APATITE FISSION TRACK AND RE-OS GEOCHRONOLOGY OF THE XUEFENG UPLIFT, CHINA: TEMPORAL IMPLICATIONS FOR DRY GAS ASSOCIATED HYDROCARBON SYSTEMS

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ABSTRACT

Hydrocarbon evolution is extremely challenging to determine, both temporally and spatially, in complex tectonic settings. Here we investigate the western margin of the Xuefeng Uplift, China, which records multiple and protracted tectonic and hydrocarbon generation events. This timing of initial oil generation is recorded by low maturity bitumen (Type A), which yields a Re-Os bitumen date of ~430 Ma, consistent with basin models and a ~405 Ma bitumen Rb-Sr date. In contrast, Apatite Fission Track (AFT) data yield considerably younger dates that reflect the timing and tectonic evolution of the Yanshan Orogeny from the northwest (~150 Ma) to southeast (~70 Ma). The youngest AFT date coincides with the western margin of Xuefeng Uplift, where high maturity bitumen (Type B) occurs, which yields a ~70 Ma Re-Os date. The AFT and Re-Os dates imply that both the last stage of the Yanshan Orogeny and, by inference, the cessation of dry gas generation, occurred at ~70 Ma. The Re-Os data of this study imply that the Re-Os chronometer can aid in constraining the timing of oil generation, and of secondary and/or more mature hydrocarbon processes (e.g., thermal cracking/gas generation) in hydrocarbon systems worldwide.

INTRODUCTION

Being able to accurately constrain the timing of hydrocarbon generation is vital for understanding the evolution of a petroleum system and for hydrocarbon exploration. Although the timing of oil generation can be estimated by numerous methods, establishing the timing of gas formation during hydrocarbon evolution is currently less definitive (Schaefer, 2005). To date, basin modelling, as well as hydrocarbon fluid inclusion analysis, has been widely used to evaluate the timing of gas generation from oil cracking (Roberts et al., 2004). However, imperfect kinetic models and poorly constrained parameters, such as the palaeo-geothermal gradient, pressure conditions, and the physical properties of the strata, hamper the accuracy of any derived age model (Braun and Burnham, 1992). Although studies are limited (Qiu et al., 2011), quartz fluid inclusion Ar-Ar dating has shown potential to yield the timing of gas emplacement; however this method is hampered by requiring abundant gas-liquid inclusions and the challenging analytical protocol (Liu et al., 2011; Qiu et al., 2011). Apatite fission track (AFT) dating has also proven useful, as it can directly track the thermal history of a sedimentary basin (Donelick et al., 2005). Hitherto, the rhenium and osmium (Re-Os) isotope system has provided temporal constraints for oil generation and migration (Lillis and Selby, 2013; Selby and Creaser, 2005), but without any reference to the timing of gas formation. In this study, we apply both AFT and Re-Os geochronology to the Majiang and Wanshan reservoirs of the Xuefeng Uplift, China, to quantitatively constrain the timing of tight gas generation, which is currently highly debated (Schenk et al., 1997).

