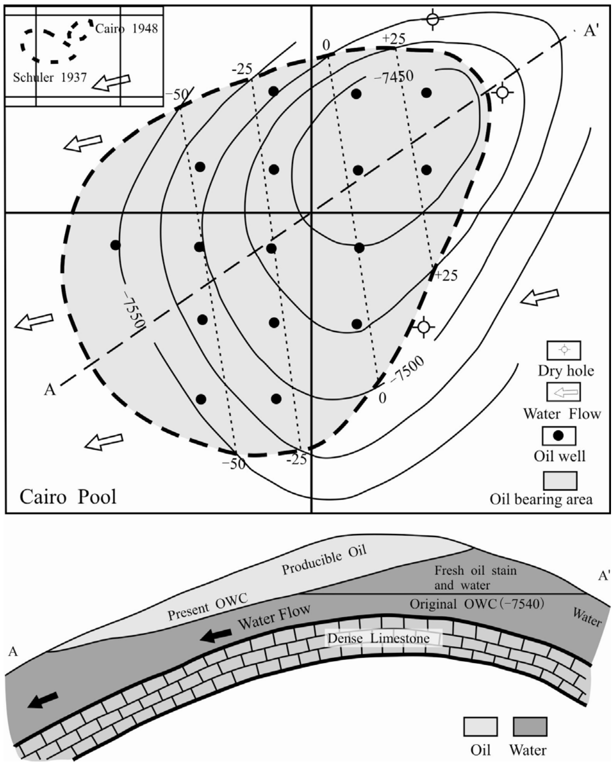

Fig. 8. Map and cross section showing the Cairo Pool, Arkansas oilfield (modified from Goebel, 1950).

4 Analysis of Tilted Oil-Water Contact Formation Mechanisms

The effect of hydrodynamic conditions and their effect on tilted oil-water contacts was first proposed by Hubbert (1953). With an increase in oil and gas exploration and technologies world-wide, more reservoirs with tilted oil-water contacts have been discovered, and there has been an increase in research and understand on the mechanisms of formation. Based on research and analysis on different geological characteristics of several reservoirs with tilted oil-water contact, there are several proposed controlling factors of these contacts, including structural characteristics, lithology, physical properties, tectonic stress, oil and water filling, etc. (Zhang Houfu, 1999; Lin Jingye et al., 2007). Even some scholars believe that there is no hydrodynamic reservoir. Li Chuanliang (2006, 2009) deems that it requires that an outcrop exists at one end of the reservoir close to the ground and is used as the entrance for the groundwater supply, namely an open reservoir (reservoir surrounded by natural outcrops and communication with natural water). It also requires that an outcrop exists at another end of the reservoir close to the ground and is used as the exit of the groundwater outflow. However, if there were both underflow and oil-gas accumulation, the long-term water washing and oxidation had long destroyed the accumulated oil and gas, and it is impossible to have formed current oil and gas reservoirs.

Currently, there are four main interpretations for formation of a tilted oil-water contact: (1) affected by the hydrodynamic system: the oil-water contact is uplifted along the direction of water supply in the reservoir (Hubbert, 1953; Han Tao et al., 2007). (2) Affected by the capillary pressure: the area with inferior reservoir physical properties in the same oil reservoir has a higher displacement pressure, resulting in a higher oil-water contact, while the area with better reservoir physical properties has a lower displacement pressure and a lower oil-water contact, resulting in the distribution difference of oil-water contact (Li Chuanliang, 2006; Shi Dianhai, 2006; Lin Jingye et al., 2007; Qu Fang et al., 2008). (3) Affected by the neotectonics movement: the high spot of the reservoir structure is shifted. Because the adjustment of oil-water relationship lags behind the structural changes, it leads to the variable distribution of oil-water contact (Jiang Tongwen et al. 2008). (4) Affected by the late exploitation of oilfield: results in the variable distribution of the oil-water contact (Russell, 1956; Nie Changmou, 2005). In addition, some researchers have mentioned that factors as the earth rotation (Stenger et al., 2001), earthquake (Stenger et al., 2001), variable reservoir fluid densities (Stenger et al., 2001), change in the earth gravity (Nie Changmou, 2005) and thermal convection (Stenger, 1999, 2001) would affect the inclination of oil-water contact.

4.1 Tilt of oil-water contact caused by hydrodynamics

The seepage of underground fluid is a process of mechanical movement, and the fluid always spontaneously flows from the high energy region to the low energy region. Stable oil and gas usually accumulate in the middle of the anticlines, but they can also develop in structural platforms, nasal structures, monoclinic strata, and other unclosed structures lacking complete lithological boundaries. Hubbert (1953) argue that the energy of oil and gas is related to their location and environment, and when the energy is associated with unit mass, it may be considered as potential energy at any point in the fluid, then the oil and gas from the underground are dispersed from a high energy point towards the low energy point, and eventually stops in the constitute traps. In almost all cases, the traps for oil accumulation are located in the low potential energy region, which are closed by higher potential energy and impermeable barriers. Hubbert (1953) defined the total mechanical energy of the underground fluid per unit mass with respect to the base level as the fluid potential, and considered that the fluid potential at each point under the hydrostatic conditions is identical. He deem that if the water move in a non-vertical direction, the oil and gas equipotential would be inclined downward in the flow direction, and the angles of inclination of the oil will be greater than those for gas. The propulsive forces for oil and for gas will be non-parallel and the two fluids will migrate in a diverging directions to a trap which will not coincide (Fig. 9). Under hydrodynamic conditions, the accumulation of oil or gas will always exhibit a tilted oil- or gas-water interface (Fig. 10) with an inclination angle as shown by Eq. 2 (Hubbert, 1953),

$$\tan\theta = \frac{dz}{dx} = \frac{\rho_\omega}{\rho_\omega - \rho_o}\frac{dh}{dx} \qquad (2)$$

where dz/dx is the slope of the interface; ρ_w, the density of the water and ρ_o that of the oil (or gas); dh/dx is the component of slope of the potentiometric surface of the water in the horizontal direction x.

