

羌塘盆地南部隆鄂尼地区布曲组鞍形白云石成因

张 帅¹, 夏国清², 伊海生^{2,3}, 蔡占虎², 李启来²(1. 成都理工大学 地球科学学院, 四川 成都 610059; 2. 成都理工大学 沉积地质研究院, 四川 成都 610059;
3. 成都理工大学 油气藏地质及开发工程国家重点实验室, 四川 成都 610059)

摘要:羌塘盆地南部隆鄂尼地区中侏罗统布曲组砂糖状白云岩中发育有大量的鞍形白云石,其岩相学特征表现为正交偏光下的波状消光以及弯曲的晶面和解理,阴极发光整体呈暗红色,无明显的环带。鞍形白云石中流体包裹体均一温度主要分布于152.8~174.1℃,盐度均值(23.3%NaCl)远高于现代海水盐度,表明其形成经历了高温高盐度的演化过程。微区同位素分析显示鞍形白云石 $\delta^{13}\text{C}$ 值介于-4.81‰~4.29‰, $\delta^{18}\text{O}$ 值为-11.2‰~-7.51‰,根据白云石-流体氧同位素分馏方程得到成岩流体 $\delta^{18}\text{O}$ (SMOW)值为5‰~11‰。综合分析认为,鞍形白云石形成于相对封闭的深埋藏环境,是热液流体调整改造作用的产物。地层水加热再循环过程中在孔隙或裂缝较为发育的部位沉淀形成鞍形白云石,高盐度的地层水可能来自沉积期古海水与埋藏期地下热卤水的混合。鞍形白云石的成因研究表明,晶粒相对较粗大的砂糖状白云岩是地表/近地表形成的白云岩重结晶作用的产物。

关键词:碳、氧同位素;埋藏白云石化;鞍形白云石;布曲组;中侏罗统;羌塘盆地

中图分类号:TE121.3

文献标识码:A

Origin of saddle dolomites from the Buqu Formation of Longeni Area in southern Qiangtang Basin

Zhang Shuai¹, Xia Guoqing², Yi Haisheng^{2,3}, Cai Zhanhu², Li Qilai²

(1. College of Earth Sciences, Chengdu University of Technology, Chengdu, Sichuan 610059, China;

2. Institute of Sedimentary Geology, Chengdu University of Technology, Chengdu, Sichuan 610059, China;

3. State Key Laboratory of Oil / Gas Reservoir Geology and Exploitation, Chengdu University of Technology, Chengdu, Sichuan 610059, China)

Abstract: Saccharoidal dolostones in the Middle Jurassic Buqu Formation of Longeni Area in southern Qiangtang Basin were found to contain large number of saddle dolomites. Petrographic study shows typical sweeping extinction, curved crystal faces and cleavage traces under cross polarized light and dark red luminescence and unzoned textures. Fluid inclusions in the saddle dolomite were measured to have homogenization temperature ranging between 152.8 and 174.1℃ and salinity averaged at 23.3%NaCl, much higher than the salinity of modern seawater, indicating a high temperature and high salinity diagenetic environment. In-situ isotopic analysis shows $\delta^{13}\text{C}$ value ranging from -4.81‰ to 4.29‰, and $\delta^{18}\text{O}$ value varying from -7.51‰ to -11.2‰. The $\delta^{18}\text{O}$ (SMOW) value of diagenetic fluid was calculated to be 5‰ - 11‰ by using the fractionation equation of dolomite-fluid oxygen isotope. It is believed based on a comprehensive analysis that the saddle dolomites were formed in a relatively closed deep burial setting and were the products of thermal fluid modification. The saddle dolomites were probably formed in places where pores and fractures were well developed during a recirculation of heated formation water. The high salinity formation water could be the mixture of paleo-seawater during sedimentation period and underground hot brine during burial period. Origin of the saddle dolomite reveals that the saccharoidal dolostones with coarse grains are the result of recrystallization of surface or near surface dolostones.

