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⁴⁰Ar/³⁹Ar geochronology constraints on hydrocarbon accumulation and destruction periods in the Bankeng paleo-reservoir in the southern margin of the middle Yangtze block

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The exact determination of isotopic ages of hydrocarbon accumulation, reconstruction and destruction periods using traditional isotopic dating methods is complex because of the small numbers of minerals that correlate with hydrocarbons. The quantitative and direct study of hydrocarbon geochronology is therefore an important scientific problem for isotope geochronology and petroleum geology. This study obtains two isotopic ages from a quartz vein sample associated with bitumen in a reverse fault located in the Bankeng paleo-reservoir on the southern margin of the middle Yangtze block (the northern margin of the Jiangnan-Xuefeng uplift) by inclusion 40Ar/39Ar stepwise crushing in a vacuum. Two different and good linear inverse isochrons that correspond to two age plateaus were determined. The two ages correspond to primary inclusions of about 228 Ma and secondary inclusions of about 149 Ma. These inclusion groups represent two distinct kinds of fluids. Quartz veins associated with bitumen in faulted paleo-reservoirs, which have a strict response relationship with tectonization and hydrocarbon accumulation, are the unified products of tectonic processes, hydrocarbon accumulation and reconstruction. Therefore, they can be used to constrain the hydrocarbon accumulation, reconstruction and destruction periods that are controlled by multiphase and complicated tectonic actions. The evolutionary processes of hydrocarbon accumulation can be divided into two periods consisting of a primary oil and gas reservoir formation period in the late Indosinian epoch (about 228 Ma) and a period of oil and gas reservoir reconstruction in the early Yanshan epoch (about 149 Ma). This study quantitatively reconstructs the hydrocarbon accumulation and destruction chronological framework of a giant hydrocarbon accumulation belt along the southern margin of the middle Yangtze block (the northern margin of the Jiangnan-Xuefeng uplift) controlled by multiphase and complicated tectonism. The two ages associated with hydrocarbons here correspond to the special controlling actions of continental tectonics in the Jiangnan-Xuefeng uplift that affected the timeline of reconstruction and destruction in this giant marine hydrocarbon accumulation. This study shows the feasibility and usefulness of dating inclusions with the 40Ar/39Ar technique for hydrocarbon geochronology, especially in the marine hydrocarbon accumulation region of southern China within a geological setting of old strata, high thermal evolution hydrocarbons, and complex, multiphase and multicycle tectonization.

hydrocarbon geochronology, fluid inclusion, 40 Ar/ 39 Ar dating method, paleo-reservoir, middle Yangtze block, Jiangnan-Xuefeng uplift

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Many methods and technologies can be used to determine the age of hydrocarbon accumulations, such as constraining the earliest time of hydrocarbon accumulation based on the age of a regional structural slope, matching the trap evolution history and hydrocarbon generation-expulsion history, determining the gas reservoir emplacement time by gas law, the petroleum reservoir saturation pressure method [1], the petroleum reservoir geochemistry method [2], the iodine isotope dating method for oil field brine [3], the water/oil/ gas interfaces retroaction method [4], the authigenic minerals dating method for a reservoir [5-7], paleomagnetic dating methods [8], the fluid inclusion homogenization temperature method [9,10], the fluid inclusion composition analysis method [11,12] and evaluating the hydrocarbon generation and migration time by bitumen reflectance [13]. However, most of these methods and technologies are inaccurate because they are indirect, macroscopic and qualitative [1,14].

In contrast, isotopic dating methods are microcosmic and quantitative. However, determining an exact isotopic age of a hydrocarbon accumulation is complex because the minerals suitable for dating with common isotopic methods (mainly calcite, quartz, illite and pyrite) are often rare in hydrocarbon environments. Determining the timing of hydrocarbon accumulation directly and qualitatively is a challenging scientific problem, which has not yet been settled. Nevertheless, isotopic dating methods are the inevitable development trend in microcosmic, direct and quantitative hydrocarbon geochronology. Some hydrocarbon migration relational minerals [5,15-21] and hydrocarbon generation primary materials or products [22-26] such as kerogen, bitumen and heavy oil can be used to determine the hydrocarbon accumulation time with feasible isotopic dating methods. K-Ar and 40Ar/39Ar dating of authigenic illite in a reservoir is relatively widely used, but it can only estimate the earliest time of hydrocarbon migration [15]. Mark et al. [27,28] applied a high-spatial-resolution ultraviolet (UV) ⁴⁰Ar/³⁹Ar dating method on authigenic K-feldspar overgrowths in a reservoir, thereby combining high-resolution petrography with microthermometry to analyze oil-bearing fluid inclusions in overgrowths. The results of this analysis can be integrated into temperature-composition-time (T-X-t)data that are capable of constraining the timing, duration, temperature, and composition of fluid flow. This represents an advance in the exploration for hydrocarbon geochronology.

