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RESEARCH PAPER

Geochemical differences in natural gas of Sinian Dengying Formation on the east and west sides of the Deyang–Anyue rift trough and their genesis, Sichuan Basin, SW China

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Abstract: Taking the natural gas reservoirs of the Sinian Dengying Formation on the east and west sides (Gaoshiti–Moxi area and north slope of central Sichuan paleo-uplift on the east; Weiyuan and Well Datan-1 block on the west) of the Deyang–Anyue rift trough in the Sichuan Basin, China, as the research object, the geochemical parameters (component, isotopic composition) of natural gas from the Dengying Formation in different areas are compared, and then the differences in geochemical characteristics of Dengying natural gas on the east and west sides of the Deyang–Anyue rift trough and their genesis are clarified. First, the Dengying gas reservoirs on both sides of the rift trough are predominantly composed of oil-cracking gas with high maturity, which is typical dry gas. Second, severely modified by thermochemical sulfate reduction (TSR) reaction, the Dengying gas reservoirs on the east side exhibit high H_2S and CO_2 contents, with an elevated $\delta^{13}C_2$ value (average value higher than −29‰). The Dengying gas reservoirs in the Weiyuan area are less affected by TSR modification, though the $\delta^{13}C_1$ values are slightly greater than that of the reservoirs on the east side with partial reversal of carbon isotope composition, likely due to the water-soluble gas precipitation and accumulation mechanism. The Dengying gas reservoir of Well Datan-1 shows no influence from TSR. Third, the Dengying gas reservoirs reflect high helium contents (significantly higher than that on the east side) in the Weiyuan and Datan-1 areas on the west side, which is supposed to attribute to the widespread granites in basement and efficient vertical transport along faults. Fourth, controlled by the paleo-salinity of water medium in the depositional period of the source rock, the $\delta^2H_{CH_4}$ values of the Dengying gas reservoirs on the west side are slightly lighter than those on the east side. Fifth, the Dengying natural gas in the Datan-1 area is contributed by the source rocks of the Sinian Doushantuo Formation and the third member of the Dengying Formation, in addition to the Cambrian Qiongzhusi Formation.

Key words: thermochemical sulfate reduction (TSR); Well Datan-1; helium-rich gas reservoir; Sinian Dengying Formation; Deyang–Anyue rift trough; Sichuan Basin

Introduction

The Sinian Dengying Formation (Z_2dn) in the Sichuan Basin, SW China, is characterized by abundant natural gas resources. By the end of 2023, the proven natural gas reserves in the Z_2dn account for 17.55% of the total proven natural gas reserves in the Sichuan Basin and 41.15% of the total proven marine natural gas reserves [1]. It serves as the primary target interval for deep to ultra-deep marine natural gas exploration.

The exploration history of natural gas in the Z_2dn of the Sichuan Basin can be traced back to 1964, when Well

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Weiji deployed in the paleo-uplift high area on the west side of the Deyang–Anyue rift trough obtained industrial gas flow, leading to the discovery of the Weiyuan Gas Field and marking the beginning of natural gas exploration in the Z_2dn. Over the following four decades, discoveries of natural gas in the Z_2dn remained limited. In recent 20 years, with the deepening study on the sedimentation and evolution of the Deyang–Anyue rift trough, Exploration and Development Research Institute of PetroChina Southwest Oil and Gas Field Company has made a series of major exploration breakthroughs by aiming at the key geological issues and strengthening the basic geological research: In 2011, the Anyue Gas Field, a giant integrated marine carbonate gas field with over one trillion cubic meters of reserves, was confirmed in the Gaoshiti–Moxi area (referred to as Gao-Mo area) on the platform margin belt on the east side of the Deyang–Anyue rift trough (referred to as the east side). In 2020, Well Pengtan-1 in the paleo-uplift slope area on the east side achieved a major breakthrough, obtaining a high-yield gas flow of 121.98×10^4 m^3/d from the second member of the Dengying Formation (referred to as Z_2dn_2), leading to the discovery of another trillion cubic meters gas field – the Penglai Gas Field. These discoveries demonstrate the enormous natural gas exploration potential in the platform margin belt of the Z_2dn on the east side of the rift trough [2].

Compared to the east side of the rift trough, natural gas exploration in the Z_2dn on the west side of the Deyang–Anyue rift trough (referred to as the west side) has progressed slowly. Since the exploration breakthrough in the Weiyuan area in 1964, wells such as Well Laolong-1 (1988), Well Zhougong-1 (1991), and Well Hanshen-1 (2009) were drilled, but all tested water [3]. Over the past five years, guided by the principle of "prioritizing risk exploration and targeting large-scale resource zones", the Exploration and Development Research Institute of PetroChina Southwest Oil and Gas Field Company has continued to deepen research on the hydrocarbon accumulation conditions of the Z_2dn on the west side. In 2018, Well Datan-1 was deployed in the Daxingchang area, achieving an exploration breakthrough. In October 2023, Well Datan-1 yielded high industrial gas flow, with Z_2dn_2 producing 42.16×10^4 m^3/d of natural gas and the fourth member of the Dengying Formation (referred to as Z_2dn_4) producing 81.85×10^4 m^3/d of natural gas. This marks the first high-yield industrial gas well in the platform margin belt of the Z_2dn on the west side.

The previous studies on natural gas reservoirs in the Z_2dn have predominantly focused on isolated areas such as the Anyue Gas Field in the Gao-Mo area on the east side, the Penglai Gas Field in the north slope, or the Weiyuan area on the west side [4−8]. In contrast, geochemical research on natural gas in the Z_2dn of the newly explored Daxingchang area (Well Datan-1) on the west side remains in its nascent stage. There is an urgent need to compare the composition and isotopic characteristics of natural gas in the Z_2dn across multiple regions on both sides of the rift trough systematically. This study focuses on the natural gas reservoirs in the Z_2dn along both sides of the Deyang–Anyue rift trough, aiming to elucidate the differences in these geochemical features between the two sides of the rift trough and their underlying causes by conducting a comprehensive comparative analysis of the geochemical characteristics (components, isotopic composition) of natural gas in the Z_2dn from different areas, the findings will advance the understanding of natural gas reservoirs in the Z_2dn on both sides of the Deyang–Anyue rift trough and provide technical support for the exploration and development of deep to ultra-deep marine carbonate natural gas.

1. Regional geology

1.1. Tectonic-sedimentary geological setting and stratigraphic characteristics

The Deyang–Anyue rift trough was developed during the late Tongwan Movement II episode and represents the most significant tectonic unit in the Sichuan Basin during the Sinian to Early Cambrian. It covers an area of approximately 6×10^4 km^2 within the basin, characterized by a "wide and steep northern section, and narrow and gentle southern section" [3, 9] (Fig. 1a). Based on depth and width, the rift trough is subdivided into northern, central, and southern section. The key study areas include the Anyue Gas Field in the Gao-Mo area and the Penglai gas field in the north slope on the east side, the Weiyuan Gas Field and Well Datan-1 block in the Daxingchang area of southwestern Sichuan on the west side (Fig. 1a).

The formation and evolution of the Deyang–Anyue rift trough began during the depositional period of the Z_2dn and concluded by the depositional period of the Cambrian Longwangmiao Formation ($Є_1$l). The Z_2dn is further divided into four members, the first member to the fourth member (referred to as Z_2dn_1 to Z_2dn_4), with Z_2dn_2 and Z_2dn_4 being the primary depositional intervals [2], the lithology is dominated by dolostone. The Lower Cambrian strata can be divided into the Maidiping Formation ($Є_1$m), Qiongzhusi Formation ($Є_1$q), Canglangpu Formation ($Є_1$c), and Longwangmiao Formation from oldest to youngest [10] (Fig. 1b). Among them, the $Є_1$c and $Є_1$l develop high-quality carbonate reservoirs (Fig. 1c). the $Є_1$m is absent on platform margin belt in the Gao-Mo area, and the Z_2dn exhibits a paraconformable contact with the overlying $Є_1$q (Fig. 1c), while its lower boundary conformably contacts the Doushantuo Formation (Z_1d) [11]. In contrast, the Z_2dn in the southwestern Sichuan Basin shows a conformable contact with the $Є_1$m [3].

