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Geochemical characteristics and diagenetic systems of dolomite reservoirs of the Changxing Formation in the eastern Sichuan Basin, China

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Abstract: In order to discuss the relationship between dolomite reservoirs and diagenetic systems of the Changxing Formation, we studied carbon, oxygen and strontium stable isotopes, iron, manganese and strontium trace elements and the Mg/Ca (mol%) ratio, dolomite order degree, and determined that burial dolomitization is the key to controlling the distribution of high quality dolomite reservoir in the Changxing Formation in the eastern Sichuan Basin. The dolomite of the Changxing Formation is divided into four diagenetic systems: (1) penecontemporaneous stage syngenetic brine diagenetic system, (2) early diagenetic stage strata seal brine diagenetic system, (3) middle-late diagenetic stage mixed hot brine diagenetic system and (4) tectonic uplift stage mixed hydrothermal fluid diagenetic system. New understanding of the controlling factors and distribution of dolomite reservoir development is discussed. Reef shoal facies belts controlled regional reservoir distribution and the scale of development. Burial dolomitization of a strata seal brine diagenetic system is the foundation of reservoir development, mainly developing pore reservoir. Burial dolomitization of mixed hot brine diagenetic system expanded the reservoir distribution and improved the reservoir quality, mainly developing pore-vug reservoir. Fracturing and dissolution of a mixed hydrothermal fluid diagenetic system is the key to improving the reservoir quality, mainly developing pore-vug-crack complex reservoirs.

Key words: Eastern Sichuan Basin, Changxing Formation, dolomite reservoir, diagenesis, geochemical characteristics, diagenetic system

1 Introduction

The Changxing Formation in the eastern Sichuan Basin is an exploration target for marine carbonate rocks in South China. A series of large and medium gas fields such as Huanglongchang, Datianchi, Gaofengchang, Puguang and Yuanba has been found in Changxing Formation reef shoal facies. The proven reserves is over 200 billion m^3. The genesis, distribution and controlling factors of the marine carbonate reservoirs in the Changxing Formation are very important (Ma et al, 2005; Zhang et al, 2006). Previous researchers studied the sedimentary facies, reservoir space, diagenesis type and gas accumulation characteristics and genesis, and there is a considerable controversy about the genesis of dolomite reservoirs (Hardie, 1986; Whitaker et al, 2004; Green and Mountjoy, 2005; Davies and Smith, 2006). Most researchers in China think that the formation of dolomite reservoirs of the Changxing Formation in the eastern Sichuan Basin is due to infiltration reflux and mixed water dolomitization (Wang et al, 2006; Mou et al, 2005). Based on the rock structure, trace elements and stable isotope geochemical characteristics, Zheng et al (2010) demonstrated that the dolomite reservoirs of Changxing reef shoal facies are independent of atmospheric water or mixed water, they are the product of multi-stage hydrothermal dolomitization during burial diagenesis. Therefore, new understanding of the genesis of dolomite reservoirs extensively developed in the Changxing Formation in the eastern Sichuan Basin is needed, to increase the success rate of dolomite reservoir prediction. Based on the analysis of rock structure–genesis, and the data of Mg/Ca (mol%) ratio, dolomite order degree, iron, manganese and strontium trace elements, and carbon, oxygen and strontium stable isotopes, we studied the geochemical characteristics of Changxing Formation dolomite and the water-rock reaction processes and relationships in each stage of dolomitization. According to fluid properties and sources of dolomite (Middleton, 2003; Worden

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and Burley, 2003; Li et al, 2006a; 2006b; Li and Liu, 2009; Zheng et al, 2010), we divide the dolomitization process of the Changxing Formation into four diagenetic systems, further discuss the relationships between the dolomite reservoirs of Changxing Formation reef shoal facies and diagenetic systems, and reveal the reservoir properties and type of every diagenetic stage. This study is significant for marine carbonate reservoir exploration in China.

2 Characteristics of sedimentary geology

The study area is located in Xuanhan and Kaijiang counties of Dazhou city, east Sichuan and Wanzhou District of Chongqing. It is in the northeastern margin of the east Sichuan arc fold belt, including Wubaiti, Damaoping, Gaofengchang and Huanglongchang tectonic belts, striking northeast-southwest, and covers nearly 10,000 km^2 (Fig. 1). The Upper Permian Changxing Formation and the underlying Upper Permian Longtan Formation (locally known as the Wujiaping Formation) were deposited continuously. The Changxing Formation is unconformably overlain by the lower Triassic Feixianguan Formation. From field profiling, drill core observation and thin section analysis, we conclude that the lithology of Changxing Formation is mainly limestone, secondly dolomite and occasionally thin layers of shale. The limestone can be subdivided into mud-microcrystalline limestone, calcarenite, bioclastic limestone, and reef limestone. Dolomite can be subdivided into mud-microcrystalline dolomite, granular dolomite, reef dolomite, and crystalline dolomite. The type of sedimentary facies is various, and the favorable reservoir development facies in the study area is mainly platform margin reef and shoal facies dolomite (Fig. 1).

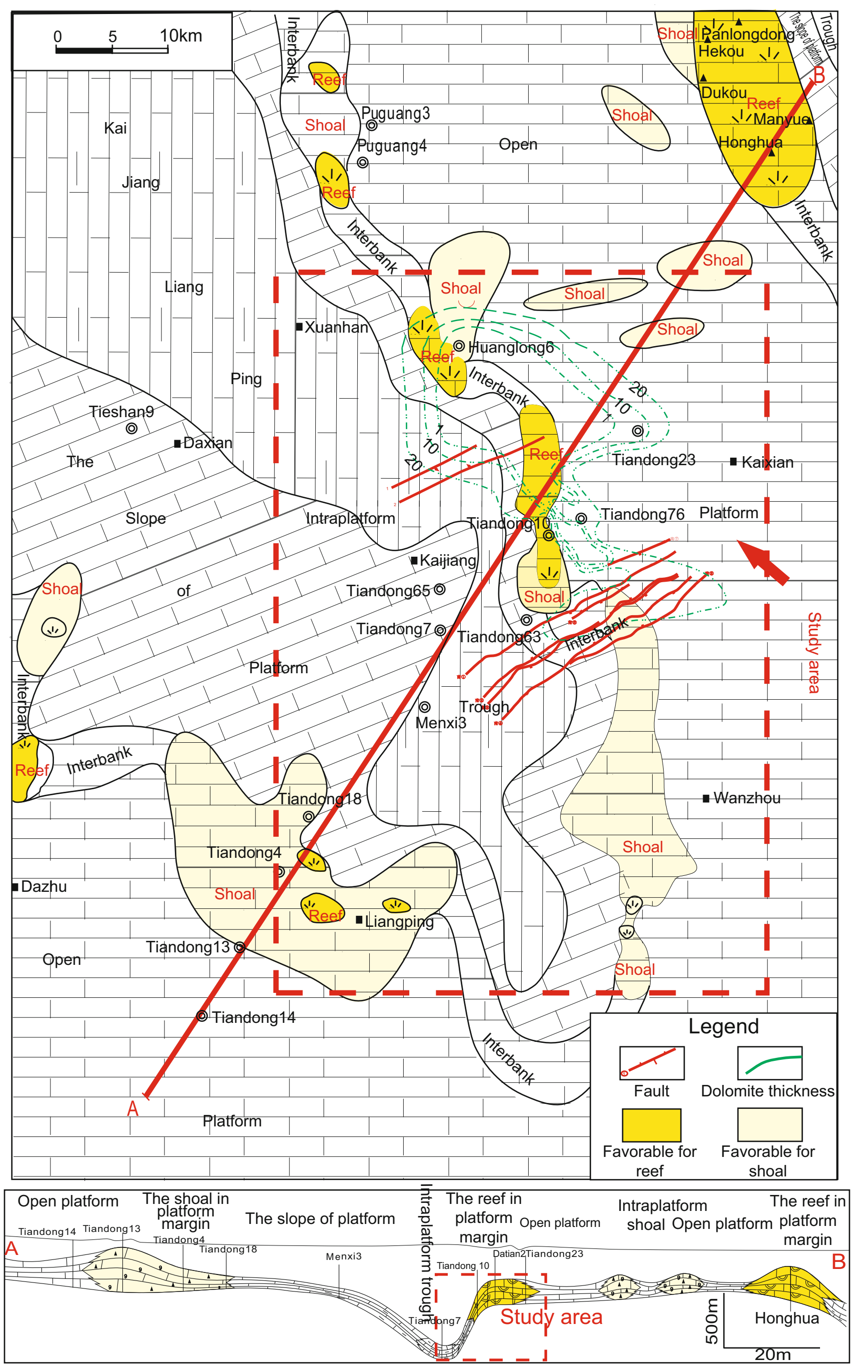

Fig. 1 Lithofacies palaeogeography of the Changxing Formation in the eastern Sichuan Basin