The fluid inclusion ⁴⁰Ar/³⁹Ar dating method has been used successfully and widely in hydrothermal mineral deposit and ultra-high pressure metamorphic rock analysis [29]. However, it has been used less in hydrocarbon geochronology studies. Some minerals (e.g., quartz, calcite and pyrite) are associated with hydrocarbon accumulation and reconstruction processes and frequently fill fractures, joints and cavities. Dating these minerals with the ⁴⁰Ar/³⁹Ar dating method could determine the time of migration of any syn-

chronal hydrocarbon fluid. The times of migration of multiphase hydrocarbon fluids are determined accurately if the ⁴⁰Ar/³⁹Ar dating result can separate the formation time of the primary, secondary, and even multiphase inclusions. In this way, the results can be used to restrict the time of hydrocarbon accumulation, reconstruction and destruction. A special apparatus designed by Qiu et al. [17,30,31] has been used to clean up the organic gases in samples contaminated with residues from oil or gas fields, resulting in credible ⁴⁰Ar/³⁹Ar data. This technique has been used to date the CH₄-CO₂-saline bearing secondary inclusions in quartz from deep volcanic rocks of the Yingcheng Formation in the Songliao Basin by the 40Ar/39Ar stepwise crushing technique and thereby determine the CO₂ gas emplacement age [18,19,31]. The exact isotopic age for this CO₂ gas reservoir shows the good and wide application of the quartz inclusion ⁴⁰Ar/³⁹Ar dating technique to hydrocarbon geochronology research.

Numerous large-scale paleo-reservoirs and hydrocarbon shows have developed in Mesozoic and Paleozoic marine strata in the northern margin of the Jiangnan-Xuefeng uplift (the southern margin of middle Yangtze block). These include the Majiang, Nanshanping and Bankeng paleo-reservoirs. The intra-continental structural evolution spanning the Indosinian to Himalayan epochs on the northern margin of the Jiangnan-Xuefeng uplift is typical of complicated continent structural evolution periods in China that involve a varied and dynamic evolution in time and space. Different tectonic regimes developed in different locations at the same time and, similarly, different structural properties were tectonically superimposed because of structural transitions (reversions) between tectonic stages. The interaction of different structures resulted in a spatial superposition and variation in the structural framework [32-35]. These tectonic events had a significant effect on hydrocarbon accumulation and reconstruction in Mesozoic and Paleozoic marine strata. Lengthy and complicated geochronological processes resulted in a unique and complicated marine hydrocarbon evolutionary history. Tectonism, as the main controlling process in hydrocarbon accumulation and reconstruction, is a common element of marine hydrocarbon research in southern China [33,36-41]. Nevertheless, there are disagreements regarding the ages of hydrocarbon accumulation, reconstruction and destruction in the northern margin of Jiangnan-Xuefeng uplift (the southern margin of middle Yangtze block). The main opinions are the Caledonian [42,43], Yanshan [44-48], or Himalayan [44-46] epochs, and multiple phase [49] or polycycle [33,35] timings. Previous studies of hydrocarbon accumulation time focused on macroscopic geologic analyses of structural evolution and hydrocarbon thermal evolution [45,50-54]. Some researchers have estimated the hydrocarbon emplacement time by the fluid inclusion homogenization temperature-burial history combination method and bitumen thermal evolution analysis determined by laser Raman

spectroscopy [46,54]. Few researchers have used isotopic dating methods on low-temperature minerals (such as calcite) associated with paleo-reservoirs to determine the hydrocarbon accumulation time from the structural evolution point of view [48]. It is difficult to build up a complete and exact time line or geochronological framework, from hydrocarbon accumulation to reconstruction, using qualitative or semi-quantitative analysis. Bitumen in a reservoir or on the surface, which contains an important record of hydrocarbon accumulation, reconstruction and (or) destruction, is the final product of oil cracking in paleo-reservoirs and (or) the residue of paleo-reservoirs that have experienced oxidation.