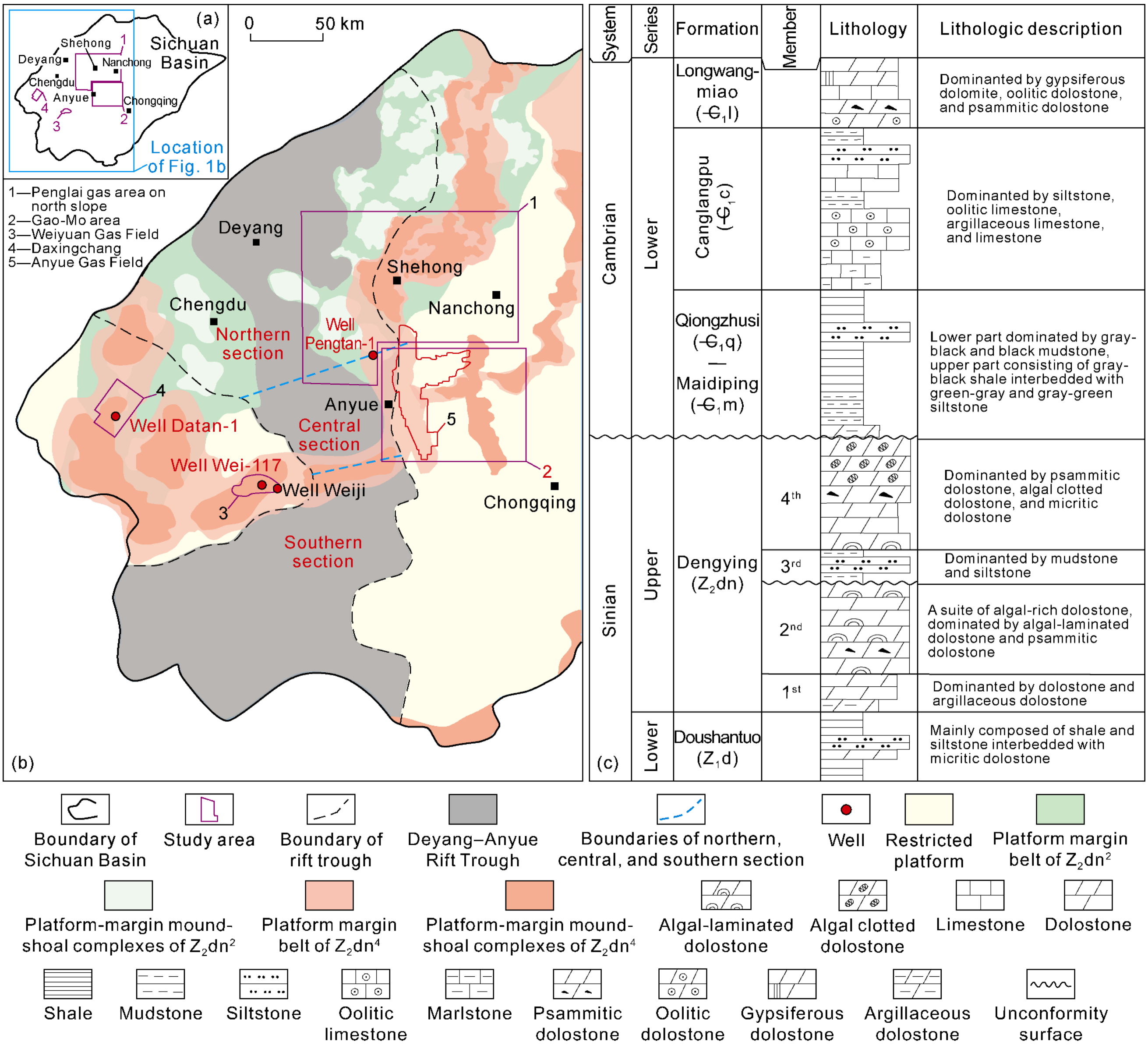


Fig. 1. Location of the study area in the Sichuan Basin (a), overlay map of the Deyang–Anyue rift trough and sedimentary facies belts of the Dengying Formation in the Sichuan Basin (modified from references [3, 9]) (b), and simplified stratigraphic column of the Sinian–Cambrian in the study area (modified from Reference [10]) (c).

1.2. Source rocks

Three primary sets of source rocks are developed within and around the Deyang–Anyue rift trough: Z_2dn_3, Ꞓ$_1$m and Ꞓ$_1$q. Additionally, the Z_1d source rocks are locally developed in the Sichuan Basin, primarily distributed along the basin margins.

The Qiongzhusi Formation source rocks primarily consist of gray-black mudstone and black shale, with high organic matter abundance. The average total organic carbon (TOC) content is 1.95%, and their thicknesses are 300–350 m within the rift trough. Well Datan-1 encountered the Qiongzhusi Formation with a thickness of approximately 133 m, which is relatively thinner compared to its thickness within the rift trough. The Maidiping Formation comprises siliceous shale and carbonaceous mudstone-dominated source rocks with high TOC (averaging 1.68%), and it is mainly developed within the trough, with thicknesses of 50–100 m. The Z_2dn_3 is primarily composed of bluish-gray mudstone with relatively low TOC (averaging 0.65%), and its thickness is 5–30 m within the basin, but the thickness of Z_2dn_3 is only about 10 m in the southwestern Sichuan region. The organic-rich shale of the Doushantuo Formation has an average TOC content of approximately 1.51%, it is encountered by only a few wells within the basin, such as Well Wei-117, where the revealed thickness is 10–50 m. However, the Doushantuo Formation is more extensively developed along the basin margins, reaching a thickness of 120–480 m. The Qiongzhusi Formation has been confirmed as the main source rock for the natural gas reservoirs in the Z_2dn of the Gao-Mo area and the north slope on the east side. It exhibits strong hydrocarbon generation capacity, providing high-quality and abundant material basis for hydrocarbon accumulation. Additionally, the Qiongzhusi Formation and Maidiping Formation can serve as regional mudstone-shale cap rocks, offering effective sealing for the natural gas reservoirs in the Z_2dn_2 and Z_2dn_4.

1.3. Reservoirs of the Dengying Formation

The platform margin belts of the Z_2dn are developed on the high structural positions on the east and west sides of the Deyang–Anyue rift trough, these belts host large-scale, vertically stacked, and laterally continuous high-quality reservoir bodies, including mound-shoal complexes and platform-margin residual hills within the rift trough (Fig. 1b). The mound-shoal complexes of the Z_2dn_2 and Z_2dn_4 cover approximately 3 000 km^2 and 4 000 km^2 on the west side of the rift trough. In contrast, the mound-shoal complexes in the Z_2dn_2 and Z_2dn_4 cover areas of approximately 10 000 km^2 and 5 000 km^2 respectively in the Suining–Guangyuan area on the east side of the rift trough.

The thickness of the Z_2dn is strongly controlled by the Deyang–Anyue rift trough, the total thickness of Z_2dn_1 and Z_2dn_2 is 50–150 m within the rift trough, while that of Z_2dn_3 and Z_2dn_4 is 50–100 m. Outside the rift trough, the total thickness of Z_2dn_1 and Z_2dn_2 is 350–800 m, and that of Z_2dn_3 and Z_2dn_4 is 100–450 m. The lithology of the Z_2dn is mainly composed of algal dolomite and micritic dolomite interbedded with minor clastic rocks. The reservoir of the Z_2dn_2 is characterized by typical algal dolomite (Fig. 1c), with reservoir spaces dominated by dissolution pores, algal framework pores, intergranular dissolution pores, and fractures. In contrast, the reservoir of the Z_2dn_4 primarily consists of algal clotted dolostone and psammitic dolomite.

2. Geochemical characteristics of gas reservoirs in the Dengying Formation on the east and west sides of the Deyang-Anyue Rift Trough

Based on experimental data and relevant literature, 349 sets of natural gas test data from 158 wells on both sides of the rift trough [4–6, 12–18] were statistically analyzed. The natural gas in the Z_2dn_2 and Z_2dn_4 on both sides of the Deyang–Anyue rift trough is predominantly composed of hydrocarbon gases. Compared to the Cambrian strata, the natural gas in the Z_2dn exhibits lower CH_4 and C_2H_6 content, with a volume fraction of less than 95%, and almost no C_3H_8. However, non-hydrocarbon components such as CO_2, H_2S, N_2 and He are significantly higher [6, 12–14, 17–18] (Table 1). Additionally, distinct differences in gas composition and carbon/hydrogen isotopic composition are observed between the natural gas in the Z_2dn on the east and west sides of the rift trough.

