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CHARACTERISTICS AND ORIGIN OF THE DOLOSTONES OF THE EDIACARAN DENGYING FORMATION IN THE EASTERN SICHUAN BASIN, SOUTH CHINA

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Abstract: The Ediacaran Dengying Formation dolostones were the crucial carrier of the co-evolution between the biota and environment before the Cambrian Explosion and the solid mineral and petroleum resources. Based on the petrological and mineralogical analyses, the Dengying Formation at the Liaojiacao Section consists of micritic, fine-crystalline and medium-crystalline dolostones and algal-bonded or algal-clastic dolostones. Moreover, the micritic and algal-bonded dolostones mostly retain the original sedimentary structure with widespread microbial mats, algal spots, algal traces, and other microbial fossils. Recrystallization, dissolution, and other diagenetic alterations occurred in the fine-crystalline and medium-crystalline dolostones as well as algal-clastic dolostones, and their original sedimentary structures had been significantly altered. Furthermore, in situ geochemical analysis shows that the micritic and algal-bonded dolostones of the Dengying Formation, which retain the original sedimentary structure, have Mg/Ca ratios close to the ideal primary dolomite; Na, Fe, Mn, and Sr concentrations located in the distribution range of calcites and dolomites formed in a normal marine environment, negative Ce anomaies and positive Eu anomaies with the patterns of light rare earth element depletion and medium and heavy rare earth element enrichment. In addition, the whole-rock stable isotopic analyses show that the $\delta^{13}C_{dol}$ values of dolostones that retain the original sedimentary structure are consistent with the distribution range of the original marine carbonate rocks, but the $\delta^{18}O_{dol}$ values are slightly lower than those of the original marine carbonate rocks. Therefore, we infer that the dolostones of the Dengying Formation at the Liaojiacao Section with original sedimentary structure are the products of mimetic dolomitization and formed in an environment with extensive microbial activity, calcite as the preexisting mineral, normal salinity, and oxidized seawater as the dolomitization fluid. Moreover, the fine- and medium-crystalline dolostones were the results of recrystallization that retained the original sedimentary structures during diagenesis.

Keywords: Precambrian dolomite; origin; mimetic dolomitization; microbial dolomite

1. INTRODUCTION

As the first large-scale carbonate rock (mainly dolostones) formation after the middle Neoproterozoic glaciation in the South China Plate, the Ediacaran Dengying Formation not only records the environmental response of the late Neoproterozoic gradual warming but also the key information about biological development and co-evolution between organisms and the environment prior to the Early Cambrian skeletonization explosion (Zhou et al., 2019). Moreover, the Dengying Formation dolostones formed by microorganisms are an important reservoir of oil and gas resources and a production layer of solid minerals (lead–zinc ore, etc.), making the Ediacaran Dengying Formation dolostones as the carrier of the above key geological information and mineral resources of great research value (Hou et al., 2020; Wang et al., 2020).

The dolomite problem has been a prominent unsolved mystery in sedimentology for centuries. The Precambrian marine sedimentary record contains large-scale dolostone deposits, e.g., the dolostones of the Ediacaran Dengying Formation that are several

hundred meters thick, and their distribution usually extends for hundreds or even thousands of square kilometers, in contrast with the absence of massive dolostone deposits in modern marine environments (Liu et al., 2015; Chang et al., 2020). Geologists generally believe that the early large-scale marine dolomites were formed from calcium carbonate minerals, such as calcite or aragonite, which were deposited from the initial seawater, and then metasomatized by hydrothermal or magnesium-rich fluids during the long burial process at high temperatures, a process referred to as high-temperature dolomitization (Mei, 2012). Although this late thermal metasomatism of preexisting calcium carbonate minerals seems to explain the dolomite mystery, there are still unknowns for the Ediacaran Dengying Formation dolomites, which are thousands of meters thick and exhibit massive texture, such as persistent sources of Mg^{2+} for the dolomitization and the dynamic conditions of the potential Mg-rich fluid. In recent years, considering that the dolostones of the Ediacaran Dengying Formation mainly retain the primary sedimentary fabric with the pervasive presence of microbial structures (oolite, stromatolite, and oncolite; Zhao et al., 2018; Lin et al., 2018), geologists have successively established models, such as mimetic dolomitization and microbial dolomitization, to explain these processes (Vasconcelos et al., 1995; Lowenstein et al., 2003). These explanations emphasized that the widespread occurrence of the Ediacaran dolostones generally preserved the primary textures, which would be difficult under a limited and special geochemical conditions genetic model, and it is more likely that the early Earth had a specific, widespread ocean condition that could have led to massive dolomite formation. However, this specific and widespread ocean condition remains controversial, and the dolomite formation process and dynamic mechanism have not been confirmed by experiments. In addition, it is controversial whether the formation of the Ediacaran Dengying Formation dolomites, characterized by large burial depth and long-term complex diageneses can be explained by a single model (Wood et al., 2017; Zhao et al., 2020). Therefore, the formation environment and genesis mechanism of Precambrian dolomite have not been comprehensively solved.

In this work, we analyze the petrological, mineralogical, and geochemical characteristics of the Ediacaran Dengying dolostones in the Sichuan Basin. The accumulation and collection of basic data and evidence for the origin of the Precambrian dolomites, it is helpful to reveal whether and what kind of specific and extensive marine conditions existed during the early Earth, which might have led to the formation of large-scale dolostone deposits during the Late Ediacaran period.

