Journal of Earth Science, Vol. 24, No. 4, p. 599–605, August 2013 *ISSN 1674-487X*
Printed in China
DOI: 10.1007/s12583-013-0355-9

Mesozoic Tectonic Evolution and Thermal History of the Yuanba Area of Northeast Sichuan Basin—Low-Temperature Thermochronology of Apatite and Zircon

Jie Wang* (王杰), **Tenger Boltsjun** (腾格尔), **Jianzhong Qin** (秦建中),
Wenhui Liu (刘文汇), **Cheng Tao** (陶成), **Ping Wang** (王萍)
Wuxi Institute of Petroleum Geology, SINOPEC, Wuxi 214151, *China*

ABSTRACT: By means of the vitrinite reflectance and U-Th/He dating of apatite and zircon in cutting samples from the T_3x–K_1j formations in the Yuanba (元坝) area of Northeast Sichuan (四川) Basin, a correlation has been established between the He-derived age and depth/temperature in this area assuming helium closure temperature of apatite in this area being 95 ℃. Mesozoic strata (T_3x–K_1j) experienced helium closure temperature of apatite approaching 95 ℃, but didn't reach the helium closure temperature of zircon (ca. 170–190 ℃) although some reached the highest palaeogeothermal temperature of about 170 ℃. The Mesozoic strata in the Yuanba area experienced an important uplift and denudation during Paleogene–Neogene periods (0.2–36.4 Ma), the erosion rate being about 109.9 m/Ma. The K_1j Formation and overlying strata experienced a maximum denudation loss of about 4 000 m. Geotemperatures gradually fell to the helium closure temperature of apatite and then fell further to the current temperature. The thermal evolution history of this area indicates that the maximum palaeogeothermal temperature of Mesozoic strata was close to 170–190 ℃, prior to the strata being uplifted. During the period between 176 and 36 Ma, the palaeogeothermal temperature fell to 95–170 ℃, and after 36 Ma, it continued to fall to the present geotemperature of less than 95 ℃.

KEY WORDS: vitrinite reflectance, U-Th/He dating of apatite and zircon, denudation thickness, thermal evolution history, Yuanba.

INTRODUCTION

There are three methods available to determine the thermal evolution reconstruction of a sedimentary basin: 1. Forward method using a thermal kinetic model to recover the thermal history (He, 2000; Mckenzie, 1978). 2. Inversion method which uses a range of geothermometers to recover the paleogeotemperature (Qin et al., 2008a, b; Xu et al., 2008; Yuan et al., 2008). 3. Synthesis method which combines the forward method with the inversion method (Ren et al., 2008). The geothermometer method is recognized as highly precise and practical and has been employed successfully in many scientific studies

This study was jointly supported by the National Basic Research Program of China (No. 2012CB214801) and China Petroleum and Chemical Corporation Program (No. P120009).
*Corresponding author: wangjielz@126.com
© China University of Geosciences and Springer-Verlag Berlin Heidelberg 2013

Manuscript received October 22, 2012.
Manuscript accepted February 6, 2013.

?1994-2015 China Academic Journal Electronic Publishing House. All rights reserved. http://www.cnki.net

(Qiu et al., 2006; He et al., 2004; Cao et al., 2000; Wang and Liu, 1996). In recent years, the developing method of U-Th/He dating of apatite and zircon provides a new paleothermometer able to provide information on the cooling history of geological bodies under low temperatures and can be applied to analyze the thermal history reconstruction of a sedimentary basin, in combination with vitrinite reflectance and fission track data (Qin et al., 2010). Several minerals have been investigated for U-Th/He dating, such as apatite, zircon, titanite and fluorite (Evans et al., 2005) which exploit differences in the closure temperatures of different minerals (Reiners et al., 2002; Reiners and Farley, 1999; Wolf et al., 1996). By combining U-Th/He thermochronology with other paleogeothermometers (fission track, vitrinite reflectance, etc.), the dynamic evolution history of sedimentary basin can be inferred (Wolf et al., 1998).