The characteristics of tilted oil-water contacts under hydrodynamic conditions have been studied in oilfields

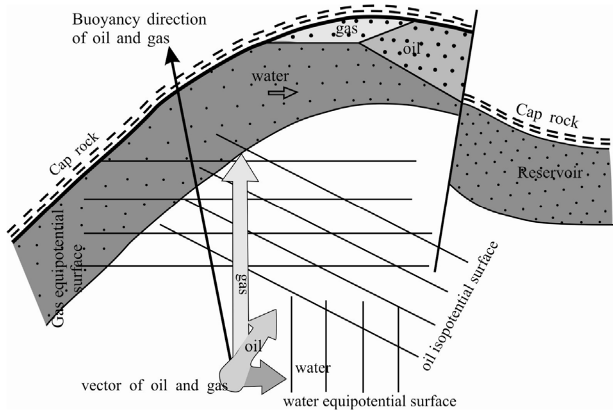

Fig. 9. Oil and gas transport and equipotential surface distribution under dynamic water condition (after Dahlberg, 1995).

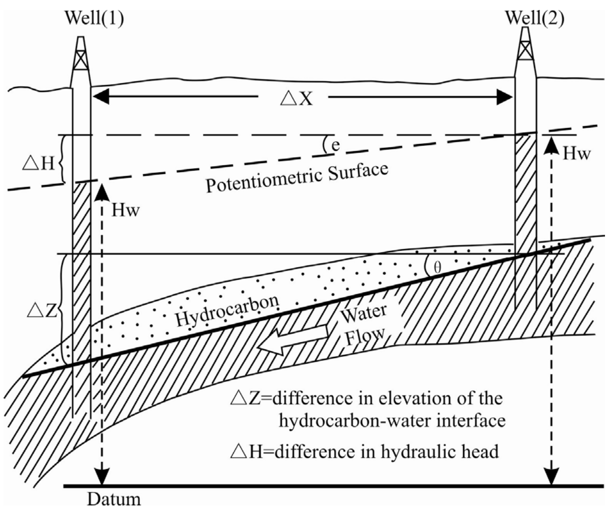

Fig. 10. Relation between tilted oil-water contact in hydrodynamic trap and slope of potentiometric surface (after Hubbert, 1953).

across multiple basins worldwide (Dennis et al., 1998, Fig. 1). Most of these examples are inward flow or basin inflows, driven by atmospheric water in adjacent highlands. Few examples are from overpressures and outflow basins. Notable examples occur in oilfields of the Persian Gulf and Zagros fold belts (Wells, 1988; Pelissier et al., 1980; Hubbert, 1967), the Illizi Basin in Algeria (Chiarelli, 1978), the Williston Basin in North Dakota, North America (Berg et al., 1994), and the Powder River Basin, Wyoming (Momper and Williams, 1984), the Maracaibo Basin in Venezuela (Hubbert, 1967), and the Sakhalin field, Russia (Ostistyy et al., 1967).

The reservoir profile in Northwest Lake-bay oilfield, Wyoming, USA, clearly shows significant effect on the oil-water contact by the regional water flowing towards the northwest (Fig. 11). This indicates that the water flow in Tensleep sand layer passed most of the oil to the lower part of the nose-like structure for miles, thus a large inclination of oil-water contact occurred in the direction of water flow, which is consistent with the hypothesis. The characteristics of the overlying strata of the Phosphoria reservoir are similar to the ones in the Tensleep sand layer, and the conditions of water flow in these two layers are identical. It shows that the hydrodynamic condition in the region is the main cause for the inclination of oil-water contact in the Phosphoria reservoir and Tensleep reservoir. A high inclination of the oil-water contact occurs in the South Glenrock reservoir, Wyoming, USA. Its potentiometric surface is significantly reduced to northeast, which reflects the regional water flow towards northeast. As predicted by hydrodynamics, the slope of the oil-water contact observed in Dokata sandstone is about 500 ft/mile (95 m/km).

In this paper, hydrodynamic activity is defined as the lateral movement of groundwater through an aquifer. In a hydrostatic environment, there is no horizontal component of groundwater movement, and in hydrodynamic conditions, the internal pressure changes resulting in lateral flow of water (Bachu and Hitchon 1996; Bachu, 1997). Where these pressure variations coincide with trapped oil, the depth of the free water level will also change, resulting in a TOWC (Frederick, 1989; Dahlberg, 1995). The principle of the migration is shown Fig. 12.

4.2 Tilting of an oil-water contact caused by reservoir heterogeneity

The influences on an oil-water contact resulting from a change in lithology and physical properties is extremely important. Sedimentary differentiation causes a regular change of fragmentary material granularity, further leading to a change in lithology and physical properties, and thus results in a change in the oil-water contact. For

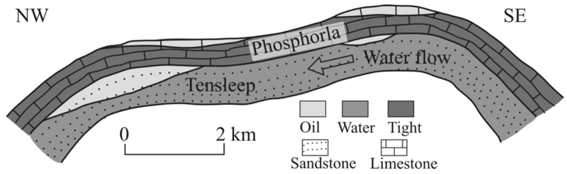

Fig. 11. The reservoir section of the Northwest Lake-bay oilfield in Wyoming, USA (after Dahlberg, 1995).

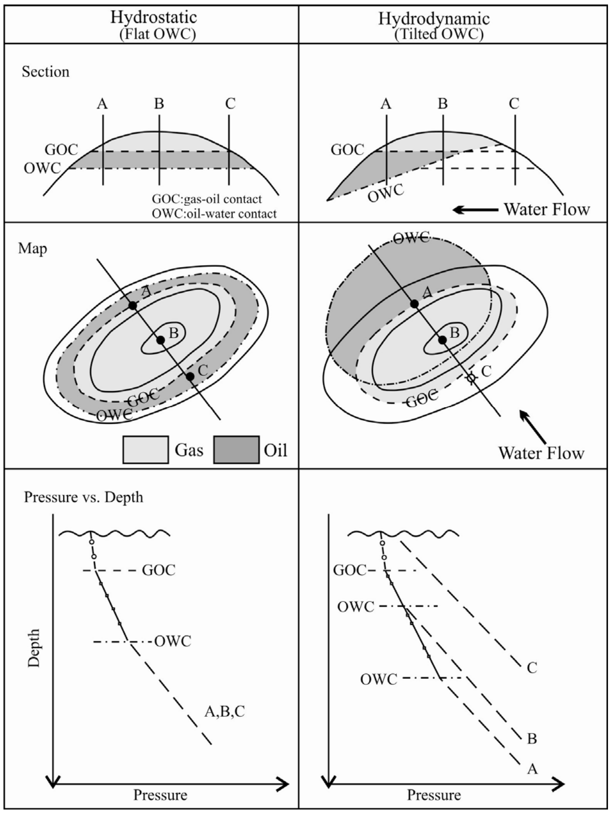

Fig. 12. The effect of hydrodynamic behavior on oil and gas accumulations (after Wells, 1987; Dennis et al., 1998).

example, if the sandstone reservoir was deposited in an aqueous environment and hydrophilic, the migration and accumulation of oil and gas are generally considered to be hydrophilic (Pittman, 1992). The pore structure is the main geological condition that determines fluid flow and hydrocarbon migration and accumulation in the micro pore throat. The influence of capillary pressure, interlayer on the titled oil-water contact, and the mechanism of oil-water contact caused by discharge are mainly discussed in the following section.

