

文章编号: 1000-0550(2011)06-1041-07

# 塔里木盆地东部地区寒武纪海盆局限期深水准同生白云岩化作用研究

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**摘要** 塔东地区寒武纪盆地相以及斜坡相发育泥晶白云岩及泥质泥晶白云岩,具有深水环境标志。通过样品岩石学特征研究、碳、氧同位素分析、有序度分析、锶同位素比值分析以及阴极发光特征分析,提出了塔东地区海盆局限期海水咸化深水准同生白云岩化机理。海盆局限阶段水体盐度变高,使得斜坡以及海底松软碳酸盐沉积物发生白云石化形成深水环境的泥粉晶白云岩。深水准同生白云岩由泥粉晶级白云石构成、有序度值低、碳、氧同位素值高、锶同位素比值高,与潮坪准同生白云石晶体粒级相同且地球化学特征相同,但深水准同生白云岩发育于盆地相以及斜坡相,以此与潮坪准同生泥粉晶白云岩相区别。

**关键词** 泥晶白云岩 深水 盆地相 斜坡相 准同生成岩阶段 白云岩化作用

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**中图分类号** P588.24<sup>+</sup>8 **文献标识码** A

## 0 引言

白云岩成因主要是从白云岩岩石结构<sup>[1-2]</sup>、结晶有序度、阴极发光特征、地球化学分析等方面来进行研究<sup>[3-7]</sup>。塔里木盆地白云岩类型多样,经受的成岩改造作用复杂。特别是塔东地区寒武系—奥陶系白云岩成因类型较多且复杂。岩石类型有泥粉晶白云岩以及砂糖状白云岩。通常认为泥粉晶白云岩为潮坪环境准同生白云岩<sup>[8-10]</sup>,但是塔东地区岩性及沉积相综合分析表明,泥粉晶白云岩普遍发育于深水环境,即盆地相以及斜坡相。这些泥粉晶白云岩如果用潮坪蒸发泵机理来解释其成因显然不合适,因此本文在综合研究沉积相以及泥粉晶白云岩的岩石学特征、白云石结晶有序度、阴极发光特征、碳、氧、锶同位素特征等基础上,提出了海盆局限阶段海水咸化深水准同生白云岩化机理。

## 1 研究区概况

研究区位于塔里木盆地东部,面积约10万平方千米,构造单元主要有塔东低凸起、满加尔凹陷、英吉苏凹陷,南北受车尔臣大断裂及孔雀河断裂的控制<sup>[11]</sup>。塔东地区也是塔里木盆地深水相发育的主要

区域。在构造单元中,塔东低凸起带是塔东地区下古生界碳酸盐岩油气勘探最有利的地区。自海西期以来,塔东低凸起带发育成北东走向的大型正向构造单元<sup>[12,13]</sup>。目前研究区能揭示寒武纪—奥陶纪碳酸盐岩特征的钻井共有6口井,都分布于塔东低凸起带上(图1),不同程度地揭示了塔东地区白云岩发育的情况。

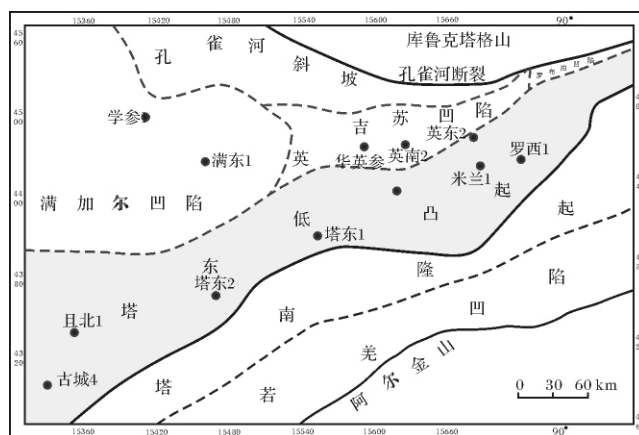


图1 塔东低凸起带构造单元及沉积单元

Fig. 1 Tectonic and sedimentary units in the eastern Tarim Basin

塔东沉积相类型较齐全,古城地区以及罗布泊地

区为碳酸盐岩缓坡逐渐发育而来的镶边台地,发育台地边缘、开阔台地、潮坪、斜坡等相类型,塔东1井、塔东2井为继承性发育的盆地相,米兰1井、英东2井一带也为盆地相逐渐发育为斜坡相。白云岩在不同相带发育状况差异较大。