GEOLOGICAL SETTINGS

The Northeast Sichuan Basin lies between the Wangcang-Nanjiang and Xuanhan-Dazhou areas and has an area of about 2.5×10^4 km^2. It is situated in the northern part of the Upper Yangtze Block, which is a complex pellicle distortion system made up of the Paleozoic and Mesozoic strata. Following basement formation in the Jinning Period, the area evolved successively into a passive continental margin basin from the Sinian to the Middle Triassic, a foreland basin in the Late Triassic, an intracontinental depression basin from the Jurassic to the Early Cretaceous, a shrinkage basin in the Late Cretaceous, followed by a tectonic evolution of uplift and denudation (Guo et al., 1996). Marine facies made up of carbonate and clastic rocks developed between the Sinian and the Middle Triassic, followed by clastic rocks deposited on land from the Upper Triassic to the Lower Cretaceous. There have been some studies of the thermal history in this region (Shen et al., 2007; Lu et al., 2005; Wang et al., 1998; Han and Wu, 1993) but there has been little research on the thermal history of geotemperature changes over time in the area. Given the importance of the Northeast Sichuan Basin as an emerging exploration target, there is a need to study the structure and thermal history of the area to evaluate its natural gas potential. Commercial gas flows from the Feixianguan and Changxing formations demonstrate the high prospectivity of the Northeast Sichuan Basin. By means of U-Th/He dating of apatite and zircon, the thermal evolution history of the Northeast Sichuan Basin has been elucidated and a picture developed of the tectonic evolution and reservoir formation in this area.

SAMPLE AND EXPERIMENT

Finding appropriate apatite and zircon grains is the key to acquire accurate helium age data. Because the T_3x–K_1j formations in Yuanba area comprises clastic rocks namely sandstone or sand-bearing mudstone, appropriate apatite and zircon grains could be obtained for U-Th/He analysis. Samples were obtained from drilling cuttings of the T_3x–K_1j formations of the Yuanba 3 well, at depths derived from the drilling data. Suitable apatite and zircon grains were selected and then their U-Th/He ages were determined at the Commonwealth Scientific and Industrial Research Organization (CSIRO) laboratories in Australia as described elsewhere. U-Th/He ages were corrected for the alpha emission effect (Farley et al., 1996). U-Th/He ages of apatite and zircon in the area are given in Table 1.

TECTONIC AND DYNAMIC THERMAL EVOLUTION HISTORY INVERSION

Because the closure temperatures of different minerals vary greatly, so the denudation rate and denudation thickness of sedimentary strata are recovered and then the time-temperature dynamic thermal evolution history are reversed in accordance with the differences of He age and closure temperature, and geotemperature gradient in different mineral in U-Th/He system (Qin et al., 2010) (Fig. 1).

U-Th/He Closure Temperature and Age

The U-Th/He ages of apatite from the T_3x^2–K_1j formations in the Yuanba area of Northeast Sichuan Basin are much less than the sample depositional ages, which indicates that all the samples have undergone He closure temperature of apatite. The U-Th/He ages of apatite in drill samples in the Yuanba area gradually decrease with burial depth or geotemperature increasing in the present (Fig. 2), indicating that the

?1994-2015 China Academic Journal Electronic Publishing House. All rights reserved. http://www.cnki.net

Table 1 The U-Th/He ages of apatite and zircon in Yuanba 3 in Northeast Sichuan Basin