3 Reservoir diagenesis characteristics of the Changxing Formation

Different diagenesis stages have different diagenesis environments, fluid properties, diagenesis combination types and reservoir formation processes. The Changxing Formation has many reservoir diagenesis types. According to the relation between diagenesis and reservoir development, compaction, pressure solution and cementation have the most destructive effect on reservoir properties, and dolomitization, dissolution and recrystallization are constructive for the reservoir development.

3.1 Destructive diagenesis

3.1.1 Compaction and pressure solution

Compaction and pressure solution are common developed in the Changxing Formation, and are destructive to reservoir development. Compaction primarily acts as the compaction and deformation of carbonate rock sediments. Pressure solution acts as dissolution and suture line development. Compaction and pressure solution caused strong shrinkage of primary pores, which is the main reason of bad reservoir development. Pressure solution made suture lines filled with clay interlayer or carbonaceous organic matter, and reservoir porosity and permeability are poor.

3.1.2 Cementation

Cementation is common in the Changxing Formation. Most primary intergranular pores are filled with cements, which is unfavorable for reservoir development. Cementation has following types: early generation ring edge comb cementation, even grained powder–fine crystalline calcite cementation, medium-coarse crystalline and intergrowth calcite cementation, and coarse-macro crystalline calcite cementation.

3.2 Constructive diagenesis

3.2.1 Dolomitization

The Changxing Formation dolomitization is characterized by multiple stages and multiple genesis. It is divided into penecontemporaneous dolomite and diagenetic burial dolomite according to structure–genesis classification. There are many types of dolomite reservoir development. They are mud–micro crystalline dolomite, micro–powder crystalline biological reef dolomite, powder–fine crystalline biological shoal dolomite, powder–fine crystalline bioclastic dolomite, powder–fine crystalline dolomite, fine-medium crystalline dolomite, and fragmentation dolomite.

Penecontemporaneous dolomite

Penecontemporaneous mud–microcrystalline dolomite (Fig. 2(a)) is one of the common types of Changxing Formation dolomite. It is allotriomorphic-subhedral, and often with tides and exposed genesis signs such as clay bands, bird eye, gypsum false crystal, calcium crusts and algal layers–algae aggregate structures. The degree of order of penecontemporaneous dolomite is lowest, averaging 0.615, and the Mg/Ca (mol%) is also the lowest at 0.906 (Table 1). Its genesis is not controversial, and all researchers suggest an evaporation pumping dolomitization origin. It is mainly developed in the sabkha environment such as the top reef flat of intermittent exposure evaporation, and the barrier protected lagoon-tidal flat. Since this kind of dolomite is still very dense, it generally does not have the reservoir significance.

Diagenetic burial dolomite

According to the microscopic thin section identification, the dolomite which has reservoir significance in the Changxing Formation is most developed in geologic bodies such as sponge reefs and shoal facies, but poorly developed in mud–micro crystalline limestone and clastic mud–micro crystalline limestone. So the rock fabric with better properties is more conducive to dolomitization occurrence. It can be determined that diagenetic burial dolomitization is the most important diagenesis for the Changxing Formation reservoirs. Dolomitization in the study area can be divided into four stages: early diagenetic stage, middle diagenetic stage, late diagenetic burial dolomitization and tectonic uplift dolomite fragmentation. 1) early diagenetic stage, the granular and reef dolomites with the primary structure well preserved (Fig. 2(b), (c)), the Mg/Ca (mol%) ratio and degree of order slightly higher than penecontemporaneous dolomite, respectively 0.915 and 0.618. 2) middle diagenetic stage, the residual powder–fine grained dolomites with the primary structure damaged (Fig. 2(d), (e)), the Mg/Ca (mol%) ratio and degree of order significantly higher than those in early diagenetic stage, respectively 0.944 and 0.802. 3) late diagenetic stage, the middle-coarse grained dolomites with the primary structure almost disappeared. The dolomites have good crystalline form, and some have bright border of fog center and a strong recrystallization structure. The intercrystal pores, intercrystal dissolved pores and large dissolved pores were well developed. The pores were often filled with carbonized asphalt and saddle-shaped dolomites with a ring structure (Fig. 2(f), (g)), the Mg/Ca (mol%) ratio is a little higher and the degree of order is significantly higher than those in middle stage, respectively 0.946 and 0.928. 4) the fragmentation dolomites (Fig. 2(h), (i)) with strong dissolution, the dissolution cracks and large pores are all well developed and the dissolved pores are filled with authigenic quartz, the degree of order is highest, averaging 0.95, the Mg/Ca (mol%) ratio is 0.947. The degree of order and Mg/Ca ratio of different diagenetic stages have a weak positive correlation, the correlation index R^2 is 0.1142 (Fig. 3). With increasing diagenetic strength, the dolomite crystallinity gets better.

Table 1 The statistics of X-ray diffraction analysis data of dolomite samples in the Changxing Formation

Sample type	Sample number	Mg/Ca (mol%)		Degree of order	
		Variation range	Average	Variation range	Average
Penecontemporaneous dolomite	2	0.86-0.95	0.906	0.59-0.64	0.615
Dolomite of early diagenetic stage	16	0.86-0.98	0.915	0.36-0.85	0.618
Dolomite of middle diagenetic stage	22	0.82-1.00	0.944	0.51-1	0.802
Dolomite of late diagenetic stage	12	0.86-1.03	0.946	0.73-1	0.928
Structural fragmentation dolomite	3	0.91-0.98	0.95	0.93-0.96	0.947

