Vol. 92 No. 3 pp. 1157–1169 ACTA GEOLOGICA SINICA (English Edition) June 2018

Tectono–Thermal Evolution, Hydrocarbon Filling and Accumulation Phases of the Hari Sag, in the Yingen–Ejinaqi Basin, Inner Mongolia, Northern China

YANG Peng[1,2,3], REN Zhanli[1,*], XIA Bin[2,4], TIAN Tao[5], ZHANG Yong[2], QI Kai[1] and REN Wenbo[1]

1 *State Key Laboratory of Continental Dynamics, Department of Geology, Northwest University, Xi'an 710069, China*

2 *Guangdong Key Laboratory of Offshore Oil Exploration and Development, School of Marine Science, Sun Yat–sen University, Guangzhou 510006, China*

3 *Radiogenic Isotope Facility, School of Earth and Environmental Sciences, The University of Queensland, Brisbane Qld 4072, Australia*

4 *State Key Laboratory of Ore Deposit Geochemistry, Chinese Academy of Sciences, Guiyang 550002, China*

5 *Key Laboratory Coal Resource Exploration and comprehensive Utilization, Ministry of Land and Resources, Xi'an 710026, China*

Abstract: This work restored the erosion thickness of the top surface of each Cretaceous formations penetrated by the typical well in the Hari sag, and simulated the subsidence burial history of this well with software BasinMod. It is firstly pointed out that the tectonic subsidence evolution of the Hari sag since the Cretaceous can be divided into four phases: initial subsidence phase, rapid subsidence phase, uplift and erosion phase, and stable slow subsidence phase. A detailed reconstruction of the tectono–thermal evolution and hydrocarbon generation histories of typical well was undertaken using the EASY R_o% model, which is constrained by vitrinite reflectance (R_o) and homogenization temperatures of fluid inclusions. In the rapid subsidence phase, the peak period of hydrocarbon generation was reached at c.a. 105.59 Ma with the increasing thermal evolution degree. A concomitant rapid increase in paleotemperatures occurred and reached a maximum geothermal gradient of about 43–45°C/km. The main hydrocarbon generation period ensued around 105.59–80.00 Ma and the greatest buried depth of the Hari sag was reached at c.a. 80.00 Ma, when the maximum paleo–temperature was over 180°C. Subsequently, the sag entered an uplift and erosion phase followed by a stable slow subsidence phase during which the temperature gradient, thermal evolution, and hydrocarbon generation decreased gradually. The hydrocarbon accumulation period was discussed based on homogenization temperatures of inclusions and it is believed that two periods of rapid hydrocarbon accumulation events occurred during the Cretaceous rapid subsidence phase. The first accumulation period observed in the Bayingebi Formation (K_1b) occurred primarily around 105.59–103.50 Ma with temperatures of 125–150°C. The second accumulation period observed in the Suhongtu Formation (K_1s) occurred primarily around 84.00–80.00 Ma with temperatures of 120–130°C. The second is the major accumulation period, and the accumulation mainly occurred in the Late Cretaceous. The hydrocarbon accumulation process was comprehensively controlled by tectono–thermal evolution and hydrocarbon generation history. During the rapid subsidence phase, the paleo temperature and geothermal gradient increased rapidly and resulted in increasing thermal evolution extending into the peak period of hydrocarbon generation, which is the key reason for hydrocarbon filling and accumulation.

Key words: fluid inclusion, erosion thickness, subsidence burial history, tectono–thermal evolution, hydrocarbon generation history, hydrocarbon accumulation phase, Inner Mongolia, China

* Corresponding author. E-mail: renzhanl@nwu.edu.cn

1 Introduction

The Hari sag of the Yingen–Ejinaqi Basin has attracted much attention after it was selected as a new important target area during strategic planning of the Chinese hydrocarbon energy reserves. The China Geological Survey (CGS) has conducted basic geological research in the Yingen–Ejinaqi Basin and accomplished many achievements in the recent decade. The CGS began working closely with the Shaanxi Yanchang Petroleum (Group) Co., Ltd in 2013 and has since then obtained a daily open flow output capacity of high-production industrial gas of 9.15×10^4 m^3, which has led to a great breakthrough in the exploration of hydrocarbon reserves in the Yingen–Ejinaqi Basin and has shown great promise for exploration and development (Zhao Chunchen et al., 2017; Chen Zhijun et al., 2018). The organic matter content and type, hydrocarbon reservoir formation condition, trap characteristics, and favorable zones in the Hari sag of the Yingen–Ejinaqi Basin have only been partly analyzed to date (Wang Xiaoduo et al., 2015; Yang et al., 2017a). Chen Zhijun et al. (2016) predicted and evaluated the source of rocks using geophysical methods. Zhao Chunchen et al. (2017) studied the geological setting of the YHC-1 well in the Cretaceous reservoir by combining geological and geophysical methods with drilling, logging, seismic, paleontological, and geochemical data. Yang et al. (2017a) and Chen Zhijun et al. (2017, 2018) reported the geochemical characteristics of the Lower Cretaceous source rocks, and Yang et al. (2017a) further suggested that the sag reached a maximum geothermal gradient at the end of the Early Cretaceous. However, few detailed studies have investigated the tectono–thermal evolution and hydrocarbon accumulation phases of the Hari sag in the Yingen–Ejinaqi Basin of Inner Mongolia, northern China.

The tectono–thermal evolution history of sedimentary basins is closely related to hydrocarbon migration and accumulation, and is also one of the frontiers and challenges in basin analysis and petroleum geology (Allen, P., and Allen, J.R.,1990; Zhao Zhongyuan et al., 1990; Ren Zhanli, 1991, 1992, 1999; Ren Zhanli et al., 2008, 2014a, 2014b, 2015b; Belaid et al., 2010; Carminati et al., 2010; Hudson and Hanson, 2010; Sahu et al., 2013; Yang Peng et al., 2017b). The method is highly precise which determined the period and phases of hydrocarbon filling and accumulation based on the accurate reconstruction of erosion thickness, a fine description of burial history, tectono–thermal evolution history, and a combination of petrographic characteristics and geological ages corresponding to the homogenization temperature of the formation process of brine inclusion comparable to hydrocarbon inclusion (Haszeldine et al., 1984; Horsfield and Mclimans, 1984; Mclimans, 1987; Karlsen et al. 1993; Nedkvitne et al., 1993; Liu Shaobo and Gu Jiayu, 1997a, 1997b; Lu Huangzhang and Guo Dijiang, 2000; Lu Huangzhang et al., 2004; Li Rongxi et al., 2006; Liu Xinshe et al., 2007; Liang Yu et al., 2010, 2011;Xu Guosheng et al., 2014; Shi Baohong et al., 2014, 2015; Zheng Lei et al., 2015; Li Hongtao, 2016; Luo Xiao et al., 2015;Xu Fanghao et al., 2016).

In this study, the erosion thickness of the top of the Cretaceous formations in typical well was reconstructed and a corresponding burial history model was established using interval transit time (AC), vitrinite reflectance (R_o), and inclusion homogenization temperatures methods. We recovered the tectono–thermal evolution history of typical well constrained by vitrinite reflectance (R_o) and inclusion homogenization temperature and based on the widely used model of EASY R_o% (Sweeney and Burnham, 1990). According to the burial history, tectono–thermal evolution history and the petrographic analysis and the homogeneous temperature distribution characteristics of inclusions, a new understanding of hydrocarbon accumulation phases in the Hari sag was elucidated.

2 Geological Setting

The Yingen–Ejinaqi Basin is one of the most important continental basins in China (Fig. 1a). The Hari sag is located in the northern part of the Yingen–Ejinaqi Basin (Fig. 1 b), Inner Mongolia, and covers an area of 1350 km^2 (Lu Jincai et al., 2010, 2011a; Wang Xiaoduo et al., 2015). The whole sag is oriented in a northeastern direction with a narrow strip distributed on the plane. It is surrounded to the west by the Dagu Depression, to the south by the Zongnaishan Uplift, and to the north by Mongolia (Lu Jincai et al., 2011b; 2011c) (Figs. 1b and 1c). It is a Meso–Cenozoic faulted sag that developed on the basement of the Hercynian fold. The Jurassic and Triassic strata are absent in most areas of the sag, and the Jurassic strata occur only inparts of the southern region (Wang Xiaoduo et al., 2015). The sedimentary strata from bottom to top are Lower Cretaceous (K_1b, K_1s, and Yingen Formation (K_1y)), Upper Cretaceous Wulansuhai Formation (K_2w) and Cenozoic strata. All strata are in unconformable contact with each other. The formation mainly comprises mudstone with a small amount of sandstone. The mudstone is mainly composed of dolomitic mudstone, gray mudstone, and gypsum rock (Fig. 2).