Key words: carbon and oxygen isotope, burial dolomitization, saddle dolomite, Buqu Formation, Middle Jurassic, Qiangtang Basin

羌塘盆地作为中国最大的中生代海相沉积盆地,与中东特提斯构造域富油气盆地具有相似的沉积演化

特征和石油地质条件^[1-2]。盆地内各类油气显示多达200余处,显示出巨大的资源潜力^[3-4]。尤以盆地南

收稿日期:2015-05-14;修订日期:2016-06-06。

第一作者简介:张 帅(1985—),男,博士研究生,储层矿物岩石学。E-mail:zsdolomite@mail.com。

通讯作者简介:夏国清(1982—),男,博士、讲师,沉积地质学。E-mail:xiaguqing2012@cdut.cn。

基金项目:国家自然科学基金项目(41572089,41402099)。

部中侏罗统布曲组油藏带关注程度最高,研究成果最多^[5-6]。对于油藏带砂糖状白云岩成因的研究仍存在一定的争议,早期主要根据白云岩的沉积特征和显微结构提出了混合水模式^[7-10]。近年来包裹体测温以及碳氧同位素数据均显示其为高温埋藏成因^[11]。进一步研究发现,砂糖状白云岩中除发育雾心亮边白云石外,还广泛分布一类具有特殊形态的白云石晶体——鞍形白云石。在前期工作的基础上,运用阴极发光、包裹体测温、微区同位素等分析手段对鞍形白云石成因展开了讨论,以期对油藏带白云岩形成机理及空间分布特征提供参考。

1 区域地质背景

羌塘盆地位于青藏高原中北部,处于特提斯—喜马拉雅构造域中段。盆地夹持于可可西里—金沙江缝合带和班公湖—怒江缝合带之间,总体呈“两坳一隆”的构造格局^[12-13]。南部坳陷带隆鄂尼地区牙尔根、格鲁关那以及德如日等地出露含油白云岩带,层位为中侏罗统布曲组(图1)。白云岩油浸后呈黄褐色、深褐色,晶粒结构,中—厚层状构造。岩石风化后较疏松,常呈砂糖粒状。实测剖面中砂糖状白云岩与介壳灰岩、鲕粒灰岩、生物碎屑灰岩或核形石灰岩相伴生,为一套典型的台地边缘礁滩相沉积(图2)。受白云石化作用和重结晶作用影响,砂糖状白云岩原始沉积组构消失殆尽,成岩组构主要为不等粒结构与雾心亮边结构等。

2 测试方法

样品主要为砂糖状白云岩,首先磨制了普通薄片,经茜素红染色后详细观察岩石结构。在此基础上选

取不同剖面的典型样品磨制阴极发光片与包裹体片。流体包裹体测试由长江大学地球科学学院完成,采用英国 Linkam 公司 THMSG600 冷热台,分析精度 $\pm 0.1\text{ }^{\circ}\text{C}$,加热冷冻过程中设置的控温速率一般为 $20\text{ }^{\circ}\text{C}/\text{min}$,相变点附近速率为 $4\text{ }^{\circ}\text{C}/\text{min}$ 。

进一步研究中对鞍形白云石含量较高的样品进行激光微区碳、氧同位素测试,实验由西南油气田分公司勘探开发研究院完成。具体方法为:同轴安装 Nd, YAG 激光器与偏光显微镜,利用显微镜光学系统定位后通过激光束加热分解取样(束斑直径 $< 20\text{ }\mu\text{m}$);真空提纯净化后收集 CO_2 气样采用 MAT252 型稳定同位素质谱仪检测, PDB 标准,测试精度 δ 小于 0.2 ‰ 。

3 结果分析

3.1 显微结构特征

布曲组白云岩类型主要包括粒屑白云岩和晶粒白云岩(图3)。粒屑白云岩由残余粒屑结构组成(图4a),粒屑类型主要包括鲕粒、内碎屑、以及生物碎屑等,形态多呈球形或椭球形。晶粒白云岩中白云石自形程度较高,多呈菱面体,根据粒径大小可分为三类。粉—细晶白云岩中白云石晶体以它形曲面为主,晶粒大小为 $0.03\sim 0.25\text{ mm}$,常呈镶嵌结构,发育弥散状的晶间微孔(图4b)。细—中晶白云岩由自形—半自形白云石组成粒状镶嵌结构,晶粒大小为 $0.1\sim 0.5\text{ mm}$,可见雾心亮边构造,晶间溶孔及溶孔、溶缝中可见方解石、沥青质充填(图4c)。中—粗晶白云岩由晶粒大小为 $0.25\sim 1\text{ mm}$ 的白云石组成,晶体间多为凹凸接触,发育晶间孔隙和溶蚀缝洞(图4d)。