2.1. Composition of natural gas

2.1.1. Hydrocarbon gas composition

The natural gas in the Z_2dn in Well Datan-1 has the highest CH_4 content on the west side of the rift trough, while the CH_4 content in the Weiyuan area and the north slope is relatively lower. The natural gas in the Weiyuan area has the highest C_2H_6 content. Overall, the natural gas is typical dry gas in the Z_2dn on both sides of the rift trough (Table 2).

The CH_4 content of natural gas in the Z_2dn on the east side varies significantly (64.16%–94.94%). In the north slope, the CH_4 content of natural gas is 64.16%–94.94% (averaging 84.09%). The average CH_4 content is 90.38% in the Gao-Mo area which is slightly higher than that of the north slope. On the west side of the rift trough, the CH_4 content in the Weiyuan area ranges from 83.23% to 89.82% (averaging 86.35%). The average CH_4 content in Well Datan-1 is 92.32% (Table 2).

The average C_2H_6 content of natural gas in the Z_2dn is 0.05% in the north slope on the east side, which is comparable to that of the Gao-Mo area. The C_2H_6 content of natural gas is the highest in the Weiyuan area on the west side (averaging 0.12%). The average C_2H_6 content in Well Datan-1 is 0.05% (Table 2).

2.1.2. Non-hydrocarbon gas composition

The average CO_2 content of the Dengying Formation exceeds 4% on both the east and west sides of the rift trough, while the H_2 content is generally low, averaging less than 0.1% (Table 2). The CO_2 and H_2S contents on the east side are higher than those on the west side; the west side is characterized by high He content (averaging greater than 0.1%); the N_2 content is significantly higher in the Weiyuan area.

The average He content exceeds 0.1% on the west side of the rift trough, indicating helium-rich natural gas reservoirs [19], and the Weiyuan area has the highest He content (averaging 0.27%). The Weiyuan area also features high N_2 content (averaging 7.51%), while the N_2 content in Well Datan-1 is relatively low. Compared to the west side, the He content on the east side is significantly lower (averaging less than 0.05%); the N_2 content in the north slope is slightly higher than that in the Gao-Mo area (Table 2).

The H_2S and CO_2 contents of natural gas in the Z_2dn are highest in the north slope on the east side. The Weiyuan area on the west side has the lowest CO_2 content, and its H_2S content is comparable to that of the Gao-Mo area; the CO_2 content is slightly higher in Well Datan-1 than that in the Weiyuan area, but its H_2S content is lower. Overall, the CO_2 and H_2S contents of the natural

Table 1. Natural gas component content and carbon/hydrogen isotopic composition data of the Dengying Formation on east and west sides of Deyang–Anyue rift trough

Region	Study area	Well	Formation	Depth/m	Component content of natural gas/%								Carbon-hydrogen isotopic composition/‰				Source
					CH_4	C_2H_6	C_3H_8	He	N_2	CO_2	H_2S	H_2	$\delta^{13}C_{CH_4}$	$\delta^{13}C_{C_2H_6}$	$\delta^{13}C_{CO_2}$	$\delta^2H_{CH_4}$	
East side	North slope	ZJ2	Z_2dn_2	6 547	76.90	0.04	0	0.05	0.67	15.43	6.80	0	−35.1	−27.4	−1.5	−141	Reference [12]
		PT1	Z_2dn_2 Z_2dn_2	5 726–5 817	94.94	0.08	0	0.06	0.13	2.32	2.46	0.01	−33.9	−29.2	−0.2	−125	
		PT108	Z_2dn_2	5 871–5 913	93.13	0.01	0	0.01	0.50	4.20	2.10	0.05	−33.0	−24.7		−141	
		PT103	Z_2dn_2	5 835	89.47	0.04	0	0.01	0.62	6.54	3.15	0	−33.7	−28.4	−2.8	−144	Reference [13]
		PT102	Z_2dn_2	5 937	89.88	0.06	0	0.02	0.80	5.25	3.71	0	−34.4	−29.1	−0.3	−137	Reference [13]
		PT101	Z_2dn_2	5 990	83.34	0.06	0	0.01	10.24	3.23	3.09	0.03	−34.7	−29.0	−3.5	−143	Reference [13]
		PS5	Z_2dn_4	5 503–5 588	79.28	0.03	0	0.01	0.37	18.20	2.08	0.03	−33.0	−28.0		−151	
		PS1	Z_2dn_4	7 467–7 680	79.64	0.05	0	0.03	0.62	10.44	8.92	0.30	−32.8	−27.8	−0.9	−148	
		DB1	Z_2dn_4	6 312–6 484	86.93	0.06	0	0.02	0.54	10.29	2.15	0.01	−32.8	−27.6	1.9		
	Gao-Mo area	MX8	Z_2dn_2	5 422–5 459	91.43	0.04	0	0.04	2.45	6.02	0.01	0	−32.2	−27.4		−146	Reference [18]
		MX8	Z_2dn_4	5 102–5 172	91.41	0.03	0	0.06	1.64	5.88	0.95	0	−32.9	−28.4		−148	Reference [18]
		MX19	Z_2dn_4	5 145	92.24	0.03	0	0.03	1.22	5.15	1.30	0.03	−33.5	−28.3		−146	
		MX18	Z_2dn_4	5 095	92.36	0.04	0	0.04	1.42	4.74	1.38	0.02	−33.7	−27.4		−146	
		MX9	Z_2dn_2	5 423–5 459	91.82	0.05	0	0.02	0.96	4.24	2.75	0	−34.4		−2.0		Reference [14]
		MX11	Z_2dn_2	5 455–5 486	90.02	0.03	0	0.05	1.29	7.65	0.94	0	−31.8	−26.7		−147	Reference [15]
		GS9	Z_2dn_2	5 504–5 871	91.40	0.04	0	0.05	2.00	5.65	0.85	0.01	−32.0	−27.5		−152	
		GS9	Z_2dn_4	5 090–5 188	90.41	0.04	0	0.03	0.85	7.77	0.88	0	−33.1	−28.5		−134	Reference [15]
		GS6	Z_2dn_4	4 958–5 210	90.93	0.04	0.01	0.03	0.09	7.91	1.00	0	−32.6	−28.8		−137	Reference [15]
		GS3	Z_2dn_2	5 799–5 810	86.62	0.03	0	0.11	4.56	7.05	0	0	−32.6	−28.0		−149	Reference [17]
		GS18	Z_2dn_4	5 150	92.15	0.04	0	0.03	1.10	6.04	0.60	0.04	−32.8	−29.6		−144	
		GS122	Z_2dn_4	5 556–6 579	90.59	0.04	0	0.02	0.30	8.45	0.59	0.01	−32.5	−26.7	0.4	−134	
		GS1	Z_2dn_4	4 956–5 130	82.65	0.04	0	0.04	2.12	14.19	0.85	0	−32.3	−28.7			Reference [14]
West side	Weiyuan area	W70	Z_2dn_4	3 064–3 170	85.95	0.09	0	0.36	8.53	4.03	1.00	0	−32.4		−2.5		Reference [14]
		W30	Z_2dn_4	2 844–2 950	86.16	0.26	0	0.30	8.15	4.13	0.91	0.09	−32.7	−32.0			Reference [14]
		W100	Z_2dn_4	2 959–3 041	86.80	0.13	0	0.30	6.47	5.07	1.18	0.01	−32.5	−31.7	−11.6	−139	Reference [6]
		W46	Z_2dn_4	2 880–2 963	86.26	0.14	0	0.27	7.44	4.55	1.30	0	−32.8	−34.8			Reference [14]
		W39	Z_2dn_4	2 986	86.74	0.12	0	0.27	7.08	4.53	1.22	0	−32.4	−33.9	−14.6	−142	Reference [6]
		W28	Z_2dn_4	2 905	88.30	0.08	0	0.27	7.12	3.30	0.90	0.00	−32.5	−31.6	−12.5		Reference [14]
		W2	Z_2dn_4	2 836	85.07	0.11	0	0.25	8.33	4.66	1.31	0	−32.5	−31.0	−11.2	−147	Reference [6]
		W12	Z_2dn_4	3 005	85.07	0.11	0	0.25	8.33	4.66	1.31	0	−32.5	−31.0	−11.2		Reference [14]
		W27	Z_2dn_4	2 851–2 995	86.23	0.12	0	0.23	7.12	4.94	1.30	0.01	−32.0	−31.2			Reference [14]
	Well Datan-1 block	DT1	Z_2dn_2	6 265–6 309	92.40	0.04	0	0.04	2.34	5.12	0.05	0.01	−31.2	−29.4		−154	
		DT1	Z_2dn_2	6 265–6 309	91.98	0.06	0	0.11	2.17	5.62	0.05	0.01	−31.2	−29.4	−0.6	−154	
		DT1	Z_2dn_4	6 040–6 110	91.92	0.06	0	0.11	2.13	5.73	0.04	0.01	−31.1	−28.7	−0.9	−143	
		DT1	Z_2dn_4	6 040–6 110	92.57	0.04	0	0.11	2.16	5.07	0.05	0.00	−31.3	−29.2	−0.5	−142	
		DT1	Z_2dn_4	6 040–6 110	92.77	0.04	0	0.11	2.15	4.88	0.05	0.00	−31.3	−28.9	−0.6	−148	
		DT1	Z_2dn_4	6 040–6 110	92.92	0.03	0	0.11	2.14	4.75	0.05	0.00	−31.5	−29.1	−0.7	−143	
		DT1	Z_2dn_4	6 040–6 110	92.15	0.05	0	0.11	2.11	5.52	0.06	0.00	−31.5	−29.1	−1.1	−146	
		DT1	Z_2dn_4	6 040–6 110	92.02	0.04	0	0.11	2.18	5.59	0.05	0.01	−31.6	−29.3	−0.5	−141	

