PS Discovery of Giant, Ultra-deep, Paleozoic Oil and Gas Reservoirs in the Tarim Basin*

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Abstract

The Tarim Basin is one of the most petroliferous basins in China. The basin contains some deeply buried Lower Paleozoic carbonate reservoirs holding rich oil and gas resources derived from highly mature deep source rocks. In December 2015, the Fuyuan-1 (FY1) well located in the Fuyuan block of the northern Tarim Basin produced commercial oil flow from a depth of 7,711 m. The daily crude oil and gas production was 214.62 m^3 and 28,970 m^3, respectively, giving a gas-oil ratio (GOR) of 135 m^3/m^3. The hydrocarbons was produced from the Ordovician Yingshan Formation. This is the deepest oil reservoir ever discovered in China. The FY101 and FY102 wells were successfully completed and also yielded commercial oil flow, confirming the oil enrichment in the deep geological formations of the Tarim Basin.

Detailed analysis of hydrocarbon compounds of the oil was carried out using a 2D gas chromatography/time-of-flight mass spectrometry (GC×GC-TOFMS). It was revealed that a small variety and a low content of adamantanes are present in the oil. No compounds were found in high temperature pyrolysis, such as thiaadamantanes, and dibenzothiophenes. The crude oil has matured normally and has yet been cracked. The carbon isotope data indicates that the gas produced in this area is dominated by oil-associated gas type, further confirming the oil in the Paleozoic reservoir at a depth of 7,711 m has not been cracked. The reservoir oil has been preserved due to a low regional geothermal gradient with the reservoir temperature being as low as 172°C. Since its formation during the Permian, the reservoir has been progressively buried deeper by the deposition of the overlying sedimentary strata. The basin underwent a rapid subsidence starting at 5 Ma, increasing its burial depth by 2,000 m, resulting in the reservoir achieving its current maximum burial depth. The oil has not been cracked because of the relatively short duration in reaching its current high temperature. This implies that there is a huge potential of finding deep liquid petroleum through exploration in the region. The hydrocarbon discovery in the FY1 well will undoubtedly lead to large-scale oil exploration in the deep sedimentary strata of the Tarim Basin in the future.

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Introduction

Thermal stability of liquid petroleum in the subsurface is closely linked to reservoir temperature. Oil cracks into gas at temperatures >160°C leading to the dominance of gas condensate and free gas accumulations in ultra-deep high-pressure high-temperature (HPHT) reservoirs. The newly discovered Fuyuan oil field is located on the southern slope of the Lunnan low uplift in the Tabei area of the Tarim Basin (Fig. 1). The exploration wells produced high-quality non-cracked oil from a ultra-deep carbonate reservoir located at a maximum depth of 7,711 m, with temperature 172°C and pressure 69.08 MPa (Table. 1). This is the deepest oil discovery in China to date and among the deepest in the world. The oil density (0.825 g/cm^3 at 20°C), gas/oil ratio (135 m^3/m^3), low variety and abundance of adamantanes as well as lack of thiaadamantanes and dibenzothiophenes indicate that the oil has moderate maturity and has not been cracked. Molecular and isotopic composition of oil-associated gases are consistent with this interpretation. That the oil did not crack is because of a short residence time (<5 Ma) at temperatures >160°C, as suggested by 1D modelling. There is significant potential to find liquid petroleum in other HPHT reservoirs with relatively low geothermal gradient and recent burial in the Tarim basin and around the world.

Well	Depth (m)	Oil production (m^3/d)	Gas production (m^3/d)	Gas-oil ratio	Temperature (°C)	Oil pressure (Mpa)
FY 1	7322.2-7711.7	214.62	28970	135	172	69.08
FY 102	7117.3-7568.9	156.87	27828	177		38.49

Table 1. Production data from Ordovician carbonate reservoirs in Fuyuan oil field

Stratigraphic Characteristics

The main target strata in Fuyuan area is the Ordovician which is comprised of the Sangtamu, Lianglitag, Tumuxiuk, Yijianfang, Yingshan, and Penglaiba formations, from top-to-bottom (Fig. 2). The Yijianfang (O_{1-2y}) and Yingshan (O_{2y}) formations are the principal hydrocarbon-producing layers, mainly comprised of sparite grainstones with biolithites and thin micritic limestones developing in shoal and patch reefs on open platforms along with calcarenite.