## 2 研究区白云岩特征

本论文所重点研究的深水泥粉晶白云岩主要分布在斜坡相和盆地相。斜坡相的泥粉晶白云岩成薄层状分布于块状砂糖状白云岩中,而最典型的深水环境泥晶白云岩分布于盆地相<sup>[14]</sup>。

深水盆地泥晶白云岩厚度小,而且通常呈硅质白云岩或者白云质硅岩以及白云质泥岩出现。图2为塔东地区中下寒武统东西向沉积相横向对比,可见在深水盆地相的厚层泥岩、硅质岩中普遍发育薄层状的泥晶白云岩。

盆地相岩石学特征如图3,硅质岩及硅质页岩是主要的岩石类型。图3(A、C、D)为盆地相岩石类型的微观特征,均以暗色为主,而且发育深水化石,如放射虫。图3(B)为深水准同生泥晶白云岩的微观特征,晶粒细小,富含泥质及硅质。图3(E、F)为深水泥晶白云岩与硅质岩宏观特征,白云岩呈夹层状分布于硅质岩中。

征,晶粒细小,富含泥质及硅质。图3(E、F)为深水泥晶白云岩与硅质岩宏观特征,白云岩呈夹层状分布于硅质岩中。

## 3 岩石学特征

### 3.1 结构特征

深水泥粉晶白云岩晶粒细小,为泥粉晶级(图3(B)、图4(A))。图4(A)样品来自米兰1井,沉积环境分析为下斜坡相,岩性主要为泥质泥粉晶白云岩,具有纹层状。宏观上厚度小,与其伴生的主要为砂糖状白云岩,晶体粒径差距较大。该样品从岩石学上找不出任何潮坪环境的标志,例如鸟眼构造、石膏铸模孔隙、藻纹层等。

白云岩晶粒粗细是判断白云岩成因的重要标志之一<sup>[7-10]</sup>,因为晶粒粗细与水中钙、镁离子浓度和白云石结晶速度有关。钙、镁离子浓度越高,形成的白云石晶核就越多,而且结晶速度越高,晶粒也就越小。因此,晶粒粗细是盐度的反映。根据现代白云岩特征研究,泥粉晶白云岩是蒸发浓缩的海水使松软未固结的灰质沉积物发生白云石化而形成的。蒸发浓

