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Cenozoic thermal history reconstruction of the Dongpu Sag, Bohai Bay Basin: insights from apatite fission-track thermochronology

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Abstract: Knowledge of the thermal history of the onshore Dongpu Sag (DPS), Bohai Bay Basin is important for understanding its tectonic development within a broader regional context and for elucidating its poorly studied source-rock maturation history. To unravel DPS time-temperature development, apatite fission-track data were acquired from eight sandstone samples in three deep wells. Thermal history modeling indicates continuous heating during the rifting stage (early Eocene to late Oligocene), followed by cooling attributed to tectonic uplift between ~27 Ma to ~16 Ma, which resulted in the removal of ~1400 to 1800 m of section. Reheating occurred during the subsidence stage from middle Miocene until present. Unlike typical passive continental margin basins, the DPS experienced accelerated post-rifting subsidence from ~5.8 Ma, which was especially marked since ~2.6 Ma. This phase was probably triggered by normal fault reactivation, in combination with a variation in the deep heat flow pattern.

Keywords: Apatite fission-track, thermal history, erosion, Dongpu Sag, Bohai Bay Basin

1. Introduction

The Dongpu Sag (DPS) in the Bohai Bay Basin (BBB) is not only one of the most important conventional oil and gas exploration areas in China, but also a target area for shale oil exploration with promising potential (Wang, et al., 2015). Along with increasing exploration demand, substantial research of the BBB thermal history has been carried out. However, most studies have focused on areas with high levels of petroleum exploration, such as the Jizhong, Jiyang, Bozhong, Huanghua, and Liaohe Depressions (Fig. 1a) (Chang, et al., 2017; Hu, et al., 2001; Qiu, et al., 2004; Qiu, et al., 2007; Qiu, et al., 2010; Qiu, et al., 2014), whereas thermal history studies on the DPS have been quite limited (Wang, et al., 1994; Zuo, et al., 2017).

During the Cenozoic, the DPS underwent Eocene-Oligocene rifting and Neogene-Quaternary subsidence (Chen, et al., 2013; Wang, et al., 2015). The syn-rift section consists of the Shahejie and Dongying Formations. Due to the Dongying Movement in the late Oligocene, the Dongying Formation (Fig. 2) was substantially denuded (Lu, et al., 2007). To date, the timing and magnitude of this erosion event remains unclear, even though a few studies have alluded to this issue (e.g. Lu, et al.,

2007; Wang, et al., 1994). The acquisition of further detailed information on the erosion history is particularly important because of its significance for constraining the timing of hydrocarbon generation and its expulsion from source rocks in the Shahejie Formation (Lu et al., 2007).

Apatite fission-track (AFT) thermochronology is a robust technique for constraining the timing and duration of thermal events as well as maximum paleo-temperatures (Gallagher, et al., 1998; Kohn, et al., 2005). This method is very useful in sedimentary basin analysis, as it is sensitive to a temperature range of ~60-110 °C, which is conducive to oil and gas generation and can provide critical temporal constraints on these processes (Armstrong, 2005). Using new AFT data this study aims to reconstruct the thermal history of the DPS and constrain the timing and magnitude of uplift events. Such information would contribute significantly towards understanding the regional tectonic characteristics of the DPS and the evolution of hydrocarbon source rocks.

2. Geological setting

The BBB, surrounded by the Yanshan Massif to the north, the Luxi Massif to the south, the Taihang Massif to the west and the Jiaoliao Terrane to the east, is composed of a series of extensional depressions (Qi and Yang, 2010) (Fig. 1a). The DPS, located west of the Linqing Depression in the southwestern BBB, was divided into the Western Slope, Western Subsag, Central Uplift, Eastern Subsag and the Eastern Slope by Zuo et al. (2017) (Fig. 1b).