4.2.1 Tilt of oil-water contact caused by capillary pressure

The capillary pressure difference caused by reservoir heterogeneity is possibly the main reason for a tilted oil-water contact. The oil accumulation rock is mostly fragments of material deposited in a flowing water environment. The water flow has a sorting effect on the sediment it carries, and after diagenesis, the differences on physical properties can be observed along the paleocurrent direction. The rock grains in the water source direction are coarser with a higher permeability, but the displacement pressure of the capillary pressure curve is low. The rock texture in the water flow direction is just the opposite. Its grains are fine grained and the permeability is low, while its displacement pressure is high, and when the oil is accumulated in the rock, the oil distribution is controlled by the capillary pressure (Dolson, 2016). The area with poor rock physical properties would have high displacement pressure, and deep oil-water contact; and the area with good rock physical properties would have low displacement pressure, and shallow oil-water contact (Shi Dianhai, 2006). The physical properties of the reservoir rocks are very different, so the capillary pressure curves vary dramatically. The physical properties of the reservoir rocks change regularly along the paleocurrent direction (the physical properties of rocks along the direction of water flow become poor). Therefore, it leads to the uplift of oil-water contact along the paleocurrent direction. Based on theoretical analysis, when oil is accumulated in the reservoir rocks, the oil distribution is controlled by the capillary pressure. The area with poor rock physical properties would have a high displacement pressure, and shallow oil-water contact; and the area with good rock physical properties would have low displacement pressure, and a deep oil-water contact. This kind of theory is based on stratigraphic deposition without any large tectonic movement (Li Chuangliang, 2006).

Li Chuanliang (1993) provided the equation for calculating the depth of oil-water contact:

$$D_{OWC} = (P_{0O} - P_{0W} - P_d)/\Delta\rho_{WO}\, g \quad (3)$$

In the formula: D_{owc} stands for the depth of oil-water contact (m), P_d for the displacement pressure (MPa), P_{0O} and p_{0W} are the residual pressure (MPa) of oil and water phase respectively, ρ_o and ρ_W are the density (g/cm^3) of underground oil and water respectively.

It can be seen from formula (3) that a higher the displacement pressure causes a shallower depth of the oil-water contact, i.e., a higher elevation of the oil-water contact. The height difference of the oil-water contact at different positions in the reservoir can be calculated by the following equation:

$$\Delta h = \Delta P_d / \Delta\rho_{WO}\, g \quad (4)$$

In the formula, ΔP_d stands for the displacement pressure difference at different points in the rock.

If the differential displacement pressure of the capillary pressure curve is 0.1 MPa, then the height difference of oil-water contact, as calculated by the equation (4), is 25.5 m; if the displacement pressure is 0.5 MPa, then the height difference of oil-water contact is 127.5 m, therefore, the capillary pressure has an important influence on the tilt level of oil-water contact (Li Chuanliang, 2006).

4.2.2 Study on tilt mechanism of oil-water contact caused by displacement pressure

The pore structure in sandstone reservoirs is the main geological condition to determine fluid flow and hydrocarbon migration and accumulation within the micro pore throat. One of the main purposes for the studying reservoir pore structure through the mercury injection method (mercury injection capillary pressure-MICP) is to determine the pressure required for the liquid in the non-wetting phase to pass through the largest connected pores and form a connected path (Hu Xuetao et al., 2017). For instance, the concepts of squeeze pressure, displacement pressure (also called replacement pressure) and threshold pressure are used for the evaluation of oil and gas traps (Lin Jingye, 2004; Hu Xuetao et al., 2017). It is known as the displacement pressure, threshold pressure, inlet pressure, or the entry pressure, etc. The direct physical meaning is that the front curved surfaces of the non-wetting phase (oil) in the reservoir pass through the pore throat, and continuously enters into the reservoir, and displace the wetting phase (water) (Hu Xuetao et al., 2017). This pressure also describes the continuous motion of wetting phase fluids in the pores. On the mercury-injection curve, the displacement pressure should be the horizontal position of the initial inflection point (or the mutation point) (Wang Yuncheng, 1993). For easy application, the corresponding pressure at 10% mercury saturation is generally defined as the displacement pressure (Schowaiter, 1979; Wang Yuncheng, 1993), which is determined according to the actual situation. The displacement pressure of each oil layer in the shallow formations of the Songliao Basin, for example, is at 3%–5% mercury saturation. The displacement pressure also has a close relationship with the reservoir porosity and permeability. In general, a reservoir with high porosity and good permeability will have a low displacement pressure value.

Lin Jingye et al. (2007) proposed the use of a buoyancy and capillary force balance principle to identify the distribution regularity of the oil-water contact caused by micro pore throat structure differences. For example, by calculation, the height difference of oil-water contact in the Lamadian reservoir of the Changyuan oilfield, Daqing, is 60 m, which is close to the actual measured difference value of 64 m. Due to changes of reservoir physical properties; the oil-water contact is generally not a horizontal plane, but a undulating toroidal. It was concluded that, when the two wings of the oil-water contact are in equilibrium, the buoyancy resulting from ΔH equals the difference of capillary force caused by r_1

and r_2, i.e., the capillary – float equation. It was applied to the study on the difference of the oil-water contact at two wings of both the Lamadian reservoir and Taipingtun oil formation of changyuan oilfield, Daqing. The dimensionless equation is as follows:

$$\left(\rho_\omega - \rho_o\right)\Delta H \times g = p_{c1} - p_{c2} = \left(\tfrac{1}{r_1} - \tfrac{1}{r_2}\right)2\delta\cos\theta \quad (5)$$

The formula (5) can be rearranged as follows:

$$\left(\rho_\omega - \rho_o\right)\Delta H \times g = \frac{2\delta(r_2 - r_1)}{r_1 r_2}\cos\theta \quad (6)$$

$$\Delta H = \frac{2\delta\cos\theta(r_2 - r_1)}{r_1 r_2\left(\rho_\omega - \rho_o\right)g} \quad (7)$$

Where: ρ_w and ρ_o are the underground water density and oil density (g/cm^3) respectively; δ is the tension force of oil-water contact (mN/m); θ is the wetting angle (°).