Formation	Depth (m)	Elevation (m a.s.l.)	Apatite He age (Ma)		Zircon He age (Ma)	Zircon undergoing temperature	Current geotemperature (℃)
			Single grain	Average			
K_1j	87	390.3	35.7 13.1 60.5	36.4 Ma Close to closure temperature <100 ℃	157.5 178.6	Haven't undgergone closure temperature of zircon	25
J_1z	4 154.5	-3 677.2	14.9 20.9 17.8 5.9	14.9 Ma Underwent closure temperature >100 ℃	194.5 135.2	Close to closure temperature of zircon	95
T_3x^4	4 372	-3 894.7	-		194.1 168.1 127.0	Close to closure temperature of zircon	98
T_3x^4	4 476.5	-3 999.2	0.2 1.2 2.8 1.3 2.4	1.6 Ma Underwent closure temperature >100 ℃	111.9 220.2 97.3 112.0	Close to closure temperature of zircon	100
T_3x^2	4 776.5	-4 299.2	0.2 0.1 0.2	0.17 Ma underwent closure temperature >100 ℃	182.1 149.1 222.2 181.0 163.6 202.0	Close to closure temperature of zircon	105

Note: Based on thermal gradient being 1.7 ℃/100 m, temperature was derived. Surface temperature is 24 ℃

smaller the sedimentation age is, the higher the apatite age is. The evolution characteristics of U-Th/He ages accompanying with temperature/depth reflect an apatite closure temperature of the U-Th/He system in the area being about 95 ℃ with the burial depth being about 4 500 m.

U-Th/He ages of apatite from the K_1j Formation are relatively dispersive, ranging from 13.1 to 60.5 Ma and located in the helium partial retention zone. The helium thermal reset of apatite demonstrates that this sample is very close to the closure temperature of apatite. The highest paleogeotemperature of these samples approaches the apatite closure temperature, but the other samples have already undergone the apatite closure temperature. U-Th/He ages of apatite in the T_3x^2–K_1j formations vary from 0.1 to 60.5 Ma in Yuanba. Their averages range from 0.2 to 36.4 Ma, indicating that the Mesozoic Formation was uplifted and denuded during the Paleogene and the Neogene (Table 1, Fig. 2). The uplift time of above formation in the Yuanba area was slightly later than that in Puguang and was earlier than that in the Tongjiang-Nanjiang-Bazhong area (Qin et al., 2010). The paleogeotemperature gradually reduced to the apatite closure temperature until current geotemperatures were reached.

Inferred U-Th/He ages of zircon from the K_1j Formation in Yuanba of 157.5 and 178.6 Ma, are far

?1994-2015 China Academic Journal Electronic Publishing House. All rights reserved. http://www.cnki.net

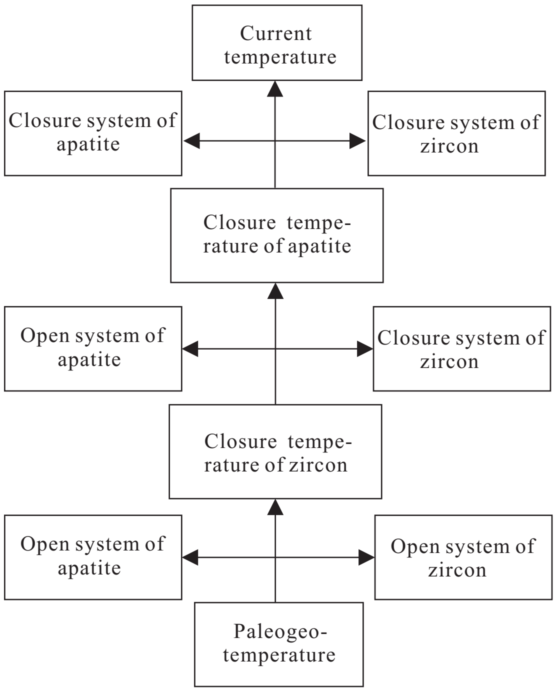

Figure 1. The U-Th/He dating system and clock effect of apatite and zircon.

greater than the sample sedimentation age (Table 1 and Fig. 2), indicating that the maximum paleogeotemperature of the sample has not exceeded the He closure temperature of zircon, and the zircon grain of this sample has not reset to the last thermal event or partly reset. The zircon grains of the K_1j Formation in the Yuanba area originate from the denudation region undergoing the closure temperature of zircon in the Jurassic. U-Th/He ages of zircon in some samples from the T_3x^2–J_1z formations are greater than the sedimentation age and relatively disperse, demonstrating that the above samples may have reached a maximum paleogeotemperature of about 170 ℃. A map of the burial history confirms this conclusion (Fig. 2).

