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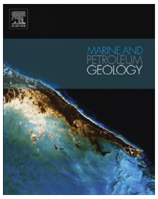

Research paper

Trapping pressure estimation of single gaseous inclusion using PVT simulation and its preliminary application in NE Sichuan, China

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ABSTRACT

In this paper, we proposed an alternative way to estimate volumetric vapour: liquid ratio of gaseous or light-petroleum inclusions without fluorescence using regularly-shaped inclusions to estimate volumetric vapour: liquid ratios through geometric methods. The method was applied to the inclusions from the rock samples of the Lower Triassic Feixianguan and Jialingjiang Formations, NE Sichuan (China). The trapping pressures of inclusion fluids were calculated by integrating PVT simulation software, volumetric liquid: vapour ratios determined by the proposed method and homogenization temperatures measured by microthermometry. Fluid densities and gas-oil ratios (GOR) were also estimated. The estimated trapping pressures and temperatures are slightly lower for the Jialingjiang formation (29.69–31.33 MPa, 93.5–105.2 °C) than for the Feixianguan Formation (31.02–34.38 MPa, 98–148 °C), and the trapping time of the inclusions in the Jialingjiang Formation and Feixianguan Formation were estimated at about 173–170 Ma and 178-168 Ma, respectively. The distribution of high pressures correlates with the presence of pyro-bitumen in the reservoir rocks, suggesting the migrated fluid is derived mainly from the secondary cracking of oil. The modeled fluid density and GOR correspond to a typical light oil or condensate, suggesting an origin for the trapped hydrocarbons as an intermediate product in this process.

1. Introduction

According to Aplin et al. (1999), the trapping pressure of single liquid petroleum inclusion can be calculated by integrating PVT simulation software, volumetric liquid:vapour ratios measured by using a Confocal Laser Scanning Microscope (CLSM) and homogenization temperatures measured by micro-thermometry. The method of Aplin et al. applies only to fluid inclusions which fluoresce under UV illumination. However, to constrain fully the estimation of PT trapping conditions, one needs either (a) find coeval aqueous inclusions or (b) make some assumptions about the composition of petroleum inclusions (Aplin et al., 1999; Thiéry et al., 2000; 2002; Ping et al., 2011). While applying this method in NE Sichuan, we met two difficulties: one is that there are few petroleum inclusions with fluorescence under microscope in Jialingjiang and Feixianguan Formation due to high maturities, and the other is that it is difficult to find coeval hydrocarbon and aqueous inclusions. Out of twenty wells, only one (JZ-1) yielded samples that contain fluorescent petroleum hydrocarbon inclusions. For the other wells, aqueous inclusions and non-fluorescent inclusions including gaseous and light petroleum inclusions were found occasionally. In order to solve these difficulties, we try to measure liquid: vapour ratios by geometric methods for non-fluorescing inclusions. We selected regularly-shaped inclusions and estimated their volumetric liquid: vapour ratios through geometric methods. Some coeval aqueous and petroleum inclusions were found in samples from eight wells (Table 1), which allows us to check the validity of the method and to estimate the trapping pressures.

2. Methods

Roedder and Bodnar (1980) showed that true fluid trapping pressures can in principle be determined where petroleum and aqueous fluid inclusions coexist. But the method is limited by insufficient knowledge of petroleum compositions and PVT. In recent years, a non-destructive method for estimating trapping pressures and fluid compositions of single inclusion has been developed, involving the use of PVT modeling software (Wilkinson et al., 1998; Aplin et al., 1999, 2000; Thiéry et al., 2000; Tseng and Pottorf, 2003, Liu et al., 2003). Our method involves the following

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Table 1
Descriptions of carbonate samples from Jialingjiang and Feixianguan Formations, NE Sichuan.

Sample ID	Well	Depth(M)	Layer	Lithology	Sample ID	Well	Depth(M)	Layer	Lithology
TS13-1	T-13	2456.2	T_{1j}	Dolomite	PO2-1	P-2	3457.2	T_{1f}	Dolomite, Calcite
TS13-2	T-13	2464.5	T_{1j}	Dolomite	DU3-1	Du-3	4311.1	T_{1f}	Dolomite, Calcite
TX1-1	TX-1	2196.04	T_{1j}	Dolomite	LJ1-1	LJ-1	3474	T_{1f}	Dolomite, Calcite
TX1-2	TX-1	2188.98	T_{1j}	Dolomite	Tie4-1	T-4	3112.2	T_{1f}	Dolomite, Calcite
TS13-3	T-13	3022.5	T_{1f}	Dolomite, Calcite	Tie5-1	T-5	3096.5	T_{1f}	Dolomite, Calcite
TX1-3	TX-1	2307	T_{1f}	Dolomite, Calcite	JZ1-1	JZ-1	2977	T_{1f}	Dolomite, Calcite

steps:

(1) Find and locate the regular-shape gaseous inclusions such as spherical, cuboid or square ones and measure their homogenization temperature by micro-thermometry. In some cases, negative crystal-shape inclusions are also selected.
(2) Obtain microscopic images and estimate volumetric proportions of the gaseous and liquid phases in the volumes of gaseous and liquid phases of hydrocarbon inclusions using image processing software. Ideally, the gas bubble is in spherical. It is assumed an ideal negative crystal form based on crystallography of dolomite/calcite.
(3) Pre-set the initial composition of the inclusion fluid for PVT modeling by using the gas compositions from the wells in the same areas (Wilkinson et al., 1998). Here, gas compositions from Well JZ-1 were selected as initial fluid compositions: C_1: 94.95%, C_2: 2.05%, C_3: 0.89%, C_4: 0.22% and C_5: 0.08% (Liu et al., 2006). For aqueous inclusions, water was added into the fluid composition, and its proportion was pre-set generally according to the volumetric liquid: vapour ratio because it will change during the modeling process.
(4) Calculate the minimum trapping pressures derived from homogenization temperatures using PVT modeling software. Here, the Multi-flash module of a commercial software PVTSim (V.10.0) developed by CALSEP company was used, and the corresponding volume of whole system (Vh) can be obtained.
(5) Compare the volumetric liquid: vapour ratio at room temperature determined by the PVT modeling with the result estimated by step (2).
(6) Repeat steps (3) to (5) until the calculated volumetric liquid: vapour ratio matches the estimated one. At this stage, the modeled homogenization pressure is the internal pressure of inclusion fluid represents the best estimate of the minimum trapping pressure of the inclusion and the modeled fluid composition represents the composition of inclusion fluid. Although the modeled composition doesn't constrain the actual composition of the inclusion, it gives a reasonable approximation of its PVT properties.
(7) Calculate the minimum trapping pressure at homogeneous temperature using the modeling fluid composition.
(8) Calculate the pressure of the inclusion fluid above the two-phase curve using a temperature step (ΔT) close to the homogenization temperature by using the Multi-flash module and build the isochore equation that represents the PT path of the particular inclusion in the one-phase field.
(9) Where present, determine the isochore equation of the aqueous fluid inclusion by using the Multi-flash module of the PVTSim software with the similar steps using the same approach as for the gaseous inclusions. The salinity of the aqueous phase is determined by measuring the melting temperature of ice by micro-thermometry and referring this to the equation of Bodnar (1993).
(10) Estimate the trapping pressure by intersecting the isochore equations of coeval gaseous inclusion and aqueous inclusions.
(11) Calculate the differences between the estimated trapping pressures and minimum trapping pressure, which can be applied to estimate the trapping pressures in the cases of no coeval petroleum fluid inclusions existing.

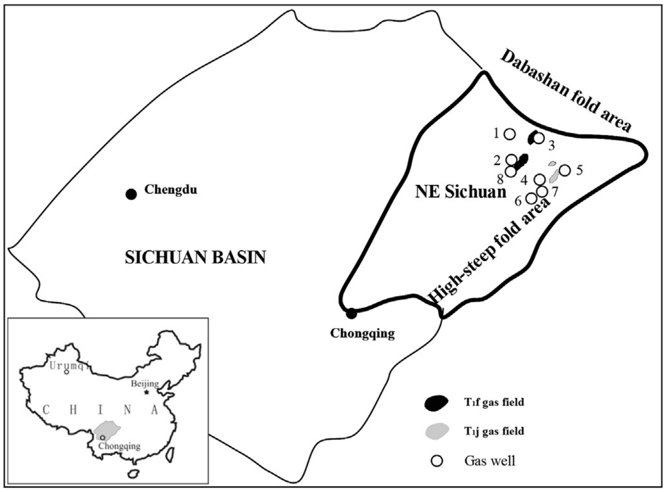

Fig. 1. Study area of Northeastern Sichuan Basin and the map of Lower Triassic gas fields (1. P-2; 2.Du-3; 3.LJ-1; 4. TX-1; 5. TX-13; 6.T-4; 7. T-5; 8.JZ-1).