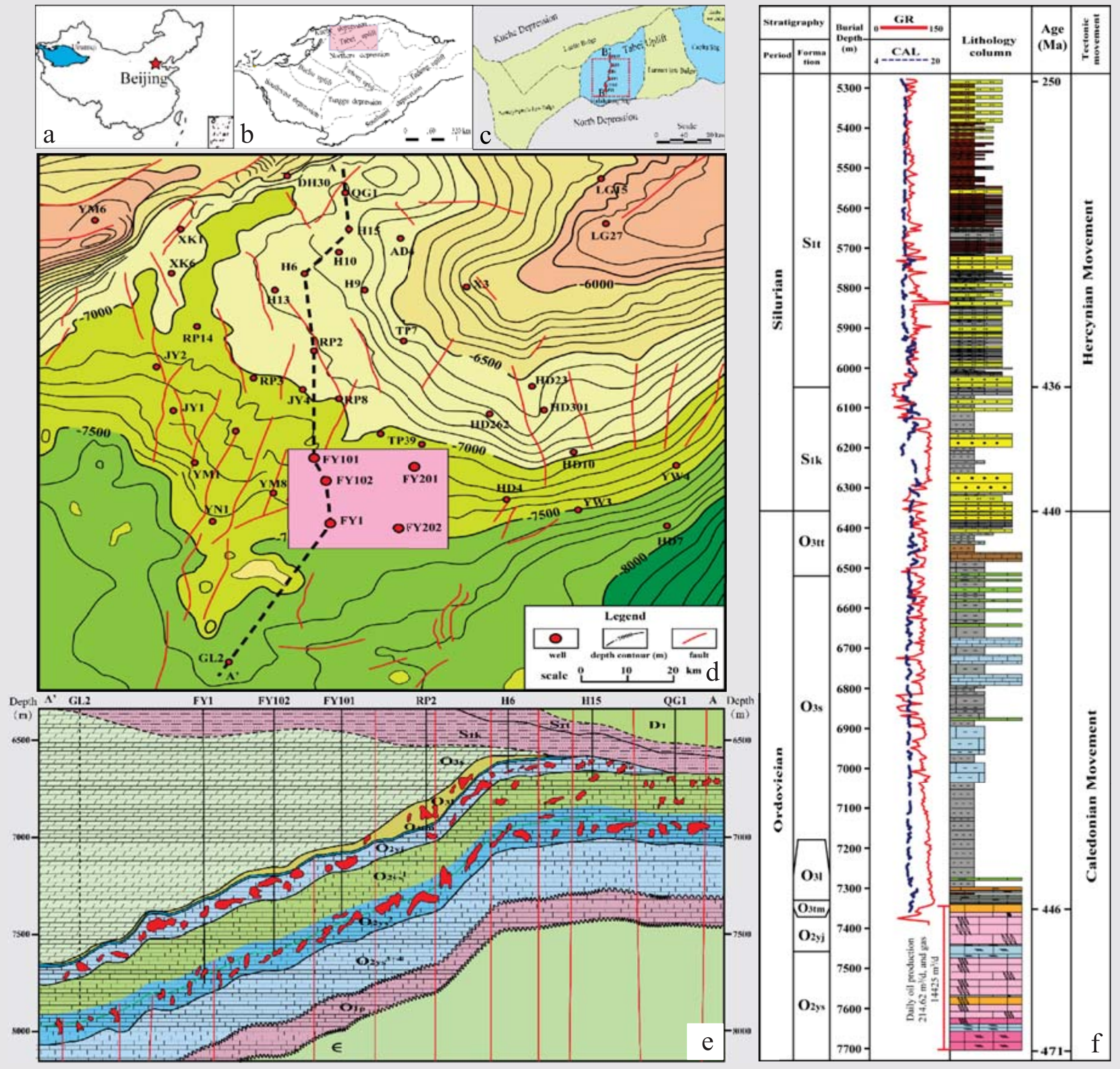

Figure 1. The Fuyuan oil field location map

Ultra-deep Reservoir Features

Carbonate karst reservoirs in the Fuyuan block developed in Ordovician rocks, principally within the Yijianfang Formation and in the middle section of the Yingshan Formation. Both of the reservoirs are composed predominantly of heterogeneous fractured-vuggy and fractured limestones. The matrix porosity and permeability are low, with porosity generally less than 8% and an average around 3.6% (Fig. 2). Pseudo-layered reservoirs were formed by the combination of karsts, faulting and fracturing. The strata above the oil reservoirs are composed of dense muddy limestones and mudstones of the Ordovician Tumuxiuk, Lianglitag and Sangtamu Formations (Fig. 2, Fig. 3).