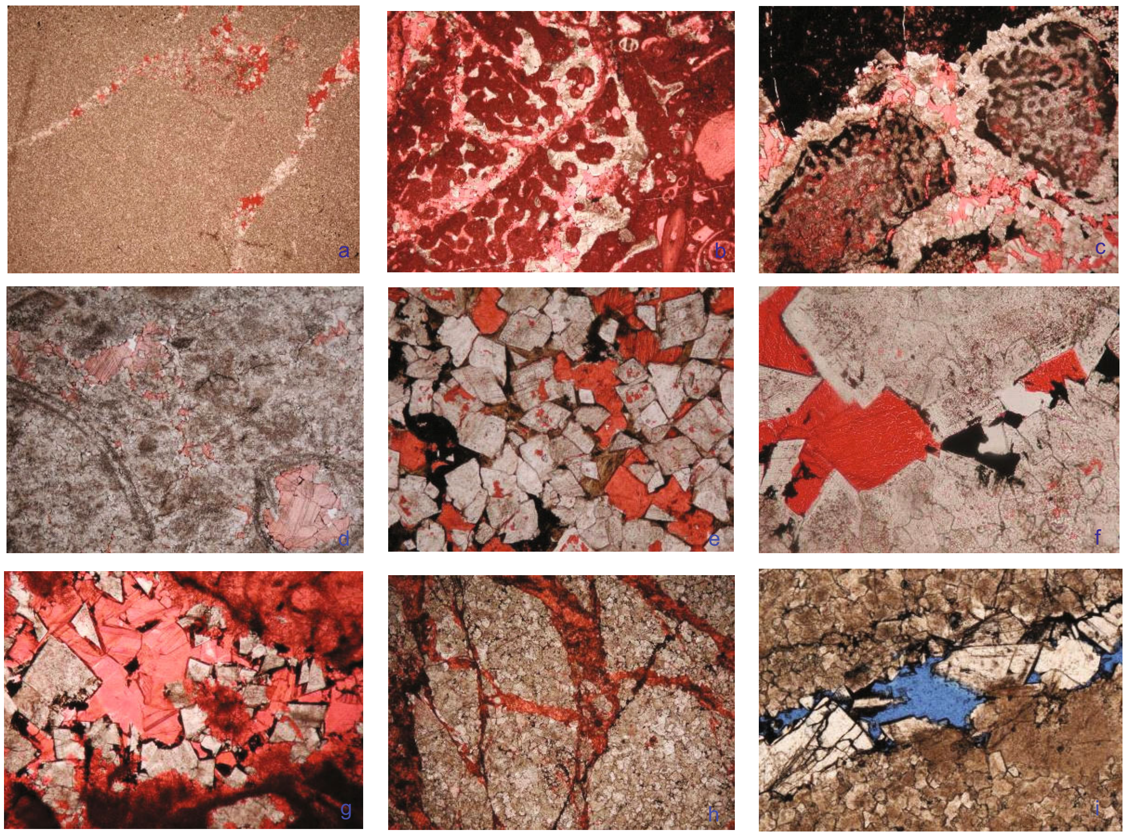

Fig. 2 Photos of the dolomitization and evolution process of different diagenetic stages from the Changxing Formation in the eastern Sichuan Basin. a: Penecontemporaneous mud-microcrystalline dolomite, developing fractures, filled with dolomite and calcite, Feng 003-2 well, 4471.11 m, stained thin section, 10×20 (-); b: Clay-powder crystalline sponge limestone, early burial dolomitization occurred in the sponge, Tiandong 53 well, 4329.08 m, conventional thin section, 10×20 (-); c: Sponge barrier reef dolomitic limestone, burial dolomitization occurred in the shell-like cement filled with reef skeleton pores in the early diagenetic stage, the remaining pores of skeleton were filled with calcite, Tiandong 002-11 well, 3886.03 m, stained conventional thin section, 10×20 (-); d: Residual bioclastic powder-fine granular gray dolomite, the biological cavity holes and the intergranular pores were filled with calcite, Tiandong 74 well, 4329.08 m, stained conventional thin section, 10×20 (-); e: Fine-grained gray dolomite, the dolomite intergranular pores filled with clay, organic matter and diagenetic calcite, part of the dolomite was dedolomitizated, Tiandong 002-11 well, 4329.08 m, stained conventional thin section, 10×50 (-); f: Residual bioclastic powder-fine grained dolomite, the intergranular pores were filled with calcite and carbonized asphalt, Tiandong 002-11 well, 3832.04 m, stained conventional thin section, 10×100 (-); g: Mud crystalline sponge dolomite, filled with dolomite, calcite and bitumen, Tiandong 002-11 well, 3879.12 m, stained conventional thin section, 10×20 (-); h: Fragmentation fine crystalline dolomite, cracks fractured the rock into breccias-shape, the fractures are filled with asphalt, Tiandong 002-11 well, 3835.59 m, casting thin section, 10×20 (-); i: Fragmentation fine crystalline dolomite, the cracks are filled with coarse crystalline dolomite, Tiandong 10 well, 3782.55 m, casting thin section, 10×20 (-)

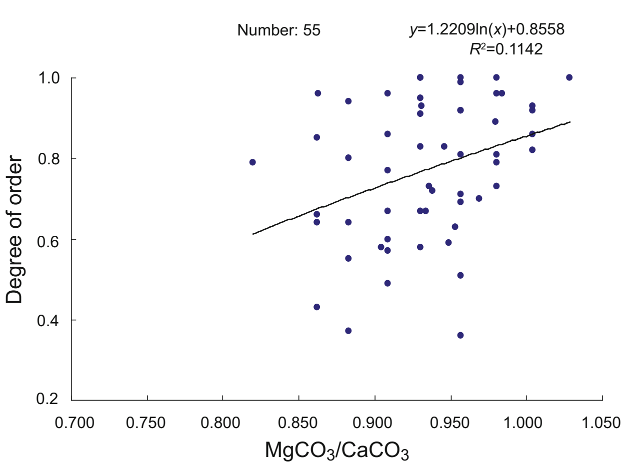

Fig. 3 The relation between degree of order and $MgCO_3$/ $CaCO_3$ of dolomite

3.2.2 Recrystallization

Recrystallization is the most common diagenesis of the Changxing Formation. The dolomite recrystallizes from micro, powder, fine crystals to medium-fine crystals. This causes the destruction of the internal structure of bioclastics and recrystallization residual bioclastic structure is well developed. The strength of recrystallization has a big influence on the reservoir properties. Some granular limestones and dolomites were transformed by strong recrystallization, which increased the intercrystal pores of the original rock and provided a dissolution space for diagenetic fluids. Generally the structure of the medium recrystallization powder–fine crystalline dolomite is well-distributed, and the intercrystal pores are well developed, which improve the rock properties. The recrystallization of the micro–powder crystalline dolomite is weak, so its porosity and permeability are low, unfavorable for reservoir development.

3.2.3 Dissolution

Dissolution occurred commonly in the Changxing Formation, including middle stage medium-deep burial dissolution and late stage deep burial dissolution. The former usually occurred in the fine-medium crystalline dolomite, and intercrystal and intragranular dissolution pores were developed, which were partially filled with calcite, dolomite and celestite. Although the filling has some influences on the quality of the reservoir, generally it is favorable for the reservoir development. The latter usually occurred in the coarse crystalline dolomite, and extra-large dissolution pores, intercrystal dissolution pores, moldic pores and karst caves were mainly developed, which were not completely filled with celestite, ferroan calcite, unusual shape dolomite and carbonized asphalt. The reservoir space was preserved, so this stage is the most favorable for reservoir development.

3.3 Diagenetic evolution modes

Based on the diagenesis characteristics analysis, referring to the national standard of carbonate rocks diagenesis (SY/T5478-2003), we divided the evolution process of the Changxing Formation dolomite reservoir into five stages: penecontemporaneous stage, early diagenetic stage, middle diagenetic stage, late diagenetic stage and tectonic uplift stage (Fig. 4). The diagenetic stage division and evolution characteristics can provide a basis for the study of diagenesis systems.

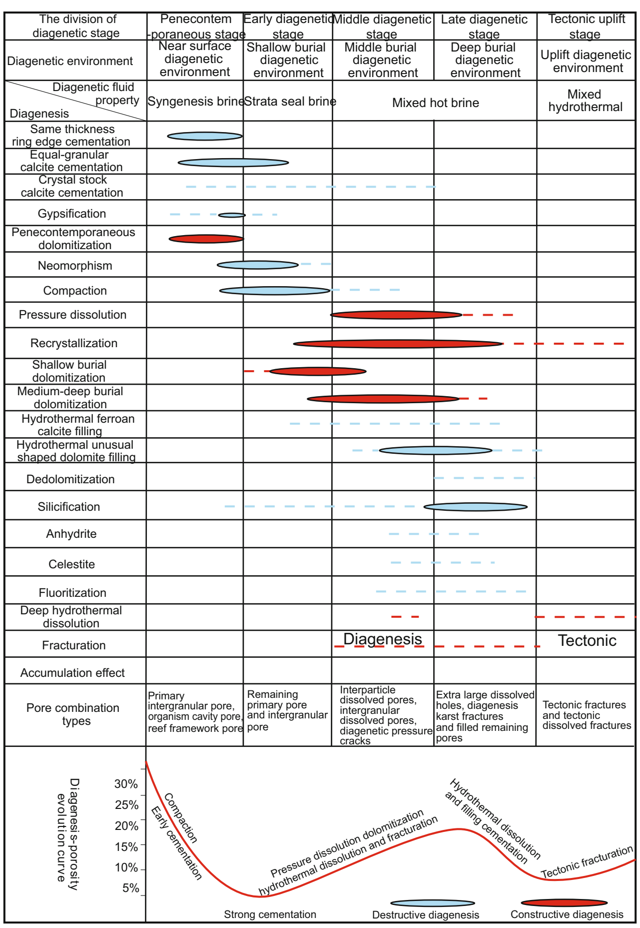

Fig. 4 The diagenesis stages and evolution models of the Changxing Formation in the eastern Sichuan Basin