For microscopic observation of inclusions, we used the reflection and fluorescence systems of a LEITZ LABORLUX 12 POL S and a LEICA DMR XP, respectively. The conditions for fluorescence observation were: 100 W Hg lamp, 420–490 nm excitation wavelength, RKB-510 nm dichromatic reflection mirror and 515 nm protection filter wavelength. For image scanning and processing for gas: liquid ratio calculations, we used a LEICA DC350 digital camera system and QWIN image analysis software (Standard version) together with a LEICA DMR XP-Nikon DXM 1200F digital imaging system. For the measurement of homogenization temperatures and freezing temperatures of inclusions, USGS FLUID INC gas flow stage and LINKAM THMS-G600 stages were used, respectively at heating rates of 1–5 °C/min (Liu et al., 2006).

3. Application in NE Sichuan, China

The Sichuan Basin is a main gas province in China. Natural gases have been known in the Lower Triassic Feixianguan Formation (T_1f) of Northeastern Sichuan for the past twenty years. This unit is now becoming the main target for natural gas exploration in the Sichuan Basin (Zhu et al., 2006). Gases have been also discovered in the adjacent Lower Triassic Jialingjiang Formation (T_1j) in some wells in the NE Sichuan area. Due to the similar structural, depositional and lithological characteristics of the two formations, there is increasing interest in the prospectivity of the Jialingjiang Formation