With the augment of burial depth or current geotemperatures, He ages of apatite and their ranges gradually decrease, indicating that the sample in this region have undergone the closure temperature of apatite (Fig. 3). He ages indicate that the formation has undergone a strong uplift and denudation during the Paleogene and the Neogene. The He ages of zircon and their range increases with the current geotemperature or the burial depth increasing demonstrates that the Mesozoic Formation in this region has not undergone the closure temperature of zircon and is still located in the helium partial retention zone. The uppermost geotemperature of these samples was close to the closure temperature of zircon, so the zircon He ages reflects to a certain extent the sample sedimentary age.

Denudation History Reconstruction

In Yuanba area, the Mesozoic Formation was uplifted and denuded during the Paleogene and the Neogene. If we assume a constant paleogeotemperature gradient, by means of the age-elevation method (Gleadow and Fitzgerald, 1987), we calculated that the average exhumation rate is about 109.9 m/Ma and the average cooling rate was about 1.9 ℃/Ma. Since the apatite grains of the K_1j Formation are located in the helium partial retention zone, its uppermost paleogeotemperature has ever been close to the closure temperature of apatite. The maximum denudation thickness of the K_1j Formation and above the formations is about 4 000 m. According to zircon-derived He ages, the region experienced uplift and denudation in the Jurassic.

The equation between for the observed *R*o (*R*b) and the buried depth in Yuanba area is: D=4 305.8Ln(VRo/R_b)+1 655.3 (R^2=0.89), where D is the depth (m), and *VR*o or *R*b means the vitrinite reflectance or asphalt reflectance, respectively. The bigger the line gradient in this plot is, the lower the paleogeotemperature gradient is (Fig. 4). When the *R*o value is about 0.25% at the surface, the corresponding depth is -4 300 m. It was calculated that the maximum denudation thickness of the well is about 4 300 m in accordance with the denudation thickness obtained from the U-Th/He age of apatite and the closure temperature in the region. So the calculated denudation thickness of the K_1j Formation and above is about 4 000 m.

Dynamic Thermal History

The U-Th/He ages of apatite of drill samples from T_3x^2–K_1j formations in Yuanba area gradually decrease with increasing burial depth or present-day geotemperatures indicating that all samples have undergone the closure temperature of apatite (Table 1 and Fig. 4). When the buried depth is about 4 800 m, the helium ages of zircon are less than the stratum

?1994-2015 China Academic Journal Electronic Publishing House. All rights reserved. http://www.cnki.net