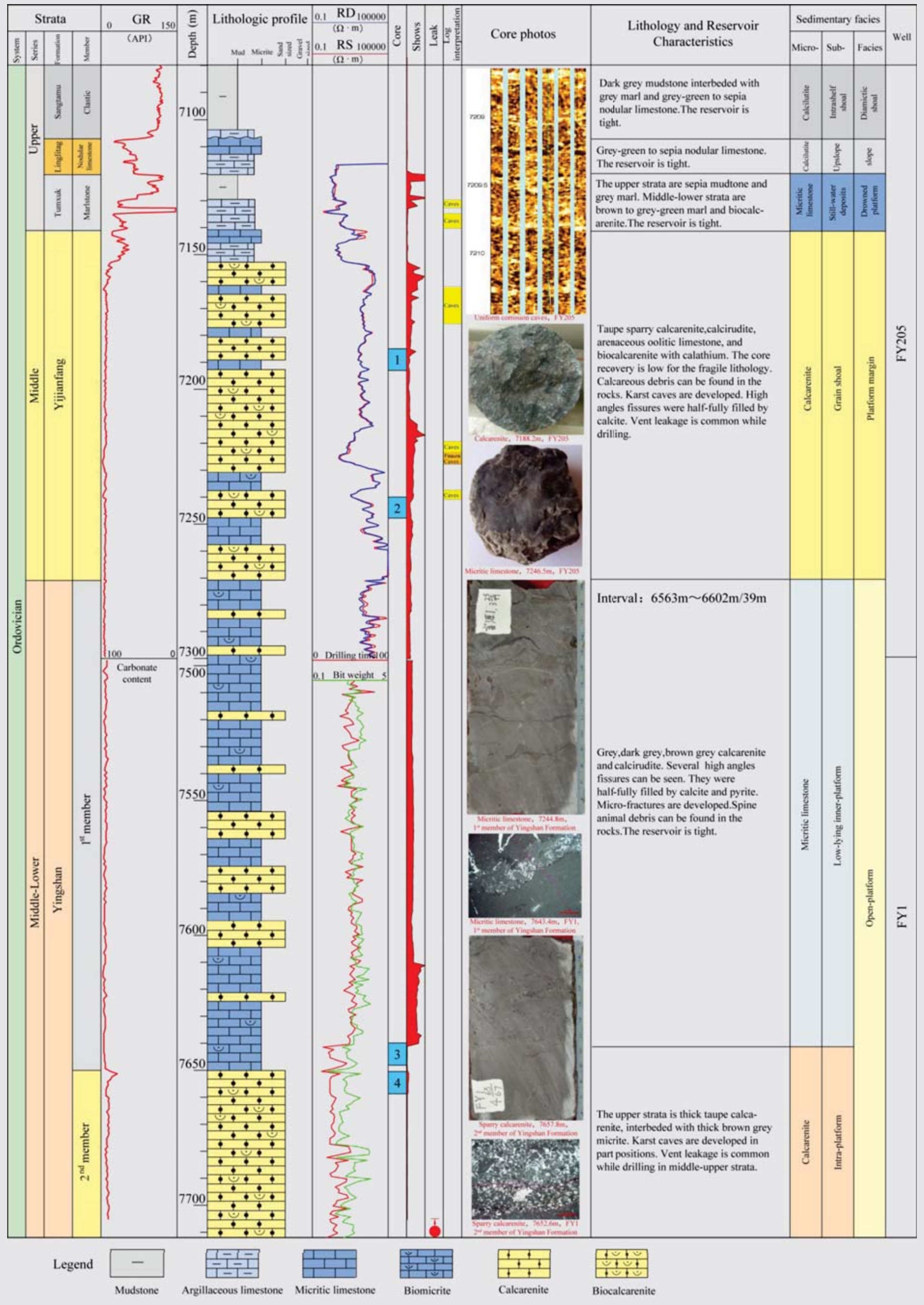

Figure 2. Synthetic stratigraphic column for the Ordovician strata in Fuyuan area

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The formation and evolution of the reservoirs are based on the favorable high-energy environment and rock types, mainly dominated by the unconformity karsts. Faults and fracture networks further reformed the fracture-cave reservoirs (Fig. 3).