Table 2. Composition of natural gas in Dengying Formation on east and west sides of Deyang–Anyue rift trough

Region	Study area	Number of samples	CH_4/%	C_2H_6/%	N_2/%	He/%	CO_2/%	H_2S/%	H_2/%	Drying coefficient
East side	North slope	41	64.16–94.94 / 84.09	0–0.27 / 0.05	0.08–31.85 / 2.48	0.00–0.38 / 0.04	0.07–34.05 / 9.78	0–20.47 / 3.56	0–0.58 / 0.08	Mean >0.99
	Gao-Mo area	157	66.42–96.21 / 90.38	0.01–0.12 / 0.04	0.02–24.95 / 1.43	0.01–0.18 / 0.04	0.09–26.27 / 7.07	0–3.19 / 1.07	0–0.68 / 0.06	
West side	Weiyuan area	77	83.23–89.82 / 86.35	0.02–0.26 / 0.12	4.27–10.30 / 7.51	0.14–0.38 / 0.27	3.30–6.46 / 4.62	0.40–1.53 / 1.08	0–0.16 / 0.01	
	Well Datan-1 block	9	91.92–92.92 / 92.32	0.03–0.08 / 0.05	2.04–2.34 / 2.16	0.04–0.11 / 0.10	4.75–5.73 / 5.32	0.04–0.06 / 0.05	Mean< 0.01	

Note: The numerator represents the value range, and the denominator represents the average value.

gas in the Z_2dn on the east side are higher than those on the west side (Table 2).

2.2. Isotopic composition of the natural gas

The $\delta^{13}C_1$ values on the west side of the rift trough are slightly heavier than those on the east side, with the $\delta^{13}C_1$ value of Well Datan-1 being the heaviest. In contrast, the $\delta^{13}C_2$ values on the east side, with an average greater than −29‰, are significantly greater than those on the west side. The $\delta^2H_{CH_4}$ values on the west side are slightly lower than those on the east side.

The $\delta^{13}C_1$ values of natural gas in the Z_2dn show similar distributions in the Gao-Mo area and the north slope on the east side of the rift trough (averaging −32.9‰); the $\delta^{13}C_1$ value of natural gas from Well Datan-1 is the greatest on the west side (averaging −31.3‰). The $\delta^{13}C_1$ composition in the Weiyuan area is significantly greater than that of more than half of the samples from the east side (averaging −32.5‰). The average $\delta^{13}C_2$ values of natural gas in the Z_2dn are −28.2‰ and −28.1‰ in the Gao-Mo area and the north slope on the east side, respectively. In contrast, the average $\delta^{13}C_2$ value is −29.1‰ in Well Datan-1 on the west side, and the average $\delta^{13}C_2$ value is −32.1‰ in the Weiyuan area, which is smaller than that on the east side. The east side and Well Datan-1 exhibit a clear positive carbon isotopic sequence ($\delta^{13}C_1<\delta^{13}C_2$, no reversal), while some gas samples from the Weiyuan area show a reversed carbon isotopic composition ($\delta^{13}C_1>\delta^{13}C_2$) (Table 1).

The $\delta^2H_{CH_4}$ values of natural gas is from −162‰ to −121‰ in the north slope on the east side, with an average of −141‰, the average $\delta^2H_{CH_4}$ value in the Gao-Mo area is −142‰; compared to the east side, the $\delta^2H_{CH_4}$ value in Well Datan-1 on the west side is smaller, with an average of −146‰, while the average $\delta^2H_{CH_4}$ value in the Weiyuan area is −143‰.

2.3. Maturity of natural gas

The $\delta^{13}C_1$ values of natural gas can be used to calculate the equivalent vitrinite reflectance (R_{oe}) to reflect its maturity, but the results obtained by different calculation methods vary significantly [20]. Previous studies have often used the $\delta^{13}C_1$-R_o method [20] to evaluate the maturity of natural gas in the Cambrian Longwangmiao Formation in the Sichuan Basin, with better results. The results calculated using this method (Table 3) show that the natural gas in the Z_2dn on both the east and west sides of the rift trough is highly to over-mature (with an average R_{oe} greater than 2.0%), and the natural gas from Well Datan-1 has the highest maturity.

2.4. Genetic types of natural gas

The composition and isotopic characteristics of natural gas can effectively indicate its genetic type. The $\delta^{13}C_1$ value can distinguish between organic and inorganic origins of natural gas. It is generally accepted that $\delta^{13}C_1<-30‰$ indicates an organic origin, while the $\delta^{13}C_2$ value can differentiate between oil-type gas and coal-type gas, with $\delta^{13}C_2$ = −28‰ commonly used as the boundary between the two [21]. However, various abnormal thermal alterations in deep burial environments can differentially modify natural gas in highly to over-mature stages, leading to greater carbon isotopic values [7]. The $\delta^{13}C_2$ values of natural gas in the Z_2dn on the west side all conform to the characteristics of oil-type gas, while the Gao-Mo area and the north slope often exhibit $\delta^{13}C_2>-28‰$ (Table 1), reflecting coal-type gas characteristics, further analysis is required by using genetic identification charts [21-22] (Fig. 2). The natural gas in the Z_2dn on both the east and west sides of the rift trough is oil-type cracking gas (Fig. 2a) and crude oil-cracking gas (Fig. 2b), formed through secondary cracking of crude oil, and is currently in a highly to over-mature stage (R_o>2.0%).

3. Causes of different natural gas characteristics of the Dengying Formation on the east and west sides of the Deyang–Anyue Rift Trough

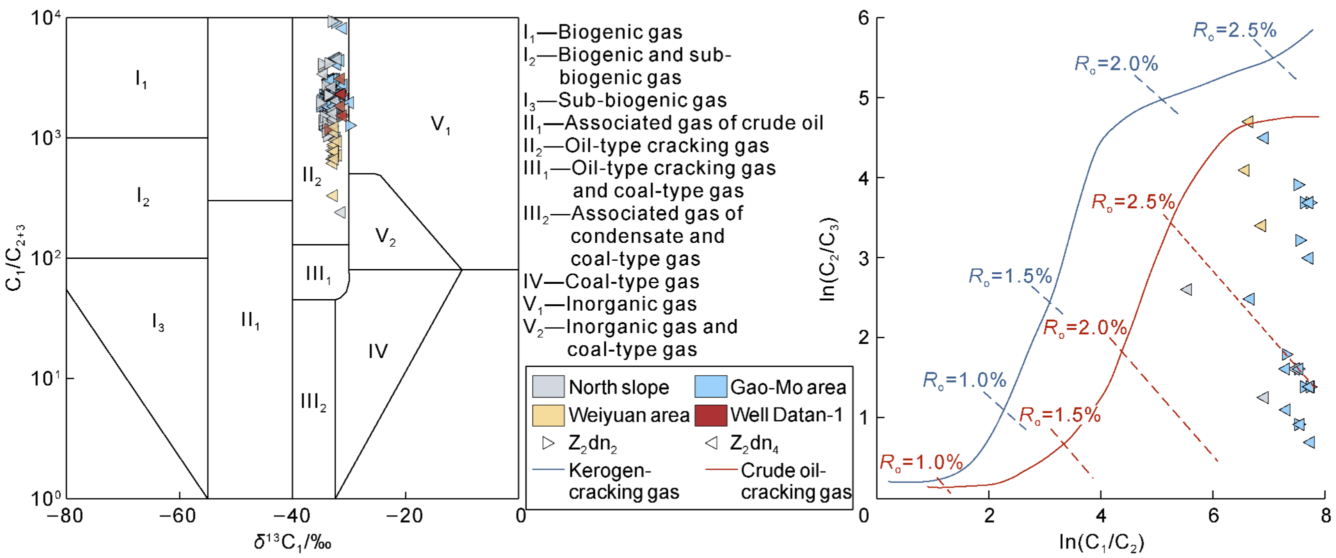
3.1. Causes of different natural gas component contents in the Dengying Formation