GEOLOGICAL SETTING

The Majiang and Wanshan hydrocarbon reservoirs are the two largest in Southern China, containing a reserve exceeding 10 BBL of oil and 200 BCM of gas (Deng et al., 2014; Wu, 1989) (Fig.1). The gas reserve is close to that of the second largest gas field in China, Puguang (Ma et al., 2007), and the Ledovoe gas field, Russia (Pavlenko and Glukhareva, 2010), which each contain ~300 BCM of gas. The Majiang and Wanshan reservoirs are located in the foreland basin belt along the western margin of the Xuefeng Uplift of the mid-Yangtze block (Deng et al., 2014) (Fig. 1). The foreland basin is characterized by multiple tectonic events (the Paleozoic Caledonian, Triassic Indosinian, and the Cretaceous-present Yanshan-Himalaya orogenies) (Mei et al., 2012), which has resulted in numerous tectonic models and timing constraints for hydrocarbon generation (Bai et al., 2013; Liu et al., 2011; Tang and Cui, 2011). Oil and bitumen generation from Palaeozoic strata is proposed to have occurred during tectonic subsidence associated with the Late Silurian Caledonian and Triassic Indosinian Orogenies (Bai et al., 2013; Liu, 2011). However, the timing of gas generation is less certain, with estimates tied to both the Triassic Indosinian and Cretaceous Yanshan Orogenies (Liu, 2011; Xiang et al., 2008). For example, a ~228 Ma date derived from Ar-Ar analysis of hydrocarbon-bearing fluid inclusions in the Majiang reservoir have been used to suggest that hydrocarbon generation of both oil and wet gas was contemporaneous with the Indosinian Orogeny (Liu, 2011). In contrast, basin modelling~~-~~ of the burial history of the foreland basin belt,~~(gas generated ~100Ma)~~ coupled with fluid inclusion ~~analysis (H~~homogenization temperatures being > 150 ºC~~)~~, suggests that dry gas formation occurred during the Cretaceous (Xiang et al., 2008), which coincides with the Yanshan Orogeny as constrained by AFT dates (~92 Ma) from ~100 km to the north of the study area, and quartz electron spin resonance (ESR) dates (75-62 Ma) along the Jiangnan fault Zone in the Xuefeng Uplift, ~500 km to the east of the study area (Mei et al., 2010; Zhu et al., 2011) (Fig.1).

Bitumen is commonly hosted within the pore spaces of Cambrian to Ordovician limestone units, but is also present along fractures/cleavage planes of Silurian sandstone units (Zhou, 2006). Organic geochemistry defines two types of bitumen in the Majiang and Wanshan reservoirs. In the Kaili area only, which represents a structural high, of the Majiang reservoir

(Fig.1), bitumen (Type A) has low maturity (Ro< 1.0), low T_{max} (~450ºC), yellow fluorescence, and high H/C ratio (>0.8) (Han et al., 1982; Zhou, 2006). In contrast, bitumen (Type B) throughout the rest of the Majiang and Wanshan reservoirs (Fig. 1) has high maturity (Ro>2.0), high T_{max} (~550ºC), low H/C ratio (<0.6), no fluorescence, and contains high adamantine (3-4+ diamondoids) concentration (~50-300 ppm), which classifies the bitumen as pyrobitumen (Shi et al., 2015; Wang et al., 2013). Though several processes can form pyrobitumen (Lewan, 1997), dry gas and pyrobitumen can form contemporaneously by thermal cracking of low maturity bitumen (e.g., Type A of this study) and crude oil (Huc et al., 2000). To evaluate the timing of both bitumen types of the Majiang and Wanshan reservoirs, and by inference the timing of oil and gas generation, we conduct AFT analyses on the Paleozoic and Jurassic sandstones, and Re-Os analyses on both Type A and B bitumen.

SAMPLES AND METHODOLOGY

Samples for AFT analysis were collected from the Ordovician Dawan Formation (sample 2-33; Majiang reservoir), Jurassic Ziliujing Formation (sample 2-3; Majiang reservoir), Silurian Shiniulan Formation (sample 3-67; Wanshan reservoir), Triassic Guanling Formation (sample 3-97; Wanshan reservoir), and the Triassic Xiaojiangkou Formation (sample 3-18; Xuefeng Uplift) (Fig.1A, Table DR1). Three samples (samples 3-97, 3-67 and 3-18) were broadly collected along a NW-SE profile in the north of the study area, parallel to the propagation direction of the Yanshan Orogeny. Samples 2-33 and 2-3 were collected ~200 km to SW of samples 3-97, 3-67 and 3-18 (Fig. 1A).