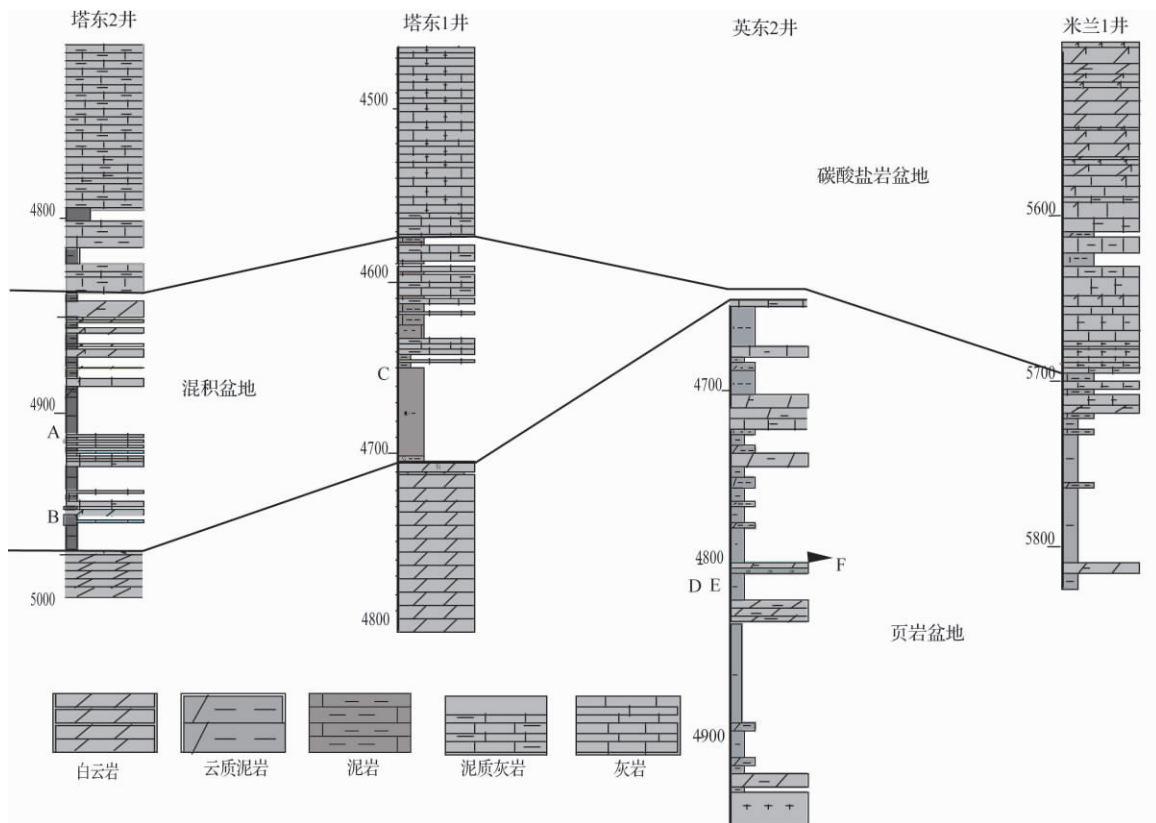


图2 塔东地区中下寒武统沉积相对比及深水泥晶白云岩分布特征

Fig. 2 Horizontal comparison diagram of basin facies of Lower-Middle Cambrian in the eastern Tarim Basin