中—粗晶白云岩中发育有鞍形白云石,呈不均匀的斑点状充填孔洞及裂缝,含量 $5\%\sim 10\%$ 不等,晶粒一般大于 0.5 mm 。正交偏光下具有典型的波状消光,可见弯曲的晶面和解理,总体形态为菱面体的弯曲变形;晶体边界呈曲折的轮廓和弧形的端面,内部可见阶步式的断裂,边缘洁净度与透明度相对较好(图5a, b)。鞍形白云石阴极发光整体呈暗红色,无明显环带,沿解理发育部位发光呈亮红色,局部可见后期溶蚀作用沉淀的方解石呈暗橘黄色(图5c, d)。

3.2 包裹体测温与盐度

镜下观察自形白云石中盐水包裹体形态较规则,大小主要分布在 $5\sim 8\text{ }\mu\text{m}$,沿晶体生长面呈带状分布。鞍形白云石中原生盐水包裹体大小一般为 $2\sim 5\text{ }\mu\text{m}$,形态不规则。布曲组砂糖状白云岩19件样品153个气液两相盐水包裹体的测试结果显示(图6):自形白云石盐水包裹体均一温度变化范围为 $139.5\sim 180.7\text{ }^{\circ}\text{C}$,平均值为

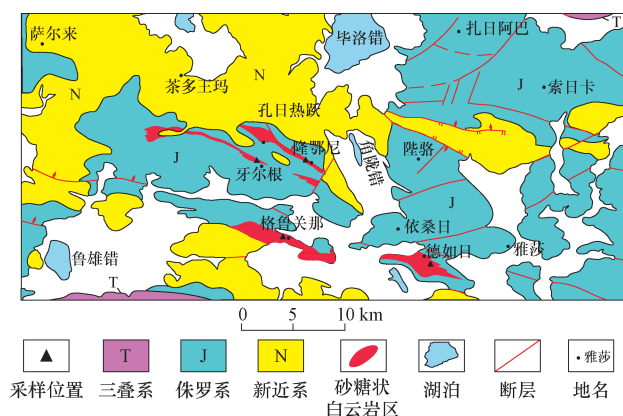


图1 隆鄂尼地区布曲组砂糖状白云岩地表分布及采样位置

Fig.1 Distribution and sampling location of saccharoidal dolostones in the Buqu Formation of the Longeni area