2. GEOLOGICAL SETTING

The During the Neoproterozoic period, the Rodinia supercontinent gradually split and paleo-oceans formed simultaneously. In the Late Ediacaran, the tectonic movement gradually stabilized, and the South China Plate drifted northward to 20° N paleolatitude approximately as a relatively independent continental block (Peng et al., 2012; Zhang et al., 2019). Meanwhile, the Yangtze Block, located in the northwestern South China Plate, was mainly surrounded by open sea except on its southeastern side, and the Sichuan Basin, located in the northwestern Yangtze Block, was surrounded by the Paleotethys Ocean in the epicontinental-sea environment (Fig. 1a) and therefore highly sensitive to sea-level changes (Ding et al., 2019).

Moreover, during the Dengying stage of the Late Ediacaran, the Yangtze Block had evolved into the stage of a relatively stable platform accompanied with the slow rising of sea level, and the Sichuan Basin correspondingly developed shallow-water carbonate platform deposit significantly affected by sea-level fluctuations (Fig. 1b). The faulted depression in the center of the platform developed a thin set of relatively deep-water shelf deposits (only 50–150 m), which was composed of thin layers of micritic dolostone and/or limestone (Liu et al., 2015). Furthermore, the margins of the faulted depression developed 600–1400 m of shallow-water shoals, which were composed of bioherm or microbial carbonates in the accretion process (Liu et al., 2021). The other parts of the platform mainly obtained relatively gentle paleotopography in shallow water, and correspondingly developed microbial mounds or shoals with intermediate thinness.

The widespread Dengying Formation is mainly composed of algae-rich fine grainstones. The Dengying Formation has a conformable contact with the underlying Ediacaran Doushantou Formation in the Sichuan Basin but an unconformable contact with the Upper Cambrian Maidiping Formation, attributed to the second stage of the Tongwan Movement (Wang et al., 2020).

3. SAMPLING AND ANALYTICAL TECHNIQUES

3.1. Samples Collection

The Liaojiacao Section (29°43′N, 108°16′E), located in Pengshui County of the southeastern Sichuan Basin, South China (Fig. 1c), contains, in

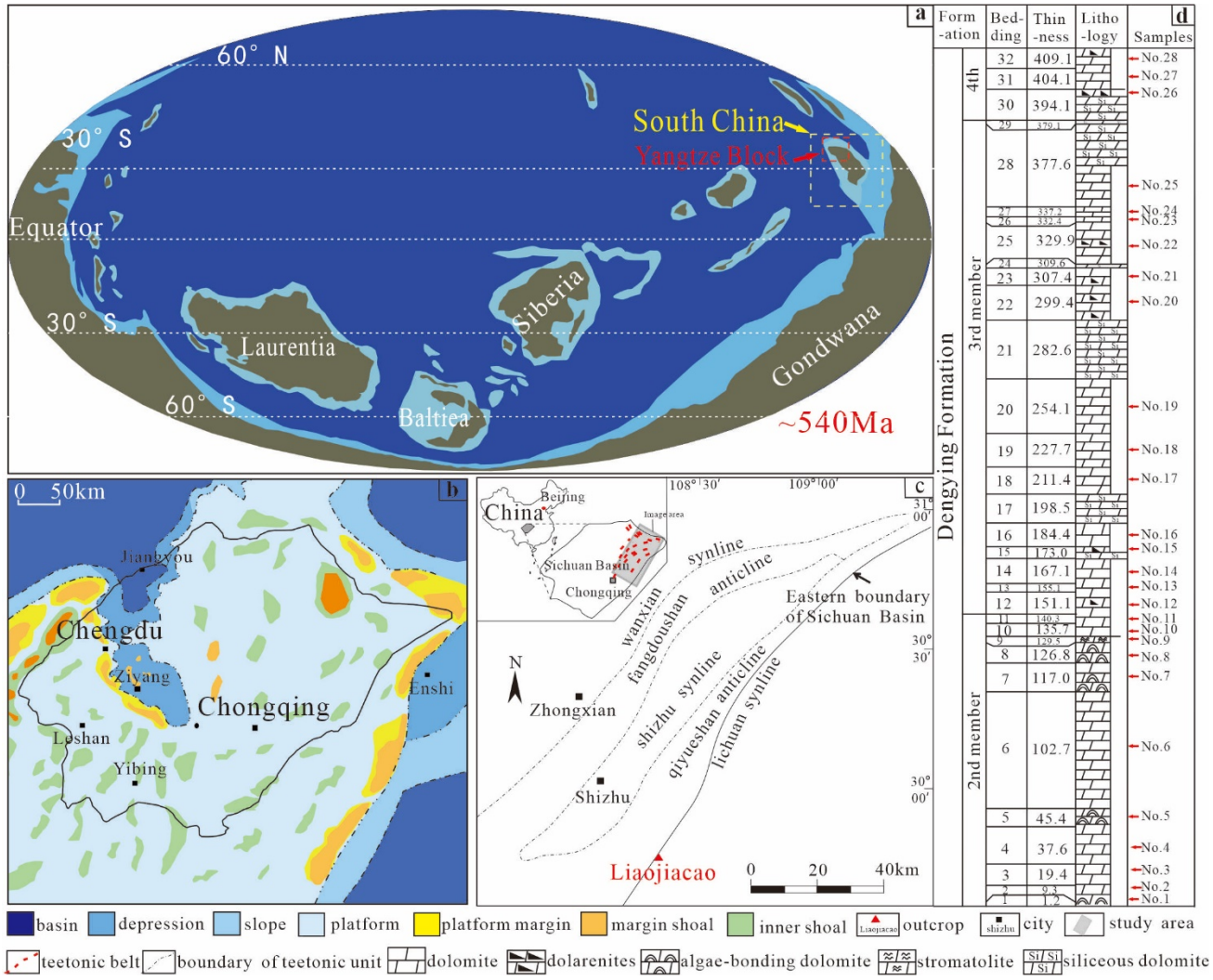

Figure 1. (a) Map of the locations of plates during the Ediacaran Dengying Stage (modified after Zhang et al., 2019), (b) paleogeographic map of the first and second members of the Denying Formation in the Sichuan Basin (modified after Wang et al., 2020), (c) simplified tectonic map (modified after Ren et al., 2019) and (d) lithostratigraphic columns and sampling locations of the Liaojiacao Section