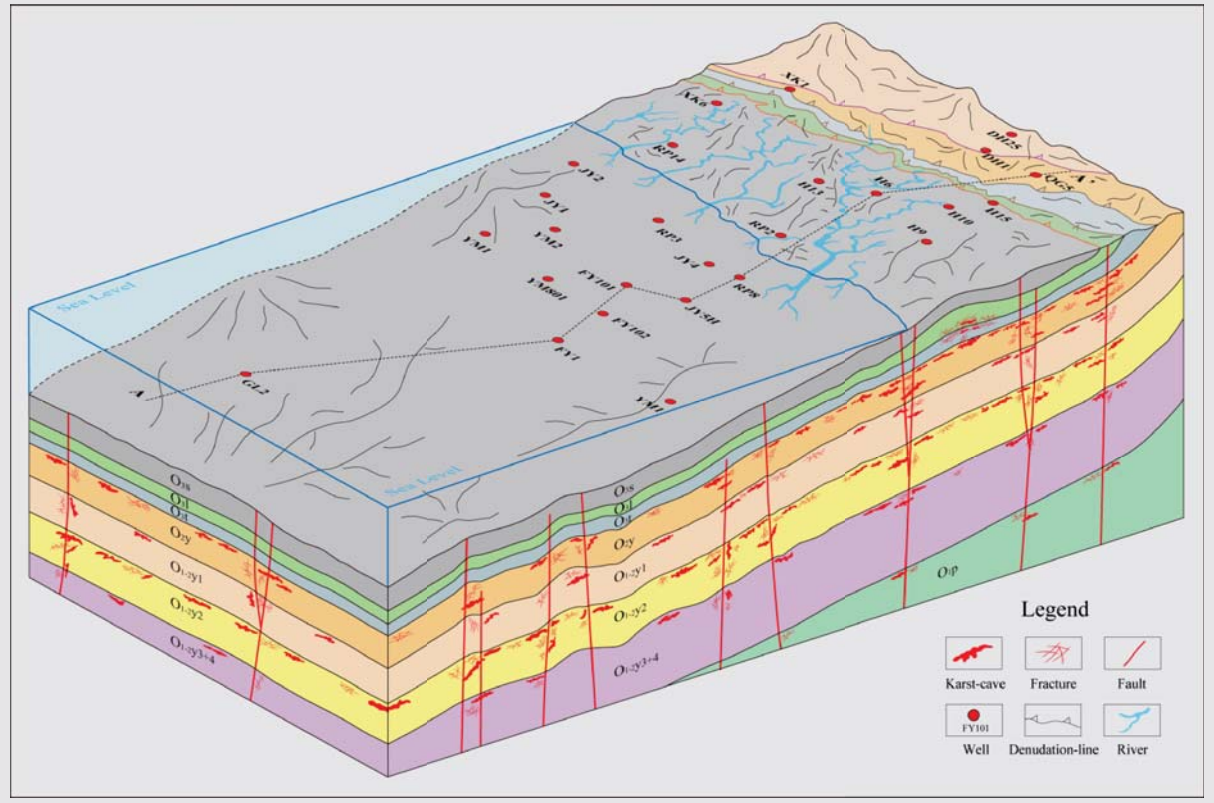

Figure 3. Development of the Ordovician karst reservoirs in the Tabei area

Non-cracked oil

The crude oils sampled from the Fuyuan area are classified as normal oils (density: 0.825~0.843 g/cm^3; viscosity: 3.1~5.2 MPa.s at 20^{o}C) and of high quality (saturated hydrocarbon: 69~83.7%; low non-hydrocarbon, asphalt-enes, sulfur and wax content. Table. 2).

Well	Depth (m)	Density (g/cm³)		Viscosity (mPa·s)		Wax (%)	Sulfur (%)	Saturate (%)	Aromatic (%)	Resin (%)	Asphaltene (%)	Saturate/ Aromatic
		20◦C	50◦C	20◦C	50◦C							
FY1	7322-7711	0.825	0.803	4.231	3.398	16.0	0.051	83.71	11.76	2.31	0.38	7.12
FY101	7211-7415	0.843	0.821	3.100	2.546	2.8	0.241					
FY102	7177-7569	0.832	0.811	5.155	4.180	8.7	0.083	74.85	13.58	2.25	1.04	5.51
FY201	7003-7106	0.827	0.805	3.138	2.526	4.1	0.250	75.73	19.17	2.28	0.15	3.95
FY202	7347-7530	0.829	0.807	3.264	2.634	5.2	0.221	69.11	16.38	2.95	1.74	4.22

Table 2. Physical properties and bulk composition of crude oil samples from the Fuyuan area

Two samples from FY1 and FY102 wells were analyzed through GC×GC-TOFMS, with a detection of 3,630 and 3,162 compounds, respectively, indicating similar distribution of compounds for the two samples (Fig. 4).

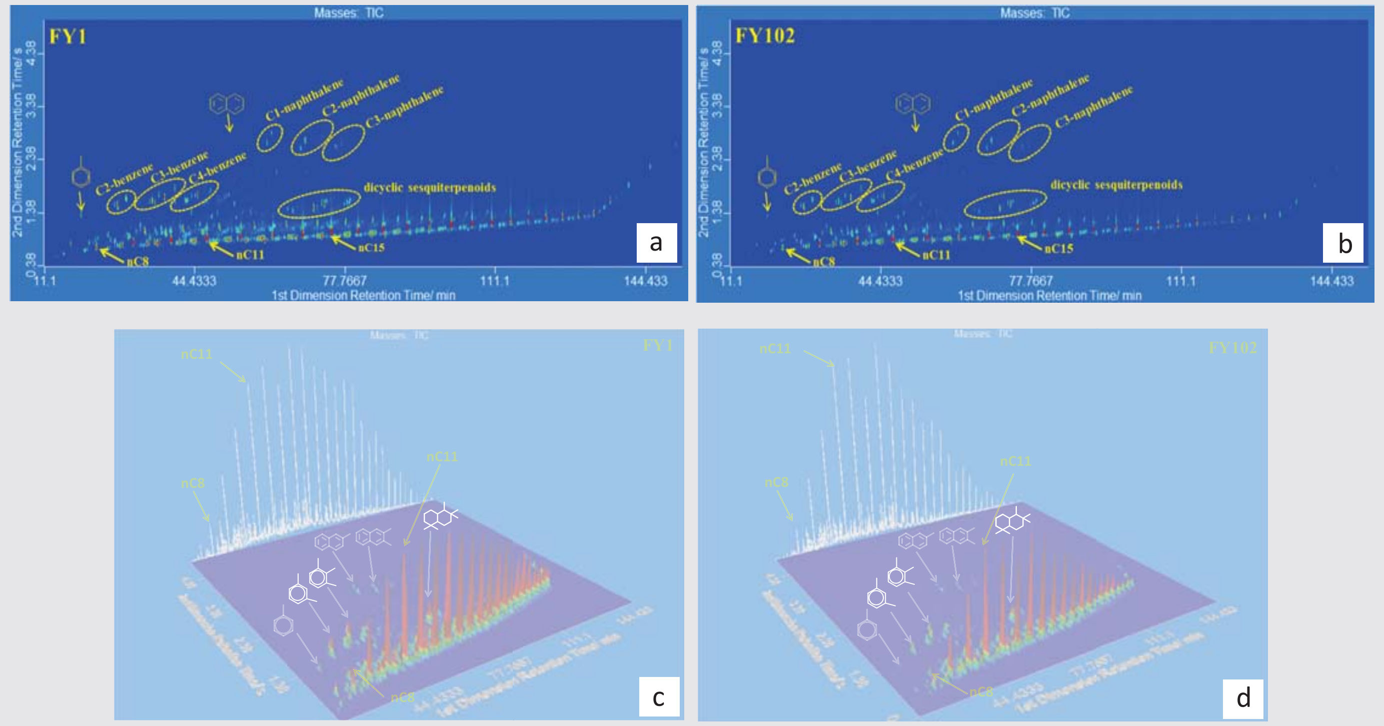

Figure 4. Two-dimensional stereograms of oil samples. The peak positions of some typical compounds are indicated by arrows

Two-dimensional stereograms revealed very low contents and poor variety of adamantanes in the two Fuyuan oil samples with only 10 compounds being detected. Two of them with one substituent were detected in selected ion at m/z 135, while five at m/z 149 and three at m/z 163 (Fig. 5). Adamantanes with four substituents as well as diadamantanes were not detected from the oil samples (Fig. 6).