In this study, a quartz vein sample associated with bitumen in a fracture from the Bankeng paleo-reservoir was analyzed using the ⁴⁰Ar/³⁹Ar stepwise crushing in a vacuum isotopic dating technique to determine the age of inclusions. This quartz vein, which has a well-defined response relationship with tectonic activity and hydrocarbon migration and accumulation, is a testimony mineral for tectonic processes and paleo-reservoir hydrocarbon accumulation. Accordingly, this study analyzes the accumulation, reconstruction and destruction ages of the Bankeng paleo-reservoir, builds a framework for the hydrocarbon geochronology controlled by multiphase and complicated tectonic action, and reveals the main control function of tectonization for hydrocarbon accumulation. This study provides a direct and qualitative analysis of hydrocarbon geochronology in the study area, extending to the whole marine polycyclic tectonization region of southern China. This region has potential significance and value for hydrocarbon accumulation research within geological settings that involve relatively old depositional ages, high thermal evolution and polycyclic tectonic activity.

1 Regional geology and paleo-reservoir characteristics

The Jiangnan-Xuefeng uplift, which is located on the southeastern margin of the Yangtze block where it is clamped between the Yangtze and Cathaysian blocks, is a peculiar geotectonic unit [55] that extends from eastern Zhejiang in the east to northern Guangxi in the west. It includes the narrowly-defined Jiangnan, Jiuling, Wuling and Xuefeng uplifts that together record a complicated history of mostly-continental structural evolution [34,56–58]. The northern margin of the Jiangnan- Xuefeng uplift shows fault or stratal transitive contacts with the southern margin of Yangtze block. The intra-continental tectonic action of Jiangnan-Xuefeng uplift from south to north started in the Indosinian epoch and formed progressive thrust nappe structures in the direction of the Yangtze block. In the early Yanshan epoch, successive nappes advanced to the interior of the Yangtze block and developed numerous basementinvolved compressive and transpressive fault-blocks and basement thrust folds along the northern margin of the uplift and the southern margin of the middle Yangtze block. In the late Yanshan epoch and early Himalayan epoch, the Yangtze block entered an extensional phase. In the late Himalayan epoch, the extension of the middle Yangtze block transformed to uplift and the main tectonic actions of the Jiangnan-Xuefeng uplift were uplift and denudation [33].

A giant hydrocarbon accumulation belt about 1400 km long and 40-80 km wide developed from west to east crossing Guizhou, Hunan, Hubei, Anhui, Jiangsu and Zhejiang provinces along the northern margin of the Jiangnan-Xuefeng uplift (the southern margin of the Yangtze block). According to incomplete statistics, 156 giant paleo-reservoirs, subaerial bitumen and oil seepages developed in Neoproterozoic, Mesozoic and Paleozoic marine strata of this hydrocarbon belt, such as the following giant paleo-reservoirs: Majiang in Guizhou (O₁-S₁₋₂), Wengan in Guizhou (\in_1), Nanshanping in Cili (Z_2), Wangcun in western Hunan (€2), Bankeng in Tongshan (S), Kangshan in Anji (S), Taishan in Zhejiang (Z₂), Miaoshi in Cili (P₂q), Beimencha in Chibi (P_2q) , Shuidatian in Fenghuang (\in_1) , Alaying in Fenghuang (\in_3) and Tongren in Guizhou (\in_2) [42,43,45,52-54,59,60]. The original oil in place of first seven paleo-reservoirs above could be close to 50 million tons [44,45,60-63]. The original oil in place of the entire hydrocarbon belt in Neoproterozoic, Mesozoic and Paleozoic marine strata, based on the field-scale sequence method, could be close to 350 million tons. This amazingly huge resource of marine hydrocarbon is what remains from a history of extensive exposure and destruction of marine oil and gas reservoirs over a long period of geologic time.