Type A and B bitumen were sampled from outcrops across the Majiang and Wanshan reservoirs (Fig.1A; Table DR2). ~~Five~~ Type A bitumen is~~samples,~~ only known in outcrop in the Majiang reservoir.~~,~~ ~~in~~ In a ~20 m long exposure in the Ordovician Honghuayuan Limestone Formation (O_1h) which is part of a structural high, ~~-~~~20 km west from the city of Kaili, 5 samples were collected (Fig.1A). In contrast to Type A bitumen, Type B bitumen is widely found, and predominantly occurs in a northeast-southwest trending belt in Early Paleozoic limestone in both the Majiang and Wanshan reservoirs west of the Xuefeng Uplift (Fig.1A). Nine samples were collected from the Ordovician Honghuayuan (O_1h) Formation in the Majiang reservoir. Samples MJ-S1-B, MJ-S2-B, and MJ-S4-B were collected with an ~10 m interval spacing from an ~30 m section ~2 km south of the city of Majiang. Sample XR-S1-B is from ~3 km west of the town of Xingren. Samples, HBZ-S1-B, HBZ-S4-B, HBZ-S6-B and HBZ-S7-B are from a 20 m section, collected ~4 m apart, ~1 km northeast of the town of Huoba. Sample MJ1-2 was collected from ~1 km northeast of the town of Pojiao. In addition, three samples were collected from the Cambrian Aoxi Formation ($\in_2a$) in the Wanshan reservoir. Samples WS-S3-B, WS-S4-B and WS-S4-B6 were collected with an ~5m interval spacing from an ~30 m section ~3 km from the city of Wanshan (Fig.1A).

The detailed analytical protocol and data for both the AFT and Re-Os analysis are presented in the DR.

RESULTS

The AFT data for the samples collected along a profile parallel to the propagation direction of the Yanshan Orogeny yield dates of 155 ± 13 Ma (sample 3-97), 97 ± 7 Ma (sample 3-67), and 71 ± 6 Ma (sample 3-18) from NW to SE, respectively (Fig.1A; Table DR1). The two samples in the southwest of the study area yield AFT dates of 150 ± 7 Ma (sample 2-3), and 123 ± 7 Ma (sample 2-33) (Fig.1A; Table DR1). The mean track lengths of all samples are 12.66-13.71 μm (1 SD = 1.43 - 2.21 μm; Table DR1). Thermal history modelling of the AFT data shows continuous cooling from ~ 160 to 70 Ma from NW to SE (Fig.1B).

Type A bitumen samples possess 1.5-4.3 ppb Re, and 76.4-206.4 ppt Os, with $^{187}Re/^{188}Os$ and $^{187}Os/^{188}Os$ compositions of 113-121 and 1.60-1.66, respectively (Table DR2). The Type A bitumen Re-Os data yield a Model 1 (assumes that the assigned uncertainties are the only reason for any scatter in the fit of the data) date of 429 ± 140 Ma, with an initial $^{187}Os/^{188}Os$

(Os_i) value of 0.79 ± 0.27 (MSWD = 0.41) (Fig.2A). Type B bitumen possess typically higher Re (2.5-15.2 ppb) and Os (40.0-498.1 ppt) abundances, and have a greater variability in their $^{187}Re/^{188}Os$ and $^{187}Os/^{188}Os$ compositions (87-497 and 1.52-1.97, respectively; Table DR2). The Type B bitumen Re-Os data yield a Model 3 (assumes that the scatter in the degree of fit of the data is a combination of the assigned uncertainties, plus a normally distributed variation in the $^{187}Os/^{188}Os$ values) date of 69 ± 24 Ma (Os_i = 1.45 ± 0.09, MSWD = 9.6) (Fig.2B).

DISCUSSION AND IMPLCATIONS

The Xuefeng Uplift and adjacent districts to the west are part of a piggyback thrust system that has a NW transport direction (and therefore youngs towards the SE), which developed from the late Mesozoic, as a result of the Pacific-Yangtze plate collision (Yangshan Orogeny) (Yan et al., 2003) (Fig.1A). Restoration of the section across the Majiang reservoir shows ~20 % (~12 km) shortening occurred during the Cretaceous (Zhang, 2010). The AFT dates (~150-70 Ma) obtained in this study coincide with the estimated timing of the Yanshan Orogeny and support the SE younging direction of the thrust system (Mei et al., 2010; Zhu et al., 2011). For example, samples 2-3 and 3-97 from 150 km to the northwest of the Xuefeng Uplift belt possess similar AFT dates of ~150 Ma. Significantly younger AFT dates (~120 and ~100 Ma) were obtained for samples 2-33 and 3-67 from ~90 km NW of the Xuefeng Uplift. An AFT date of 92 Ma was also obtained from ~50 km NW of Xuefeng Uplift (Mei et al., 2010). The ~70 Ma AFT date (sample 3-18) recorded within the Xuefeng Uplift (Fig.1; Table DR1) is similar to the ESR dates (75-62 Ma) for the northern part of Xuefeng Uplift (Zhu et al., 2011). The AFT dates indicates that the Yangshan Orogeny was a prolonged (~80-90 Ma) tectonic event, with the last phase occurring at ~70 Ma.