3.1.1. Causes of different He and N_2 contents

The $^3He/^4He$ ratios of natural gas compared to those of

Table 3. Natural gas maturity statistics of Dengying Formation on east and west sides of the rift trough

Region	Study area	R_{oe}/%	R_{oe}-average/%	Number of samples
East side	North slope	1.84–3.48	2.45	76
	Gao-Mo area	1.98–2.44	2.44	143
West side	Weiyuan area	2.42–2.64	2.51	17
	Well Datan-1 block	2.73–2.91	2.81	12



(a) $\delta^{13}C_1$ vs. C_1/C_{2+3} diagram (b) $\ln(C_1/C_2)$ vs. $\ln(C_2/C_3)$ diagram

Fig. 2. Genetic identification diagram of natural gas in Dengying Formation (plate modified from references [21–22]).

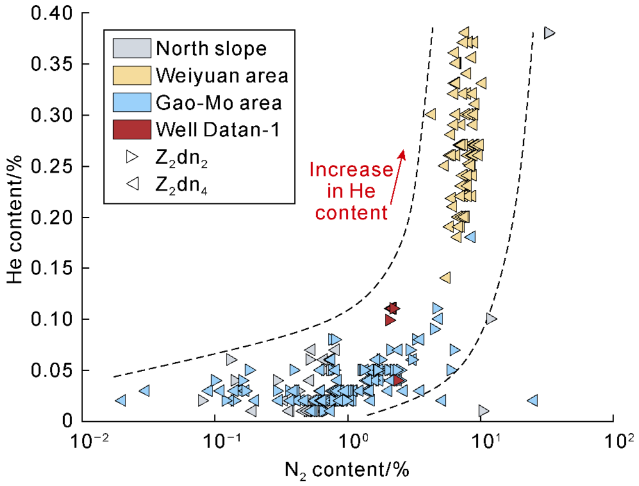


Fig. 3. Relationship between He content and N_2 content of natural gas in Dengying Formation.

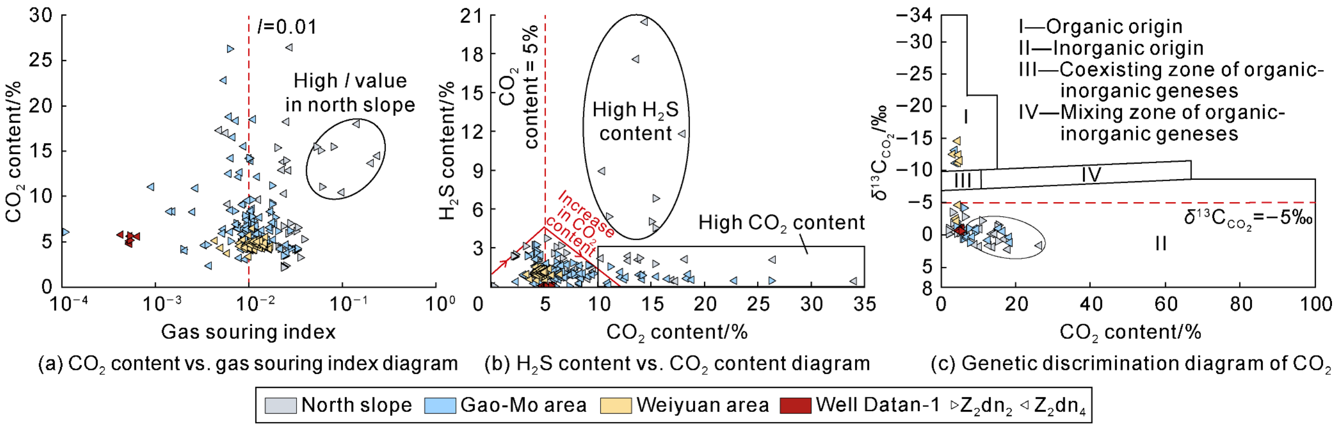
air indicate that the He of the natural gas in the Z_2dn on both the east and west sides of the rift trough is of crustal origin [13, 19], that is, it's generated by the decay of U and Th in highly radioactive rocks (e.g. granite, argillaceous rocks, and tight sandstones) in the crust. N_2 in natural gas can be produced by the thermal ammoniation of organic matter and the thermal metamorphism of granite [23]. Since both N_2 and He can originate from argillaceous source rocks and granites rich in U and Th, they often share the same source and exhibit a significant positive correlation (Fig. 3).

On the east side of the rift trough, the He in natural gas in the Z_2dn mainly originates from source rocks in the Gao-Mo area and the north slope [5, 12], with a low content (Fig. 3) and an average value of 0.04%. Since the east side is close to the hydrocarbon generation center, the gas generation intensity of the source rocks is (40–200)×10^8 m^3/km^2 [2], the large amount of CH_4 generated dilutes the enrichment of He. The N_2 of natural gas in the Z_2dn on the east side is mainly formed through the thermal ammoniation of organic matter in the source rocks [5, 12], and its content is lower than that in the Z_2dn gas reservoir of Weiyuan (Fig. 3).

The He content of natural gas in the Z_2dn is high in Well Datan-1 and the Weiyuan area on the west side of the rift trough, with an average value exceeding 0.10%. In Well Datan-1 block, the thickness of the Qiongzhusi Formation source rocks is relatively thin, but the basement is granites which are rich in U and Th, and the widely developed strike-slip faults connect the helium source rocks with the Z_2dn gas reservoir [19], promoting the enrichment of He. In addition to the Qiongzhusi Formation source rocks, the Weiyuan area also has ancient Pre-Sinian granites in the deep, which are not only important helium source rocks but also significant sources of N_2 [23]. During the late Himalayan period, intense tectonic uplift occurred in the Weiyuan area, accelerating the exsolution of He and N_2 from formation water. These gases migrated upward along deep faults and accumulated in the Z_2dn gas reservoir [23]. This accumulation model results in significantly higher He and N_2 content in the Z_2dn gas reservoir in the Weiyuan area compared to other areas (Fig. 3).

3.1.2. Causes of different CO_2 and H_2S contents

CO_2 and H_2S are present in the natural gas reservoirs of the Z_2dn (Table 1). Thermochemical sulfate reduction (TSR) is the only factor that can lead to H_2S content greater than 10% in natural gas reservoirs, the gas souring index (I, $H_2S/(H_2S + C_nH_{2n+2})$) is commonly used to characterize the extent of TSR [24]. When I>0.01, it indicates that TSR has occurred, and when I>0.10, it suggests that the gas reservoir has undergone intense TSR alteration. The I value of the natural gas is far below 0.01 in the Z_2dn in Well Datan-1 on the west side, indicating that TSR has essentially not occurred, and the small amount of H_2S may originate from the thermal cracking of kerogen or sulfur-bearing minerals in the reservoirs. The souring index of the Z_2dn gas reservoirs is around 0.01 in the Weiyuan area (Fig. 4a), indicating that TSR has occurred but with low intensity. In contrast, the gas reservoirs of the Z_2dn have generally undergone stronger TSR alteration on the east side: nearly half of the gas samples in the Gao-Mo area have a souring index greater than 0.01,



(a) CO_2 content vs. gas souring index diagram (b) H_2S content vs. CO_2 content diagram (c) Genetic discrimination diagram of CO_2

Fig. 4. Non-hydrocarbon components of natural gas in Dengying Formation on the east and west sides of the rift trough (plate of Fig.4c modified from Reference [21]).

while some samples from the north slope even exceed 0.1, with H_2S content exceeding 10% in the gas reservoirs (Fig. 4a and 4b).