The displacement pressure is closely related to the porosity and permeability of a reservoir. In general, when the reservoir has high porosity and permeability, the displacement pressure value is low. Pittman (1992) took the pore radius (r_d, μm) corresponding to the displacement pressure as the dependent variable, and obtained the following equation per multiple regressions of air permeability (K, 10^{-3}μm^2) and porosity (φ) measurements:

$$\text{Lg } r_d = 0.137 + 0.4791\text{lg}K - 0.1331\text{lg}\varphi \quad (R=0.9) \quad (8)$$

By Eq.(7), it is known that the δ, $cos\theta$, g and（ρ_w- ρ_o）are the constants greater than zero. Therefore, when ΔH =0, r_2=r_1; when ΔH >0, r_2>r_1. At the oil-water contact, the smallest pore radius that oil can enter in a sandstone reservoir is the pore radius (r_d) corresponding to the displacement pressure.

By Eq.(8), r_d has a positive correlation with the sandstone reservoir physical properties, i.e., the permeability and porosity. Therefore, the better the reservoir physical properties in the oil-water transition zone, the shallower the oil-water contact will be. When the reservoir physical properties in the oil-water transition zone change little, the oil-water contact is approximately a horizontal plane.

4.2.3 The effect of interlayers on tilted oil-water contact

The interlayers are referred to be an impervious or low-permeability bed within a single sand body. In a sandstone or mudstone profile, an interbed is generally composed of mudstone, sandy mudstone, argillaceous siltstone, or calcareous sandstone, and the thickness is a few to dozens of centimeters. And the insulating layers refer to layers with a large thickness and no permeability (relative to the sand bodies) between the two sand bodies. The number of interlayers (insulating layers) and their permeability also has important influence on the tilt of the oil-water contact (Han Rubing et al., 2014). Zhang Ji et al. (2003) deem that interlayers between the terrigenous clastic reservoirs is one of the main causes that the formation of reservoir fluid heterogeneity, and control the movement of oil and water at different levels. Jiang Yumeng et al. (2015) analyzed interlayer study on D sand layer of the H oilfield B reservoir, also thought that the interlayers on the bottom of the water layer has a certain sealing effect, which result in the uniform of oil-water contact.

Lu Hongjiang and Jiang Xue (2009), Muggeridge and Mahmode (2012), and Zhao Hong et al. (2014) deem that the interlayer plays an important role in the vertical infiltration of reservoir fluids by studying the development status and the interbedded analysis of reservoirs with inclined oil-water contact (Fig. 13). It may be one of the main reasons for the formation mechanism of such complex oil and water relationships. Horizontal well HD4-45H without water-free oil production (Fig. 13), HD4-26H and HD4-64H with a period of water-free oil production, HD4-32H and HD4-65H with a prolonged period of water-free oil production. Combined with core observations, it was found that many interlayers developed in the reservoirs of horizontal well HD4-64H, which may result in poor fluid connectivity. It is concluded that the interlayer has a certain barrier effect on the fluid flow, and the velocity of the fluid flow will be obviously reduced (Zhao Hong et al, 2014).

Liu Zhuo et al. (2013) simulated the characteristics of the water in the fourth reservoir in the Zubeir Group, Rumaila oilfield, Iraq, by use of the reservoir simulation method, and deemed that the development of the interlayers and vertical barrier belt have a great impact on the adjustment time, which obviously prolongs the equilibrium time. The number and conduction rate of the barrier belts have considerably large influence on the adjustment time. With different barrier belts, the adjustment time of the reservoir is 900–6,000 years.

4.3 The influence of neotectonics movement on tilted oil-water contact

The neotectonics movement has great influence on the tilted oil-water contacts, and it is mainly due to the structural height tectonic changing caused by the neotectonics movement (Engelder et al., 2009; Veen et al., 2009; Brogi et al., 2010), and the adjustment of the oil-water contact lag behind the structural change, resulting in inconsistent oil-water contact depth (Jiang Tongwen et al., 2008), e.g., the Hudson Oilfield, Tarim Basin (Jiang Tongwen et al., 2008), the oil-water contact of the structural reservoir in Block 438, Shuanghe Oilfield, Nanxiang Basin (Xu Honglong et al., 2015), Iranian Sarvak oil reservoir (Du Yang et al., 2016), and so on.

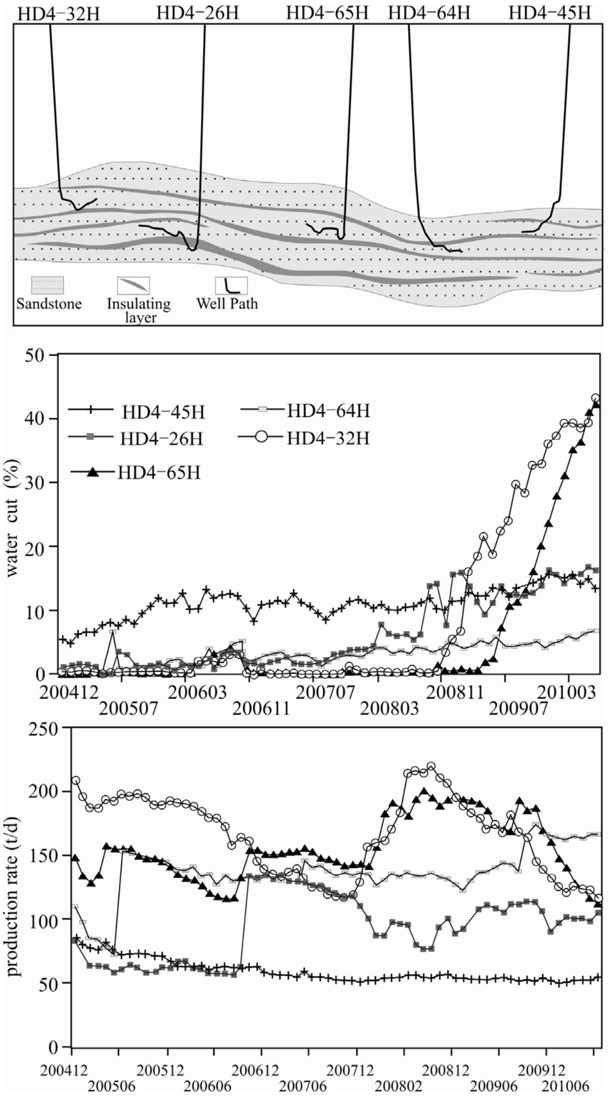

Fig. 13. Reservoir model profile and the curve of water-cut and oil production (after Zhao Hong et al., 2014).