The drilling wells No. S–1 and HR–1 show signs of some hydrocarbons at the bottom of the thin sandstone section in the K_1s. The wells HC–1and HC–2 were drilled in 2015 and better indicate the presence of hydrocarbon at the bottom of the K_1y and the top of the K_1s and K_1b. The

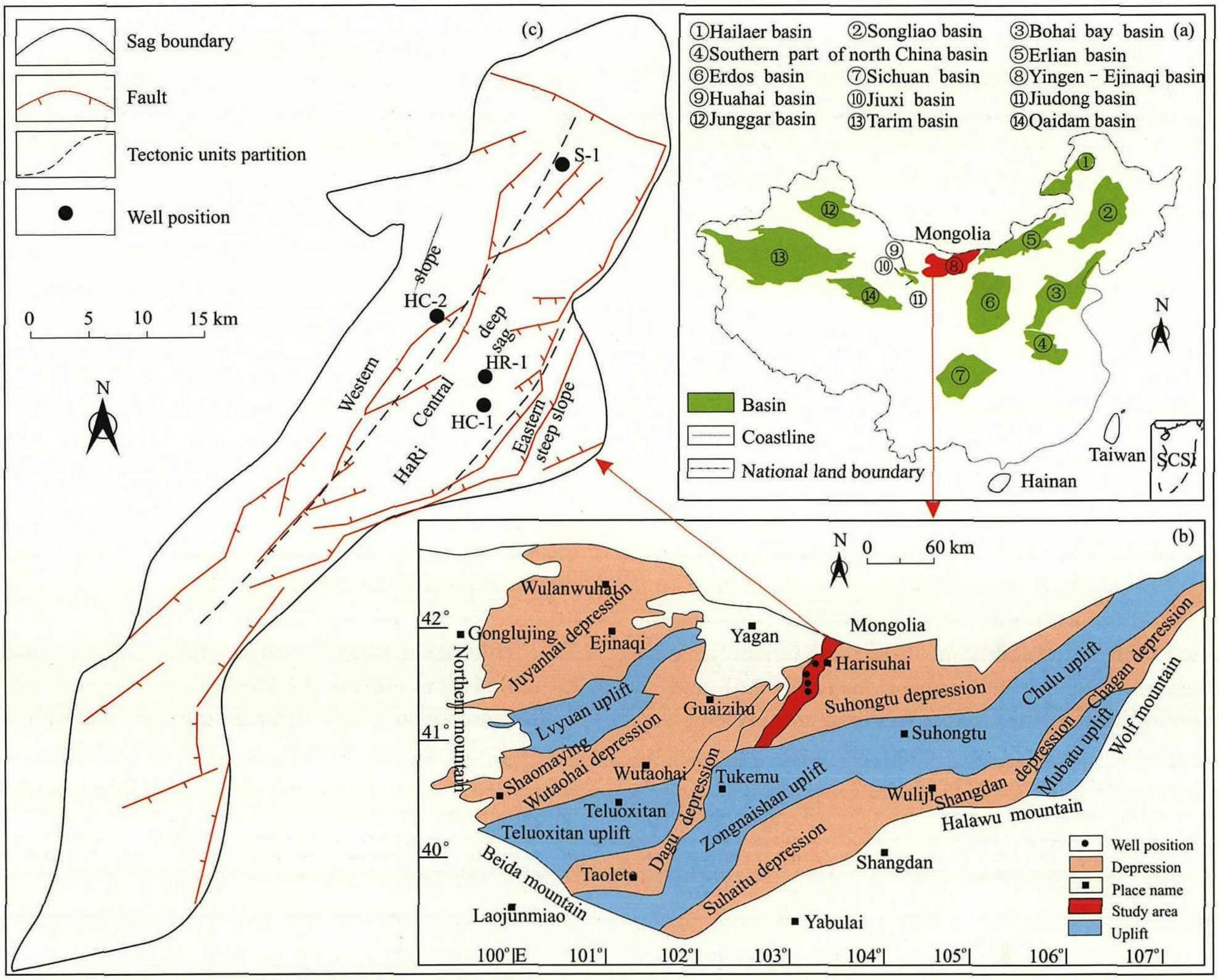

Fig. 1. (a), Major oil and gas basins on land in China (modified from Zuo et al., 2015b); (b) and (c), Structural location and well distribution of the Hari sag in the Yingen–Ejinaqi Basin.

Fig. 2. Photos of cores taken from the Hari sag.
(a), Depth: 436 m, stratum: K_1y, lithology: mudstone; (b), Depth: 1106m, stratum: K_1s, lithology: mudstone; (c), Depth: 2592m, stratum: K_1b, lithology: mudstone; (d), Depth: 1722m, stratum: K_1s, lithology: gray sandstone; (e), Depth: 3073m, stratum: K_1b, lithology: gray sandstone.

well HC-1, in particular, has obtained a daily open flow output capacity of high-production industrial gas of 9.15×10^4 m^3, which confirms the promising prospect of hydrocarbon exploration and development. However, the Hari sag lacks studies regarding its tectono–thermal evolution history and hydrocarbon accumulation phases. The research presented in this paper has important significance for further analysis of hydrocarbon generation conditions, hydrocarbon accumulation laws, and comprehensive evaluation of hydrocarbon exploration and development prospects of the sag.

3 Samples and Methods

3.1 Methods of analysis of the inclusions

The particle size of the Cretaceous strata in the Hari sag is relatively fine and the lithology is dominated by mudstone, which is unfavorable for the observation and analysis of the inclusions under microscope. As such, the coarse-grained sandstone cores from the K_1b and K_1s were selected to conduct temperature measurements and to determine the formation stages of the inclusions (Fig. 2e). The specific methods of homogenization temperature measurements and formation stages of inclusions have been studied extensively (Li Rongxi et al., 2006; Tao Shizhen, 2006; Xiao Hui et al., 2012; Jiang Youlu et al., 2016; Fang Ronghui et al., 2017; Shen Lijian et al., 2017; Zheng Chaofei et al., 2017). It should be noted that due to the variability and uncertainty of the homogenization temperature of hydrocarbon inclusions, it is necessary to select the brine inclusions that correspond to the hydrocarbon inclusions as the observation and test objects (Lu Huangzhang et al., 2004; Tao Shizhen, 2006; Tian Tao et al., 2015).

3.2 Methods to determine erosion thickness and reconstruct subsidence burial history

Different subsidence and burial histories of tectonic units will lead to different thermal evolution processes, which play key roles during the process of hydrocarbon generation, filling, and accumulation (Ren Zhanli et al., 2000, 2014a). It is necessary to reconstruct the burial history of a study area before the reconstruction of the tectono–thermal evolution and hydrocarbon generation history, and the first step in establishing burial history is to estimate erosion thickness (Ren Zhanli et al., 2000; Tian Tao et al., 2014; Malaza Ntokozo et al., 2016; Yang Peng et al., 2016). The estimation of erosion thickness and the reconstruction model of burial history are especially important for further analysis of thermal evolution history, hydrocarbon generation history, and hydrocarbon filling and accumulation phases. The methods used for estimating erosion thickness include stratigraphic correlations, settlement velocity, AC, R_o, inclusion homogenization temperatures, wave equations, apatite fission track (AFT) and comprehensive sedimentary structure analysis methods (Magara, 1976; Dow, 1977; Katz, 1988; Liu Guocheng et al., 1995; Liu Yiqun and Zhou Lifa,1997; Hu Shaohua, 2004; Zhao Libin et al., 2006; Ren Zhanli et al., 2008, 2014a, 2014b, 2015a, 2015b; Qiu Nansheng et al., 2010, 2011, 2012a, 2012b; Shi Changlin et al., 2011; Zuo Yinhui et al., 2011; He Sheng and Wang Qingling, 2012; Yin Jiyuan et al., 2015). Due to ongoing developments and improvements, AC, R_o and inclusion homogenization temperatures are the most precise methods (Chen Zengzhi et al., 1999; Hu Shengbiao et al., 1999; Tong Yanming et al., 2005; Tong Yanming and Zhu Guanghui, 2006; Cao Zhanpeng et al., 2016; Tian Tao et al., 2016). This study focuses on using these three methods to estimate the erosion thickness of Cretaceous strata.

3.3 Homogenization temperature of inclusions estimated from erosion thickness

The homogenization temperature of inclusions in minerals during the process of basin sedimentation and subsidence is relatively higher, and the inclusions homogenization temperature is relatively lower after undergoing geological process of uplifting, erosion and cooling. The difference in homogenization temperatures of fluid inclusions before and after stratigraphic uplift and erosion, combined with the geothermal gradient, are used to estimate the erosion thickness of some strata. The erosion thickness estimation formula is given as:

$$H=\frac{T_a-T_b}{d_T/d_Z} \quad (1)$$

Where H is the erosion thickness, T_a is the paleotemperature before uplifting, erosion, and cooling, T_b is the paleotemperature after uplifting, erosion, and cooling, and d_T/d_Z is the paleo–geothermal gradient during the process of uplifting, erosion and cooling (Shi Changlin et al., 2011; Tian Tao et al., 2016).