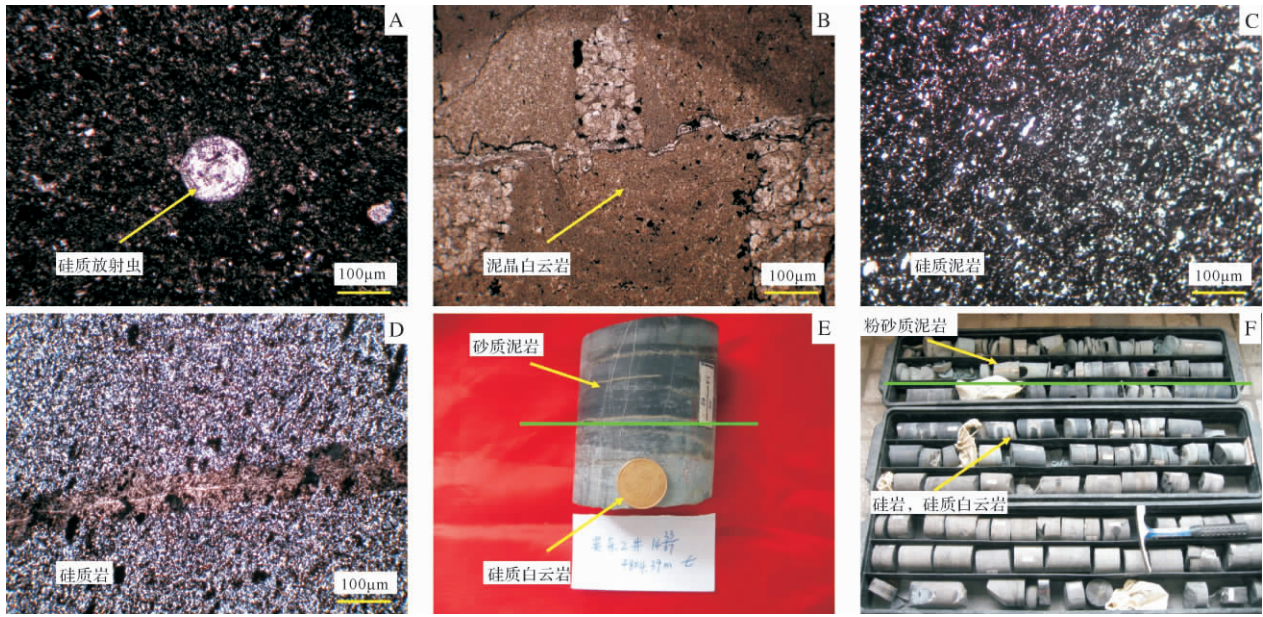


图 3 塔东地区中下寒武统盆地相岩石学特征

A. 黑色碳质硅岩,含深海放射虫,典型盆地相岩石类型,塔东 2 井,  $\epsilon_1$ , 西大山组 # 917.31 m,  $\times 10$ ; B. 泥质泥晶白云岩,深水白云岩类型,呈岩溶角砾状,塔东 2 井,  $\epsilon_1$ , 西大山组 # 970.63 m,  $\times 4$ ; C. 硅质泥岩,典型硅质盆地岩石类型,塔东 1 井,  $\epsilon_1$ , 西大山组 # 660.88 m,  $\times 10$ ; D. 含云硅岩,硅化+白云石脉,英东 2 井,  $\epsilon_2$ , 莫合尔山组 # 803.77 m,  $\times 4$ ; E. 岩性界面,砂质泥岩与硅质泥晶白云岩的界面,英东 2 井,  $\epsilon_2$ , 4804.39m; F. 下部灰黑色砂质泥晶与硅化泥晶白云岩,上部灰绿色含粉砂质泥岩,英东 2 井,  $\epsilon_2$  # 801.00 ~ 4 807.10 m

Fig. 3 Petrologic characteristics of basinal facies of lower Cambrian in the eastern Tarim Basin

A. Carboniferous silicalite, Radiolaria, typical rock of basinal facies, Well Tadong 2,  $\epsilon_1$ , Xidashan group # 917.31 m,  $\times 10$ ; B. Argillaceous dolomitic breccia, formed in deepwater environments, karst breccia, Well Tadong 2,  $\epsilon_1$ , Xidashan group # 970.63 m,  $\times 4$ ; C. Siliceous shale, formed in deepwater environments, Well Tadong 1,  $\epsilon_1$ , Moheershan Group # 803.77 m,  $\times 4$ ; D. Dolomitic siliceous rocks, silification & dolomitic gangue, Well Yingdong 2,  $\epsilon_2$ , Moheershan Group # 803.77 m,  $\times 4$ ; E. Lithologic interface, sandy mudstone & siliceous dolomitic breccia, Well Yingdong 2,  $\epsilon_2$  # 4804.39m; F. Siliceous dolomitic breccia & sandy mudstone, Well Yingdong 2,  $\epsilon_2$  # 801.00 ~ 4 807.10 m

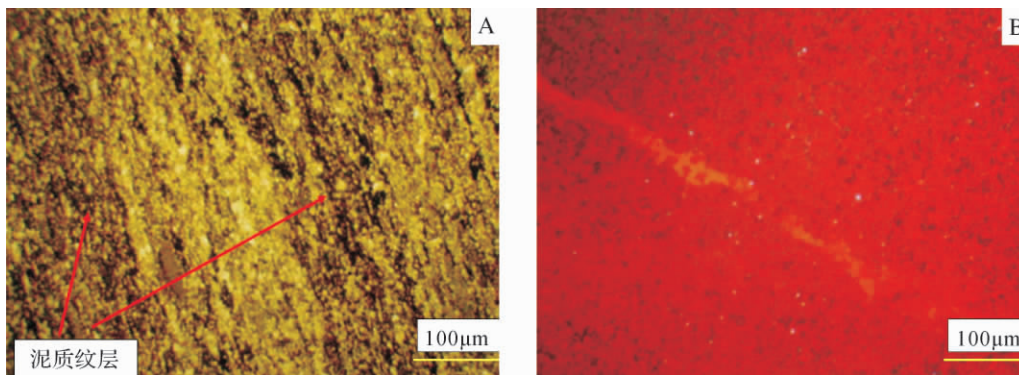


图 4 深水白云岩微观特征及阴极发光特征

A. 纹层状粉晶白云岩,米兰 1 井 # 588.53 m,  $\epsilon_1$ ,  $\times 140$  (单偏光); B. 深水准同生白云岩阴极发光特征,米兰 1 井 # 5252.49 m,  $\epsilon_1$ ,  $\times 60$

Fig. 4 Microscopic properties and cathodoluminescence features of deepwater dolomitic breccia