The giant Bankeng paleo-reservoir, close to the Jiugongshan anticlinal arch in the Jiannan-Xuefeng uplift, is the focus of this paper. The strata in the region of the paleoreservoir are distributed to the ENE and developed through the Silurian, Ordovician, Cambrian, and Neoproterozoic; the Jiugongshan granite mass formed in the Yanshan epoch from north to south (Figures 1 and 2). Some Permian and Lower Carboniferous sedimentary units outcropped in the core of the NE-trending syncline. Devonian and Upper Carboniferous strata are absented in the research region area (Figure 2). Lower Cambrian and Lower Silurian units are the main source rocks. NE-trending compressive faults, NW-trending compressive or transpressive faults, NNWtrending compressive or transpressive faults and induced secondary faults were mainly developed in the research region. Occurrences of paleo-reservoir bitumen in the above faults are totally controlled by faults. The surrounding rock consists of Lower Silurian sandstones and siltstones. Bitumen developed along faults in a manner similar to the development of veins or lenses (1-3 m width, branched and combined) without bedding. Bitumen is black has a granular or flaky texture, circumferential conchoidal fracture and angular, suggesting that it was broken by tectonic compression.

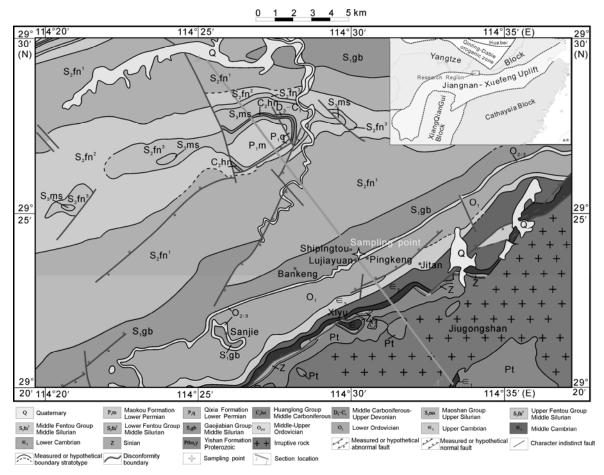


Figure 1 Regional geological map of Bankeng paleo-reservoir.

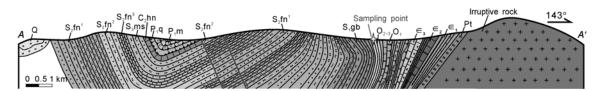


Figure 2 Geological cross section of Bankeng paleo-reservoir (see Figure 1 for the location of cross section and legend).

The bitumen reflectance reaches 6.23% [54]. The characteristic physical properties of bitumen are high heat generation, low ash content, low sulfur and high vanadic oxide [50]. Ellipsoidal dynamic breccias, macro-axis flasers, polyformative structural mirror surfaces and quartz veins developed in faults with bitumen. The genesis of bitumen in the Bankeng paleo-reservoir was typically weak oxidization in the early stage followed by thermal evolution. The source rock of bitumen lies in the Lower Cambrian and/or Lower Silurian [53,54].

2 Sample collection and characteristics

Sample BG-6 was collected from a NNW-trending transpressive fault with a $71^{\circ} \angle 30^{\circ}$ attitude in Bankeng village,

Tongshan town. This ~40-cm-wide fault pinched out in an updip direction to the north and was filled by black bitumen. A series of diminutive structural indicators such as dynamic breccias, sand lenses and quartz veins can be found in this fault. Dynamic breccias are ellipsoid, 0.5-3 cm in size, well-rounded and well-graded. These characteristics indicate that the dynamic breccias are compressive or transpressive. The sand lenses have a macro-axis with length × width of 25 cm \times 4 cm. The macro-axis of the sand lenses intersects with the fault surface in an acute angle. Ouartz veins, ~1-2 cm wide, were distributed, superimposed and distorted by the compression. Additionally, the macro-axes of the quartz veins are in the same direction as the fault's longitudinal bearing. Cataclastic rocks on the two sides of the fault show the probability of matching. The BG-6 sample that was selected for inclusion 40Ar/39Ar dating analysis was collected from a quartz vein in this fault (Figure 3).

Quartz veins interfingering with black bitumen were observed under a micropolariscope (Figure 4(a)). Abundant gas-liquid two-phase inclusions developed in the quartz and can be separated into primary and secondary inclusions. The primary inclusions (~1–4 μ m in diameter), which are bigger than the secondary inclusions, are tuberose, and have an isolated or colony planar distribution (Figure 4(g)–(i)). The tiny secondary inclusions (~1–2 μ m in diameter), which have round or oval shapes, pass the grain's crack and have linear distributions (Figure 4(b)~(e)). Primary and secondary inclusions represent the initial quartz forming fluid event and another fluid event after the quartz formed, respectively. Primary and secondary bitumen inclusions that correspond to primary and secondary gas-liquid inclusions,

respectively, can be found in the quartz (Figure 4(j),(f)). The primary bitumen inclusions are black, tuberose and $\sim 1-3~\mu m$ in diameter under plain light. The secondary inclusions are black or gray black, oval, linear distribution and $\sim 1-3~\mu m$ in diameter under plain light.