The CO_2 content of natural gas in the Z_2dn is generally high on the east side of the rift trough, with an average exceeding 5%, and in some cases even exceeding 10% (Fig. 4b). This phenomenon may be attributed to the following two factors: (1) TSR-H_2S accumulation effect: TSR produces both CO_2 and H_2S. In the early stages of the reaction, CO_2 content increases with the rise in H_2S content. However, in the later stages of TSR, the accumulated H_2S gradually dissolves into formation water, increasing its acidity. This acidic water then dissolves carbonate reservoirs, releasing CO_2, which leads to an increase in CO_2 content and a decrease in H_2S content, with sulfur minerals formed in the reservoir [15, 25] (Fig. 4b). (2) Acidification operations on carbonate reservoirs can also lead to an increase in CO_2 content. It is generally believed that CO_2 content exceeding 8% in gas reservoirs is mostly caused by acidification operations [12]. For example, the CO_2 content reaches 14.19% in the Z_2dn_4 in Well Gaoshi-1 (Table 1).

In addition to content, the carbon isotopic composition can also indicate the origin of CO_2 [21] (Fig. 4c). It is generally accepted that when $\delta^{13}C_{CO_2}$<−10‰, CO_2 is of organic origin [21]; when −4‰<$\delta^{13}C_{CO_2}$<4‰, it is of inorganic origin, derived from carbonate dissolution or thermal metamorphism [26]. The gas reservoirs of the Z_2dn have undergone TSR in the Weiyuan area. In the TSR reaction, SO_4^{2-} preferentially reacts with ^{13}C-depleted hydrocarbons to produce ^{13}C-depleted CO_2, resulting in relatively lighter $\delta^{13}C$ values for CO_2. Therefore, the CO_2 in natural gas from the Weiyuan area exhibits an organic origin (Fig. 4c).

The average $\delta^{13}C$ values of CO_2 in natural gas in the Z_2dn are −1.3‰ and −0.9‰ in the Gao-Mo area and the north slope on the east side, respectively, indicating an inorganic origin overall (Fig. 4c). Different from the west side, the gas reservoirs of the Z_2dn on the east side have undergone intense TSR alteration. Under the combined effects of the TSR-H_2S accumulation effect and acidification operations, carbonate reservoirs are dissolved, leading to a significant increase in CO_2 content and greater $\delta^{13}C$ values for CO_2, indicating an inorganic origin. In contrast, the gas reservoirs of the Z_2dn in Well Datan-1 on the west side have essentially not undergone TSR, with an average $\delta^{13}C$ value of −1.11‰ for CO_2, also indicating an inorganic origin (Fig. 4c).

3.2. Causes of different carbon isotopic compositions of natural gas

TSR preferentially consumes ^{12}C-enriched hydrocarbons, leading to greater carbon isotopic compositions in natural gas [24]. Additionally, it preferentially consumes hydrocarbons with higher carbon number (C_{2+}). In the Gao-Mo area and the north slope on the east side, as well as in the Weiyuan area on the west side, the C_2H_6 content gradually decreases with the increasing TSR intensity (Fig. 5a), and the $\delta^{13}C$ values of C_2H_6 gradually increase (Fig. 5b). Since the natural gas in the Z_2dn is more significantly affected by TSR on the east side, its $\delta^{13}C_2$ values get greater than those on the west side.

It is generally believed that when I>0.10, TSR begins to consume CH_4 [24]. However, the I values of the gas reservoirs in the Z_2dn are generally less than 0.10 on both the east and west sides of the rift trough. Moreover, as the I value increases, $\delta^{13}C_1$ does not become greater, and the two show a certain negative correlation, indicating that the $\delta^{13}C_1$ of natural gas in the Z_2dn is essentially unaffected by TSR alteration (Fig. 5c).

The $\delta^{13}C_1$ values of natural gas in the Z_2dn in the Weiyuan area are concentrated and are 2‰–3‰ greater than those of more than half of the gas samples in the Z_2dn on the east side (Fig. 5c). The degassing accumulation model of natural gas in the Z_2dn of the Weiyuan Gas Field [27] results in greater $\delta^{13}C$ values for CH_4: compared to $^{12}CH_4$, $^{13}CH_4$ is more easily dissolved in formation water [28], leading to fractionation. During the late large-scale tectonic uplift, $^{13}CH_4$ exsolves [27], causing the $\delta^{13}C$ of CH_4 in the natural gas of the Z_2dn to become greater, and the carbon isotopic composition of some gas samples to reverse.

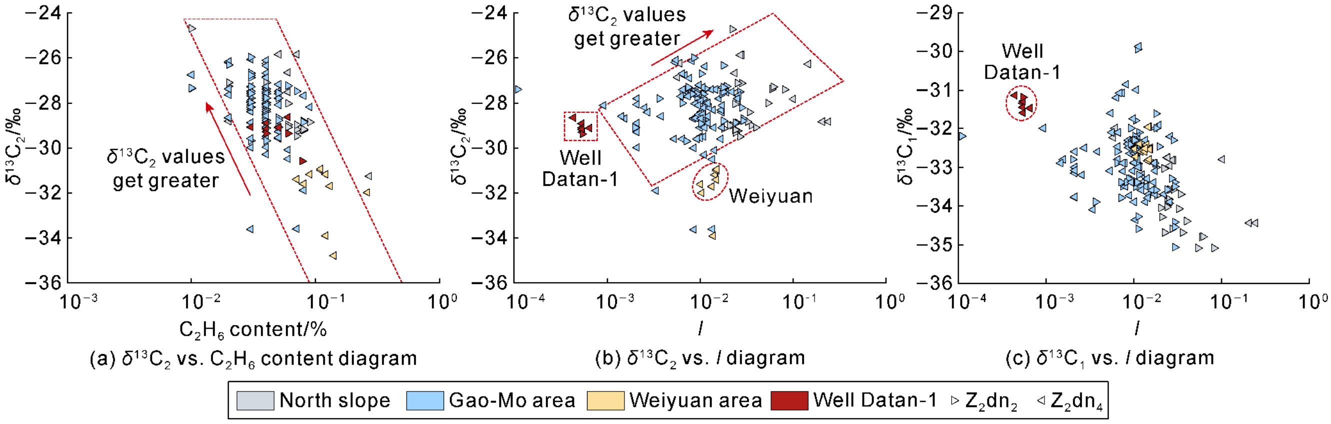


Fig. 5. Correlation between carbon isotopic composition, C_2H_6 content, and I (gas souring index) of natural gas in Dengying Formation.

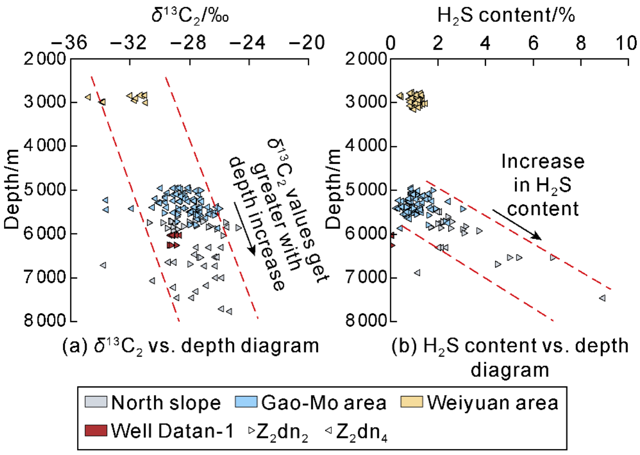


Fig. 6. Variations of $\delta^{13}C_2$ values and H_2S content with depth in Dengying Formation on east and west sides of the rift trough.