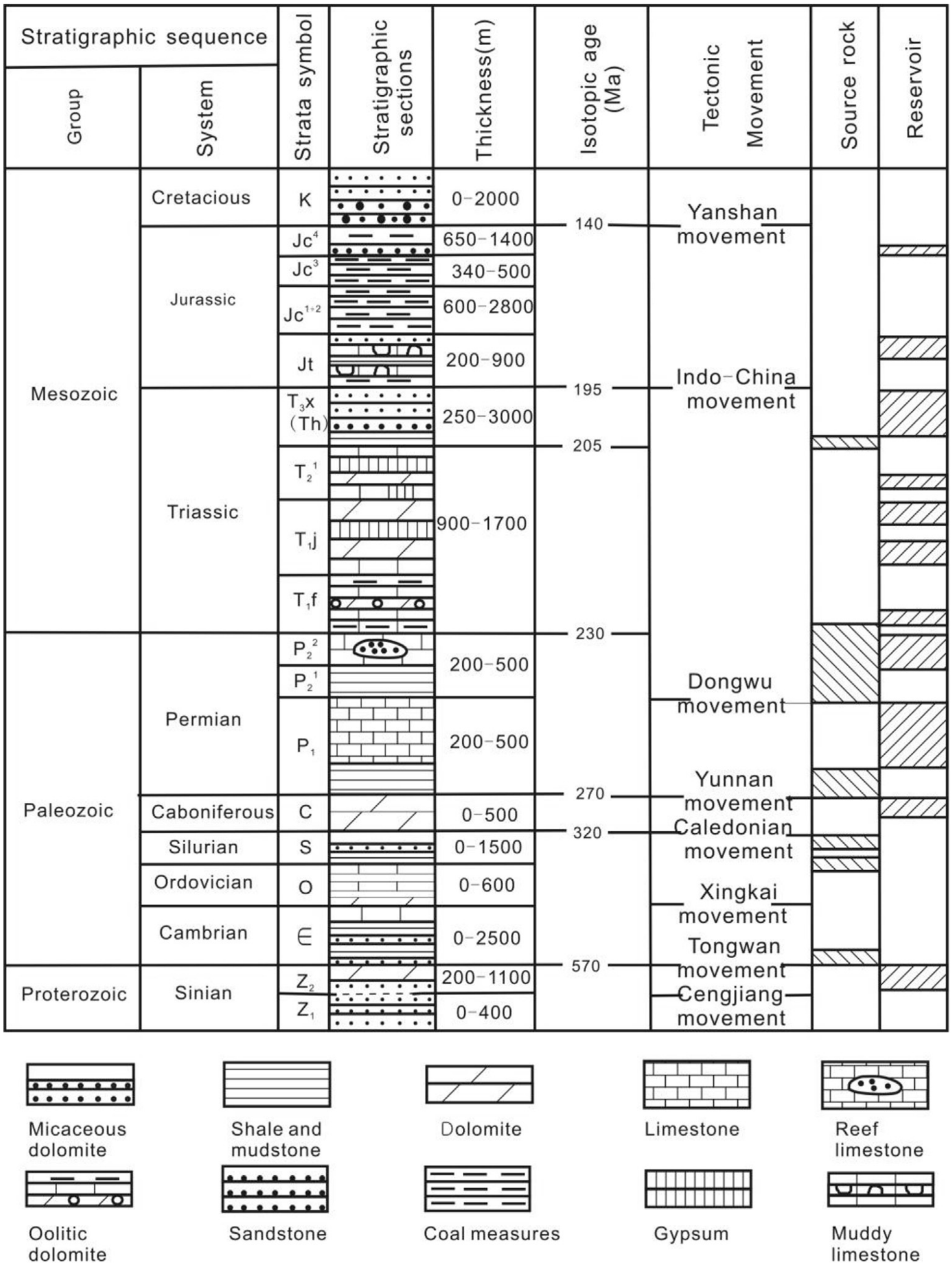

Fig. 2. Stratigraphic sequences of Sichuan Basin (Wang et al., 2013).

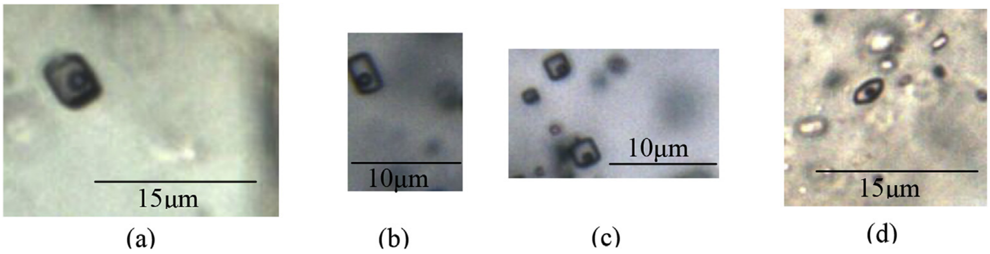

Fig. 3. Examples of microscopic images with inclusions with regular shapes selected for volumetric vapour:liquid ratio estimates (a) octahedral; (b) cuboid; (3) cuboid; (4) ellipsoid.

Table 2
The measured and calculated results of gaseous HC inclusions from Lower Triassic rocks, NE Sichuan.

Sample ID	Well	Gas volume (%)	Volumetric Gas:liquid	Homogenization temperature (°C)	Homogenization pressure (MPa)	Isochore equation
TS13-1	T-13	19.54	0.243	93.5	27.92	$P = 0.187T + 10.424$
TS13-2	T-13	14.49	0.169	100.8	26.97	$P = 0.156T + 11.28$
TX1-1	TX-1	20.80	0.263	105.2	28.66	$P = 0.16T + 11.91$
TX1-2	TX-1	19.33	0.240	98.6	28.37	$P = 0.174T + 11.256$
TS13-3	T-13	33.94	0.514	98.2	31.06	$P = 0.189T + 12.527$
TX1-3	TX-1	28.29	0.394	105.9	29.5	$P = 0.173T + 11.163$
PO2-1	P-2	29.58	0.420	95.6	28.5	$P = 0.183T + 11.00$
DU3-1	Du-3	20.38	0.256	148.6	29.4	$P = 0.13 T + 10.42$
LJ1-1	LJ-1	42.18	0.730	119.2	28.77	$P = 0.154T + 10.357$
Tie4-1	T-4	17.65	0.214	124.6	28.53	$P = 0.142 T + 10.815$
Tie5-1	T-5	23.87	0.314	115.9	29.31	$P = 0.155T + 11.344$
JZ1-1	JZ-1	11.6	0.131	98.0	31.07	$P = 0.188T + 12.549$

Table 3
The measured and calculated results of aqueous inclusions from Lower Triassic rocks, NE Sichuan.

Sample ID	Well	Homogenization temperature(°C)	Ice Melting Point (°C)	Salinity (NaCl,wt% equivalent)	Isochore equation
TS13-1	T-13	97	−0.05	0.09	$P = 1.587T -150.954$
TS13-2	T-13	102.8	−0.65	1.14	$P = 1.58T-167.48$
TX1-1	TX-1	106.6	−1.2	1.98	$P = 1.56T-160.33$
TX1-2	TX-1	100.6	−0.65	0.266	$P = 1.694T-171.196$
TS13-3	T-13	100.1	−0.3	0.01	$P = 1.558T-156.12$
TX1-3	TX-1	107.4	−1.15	1.978	$P = 2.0132T-216.4$
PO2-1	P-2	95.6	−1	1.74	$P = 1.57x-151.03$
DU3-1	Du-3	148.6	−1.65	2.82	$P = 1.678T-252.46$
LJ1-1	LJ-1	119.3	−0.25	0.27	$P = 1.66T-199.42$
Tie4-1	T-4	126.7	−1.64	2.81	$P = 1.675T-211.55$
Tie5-1	T-5	118.9	−3	2.82	$P = 1.576T-187.38$
JZ1-1	JZ-1	98.0	−0.25	0.65	$P = 1.607T-156.022$

in this region (Dai et al., 2008). However, one problem is that the fluid properties of the Jialingjiang Formation, as well as its relationship to the Feixianguan Formation, are not well understood (Ma et al., 2008). The inclusions in these two formations are mainly gaseous ones due to higher maturities of the source rocks and the fluids. The motivation of this study is to understand the fluid properties by using our proposed method to study gaseous inclusions and to find clues for gas exploration of Jialingjiang Formation.