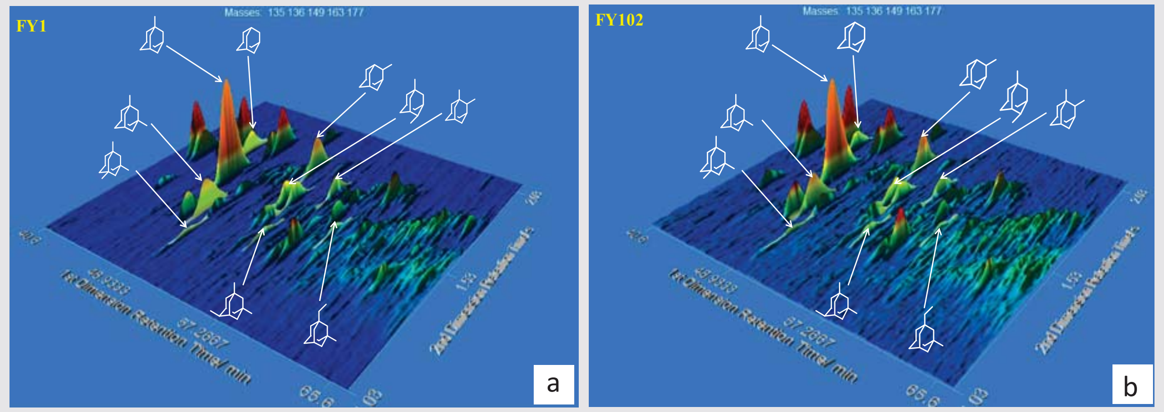

Figure 5. Two-dimensional stereograms of oil samples. The selected ions are at m/z 135, 136, 149, 163 and 177. Typical adamantine compounds are indicated by arrows.

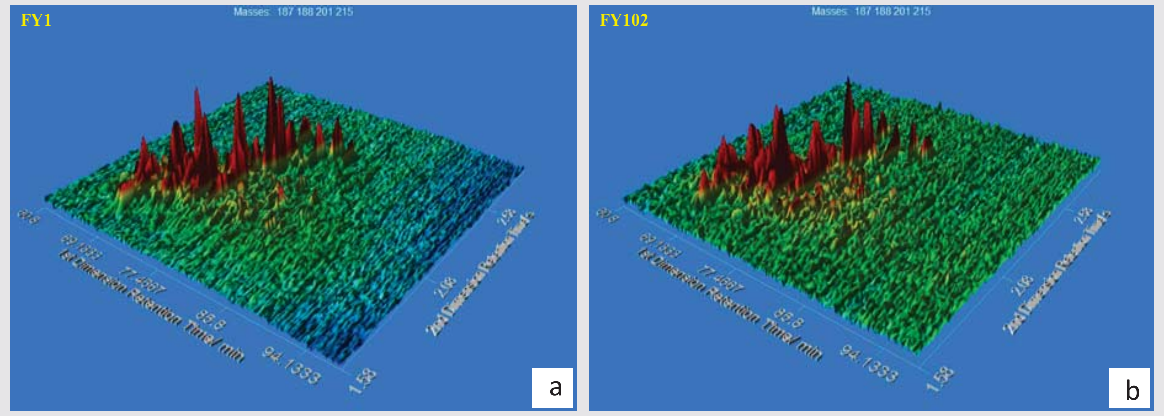

Figure 6. Tow-dimensional stereograms of oil samples. The selected ions are at m/z 187, 188, 201 and 215. Diadamantines have not been detected.

With the supplement of the bulk and molecular composition (Table. 3, Fig. 7), crude oils from the Fuyuan area have maturity consistent with those expulsed from source rocks at temperatures ~140^{o}C and vitrinite reflectance 0.8-1% (middle-upper oil window). This moderate maturity is consistent with types and low concentrations of measured adamantanes. The results indicate that the Fuyuan crude oils have not started to crack. Furthermore, the lack of thiadamantanes suggests that the oils did not undergo TSR alteration. Therefore, the crude oils were well-preserved.