A thermal history derived from the AFT lengths using the HeFTy (*v.*1.8.1) software and employing a fanning curvilinear annealing model (Ketcham et al., 2009), with the parameters of; 1) the annealing temperature (60-120 ºC) of the apatite fission tracks, and 2) a present day surface temperature of 20 ºC, yields the same outcome as the determined by the AFT dates – e.g., uplift events at ~150, ~100 and ~70 Ma from the NW to the SE across the western margin of the Xuefeng Uplift (Fig.1; Table. DR1). The AFT dates and thermal history model also yield, by inference, a timeframe for the cessation of hydrocarbon generation. Given that the thermal cracking of oil/bitumen requires temperature of ≥150˚C (Huc et al., 2000), the spatial association of Type B bitumen and gas within/near the Xuefeng Uplift suggests that hydrocarbon generation had ceased by ~70 Ma during the final stage of the Yanshan Orogeny.

~~For the Re-Os analysis,~~ A ~~a~~ Late Silurian-Early Devonian Re-Os date ~~timing~~ is recorded for Type A bitumen (429 ± 140 Ma) (Fig. 2a). Although possessing a large uncertainty likely because of the low Re and Os abundance and limited spread in $^{187}Re/^{188}Os$ and $^{187}Os/^{188}Os$ values, the nominal date calculated by the Re-Os data for Type A bitumen broadly coincides with the timing for the ~~records the~~ initial ~~timing of~~ oil generation ~~in the reservoirs~~ along the western margin of the Xuefeng Uplift in the Majiang reservoir based on~~and coincided well with previous results. For example,~~ burial ~~basin~~ models of the basin, ~~ling~~ oil-bearing~~and hydrocarbon~~ fluid inclusions with homogenization temperatures of $\sim$100˚C ~~analysis in Majiang area show Cambrian shales got matured and began to generate oil during late Ordovician to early Devonian~~ (Bai et al., 2013), and ~~besides,~~ Rb-Sr bitumen geochronology that yields an age of ~~(~~405 ± 20 Ma ~~) on the bitumen from the Majiang reservoir suggests hydrocarbon generated at late Silurian~~ (Tang and Cui, 2011).

In agreement with the ~70 Ma AFT date is the Re-Os date (69 ± 24 Ma, MSWD = 9.6) for Type B bitumen (Fig. 2b). As noted above Type B bitumen possess different geochemical characteristics from that of Type A bitumen, e.g., Type B bitumen possesses no fluorescence and contains adamantane, which indicate that the bitumen is pyrobitumen. Pyrobitumen could form by the thermal cracking of bitumen and/or oil at temperatures >150 ºC (Huc et al., 2000). Along the western margin of the Xuefeng Uplift, continuous subsidence since the Late Triassic lead to the burial of Paleozoic strata to a depth of ~5000 m, with temperatures >150 ºC being attained during the Late Jurassic to Early Cretaceous (Bai et al., 2013; Han et al., 1982). At this temperature, coincident with the formation of pyrobitumen, gas dominated by methane, which is found in the Majiang and Wanshan reservoirs, also formed (Zhou, 2006). Al~~Even~~ though spatially close to the Type B bitumen (~40 km), Type A bitumen in the Kaili area did not suffer thermal cracking because it occurs structurally higher on the footwall of the Shanban Fault (Fig. 1), and as a result, only experienced temperatures associated with oil generation during the late stages of the Caledonian Orogeny (Latest Silurian) (Zhang, 2010). Our AFT dates indicate that the Yanshan Orogeny caused the uplift of both the Majiang and Wanshan reservoirs to a level where the ambient temperature was between 120 and 60 ºC by ~70 Ma. The AFT dates, coupled with basin burial models, fluid inclusion ~~analysis~~ homogenization temperatures, and hydrocarbon composition~~-~~ numerical modelling (evolution of C_{14}^{+} to C_1 compounds with time), suggest that thermal cracking of hydrocarbons (e.g., Type A bitumen and oil) may have occurred over a duration of 75 myrs (Late Jurassic to Late Cretaceous) (Huc et al., 2000; Xiang et al., 2008). Although the Re-Os date for Type B bitumen agrees with the AFT dates, the statistical fit of the Re-Os data yields a large MSWD of 9.6 and a large date uncertainty (34%), which suggests that the Re-Os data have not fully met the criteria to obtain a precise isochron~~ age~~. For example the requirements to yield a precise isochron are;~~,~~ the sample set ~~-~~represent contemporaneous formation, possess identical initial isotope compositions (*I*Os), and ~~have experienced no disturbance to the~~that the Re-Os systematics ~~post-formation~~have not been disturbed. Nevertheless, the agreement of the AFT and Re-Os chronometers suggests that the process of thermal cracking has reset the Re-Os systematics in the thermal cracked Type A bitumen. As such, the Re-Os Type B bitumen date