3.4 AC estimate for erosion thickness

The lithology of the Hari sag K_1y Formation which deposited over the K_1s Formation is dominated by mudstone and lacks inclusions that are suitable for observing formation stages and testing homogeneous temperatures. In addition, the method of R_o is restricted. Accordingly, in this study, AC was used for the estimation of total erosion thickness. When estimating erosion thickness using AC, the sedimentation rate before and after the denudation event must be considered and the compaction law under the unconformity surface cannot be damaged by the over compensating deposition (Fu Xiaofei et al., 2004; Zhou Lu et al., 2007; Tian Tao et al., 2016). The commonly used method of judging the relative sedimentation rate before and after the uplift event, via segmentation characteristics of R_o versus depth, is not applicable. However, it can be inferred from the geotectonic position of the Hari sag and the evolution law of the Yingen–Ejinaqi Basin, Inner Mongolia. The Yingen–Ejinaqi Basin is located at the junction of the Paleo–Asian Ocean and Tethys Ocean, where is amoung the Siberia plate, north China plate, Tarim microplate, and Qaidam microplate (Ren Jishun, 1999; 2003). During the later period of the Early Cretaceous, the tectonic setting of the Yingen–Ejinaqi Basin influenced by the Yanshan movement which changed from the NW extension into strong compression, and most areas incurred occurred uplift and erosion (Zhai Guangming, 2002; Ye Jiaren and Yang Xianghua,2003; Lu Jincai et al., 2012). It is speculated that the Hari sag did not experienced long-term rapid subsidence after the Late Cretaceous. In addition, the transformation dynamics, accumulation processes, and burial history of the Yingen–Ejinaqi Basin indicate that the basin was in a rapid subsidence phase before 100–97 Ma, after which was dominated by uplift, erosion, and slow subsidence (Wang Xinming et al., 2004; Zuo Yinhui et al., 2013, 2015a; Zuo et al., 2015b). According to the above statement, the AC method is suitable for estimating the erosion thickness at the surface of the Upper Cretaceous.

3.5 R_o estimate for erosion thickness

The R_o method used to estimate erosion thickness possesses high accuracy and wide application. A great deal of research about the principles and improvement of the method has shown that, due to the irreversibility of R_o itself, it cannot accurately reflect the early thermal events, but has high reliability to estimate the erosion thickness of the late thermal events (Hao Fang and Chen Jianyu, 1988; Chen Zengzhi et al., 1999; Hu Shengbiao et al., 1999; Tong Yanming et al., 2005; Tong Yanming and Zhu Guanghui, 2006). This study used the R_o method to estimate erosion thickness after the maximum paleotemperature was experienced.

4 Results

4.1 Homogenization temperature of inclusions

The microscopy results show that minerals parasitized by brine inclusions are mostly quartz. Fluid inclusions in the K_1b Formation are well developed and are mainly distributed as a string of beads in the quartz particles and cracks. Few fluid inclusions can be observed in the K_1s Formation with only minor distributions in quartz cracks (Fig. 3). The comprehensive observations and test results show that the homogenization temperature of the inclusions in the Cretaceous strata contain peak intervals that are mainly distributed around 120–130°C, 135–145°C. In addition, the homogenization temperature of the inclusions in the K_1s and K_1b are mainly distributed around 120–130°C and 125–150°C respectively (Fig. 4).

4.2 Erosion thickness determined from the homogenization temperature of inclusions

The seismic profile showed that no erosion occurred on the top of the K_1b Formation. It is assumed that this is because of the K_1b Formation being in unconformable contact with the K_1s Formation. The average inclusions homogenization temperature of the Lower Cretaceous K_1b Formation is 137.28°C, which can be defined as the paleotemperature before uplifting, erosion and cooling. The average inclusions homogenization temperature of the

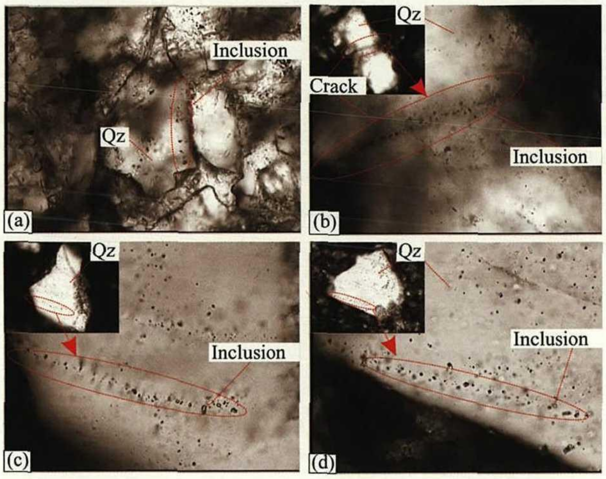

Fig. 3. Micrographs of fluid inclusions.

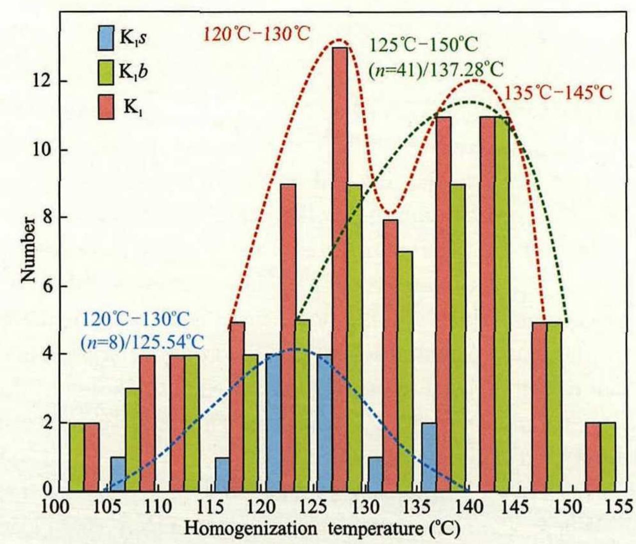

Fig. 4. Distribution of the homogenization temperature of fluid inclusions.

Lower Cretaceous K_1s is 125.54°C which can be defined as the paleotemperature after uplifting, erosion, and cooling. The geothermal gradient during the process of uplifting, erosion, and cooling is 40° C/km which is inverted by R_o. According to Equation (1), the formula for estimating erosion thickness at the top of the K_1b Formation can be given as:

$$\Delta H_B = \frac{T_a - T_b}{d_T/d_Z} = \frac{137.28 - 125.54}{42} \times 10^3 \text{ m} = 293.5\text{m} \quad (2)$$

However, the formation of the inclusions occurred at a later time than the first uplift period of the K_1b Formation presented by the tectono–thermal evolution and hydrocarbon filling and accumulation history of typical well in the Hari sag, which means that the erosion thickness of 293.5 m at the top of the K_1b Formation is not significant. This conclusion is consistent with previous research (Chen Jianping et al., 2001; Zuo Yinhui et al., 2013, 2015a; Zuo et al., 2015b; Niu Zicheng, 2016), and we suggested that K_1b Formation is overlain conformably by K_1s Formation.

4.3 Erosion thickness determined from AC

The regression equation for AC versus depth under the unconformity surface can be defined as:

$$H = -6.3212\ \Delta t + 2574.8\ (X^2=0.7003) \quad (3)$$

Where AC of earth's surface is given as Δt=620–650 μs/m (Chen Heli et al., 1990; Henry, 1996; Zhao et al., 2015; Cao Zhanpeng et al., 2016; Tian Tao et al., 2016). According to Equation (3), the total erosion thickness (ΔH) is 1344.34–1533.98 m and the average value can be given as 1439 m using the AC (Fig. 5). The erosion thickness is far greater than the later deposition thickness which satisfied the application conditions and verified the rationality of estimating erosion thickness using AC in this study.

4.4 Erosion thickness determined from the R_o

There is no obvious segmentation of R_o versus depth between the K_1b, K_1s Formations, and K_1y Formation, and the seismic profiles reflect no obvious occurrence of erosion between the K_1y and the K_2w Formation (Fig. 6). The differences caused by the early uplift events were weakened or even eliminated by the rapid subsidence, burial, and warming processes that occurred in the Early Cretaceous. This would indicate that the Hari sag reached its maximum paleotemperature in the Late Cretaceous, and that R_o can be used to estimate the erosion thickness of the Upper Cretaceous K_2w Formation. The relation between the R_o and H can be described as:

$$H = 2149.22\ \ln(R_o) + 2237.5\ (X^2=0.9382) \quad (4)$$

Where, R_o of the earth's surface is given as R_o=0.2 (Tian Tao et al., 2016; Yang Peng et al., 2016). According to the Equation (4) and using the R_o versus depth method, the erosion thickness of the top of K_2w Formation (ΔH_w) is 1221.50 m (Fig. 6).

4.5 Results of erosion thickness

The Yingen–Ejinaqi Basin began to shrink at the end of

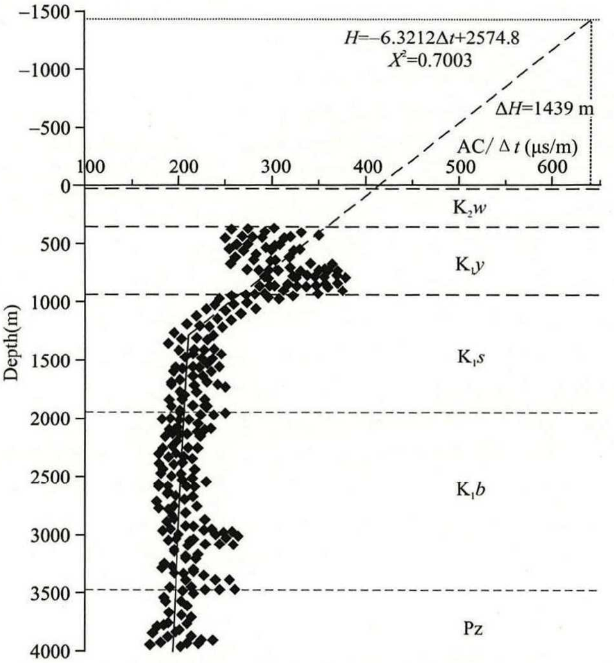

Fig. 5. Erosion thickness determined from the AC.