ascending stratigraphic order, an incomplete 409.1m Ediacaran Dengying sequence outcrop of the second, third and fourth members of the Dengying Formation (Fig. 1d). The Dengying Formation at Liaojiacao is mainly composed of dolostones, e.g., crystalline dolostone, microalgae-bounded dolostone, and dolarenite, of which the sand-sized grains are dominantly derived from microalgae debris or microalgae-bonded debris. Moreover, the Dengying Formation also contains small quantities of siliceous dolostones in the third and fourth members (Fig. 1d). According to the types and vertical variation of the lithologies, the Dengying Formation in the Liaojiacao Section is subdivided into 32 intervals, and the 28 samples used in this study were collected from each interval except the Nos. 21, 24, and 29 intervals that were mainly composed of siliceous dolostones (Fig. 1d).

3.2 Analytical Techniques

In this study, we cut each sample into slabs and chose the cleanest part, avoiding secondary veins. Subsequently, each selected slab was cut into two mirror-image symmetrical chips, and one of the chips was thin-sectioned to a thickness of 0.03 mm, while the other was thin-sectioned to 0.08 mm at the State Key Laboratory of Petroleum Resource and Prospecting at the China University of Petroleum (Beijing). The 0.03-mm chips were observed under a polarizing microscope following Dickson (1965) to differentiate between carbonate minerals, while the 0.08-mm chips were analyzed for major elements with an electron probe microanalyzer (EPMA) and for major, trace, and rare earth elements with a laser ablation inductively coupled plasma mass spectrometer (LA-ICP-MS) at the National Research Center for Geoanalysis of the Chinese Academy of

Geological Sciences.

Furthermore, the remains of each sample were finely powdered into 200 μm for X-ray diffraction (XRD) and isotopic composition analyses, which were conducted at the State Key Laboratory of Petroleum Resources and Prospecting, China University of Petroleum (Beijing) and the State Key Laboratory, Nanjing Institute of Geology and Paleontology, Chinese Academy of Sciences, respectively.

4. PETROGRAPHIC AND MINERALOGICAL ANALYSES

The fieldwork, thin sections, and XRD analyses showed that the Dengying Formation at the Liaojiacao section has conspicuous petrographic characteristics, almost entirely composed of dolostones. The dolostones of the Dengying Formation contain crystalline dolostone, microalgae-bonded dolostone, and dolarenite (Table 1), of which the sand-sized grains are dominantly derived from microalgae debris or microalgae-bonded debris.

4.1 Crystalline Dolostones

The crystalline dolostones are further subdivided into micritic, fine-crystalline and medium-crystalline dolostone according to the dolomite crystal sizes. Micritic dolostones generally have gray and massive structure (Fig. 2a) and are concentrated in the second member of the Dengying Formation in the Liaojiacao Section (Table 1). Furthermore, these micritic dolotones are dominantly composed of micritic dolomite according to the XRD results, while several samples contain slight quantities of quartz and feldspar (Table 1). The micritic dolostones have dolomite crystals that vary from 5 μm to 20 μm in diameter (Fig. 2b) with microbial trace fossil remains, such as microalgae spots with aphanitic texture (Fig. 2b, shown by red arrows) and microalgae trace fossils (Fig. 2b, shown by yellow arrows). In addition, the ordering degrees (σ) of these micritic dolostones vary from 0.65 to 0.90 with an average of 0.79, indicating poor ordering of the elements in these dolostones and accordingly low crystallinity.

Table 1 Mineral compositions, ordering degree, carbon and oxygen isotopic compositions of the Dengying Formation dolostones at the Liaojiacao Section