4 Dolomite geochemical characteristics

To better understand the fluid properties, origin, evolution history and the influence on the reservoir development of the diagenesis systems in the Changxing Formation, we studied the Fe, Mn, Sr trace elements and C, O, Sr isotopic geochemical characteristics. The samples were taken from fresh drill cores by micro-drilling. After microscopic thin section detection and decontamination, ensuring the reliability and representativeness of samples classified by structure–genesis, the selected samples were ground to 200 mesh, and split into four sub-samples. One was for standby application, and the other three were respectively used for measurements of Fe, Mn, Sr contents, $\delta^{13}C$, $\delta^{18}O$ values and $^{87}Sr/^{86}Sr$ ratio. Sample numbers, distribution and analysis results are shown in Table 2. Fe, Mn, Sr contents were analyzed by Chengdu Minerals Complex Utilization Institute of Chinese Academy of Geological Sciences, using a Perkin Elmer 2000DV ICP-AES (identifier: 1-44-40), test basis is JY/T105-1996 (inductively coupled plasma atomic emission spectrum general method). The analysis results are shown as single element content, limit of detection is 0.001%, and error is 0.002%. C and O isotopes were analyzed by Exploration and Development Research Institute Geology Laboratory of PetroChina Southwest Oil and Gasfield Company, using a Finnigan MAT 252 isotope ratio mass spectrometer, test basis is SY/T 6039-94, working standard is TTB-2. The analysis error of $\delta^{13}C$ ranges in 0.006-0.042, and that of $\delta^{18}O$ ranges in 0.009-0.043. $^{87}Sr/^{86}Sr$ was analyzed by Professor Yin Guan from Isotope Laboratory of State Key Laboratory of Oil and Gas Reservoir Geology and Exploitation Engineering in Chengdu University of Technology, also using a Finnigan MAT 252 isotope ratio mass spectrometer, experiment condition is 22°C, humidity 50%, test basis is standard sample NBS987 of American National Standards Institute, measurement error is less than 0.02%.

4.1 Geochemical characteristics of iron, manganese, strontium trace elements

In the 46 analysis samples (Tables 2 and 3), 38 are dolomite, six are marine mud–microcrystalline limestone, and two are calcite. The results showed that the contents of Fe, Mn and Sr trace elements in various types of dolomite are very similar (Fig. 5). The content of Fe is high, followed by Sr, and Mn is the lowest. However, the late diagenetic stage dissolution vugs and cracks filled with calcites have high content of Sr, and the next are Fe and Mn. The content and distribution of Fe, Sr and Mn of dolomite in different diagenetic stages are very similar, indicating that dolomitization fluids of different diagenetic stages have the same fluid source. The low content of Mn and the high content of Fe and Sr in dolomite show that the diagenetic fluid had strong reducibility and was not affected by continental fresh water, that is, dolomitization is independent of atmospheric water, a closed diagenetic environment. The fluid in open conditions can only precipitate calcite with medium Sr content, while the late dolomitization coexisting calcite has an unusually high Sr content (up to 0.614‰), so it can be inferred that the dolomitization occurred in a relatively closed system (Zheng et al, 2007), which confirms again that dolomitization is independent of atmospheric water and mixed water.

Table 2 The content of Fe, Mn, Sr and the distribution of C, O, and Sr isotopes of carbonate rocks in the Changxing Formation

Well number	Depth number	Lithology	Genetic type	ω(Fe), ‰	ω(Mn), ‰	ω(Sr), ‰	$\delta^{13}C$, ‰	$\delta^{18}O$, ‰	$^{87}Sr/^{86}Sr$
Datian 002-1	3942.59	Micrite	Marine limestone	0.1911	0.00789	0.5043	4.847	-4.71	0.709062
Feng 003-2	4498.09	Microcrystalline bioclastics limestone		2.621	0.0612	0.7852	2.706	-5.947	0.709609
Tiandong 10	3896.3	Microcrystalline bioclastics limestone		0.2544	0.0103	0.469	1.881	-4.183	0.710847
Tiandong 53	4329.18	Micritic reef limestone		0.5495	0.0654	0.278	2.827	-5.857	0.709303
Huanglong 5	4315.29	Micritic-crystallite limestone		0.9462	0.0956	0.265	1.762	-6.216	0.709254
Yunan 1	3565.72	Micritic-crystallite limestone		3.091	0.0151	2.409	3.517	-4.396	0.708825
Feng 003-2	4470.26	Granophyric mud-powder crystalline dolomite	Penecontemporaneous dolomite	6.1	0.4418	0.1982	1.771	-5.11	0.7091
Puguang 6	5-38/101	Micritic-crystallite dolomite		3.7	0.08	0.14	2.186	-2.979	0.7095
Feng 003-2	4488.21	Fine medium crystalline residual sponge reef dolomite	Early diagenetic burial dolomite	2.79	0.3179	0.2298	1.393	-5.989	0.707334
Tiandong 021-3	4259.17	Fine crystalline powder dolomite		2.182	0.2004	0.2016	2.298	-4.179	0.707163
Tiandong 10	3748.65	Fine crystalline powder dolomite		4.9	0.2251	0.4419	1.961	-4.651	0.707023
Tiandong 10	3756.5	Fine crystalline powder dolomite		6.9	0.4347	0.2393	2.387	-3.664	0.708201
Tiandong 10	3761.55	Fine crystalline powder dolomite		43.1	0.2069	0.4498	4.292	-7.056	0.708408
Tiandong 10	3824.73	Fine crystalline powder dolomite		0.7636	0.0847	0.221	3.804	-4.698	0.70969
Tiandong 21	4308.93	Spines fine crystallite dolomite		1.777	0.1869	0.1401	2.916	-6.64	0.708622
Tiandong 53	4286.06	Fine crystalline powder residual sponge reef dolomite		1.842	0.197	0.7352	2.638	-5.699	Abnormally
Huanglong 5	4362.63	Powder crystalline dolomite		0.708	0.1223	0.1291	3.648	-5.905	0.708112
Huanglong 5	4380.46	Powder crystalline dolomite		2.309	0.1067	0.1191	2.251	-3.643	0.71275
Puguang 6	11-128/148	Granophyric powder-fine crystalline dolomite		3.5	0.11	0.24	2.76	-4.066	0.707372
Puguang 6	10-51/137	Powder crystalline gravel dolomite		2.3	0.09	0.13	2.965	-4.017	0.709327
Feng 003-2	4484.14	Dissolved pore powder crystalline dolomite	Middle diagenetic burial dolomite	3.419	0.3036	0.2535	1.572	-5.781	Abnormally
Tiandong 002-21	3857.65	Powder-fine crystalline dolomite		0.9303	0.092	0.4601	3.155	-5.396	0.707348
Tiandong 10	3733.79	Fine crystalline dolomite		0.8082	0.0798	0.861	2.178	-4.082	0.708097
Tiandong 10	3801.59	Fine crystalline dolomite		1.36	0.0803	0.3626	2.591	-5.902	Abnormally
Tiandong 10	3839.96	Fine crystalline dolomite		0.525	0.0806	0.119	4.048	-5.999	0.709677
Tiandong 53	4353.17	Powder-fine crystalline dolomite		0.7335	0.0809	0.2696	3.471	-6.822	0.709686
Tiandong 53	4356.88	Fine crystalline dolomite		0.3858	0.0854	0.1933	3.609	-6.097	0.707492
Tiandong 74	4129.36	Dissolved pore clastic fine crystalline dolomite		0.7151	0.0794	0.1523	2.369	-5.738	Abnormally
Tiandong 74	4146.92	Dissolved pore powder-fine crystalline dolomite		0.6039	0.0754	0.1078	1.501	-6.525	0.709041
Huanglong 5	4390.2	Residual spines powder-fine crystalline dolomite		0.6384	0.0833	0.1274	2.814	-7.205	0.711328
Maoba 3	14-10/34	Dissolved pore spherulite unequal crystalline dolomite		2.8	0.08	0.18	3.064	-4.484	0.706592
Puguang 6	8-88/130	Dissolved pore residual sand coarse crystalline dolomite		2.1	0.1	0.22	2.584	-4.42	0.706635
Puguang 6	9-105/121	Dissolved pore fine crystalline reef dolomite		2.1	0.08	0.44	2.921	-3.652	0.70667