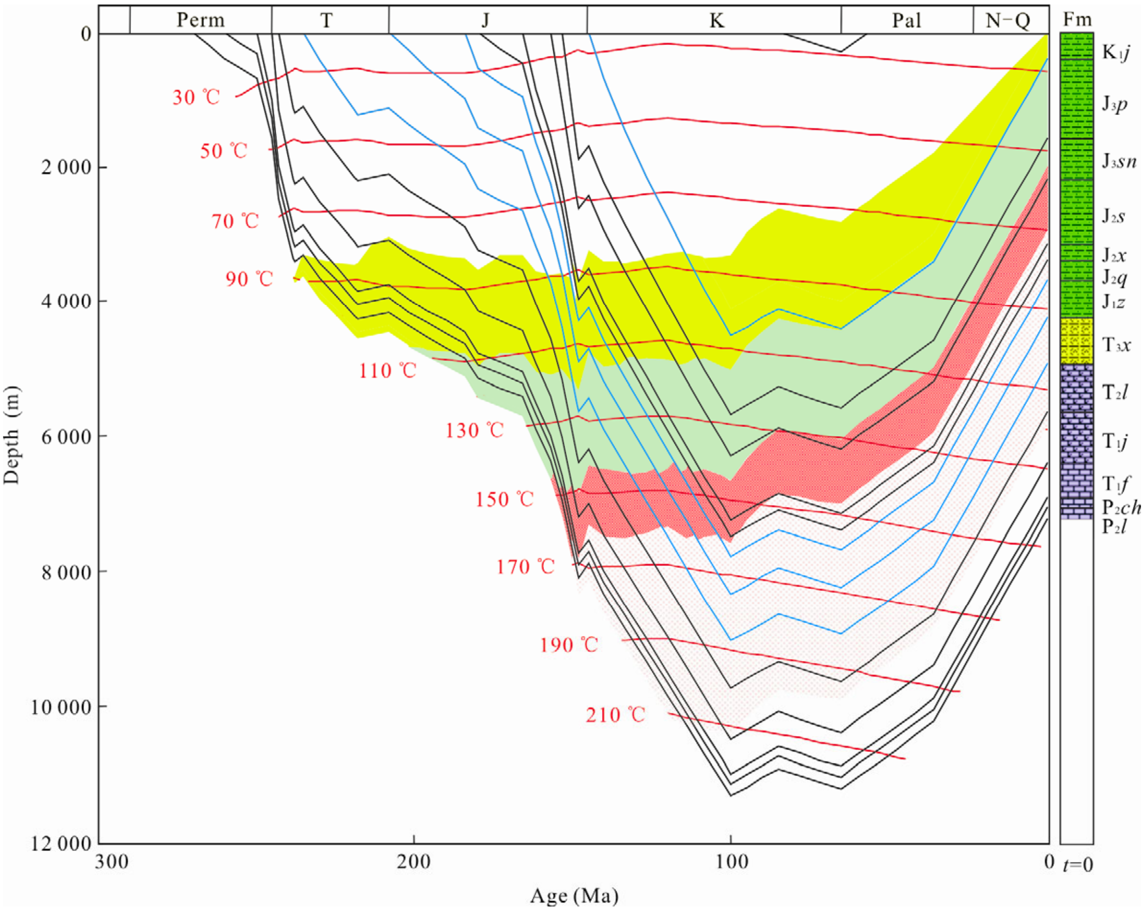

Figure 2. The burial history and thermal evolution history map of the well of Yuanba 3 in the northeast of Sichuan Basin.