Member	Sample	Petrology	Dolomite	Quartz	Feldspar	Order degree	$\delta^{13}C_{dol}$	$\delta^{18}O_{dol}$
			%				‰, VPDB	
	No.1	Microalgae-bonded dolostone	97.70	0.90	1.30	0.91	2.988	−3.774
	No. 2	Micritic dolostone	99.60	0.20	0.20	0.89	3.326	−4.665
	No. 3	Micritic dolostone	99.40	0.60	0	0.90	3.450	−3.933
	No. 4	Micritic dolostone	97.70	2.00	0.20	0.72	3.152	−2.725
2nd	No. 5	Microalgae-bonded dolostone	100.00	0	0	0.82	2.763	−4.779
	No. 6	Micritic dolostone	100.00	0	0	0.65	3.243	−2.766
	No. 7	Microalgae-bonded dolostone	98.90	1.10	0	0.94	2.230	−4.326
	No. 8	Microalgae-bonded dolostone	100.00	0	0	0.72	1.686	−1.526
	No. 9	Microalgae-bonded dolostone	97.40	2.60	0	0.93	1.924	-4.284
	No. 10	Fine-crystalline dolostone	99.40	0	0.60	——	2.503	−4.673
	No. 11	Fine-crystalline dolostone	100.00	0	0	——	2.887	−4.682
	No. 12	Dolarenite	100.00	0	0	0.74	3.656	−2.728
	No. 13	Fine-crystalline dolostone	100.00	0	0	——	2.689	−8.273
	No. 14	Fine-crystalline dolostone	100.00	0	0	0.95	1.851	−7.917
	No. 15	Dolarenite	100.00	0	0	0.86	2.235	−8.118
	No. 16	Fine-crystalline dolostone	97.90	2.10	0	0.83	3.290	−8.525
3rd	No. 17	Medium-crystalline dolostone	99.10	0.90	0	0.82	3.452	−8.440
	No. 18	Fine-crystalline dolostone	100.00	0	0	0.91	3.356	−8.549
	No. 19	Fine-crystalline dolostone	99.40	0	0.60	0.83	3.165	−7.247
	No. 20	Medium-crystalline dolostone	96.60	3.40	0	0.84	3.105	−8.927
	No. 21	Fine-crystalline dolostone	99.00	1.00	0	0.74	3.845	−7.804
	No. 22	Dolarenite	100.00	0	0	0.94	3.156	−8.467
	No. 23	Medium-crystalline dolostone	100.00	0	0	0.72	3.680	−7.187
	No. 24	Medium-crystalline dolostone	99.40	0.60	0	0.74	3.529	−0.140
	No. 25	Medium-crystalline dolostone	99.40	0	0.60	0.79	3.733	−6.673
	No. 26	Dolarenite	99.60	0.10	0.40	0.84	4.102	−8.397
4th	No .27	Fine-crystalline dolostone	97.70	0.90	1.30	0.85	3.988	−6.682
	No. 28	Dolarenite	99.60	0.20	0.2	0.91	4.110	−8.507

Fine-crystalline dolostones, concentrated in the third member of the Dengying Formation and scattered in the second and fourth members (Table 1), generally have gray and massive texture, but significant weathering occurs in some intervals (Fig. 2c). These dolostones are also dominantly composed of dolomites (Table 1) with crystal sizes that vary from 10 μm to 40 μm and textures that are genetically related to microalgae, such as microalgae spots (Fig. 2d, shown by red arrows), microalgae trace fossils (Fig. 2d, shown by yellow arrows), microbial mats (Fig. 2d, shown by dotted yellow lines), and sand-sized microalgae particles (Fig. 2d, shown by dotted red lines). Furthermore, these fine-crystalline dolostones suffered from significant diagenetic alteration, especially recrystallization (Fig. 2d, shown by dotted blue lines).

Medium-crystalline dolostones, concentrated in the third member of the Dengying Formation (Table 1), generally have massive structure and scattered dissolved-pores (Fig. 2e). These dolostones are composed of dolomites that vary from 50 μm to 100 μm in diameter, with sporadic textures that are genetically related to microalgae (Fig. 2f). Furthermore, these medium-crystalline dolostones have suffered from intense diagenetic processes, especially recrystallization and dissolution (Fig. 2e and 2f). In addition, the ordering degrees (σ) of these dolostones vary from 0.74 to 0.84 with an average of 0.80, indicating poor ordering of the elements in these dolostones and low crystallinity, which might be attributed to incomplete dolomitization due to the insufficient supply of Mg^{2+} during the dolomitization process (Zeng et al., 2004; Zhang et al., 2014).

4.2 Microalgae-bonded Dolostones

Microalgae-bonded dolostones mainly occur in the second member of the Dengying Formation, and are subdivided into two types according to their internal texture and morphological characteristics: dolostones with algae clotted texture and dolostones with algal-laminae texture. The dolostones with algal-clotted texture mainly occur in the lower part of the second member (Table 1) and are characterized by widespread microalgae spots with aphanitic internal structure and morphology. Moreover, the generally dark colored microalgae spots are filled with crystalline dolomite cements.

The dolostones with algal-laminae texture (Fig. 2g) are only present in the upper part of the second member of the Dengying Formation (Table 1) and have conspicuous internal texture characteristics with alternating dark and bright laminae (Fig. 2h). The bright laminae consist of slightly large size dolomites, and the dark laminae are dominantly composed of microbial mats (Fig. 2h, shown by the yellow double