(To be continued)

(Continued)

Well number	Depth number	Lithology	Genetic type	ω(Fe), ‰	ω(Mn), ‰	ω(Sr), ‰	$\delta^{13}C$, ‰	$\delta^{18}O$, ‰	$^{87}Sr/^{86}Sr$
Feng 003-2	4478.17	Powder-fine crystalline dolomite	Late diagenetic burial dolomite	2.141	0.2834	0.22	-0.647	-6.732	0.70757
Tiandong 002-11	3831.8	Residual sponge powder crystalline dolomite		0.7285	0.0858	0.2764	1.463	-6.558	0.707397
Tiandong 10	3795.5	Coarse crystalline residual sponge reef dolomite		0.7461	0.0768	0.1548	3.15	-6.913	0.708831
Tiandong 10	3874.86	Residual spines fine mesocrystalline dolomite		0.5281	0.0624	0.1513	4.581	-5.561	0.708386
Tiandong 21	4337.21	Pore powder-coarse crystalline dolomite		0.6035	0.0974	0.2392	3.437	-4.526	0.708297
Tiandong 74	4141.18	Residual grain powder-fine crystalline dolomite		0.8698	0.0705	0.1704	2.337	-5.401	0.706599
Huanglong 5	4396.54	Mesocrystalline dolomite		0.1998	0.078	0.1587	3.184	-6.611	0.708392
Maoba 3	19-35/41	Residual maerl coarse crystalline dolomite		1.8	0.08	0.26	2.535	-4.044	0.706755
Tiandong 10	3782.55	Fragmentation residual powder-fine crystalline dolomite	Tectonic fragmentation dolomite	1.441	0.0952	0.3072	3.211	-5.525	0.706013
Puguang 6	6-24/96	Fragmentation dissolved pore fine mesocrystalline dolomite		2	0.05	0.1	2.61	-4.473	0.707488
Puguang 6	7-67/147	Fragmentation residual fine mesocrystalline dolomite		1.9	0.05	0.12	2.021	-4.001	0.708821
Huanglong 1	2-35	Calcite	Filling calcite	0.1691	0.0325	0.5715	2.687	-7.289	0.70994
Tiandong 002-3	4396.69	Calcite		0.6693	0.0147	0.6567	-0.513	-6.942	0.708721

Table 3 The content of Fe, Mn, Sr and the composition characteristics of C, O, and Sr isotopes of each diagenetic stage of the Changxing Formation dolomites

Genetic classification of carbonate rocks	Trace elements				Carbon and oxygen isotopes (PDB)			Strontium isotope	
	Total number of samples	ω(Fe) ‰	ω(Mn) ‰	ω(Sr) ‰	Total number of samples	$\delta^{13}C$, ‰	$\delta^{18}O$, ‰	Total number of samples	$^{87}Sr/^{86}Sr$ ratio
Ordinary marine mud-micrite	6	1.28	0.043	0.785	6	2.923	-5.218	6	0.7094
Penecontemporaneous dolomite	2	4.90	0.261	0.169	2	1.98	-4.045	2	0.7093
Early diagenetic stage dolomite	12	6.09	0.190	0.273	12	2.776	-5.017	11	0.7085
Middle diagenetic stage dolomite	13	1.32	0.101	0.288	13	2.760	-5.546	10	0.7083
Late diagenetic stage dolomite	8	0.95	0.104	0.203	8	2.505	-5.793	8	0.7078
Structural fragmentation dolomite	3	1.78	0.065	0.176	3	2.614	-4.666	3	0.7074
Late diagenetic stage filling calcite	2	0.42	0.024	0.614	2	1.087	-7.116	2	0.7093

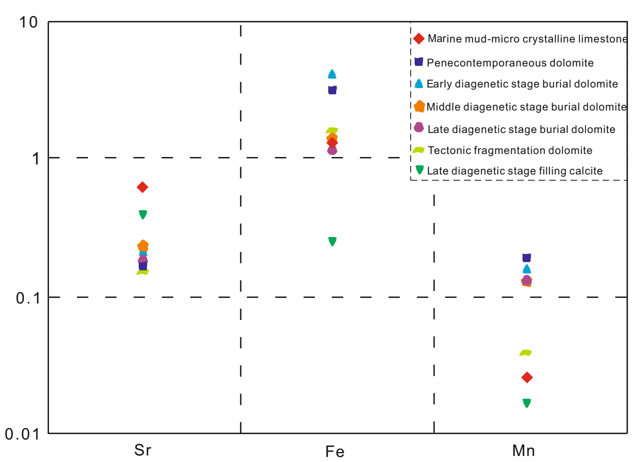

Fig. 5 Cross plots of Sr, Fe and Mn contents in the Changxing Formation

4.2 Geochemical characteristics of carbon and oxygen isotopes

The carbon and oxygen isotopic compositions of the samples have the following characteristics.

The $\delta^{13}C$ (PDB) values are all in the corresponding period global ancient seawater variation range. Compared with normal marine mud–microcrystalline limestone (2.923‰) and penecontemporaneous dolomite (1.98‰), the $\delta^{13}C$ (PDB) average of burial dolomites and tectonic uplift dolomites is between them, with small variation range and high value (2.505‰-2.776‰). It proved that this type is the product of diffusion burial dolomitization of normal marine sediments.

The $\delta^{18}O$ value variation range is -7.12‰ – -4.04‰, generally consistent with the data from Veizer and other scholars that the $\delta^{18}O$ (PDB) value of the late Paleozoic

(Changxing Formation sedimentary period) global ancient seawater ranges in -7.5‰ – -3.5‰. In Fig. 6, the $\delta^{18}O$ of carbonate rocks has a trend that with the diagenetic intensity increasing, the negative bias values increase. The penecontemporaneous dolomite has the lowest negative bias value, with an average of -4.045‰. The late stage calcite has the highest negative bias value, with an average of -7.116‰. The other types of diagenetic dolomites fall in between them, indicating burial metasomatism characteristics. According to the isotopic fractionation principle, the isotopic evaporation made the relatively light isotopic water evaporate, and the relatively heavy isotopic water remained in the evaporation water. This isotope fractionation dynamic process ultimately made the stable isotope in evaporation sea water more positive than that in normal sea water. Therefore the oxygen stable isotope values of penecontemporaneous dolomite should be more positive than those of the sea cements and burial dolomite.