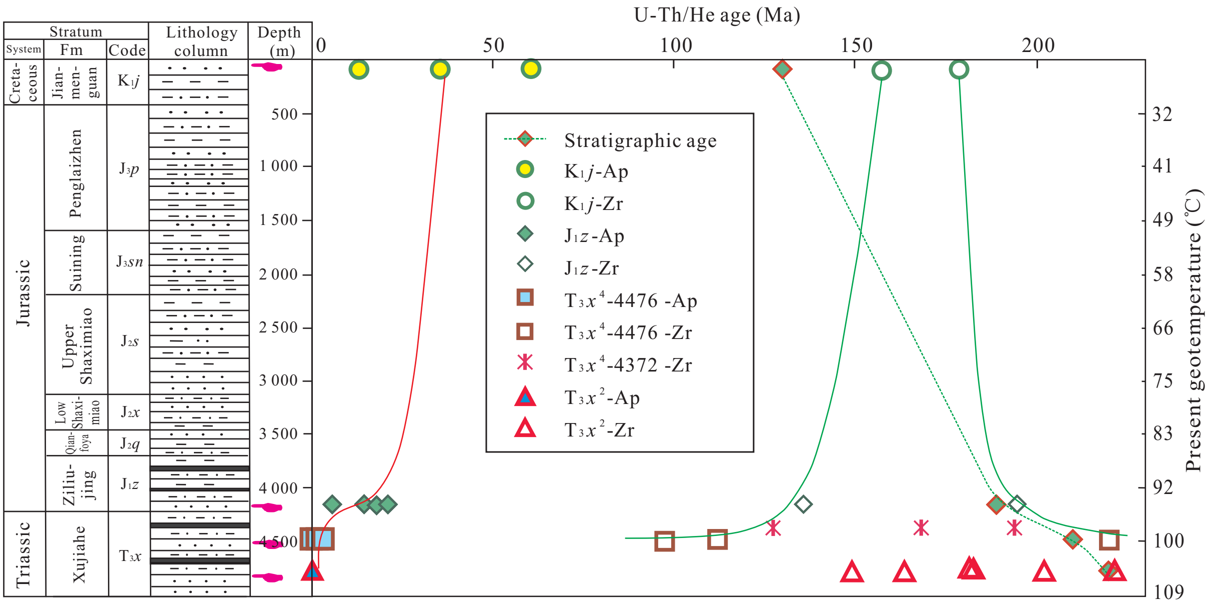

Figure 3. The relationship between present temperature and U-Th/He ages of apatite and zircon, and burial depth in Yuanba area (according to data from Yuanba 1, the surface average temperature is 24 ℃ and average geothermal gradient is 1.7 ℃/100 m).

?1994-2015 China Academic Journal Electronic Publishing House. All rights reserved. http://www.cnki.net

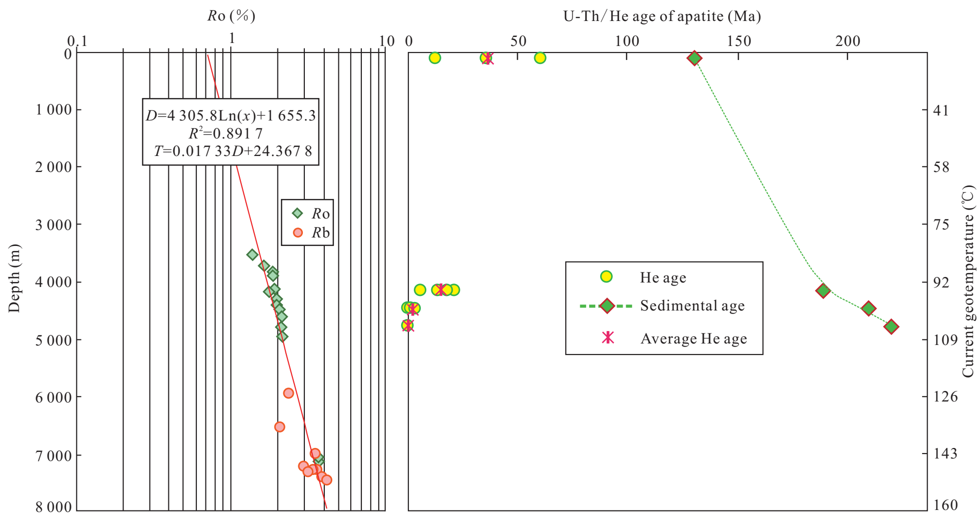

Figure 4. The correlation among vitrinite/bitumen reflectance, the U-Th/He ages of apatite and zircon, and present burial depth of Yuanba 3 well in the Northeast Sichuan Basin.

sedimentary age, and the maximum paleogeotemperature is probably close to the closure temperature of zircon. When the burial depth of the samples is greater than 4 800 m, the maximal paleogeotemperatures of Mesozoic strata are close to 170–190 ℃. After the Jurassic, the Mesozoic strata began to uplift and the paleogeotemperature dropped. During the period between 176 and 35.7 Ma, the paleogeotemperature of the Mesozoic strata fell to a certain point between 95 and 170 ℃. After 35.7 Ma, the paleogeotemperature continued to get into the closure temperature of apatite and the present temperature is less than 95 ℃. So the burial history is restricted by the time by which the apatite closure temperature of the samples in different strata is reached.

CONCLUSIONS

According to these new U-Th/He ages of apatite and zircon from drill cuttings in the Yuanba area, combined with data from the organic matter vitrinite reflectance and other paleothermometers, it has been possible to reconstruct the dynamic thermal history of the Mesozoic strata in the Yuanba area in the Northeast Sichuan Basin.