As a Cenozoic rift basin, the Dongpu Sag developed on the Paleogene-Mesozoic sedimentary basement. After the late Cretaceous Yanshan movement (Wu, et al., 2005), the sag underwent two evolutionary stages: rifting during the Eocene-Oligocene followed by Neogene-Quaternary subsidence (Chen, et al., 2013; Wang, et al., 2015). Sediments deposited during the syn-rift stage were controlled by contemporaneous normal faults, which formed half, asymmetric graben structures (Luo, et al., 2015). Rifting of the DPS resulted in deposition of the Paleogene Shahejie and Dongying Formations (Fig. 2). The Shahejie Formation can be divided into four members from bottom to top: Sha-4, Sha-3, Sha-2, and Sha-1 Members. Amongst these, the Sha-3 Member is recognized as the most important hydrocarbon source rock in the study area (Jiang, et al., 2016; Shao, et al., 2018). The post-rift sediments comprise the Neogene Guantao and Minghuazhen Formations, and the Quaternary Pingyuan Formation (Fig. 2) (Huang, et al., 2014; Qi, 2004). A regional

unconformity above the Dongying Formation records the transition from syn-rifting to post-rifting subsidence, indicating that regional uplift and erosion occurred prior to deposition of the Guantao Formation (Allen, et al., 1997).

3. Samples and methodology

Eight samples were collected from the Shahejie Formation in three deep wells (Fig. 1b, Table 1). Following conventional mineral separation techniques, euhedral apatite crystals were picked and dated using the external detector method in the Fission-track Laboratory of the Institute of High Energy Physics, Chinese Academy of Sciences. Spontaneous tracks were revealed by etching using 5M HNO₃ for 20s at 20°C. Other details of the dating procedure followed those described by Yuan et al. (2006).

4. Results and interpretation

AFT data are listed in Table 1. All samples failed the χ^2 -test ($P(\chi^2) < 5\%$) and their AFT ages were decomposed into age components using RadialPlotter (Vermeesch, 2009) (Fig. 3).

In well CG1, sample CG1-1 yields a central age of 113.5 ± 8.1 Ma, significantly older than its stratigraphic age (as are almost all single-grain ages, see Fig. 4a). These characteristics indicate that this sample did not experience any or only experienced weak post-depositional track annealing. The central age of 43.6 ± 4.6 Ma for sample CG1-2, overlaps with its stratigraphic age. Although samples CG1-3 and CG1-4 yield central ages (29.7 ± 7.4 , 20.8 ± 3.0 Ma, respectively) younger than their stratigraphic age, the single-grain ages are somewhat scattered, and some are older than the corresponding stratigraphic age (Fig. 4a). Apatite with high Dpar value may be more resistant to annealing (Carlson, et al., 1999), but a plot of AFT age and Dpar shows no clear relationship (Fig. S1c-d). This may suggest that the broad age dispersion observed in these samples does not result from variations in chemical composition, but rather are inherited from different pre-depositional cooling histories or/and complex post-depositional annealing history.

For well W33-105, the central age of sample W33-105-1 is 31.2 ± 5.2 Ma, slightly younger than its stratigraphic age (Fig. 4b). Again, the absence of a clear relationship between AFT age and Dpar values (Fig. S1e) indicates that the large dispersion of single-grain ages probably did not result from different degrees of resistance to annealing (Donelick, et al., 2005).

In well P6-65, sample P6-65-1, P6-65-2 and P6-65-3 yield central ages of 12.8 ± 1.6 , 14.0 ± 1.7 , and 14.3 ± 1.4 Ma, respectively, all younger than their stratigraphic ages (Fig. 4c). Given the high present day down-hole temperature of 121–129°C, total resetting of fossil tracks in apatite grains would be predicted. Since the mean Dpar values are not particularly high (1.6 ± 0.3 to 1.8 ± 0.4 µm), the preserved AFT ages and confined tracks (mean length of 9.2 ± 1.8 to 10.0 ± 1.5 µm) (Table 1) may suggest that these samples have only relatively recently been subjected to high temperatures.