3.1. *Geological setting*

The Sichuan Basin is situated in southwestern China and the study area of this paper is located in the northeastern part of the basin, which is a transition area between the steep fold area and the Dabashan Fold Belt (Fig. 1). In general, gas-bearing traps occur along a NE trend and the trap structures are very complicated due to the influence of multiple deformation events. From the deposition analysis, Triassic is a key period of conversion from marine deposition to terrestrial one. A stratigraphic sequence of Sichuan Basin shown in Fig. 2 illustrates the depositional evolution of the study area (Fig. 2). The oldest sequences before middle Triassic in northeastern Sichuan deposited on a wide shelf (Hu, 1997). These rocks were uplifted during the Caledonian orogeny, and the Devonian and early Carboniferous strata have been eroded. During late stage Caledonian movements, NE Sichuan experienced a transgression as manifested by a sequence of mudflat carbonates (Huanglong Formation, C2hl) which keeps 10–20 m residual depth now. At the end of the Carboniferous, the area was uplifted and the top part of C_{2hl}, the Huanglong Formation, was strongly weathered to produce abundant secondary porosity. These rocks form a series of important reservoirs in eastern Sichuan. From the Permian to the Triassic, the study area experienced a new deposition cycle including the formation of Permian reef carbonates, slope clastics, and thin coal seams followed by earlier Triassic oolitic carbonates that also act as an important hydrocarbon reservoir. The NE-trending Kaijiang-Liangping trough formed in Upper Permian to Lower Triassic time and controlled the deposition of sapropel-type calcareous mudstone source rocks (Changxing and Feixianguan Formations). The Changxing Formation mud rocks have total organic carbon (TOC) concentrations of 0.4%–1.1%, whereas those of the Feixianguan Formation have TOC contents of 0.4%–0.5% (Wang et al., 2004; Zhao et al., 2006). Multiple layers of gypsum-salt and pelitic rocks occur in Jialingjiang and Feixianguan Formations, forming the direct and regional cap rocks. From the Middle Triassic onwards, terrestrial sediments were deposited. Four gas fields (Luojiazhai, Dukouhe, Tieshanpo and Jinzhuping) were selected for sampling. Rock samples comprised both limestone and dolomitized limestone from Jialingjiang and Feixianguan Formations. The detailed descriptions of samples are listed in Table 1.

3.2. *Occurrence and property of inclusions*

Microscopic observations indicate the inclusions are very small in finely crystallized carbonate rocks, coarse-grained milky-white calcite and dolomite veins, and are unsuitable for temperature measurements. By contrast, inclusions are well developed in recrystallized sparite and dolomite, oolitic carbonate cement, authigenic calcite and dolomite, and quartz infilling secondary porosity, as well as secondary gypsum-anhydrite in rock pores. Among a variety of inclusion types, such as aqueous inclusions, gaseous hydrocarbon inclusions, light petroleum inclusions, solid bitumen inclusions, and two-phase gas-liquid inclusions, gaseous or light hydrocarbon and coeval aqueous inclusions were selected for thermometric measurement. In order to meet the requirements of the PVT simulation, the regular-shape inclusions described above were used for volumetric vapour: liquid ratio estimations. Examples of microscopic images with inclusions with regular shapes