A. Microscopic properties of deepwater dolomitic breccia, Well Milan 1 # 588.53 m,  $\epsilon_1$ ,  $\times 140$ ;

B. Cathodoluminescence features of deepwater dolomitic breccia, Well Milan 1 # 5252.49 m,  $\epsilon_1$ ,  $\times 60$

缩的海水中钙、镁离子浓度高,同时松软的沉积物孔隙度和渗透率高,保证了孔隙流体流动通畅,及时供

应白云石化消耗的钙、镁离子。高盐度和沉积物松软是形成泥晶白云岩的两个必要条件,反过来,泥晶

晶白云岩可以反映白云化流体是浓缩的海水,而且是在准同生期发生的白云石化。英东2井、米兰1井、塔东1井、塔东2井深水准同生白云岩在斜坡相区主要为纹层状泥粉晶白云岩,与其它成因的细晶、粗晶白云岩相伴生。在盆地相发育的深水准同生白云岩主要呈夹层状分布于混积盆地中。泥粉晶白云岩与深水沉积相伴生,这一点与潮坪环境的准同生泥—粉晶白云岩相区别<sup>[15]</sup>。

### 3.2 阴极发光特征

塔东地区的泥粉晶白云岩普遍呈灰黑色、深灰色等还原色,而且其黄铁矿含量较高,呈结核、条带状出现,也反映强还原环境。根据岩相古地理研究,塔东地区在寒武纪和奥陶纪为深水盆地。此外,与潮坪准同生白云岩不同,本区深水准同生白云石的阴极发光普遍呈暗红色(图4(B)),反映 $Mn^{2+}$ 和 $Fe^{2+}$ 含量较高<sup>[14]</sup>。 $Fe$ 和 $Mn$ 作为类质同象离子置换白云石晶格中钙、镁离子的主要是低价离子,因此,只有在还原环境中生成的白云石,才可能具有较高的 $Fe^{2+}$ 、 $Mn^{2+}$ 含量<sup>[14]</sup>。所以,这也表明这类白云岩是在较深的还原性海底形成的。

### 3.3 有序度

白云石有序度是其结晶程度好坏的标志,与白云石结晶速度密切相关,而结晶速度与海水盐度有关<sup>[16]</sup>。在同生和准同生成岩环境中,沉积物松软,孔隙度和渗透率都很高,孔隙水能自由流动,当水溶液盐度高、 $CO_3^{2-}$ 、 $Mg^{2+}$ 、 $Ca^{2+}$ 等离子浓度高时,白云石的结晶速度较快,形成的白云石具有低的有序度。

本次研究区泥粉晶白云岩样品主要取自于米兰

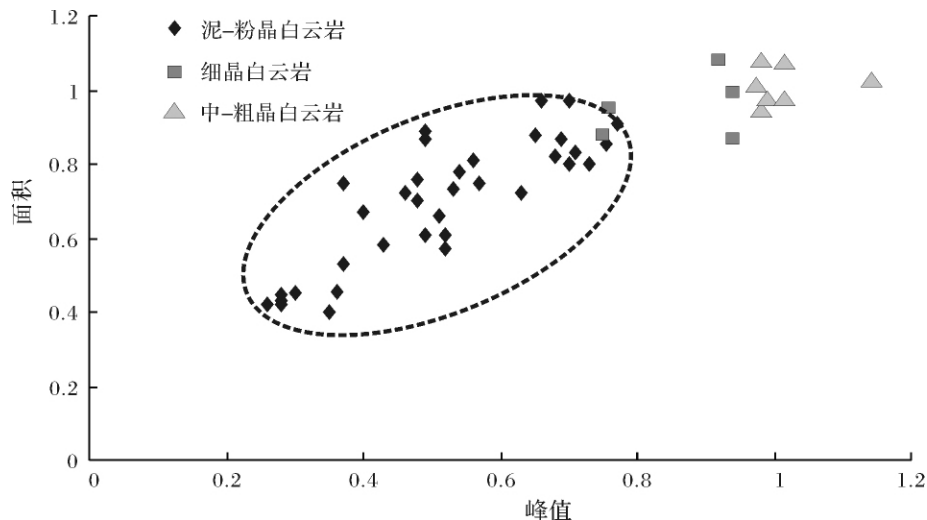


图5 塔东地区白云岩不同粒度白云岩有序度分布

Fig. 5 Distribution scatter of degree of order of dolomite in the eastern Tarim Basin