(1) U-Th/He ages of apatite in the drilling samples gradually decrease with increasing burial depth or present-day geotemperatures, indicating that the smaller the sedimentation age, the bigger the apatite age. The evolution model between U-Th/He ages of apatite and geotemperature/depth is established and reflects a closure temperature of apatite in the area being about 95 ℃ with the burial depth being about 4 500 m.

(2) The Mesozoic strata underwent significant uplift and denudation during the Paleogene and the Neogene in Yuanba. The average exhumation rate is about 110 m/Ma and the maximum denudation thickness of the K_1j Formation and above the formations is calculated to be about 4 000 m.

(3) Temperatures in the Mesozoic strata fell from just below the closure temperature of zircon to about the closure temperature of apatite in Yuanba. In contrast, the maximum geotemperature of the sample from the K_1j Formation is close to the closure temperature of apatite. After the Jurassic, the Mesozoic strata began to uplift and the paleogeotemperature dropped. During the period between 176 and 35.7 Ma, the paleogeotemperature of the Mesozoic strata fell to 95 from 170 ℃. After 35.7 Ma, the paleogeotemperature continued to fall to the closure temperature of apatite and the present geotemperature is lower than 95 ℃. So reconstructions of the burial history are restricted by the time at which sediments reach the apatite closure temperature in different strata.

REFERENCES CITED

Cao, C. Q., Shang, Q. H., Fang, Y. T., 2000. The Study of Graptolite Reflectance as the Indicator of Source Rock Maturation in Ordovician and Silurian of Tarim Basin, Ordos, Jiangsu Areas. *Acta Palaeontologica Sinica*, 39(1): 151–156 (in Chinese

?1994-2015 China Academic Journal Electronic Publishing House. All rights reserved. http://www.cnki.net

with English Abstract)

Evans, N. J., Wilson, N. S. F., Cline, J. S., et al., 2005. Fluorite (U-Th)/He Thermochronology: Constraints on the Low Temperature History of Yucca Mountain, Nevada. *Applied Geochemistry*, 20(6): 1099–1105

Farley, K. A., Wolf, R. A., Silver, L. T., 1996. The Effects of Long Alpha Stopping Distances on U-Th/He Ages. *Geochimica et Cosmochimica Acta*, 60(21): 4223–4229

Gleadow, A. J. W., Fitzgerald, P. G., 1987. Uplift History and Structure of the Transantarctic Mountains: New Evidence from Fission Track Dating of Basement Apatite in the Dry Valleys Area, Southern Victorialand. *Earth and Planetary Science Letters*, 82(1–2): 1–14

Guo, Z. W., Deng, K. L., Han, Y. H., et al., 1996. The Formation and Evolution of Sichuan Basin. Geological Publishing House, Beijing. 48–88 (in Chinese)

Han, Y. H., Wu, C. S., 1993. Geothermal Gradient and Heat Flow Values of Some Deep Wells in Sichuan Basin. *Oil* & *Gas Geology*, 14(1): 80–84 (in Chinese with English Abstract)

He, L. J., 2000. Advance in Tectono-Thermal Modeling of Sedimentary Basins. *Advance in Earth Sciences*, 15(6): 661–665 (in Chinese with English Abstract)

He, M. C., Lü, X. B., Liu, Y. R., 2004. Elementary Investigation on the Application of Laser Raman Microprobe in Petroleum Exploration. *Spectroscopy and Spectral Analysis*, 24(11): 1363–1366 (in Chinese with English Abstract)

Lu, Q. Z., Hu, S. B., Guo, T. L., et al., 2005. The Background of Geothermal Field for the Formation of Abnormal High Pressure in Northeastern Sichuan Basin. *Chinese Journal of Geophysics*, 48(5): 1184–1191 (in Chinese with English Abstract)

Mckenzie, D., 1978. Some Remarks on the Development of Sedimentary Basins. *Earth and Planetary Science Letters*, 40(1): 25–32