Well	Moretane/Hopane	C_{29}(20S)/(20S+20R)	C_{29}(ββ)/(αα+ββ)	C_{31}(22S)/(22S+22R)	Ts/(Ts+Tm)	n-C_{17}/Pr	n-C_{18}/Ph	CPI	OEP
FY1	0.26	0.53	0.66	0.3	0.9	4.34	5.88	1	1
FY102	0.34	0.46	0.64	0.32	0.7	4.76	5.26	1	1

Table 3. Selected biomarker ratios for crude oil samples from the Fuyuan area

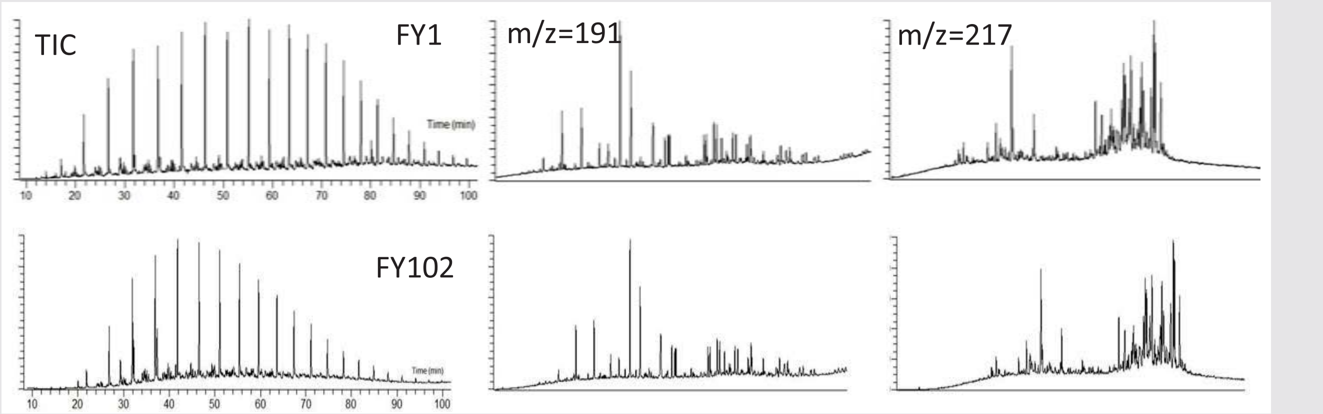

Figure 7. GC and GC-MS (m/z 191, m/z 217) traces for crude oil samples from the Fuyuan area

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Molecular and isotopic composition of oil-dissolved gases (Fig. 8, Table. 4) suggest that the gases were generated in close associations with and at the same maturity levels as the oils. Previous investigations have shown that methane and ethane in reservoirs with cracked oil in the Tarim basin are relatively depleted in ^{12}C and have $\delta^{13}C$ values ranging from -35 ‰ to -45‰ and from -28‰ to -36‰ respectively. Natural gases from FY102 and FY201 wells (Fig. 8) are much more enriched in ^{12}C than gases associated with oil cracking. We conclude that natural oil-dissolved gases in the Fuyuan field have the same genesis as the crude oil.

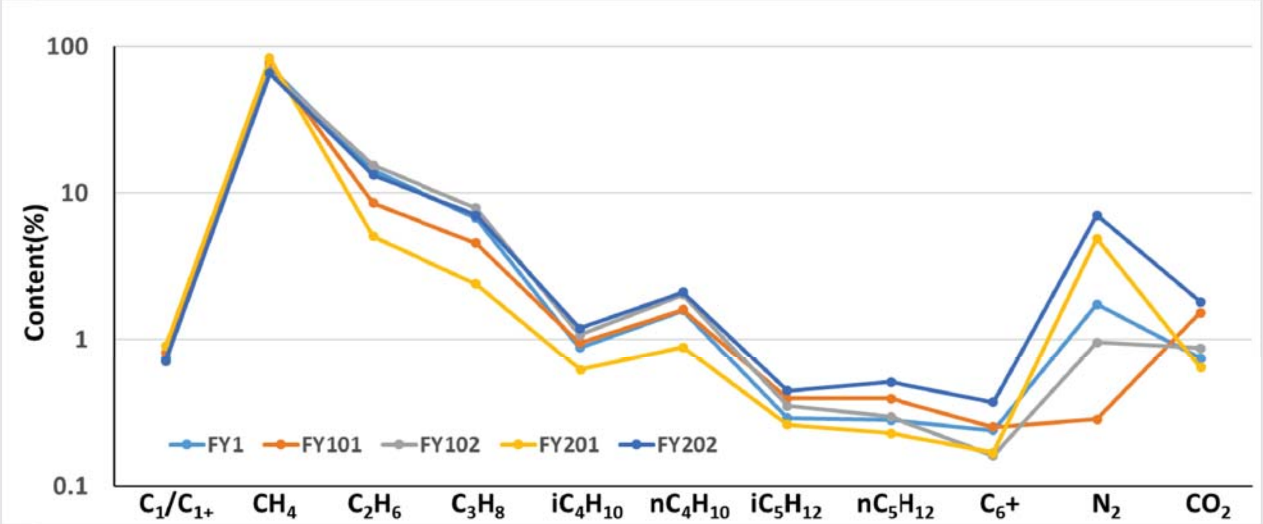

Figure 8. Molecular composition of oil-dissolved gases samples from the Fuyuan area

Well	Isotope $\delta^{13}C$ (‰, PDB)				
	CH_4	C_2H_6	C_3H_8	iC_4H_{10}	nC_4H_{10}
FY 102	-49.5	-38.1	-35.1	-35.9	-33.8
FY 201	-46.9	-37.5	-34.7	-35.4	-34.7

Table 4. Isotope composition of oil-dissolved gases samples from the Fuyuan area

Hydrocarbon Accumulation and Preservation

The 1D modeling of the burial history of FY1 well suggests that the main pool-forming event occurred from the Middle and the Late Permian to the Triassic periods, during the uplift and deformation associated with the late Hercynian orogeny (Fig. 9, 10, 11). Gas charging and flushing was wide-spread in the Tarim Basin during the Late Himalayan tectonism (10 Ma) but it clearly did not affect the Fuyuan oil field.