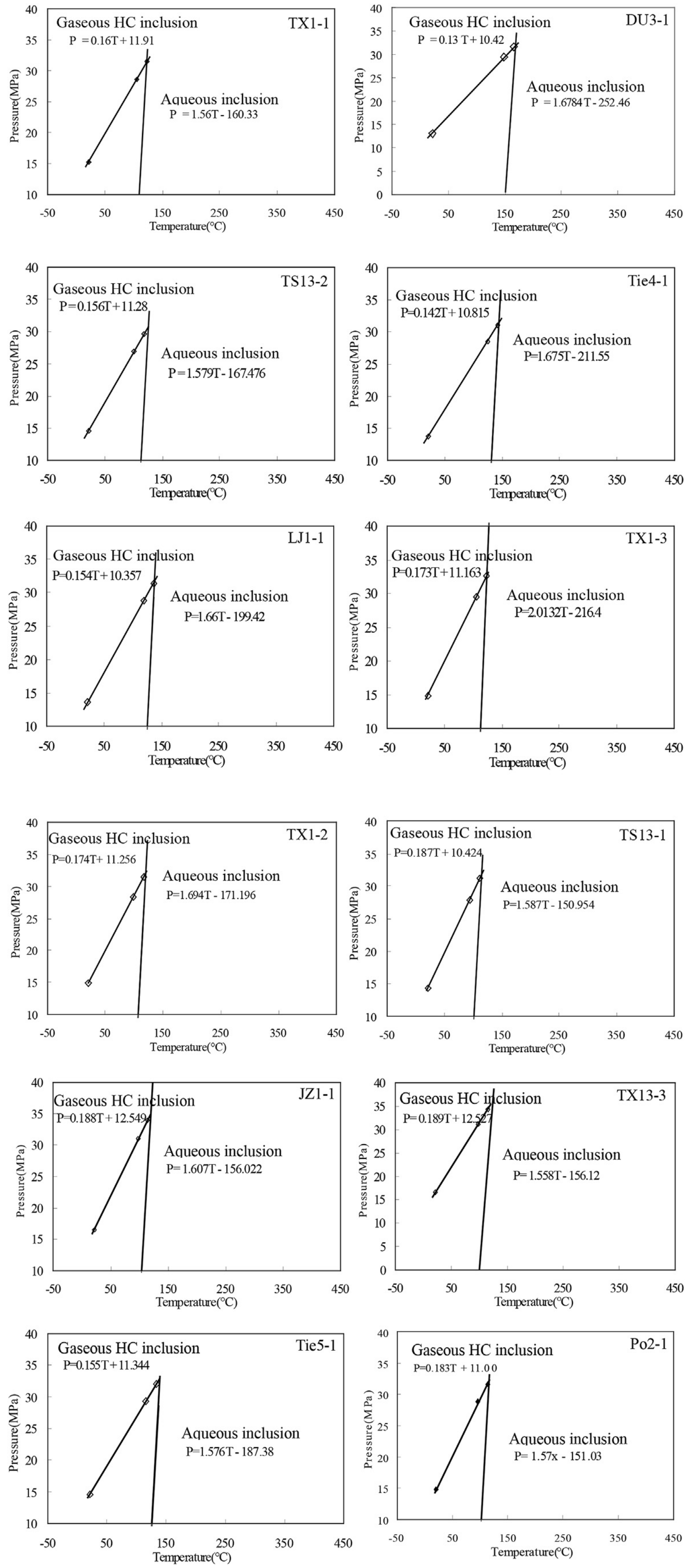

Fig. 4. P-T diagrams showing calculated trapping temperature and pressure of coexisting gaseous HC and aqueous fluid inclusions from the Wells of NE Sichuan.

Table 4
The estimated trapping pressure by intersecting isochores of gaseous HC inclusions and coeval aqueous inclusions from Lower Triassic rocks, NE Sichuan.

Sample ID	TS13-1	TS13-2	TX1-1	TX1-2	TS13-3	TX1-3	PO2-1	DU3-1	LJ1-1	Tie4-1	Tie5-1	JZ1-1
Well	T-13	T-13	TX-1	TX-1	T-13	TX-1	P-2	Du-3	LJ-1	T-4	T-5	JZ-1
Layer	T_{1j}	T_{1j}	T_{1j}	T_{1j}	T_{1f}	T_{1f}	T_{1f}	T_{1f}	T_{1f}	T_{1f}	T_{1f}	T_{1f}
Trapping Temperature (°C)	111.2	118.5	122.7	116.2	116.1	123.4	113.7	166.1	136.7	137.2	133.5	114.2
Trapping pressure (MPa)	31.19	29.69	31.44	31.4	35.18	32.53	33.47	31.64	31.47	31.02	32.92	34.07