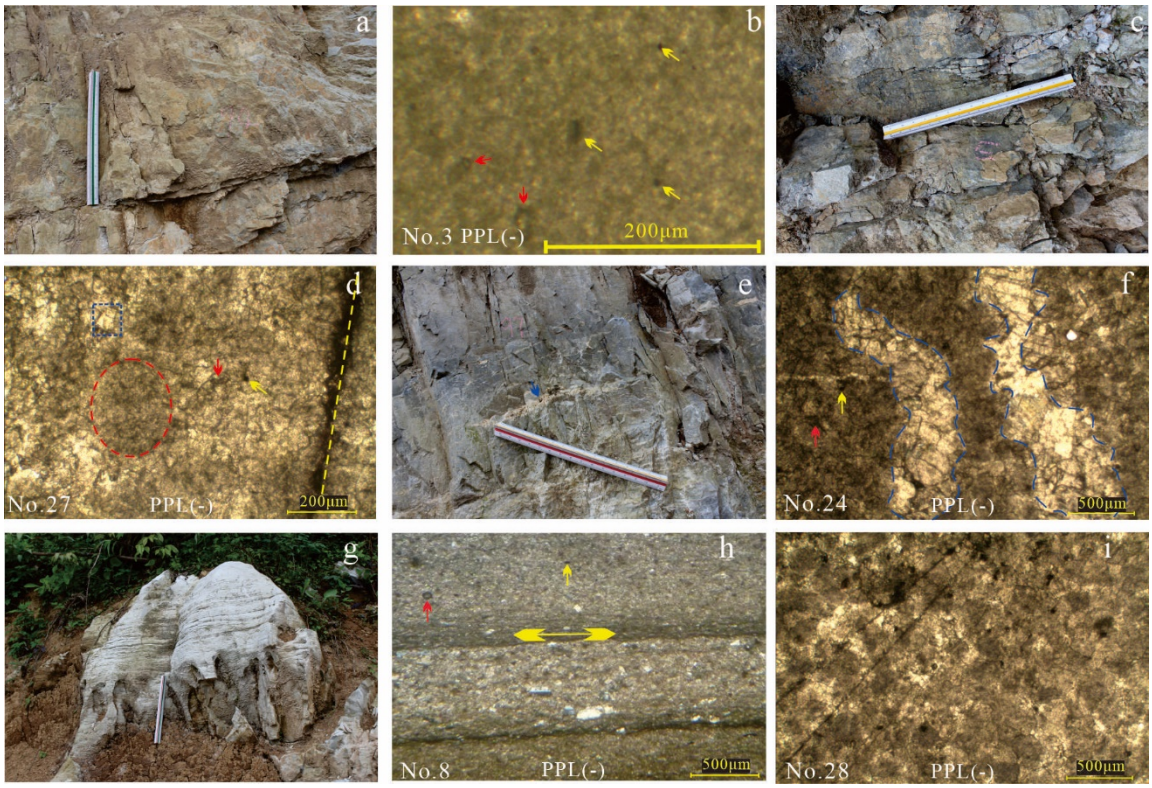

Figure 2. Typical characteristics under the polarizing microscope and field macroscopic observation of the Dengying Formation at the Liaojiacao Section

arrow) which formed by thin plate-like clay minerals encapsulating microorganisms and dolomite crystals (Lin., 2018; Bontognali et al., 2014). The internal structure and morphological characteristics of both dark and bright laminae are diverse (Fig. 2h) and the edges vary from straight to gently sinuate or even internally truncated. Furthermore, the differences in the morphological characteristics may be related to the stage and manner of microbial activity, e.g., the macroscopic morphology of the microbial mats was significantly influenced by the metabolic activity intensity of the microorganisms (Lin., 2018).

4.3 Dolarenites

The dolarenites are dispersed in the third and fourth members of the Dengying Formation (Table 1) and are mainly composed of sand-sized grains under microscopic view (Fig. 2i). Observation under the polarized light microscope shows that these grains, with diameters of 0.5–1.0 mm, generally have dark color, oval and/or fusiform shapes, well sorting and roundness and close contact relationships with one another (Fig. 2i). Moreover, these grains are mainly composed of micritic and fine-crystalline dolomites that are derived from the intensive recrystallization during diagenesis, and the original internal textures of these grains are almost destroyed, with the sporadic remains of microalgae spots and microalgae trace fossils (Fig. 2i) indicating that these grains primarily originated from microalgae debris or microalgae-bonded debris. In addition, cements of different generations are occasionally found among the grains.

5. GEOCHEMICAL ANALYSES

5.1 Major Elements

The Dengying Formation dolostones possess Mg/Ca ratios that range from 0.94 to 1.19 with an average of 1.04 (Table 2), approximating the value of protogenetic dolomite (1.00), indicating their origin of primary precipitation or mimetic dolomitization. Moreover, the Mg/Ca ratios of micritic dolostones (1.05–1.19, average 1.10) are slightly higher than those of microalgae-bonded dolostones (0.98–1.19, average 1.04). The decline in Mg/Ca ratios from micritic dolostones to microalgae-bonded dolostones might indicate that microorganisms play an active role in promoting dolomite precipitation and removing the dynamic obstacles to dolomitization (Bontognali et al., 2014; Li et al., 2010). Whereas, the wide distribution range of Mg/Ca ratios in microalgae-bonded dolostones may be related to the differences in adsorption and enrichment of Mg, Si, and other cations by the extracellular polymeric structure of the microorganisms during the formation of dolomite (Bontognali et al., 2014).

5.2 Trace Elements

Na concentrations of the Dengying Formation dolostones vary from 89.85 mg/kg to 348.56 mg/kg, with an average of 175.54 mg/kg (Table 2). Carbonate minerals of different geological ages exhibit variable Na concentrations mainly in the range of 100×10^{-6} to 5000×10^{-6}. Aragonites deposited from the modern ocean have Na concentrations of 1500×10^{-6}, the concentrations of calcites varying from 200×10^{-6} to 300×10^{-6}, and those of dolomites are generally 110×10^{-6} to 160×10^{-6} (Veizer, 1983; Tucker, 1984). Therefore, the Dengying Formation dolostones have Na concentrations that approximate the values for calcites and dolomites but are extremely lower than those of aragonites. Thus, we infer that the formation fluid of the Dengying Formation dolomites was seawater with normal salinity, and the preexisting minerals (if present) negatively tend to be aragonites and high-Mg calcites (Zhao et al., 2020; Tucker, 1984).

Fe and Mn concentrations of the fine- to medium-crystalline dolostones in the Dengying Formation mostly range from 407.87 mg/kg to 1419.44 mg/kg and from 139.90 mg/kg to 509.56 mg/kg, respectively (Table 2). However, the Fe and Mn concentrations of micritic dolostones, microalgae-bonded dolostones, and dolarenites are relatively low, ranging from 277.98 mg/kg to 568.17 mg/kg (except samples No. 3 and No. 26) and 277.98 mg/kg to 568.17 mg/kg, respectively (Table 2). Moreover, the Fe and Mn concentrations of micritic dolostones, microalgae-bonded dolostones, and dolarenites show positive correlation (Fig. 3a).