1井、英东2井、塔东1井、塔东2井混积盆地相泥粉晶白云岩,另外细晶白云岩及中粗晶白云岩样品也取自相邻的岩芯段。根据本区68个白云岩样品统计分析,塔东地区泥粉晶白云岩有序度明显偏低,峰高分布范围0.26~0.9,平均值0.5573,峰面积分布范围0.4~1.33,平均值0.7498(表1)。

表1 塔东地区白云岩有序度分布范围及平均值

Table 1 Distribution range and average of degree of order of dolomite in the eastern Tarim Basin

岩性	样品数	峰高		峰面积	
		分布范围	平均值	分布范围	平均值
泥粉晶白云岩	48	0.26 ~ 1.01	0.5573	0.4 ~ 1.33	0.7498
细中晶白云岩	17	0.57 ~ 1.14	0.8676	0.61 ~ 1.09	0.9488

图5为不同粒径白云岩有序度值分布图,准同生泥粉晶白云岩有序度值小,离散度大。有序度普遍低反映这类准同生白云岩是咸化海水在准同生阶段白云化石形成的。

## 4 地球化学特征

### 4.1 碳、氧同位素

深水准同生泥粉晶白云岩碳、氧同位素呈高值。碳、氧同位素组成也表明,泥粉晶白云岩是浓缩海水白云化形成的。塔东地区的泥粉晶白云岩的 $\delta^{13}C$ 及 $\delta^{18}O$ 值普遍比细晶、中粗晶白云岩的高。表2为塔东地区不同粒径白云岩碳、氧同位素值的分布范围及其平均值。泥—粉晶白云岩的 $\delta^{13}C$ 值分布范围为0~2.5‰(PDB),平均值为1.2‰,基本上都为正值。



表 2 塔东地区碳、氧同位素分布范围及平均值

Table 2 Distribution range and average of  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$  of dolomite in the eastern Tarim Basin

白云岩类型	井号(样品数)	碳、氧同位素			
		$\delta^{13}\text{C}/\text{‰}$	均值	$\delta^{18}\text{O}/\text{‰}$	均值
泥粉晶白云岩	YD-2(22); ML-1(33)	0 ~ 2.5	1.2	-8 ~ -2.5	-5.8
细晶白云岩	YD-2(6); ML-1(15); GC-4(1)	-0.7 ~ 1.6	-0.4	-9.9 ~ -7.5	-8.8
中粗晶白云岩	YD-2(1); ML-1(23); GC-4(6)	-0.8 ~ 1.7	-0.6	-10.1 ~ -16.2	-12.1

$\delta^{18}\text{O}$  值分布范围  $-8\text{‰} \sim -2.5\text{‰}$  (PDB), 平均值为  $-5.8\text{‰}$  (PDB), 相对于细—中晶及粗晶白云岩的碳氧同位素值要偏正。

图 6 为米兰 1 井和塔东地区白云岩按照不同晶径统计的  $\delta^{13}\text{C}$  及  $\delta^{18}\text{O}$  值分布, 泥粉晶白云岩的同位素值均偏正。

#### 4.2 锶同位素比值

表 3 为泥粉晶白云岩及细、中晶白云岩  $^{87}\text{Sr}/^{86}\text{Sr}$  值分布范围及平均值。泥粉晶白云岩的  $^{87}\text{Sr}/^{86}\text{Sr}$  分布范围为  $0.70892 \sim 0.71331$ , 平均值为  $0.71064$ , 比细、中晶白云岩  $^{87}\text{Sr}/^{86}\text{Sr}$  值明显偏高。这也反映形成泥粉晶白云岩的水体盐度较高。

表 3 不同粒度白云岩  $^{87}\text{Sr}/^{86}\text{Sr}$  值分布范围及平均值

Table 3 Distribution range and average of  $^{87}\text{Sr}/^{86}\text{Sr}$  of dolomite with different crystal diameter

岩性(样品数)	$^{87}\text{Sr}/^{86}\text{Sr}$ 分布范围	平均值
泥粉晶白云岩(14)	0.70892 ~ 0.71331	0.71064
细—中晶白云岩(5)	0.70922 ~ 0.71021	0.70934