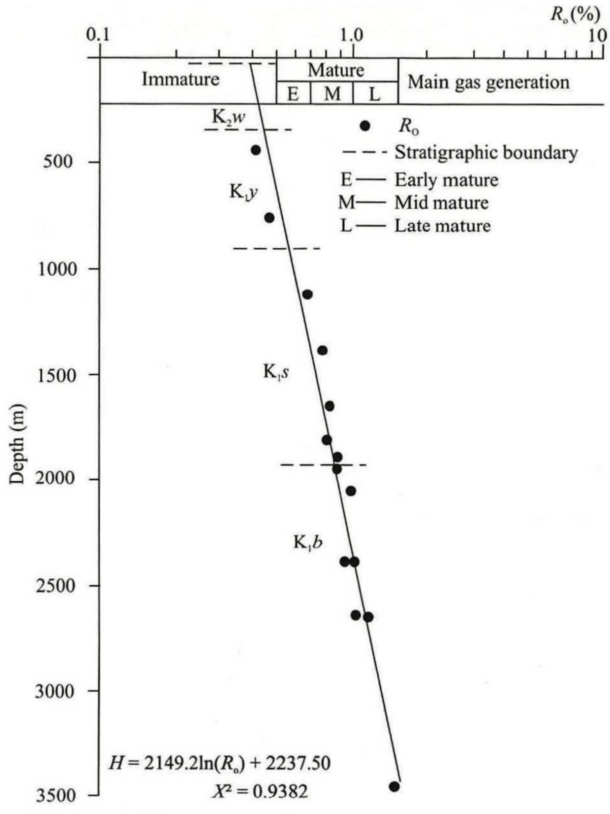

Fig. 6. Plots of R_o vs. depth of typical well in the Hari sag of Yingen–Ejinaqi Basin.

the Late Cretaceous and whole mainly occurred as uplift and erosion. The erosion thickness of K_1s (ΔH_S) is 375m via estimating according to comprehensive wells data (Zuo Yinhui et al., 2013, 2015a; Zuo et al., 2015b). The R_o showed no obvious segmentation between the K_1b, K_1s, and K_1y Formations, and the seismic profiles reflect no obvious erosion between the K_1y and the K_2w Formations. In addition, the typical well is located in the central deep zone of the Hari sag, and the erosion thickness of K_1y (ΔH_Y) should be small and can be given as 315 m according to result of Chagan sag, Yingen–Ejinaqi Basin (Zuo Yinhui et al., 2015a). It is concluded that the erosion thickness of top of the K_2w Formation is given as ΔH_w=1330.25 m, which can be estimated from the results obtained by R_o and AC approaches.

5 Discussions

5.1 Subsidence burial history

According to the actual measured values obtained from the boreholes, the age of the Cenozoic stratum and each Cretaceous stratum, which includes K_2w, K_1y, K_1s_2, K_1s_1, K_1b_2, and K_1b_1 Formations, can be set at c.a. 65, 95, 100, 105, 110, 128, and 135 Ma, respectively (Zuo Yinhui et al., 2013, 2015a; Zuo et al., 2015b). At the bases of the estimation erosion thickness of regional unconformities via various methods, reconstructs subsidence burial history model of typical well in the Hari sag by BasinMod basin modeling software. The simulation results of the tectonic subsidence curve and sedimentation rate indicated that the tectonic subsidence evolution process of the Hari sag can be divided into four phases: initial subsidence phase, rapid subsidence phase, uplift and erosion phase, and stable and slow subsidence phase (Fig. 7).

The early deposition period of the K_1b Formation in the Hari sag occurred in the Early Cretaceous is denoted by an initial subsidence phase, where the sedimentation rate was

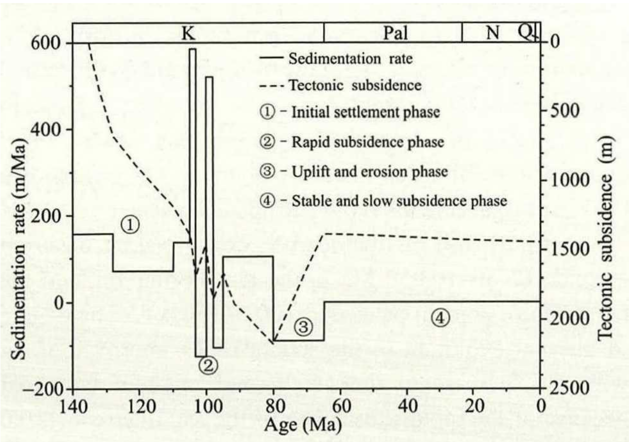

Fig. 7. Tectonic subsidence and sedimentation rate of the Hari sag in the Yingen–Ejinaqi Basin.

about 157.36 m/Ma, which then stabilized at 70.76 m/Ma at c.a. 128.00 Ma. The sedimentation rate increased to 106.60 m/Ma and the sag entered into the rapid subsidence phase at c.a. 110.00 Ma. The maximum sedimentation rate of 585.47–520.11 m/Ma occurred during the depositional period of the K_1s and K_1y. During the early depositional period of the K_2w Formation, the sedimentation rate was 105.07 m/Ma and corresponded to the end of the rapid subsidence phase. A short period of rapid uplift occurred in this stage, but the sag was still dominated by rapid subsidence as a whole. The sag then entered into the uplift and erosion phase and during the Late Cretaceous about 80–65 Ma, when the erosion rate of the deposited K_2w Formation was about 88.68 m/Ma. The sag entered into the stable and slow subsidence phase at c.a. 65.00 Ma since the Cenozoic Era with a sedimentation rate of 1.54 m/Ma.

5.2 Thermal evolution and hydrocarbon generation history

The methods used for reconstructing the thermal evolution and hydrocarbon generation history, include the geotherm–meter methods and the thermodynamic modeling methods of basin evolution. The geotherm–meter methods, which include R_o, fluid inclusion, clay mineral conversion, and apatite and zircon fission track, are universally used because of their high accuracy and their ability to verify the simulation results against actual measurement data (Gleadow, 1983; Naeser et al., 1989a; Naeser and Mccullon, 1989b; Allen, P. A. and Allen, J. R.,1990; Ren Zhanli, 1992, 1999; Ren Zhanli et al., 1994, 2014a, 2014b, 2015a, 2015b; Hu Shengbiao and Wang Jiyang, 1995; Suggate, 1998; Qiu Nansheng et al., 2004; Zhu Yanming et al., 2010; Zuo Yinhui et al., 2015a; Zuo et al., 2015b). Reconstructed the tectono–thermal and hydrocarbon generation evolution history of Cretaceous strata in the typical well which located at Hari sag constrained with vitrinite reflectance (R_o) and inclusion homogenization temperature and based on the widely used model EASY R_o% (Sweeney and Burnham, 1990).

The simulation of the history of thermal evolution and hydrocarbon generation shows that the paleo–geothermal field of the Hari sag was greatly affected by the rapid subsidence, uplift and erosion. This is reflected in the rapid subsidence of the sag and the culmination of the maximum palaeotemperature at 180°C at the end of the depositional period of the K_2w Formation (Fig. 8). The paleo–geothermal gradient was 39–41°C/km at the end of the depositional period of the K_1b Formation. The geothermal gradient gradually increased to 41–43°C/km following the depositional period of the K_1s Formation, and the maximum geothermal gradient reached about 43–45°C/km during the depositional period of the K_1s and K_1y