The Ordovician reservoir was charged with oil during the Permian period and then experienced continuous subsidence and deep burial with the increasingly thickening of the overlaying strata (Fig. 9, 10, 11). The traps largely have the same characteristics as they had during the formation period in the late Hercynian. No new hydrocarbons have been captured since the Triassic and reservoir quality was preserved.

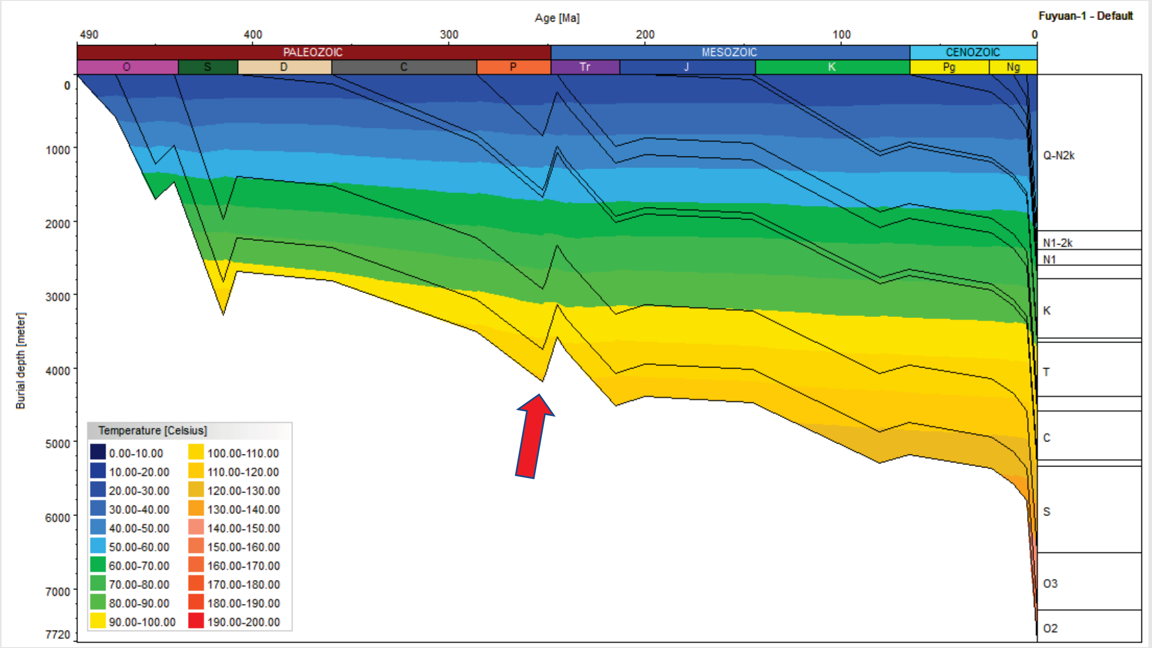

Figure 9. Burial history curve and hydrocarbon charging periods for samples from well Fuyuan 1 in the Fuyuan area