The Dengying Formation has a large burial depth on the east side of the rift trough, and sulfur-bearing minerals are observed in reservoir pores [4, 7]. Intense hydrothermal activity in the deep basin [29] brings abundant SO_4^{2-}, providing the sulfur source required for TSR. The high temperatures resulting from the deep burial environment (burial depth greater than 5 000 m) further promote TSR. Therefore, the $\delta^{13}C_2$ values and H_2S content of natural gas increase with burial depth, particularly in the north slope (Fig. 6). The current burial depth of the Z_2dn is only about 3 000 m in the Weiyuan area, and the geo-temperature does not meet the conditions for TSR. However, before the Himalayan movement, its maximum burial depth exceeded 6 000 m, with temperatures above 200 °C [30]. Previous studies [30] confirmed the TSR origin of H_2S in the natural gas of the Z_2dn in the Weiyuan area based on sulfur isotopes. However, due to the relatively short duration of deep burial, TSR alteration was limited, resulting in smaller $\delta^{13}C_2$ values compared to the natural gas in the Z_2dn on the east side.

3.3. Causes of different hydrogen isotopic compositions of natural gas

The δ^2H values of CH_4 in natural gas are controlled by the maturity of source rocks and the paleo-salinity of water medium during deposition [5, 17]. Generally, $\delta^2H_{CH_4}$ becomes progressively greater with increasing maturity and paleo-salinity [5]. As the natural gas in the Z_2dn is highly to over-mature with extremely high drying coefficients and minimal differences in source rock maturity, the influence of maturity on $\delta^2H_{CH_4}$ is relatively weak.

Compared to maturity, the paleo-salinity of water medium in the depositional period of the source rock is a more critical factor controlling $\delta^2H_{CH_4}$ in the natural gas of the Z_2dn. Previous studies determined the paleo-salinity of water medium during the deposition of the Z_2dn_3, Doushantuo Formation and Cambrian Qiongzhusi Formation in the Sichuan Basin based on boron and potassium contents in clay minerals: the Qiongzhusi Formation had the highest paleo-salinity, while Z_2dn_3 and Doushantuo Formation showed relatively lower salinity [31]. Consequently, a greater contribution from Qiongzhusi Formation source rocks results in greater $\delta^2H_{CH_4}$ values in natural gas. For example, the natural gas from the Cambrian Canglangpu Formation in Well JT1 is primarily sourced from the underlying Qiongzhusi Formation source rocks, exhibiting relatively great $\delta^2H_{CH_4}$ values of −134‰. This value is often used as representative $\delta^2H_{CH_4}$ for natural gas derived from Qiongzhusi Formation source rocks [5].

Vertically, differences in $\delta^2H_{CH_4}$ values reflect varying contributions from different source rocks. For example, wells GS3, GS6, GS9 and MX11 (Fig. 7a, 7b) show greater $\delta^2H_{CH_4}$ values in the Z_2dn_4 than that in the Z_2dn_2, likely due to greater contribution from the Qiongzhusi Formation source rocks to Z_2dn_4 natural gas compared to the Z_2dn_3. Laterally, closer proximity to the rift trough correlates with greater thickness and higher hydrocarbon generation intensity of Qiongzhusi Formation source rocks, resulting in larger relative contributions and greater $\delta^2H_{CH_4}$ values. Taking Z_2dn_4 in the Gao-Mo area on the east side of the rift trough as an example, close to the rift trough and the area where the source rocks of Qiongzhusi Formation contribute a lot, the $\delta^2H_{CH_4}$ of natural gas in the Z_2dn is generally greater than −140‰, such as wells GS6, GS9, MX102 and GS3 (Fig. 7b). In contrast, areas farther from the rift trough show smaller $\delta^2H_{CH_4}$ (less than −140‰), such as wells GS125, GS18, MX8 and MX18). Overall, $\delta^2H_{CH_4}$ becomes progressively smaller toward the platform interior, such as Well MX23 with $\delta^2H_{CH_4}$ of −152‰ in Z_2dn_4. Notably, the $\delta^2H_{CH_4}$ of natural gas in some wells in the platform margin belt is small, which may indicate that the contribution of source rocks in the Z_2dn_3 is stronger than that of the Qiongzhusi Formation. For example, although Well PS15 is located at the platform margin belt, the natural gas $\delta^2H_{CH_4}$ in the Z_2dn_4 is only −149 ‰ (Fig. 7b).

Compared with the east side, the $\delta^2H_{CH_4}$ values of natural gas in the Z_2dn in Well Datan-1 on the west side are relatively smaller (Fig. 7c), with $\delta^2H_{CH_4}$ values between −154‰ and −141‰, which is attributed to its greater distance from the rift trough, relatively thinner Qiongzhusi Formation source rocks [3], and larger contributions from the underlying Z_2dn_3 and Doushantuo Formation.

3.4. Causes of different carbon isotopic compositions in natural gas, reservoir solid bitumen, and kerogen

The natural gas in the Z_2dn is derived from cracked crude oil, and in addition to the natural gas, the reservoir contains reservoir solid bitumen [32]—a key product of

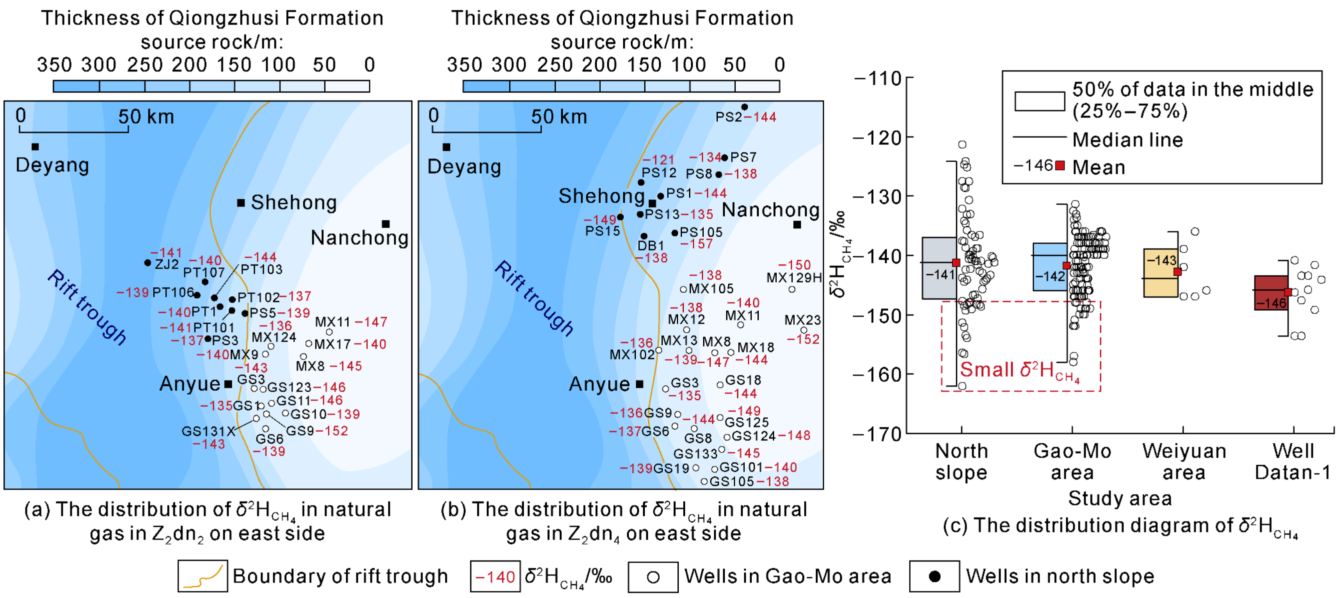


Fig. 7. $\delta^2H_{CH_4}$ **distribution of CH_4 in Dengying Formation on east and west sides of Deyang–Anyue rift trough.**