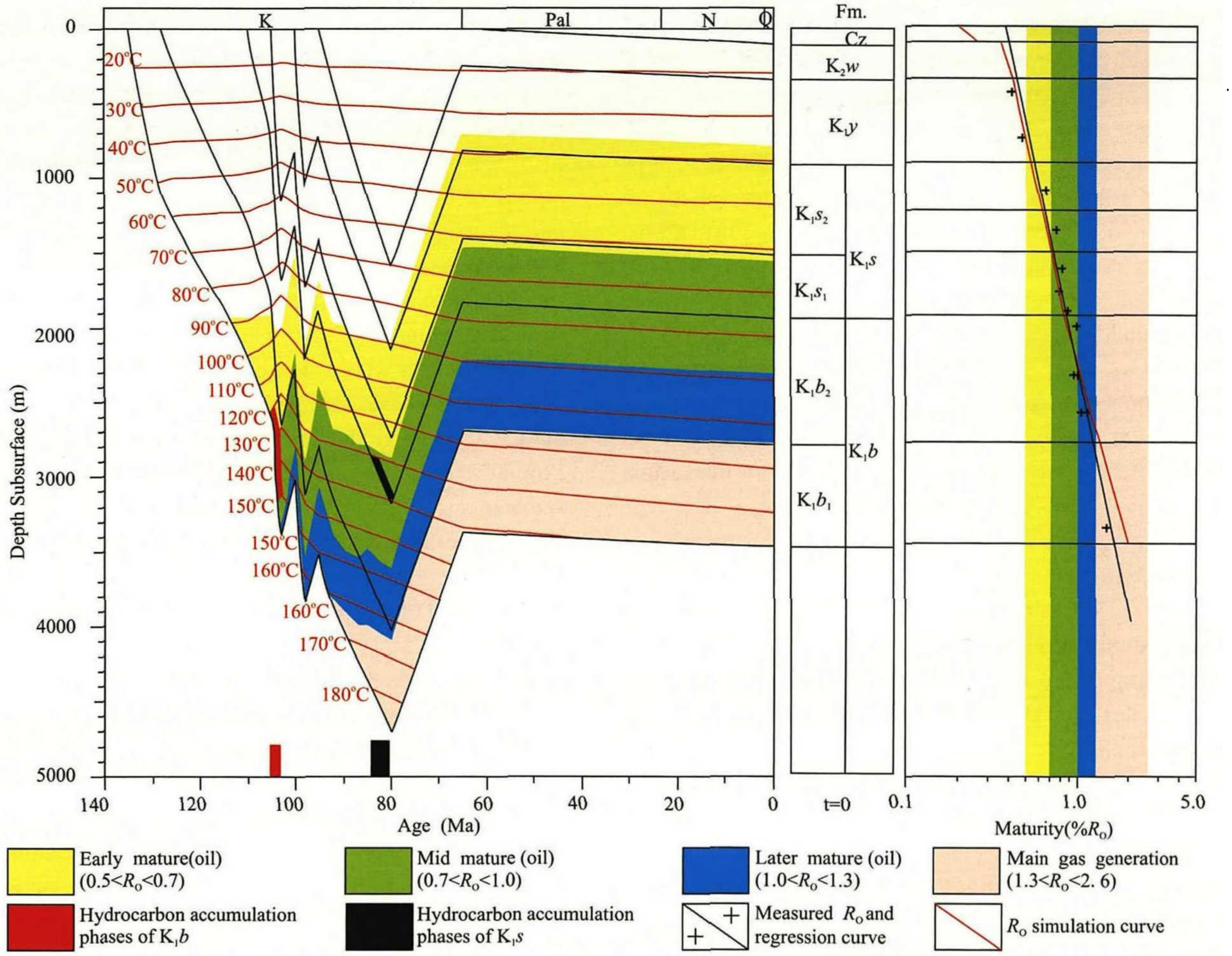

Fig. 8. Relationships between tectono–thermal evolution and hydrocarbon filling and accumulation phases of typical well in the Hari sag, Yingen–Ejinaqi Basin.

Formations. The Hari sag behaved as stable and slow subsidence with the downward trend in the geothermal gradient following the late deposition of K_2w Formation. The present geothermal gradient is about 34–36°C/km.

The R_o maturity profile (Fig. 6) and simulation results (Fig. 8) show that differences of thermal evolution and hydrocarbon generation history exit among the Lower Cretaceous strata of the Hari sag. The differences are manifested as hydrocarbon source rocks in the K_1y Formation that is in the basically immature–early mature hydrocarbon generation stage. The hydrocarbon source rocks of K_1s Formation reached hydrocarbon generation threshold at c.a. 98.14 Ma and enter into the mid maturity stage at c.a. 85.33 Ma. The hydrocarbon source rocks of K_1b Formation reached early maturity at c.a. 113.48 Ma and entered into mid maturity stage at c.a. 105.59 Ma. The geothermal gradient gradually increased and the maximum geothermal temperature reached about 180°C at the end of sedimentary period of the K_2w Formation with a sustained rapid settlement of the sag after c.a. 105.59 Ma. Hydrocarbon source rocks of the K_1b Formation reached a later maturity and main gas generation stages at c.a. 103.20 Ma and 94.27 Ma, respectively. As stated previously, the main hydrocarbon generation period of the Hari sag was 105.59–80.00 Ma.

5.3 Hydrocarbon accumulation phases

In synthesizing the previous statement, it can be concluded that hydrocarbon filling and accumulation of the sag is integrally controlled by relevant tectono–thermal evolution and hydrocarbon generation history. The simulation of tectono–thermal evolution and hydrocarbon generation history, combined with the homogenization temperature of inclusions show that two rapid hydrocarbon filling and accumulation events occurred in the Hari sag during the rapid subsidence phase.

The first phase of hydrocarbon accumulation occurred around 105.59–103.50 Ma in the K_1b Formation, and the temperature domain peaked at 120.0–150.0°C. The degree of thermal evolution of the source rocks improved along with the increase in the geothermal gradient increased because of the rapid subsidence of the sag after c.a. 110.0 Ma. The main reason for this accumulation period is that the hydrocarbon source rocks of the K_1b Formation entered into a period of peak hydrocarbon generation. The rapid sedimentation and burial occurring during the end of depositional period of the K_1s Formation to depositional period of the K_1y Formation may have led to the poor physical properties of the K_1b reservoir, which further restricted the hydrocarbon filling and accumulation.

The second phase of hydrocarbon accumulation mainly occurred around 84.00–80.00 Ma in the K_1s Formation, and temperature domain peaked at 120–130°C. It is the major accumulation period. The sag was in the rapid subsidence phase and the main hydrocarbon generation stage during this phase. The rapid subsidence and temperature increasing during the depositional period of the K_1y and K_2w Formations strengthen hydrocarbon generation again, which played an important role in this hydrocarbon filling and accumulation. However, the sedimentation rate might be too large to be an advantage for the hydrocarbon filling and accumulation, which is one of the possible reasons for the short duration of the rapid hydrocarbon filling and accumulation phase.

6 Conclusions

(1) The tectonic subsidence evolution process of the Hari sag since the Cretaceous can be divided into four phases: initial subsidence phase, rapid subsidence phase, uplift and erosion phase, and stable slow subsidence phase.

(2) The rapid subsidence phase began at c.a. 110.00 Ma, and the maximum sedimentation rate reached 585.47–520.11 m/Ma during the depositional period of the K_1s and K_1y Formations. During this time, the geothermal increased rapidly, the maximum geothermal gradient reached to about 43–45°C/km, and the degree of thermal evolution improved. The hydrocarbon source rocks of the K_1b Formation entered into a primary hydrocarbon generation stage c.a. 105.59 Ma, when the maximum burial depth of the sag occurred at c.a. 80.00 Ma. The maximum geothermal temperature reached 180°C at c.a. 80.00 Ma when the Hari sag reached its maximum depth. The sag entered into the uplift and erosion phase and stable and slow subsidence phase in turn after 80.00 Ma. The thermal evolution and hydrocarbon generation degrees of source rocks decreased and weakened, after which the geothermal gradient gradually decreased to 34–36°C/km.

(3) Two rapid hydrocarbon filling and accumulation events of the Hari sag occurred in the rapid subsidence phase during the Cretaceous period. The first phase of hydrocarbon accumulation mainly occurred around 105.59–103.50 Ma in the K_1b Formation, and the temperature domains peaked at 120–150°C. The second phase of hydrocarbon accumulation mainly occurred around 84.00–80.00 Ma in the K_1s Formation, and the temperature domains peaked at 120–130.0°C. The two processes synthetically controlling hydrocarbon filling and accumulation are the tectono–thermal evolution and hydrocarbon generation history.

Acknowledgements

This study was supported by the project of "Constraints on Lithospheric Dynamic Evolution and Hydrocarbon Accumulation from Late Mesozoic Paleo-geothermal Field in Ordos and Qinshui Basins" (grant No. 41630312), the National Nature Science Foundation of China (grants No. 41372208 and 40534019), and the Open Found of the State Key Laboratory of Ore Deposit Geochemistry, CAS (grant No. 201304). In addition, this study supported by international program for Ph.D. candidates, Sun Yat-Sen University.

Manuscript received July 16, 2017
accepted Dec. 8, 2017
edited by Hao Qingqing

References

Allen, P.A., and Allen, J.R., 1990. *Basin analysis principles and application.* Oxford London: Blackwell Scientific Publication.

Belaid, A., Krooss, B.M., and Littke, R., 2010. Thermal history and source rock characterization of a Paleozoic section in the Awbari Trough, Murzuq Basin, SW Libya. *Marine and Petroleum Geology*, 27(3):612–632.

Cao Zhanpeng, Ren Zhanli, Xiong Ping, Qi Kai and Chen Zhanjun, 2016.The Ordovician thermal evolution and hydrocarbon generation history in the southwestern margin of Weibei uplifting of the Ordos basin: A case study of the Linyou–Xunyi Region. *Acta Geologica Sinica*, 90(3): 513–520 (in Chinese with English abstract).

Carminati, E., Cavazza, D., Scrocca, D., Fantoni, R., Scotti, P., and Doglioni, C., 2010. Thermal and tectonic evolution of the southern Alps (northern Italy) rifting: coupled organic matter maturity analysis and thermokinematic modeling. *AAPG Bulletin*, 94(3), 369–397.

Chen Heli, Liu Yong and Song Guochu, 1990. An analysis of the distribution of subsurface fluid pressure and its relation to the petroleum migration and accumulation in Yanchang group, Shaanxi–Gansu–Ningxia Basin. *Acta Petrolei Sinica*, 11(4): 8–16(in Chinese with English abstract).