4.3.1 The influences of the neotectonics on TOWC Donghe sandstone reservoir

The neotectonics movement mainly refers to the vertical movement of the Himalayan movement (especially from the Pliocene to the third act of the Pleistocene Himalayan Movement) in China. There is still great disagreement on the time limit of the neotectonics movement, e.g., Late Eocene (Yi Mingchu, 1993), Late Oligocene (30 Ma) (Liu Yixuan et al., 1994; Dong Hanwen et al., 2016), Early Miocene or Early Neogene (24 Ma) (Xu Yijian et al., 1965), the middle Miocene (15–10 Ma) (Xu Jie et al., 2012), the Pliocene (5.3 Ma) (Gong Zaisheng et al., 2001, 2004; Zhu Weilin et al., 2009), the late Pliocene-Quaternary (3.4 Ma) (Ding Guoyu and Lu Yanchou, 1983; Li Xianggen, 2003), the Middle Pleistocene (0.73 Ma) (Wan Tianfeng, 2001). Although there is great difference in the definition of neotectonics movement time, it is generally accepted that it is associated with the Himalayan movement, and the tectonic movement has a strong control over the sedimentary basins, especially the late oil and gas accumulation are constrained by the nature of the Himalayan movement, duration, mode and intensity (Jia Chengzao et al., 2006).

The neotectonics movement has great influence on the late oil and gas accumulation of the oil and gas basins in China, especially in the unconventional reservoirs such as the titled oil-water contacts reservoir, tight oil and shale gas (Li Xinzi et al., 2013; Pan Yanan et al., 2015; Zou Caineng et al., 2016; Ran Bo et al., 2016; Fan Jianming et al., 2016). In China, the oil and gas basins affected by the neotectonics movement are more developed, such as the Bohai low-uplift area, Bohai Bay continental faulted depression area, Daqing Changyuan belt, western foreland thrust belt, western structural tectonic uplift area, Tarim Craton Paleoproterozoic, East Sichuan fault fold belt, biogas area of Qaidam basin (Jia Chengzao et al., 2006), including the Hudson oil field, Sa er tu, Pu tao hua and Gao tai zi oilfields in Daqing, and other oilfields with large titled oil-water contact.

Currently, the drastically tilted oil-water contact shows the features of the ancient reservoir with an incomplete adjustment, with traits of a type of steady reservoir. The physical simulation experiment for the adjustment process of the Donghe sandstone reservoir based on the research of neotectonic movement in the Hudson area was performed by Jiang Tongwen et al. (2008). It was concluded that the tectonic change caused by the neotectonic movement is the main cause for the substantial tilt of the oil-water contact in the Donghe sandstone reservoirs. The current Donghe sandstone reservoirs in the Hudson area formed from oil-gas migration of the paleoreservoir resulted from the neotectonic movement during the late Himalaya. Because the neotectonic movement has not yet ended, the current Donghe sandstone reservoirs may also be in the adjustment phase, and the oil-gas accumulation has obvious instability.

4.3.2 The influences of the neotectonics on TOWC Sarvak oilfield

According to the analysis on the causes of capillary pressure difference resulting from hydrodynamic drive or reservoir heterogeneity performed by Du Yang et al. (2015), it showed that both hydrodynamic drive and reservoir heterogeneity are not the causes for the tilt of oil-water contact in the Cretaceous Sarvak reservoir, SA Oilfield, Iran. The paleo-structural trap in different periods of the oilfield was restored by using a seismic layer flattening technique, and it appears that the ultra-late adjustment of the trap resulting from the Jager Ross' tectonic movement is the main cause for the tilt of the oil-water contact in this zone. This ancient anticline trap reservoir was formed in the Sarvak layer of the SA oilfield during the late Miocene, with the form of higher in the north and lower in the south, contrary to the current structure pattern. The Neogene Jager Ross orogeny caused the second change of the trap forms. The southern ancient tectonic lows were greatly raised in the mode of wrap and the new secondary traps formed, which evolved into the present structure pattern of two structural highs and high in north and low in south. The change of paleo reservoir trap conditions broke the dynamic balance of the former ancient reservoir, leading to the secondary hydrocarbon migration adjusted to the south secondary high trap for the hydrocarbon fluids (Fig. 14). The oil-water contact of this reservoir is still in the adjustment process.

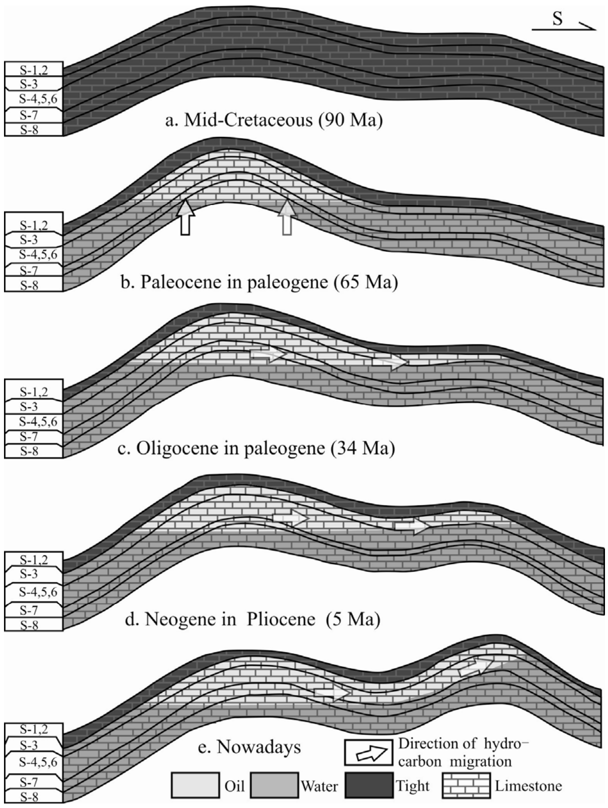

Fig. 14. Reservoir evolution of the Sarvak Formation in SA oilfield, Iran (after Du Yang et al., 2015).