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is recording the end of pyrobitumen formation and, by inference, the cessation of dry gas generation. The agreement of the AFT and Re-Os Type B bitumen dates may also indicate that the Re-Os systematics in hydrocarbons have a similar closure temperature range to that of AFT (e.g., 120-60 ºC; (Kohn and Green, 2002)). This range also coincides with the temperature condition (~100-140 ºC) of thermochemical sulfate reduction (TSR) (Machel, 2001), a process which has also been proposed to disturb/even reset the Re-Os isotope systematics in oil (Lillis and Selby, 2013). Assuming no significant disturbance to the Re-Os systematics of the Type B bitumen since the uplift related to the Yanshan Orogeny, the scatter in the data and the large date uncertainty may be controlled by the *I*Os of the Type B bitumen sample set.

Calculating *I*Os values for the samples at 70 Ma results in a range from 1.32 to 1.51 (Table. DR2), which is broadly defined by two groups (Group 1 = 1.32 to 1.39, n = 3; Group 2 = 1.42 and 1.53, n = 9; Fig. 2). Treated as two groups, the Re-Os data yield identical, but more precise (±16 %) Model 1 Re-Os dates (Group 1 = 80 ± 13 Ma, *I*Os = 1.30 ± 0.05, MSWD = 1.3; Group 2 = 78 ± 13 Ma, *I*Os = 1.45 ± 0.04, MSWD = 1.7) (Fig. 2b). Although more precise, the Re-Os dates are still in agreement with the ~70 Ma AFT date and AFT thermal modelling in the Xuefeng Uplift. The coupled AFT and pyrobitumen Re-Os dates both record the last stage of tectonic uplift of the Xuefeng Uplift and yield the best estimate for the cessation of dry gas formation. The long-lived Yanshan Orogeny controlled the final evolution of the hydrocarbon system and led to the near surface exposure of pyrobitumen. Uplift, coupled with erosion, may indicate that dry gas could also have accumulated in relatively deep regions, for example, the ramp or foredeep of the foreland basin. Traps under the faults could also be potential gas reservoirs.

As illustrated by this study in the Xuefeng Uplift, the evolution of hydrocarbon systems can be extremely challenging to understand when affected by multiple tectonic events. This is particularly the situation in the Yangtze Plate block, Southern China (Mei et al., 2012; Yan et al., 2003). Although many hydrocarbon shows (e.g., bitumen, oil and gas) are known (e.g., Weng'an, Nanshanpin and Pingtang reservoirs) (Deng et al., 2014), only the Sichuan Basin currently has producing fields (e.g., Puguang gas field (Ma et al., 2007)). Further, pyrobitumen occurs widely in basins all over the world, for example, the Alberta basin, Canada, Dahoney basin, Nigeria and Basque-Cantabrian Basin, Spain. As such, Re-Os bitumen and pyrobitumen geochronology (coupled with AFT dating) show potential to yield quantitative timing of oil and gas generation, which may aid in the understanding of both the temporal and spatial evolution of hydrocarbon systems.