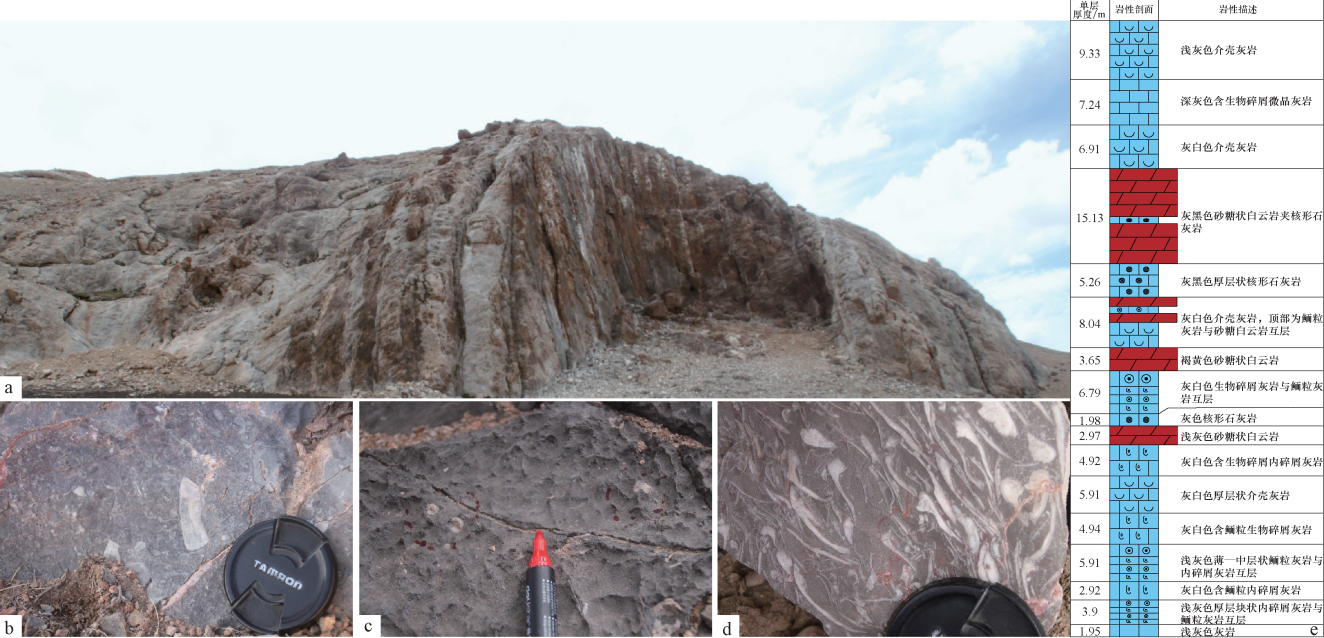


图 2 隆鄂尼地区布曲组砂糖状白云岩野外露头及剖面柱状图

Fig. 2 Saccharoidal dolostone outcrops and stratigraphic column of the Buqu Formation of the Longeni area

a. 格鲁关那剖面白云岩与灰岩互层;b. 含生物碎屑核形石灰岩;c. 砂糖状白云岩中生屑残余;d. 介壳灰岩;e. 地层柱状图



图 3 隆鄂尼地区布曲组白云岩手标本照片

Fig. 3 Photos of dolostone samples from the Buqu Formation of the Longeni area

a. 砂屑白云岩;b. 粉-细晶白云岩;c. 细-中晶白云岩;d. 中-粗晶白云岩

150.4℃,采用H₂O-CaCl₂二元体系近似换算盐度均值为20.1%。鞍形白云石均一温度介于152.8~174.1℃,平均均一温度为163.7℃,盐度均值为23.3%。鞍形白云石的包裹体均一温度介于自形白云石分布范围内,其平均值及盐度均值高于自形白云石,整体上呈高温高盐度的流体特征。孔隙和裂缝中充填

的方解石均一温度及盐度均较低(表1),可能存在大气淡水的改造。

根据现有的盆地地温梯度资料^[14-15],羌塘盆地南部地温梯度普遍偏低,一般介于26~28℃/km,其中隆鄂尼地区平均地温梯度为26.4℃/km。假定地表温度20℃,参考前人对盆地埋藏史的研究^[15],按布曲组最