5. Thermal history modeling

Two samples (CG1-4 and W33-105-1) were chosen for thermal history reconstruction using HeFTy (version 1.9.3) (Ketcham, et al., 2018) and the annealing model of Ketcham et al. (2007). Models can be generated in either a forward or inverse sense, and here we follow a strategy that first uses a forward model based approach, with a subsequent, refined search of t-T space using inverse modeling on the basis of the best forward model. The HeFTy inversion mode uses a Monte Carlo approach to test tens of thousands of t-T paths that pass through certain, user-prescribed t-T constraint boxes. Except for the AFT age, track length and Dpar data, additional constraints incorporated included: (1) temperature at time of deposition ($15 \pm 10^\circ\text{C}$), (2) present-day temperature (Table 1), (3) erosion and cooling during late Oligocene time (Lu, et al., 2007) and (4) heating since deposition of the Guantao Formation. Furthermore, a broad initial time-temperature box was inserted as the partially reset AFT ages contain thermal history information from the source area. Following modelling strategies suggested by Ketcham et al. (2003), the initial box assumes that samples were totally annealed at a sufficiently high temperature ($160\text{--}200^\circ\text{C}$) at a time at least 1.5 times older than the apparent AFT age. For each simulation, random t-T paths were generated, until 100 good paths were found.

Fig. 5 presents a summary of the modeled t-T paths, showing a four-phase thermal history pattern. Based on the partially reset AFT ages, the cooling history in the source area is poorly constrained and therefore will not be discussed further in this work. Since the deposition of the Shahejie Formation, samples underwent heating from 15°C to $88\text{--}107^\circ\text{C}$. Cooling occurred between the late Oligocene (~ 27 Ma) and middle Miocene (~ 16 Ma). Since then, reheating can be observed throughout the final part of the thermal history.

6. Coupling thermal history with tectonic evolution

The dynamics driving Cenozoic rifting of the BBB are still controversial. Fundamental mechanisms proposed include: regional extension induced by active mantle convection, India–Eurasia collision (Liu, et al., 2004) or subduction of western Pacific Plate (Zhang, et al., 2003). During the early Tertiary, the convergence rate of the Pacific–Eurasian Plates decreased substantially and reached a minimum in the Eocene of 30–40 mm/year (Northrup, et al., 1995). Meanwhile, the convergence rate of the Indian–Eurasian Plates decreased but remained higher than that of the Pacific–Eurasian Plates until ~40 Ma (Lee and Lawver, 1995) (Fig. 6d). The fast northward movement of the Indian Plate relative to the Pacific Plate would have resulted in a NW–SE-trending extensional stress field, triggering the Cenozoic rifting of the DPS. It would also have caused mantle flow eastward or southeastward, which might have also induced asthenosphere upwelling assisting the rifting process (Chen, et al., 2011; Ren, et al., 2002). The Shahejie and Dongying Formations were deposited during the rifting stage, and samples were heated to temperatures of ~85–107°C until ~27 Ma (Fig. 5). Given the present-day geothermal gradient of ~32°C/km (Zuo, et al., 2017), a subsidence rate of ~0.14 mm/a is calculated.

In the late Oligocene, the collision of arc fragments on the Philippine Sea Plate with the Asian margin (Allen, et al., 1997) and the increased Pacific–Eurasian convergence rate (Northrup, et al., 1995) (Fig. 6d) could have changed the extensional eastern China regime into one of compression, resulting in the termination of significant rifting. An unconformity overlying the Oligocene Dongying Formation records the Dongying Movement, which is considered to represent regional uplift and erosion across the entire BBB and adjacent areas (Wu and Han, 2000). The regional uplift and erosion has also been recorded by AFT data from the Taishan Mountain, Luxi Massif (Li and Zhong, 2006) and AHe ages from the Cangxian Uplift (Chang, et al., 2017). Modeled t–T paths show that cooling in the DPS occurred from ~27 Ma to ~16 Ma, with temperature decreasing from ~85–107 °C to ~39–48 °C (Fig. 6b). The amount of erosion is estimated at between ~1500 to 1800 m, roughly consistent with previous estimates of ~800 to >2000 m (Lu, et al., 2007; Wang, et al., 1994).