Marine carbonates of different geological ages obtain variable Fe concentrations mainly in the range of $210 \pm 170 \times 10^{-6}$ (Li et al., 1984), and the Ediacaran marine carbonates deposited under anoxic conditions generally have Fe concentrations $>2000 \times 10^{-6}$ (Zhao et al., 2020). And the Fe and Mn concentrations of the Dengying Formation dolostones both show positive correlations with MgO contents (Fig. 3b and 3c). Therefore, we infer that the Fe and Mn elements in the Dengying Formation micritic dolostones, microalgae-bonded dolostones, and dolarenites were derived from normal seawater, and not significantly affected by external fluids, such as atmospheric water,

Table 2. Major, trace, rare earth element compositions, and calculated results of the Dengying Formation dolostones at the Liaojiacao Section

Sample	Petrology	CaO (%)	MgO (%)	MgO /CaO	Sr (mg/kg)	Na (mg/kg)	K (mg/kg)	Fe (mg/kg)	Mn (mg/kg)	ΣREE (mg/kg)	ΣLREE/ΣHREE	Ce/Ce*	Eu/Eu*
No.1	Microalgae-bonded dolostone	30.00	21.75	1.02	46.99	——	31.76	568.17	153.38	1.864	1.22	0.46	2.40
No.5		29.32	21.88	1.05	49.90	——	71.93	316.09	107.91	10.297	8.69	6.20	2.41
No.7		30.08	21.47	0.99	43.93	——	4.59	391.14	99.31	2.383	1.86	0.30	0.05
No.8		30.50	21.24	0.98	46.93	——	21.67	351.32	68.04	2.708	2.72	0.78	0.70
No.9		28.08	23.86	1.19	37.16	130.95	——	277.98	40.00	0.206	0.19	0.01	4.69
Average values		29.60	22.04	1.05	44.98	130.95	32.49	380.94	93.73	3.492	2.94	1.55	2.05
No.12	Dolarenite	29.74	22.11	1.04	47.35	247.73	124.47	441.23	251.99	0.853	1.19	0.34	2.72
No.15		30.40	21.28	0.98	40.36	——	25.90	371.86	217.99	2.576	1.28	0.40	4.69
No.22		28.39	22.57	1.12	26.57	——	36.20	675.73	311.72	1.942	1.70	0.70	11.79
No.26		29.78	21.82	1.02	39.82	108.77	72.34	910.78	347.66	1.872	1.77	0.34	18.38
Average values		29.58	21.95	1.04	38.53	178.25	64.73	599.90	282.34	1.811	1.49	0.45	9.39
No.2	Micritic dolostone	29.63	22.16	1.05	46.96	——	9.46	329.86	78.32	1.749	1.56	0.49	4.69
No.3		27.60	23.56	1.19	42.27	——	——	919.33	159.81	4.007	1.54	0.57	0.34
No.4		29.20	22.08	1.06	68.01	——	27.57	405.53	72.43	2.561	1.68	0.45	23.68
No.6		29.26	22.65	1.08	48.63	117.15	41.16	287.86	71.45	2.386	1.30	0.33	2.79
Average values		28.92	22.61	1.10	51.47	117.15	26.06	485.65	95.50	2.6876	1.52	0.46	7.88
No.10	Fine -crystalline dolostone	27.84	23.4	1.18	33.69	205.07	195.33	407.87	148.73	5.58	5.50	0.20	0.98
No.11		28.48	22.56	1.11	34.55	211.15	46.43	563.34	139.90	1.797	1.68	0.93	0.09
No.13		30.31	21.4	0.99	53.65	162.78	204.04	1130.89	310.63	2.092	2.25	0.41	4.02
No.14		30.32	21.27	0.98	46.00	156.77	78.41	1078.78	488.96	1.242	1.64	0.81	4.69
No.16		30.82	20.67	0.94	37.33	——	30.27	983.89	326.36	2.837	1.26	0.69	1.79
No.18		30.19	21.17	0.98	36.34	18.97	159.32	882.00	238.82	2.237	1.69	0.76	0.13
No.19		30.09	21.36	0.99	31.63	241.20	102.15	1176.78	296.77	2.222	1.89	0.69	0.32
No.21		27.95	23.68	1.19	34.18	322.07	40.83	766.58	421.33	2.833	2.72	0.48	0.02
No.27		30.32	21.16	0.98	33.08	89.85	92.52	1099.78	243.16	1.711	0.86	0.48	1.57
Average values		29.59	21.85	1.04	37.83	175.98	105.48	898.88	290.52	2.506	2.16	0.61	.51
No.17	Medium -crystalline dolostone	30.41	21.17	0.98	29.23	96.60	65.27	884.33	233.94	1.733	1.32	0.68	0.03
No.20		29.95	21.54	1.01	30.19	——	71.48	1085.78	372.30	2.994	1.22	0.51	2.39
No.23		29.35	21.47	1.02	27.21	——	274.16	840.00	305.91	4.540	1.76	0.35	1.17
No.24		29.80	21.9	1.02	40.88	348.56	226.61	910.00	377.72	3.848	2.19	0.56	1.50
No.25		29.92	21.73	1.02	42.20	——	41.83	1419.44	509.56	2.598	1.13	0.78	0.60
Average values		29.89	21.56	1.01	33.94	222.58	135.87	1,027.91	359.89	3.143	1.52	0.58	1.14