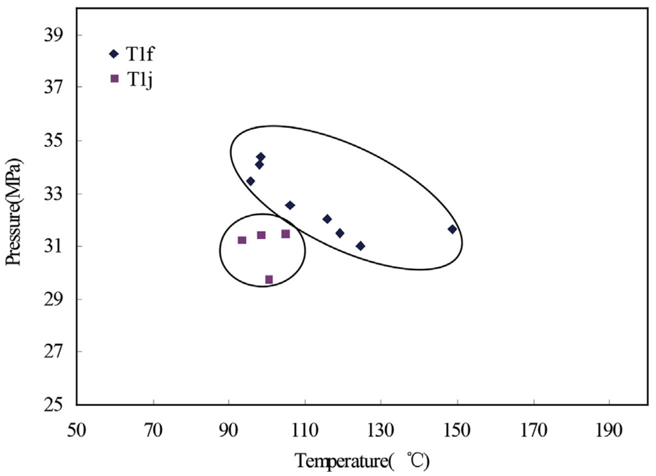

Fig. 5. Scatter diagram of trapping pressures vs. trapping temperatures of inclusions from Lower Triassic Jialingjiang(T1j) and Feixianguan formations(T1f), NE Sichuan.

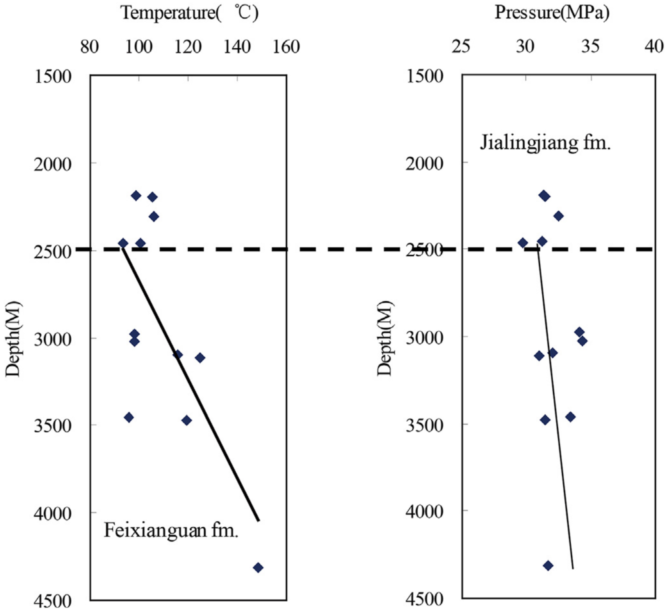

Fig. 6. The relationships between trapping T/P vs. burial depths of inclusions from Lower Triassic rocks, NE Sichuan.

such as octahedral, cuboid, cuboid and ellipsoid selected for volumetric vapour:liquid ratio estimates were shown in Fig. 3.

The calculated volumetric vapour: liquid ratios of gaseous hydrocargon inclusions are listed in Table 2. In general, the gaseous volume varied significantly from 11.6 to 42.18% and the corresponding volumetric vapour: liquid ratio from 0.13 to 0.73. Both hydrocarbon and aqueous inclusion homogenization temperatures showed great variation, ranging from 93.5 °C to 148 °C. Freezing point determinations showed limited variation between −0.05.°C and −3.°C. Using the method described above, we calculated the homogenization pressure for gaseous hydrocarbon inclusions and salinity (NaCl, wt%) for aqueous inclusions, and the isochore equations for both gaseous HC and aqueous inclusions (Tables 2 and 3).

3.3. *Trapping pressure of inclusions*

By intersecting isochores of gaseous hydrocarbon inclusion and coeval aqueous inclusion, the average trapping pressure for each sample was estimated (Fig. 4, Table 4). It can be found the trapping pressures of inclusions from the Jialingjiang formation range from 29.69 MPa to 31.33 MPa with mean value of 30.44 MPa whereas those of inclusions from the Feixianguan formation range from 31.02 MPa to 34.38 MPa with a mean value of 32.58 MPa suggesting a slight difference between the two formations. Comparison of trapping pressures and trapping temperatures of inclusions between the two formations suggests lower trapping pressures are generally associated with lower temperatures in the Jianlingjiang Formation (Fig. 5).

3.4. *Fluid evolution*

The trapping pressure and temperature of the inclusions record part of the fluids evolution history of the host strata. Plotting the time–temperature and pressure–temperature histories of the Jialingjiang and Feixianguan Formations from Well T-13 of the study area allows constraints to be placed on the nature of the fluid pressure regime and the timing of inclusion trapping (Fig. 6). The trapping times of the inclusions in the Jialingjiang and Feixianguan Formations were estimated to be between 173-169 Ma and 178-168 Ma, respectively. From Fig. 7, the results also suggest that the trapping pressures of inclusions from the Jialingjiang Formation are close to hydrostatic at the inferred time of trapping whereas those from the Feixianguan Formation are perhaps slightly above hydrostatic ones. Comparison with the burial history of the dominant gas source rocks, the Lower Permian Changxing Formation shows that 178 Ma corresponds to the beginning of a fast burial stage and an organic maturity of about 1.3–1.5% Ro, corresponding to a condensate to light oil stage (Wang et al., 2008). The modeled fluid density and GOR for inclusions from Feixianguan Formation are about 0.63 g/cm^3 and 1.9, respectively. These data suggest that the hydrocarbon inclusions trapped in the fluid in reservoir rocks of Feixianguan Formation likely represent an intermediate in the process of secondary cracking of oil to gas.