3 ⁴⁰Ar/³⁹Ar dating results

Quartz sample BG-6 was analyzed by the ⁴⁰Ar/³⁹Ar stepwise crushing in vacuum dating method. The sample was first soaked in thin nitric acid to corrode the carbonate, and then soaked in acetone to remove possible organic material from the grain surface. Finally, it was cleaned with ionized water and dried. The samples were irradiated in a 49-2

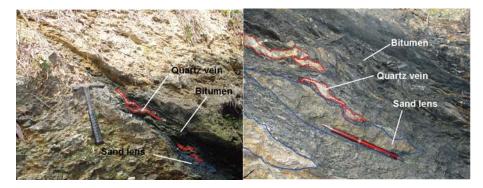


Figure 3 Sampled fault and bitumen, sand lenses and quartz veins in it. Partial quartz veins and sand lenses associated with bitumen in this fault were marked out by red and blue broken lines respectively. The quartz vein sample analyzed by inclusion ⁴⁰Arr³⁹Ar dating technique was collected from this fault.

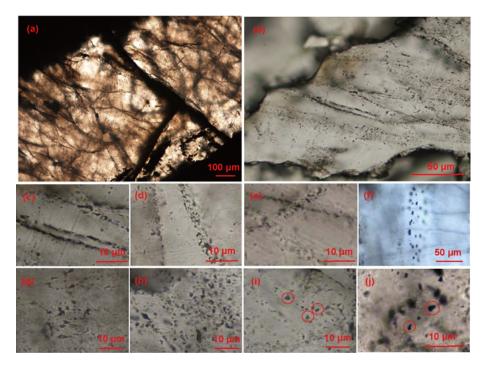


Figure 4 Photomicrographs showing microscopic characteristics of quartz vein and inclusions. Photomicrographs were taken under plainlight. (a) Quartz vein in bitumen. Yellowish white part is quartz mineral; (b)–(e) round or oval secondary inclusions of \sim 1–2 μ m in diameter distributed as line; (g)–(i) tuberose primary inclusions of \sim 1–4 μ m in diameter distributed as isolated or colony planar; (f) secondary bitumen inclusions; (j) primary bitumen inclusions.

reactor at the China Institute of Atomic Energy in Beijing, China. The argon isotope analyses were carried out on a GVI-5400 mass spectrometer at the Guangzhou Institute of Geochemistry, Chinese Academy of Sciences, Guangzhou, China using the all metal extreme vacuum stepwise crushing apparatus to extract inclusions [29]. Prior to the experiments, the extraction and purification systems were baked with heating tapes at 130°C overnight to reduce system blanks. The sample in the crusher was also heated in a temperature-controlled furnace at 130°C overnight to remove the adsorbed gas on the sample's surface. During the experiments, a special apparatus [17,30,31] and two Saes NP10 Zr/Al getters [64] were used to exclude organic gas in the released gas, resulting in gas that was sufficiently pure for the argon isotope analyses in the mass spectrometer. The ⁴⁰Ar/³⁹Ar results were calculated and plotted using the Ar-ArCALC [65] software. Sample BG-6 was crushed in 16 steps with a total pestle drop of 3815 (Table 1).

The ³⁶Ar/⁴⁰Ar vs. ³⁹Ar/⁴⁰Ar diagram presents two different and good linear inverse isochrons (Figure 5(a)), which reflect the obvious difference of gas released and represent two kinds of distinct fluid inclusions. The apparent ages of the two data groups correspond to the two inverse isochrons and present age plateaus positioned at steps 3–6 and steps 7–16 (Figure 5(b)). The two plateau ages agree well with the two isochron ages. Therefore, the ages of steps 3–6 and 7–16 represent the ages of one stage secondary and primary inclusions. The two inclusion groups correspond to the two kinds of inclusions that were observed under a micropolariscope.