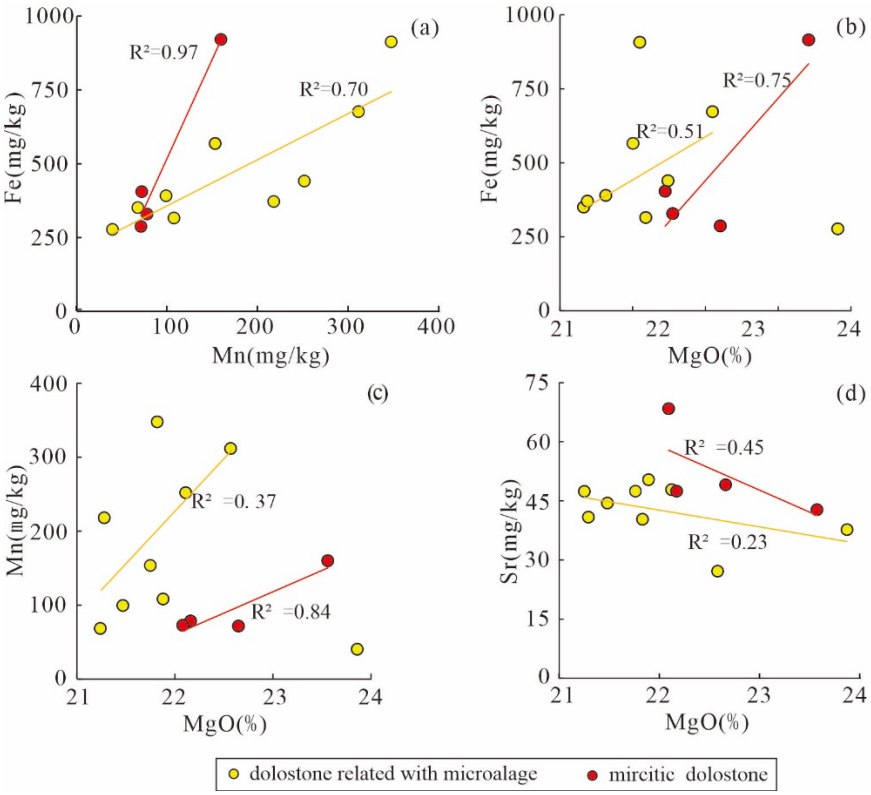

Figure 3. Cross plots of Fe-Mn (a), Fe-MgO (b), Mn- MgO (c) and Sr- MgO (d) of the micritic dolostones, microalgae-bonded dolostones, and dolarenites in the Dengying Formation at the Liaojiacao Section

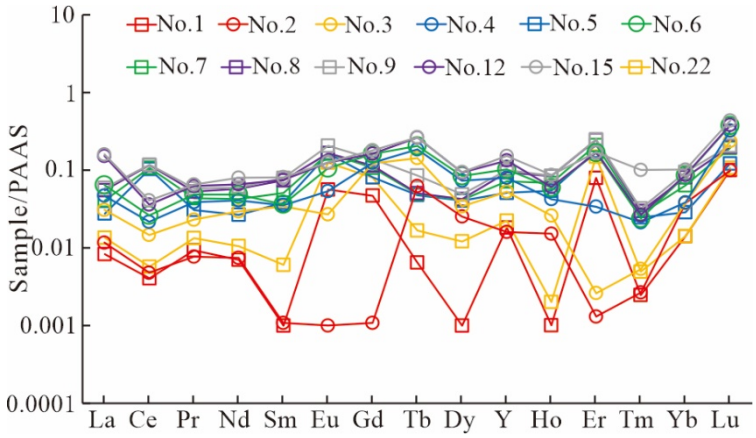

Figure 4. PAAS-normalized REE patterns for the Dengying Formation dolostones at the Liaojiacao Section

terrigenous water, or hydrothermal fluids. Furthermore, the Mg in the crystal lattice of dolomite might be partially replaced by Fe and Mn ions because these three ions have similar ionic radius (Mei, 2012), we consequently infer that the variable Fe and Mn concentrations herein may be related to the degree of replacement of Mg^{2+} by Fe^{2+} or Mn^{2+}.

Sr concentrations of micritic dolostones, microalgae-bonded dolostones, and dolarenites are extremely low, in the range from 33.69 mg/kg to 68.01 mg/kg, and consistent with the reported Sr concentrations of the dolostones that preserve the original sedimentary texture in the Denying Formation in the Sichuan Basin (Lin et al., 2018; Zhao et al., 2020; Jin et al., 2019). However, the medium-crystalline dolostones in the Dengying Formation at the Liaojiacao Section even obtain lower Sr concentrations, varying from 22.71 mg/kg to 53.65 mg/kg (Table 2). Furthermore, the Sr concentrations of micritic dolostones, microalgae-bonded dolostones, and dolarenites herein are weakly negatively correlated with MgO contents (Fig. 3d).

Sr concentrations of protodolomites generally range from 246 × 10^{-6} to 600 × 10^{-6}, and dolomitization, recrystallization, and atmospheric fresh water leaching during the diagenesis also

reduce the Sr concentrations of carbonates (Jin et al., 2019; Ren et al., 2019); especially dolomitization, which can drastically reduce Sr concentrations to 155×10^{-6}. Therefore, we infer that the low Sr concentrations of the Dengying Formation dolostones at the Liaojiacao Section are derived from dolomitization during the early stage of mineral symbiotic sequence, and the preexisting minerals tend to be calcites rather than aragonites or high-Mg calcites. Moreover, the low Sr concentrations of fine- and medium-crystalline dolostones herein tend to be a result of recrystallization of micritic dolostones, microalgae-bonded dolostones, and dolarenites.