4. Conclusions

1. Regularly-shaped inclusions can be used to estimate volumetric liquid: vapour ratios through geometric methods, providing alternative way to estimate volumetric liquid: vapour ratio of gaseous or light-petroleum inclusions without fluorescence.
2. The estimated trapping pressures and temperatures are slightly lower for the Jianlingjiang formation (29.69–31.33 MPa,

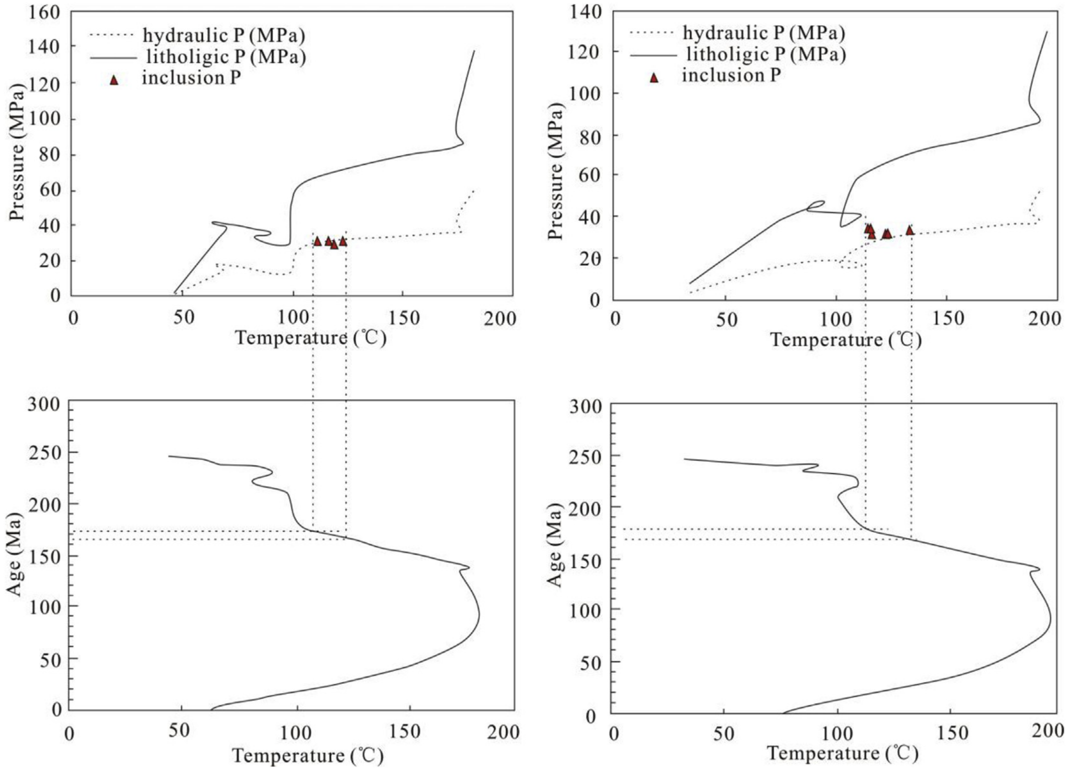

Fig. 7. Time–temperature and pressure–temperature histories of Lower Triassic Jialingjiang Formation (left) and Feixianguan Formation (right) from Well T-13, NE Sichuan.

93.5–105.2 °C) than for the Feixianguan Formation (31.02–34.38 MPa, 98–148 C).

3. Based on burial history modeling, the time of trapping of, the trapping time of the inclusions in the Jialingjiang Formation and Feixianguan Formation were estimated at about 173–170 Ma and 178-168 Ma, respectively. The Jialingjiang Formation was hydrostatically pressured in a normal pressures conditions during the trapping process, whereas Feixianguan Formation showed slight overpressures.
4. Modeled fluid densities for the inclusions in the Feixianguan Formation are about 0.63 g/cm^3 and GOR is around 1.9, also corresponding to a typical light oil or condensate, suggesting derivation via cracking of oil to gas.

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