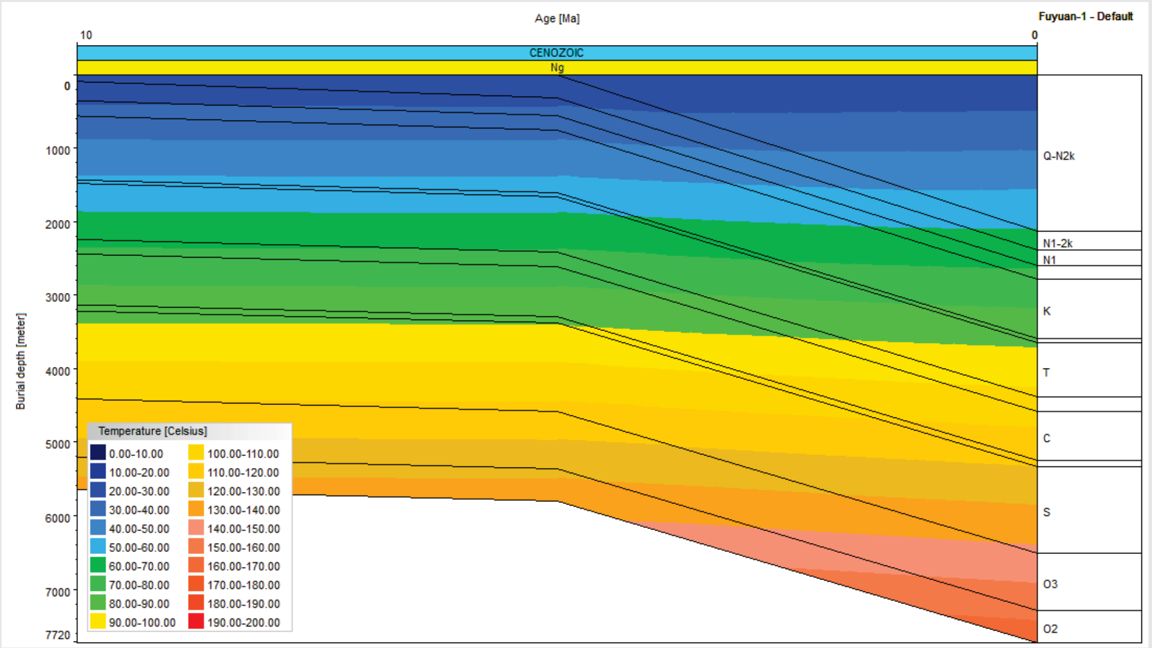

Figure 10. Part of Fig 9., showing the burial history after 10 Ma

According to the GC×GC-TOFMS analysis, the crude oil shows no evidence of significant cracking at a depth of 7,711 m and a temperature of 172 °C, suggesting that the oil thermal stability may be higher than previously envisioned. In addition, the lack of thiaadamantanes and hydrogen sulfide indicates that the oils have not undergone TSR which can result in hot oil cracking into gas. These may explain the preservation of deep crude oils at a high temperature.

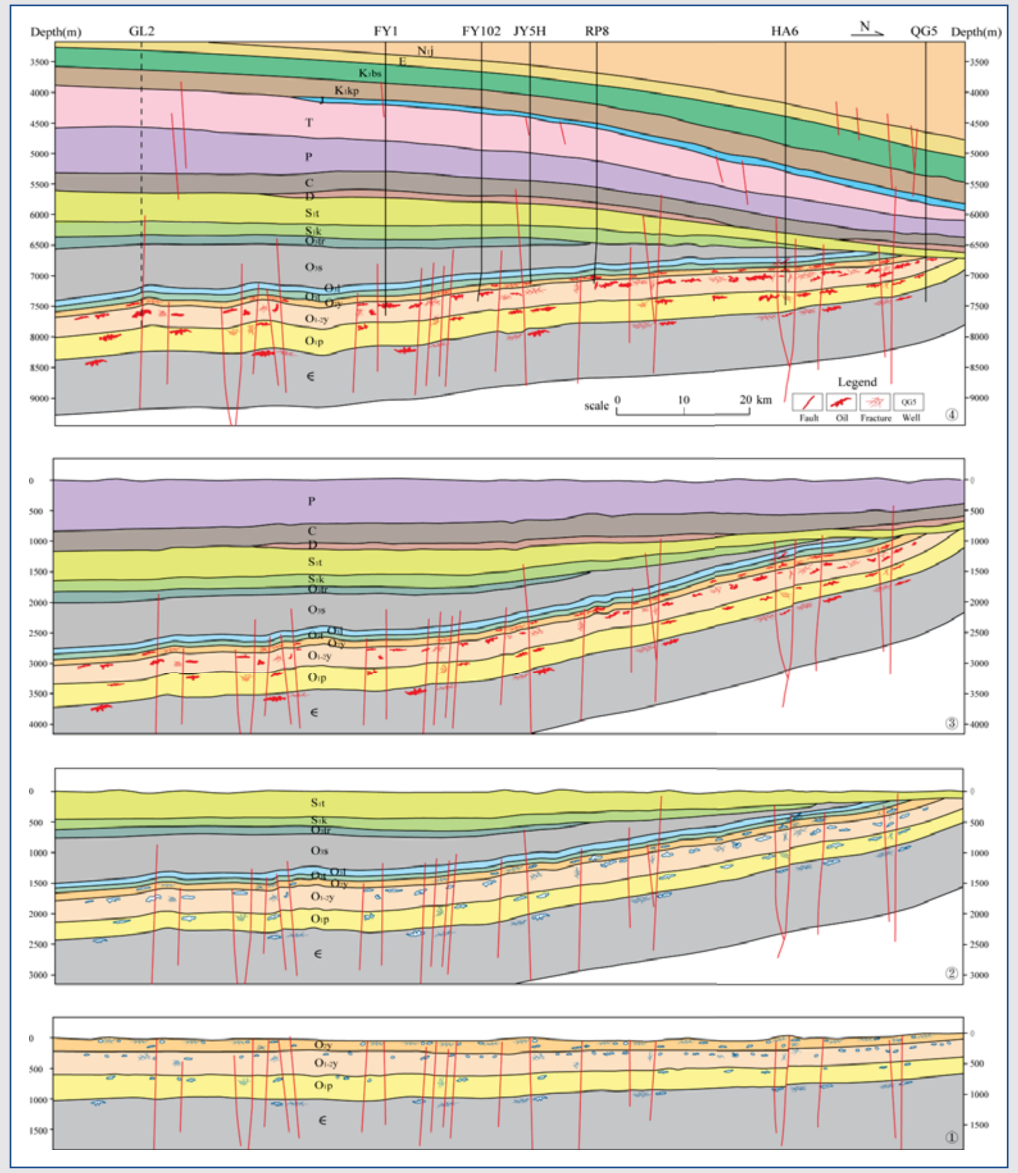

Figure 11. Ordovician hydrocarbon accumulation and evolution in the Fuyuan area

Discovery of non-cracked oil in the Fuyuan field opens a new frontier of exploration for ultra-deep HPHT oil reservoirs in the Tarim basin as well as in other basins with similar geological settings around the world, especially those areas with low geothermal gradients that have experienced initial continuously slow burial and late rapid burial.