5.3 Rare Earth Elements

The Dengying Formation dolostones contain low total rare earth element (ΣREE+Y) concentrations ranging from 0.206 mg/kg to 10.297 mg/kg (Table 2), which are in the range of ΣREE+Y values for normal marine carbonates and the reported values for microbial dolostones that preserve the original sedimentary texture of the Dengying Formation in the Sichuan Basin (Jin et al., 2019; Wang et al., 2014; Lin, 2014). Furthermore, these dolostones exhibit typical light rare earth element (LREE) depletion and medium and heavy earth element (MREE and HREE) enrichment patterns (Fig. 4), and significantly negative Ce anomalies and positive Eu anomalies (Table 2)

The MREE enrichment may be attributed to the influence of early diagenetic alteration, low oxygen or even anoxic conditions in the pore water, and microbial activities (Chen et al., 2015), but only microbial activities can also lead to the simultaneous enrichment of HREE (Takahashi et al., 2007).

In addition, significantly negative Ce anomalies in carbonates generally result from oxidized conditions in their formation fluid. Therefore, we infer that microbial activities play an important role during the formation of dolomites in the Dengying Formation, and the dolomitization probably took place in oxidative environment.

5.4 Carbon and Oxygen Isotopic Compositions

The micritic dolostones, microalgae-bonded dolostones, and dolarenites of the Dengying Formation have $\delta^{13}C$ values ranging from 1.686‰ to 4.102‰ and $\delta^{18}O$ values ranging from −1.526‰ to −8.467‰ (Table 1); whereas, the fine- and medium-crystalline dolostones have lower $\delta^{13}C$ and $\delta^{18}O$ values, which range from 1.851‰ to 3.988‰ and from −6.673‰ to −8.927‰, respectively. Furthermore, the $\delta^{13}C_{dol}$ values of the Dengying Formation are mostly located in the range of those for normal marine carbonates deposited during the Dengying stage in South China (Jin et al., 2019; Huang et al., 1999). However, the $\delta^{18}O_{dol}$ values at the Liaojiacao Section, especially of the fine- and medium-crystalline dolostones, are prominently lower than those of normal marine carbonates deposited during the Dengying stage in South China.

Therefore, we may infer that the Dengying Formation dolostones at the Liaojiacao Section have been influenced by diagenetic alteration. The micritic dolostones, microalgae-bonded dolostones, and dolarenites are derived from mimetic dolomitization during the early stage of the mineral symbiotic sequence or the slight diagenetic alteration of protodolomites after deposition, whereas the fine- and medium-crystalline dolostones have suffered from intense diagenetic alteration.

6. DISCUSSION

6.1 Origin of Dolostones with Original Sedimentary Textures

The micritic dolostones, microalgae-bonded dolostones, and dolarenites of the Dengying Formation at the Liaojiacao Section generally preserve the original sedimentary textures (microalgae spots, microalgae trace fossils, and microbial mats), and also have Mg/Ca ratios that approximate to the values of protodolomite. Moreover, these dolostones with original sedimentary textures have similar Na and Sr concentrations but lower Fe and Mn concentrations compared with marine carbonates, and exhibit typical LREE depletion and MREE as well as HREE enrichment patterns with significantly negative Ce anomalies and positive Eu anomalies. In addition, these dolostones have similar $\delta^{13}C$ values but lower $\delta^{18}O$ values compared with marine carbonates.

Therefore, these features indicate that micritic dolostones, microalgae-bonded dolostones, and dolarenites of the Dengying Formation at the Liaojiacao Section are the products of mimetic dolomitization and formed in an environment with extensive microbial activity from calcite as the preexisting mineral and with oxidized seawater of normal salinity as the dolomitization fluid.

6.2 Origin of Fine- and Medium-crystalline Dolostones

Compared with dolostones with original

sedimentary textures, the fine- and medium-crystalline dolostones of the Dengying Formation have relatively low Sr concentration, high Fe and Mn concentrations, and low $\delta^{18}O$ values, as well as low degrees of ordering. In addition, the original sedimentary textures of these dolostones have been intensively destroyed by diagenetic alteration (e.g., recrystallization and dissolution). Therefore, we infer that fine- and medium-crystalline dolostones were the recrystallization products of the dolomites with original sedimentary textures during diagenesis.

7. CONCLUSION

The Dengying Formation contains widespread dolostones with original sedimentary textures and fine- and medium-crystalline dolostones. Dolostones with original sedimentary textures contain micritic dolostones, microalgae-bonded dolostones, and dolarenites, and generally have microbial trace fossil remains related to microalgae, such as microalgae spots, microalgae trace fossils, microbial mats, and sand-sized particles. Fine- and medium-crystalline dolostones have significantly altered sedimentary textures derived from dissolution and recrystallization, such as dissolved pores and voids and dolomites with relatively large crystal size.

The dolostones with original sedimentary textures have Mg/Ca ratios approximate to protogenetic dolomite, Na and Sr concentrations as well as $\delta^{13}C$ values similar to marine carbonates but low Fe and Mn concentrations and $\delta^{18}O$ values, and typical LREE depletion and MREE as well as HREE enrichment patterns with significantly negative Ce anomalies. However, compared with these dolostones, fine- and medium-crystalline dolostones obtain relatively low Sr concentrations, high Fe and Mn concentrations, and low $\delta^{18}O$ values, as well as low order degrees.

The dolostones of the Dengying Formation at the Liaojiacao Section with original sedimentary structure are the products of mimetic dolomitization, and formed in the environment with extensive microbial activity, calcite as the preexisting mineral, normal salinity, and oxidized seawater as the dolomitization fluid. Moreover, the fine- and middle-crystalline dolostoness were the recrystallization products of the dolomites with original sedimentary structure during diagenesis.

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