阶段, 海水蒸发导致盐度升高, 使得位于斜坡和盆地的松软沉积物发生白云岩化形成深水准同生白云岩。

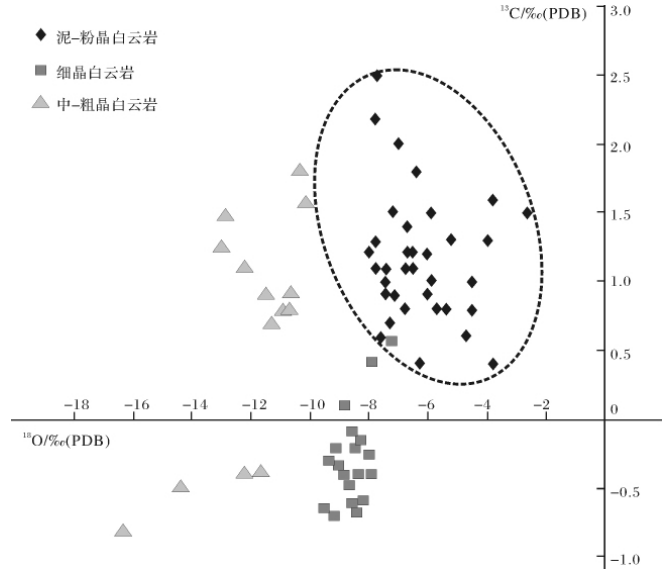


图 6 塔东地区不同粒径白云岩的碳、氧同位素分布

Fig. 6 Distribution of  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$  value of dolomite with different crystal diameter in the eastern Tarim Basin

### 5 深水准同生白云岩化机理

深水泥粉晶白云岩成因模式如图 7。海盆局限

白云岩化作用主要取决于两方面: 一是  $\text{Mg}^{2+}$  的来源; 二是动力学机制。浓缩的海水是  $\text{Mg}^{2+}$  离子的

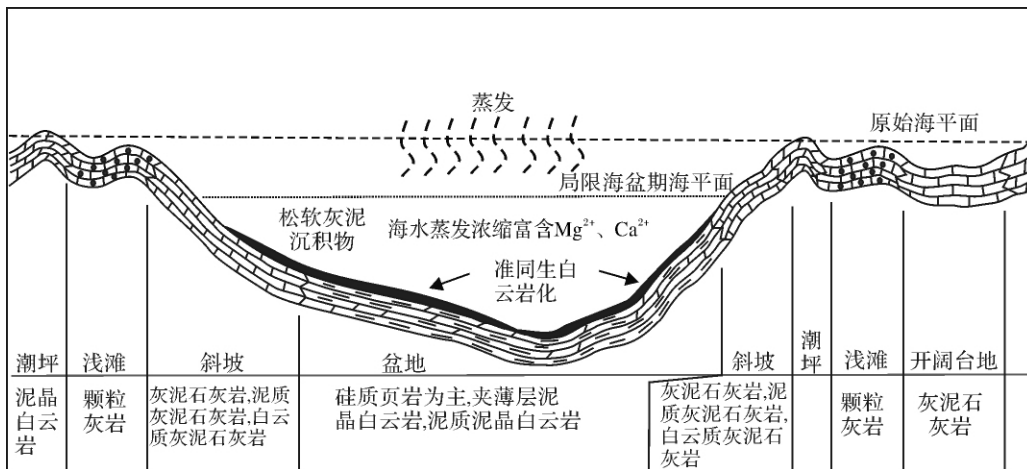


图 7 塔东地区深水准同生白云岩化模式图

Fig. 7 Mode of deepwater pencontemporaneous dolomitisation in the eastern Tarim Basin

主要来源。当海盆局限时,海水蒸发,盐度变高,海水稍加浓缩就会成为白云岩化的有效流体<sup>[10]</sup>。当海底松软的灰泥沉积物还未固结成岩时比较疏松,具有较高的孔隙度和渗透率。只要海水水体能够进入并保证一定的时间,这种快速的准同生白云化作用就能发生。海水浓缩时,盆地底部的热量加剧海水的循环流动,在流动的过程中,高盐度的海水在疏松的灰泥沉积物中通过保证了准同生白云化作用的发生。