Chen Jianping, He Zhonghua, Wei Zhibin, Wang Dongliang, Qin Jianzhong and Guo Jianying, 2001. A study on the principal conditions of hydrocarbon generation in Chagan sag of Yingen–Ejinaqi Basin, Northwest China. *Petroleum Exploration and Development*, 28(6): 23–27 (in Chinese with English abstract).

Chen Zengzhi, Liu Guangdi and Hao Shisheng, 1999. A corrected method of using vitrinite reflectance data to estimate the thickness of sediment removed at an unconformity. *Acta Sedimentologica Sinica*, 17(1): 141–144 (in Chinese with

English abstract).

Chen Zhijun, Ren Laiyi, Liu Huchuang, Gao Yiwen and Wang Baojiang, 2016. Geophysical methods in hydrocarbon source rock prediction and evaluation of Hari sag. *Petroleum Geology and Engineering*, 30(6): 30–35 (in Chinese with English abstract).

Chen Zhijun, Ren Laiyi, He Yonghong, LiuHuchuang and Song Jian, 2017. Geochemical characteristics and formation environment of high-quality hydrocarbon source rocks of Yingen Formation in Hari Sag, Yingen-Ejinaqi Basin. *Journal of Jilin University* (Earth Science Edition), 47(5): 1352–1364.

Chen Zhijun, Gao Yiwen, Liu Huchuang, He Yonghong, Ma Fangxia, Meng Jiahui, Zhao Chunchen and Han Changchun, 2018. Geochemical characteristics of Lower Cretaceous source rocks and oil-source correlation in Hari sag, Yingen-Ejinaqi Basin. *Acta PetroleiSinica*, 39(1): 69–81.

Dow, W.G., 1977. Kerogen studies and geological interpretations. *Journal of Geochemical Exploration*, 7(2): 79–99.

Fang Ronghui, Li Meijun, Lü Haitao, Wang T.G., Yuan Yuan, Liu Yongli and Ni Zhiyong, 2017. Oil charging history and pathways of the Ordovician carbonate reservoir in the Tuoputai region, Tarim Basin, NW China. *Petroleum Science*, (4): 662–675.

Fu Xiaofei, LiZhaoying, Lu Shuangfang and Fu Guang, 2004. The study and application on using DT data to calculate the eroded strata. *Petroleum Geology and Oilfield Development in Daqing*, 23(1): 9–11 (in Chinese with English abstract).

Gleadow,A.J.W., Duddy, I.R., and Loving, J.F., 1983. Fission track analysis, a new tool for the evaluation of thermal histories and hydrocarbon potential. *Journal of the Australian Petroleum Production & Exploration Association,* 23(1): 93–102.

Haszeldine, R.S., Samson, I.M., and Cornfort, C., 1984. Dating diagenesis in a petroleum basin, a new fluid inclusion method. *Nature*, 307: 354–357.

Horsfield, B., and Mclimans, R.K., 1984. Geothermometry and geochemistry of aqueous and oil–bearing fluid inclusions from Fateh Field, Dubai. *Organic Geochemistry*, 6: 733–740.

Hao Fang and Chen Jianyu, 1988. Vitrinite reflectance may be used as marker of organic facies. *Geological science and technology information*, 7(4): 111–117 (in Chinese with English abstract).

He Sheng and Wang Qingling, 2012. The questions and discussion about the method by vitrinite reflectance to recover the thickness of eroded strata. *Geological review*, 35(2): 119–125 (in Chinese with English abstract).

Henry, P.H., 1996. Analysis of sonic well logs applied to erosion estimates in the Bighorn basin, Wyoming. *AAPG Bulletin*, 80 (5): 630–647.

Hu Shengbiao and Wang Jiyang, 1995. Principles and progresses on thermal regime of sedimentary basins: an overview. *Earth Science Frontiers*, 2(4): 171–179 (in Chinese with English abstract).

Hu Shengbiao, Wang Jiyang and Zhang Rongyan, 1999. Estimate the thickness of eroded strata by vitrinite reflectance data. *Petroleum Exploration and Development*, 26(4):42–45 (in Chinese with English abstract).

Hu Shaohua, 2004. Integrative structural–sedimentary analysis method based on seismic data: a new method for restoring denuded thickness. *Oil Geophysical Prospecting*, 39(4):478–483 (in Chinese with English abstract).

Hudson, S.M., and Hanson, A.D., 2010. Thermal maturation and hydrocarbon migration within La Popa Basin, northeastern Mexico, with implications for other salt structures. *AAPG Bulletin*, 94(3), 273–291.

Jiang Youlu, Fang Lei, Liu Jingdong, Hu Hong-Jin and Xu Tianwu, 2016. Hydrocarbon charge history of the Paleogene reservoir in the northern Dongpu Depression, Bohai Bay Basin, China. *Petroleum Science*, 13(4): 625–641.

Karlsen, D.A., Nedkvitne, T.,Larter, S.R., and Bjorlykke, K., 1993. Hydrocarbon composition of authigenic inclusions: application to elucidation of petroleum reservoir filling history. *GeochimicaEt Comochimca Acta*, 57(15): 3641–3659.

Katz, B.J., Phelfer, R.N., and Schunk, D.J., 1988.Interpretation of discontinuous vitrinite reflectance profiles. *AAPG Bulletin*, 72(8): 926–931.

Li Hongtao, 2016.Accumulation process and pattern of oolitic shoal gas pools in the platform: A case from Member 3 of Lower Triassic Feixianguan Formation in the Heba area, northeastern Sichuan Basin. *Petroleum Exploration and Development*, 43(5): 787–797.

Li Rongxi, Xi Shengli and Di Lingjun, 2006. Oil/Gas reservoiring phases determined through petrographic analysis of hydrocarbon inclusions in reservoirs taking Longdong oilfield, Ordos basin, as an example. *Oil and Gas Geology*, 27 (2): 194–199 (in Chinese with English abstract).

Liang Yu, Ren Zhanli, Wang Yanlong and Shi Zheng, 2010. Characteristics of fluid inclusions and reservoiring phases in the Yanchang Formation of Zichang area, the Ordos Basin. *Oil and Gas Geology*, 32(2): 182–190 (in Chinese with English abstract).

Liang Yu, Ren Zhanli, Shi Zheng, Zhao Xiaoyan, Yu Qiang and Wu Xiaoqing, 2011.Characteristics of hydrocarbon accumulation phases of the Yanchang Formation in the Fuxian–Zhengning area, the Ordos Basin. *Acta Petrolei Sinica*, 32(5): 741–748 (in Chinese with English abstract).

Liu Guocheng, Jin Zhijun and Li Jingchang, 1995. A new method on the quantitative study of depositional and erosional processed of sedimentary basins: an application of wave process analysis during basin evolution. *Acta Sedimentologica Sinica*, 13(3): 23–31 (in Chinese with English abstract).

Liu Shaobo and Gu Jiayu, 1997a. Application of fluid inclusions to petroleum geological study and disscussion.*Oil and Gas Geology*, 18(4): 326–331 (in Chinese with English abstract).

Liu Shaobo and Gu Jiayu, 1997b.Analytical methods of fluid inclusions and application to the study of hydrocarbon. *Petroleum Exploration and Development*, 24(3): 29–33 (in Chinese with English abstract).

Liu Yiqun and Zhou Lifa, 1997. Discussion on a method about eroded strata thickness references with Turpan and Hami Basin.*Journal of Northwest University* (Natural Science Edition), 27(4): 337–339 (in Chinese with English abstract).

Liu Xinshe, Zhou Lifa and Hou Yundong, 2007. Study of gas charging in the Upper Paleozoic of Ordos Basin using fluid inclusion. *Acta Petrolei Sinica*, 28(6): 37–41 (in Chinese with English abstract).

Lu Huangzhang, Fan Hongrui and Ni Pei, 2004. *Fluid inclusion.* Beijing: Science Press (in Chinese).

Lu Huangzhang and Guo Dijiang, 2000. Progress and trends of researches on fluid inclusions. *Geological Review*, 46(4): 385–390 (in Chinese with English abstract).

Lu Jincai, Wei Xianyang, Wei Jianshe and Li Yuhong, 2010. Petroleum geological conditions of Carboniferous– Permian in Ejina Banner and its vicinities, western Inner Mongolia, China. *Geological Bulletin of China*, 29(2/3): 330–340(in Chinese with English abstract).

Lu Jincai, Chen Gaochao, Wei Xianyang, Li Yuhong and Wei Jianshe, 2011a. Characteristics of surface hydrocarbon geochemical hydrocarbon anomalies in Ejin Banner and its vicinities, western Inner Mongolia. *Geological Bulletin of China*, 30(6): 850–858 (in Chinese with English abstract).

Lu Jincai, Chen Gaochao, Wei Xianyang, Li Yuhong and Wei Jianshe, 2011b. Carboniferous–Permian sedimentary formation and hydrocarbon generation conditions in Ejin Banner and its vicinities, western Inner Mongolia: a study of Carboniferous–Permian petroleum geological conditions (part 1). *Geological Bulletin of China*, 30(6): 811–826 (in Chinese with English abstract).

Lu Jincai, Chen Gaochao, Wei Xianyang, Li Yuhong and Wei Jianshe, 2011c. Post–sedimentary tectonic evolution, cap rock condition and hydrocarbon information of Carboniferous–Permian in Ejin Banner and its vicinities, western Inner Mongolia: a study of Carboniferous–Permian petroleum geological conditions (part 3). *Geological Bulletin of China*, 30(6): 838–849 (in Chinese with English abstract).