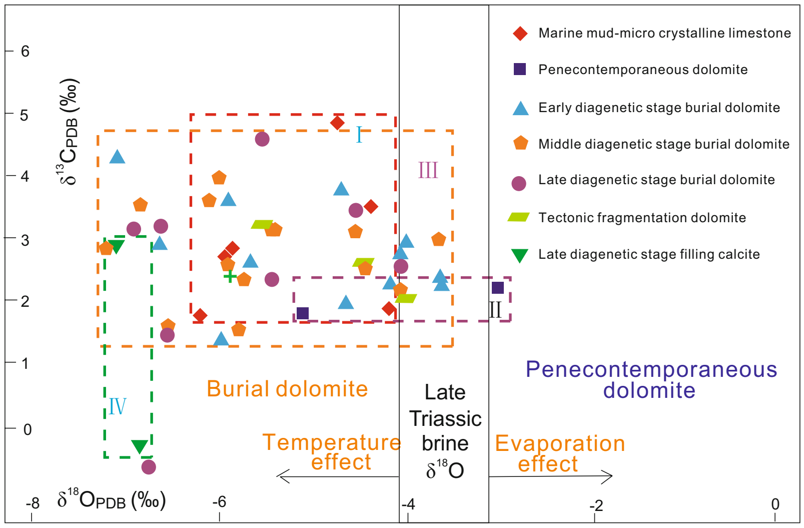

Fig. 6 The $\delta^{13}C$-$\delta^{18}O$ plot for different carbonate rocks and cements of the Changxing Formation in the eastern Sichuan Basin. Ⅰ Marine facies mud-microcrystalline limestone; Ⅱ Penecontemporaneous dolomite; Ⅲ Burial dolomite; Ⅳ Late period filling calcite

A number of foreign studies, divided burial dolomitization into two stages, the relatively low temperature early stage and the relatively high temperature late stage (Anderson and Arthur, 1983). The statistical results from Allan and Wiggins (1993) further showed that the $\delta^{18}O$ (PDB) of early low-temperature dolomite was distributed between -6.5‰ and -9.0‰, and that of the late high-temperature dolomite was between -2.5‰ and -16.0‰. The former overlapped in the latter. Because with the diagenetic intensity increasing, the negative bias values of the oxygen isotope composition of carbonate rocks in the Changxing Formation increase, the burial dolomitization of early-middle diagenetic stage occurred in relatively low temperature fluid, and the dolomite recrystallization and tectonic fragmentation of middle-late diagenetic stage occurred in relatively high temperature fluid.

4.3 Geochemical characteristics and comparison of strontium isotope

Table 2 and Table 3 list the structure type and analysis results of strontium isotopes from 42 samples. The strontium isotope ratio in alteration carbonate minerals primarily depends on the $^{87}Sr/^{86}Sr$ ratio in the diagenetic fluid, so the strontium isotope ratio of the Changxing Formation dolomite in the study area has the following important features.

The ordinary marine limestone in the study area has a high $^{87}Sr/^{86}Sr$ ratio (Fig. 7), 0.7088-0.7108, and the average is 0.7094, higher than that of global late Permian (ranging 0.7068-0.7079, averaging 0.7075) established by Veizer et al (1999) and that of the same period marine carbonate rocks in the Yangtze platform area (ranging 0.7066-0.7077, averaging 0.7071) established by Huang (1997). This is because in the last stage of the late Permian the eastern Sichuan Basin platform margin experienced a large regressive event, and due to strong erosion, a large amount of terrestrial strontium was added to sea water. Penecontemporaneous dolomite inherited similar $^{87}Sr/^{86}Sr$ ratio, and a lot of ^{87}Sr-rich marine source water was trapped in the formation, which means the study area has high $^{87}Sr/^{86}Sr$ values.

The dolomite Sr isotope characteristics of different diagenetic stages vary. The penecontemporaneous dolomite $^{87}Sr/^{86}Sr$ value (average 0.7093) was higher than that of the diagenetic stage burial dolomite, and was the highest in all samples. This can be explained by the same reason why the $^{87}Sr/^{86}Sr$ ratio of penecontemporaneous dolomite caused by brine metasomatism was higher than that of the corresponding period normal marine sediment in the Abu Dhabi sabkha environment. The value is close to the marine mud–microcrystalline limestone in the Changxing Formation (average 0.7094), illustrating that the two fluids have a close relationship.

The $^{87}Sr/^{86}Sr$ ratio of the late dissolved vugs and crack filling calcite is lower than that of the marine mud–microcrystalline limestone and penecontemporaneous dolomite while higher than that of the diagenetic dolomite.

This is because the lower Triassic Feixianguan Formation ^{87}Sr-rich sea source water and the ^{87}Sr-poor hydrothermal fluid from deep strata intermingled.

The diagenetic dolomites in the Changxing and Feixianguan formations have similar ^{87}Sr/^{86}Sr ratio distribution and evolution (Table 4). This shows that the burial dolomitization fluids of the Changxing and Feixianguan formations have similar properties, and provides the basis for determining that the Changxing Formation dolomitization fluids in the study area were derived from the overlying lower Triassic Feixianguan Formation sealed penecontemporaneous sea source pore water with high Mg and Sr contents and high salinity. The fluid migrated downward and mixed with the ^{87}Sr-rich sea water in the Changxing Formation, and then dolomitization occurred to the surrounding rocks, resulting in the Changxing Formation dolomite having higher ^{87}Sr/^{86}Sr ratio than the Feixianguan Formation. With the decrease of ^{87}Sr in the early dolomitization process, the greater the diagenesis strength, the lower the ^{87}Sr/^{86}Sr ratio of burial dolomite (Table 3, Fig. 7).

Table 4 Comparison of ^{87}Sr/^{86}Sr ratios in the Changxing Formation and Feixianguan Formation

Genetic classification of carbonate rocks	^{87}Sr/^{86}Sr of Changxing Formation			^{87}Sr/^{86}Sr of Feixianguan Formation		
	Sample number	Variation range	Average	Sample number	Variation range	Average
Ordinary marine mud-micrite	6	0.7088-0.7108	0.7094	11	0.7064-0.7075	0.7073
Penecontemporaneous dolomite	2	0.7091-0.7095	0.7093	2	0.7068-0.7093	0.7080
Early diagenetic stage dolomite	11	0.7070-0.7093	0.7085	5	0.7070-0.7085	0.7079
Middle diagenetic stage dolomite	10	0.7067-0.7097	0.7083	10	0.7066-0.7089	0.7075
Late diagenetic stage dolomite	8	0.7068-0.7088	0.7078	4	0.7068-0.7076	0.7073
Structural fragmentation dolomite	3	0.7060-0.7088	0.7074	3	0.7069-0.7075	0.7073
Late diagenetic stage filling calcite	2	0.7087-0.7099	0.7093	11	0.7077-0.7087	0.7081

The burial dolomite ^{87}Sr/^{86}Sr ratios of different diagenetic stages have a slight difference. The variation range of early diagenetic dolomite ^{87}Sr/^{86}Sr ratio is large (0.7070-0.7093), and the average is 0.7085. The variation range of medium diagenetic dolomite ^{87}Sr/^{86}Sr ratio is larger (0.7067-0.7097), and the average is 0.7083, close to that of early diagenetic dolomite (Fig. 4). The variation range of late diagenetic dolomite ^{87}Sr/^{86}Sr ratio is the smallest (0.7068-0.7088), and the average is also small (0.7078). This is because the ^{87}Sr consumption increased in the early dolomitization process, and the concentration of ^{87}Sr in fluid gradually decreased, thus showing the variation tendency that with the diagenetic strength increasing, the ^{87}Sr/^{86}Sr ratio of burial dolomite decreased (Table 3, Fig. 7).