Qin, J. Z., Rao, D., Jiang, H., 2008a. Direct Index of Paleotemperature of High Mature Marine Facies Carbonate Sequences-Homogenization Temperature of Fluid Inclusions. *Petroleum Geology and Experiment*, 30(5): 494–498 (in Chinese with English Abstract)

Qin, J. Z., Wang, J., Qiu, N. S., 2008b. Evidence of Thermal Evolution History of Northeast Sichuan Basin—(U-Th)/He Low Temperature Thermochronometry of Apatite and Zircon. *Journal of China University of Geosciences*, 19(6): 591–601

Qin, J. Z., Wang, J., Qiu, N. S., et al., 2010. New Paleo-Geothermometers for the Inversion of Dynamic Thermal Evolution History of Marine Sequences in South China—(U-Th)/He Age and Closure Temperature of Apatite and Zircon. *Oil* & *Gas Geology*, 31(3): 277–287 (in Chinese with English Abstract)

Qiu, N. S., Li, H. L., Jin, Z. J., et al., 2006. Study on the Geothermometer of Free Radicals in Organic Matter for the Reconstruction of the Thermal History of Marine Carbonate Succession. *Acta Geologica Sinica*, 80(3): 390–397 (in Chinese with English Abstract)

Ren, Z. L., Li, L., Cui, J. P., 2008. Application of Tectonic-Thermal Evolution History to Hydrocarbon Accumulation Timing in Sedimentary Basins. *Oil* & *Gas Geology*, 29(4): 502–506 (in Chinese with English Abstract)

Reiners, P. W., Farley, K. A., 1999. Helium Diffusion and (U-Th)/He Thermochronometry Titanite. *Geochimica et Cosmochimica Acta*, 63(22): 3845–3859

Reiners, P. W., Farley, K. A., Hickes, H. J., 2002. Helium Diffusion and U-Th/He Thermochronometry of Zircon: Initial Results from Fish Canyon Tuff and Gold Butte. *Tectonophysics*, 349(1–4): 297–308

Shen, C. B., Mei, L. F., Guo, T. L., 2007. Fission Track Analysis of Mesozoic–Cenozoic Thermal History in Northeast Sichuan Basin. *Natural Gas Industry*, 27(7): 24–26 (in Chinese with English Abstract)

Wang, F. Y., Liu, D. H.,1996. Take Vitrinite Like Reflectance as the Maturity Indicator for Lower Paleozoic High-Over Mature Source Rock. *Natural Gas Industry*, 16(4): 14–18 (in Chinese with English Abstract)

Wang, Y. G., Yu, X. F., Yang, Y., et al., 1998. Applications of Fluid Inclusions in the Study of Paleo-Geotemperature in Sichuan Basin. *Earth Science—Journal of China University of Geosciences*, 23(3): 285–288 (in Chinese with English Abstract)

Wolf, R. A., Farley, K. A., Silver, L. A., 1996. Helium Diffusion and Low Temperature Thermochronometry of Apatite. *Geochimica et Cosmochimica Acta*, 60(21): 4231–4240

Wolf, R. A., Farley, K. A., Kass, D., 1998. Modeling of the Temperature Sensitivity of the Apatite (U-Th)/He Thermochronometer. *Chemical Geology*, 148(1–2): 105–114

Xu, E. S., Qiu, N. S., Qin, J. Z., 2008. The Thermal Evolution of Free Radicals in Organic Matter in Sedimentary Basins: A Possible Geothermometer. *Acta Geologica Sinica*, 82(3): 413–419 (in Chinese with English Abstract)

Yuan, Y. S., Zheng, H. R., Tu, W., 2008. Methods of Eroded Strata Thickness Restoration in Sedimentary Basins. *Petroleum Geology & Experiment*, 30(6): 636–642 (in Chinese with English Abstract)

?1994-2015 China Academic Journal Electronic Publishing House. All rights reserved. http://www.cnki.net