(1) Abnormally old ages were observed in the first crushing steps (1 and 2) with large error. Then apparent ages decline from 142.5 Ma at step 3. A plateau occurs at steps 3–6, with a plateau age of 149.4 \pm 9.6 Ma (1 σ , MSWD)

=0.04) (Figure 5(b)-(2)). In the 36 Ar/ 40 Ar vs. 39 Ar/ 40 Ar diagram (Figure 5(a)-(2)), these four plateau data points define a good linear inverse isochron corresponding to an age of 149.7 ± 26.7 Ma with MSWD=0.07 and an initial 40 Ar/ 36 Ar ratio of 329.0±3.9. The isochron age agrees well with the plateau age. This initial ratio, which is a little higher than the modern air ratio of 295.5, suggests a certain excess of ⁴⁰Ar released in steps 3–6. The isochron analytical method can remove the effect of this excess 40Ar and determine reliable age information. Secondary inclusions distributed along cracks in the mineral are easier to release than primary inclusions. Thus, secondary inclusions were the main contributor to argon release at the early stage of stepwise crushing under vacuum. The age of steps 3-6 represents the age of stage one secondary inclusions, which is about 149 Ma.

(2) Apparent ages rise from 149.1 Ma at step 6 to 229.2 Ma at step 7 with no significant change at steps 7-16. A plateau occurs at steps 7–16 with a plateau age of 228.0±5.7 Ma $(1\sigma, MSWD=0.07)$ (Figure 5(b)-(1)). In the $^{36}Ar/^{40}Ar$ vs. ³⁹Ar/⁴⁰Ar diagram (Figure 5(a)-(1)), these 10 plateau data points define a good linear inverse isochron corresponding to an age of 227.8±20.7 Ma with MSWD=0.08 and an initial ⁴⁰Ar/³⁶Ar ratio of 304.7±3.1. The isochron age agrees well with the plateau age. The excess ⁴⁰Ar content of steps 7-10 is less than for steps 3-6. This initial ratio suggests a slight excess of ⁴⁰Ar released in steps 7–16 relative to the modern air ratio of 295.5. Along with the increase in crushing, primary inclusions started to release gas. The primary inclusions dominate gas release at steps 7-16, the age of which is about 228 Ma, representing the age of the primary inclusions.

The inclusion 40 Ar/ 39 Ar stepwise crushing in vacuum dating result for the quartz samples in the Bankeng paleoreservoir

Table 1	e 1 40Ar/39Ar stepwise crushing dating results of quartz BG-6 associated with bitumen in fault in the	Bankeng paleo-reservoir a)

Step	Pestle drop number	³⁶ Ar _{air}	$^{37}Ar_{Ca}$	$^{38}Ar_{Cl}$	³⁹ Ar _K	$^{40}Ar_{R}^{b)}$	t (Ma)	⁴⁰ Ar _R (%)	³⁹ Ar _K (%)
1	10	0.340	0.007	0.000	0.166	2.685	264.8±94.2	2.4	1.35
2	50	0.985	0.026	0.003	0.623	8.462	224.6±67.1	2.5	5.07
3	100	0.979	0.036	0.003	1.017	8.561	142.5±43.9	2.6	8.27
4	100	0.557	0.029	0.000	1.078	10.008	156.6±23.7	5.2	8.76
5	150	0.558	0.038	0.000	1.479	12.893	147.4±16.6	6.6	12.03
6	150	0.395	0.034	0.000	1.339	11.810	149.1±14.2	8.3	10.89
7	150	0.350	1.848	0.000	1.147	15.910	229.2±12.3	13.0	9.33
8	150	0.274	0.029	0.000	0.879	11.892	223.9±12.4	12.5	7.15
9	200	0.321	0.032	0.000	0.851	11.889	230.8±17.0	10.8	6.92
10	200	0.266	0.029	0.000	0.677	9.418	230.0±17.4	10.4	5.50
11	200	0.235	1.363	0.000	0.479	6.580	227.1±20.9	8.4	3.90
12	255	0.255	0.028	0.000	0.500	7.166	236.4±20.3	8.5	4.06
13	300	0.259	0.033	0.000	0.495	6.965	232.3±23.8	8.1	4.03
14	495	0.413	3.047	0.001	0.703	9.259	218.2±22.5	6.9	5.72
15	600	0.299	2.047	0.001	0.465	6.216	221.2±26.7	6.4	3.78

a) The argon isotopes are listed in millivolts; b) R represents radiogenic origin.