4.3.3 The influences of the neotectonics on TOWC Puerto Colon oilfield

Another typical reservoir is an unstable tilted oil-water contact in the Caballos formation, Putumayo Basin, Columbia. The important feature is the oil-water contact of the reservoir and the fact that it gradually decreases in the NW-SE direction with a maximum OWC height difference of 53 m (Gómez and Castagna, 2005). The tilt of the oil-water contact in the Puerto Colon oilfield can be explained by the tilt to the east of the already existing Puerto Colon structure under the geological tectonic extrusion. Movement occurred in the late Tertiary Miocene Epoch. The seismic information shows that the upper Orteguaza formation in the Neozoic System was deformed, indicating that new deformation occurred of the original geological structure caused by the active geological structure from the Tertiary Miocene Epoch to the recent time. All reservoirs that existed during the Miocene Epoch, such as the Puerto Colon trap, were affected by this deformation. The inclined plane of the OWC is in the NW-SE direction and consistent with the direction of adjustment for formation compression. The steep OWC in the southern oilfield is related to the anticline dip. It can be seen that, although the active formation water maintained the reservoir pressure, the large tilt of the OWC in this oilfield has nothing to do with the underground hydrodynamics, and is mainly caused by the neotectonic movement (Estrada and Mantilla, 2000).

4.3.4 The neotectonics and unsteady reservoir

Oil and gas reservoirs are typically studied as a continuous and unified system in the time domain from generation to exhaustion. This process is the unity of opposites for the periodicity and continuity. Jiang Tongwen et al. (2008), Sun Longde et al. (2009), Yang Haijun et al. (2012), and Du Yang et al. (2015, 2016) carried out related studies, and they concluded that the neotectonics movement is the main reason for the oil-water contact, such as the great titled Donghe sandstone oil reservoir, and they deem that: (1) Under the action of neotectonics movement, these reservoirs are in the process of oil reservoir adjustment, and the oil and gas accumulation is obviously unstable, i.e. unsteady reservoir. Sun Longde et al. (2009) defined the unsteady reservoirs as Oil and gas enrichment with dynamic non-equilibrium state, during the oil-gas injection or adjustment processes, where a unified oil-water contact hasn't formed yet, and the main features are that the oil-water contact is tilted or the oil-gas-water relationship is inverted in the interconnected reservoir. (2) The oil and gas accumulation process can be divided into three stages: pre-reservoir, reservoir and post-reservoir (Jiang Tongwen et al., 2008). In accordance with the current division of the unstable reservoir, the paleo-reservoirs with a considerably large-scale adjustment of oil and gas caused by the changing of trap shapes are called post-reservoirs (Yang Haijun et al., 2012). The post-reservoir stage is an extremely important accumulation stage, which causes a great transformation from the first two stages in the dynamic mechanism of oil and gas movement, and the form and characteristics of oil and gas accumulation. In the post-reservoir stage, the main motive power of oil-gas migration is the buoyancy and tectonic stress, with fluid movement mainly in the form of volume flow. When the spill point of a trap is changed due to the tectonic movement (such as tectonic tilting), the oil and gas under the effect of buoyancy has continuous lateral movement. When the cap rock of the trap is destroyed by faults, the oil and gas moves vertically along the fault. When the reservoir is uplifted to the up-dip direction of the upper reservoirs and eroded, the oil and gas has lateral movement and vertical leakage. Because the post-reservoir stage is a relatively long process, the oil and gas is typically complete lost during this stage and residual oil is left in the reservoir. But in the process of losing the oil and gas, multiple aggregations may also occur, presenting a dynamic aggregation of oil and gas in this stage. A dynamic aggregated post-reservoir generally has a tilted oil-gas contact, large difference in fluid nature, etc., as described above. This definition emphasizes the dynamic concept in oil-gas aggregation and is very different than a traditional reservoir.

4.4 Effect of oil and gas exploration on tilted oil-water contact

The secondary oil recovery in sandstone oilfields mainly relies on water flooding. Long-term water flooding could easily cause a change in the original characteristics of the oil-water contact. The distribution of the remaining oil under the comprehensive effects of injection and production wells is redistributed for the potential power. The closed area with low potential power is the potential area for oil-gas accumulation (Guo Dezhi et al., 2003; Li Yang, 2003). In Cairo oilfield, the original oil-water contact of the reservoir was close to the horizontal plane, and after the exploitation of another reservoir nearby within the same formation in the west, creating the potential difference and artificial hydrodynamic gradient, which in turn caused the movement of water within the region. This created the 150 ft/mile slope within the Cairo reservoir (Russell, 1956). The tilt of the oil-water contact in the Cairo reservoir was formed in a relatively short period of 12 years (Nie Changmou, 2005).

The influence of oil-gas infilling on the tilt of the oil-water contact is still controversial. After analyzing the formation and distribution of the fluids for patterns and the closed low potential area in the old oilfield within the Shengli oilfields, Shandong, China, there was early production with no water from the wells drilled in the lower section of the low positioned area with an extremely high water content (Pu Yuguo et al., 2000). The change of water pressure in the fourth pay reservoir, Rumaila oilfield was caused by the dynamic water. Based on numerical simulations, Liu Zhuo et al. (2013) considered the influencing factors of the reservoir scale, fluid properties, heterogeneity, dynamic strength of water, etc., and the results indicate that the adjustment time of the reservoir resulting from the dynamic water is estimated to be thousands of years, which is far more than the time scale for reservoir development and less than the time scale for reservoir formation. Further combined with the development history of the peripheral oilfield, it is inferred that the dynamic water in the fourth pay reservoir is caused by the exploitation of the South Raudhatain oilfield (Liu Zhuo et al., 2013).

5 Discussions and Research Prospects

Although detailed theory research and practical analysis on the formation mechanisms of oil-water contacts were conducted by the geologists in early twentieth century, disagreement on their origin still exist.