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REFERENCES CITED

Bai, S., Peng, J., Liu, G., and Wang, Y., 2013, Hydrocarbon accumulation features and exploration potentials in Anshun Sag, Southern Guizhou Depression: Petroleum Geology & Experiment, v. 1, p. 24-28.

Braun, R. L., and Burnham, A. K., 1992, PMOD: a flexible model of oil and gas generation, cracking, and expulsion: Organic Geochemistry, v. 19, no. 1, p. 161-172.

Deng, D., Mei, L., Shen, C., Liu, Z., Tang, J., and Fan, Y., 2014, Characteristics and distributions of marine paleo-reservoirs in the northern margin of the Jiangnan-xuefeng uplift, Southern China: Oil Shale, v. 31, no. 3, p. 225-237.

Donelick, R. A., O'Sullivan, P. B., and Ketcham, R. A., 2005, Apatite fission-track analysis: Reviews in Mineralogy and Geochemistry, v. 58, no. 1, p. 49-94.

Han, S., Wang, S., and Hu, w., 1982, The Discovery of a Paleopool in Majiang and its Geological Significance: Oil & Gas Geology, v. 3, no. 4, p. 316-327.

Huc, A. Y., Nederlof, P., Debarre, R., Carpentier, B., Boussafir, M., Laggoun-Défarge, F., Lenail-Chouteau, A., and Bordas-Le Floch, N., 2000, Pyrobitumen occurrence and formation in a Cambro–Ordovician sandstone reservoir, Fahud Salt Basin, North Oman: Chemical Geology, v. 168, no. 1, p. 99-112.

Ketcham, R. A., Donelick, R. A., Balestrieri, M. L., and Zattin, M., 2009, Reproducibility of apatite fission-track length data and thermal history reconstruction: Earth and Planetary Science Letters, v. 284, no. 3, p. 504-515.

Kohn, B. P., and Green, P. F., 2002, Low temperature thermochronology: from tectonics to landscape evolution: Tectonophysics, v. 349, no. 1–4, p. 1-4.

Lewan, M., 1997, Experiments on the role of water in petroleum formation: Geochimica et Cosmochimica Acta, v. 61, no. 17, p. 3691-3723.

Lillis, P. G., and Selby, D., 2013, Evaluation of the rhenium–osmium geochronometer in the Phosphoria petroleum system, Bighorn Basin of Wyoming and Montana, USA: Geochimica et Cosmochimica Acta, v. 118, p. 312-330.

Liu, Z., 2011, Hydrocarbon Accumulation in Marine Strata at Critical Tectonic Moment in Southern Middle and Upper Yangtze Intra-Continental Structural Belt, South China [Doctor: China University of Geoscience (Wuhan), 157 p.

Liu, Z., Mei, L., Qiu, H., Shen, C., Tang, J., and Yun, J., 2011, 40Ar/39Ar geochronology constraints on hydrocarbon accumulation and destruction periods in the Bankeng paleo-reservoir in the southern margin of the middle Yangtze block: Chinese Science Bulletin, v. 56, no. 26, p. 2803-2812.

Ma, Y., Guo, X., Guo, T., Huang, R., Cai, X., and Li, G., 2007, The Puguang gas field: New giant discovery in the mature Sichuan Basin, southwest China: AAPG bulletin, v. 91, no. 5, p. 627-643.

Machel, H., 2001, Bacterial and thermochemical sulfate reduction in diagenetic settings—old and new insights: Sedimentary Geology, v. 140, no. 1, p. 143-175.

Mei, L., Deng, D., Shen, C., and Liu, Z., 2012, Tectonic Dynamics and Marine Hydrocarbon Accumulation of Jiangnan-Xuefeng Uplift Geological Science and Technology Information, v. 31, no. 5, p. 85-93.

Mei, L., Liu, Z., Tang, J., Shen, C., and Fan, Y., 2010, Mesozoic Intra-Continental Progress Deformation in Western Hunan-Hubei-Eastern Sichuan Province of China : Evidence from Apatite Fission Track and Balanced Cross-Section Earth Science- Journal of China University of Geoscience no. 2, p. 161-174.

Pavlenko, V., and Glukhareva, E., Development of Oil and Gas Production and Transportation Infrastructure of Russian West Arctic Offshore Regions, *in*

Proceedings The Ninth ISOPE Pacific/Asia Offshore Mechanics Symposium2010, International Society of Offshore and Polar Engineers.