Lu Jincai, 2012. *Carboniferous–Permian geological conditions and resources perspective in Yingen–Ejin Banner Basin and its vicinities*. Beijing: Geological Publishing House (in Chinese).

Luo Xiao, Jiang Zhenxue, Li Zhuo, Li Feng, Liu Jianliang, Gao Tian and Feng Jie, 2015. The properties of petroleum inclusions and stages of hydrocarbon accumulation in Mesozoic–Cenozoic reservoirs in Yingmaili area of Tabei uplift, Tarim Basin. *Acta Petrolei Sinca*, 36(1): 60–66 (in Chinese with English abstract).

Magara, K., 1976.Thickness of removed sedimentary rocks, paleopore pressure and paleotemperature, southwestern part of Western Canada Basin. *AAPG Bulletin*, 60(4): 554–566.

Mclimans, R.K., 1987. The application of fluid inclusions to migration of oil and diagenesis in petroleum reservoirs. *Applied Geochemistry*, 2(5): 585–603.

Naeser, N.D., Naeser, C.W., and Mccullon, T.H., 1989a. *The application of fission track dating to depositional and thermal history of rock in sedimentary basins*. New York: Springer.

Naeser, C.W., and Mccullon, T.H., 1989b.*Thermal history of sedimentary basins: methods and case history*. Berlin: Spring–Verlag.

Nedkvitne, T., Karlsen, D.A., Bjorlykke, K., and Larter, S.R., 1993. Relationship between reservoir diagenetic evolution and petroleum emplacement in the Ula Field, North Sea. *Marine and Petroleum Geology*, 10(3):255–270.

Niu Zicheng, Liu Guangdi, Cao Zhe, Wang Peng, Chang Junhe and Zhang Kaidi, 2016. Reservoir characteristics and hydrocarbon accumulation in Chagan Sag, Yingen–Ejinaqi Basin. *Petroleum Geology and Experiment*, 38(1): 32–39 (in Chinese with English abstract).

Malaza, Ntokozo, Liu Ken and Zhao Baojin, 2016. Subsidence analysis and burial history of the late Carboniferous to early Jurassic soutpansbergbasin, Limpopo Province, South Africa. *Acta Geologica Sinica* (English Edition), 90(6): 2000–2007.

Qiu Nansheng, Hu Shengbiao and He Lijuan, 2004.*Theory and application of thermal mechanics research in sedimentary basin*. Beijing: Petroleum Industry Press (in Chinese).

Qiu Nansheng, Jiang Guang, Mei Qinghua and Wang Shengjun, 2010. Tectono–thermal evolution in the Bachu Uplift, Tarim Basin, China. *Acta Geologica Sinica* (English Edition), 84(5): 1286–1293.

Qiu Nansheng, Jiang Guang, Mei Qinghua, Chang Jian, Wang Shengjun and Wang Jiyang, 2011. The Paleozoic tectonothermal evolution of the Bachu Uplift of the Tarim Basin, NW China: Constraints from (U–Th)/He ages, apatite fission track and vitrinite reflectance data. *Journal of Asian Earth Sciences*, 41(6): 551–563.

Qiu Nansheng, Chang Jian, Zuo Yinhui, Wang Jiyang and Li Huili, 2012a. Thermal evolution and maturation of lower Paleozoic source rocks in the Tarim Basin, northwest China. *AAPG Bulletin*, 96(96): 789–821.

Qiu Nansheng, Chang Jian, Li Jiawei, Li Wenzheng, Lu Yun and Li Huili, 2012b. New evidence on the Neogene uplift of South Tianshan: Constraints from the (U–Th)/He and AFT ages of borehole samples of the Tarim Basin and implications for hydrocarbon generation. *International Journal of Earth Sciences*, 101(6): 1625–1643.

Ren Jishun, 1999.*Tectonic map of China and adjacent area (1: 5000000) and brief description–global tectonics of China*.Beijing: Geological Publishing House (in Chinese).

Ren Jishun, 2003. A brief introduction of the latest tectonic map of China. *Acta Geoscientia Sinica*, 24(1): 1–2 (in Chinese with English abstract).

Ren Zhanli, 1991. Discussion on paleogeothermal recovery in sedimentary basin. *Journal of Northwest University*, 21(S): 227–234 (in Chinese with English abstract).

Ren Zhanli, 1992. Advance on thermal histories of sedimentary basin. *Advance in Earth Science*, 7(3): 43–49 (in Chinese with English abstract).

Ren Zhanli, Zhao Zhongyuan, Zhang Jun and Yu Zhongping, 1994. Research on paleotemperature in the Ordos Basin. *Acta Sedimentologica Sinca*, 12(1): 56–65 (in Chinese with English abstract).

Ren Zhanli, 1999. *Research on tectonic thermal evolution history in sedimentary basins of North China*. Beijing: Petroleum Industry Press (in Chinese).

Ren Zhanli, Liu Chiyang, Zhang Xiaohui, Wu Hanning, Chen Gang, Li Jinbu and Ma Tuanxiao, 2000. Recovery and comparative research of thermal history on Jiuquan basin group. *Chinese Journal of Geophysics*, 43(5): 635–645 (in Chinese with English abstract).

Ren Zhanli, Liu Li, Cui Junping, Xiao Hui and Gao Shengli, 2008. Application of tectonic thermal evolution history to hydrocarbon accumulation timing in sedimentary basins. *Oil and Gas Geology*, 29(4): 502–506 (in Chinese with English abstract).

Ren Zhanli, Tian Tao, Li Jinbu,Wang Jiping, Cui Junping, Li Hao, Tang Jianyun and Guo Ke, 2014a. Review on methods of thermal evolution history in sedimentary basins and thermal evolution history reconstruction of Superimposed Basins. *Journal of Earth Sciences and Environment*, 36(3): 1–20 (in Chinese with English abstract).

Ren Zhanli, Cui Junping, Li Jinbu, Wang Jiping, Guo Ke, Wang Wei, Tian Tao, Li Hao, Cao Zhanpeng and Yang Peng, 2014b. Tectonic thermal history reconstruction of Ordovician in the Weibei Uplift of Ordos Basin. *Acta Geologica Sinica*, 88(11): 2044–2056 (in Chinese with English abstract).

Ren Zhanli, Cui Junping, Guo Ke, Tian Tao, Li Hao, Wang Wei, Yang Peng and Cao Zhanpeng, 2015a. Fission–track analysis of uplift times and processes of the Weibei Uplift in the Ordos Basin.*Chinese Science Bulletin*, 60(14): 1298–1309 (in Chinese with English abstract).

Ren Zhanli, Cui Junping, Liu Chiyang, Li Tiejun, Chen Gang, Dou Shuang, Tian Tao and Luo Yating, 2015b. Apatite fission track evidence of uplift cooling in the Qiangtang Basin and constraints on the Tibetan Plateau uplift. *Acta Geologica Sinica* (English Edition), 89(2): 467–484.

Shen Lijian, Liu Chenglin, Wang Licheng, Hu Yufei, Hu Mingyue and Feng Yuexing, 2017. Degree of brine evaporation and origin of the mengyejing potash deposit: evidence from fluid inclusions in Halite. *Acta Geologica Sinica* (English Edition), 91(1):175–182.

Shi Baohong, Zhang Yan, Chen Jie and Zhang Lei, 2014. Characteristics and geological significance of fluid inclusions in Mesozoic reservoirs in Dingbian area, Ordos basin. *Acta Petrolei Sinca*, 35(6): 1087–1094(in Chinese with English abstract).

Shi Baohong, Zhang Yan, Zhang Lei, Huang Jing and Tang Chao, 2015. Dating of hydrocarbon accumulation by fluid inclusion characteristics in the Chang9 of Yanchang Formation in Jiyuan area, the Ordos Basin. *Oil and Gas Geology*, 36(1): 17–22(in Chinese with English abstract).

Shi Changlin, Ji Youliang, Li Qingshan and Liu Dehong, 2011. Using a new method based on homogeneity temperature of fluid inclusion to restore the thickness of eroded strata of Che–Mo Paleo–Uplift in Jungger Basin. *Journal of Jilin University* (Earth Science Edition), 41(1): 64–69 (in Chinese with English abstract).

Suggate, R.P., 1998. Relations between depth of burial, vitrinite reflectance and geothermal gradient. *Journal of Petroleum Geology*, 21(1): 5–32.

Sahu, H.S., Raab, M.J., Kokn, B.P., Gleadow, A.J.W., and Bal, K.D., 2013. Thermal history of the Krishna–Godavari basin, India: constraints from apatite fission track thermochronology and organic maturity data. *Journal of Asian Earth Sciences*, 73, 1–20.

Sweeney, J.J., and Burnham, A.K., 1990. Evaluation of a simple model of vitrinite reflectance based on chemical kinetics. *AAPG Bulletin*, 74: 1559–1570.

Tao Shizhen, 2006. Sequence of diagenetic authigenic mineral, the basis of timing the inclusions formation in the sedimentary rocks. *Petroleum Exploration and development*,33(2): 154–160 (in Chinese with English abstract).