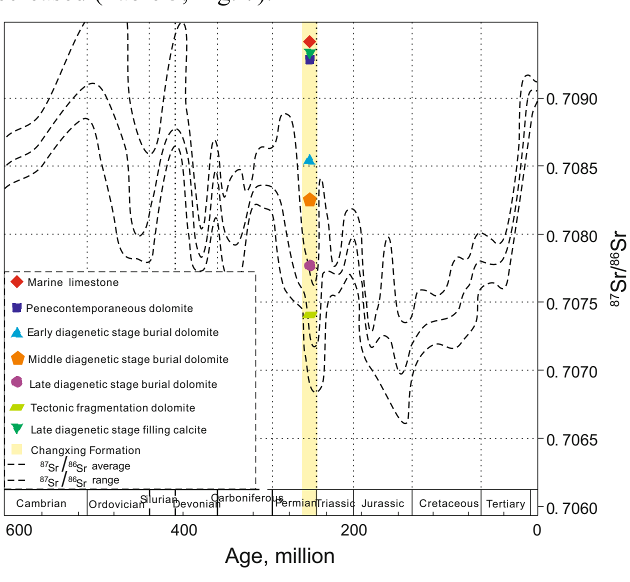

Fig. 7 ^{87}Sr/^{86}Sr ratio distribution of carbonate rocks in the Changxing Formation

5 Diagenetic system in the Changxing Formation

5.1 Diagenetic system division

The Changxing Formation dolomite in the eastern Sichuan Basin is divided into four relatively independent and successive evolving diagenetic systems: (1) syngenesis brine diagenetic system of the penecontemporaneous stage; (2) strata seal brine diagenetic system of the early diagenetic stage; (3) mixed hot brine diagenetic system of the middle-late diagenetic stage and (4) mixed hydrothermal diagenetic system of the tectonic uplift stage. Each system has its own independent diagenetic fluid sources and fluid properties, physical-chemical environment and water-rock interaction sequences, and the corresponding diagenetic combination.

5.2 Fluid properties and diagenetic evolution rules of each diagenetic system

Different diagenetic stages have different fluid properties and different diagenetic systems have different diagenetic features, diagenetic product characteristics, fluid properties and the ancient hydrological conditions, which correspond to various dolomites with different genesises.

5.2.1 The syngenesis brine diagenetic system of the penecontemporaneous stage

The penecontemporaneous stage dolomitization in the Changxing Formation occurred in a near-surface syngenetic evaporation concentrated high salinity sea source pore water diagenetic system, that is, under dry and hot climatic conditions, it developed on the top of reef and shoal or the barrier protection lagoon-tidal flat environments. This is penecontemporaneous dolomitization caused by the evaporation-concentrated high magnesium brine metasomatizing limestone. The dolomitization fluid and diagenetic environments have syngenetic origins and low temperature and high salinity, and the main products are gypsum and halite mud–microcrystalline dolomite, similar to the extremely dry and hot conditions of the modern Abu Dhabi sabkha and penecontemporaneous dolomitization environment (Müller et al, 1990).

5.2.2 The strata seal brine diagenetic system of early diagenetic stage

The early diagenetic stage dolomitization in the Changxing Formation occurred in a shallow burial strata seal brine diagenetic system. The main products of the diagenetic system are gray powder–fine crystalline particles with well-preserved primary structure or biological reef dolomite and particles due to slight dissolution. The dolomitization fluid is derived from the high salinity sea source pore brine, and the evidence is as follows.

1) The geochemical characteristics of iron, manganese, strontium trace elements and carbon, oxygen, strontium isotopes are similar to those of the penecontemporaneous dolomite (Zheng et al, 2007).

2) The strontium isotope characteristics are between the penecontemporaneous dolomite in the Feixianguan Formation and the diagenetic burial dolomite, but are different from the penecontemporaneous dolomite in the Changxing Formation, showing that the early diagenetic stage dolomitization fluid was related to the Feixianguan penecontemporaneous dolomite and burial dolomite, and the Feixianguan burial dolomitization fluid has been shown to be derived from the fourth member of the Feixianguan Formation trapped sea source high salinity pore brine (Zheng et al, 2007).

5.2.3 The mixed hot brine diagenetic system of middle-late diagenetic stage

The middle-late diagenetic stage of the Changxing Formation belongs to the pressure release mixed hot brine diagenesis system under the deep burial environment. In the middle diagenetic stage dissolution and burial recrystallization, euhedral powder–fine crystalline dolomite with residual primary particles or biological reef structure, and medium-coarse crystalline dolomite formed. In the late diagenetic stage strong recrystallization and dissolution, medium-coarse crystalline dolomite with almost no residual primary structure formed, and dissolved pores were often filled with calcite, authigenic quartz, unusual shape dolomite and asphalt. The dolomitization fluid was still mainly derived from the high salinity sea source pore water released in the deeply buried environment of the Feixianguan Formation, and some ^{87}Sr-deficient hydrothermal fluid released from deep strata, so it was mixed hot brine. The evidence is as follows.

1) The $^{87}Sr/^{86}Sr$ ratio of the late dissolved vugs and crack filling calcite is lower than that of the marine mud–microcrystalline limestone and penecontemporaneous dolomite while higher than that of the diagenetic dolomite. It is shown that as well as from the high salinity sea source pore water, the dolomitization fluid also had another deep hydrothermal source. Their interaction caused the decrease of the $^{87}Sr/^{86}Sr$ ratio.

2) Accompanied by the dolomitization and dissolution in this stage, secondary quartz precipitation began to occur in the dissolved pores and vugs. It also confirmed the existence of another silica-rich hydrothermal fluid, that is, from a deep hydrothermal source.

3) The dissolved pores, vugs and cracks were generally filled with carbonized asphalt, showing that the spaces had once been filled with liquid hydrocarbon. It can also be used for proving that in the oil and gas migration period deep hydrothermal fluid participated in the diagenesis.

5.2.4 The mixed hydrothermal diagenetic system of tectonic uplift stage

The tectonic uplift and fault activity of the Changxing Formation occurred in the late period of the early Himalayan. Folding and faulting caused widespread fragmentation of dolomite, and made SO_4^{2-}-rich hydrocarbon fluid continuously move along the dissolved holes, vugs, cracks and fractures of the fragmented dolomite. This is mixed hydrothermal diagenesis system with deep discharge and transport along the cracks. Hydrocarbon and SO_4^{2-} have thermochemical sulfate reduction (TSR) reaction. On one hand hydrocarbon in gas reservoirs and SO_4^{2-} in fluid were consumed, on the other hand large amounts of acid gas H_2S and CO_2 were produced, forming a high efficiency gas reservoir with high contents of H_2S and CO_2 in the Changxing Formation. The diagenetic system can be divided into strong recrystallization, dissolution and the most important tectonic fragmentation. The primary rock structure completely disappeared, filled with unusual shape dolomite due to mixed hydrothermal action and a small amount of authigenic quartz and carbonized asphalt, usually developing tectonic fractures.

5.3 The control of diagenetic system on the reservoirs

Through analysis of the carbonate reservoir space and different reservoir characteristics and distribution of the Changxing Formation, it is shown that the contribution of different diagenetic systems to the Changxing reservoir development has a big difference (Fig. 8, Table 5). The reservoir quality is the result of multi-stage overlaying of different diagenetic systems. Not all facies belt development areas experienced the four diagenetic systems, for example, inland ocean trough facies did not experience diagenesis, front slow slope belt, restricted platform and open platform facies experienced two or three stages. Only the platform edge reef, shoal facies belt and fracture zones experienced four diagenetic systems.

The syngenesis brine diagenetic system of the penecontemporaneous diagenetic stage mainly has compaction and cementation. Most primary intergranular and intragranular pores were filled in the penecontemporaneous period and the pores were not well developed. For example, the mud–microcrystalline limestone and the microcrystalline dolomite were very compacted, and the porosity is extremely low. The porosity of microcrystalline dolomite ranges from 0.92% to 6.46%, and the average is 1.76%, so it generally does not have reservoir significance.

In the strata seal brine diagenetic system of the early diagenetic stage, due to compaction, pressure solution and further cementation, most primary pores were completely destroyed. However, the wide range of burial dolomitization and recrystallization was in favor of the development of intragranular pores. For example, the porosities of weak dolomitization calcareous dolomite and crystalline dolomite are favorable. The former ranges from 0.46% to 12.52%, averaging 3.06%, and the latter ranges from 0.53% to 14.33%, averaging 4.41%. These have the diagenetic evolution characteristics that the burial dolomitization intensity increasing is gradually beneficial for the reservoir development.