Qiu, H.-N., Wu, H.-Y., Yun, J.-B., Feng, Z.-H., Xu, Y.-G., Mei, L.-F., and Wijbrans, J., 2011, High-precision 40Ar/39Ar age of the gas emplacement into the Songliao Basin: Geology, v. 39, no. 5, p. 451-454.

Roberts, L. N., Lewan, M. D., and Finn, T. M., 2004, Timing of oil and gas generation of petroleum systems in the Southwestern Wyoming Province: The Mountain Geologist.

Schaefer, B. F., 2005, When do rocks become oil?: Science, v. 308, no. 5726, p. 1267-1268.

Schenk, H., Di Primio, R., and Horsfield, B., 1997, The conversion of oil into gas in petroleum reservoirs. Part 1: Comparative kinetic investigation of gas generation from crude oils of lacustrine, marine and fluviodeltaic origin by programmed-temperature closed-system pyrolysis: Organic Geochemistry, v. 26, no. 7, p. 467-481.

Selby, D., and Creaser, R. A., 2005, Direct radiometric dating of hydrocarbon deposits using rhenium-osmium isotopes: Science, v. 308, no. 5726, p. 1293-1295.

Shi, C., Cao, J., Bao, J., Zhu, C., Jiang, X., and Wu, M., 2015, Source characterization of highly mature pyrobitumens using trace and rare earth element geochemistry: Sinian–Paleozoic paleo-oil reservoirs in South China: Organic Geochemistry, v. 83-84, p. 77-93.

Tang, L., and Cui, M., 2011, Multiphase tectonic movements, cap formations and evolution of the Majiang paleo-reservoir: Petroleum Science, v. 8, no. 2, p. 127-133.

Wang, G., Li, N., Gao, B., Li, X., Shi, S., and Wang, T., 2013, Thermochemical sulfate reduction in fossil Ordovician deposits of the Majiang area: Evidence from a molecular-marker investigation: Chinese Science Bulletin, v. 58, no. 28-29, p. 3588-3594.

Wu, W., 1989, The Formation and Destruction of Palaeo-Oil-Reservoirs in the East of Guizhou Province Geology of Guizhou, v. 1, p. 9-23.

Xiang, C., Tang, L., Li, R., and Pang, X., 2008, Episodic fluid movements in superimposed basin: Combined evidence from outcrop and fluid inclusions of the Majiang ancient oil reservoir, Guizhou Province: Science in China Series D: Earth Sciences, v. 38, no. 1, p. 70-77.

Yan, D.-P., Zhou, M.-F., Song, H.-L., Wang, X.-W., and Malpas, J., 2003, Origin and tectonic significance of a Mesozoic multi-layer over-thrust system within the Yangtze Block (South China): Tectonophysics, v. 361, no. 3, p. 239-254.

Zhang, J., 2010, The Research of Tectonic Evolution in Southern Guizhou Depression [Master: China University of Petroleum 97 p.

Zhou, F., 2006, Hydrocarbon Accumulation and Petroleum Formation in the North Margin of Jiangnan Uplift [Master: China University of Geoscience (Wuhan), 88 p.

Zhu, Q., Yang, K., and Cheng, W., 2011, Structure evolution of Northern Jiangnan Uplift: Evidence from ESR Dating Geoccience v. 25, no. 1, p. 31-38.

FIGURE CAPTIONS

Figure 1. A. Simplified geological map of western margin of Xuefeng Uplift showing the location of the Type A and Type B bitumen in the Majiang and Wanshan reservoirs, and sandstone samples for Re-Os and AFT analysis, respectively. B. Thermal history inversions from AFT data for sandstone samples using HeFTy software (Table DR1). See text for discussion.

Figure 2. A. ^{187}Re-^{187}Os isochron for five Type A bitutmen samples from Kaili area, Majiang reservoir. B: ^{187}Re-^{187}Os isochron diagram for twelve Type B bitumen samples from Majiang and Wanshan reservoir. All data include 2 sigma level uncertainties and the error correlation function, rho (Table DR 2). See text for discussion.