Tian Tao, Ren Zhanli, Ma Guofu, Zhang Ruisheng, Yang Zhiming, Guo Ke and Dong Xin, 2014. The relations of hydrocarbon generation to the geochemical features and maturity evolution of source rocks in the Sartai Sag, Yabrai Basin. *Progress in Geophysics*, 29(6): 2745–2753 (in Chinese with English abstract).

Tian Tao, Ren Zhanli, Wu Xiaoqing, Ma Guofu, Zhang Ruisheng, Yang Zhiming and Guo Ke, 2015.The Paleogeothermal field and hydrocarbon accumulation period in Sartai Depression, Yabrai Basin. *Acta Sedimentologica Sinica,* 33(4): 836–844 (in Chinese with English abstract).

Tian Tao, Ren Zhanli, Yang Peng, Cao Zhanpeng and Yang Fu, 2016. Application of multi–methods for recovering denuded strata thickness of the Jurassic and Cretaceous in Yabrai Basin of Inner Mongolia and its geological significance. *Journal of Palaeogeography*, 18(6): 1002–1011 (in Chinese with English abstract).

Tong Yanming, Song Lijun, Zeng Shaojun, Chen Tao and Wei Yuning, 2005.A new method by vitrinite reflectance to estimate thickness of eroded strata. *Journal of Palaeogeography*, 7(3): 417–423(in Chinese with English abstract).

Tong Yanming and Zhu Guanghui, 2006.Some important problems about the method by vitrinite reflectance to recover the formation denudation. *Journal of Hydrocarbon Technology*, 28(3): 197–199 (in Chinese).

Wang XinMing, Li Xiangbo, Guo Yanru and Li Tianshun, 2004. Transformation dynamic forces and hydrocarbon accumulation of the Yinggen–Ejinaqi Basin. *Petroleum Geology and Experiment*, 26(5): 442–447 (in Chinese with English abstract).

Wang Xiaoduo, Liu Huchuang, Yu Jun, Chen Zhijun, He Xiao, Li Keshe, Liu Tao and Han Changchun, 2015. Research on petroleum geological conditions and prediction of favorable exploration zone in Hari sag of Yingen–Ejinaqi Basin. *Science Technology and Engineering*, 15(36): 142–147 (in Chinese with English abstract).

Xiao Hui, Zhao Jingzhou, Yang Haijun, Cai Zhenzhoong, Zhang Lijuan and Zhu Yongfeng, 2012. Evidence of fluid inclusions for the hydrocarbon charging history of Ordovician reservoirs in Yingmaili low–uplift, northern Tarim Basin. *Acta Petrolei Sinca*, 33(3): 372–378 (in Chinese with English abstract).

Xu Fanghao, Xu Guosheng, Liang Jiaju, Yuan Haifeng, Liu Yong and Xu Fanggen, 2016. Multi–stage fluid charging and critical period of hydrocarbon accumulation of the Sinian Dengying Formation in central Sichuan Basin. *Acta GeologicaSinica* (English Edition), 90(4):1549–1550.

Xu Guosheng, Zhang Lijun, Gong Deyu, Wang Guozhi, Yuan Haifeng, Li Changhong and Hu Xiaofeng, 2014. Hydrocarbon accumulation process in the marine strata in Jianghanplain area, middle China. *Acta Geologica Sinica* (English edition), 88(3): 878–893.

Yang Peng, Ren Zhanli, Tian Tao, Zhao Xiaoyan and Qi Kai, 2016. The geochemical characteristics of Lower Cretaceous hydrocarbon source rocks in Modamuji depression, Hailaer basin. *Acta Scientiarum Naturalium Universitatis Sunyatseni*, 55(6): 35–43(in Chinese with English abstract).

Yang Peng, Ren Zhanli, Xia Bin, Zhao Xiao Yan, Tian Tao, Huang Qiangtai and Yu Shengrui, 2017a.The Lower Cretaceous source rocks geochemical characteristics and thermal evolution history in the Hari Sag, Yin–E Basin, *Petroleum Science and Technology*, 35(12): 1304–1313.

Yang Peng, Ren Zhanli, Xia Bin, Liu Weiliang and Huang Qiangtai, 2017b. Tectonic–thermal evolution history and its controls on petroleum geology of Weibei Uplift. *Acta Geologica Sinica* (English Edition), 91(supp.1): 144–145.

Ye Jiaren and Yang Xianghua, 2003. Characteristics of the temperature and pressure fields in the Chagan sag of Yinggen–Ejinaqi Banner basin and their petroleum geological significance. *Nature Gas Industry*, 23(2): 15–19(in Chinese with English abstract).

Yin Jiyuan, Chen Wen, Xiao Wenjiao, Zhang Bin and Cai Deka, 2015. Multi–Method chronometric constraints on the thermal evolution of the central Tianshan, NW China. *Acta Geologica Sinica* (English Edition), 89(6): 2092–2093.

Zhai Guangming, 2002. On prospective hydrocarbon resources of China in 21st Century. *Xinjiang Petroleum Geology*, 23(4): 271–278 (in Chinese with English abstract).

Zhao Zhongyuan, Liu Chiyang and Ren Zhanli, 1990. Geology of petroliferous basins and their systematic engineering in research. *Oil and Gas Geology*, 11(1): 108–113(in Chinese with English abstract).

Zhao Libin, Huang Zhilong, Gao Gang and Li Jun, 2006. A new method for estimating the removed thickness of sediment using homogenization of fluid inclusions. *Journal of Xi'an Shiyou University* (Natural Science Edition), 21(1): 15–19(in Chinese with English abstract).

Zhao, Y.T., Shao, X.L., and Sun, J., 2015. Geochemical characteristics and hydrocarbon generation processes of cretaceous source rocks in the Songliao Basin. *Petroleum Science and Technology*, 33(4): 443–451.

Zhao Chunchen, Liu Huchuang, Ren Laiyi, Chen Zhijun, Li Keshe, Bai Xiaoyin and Wang Xiaoduo, 2017. Geological environment and prospective significance of Cretaceous gas reservoir in Well YHC–1 of Yin'e Basin. *Natural Gas Geoscience*, 28(3): 439–451 (in Chinese with English abstract).

Zheng Chaofei, Zhang Zhengwei, Wu Chengquan and Yao Junhua, 2017. Genesis of the Ciemas gold deposit and relationship with epithermal deposits in West Java, Indonesia: constraints from fluid inclusions and stable isotopes. *Acta Geologica Sinica* (English Edition), 91(3):1025–1040.

Zheng Lei, Jin Zhijun, Zhou Jin,Lu Xueyan, Liu Zhiqiang, Javed Ismail and Li Yanhua, 2015. Timing of hydrocarbon accumulation of the Paleozoic reservoir in Rub Al Khail Basin.*Oil and Gas Geology*, 36(3): 378–384 (in Chinese with English abstract).

Zhou Lu, Zheng Jinyun, Lei Dewen, He Dengfa, Tang Yong, Shi Xinpu, Pang Lei and Yang Zhili, 2007. Recovery of eroded thickness of the Jurassic of Chemo palaeouplift in Junggar Basin. *Journal of Palaeogeography*, 9(3): 243–252 (in Chinese with English abstract).

Zhu Yanming, Qin Yong, SangShuxun, Chen Shangbin and LanXiaodong, 2010. Hydrocarbon generation evolution of Permo–Carboniferous rocks of the Bohai Bay Basin in China. *Acta Geologica Sinica* (English Edition), 84(2): 370–381.

Zuo Yinhui, Qiu Nansheng, Zhang Yuan, Li Cuicui, Li Jianping, Guo Yonghua and Pang Xiongqi, 2011. Geothermal regime and hydrocarbon kitchen evolution of the offshore Bohai Bay Basin, North China. *AAPG Bulletin*, 95(5):749–769.

Zuo Yinhui, Ma Weiming, Deng Yixun, Hao Qingqing, Li Xinjun, Guo Junmei, Ran Qing and Wang Lirong, 2013. Mesozoic and Cenozoic thermal history and source rock thermal evolution history in the Chagan Sag, Inner Mongolia. *Earth Science–Journal of China University of Geosciences*, 38 (3): 554–560 (in Chinese with English abstract).

Zuo Yinhui, Zhang Wang, Li Zhaoying ,Li Jiawei, Hao Qingqing and Hu Jie, 2015a. Mesozoic and Cenozoic tectono–thermal history in the Chagan Sag, Inner Mongolia. *Chinese Journal of Geophysics*, 58(7): 2366–2379 (in Chinese with English abstract).

Zuo Yinhui, Qiu Nansheng, Hao Qingqing, Pang Xiongqi, Gao Xia, Wang Xuejun, Luo Xiaoping and Zhao Zhongying, 2015b. Geothermal regime and source rock thermal evolution in the Chagan sag, Inner Mongolia, northern China. *Marine and Petroleum Geology*, 59: 245–267.

About the First Author

YANG Peng, Male; born in 1990 in Qianjiang City, Hubei Province; graduated from the Department of Geology, Northwest University (bachelor's and master's degree), and is now a 2nd Ph. D student of the School of Marine Science, Sun Yat–sen University. His current interest is structural geology and basin analysis. Address: Sun Yat–sen University, No. 135, Xingang Xi Road, Guangzhou, Guangdong Province, 510275. Email: 13909263435@163.com.