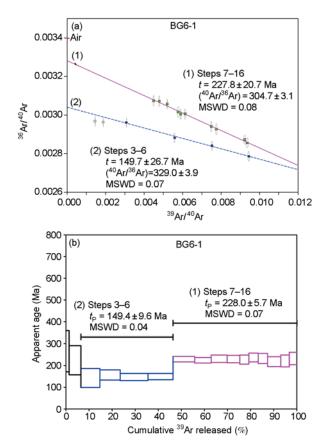


Figure 5 Age spectra and inverse isochrones of the quartz sample BG-6 by ⁴⁰Ar/³⁹Ar stepwise crushing. (a) ⁴⁰Ar/³⁹Ar inverse isochrones: (1) steps 7–16; (2) steps 3–6. (b) ⁴⁰Ar/³⁹Ar age spectra: (1) steps 7–16; (2) steps 3–6. Data points in solid symbols (squares for (1), circles for (2)) define the isochrones corresponding to the respective final plateau steps, while those in open symbols are excluded from the isochrones corresponding to the initial steps 1–2.

reveals two inclusion groups with ages that are about 228 Ma for the primary inclusions and about 149 Ma for the secondary inclusions. Because the primary inclusions have the same formation time as the host quartz mineral, the age of the primary inclusions is the formation time of the quartz. The age of secondary inclusions represents a new period of fluid activity after the formation of the host quartz mineral.

4 Discussion of hydrocarbon accumulation and reconstruction ages

Because quartz veins are syntectonic products formed in conjunction with a fault, the age of primary inclusions in quartz can reflect the formation time of a fault, in this case, about 228 Ma. The secondary inclusions' age of about 149 Ma represents the time of the fault becoming active again. The two ⁴⁰Ar/³⁹Ar dating ages belong to the early period of Late Triassic and the last period of Late Jurassic (late Indosinian Movement and early Yanshan Movement). The Late Indosinian epoch is the fault's formation time; the

Early Yanshan epoch is the fault's reconstruction time.

Regardless of the macroscopic associated attitude or the microscopic interpenetration observed under a micropolariscope of the syntectonic quartz vein and the macroscopic bitumen in faults, both lines of evidence suggest that the quartz vein and bitumen occurred at the same and under syntectonic action. In addition, the existence of primary bitumen inclusions (microscopic bitumen) in the quartz also supports the synchronization of fault formation and hydrocarbon filling in the fault. Because hydrocarbon represented by microscopic bitumen can occur in quartz in the form of primary inclusions, macroscopic hydrocarbon could fill the fault zone when faults formed and eventually evolve to macroscopic bitumen. Assuming the formation time of macroscopic bitumen is later than microscopic bitumen, then two stages of bitumen occurrence should be developed in a fault zone. However, only one stage of macroscopic bitumen was developed in the fault zone that reflects the synchronous genetic relationship between microscopic bitumen in primary inclusions in quartz and macroscopic bitumen in the fault zone. Parnell et al. [66] have demonstrated that the quartz contained in solid bitumen in fracture systems is commonly in a synchronous genetic relationship with bitumen; they applied petrography and inclusion thermometry analyses on authigenic quartz crystals extracted from fracture-bound bitumen from basins in North America and Europe. However, meticulously building up the certain and direct genetic relationships between macroscopic bitumen in a fault zone and microscopic bitumen in primary inclusions in quartz requires biomarker correlation techniques under high thermal evolution conditions, particularly in the microstate.

As expected from the discussion above, we can confirm that fault formation, primary hydrocarbon filling by macroscopic bitumen and primary inclusions in quartz (including primary bitumen inclusions, i.e. microscopic bitumen) present a time consistent genetic relationship. That is to say, the fracturing that occurred about 228 Ma (the early stage of the Late Triassic in the late Indosinian epoch) is coincident and genetically linked to hydrocarbon accumulation in the Bankeng primary oil and gas reservoir. As discussed above, secondary inclusions represent another period of fluid action after the host quartz mineral formed. Thus the development of secondary bitumen inclusions indicates a stage of hydrocarbon reconstruction that followed the hydrocarbon accumulation of in the primary oil and gas reservoir. The time was about 149 Ma, in the last period of Late Jurassic, i.e., the early Yanshan epoch.