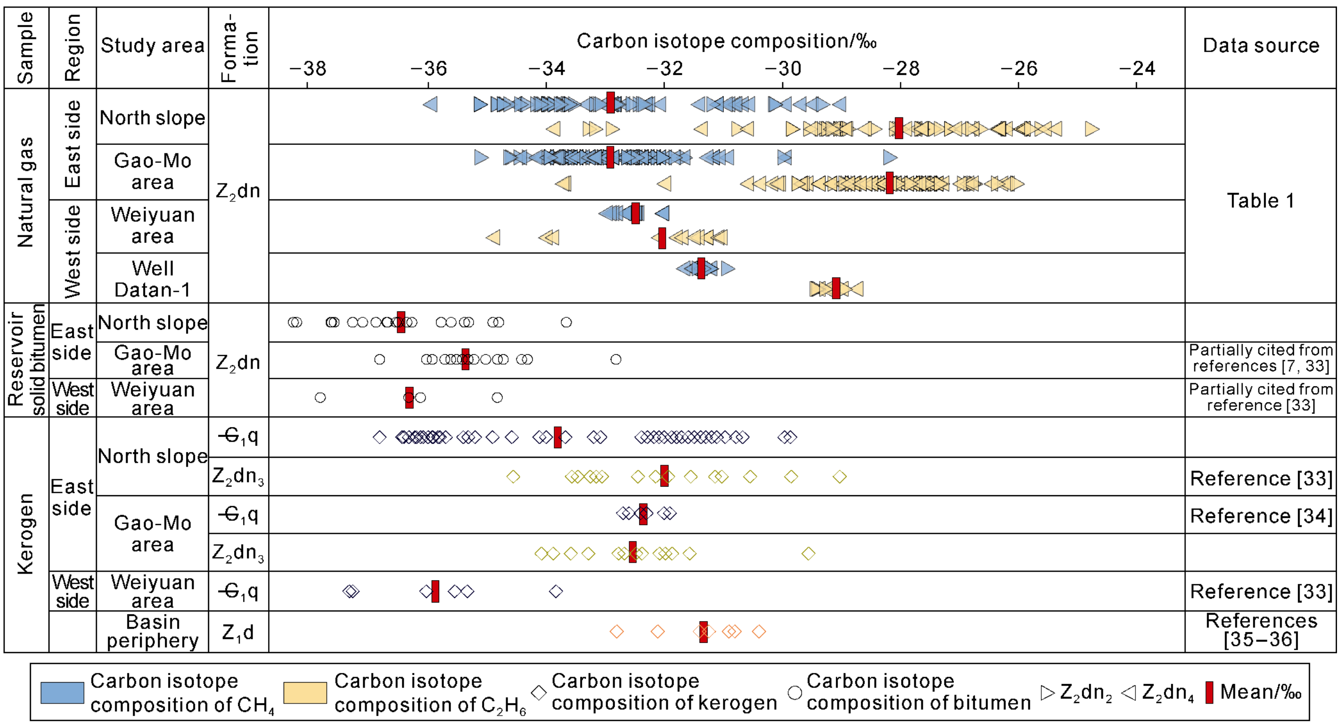


Fig. 8. Distribution characteristics of carbon isotopic compositions among natural gas of Dengying Formation, reservoir solid bitumen and source rock kerogen, Sichuan Basin. Note: Carbon isotopic compositions of some reservoir solid bitumen and source rock kerogen are from references [7, 33–36]; Z_2dn_3—the third member of Dengying Formation.

ancient oil reservoir cracking. In the Weiyuan area on the west side of the rift trough, the Dengying Formation gas reservoir has been relatively less affected by TSR. The $\delta^{13}C$ values of reservoir solid bitumen (averaging −36.3‰) closely match those of Qiongzhusi Formation kerogen (averaging −36.1‰; Fig. 8), indicating a primary contribution from the Qiongzhusi Formation source rocks [4].

The Dengying Formation gas reservoir in Well Datan-1 has essentially not undergone TSR alteration, making its $\delta^{13}C_2$ values reliable indicators of source information. However, the $\delta^{13}C_2$ value of natural gas (−29.1‰) in Well Datan-1 is significantly greater than that of the Qiongzhusi Formation source rock kerogen (−36.1‰) on the west side of the rift trough, indicating substantial contributions from other source rocks besides the Qiongzhusi Formation. The thicknesses of both the Qiongzhusi Formation and Z_2dn_3 source rocks encountered in Well Datan-1 are relatively thin. Previous studies have identified the Doushantuo Formation source rocks in the Xianfeng section on the west side of the rift trough [3], with kerogen $\delta^{13}C$ values (−31.3‰) closely matching the $\delta^{13}C_2$ values of Dengying Formation natural gas in Well Datan-1 (Fig. 8). Additionally, $\delta^2H_{CH_4}$ analysis further confirms significant contributions from the underlying Z_2dn_3 and Doushantuo Formation. Therefore, the natural gas in the Z_2dn of Well Datan-1 receives contributions not only from the Qiongzhusi Formation source rocks but also from the Z_2dn_3 and Doushantuo Formation source rocks.

In general, during the thermal maturation of hydrocarbons, the carbon isotopic compositions of source rock kerogen and its derivatives follow the fractionation sequence: reservoir solid bitumen>kerogen>crude oil> alkane gas. Under homologous conditions, solid bitumen derived from oil cracking typically exhibits $\delta^{13}C$ values 1‰–2‰ greater than its parent kerogen [37]. However, in the Gao-Mo area and north slope on the east side, the $\delta^{13}C$ values of Dengying Formation reservoir solid bitumen are significantly smaller than those of both Qiongzhusi Formation kerogen and C_2H_6 in natural gas (Fig. 8), contradicting this established fractionation pattern.

First, the $\delta^{13}C_2$ values of natural gas are greater due to TSR effects in the Gao-Mo area and north slope on the east side of the rift trough; meanwhile, H_2S generated from TSR continues to consume ^{12}C-enriched C_2H_6 to form ^{12}C-enriched ethanethiol. The ethanethiol is further incorporated into reservoir solid bitumen through aromatization and polymerization [8], resulting in progressively smaller $\delta^{13}C$ values of the reservoir solid bitumen that are smaller than those of source rock kerogen and C_2H_6 in natural gas (Fig. 8).

Based on these findings, the impact of TSR and other influencing factors should be considered for gas-source correlation in deep burial environments. Carbon isotopic compositions of reservoir solid bitumen and natural gas can no longer serve as reliable parameters alone. Additional analytical methods, such as trace elements and rare earth elements, are required to establish correlations between reservoir solid bitumen and source rocks for accurate gas-source identification—the Dengying Formation gas reservoirs in the Gao-Mo area and north slope exhibit dual-source (Qiongzhusi Formation + Z_2dn_3) charging characteristics, but the relative contributions of the two require further investigation.

4. Conclusions

The natural gas in the Dengying Formation is predominantly derived from oil-cracking gas on both sides of the Deyang–Anyue rift trough, classified as highly to over-mature natural gas (dry gas). Significant geochemical differences (gas composition, isotopes) are observed between the natural gases on the two sides of the rift trough, primarily controlled by varying factors such as mixed sources, modification by deep inorganic gas sources, the extent of TSR alteration, and the paleo-salinity of water medium during source rock deposition.

On the east side of the rift trough, the He in the natural gas of the Dengying Formation in the Gao-Mo area and north slope mainly originates from source rocks. Due to the high hydrocarbon generation intensity of the Qiongzhusi Formation, the enrichment of He is limited, resulting in low concentrations. Additionally, the Dengying Formation gas reservoirs on the east side are generally affected by TSR alteration, leading to high contents of H_2S and CO_2 as well as greater $\delta^{13}C_2$. In contrast, the TSR alteration in the Weiyuan area on the west side is less intense than that on the east side, TSR is essentially absent in the Dengying Formation gas reservoir of Well Datan-1.

Controlled by the widespread development of the granite in basement with rich U and Th, and efficient vertical transport along faults on the west side of the rift trough, the helium content in the Dengying Formation natural gas of Well Datan-1 area is high (averaging higher than 0.10%), with notable enrichment of He (averaging 0.27%) and N_2 (averaging 7.51%) in the Weiyuan area. Due to the water-soluble gas precipitation and accumulation mechanism, the $\delta^{13}C_1$ of the Dengying Formation natural gas in the Weiyuan area is relatively great, leading to partial carbon isotope reversal ($\delta^{13}C_1>\delta^{13}C_2$) in some gas samples.

The differences in $\delta^2H_{CH_4}$ of the Dengying Formation natural gas on both sides of the rift trough are mainly controlled by the paleo-salinity of water medium in the depositional period of the source rock. Furthermore, the Dengying Formation natural gas in Well Datan-1 is contributed by the source rocks of the Sinian Doushantuo Formation and the Z_2dn_3, in addition to the Cambrian Qiongzhusi Formation. In the Weiyuan area, the natural gas in the Dengying Formation is primarily sourced from the Qiongzhusi Formation. The Dengying Formation gas reservoirs in the Gaoshiti–Moxi area and north slope on the east side exhibit dual-source (Qiongzhusi Formation + Z_2dn_3) hydrocarbon supply characteristics.

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