## 6 结论

(1) 塔东地区寒武纪—奥陶纪混积盆地相以及斜坡相海盆局限期发育深水准同生白云岩,岩性主要为泥晶白云岩以及泥质泥晶白云岩,厚度不大,呈夹层状分布于页岩、页岩—硅岩中。

(2) 深水准同生白云岩晶体粒级和潮坪准同生白云岩一样,为泥粉晶白云岩;地化特征相同,具有低有序度、高碳氧同位素值、高锶同位素比值等,但是不具潮坪环境标志,如鸟眼构造、石膏铸模孔隙、藻纹层等。

(3) 海盆局限期深水准同生白云岩的识别标志主要为其与沉积相的伴生关系,如塔东地区呈夹层状分布于盆地及下斜坡等深水环境。

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## Dolomitization in Deepwater Environment of Cambrian in Penecontemporaneous Diagenetic Stage , Eastern Tarim Basin

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**Abstract** In the Cambrian formation of basin facies in the eastern Tarim Basin , thin bedded dolomicrites , argillaceous dolomicrites and siliceous dolomicrites are distributed in thick formations of silty mudstone , siliceous mudstone and silicalite. There is no obvious evidence of tide-flat where evaporative pumping dolomicrites can be formed , like bird's eye structure , pores formed by gypsum dissolution , cryptogalaminite and mudcracks , while there are many evidence of deepwater environments , such as Radiolaria , colour of strong oxygen-free environment. As a result , the mechanism forming these dolomicrites can not be interpreted by evaporative pumping. Studies are carried on by petrologic characteristics , degree of order , isotope ratio of  $^{13}\text{C}$  ,  $^{18}\text{O}$  and  $^{87}\text{Sr}/^{86}\text{Sr}$ . Dolomicrites studied in this article appear in basin facies , composed by micrite dolomites , with mud intervals and siliceous metasomatism. In basin facies , the thickness of dolomicrites is small , while in ramp , they are distributed in dolomite with saccharoidal texture. Colour of cathodoluminescence of dolomicrites is maroon , which is characteristic of high quantity of  $\text{Mn}^{2+}$  and  $\text{Fe}^{2+}$  , indicating that dolomicrites were formed in strong oxygen-free environment. Distribution range and average of degree of order of dolomite show that dolomicrites have lower value of degree of order than other dolomites. The average value of degree of order of dolomicrites is 0.749 8 , with 48 samples , while that is 0.948 8( 17 samples) of other dolomites , which means that dolomicrites were formed in relative short time. In deepwater environments , dolomicrites formed rapidly , there was no time to form big and euhedral-granular texture. Distribution range and average of  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$  of dolomite shows that dolomicrites have higher value than other dolomites. The average value of  $\delta^{13}\text{C}$  of dolomicrites is 1.2 , while that of finely crystalline dolomite is -0.4‰ and that of medium-macrocrystalline dolomite is -0.6‰. The average value of  $\delta^{18}\text{O}$  of dolomicrites is -5.8‰ , while that of finely crystalline dolomite is -8.8‰ and that of Medium-macrocrystalline dolomite is -12.1‰. The characteristics of  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$  show that dolomicrites were formed in circumstance with high salinity. The average value of  $^{87}\text{Sr}/^{86}\text{Sr}$  of dolomicrites is 0.710 64 , while that of finely crystalline and Medium-macrocrystalline dolomite is 0.709 34 , which is another evidence of circumstance with high salinity. Mechanism of dolomitization was proposed based on above evidences. Dolomicrites was formed in the period of restricted sea basin. When there was not sufficient supplement of freshwater into the sea and with strong evaporation , The salinity of seawater went high , with  $\text{Mg}^{2+}$  and  $\text{Ca}^{2+}$  concentrated. As a result , there is enough  $\text{Mg}^{2+}$  for dolomitization. For there were enough interspaces in the fluffy calcium carbonate sediments and seawater with high salinity can flows and stays sufficiently so that dolomitization occurred in penecontemporaneous diagenetic stage.

**Key words** dolomicrites; deepwater; basin facies; ramp; penecontemporaneous diagenetic stage; dolomitization