Two inclusion ⁴⁰Ar/³⁹Ar stepwise crushing dating ages of quartz associated with bitumen from a fault zone in the Bankeng paleo-reservoir were obtained in this study. We determined the hydrocarbon accumulation time and reconstruction time precisely for the two ages. Therefore, the hydrocarbon accumulation evolution process of the Bankeng paleo-reservoir can be divided into two periods as fol-

lows.

(1) Primary oil and gas reservoir formation occurred in the late Indosinian epoch (about 228 Ma). The hydrocarbon accumulation time can be restricted to the early period of Late Triassic (about 228 Ma), which corresponds to the late Indosinian Movement. The Late Indosinian epoch is the critical time of tectonic development along the northern margin of the Jiangnan-Xuefeng uplift, south of the Yangtze block. The Indosinian Movement's expression in the research region is preserved in the angular disconformity between the Jialingjiang Formation of the Middle Triassic and the Puqi Group of the Upper Triassic, and the angular disconformity between the Puqi Group of Upper Triassic and the Wuchang Group of the Lower Jurassic. During this period, the extended thrust compression of the Jiangnan-Xuefeng uplift's intra-continental tectonic action from south to north formed abundant basement-involved compressive and transpressive fault-blocks and basement thrust folds from the north margin of the uplift to the southern margin of middle Yangtze block. These structures provide traps for hydrocarbon accumulation and the synchronous faults supply effective migration pathways for oil and gas. Hydrocarbons from Lower Cambrian and/or Lower Silurian source rocks filled correlated traps and accumulated in reservoirs.

(2) Oil and gas reservoir reconstruction occurred in the early Yanshan epoch (about 149 Ma). The hydrocarbon reconstruction time can be restricted to the last period of Late Jurassic (about 149 Ma). In the early Yanshan epoch, successive thrusted nappe formation increased significantly and progressed to the interior of the Yangtze block. The Yangtze block uplifted and underwent denudation. A high angle disconformity between the Jurassic and Cretaceous provides a stratigraphic record of this tectonic movement. Intensive nappe formation and structural uplift in the late Indosinian epoch had the role of destructive reconstruction within the oil and gas reservoir. Petroleum escaped along faults exposed to the surface and was extensively destroyed. Individual outcrops of bitumen stretch over hundreds of meters.

5 Conclusions

(1) The inclusion ⁴⁰Ar/³⁹Ar stepwise crushing in vacuum isotopic dating method analysis of a quartz vein associated with bitumen in faults from the Bankeng paleo-reservoir along the southern margin of the middle Yangtze block (the northern margin of Jiangnan-Xuefeng uplift) shows two different and good linear inverse isochrons that corresponded to specific age plateaus. The two ages correspond to primary inclusions formed about 228 Ma in the early period of the Late Triassic and secondary inclusions formed about 149 Ma in the last period of the Late Jurassic. These two inclusion groups correspond to the two kinds of inclusions observed under a micropolariscope that represent dis-

tinct fluids.

(2) Quartz from veins associated with bitumen in faults, which has a strict response relationship with tectonic activity and hydrocarbon migration and accumulation, is a testimony mineral for tectonic processes and paleo-reservoir hydrocarbon accumulation. Based on the two ⁴⁰Ar/³⁹Ar dating ages, the hydrocarbon accumulation and reconstruction times of the Bankeng paleo-reservoir can be restricted from the late Indosinian epoch to the early Yanshan epoch. The hydrocarbon accumulation evolution process can be divided into a primary oil and gas reservoir formation period in the late Indosinian epoch (about 228 Ma) and a period of oil and gas reservoir reconstruction in the early Yanshan epoch (about 149 Ma).

(3) In this study, we use the quartz vein associated with bitumen in the faults of paleo-reservoirs as a response relationship to bridge tectonic activity and hydrocarbon accumulation. Furthermore, we depict the ages of hydrocarbon accumulation and reconstruction/destruction on a timeline that depends on the inclusion ⁴⁰Ar/³⁹Ar dating technique. This study builds a successful case by quantitatively reconstructing a chronological framework for the hydrocarbon accumulation and destruction of a giant hydrocarbon accumulation belt along the northern margin of Jiangnan-Xuefeng uplift controlled by complicated and multiphase tectonism. It also expresses the controlling action of the continental tectonic properties specific to the Jiangnan-Xuefeng uplift as applied to the timeline of a giant marine hydrocarbon accumulation and reconstruction/destruction in the region.

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