5.1 Classification of reservoirs with tilted oil-water contact

As mentioned above, the concept of tilted oil-water contact is still a relatively vague concept yet, because the oil-bearing area was caused by the tilted oil-water contact, the lower limit value for the study of tilted oil-water contact on late development and deployment should have an important significance. The tilted oil-water contact with large Dip_{TOWC} usually has a relatively small oil-bearing area and scale, such as Sage Creek Oilfield with the Dip_{TOWC} of 150 m/km, which reservoir is mainly developed down the southwest or basin ward limb of the structure, and the estimated ultimate recovery was estimated at approximately 1.5 million bbls (Elmer, 1959). However, the oilfield with a relatively low Dip_{TOWC} usually has a relatively large oil-bearing area, because it is in a relative static hydrostatic state, and more crude oil retained because it would have shorter movement distance. If there was a flat saddle between the two structure-trap oil reservoirs, the two reservoirs will become one reservoir with tilted oil water contact, such as the Valhall/Hod oilfield (Fig. 5) and the Hadson oilfield (Sun Longde et al, 2009). Therefore, the analysis of the titled oil-water contact formation has important implications on the discovery of the scale of reservoirs and potential for reservoir and deployments, and the scale and classification of titled oil-water contact are urgent to be put out. But there are some exceptions, such as limestone oil reservoirs (reef) or specially structure (asymmetric structure, e.g., Frannie oilfield).

According to statistics for the oil-gas reservoirs with tilted oil-water contacts in different oilfields around world

(Table 1, Fig. 15), the slopes (Dip_{TOWC}) for most reservoirs with tilted oil-water contact are distributed in a range of 2.5 m/km to 55 m/km. There are only three oilfields with a dip angle less than 4 m/km, and five oilfields with a dip angle greater than 55 m/km. From the plot-box statistical result used to show the shape of the distribution, its central value, and variability (Fig. 16), it can be seen that 4 m/km and 55m/km are the clear boundary lines for the tilted oil-water contact and can be used as the identification and classification threshold for a reservoir with a tilted oil-water contact. It is proposed in this paper that the level of the tilted oil-water contact be divided into three categories: large dip ($Dip_{TOWC} \geq 55$ m/km), medium dip (4 m/km $\leq Dip_{TOWC} <$ 55 m/km), and small dip ($Dip_{TOWC} <55$ m/km). It is conducive to grasp the characteristics of reservoirs with tilted oil-water contacts and provide the basis for oilfield exploration and evaluation of exploitation. Meanwhile, the classification and evaluation method should be combined with structure amplitude and reservoir property in the future study.

5.2 Research prospects discussion

As for the understanding a reservoir with a tilted oil-water contact, the application of some theory is limited and controversy with the complex geology background, and some research methods also need to be updated with the development of other disciplines.

First, the tilt of an oil-water contact in a hydrodynamic reservoir requires a certain extent of velocity for groundwater seepage. It requires that an outcrop exists at one end of the reservoir close to the ground and is used as the entrance for the groundwater supply, namely an open reservoir (reservoir surrounded by natural outcrops and communication with natural water). It also requires that an outcrop exists at another end of the reservoir close to the ground and is used as the exit of the groundwater outflow. However, Li Chuangliang (2006) believed that if there were both underflow and oil-gas accumulation, the long-term water washing and oxidation had long destroyed the accumulated oil and gas, and it is impossible to have formed current oil and gas reservoirs. In fact, the tilt of an oil-water contact in some oilfields proves the existence of hydrodynamic conditions. The effect in early and medium-term development of an oil field is good and the production has been continued for more than ten years without any drop, such as the Valhall oilfield (Barkved et al., 2003); some of the oilfields in the early studies were regarded as hydrodynamic reservoirs, but after development, it was realized that the formation energy was insufficient and the production dropped quickly, such as the Sultan Fula oilfield (Wang Wei and He Wei, 2010). In addition, during the evaluation for the effect of reservoir heterogeneity on the tilt of an oil-water contact, the precondition is generally the inheritance of the geological structure, namely, there was no large tectonic movement after deposition (Li Chuanliang, 2006).

The second, the tilt of the oil-water contact was formed under the effects of multiple factors. Concluded with the hydrodynamic conditions, capillary pressure (reservoir heterogeneity) or unstable structure, all can easily lead to the tilt of an oil-water contact. But field work has shown that reservoirs with similar geological background in a number of oilfields can have vastly different oil-water contact angles. As the "hydrodynamic" features existed in the pressure system for many of the giant oilfields in the Middle East (i.e. the water pressure of the reservoir show directional changes), it had caused the tilting of the oil-water contact, such as the Mishrif reservoir in the Sirrice oilfield, Iran and the Nahr Umr reservoir in the North Field, Qatar. But only a change in water pressure and no tilted oil-water contact existed in the fourth pay reservoir in the Zubair Group, Rumaila oilfield, Iraq (Liu Zhuo et al., 2013). The water flooding of oil and gas wells not only has had a great influence on the tilt of the oil-water contact, but also affects the exploitation scheme of oil and gas wells. Influenced by these factors, the effect level and mode on the oil-water contact are still controversial. A further quantitative study needs to be carried out in combination with data for future exploration and development.

The third, with the development of material science and computation science, physical simulations and numerical simulations can help identify the formation mechanisms of a reservoir, and have achieved important preliminary results in the study of tilted oil-water contacts. But because of the complexity of geological conditions, similar reference and simulation analysis are conducted under comprehensive considerations of different conditions and different types of reservoirs, and in combination with the problems typically found during exploration and development. In the comprehensive consideration of the formation mechanism of hydrodynamic features, formation heterogeneity and neotectonic movement, from the tectonic evolution-sedimentary characteristics-formation development and distribution characteristics- interlayer analysis to the analysis of oil-water contact, a 3D geological model can be established for visual analysis. The comprehensive evaluation of the formation mechanism for the reservoir with a tilted oil-water contact can be conducted. Furthermore, a more reliable assessment of the geological reserves in the reservoir can be performed as well, laying a framework for the exploration evaluation and exploitation evaluation, and reducing the risk in the exploration and