In the mixed hot brine diagenetic system of the middle-late diagenetic stage, the burial dolomitization,

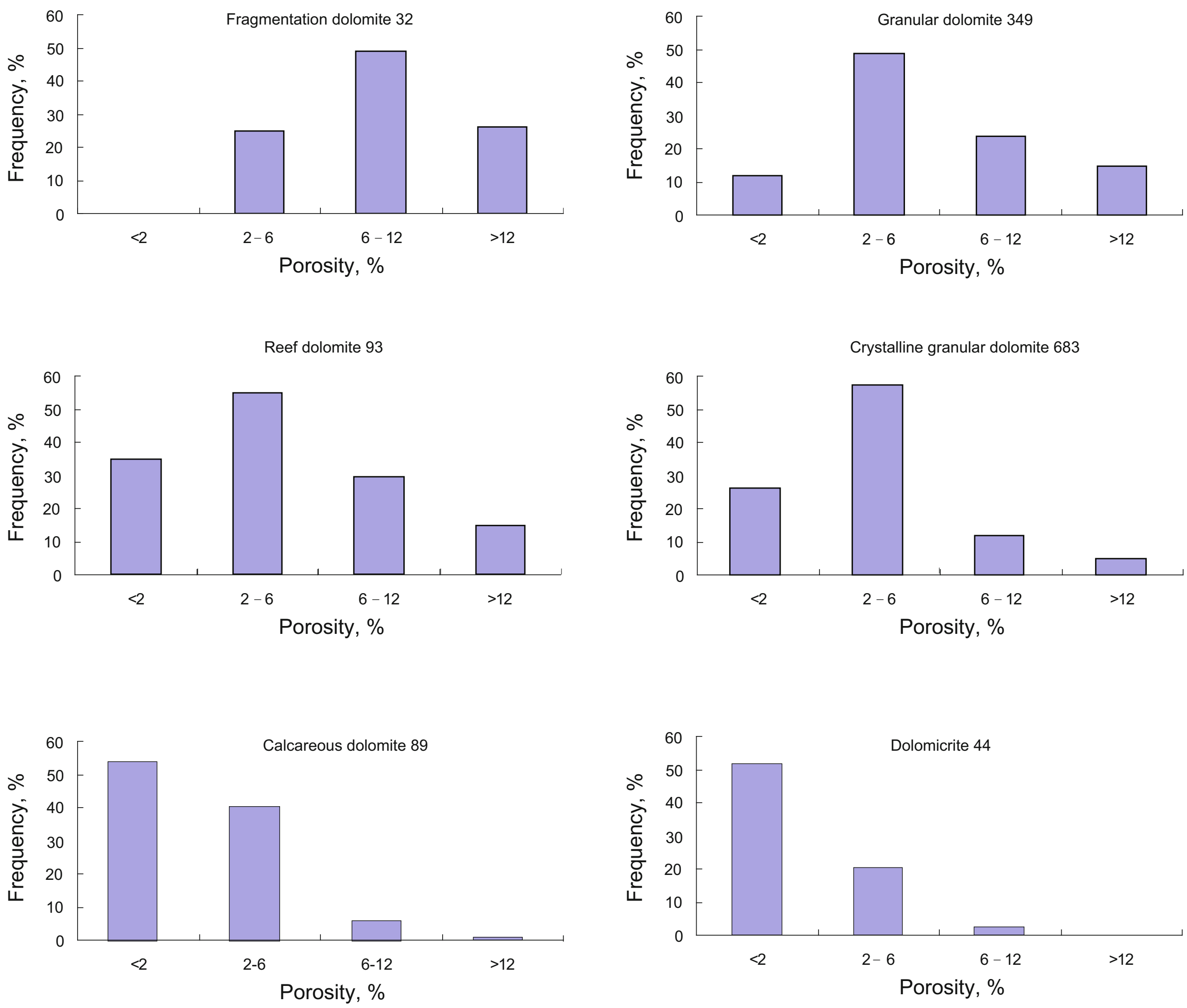

Fig. 8 Histogram of porosity distribution of the Changxing Formation in the eastern Sichuan Basin

recrystallization and pressure solution were strong, and played an extremely important role in reservoir creation. Granular dolomite and biological reef dolomite with almost no remaining primary structure formed. The former porosity is high, ranges from 1.65% to 18.92%, averaging 8.82%, and the latter ranges from 1.06% to 16.95%, averaging 6.56%. In the late diagenetic stage, some early formed pores were filled with anhydrite, celestite, silica and other secondary minerals, so that the physical properties got worse. The reservoir is mainly pore-vug type.

The tectonic stage mixed hydrothermal diagenetic system mainly had the regional tectonic uplift in the early Himalayan. Fracturing and dissolution were strong, increasing the primary pores and vugs. The fractures were seldom filled with secondary minerals, and were charged with oil and gas in a short time, so they are effective fractures. The developed fractures have a significant influence in improving reservoir properties. Finally pore-vug-fracture type reservoirs were formed. The porosity of fractured dolomite ranges from 3.20% to 19.7%, averaging 12.3%. It is the best lithology for reservoir development, and has the largest contribution to the Changxing Formation reservoirs.

Therefore, burial dolomitization of the strata seal brine diagenetic system is the basis for the reservoir development, and pore type reservoirs developed. The burial dolomitization of mixed hot brine diagenesis system expanded the reservoir distribution and improved the reservoir quality, and pore-vug type reservoir developed. The cataclasis and dissolution of the mixed hydrothermal diagenetic system is the key to improving the quality of reservoirs and developing pore-vug-fracture type reservoirs.

Table 5 Diagenetic system classification and evaluation of carbonate reservoir of the Changxing Formation in the eastern Sichuan Basin

Diagenetic system type	Syngenesis brine	Strata seal brine	Mixed hot brine	Mixed hydrothermal
Main lithology	Dolomicrite	Calcareous dolomite, crystalline granular dolomite	Granular dolomite, reef dolomite	Fragmentation dolomite
Pore-throat combination	Micro porous–micro throat	Holes—fine throat	Mesopore—fine throat	Mesopore and macropore—fine throat
Pore type	Crack	Dissolved pore, intercrystal pore, casting membrane pore	Dissolved pore, dissolved hole, intercrystal pore	Dissolved pore, dissolved hole, crack
Representative types of sedimentary facies	Restricted platform	Platform margin shoals, open platform	Platform margin biological reef and shoal	Platform margin biological reef and shoal overlap
Property comprehensive evaluation	Very low porosity, very low permeability reservoir (<2, <0.1)	Low porosity, low permeability reservoir (2-6, 0.1-1)	Medium porosity, medium permeability reservoir (6-12, 1-10)	Medium and high porosity, medium and high permeability reservoir (>12, >10)
Reservoir types	Fractured reservoir	Pore reservoir	Pore-vug reservoir	Pore-fracture complex reservoir

6 Conclusions

1) The main reservoir rocks of the Sichuan Basin Changxing Formation reservoirs are granular dolomite, reef dolomite and intercrytalline dolomite. The main destructive effect is compaction, pressure solution and cementation. The main construction effect is burial dolomitization, recrystallization and dissolution. The more thorough the burial dolomitization of the early and medium-late diagenetic stage, the better the developed dolomite porosity and permeability and the more favorable the reservoir development.

2) The main diagenetic systems and modes which are closely related with reservoir development are: burial dolomitization and recrystallization of early diagenetic sealed brine diagenetic system, burial dolomitization, dissolution and recrystallization of medium-late diagenetic mixed hot brine diagenetic system and tectonic fracturing and dissolution of tectonic stage mixed hydrothermal diagenetic system.

3) According to the time-space relationship of the diagenetic system and reservoirs, the controlling factors and distribution of the Changxing Formation high quality reef flat dolomite reservoirs can be demonstrated as follows. Reef shoal facies belts controlled regional reservoir distribution and the scale of development. Burial dolomitization of the strata seal brine diagenetic system is the foundation of reservoir development, mainly developing pore reservoirs. Burial dolomitization of mixed hot brine diagenetic system expanded the reservoir distribution and improved the reservoir quality, mainly developing pore-vug reservoirs. Fracturing and dissolution of a mixed hydrothermal fluid diagenetic system is the key to improving the reservoir quality, mainly developing pore-vug-crack complex reservoirs.

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