Following uplift and erosion, the thermal anomaly resulting from lithospheric stretching decays. The lithosphere reaches thermal equilibrium gradually and becomes cold and thick (Chen, et al., 2011). The DPS evolved during a subsidence stage and samples were reheated due to post-rifting sediment deposition. The t–T paths indicate

slow reheating from temperatures of $\sim 39\text{--}48^{\circ}\text{C}$ to $\sim 64\text{--}68^{\circ}\text{C}$ between ~ 16 and ~ 5.8 Ma; and then rapidly heating up to the present-day temperature of $\sim 99\text{--}102^{\circ}\text{C}$ since ~ 5.8 Ma, especially since ~ 2.6 Ma (Fig. 6b). The rapid heating can possibly be attributed to increased sedimentation due to accelerated subsidence during the post-rifting stage. Using the modeled t - T paths, a subsidence rate of $\sim 0.06\text{--}0.07$ mm/a in the post-rifting stage is calculated, but the rate may be as high as ~ 0.13 mm/a during $\sim 5.8\text{--}2.6$ Ma and ~ 0.31 mm/a during $\sim 2.6\text{--}0$ Ma. Accelerated post-rifting subsidence has previously been reported from other basins, such as the Rockall Basin in NW Europe (Ceramicola, et al., 2005), and the Pearl River Mouth Basin in SE Asia (Tang, et al., 2018; Tang, et al., 2017; Xie, et al., 2006). Such subsidence has also been reported from other depressions in the BBB (Lin, et al., 2004; Xie, et al., 2007) (Fig. 6c). This observation suggests that these basins are different from many typical passive continental margin basins, which are characterized by relatively slow thermal subsidence rates (e.g. Anza rift in Kenya (Bosworth and Morley, 1994); Sirt Basin of Libya (Abadi, et al., 2008)). Several mechanisms have been proposed to explain these observations, including dynamic topography (Burgess and Moresi, 1999; Liu, et al., 2005), magmatic intrusion (Xie, et al., 2006), and intensive normal faulting or a renewed rifting phase (Guo, et al., 2007; Huang, et al., 2014). Amongst these possibilities, normal fault reactivation was proposed as a contributing factor to the atypical accelerated rate observed in the DPS (Huang, et al., 2014), whereas a change in the deep heat flow pattern attributed to subduction rate increase of the Pacific slab was taken as a dominant, but indirect controlling mechanism (Xu, et al., 2018).

7. Conclusions

AFT analysis provides constraints on the thermal history of the DPS from Cenozoic to present. Following continuous heating during rifting from the early Eocene until late Oligocene, the DPS experienced cooling related to uplift until early Miocene, followed by a middle Miocene reheating phase until the present. The thickness of section removed during the cooling stage is estimated to be $\sim 1500\text{--}1800$ m. Pronounced subsidence, was identified since ~ 5.8 Ma, especially since ~ 2.6 Ma, with accelerated subsidence estimated to be as high as ~ 0.31 mm/a.

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Figure captions:

Fig. 1. (a) Map showing the regional location and (b) tectonic divisions of the Dongpu Sag in the Bohai Bay Basin (after Chang et al., 2017; Zuo et al., 2017) (b). IP = Indian Plate, EP = Eurasian Plate, BBB = Bohai Bay Basin, JS = Japan Sea, PSP = Philippine Plate, PP = Pacific Plate, AUS = Australia, AP = Australian Plate. The blue dashed line marks the coastline.

Fig. 2. Generalized stratigraphic column of the Dongpu Sag (after Zuo et al., 2017; Xu et al., 2018).

Fig. 3. (a) Apatite fission-track radial plots and (b) confined fission-track length histograms for samples. Single-grain AFT ages are color-coded according to Dpar values. n = number of analyses and dispersion gives the age-dispersion value as a percentage. Green band indicates the sample stratigraphic age. Black lines represent statistically derived AFT population ages using the automatic mixture model in RadialPlotter (Vermeesch, 2009). Length histograms illustrate the relative frequency of confined fission-track lengths, with N = number of confined tracks measured, Lm = mean track length ($\pm 1\sigma$).

Fig. 4. Apatite fission-track single-grain ages and central ages ($\pm 1\sigma$) vs depth and present-day downhole temperature of well CG1 (a), W33-105 (b), and P6-65 (c). Vertical shaded bars indicate stratigraphic ages (see Fig. 2).

Fig. 5. Modeled time-temperature paths (left) and length distribution (right) for samples CG1-4 (a) and W33-105-1 (b). In the t-T plot, the blue lines are the weighted mean paths, pink colored areas correspond to the range of good fits (GOF > 0.5) and green colored areas correspond to the range of acceptable fits (GOF = 0.05-0.5).