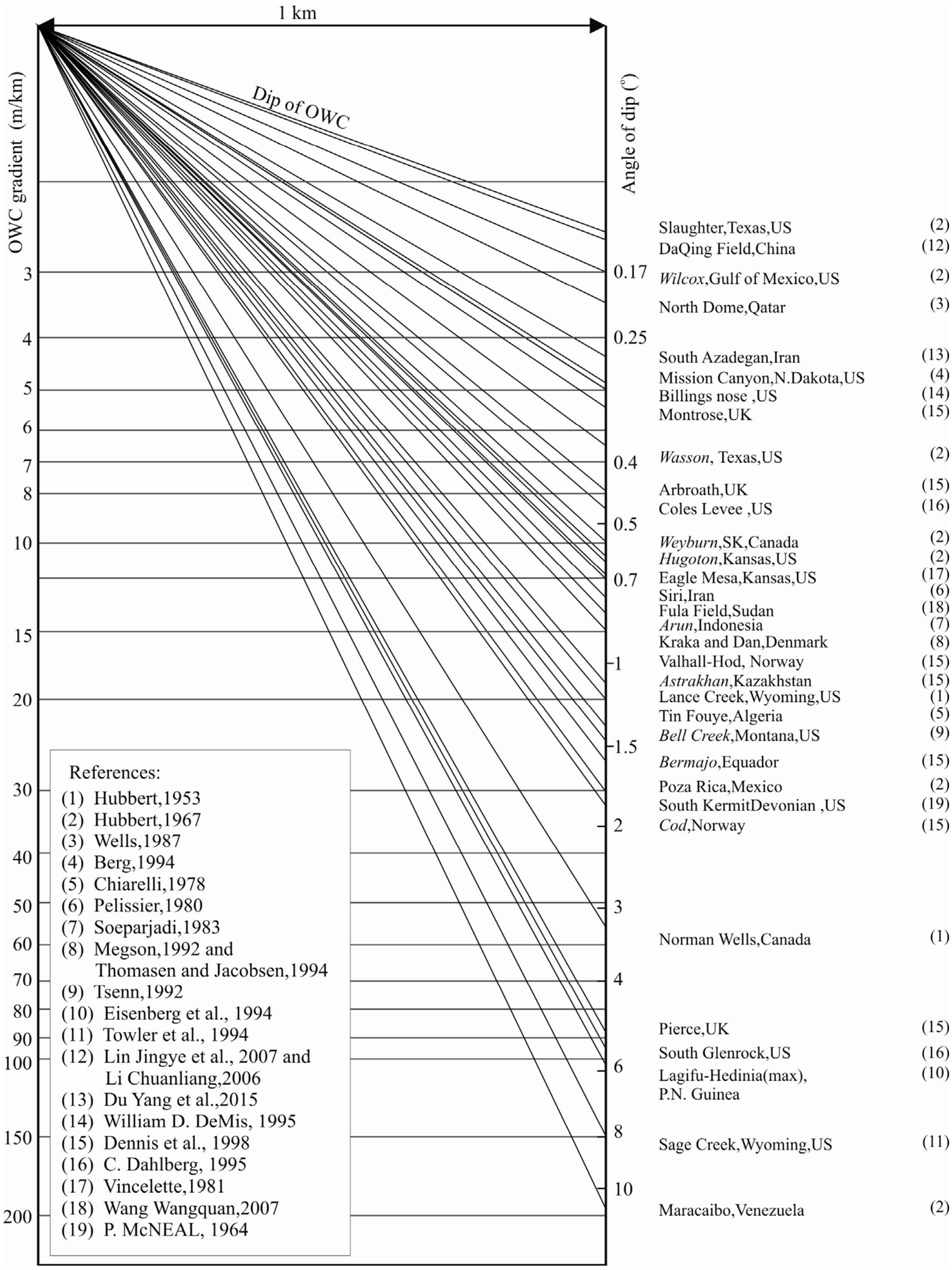

Fig. 15. Global examples of tilted oil-water contacts and their relative orders of magnitude (modified from Dennis, 1998).

exploitation.

6 Conclusions

Development and distribution characteristics of the oil-water contact are the basis for the exploration and exploitation of a reservoir, and the evaluation of reservoir reserves and resources. The reservoir with a tilted oil-water contact is a type of oil-gas reservoir with special formation mechanism. The knowledge on the distribution and formation mechanism of the reservoir with a tilted oil-water contact will directly affect the type of oil-gas reservoir, well deployment, selection of well pattern and type, determination of test section, and reserve evaluation of an oilfield. The formation mechanism of the tilted oil-water contact can be grouped into four main interpretations: the first, affected by the hydrodynamic system; the second, affected by the capillary pressure; the third, affected by the neotectonics movement; the fourth, affected by the late exploitation of an oilfield.

It can be seen that the dip gradient of the oil-water contact for each reservoir is different, and the reservoir

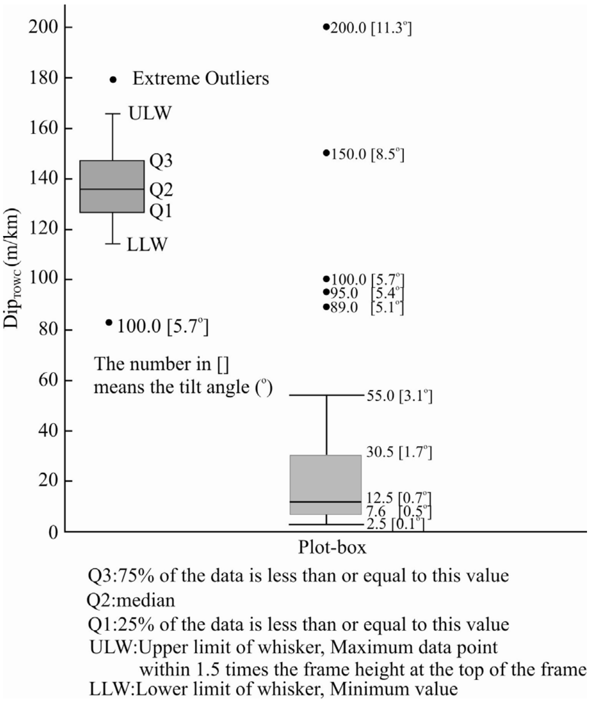

Fig. 16. Plot-box statistics of global examples of tilted oil-water contacts.

lithology is mainly the sandstone and limestone; based on the typical examples of tilted oil-water contacts worldwide, it is shown that the distribution range of the reservoirs are vastly different. The level of the tilted oil-water contacts can be divided into three categories in this paper by the inclination level (Dip_{TOWC}) of tilted oil-water contact: large dip ($Dip_{TOWC} \geq 55$ m/km), medium dip (4 m/km $\leq Dip_{TOWC} <$ 55 m/km), and small dip ($Dip_{TOWC} < 4$ m/km).

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