Fig. 6. (a) Plot presenting basin stages in evolution of the Dongpu Sag; (b) weighted mean time-temperature paths for samples CG1-4 and W33-105-1; (c) subsidence rate of the Dongpu Sag from this study, Bozhong Depression (Xie et al., 2007) and the Dongying Depression (Lin et al., 2004); (d) convergence rates between the

Indian-Eurasian Plates (Northrup et al., 1995) and Pacific-Eurasian Plates (Lee and Lawver, 1995).

Supplementary material: Fig. S1. Single-grain apatite fission-track ages (1σ) vs Dpar values for each sample.

Table 1. Apatite fission-track data from the Dongpu Depression, Bohai Bay Basin.

Well (longitude °E, latitude °N)	Sample No.	Depth (m)	Fm	Fm age	GN	ρ_d ($10^5/\text{cm}^2$) (Nd)	ρ_s ($10^5/\text{cm}^2$) (Ns)	ρ_i ($10^5/\text{cm}^2$) (Ni)	P (χ^2) (%)	Central age ($\pm 1\sigma$) (Ma)	$L_m \pm 1\sigma$ (μm) (N)	$D_{par} \pm 1\sigma$ (μm)	PG (°C/km)	PT (°C)
CG1 (114.9, 34.9)	CG1-1	1971	Sha-2	35-38	32	15.006 (7124)	4.017 (629)	11.233 (1759)	3	113.5 ± 8.1	11.7 ± 1.7 (75)	1.77 ± 0.3	32	78
	CG1-2	2774	Sha-3	38-45	35	14.378 (7124)	2.745 (368)	19.153 (2568)	0	43.6 ± 4.6	10.3 ± 1.6 (35)	1.44 ± 0.3	32	104
	CG1-3	2848	Sha-4	45-50.5	14	13.75 (7124)	3.542 (196)	31.729 (1756)	0	29.7 ± 7.4	11.1 ± 1.9 (30)	1.51 ± 0.2	32	106
	CG1-4	2875	Sha-4	45-50.5	23	13.331 (7124)	4.687 (293)	65.132 (4072)	0	20.8 ± 3.0	10.2 ± 1.3 (25)	1.55 ± 0.3	32	107
W33-105 (115.2, 35.6)	W33-105- 1	2917	Sha-3	38-45	35	13.122 (7124)	2.141 (313)	20.654 (3019)	0	31.2 ± 5.2	10.3 ± 1.4 (49)	1.74 ± 0.3	32.3	109
P6-65 (115.4, 35.7)	P6-65-1	3309	Sha-3	38-45	35	11.447 (7124)	0.914 (144)	19.111 (3002)	0	12.8 ± 1.6	9.2 ± 1.8 (8)	1.69 ± 0.3	32	121
	P6-65-2	3439	Sha-3	38-45	35	10.61	1.079	20.118	0	14.0 ± 1.7	9.2 ± 1.2	1.76 ± 0.4	32	125

						(7124)	(175)	(3263)			(4)			
	P6-65-3	3553	Sha-4	45-50.5	35	9.981	1.594	25.476	0	14.3 ± 1.4	10.0 ± 1.5	1.60 ± 0.3	32	129
						(7124)	(289)	(4618)			(5)			

424 GN = number of individual grains dated; ρ_d = induced track density in external detector adjacent to glass dosimeter; Fm = Formation; Nd = number of tracks
 425 counted.
 426 ρ_s and ρ_i = density of spontaneous and induced and dosimeter tracks, respectively. Ns and Ni = number of spontaneous and induced tracks, respectively. $P(\chi^2)$ =
 427 chi-square probability (Galbraith, 1981). L_m = mean track length. N = number of confined tracks lengths measured. PG = present geothermal gradient from Zuo et al.
 428 (2017). PT = present burial temperature, calculated according to surface temperature + PG $\times$ depth.
 429 Ages calculated using Zeta value of 410 ± 17.6 for glass dosimeter CN5. Samples were calibrated using Durango apatite. Analyses were performed at the China
 430 University of Geoscience, Beijing.

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