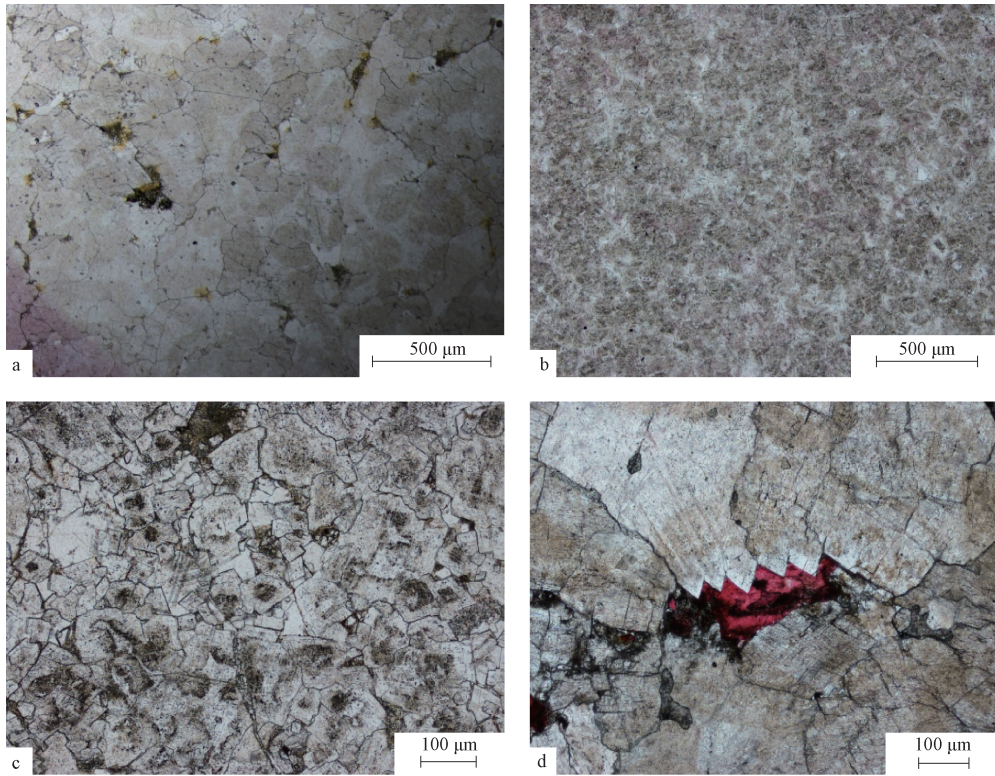


图 4 隆鄂尼地区布曲组白云岩显微结构照片

Fig. 4 Photomicrographs of dolostone from the Buqu Formation of the Longeni area

a. 粒屑白云岩;b. 粉-细晶白云岩;c. 细-中晶白云岩,雾心亮边结构;d. 中-粗晶白云岩,孔隙充填方解石

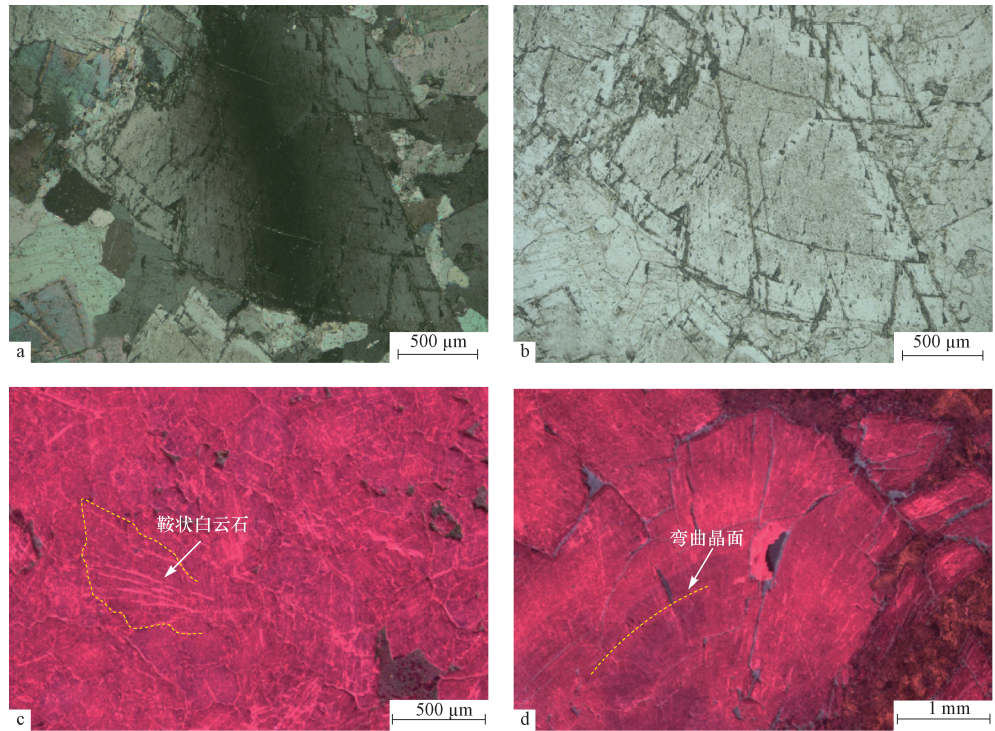


图 5 隆鄂尼地区布曲组鞍形白云石显微结构及阴极发光照片

Fig. 5 Cathodoluminescence images and photomicrographs of saddle dolomites from the Buqu Formation of the Longeni area

a. 鞍形白云石呈波状消光,正交偏光;b. 鞍形白云石弯曲的晶面和解理,单偏光;
c,d. 鞍形白云石阴极发光照片,总体发暗红色光,沿解理发育部位发光较亮,局部可见方解石胶结物发暗橘黄色光

大理深 4 500 m 计算,布曲组经历的最大古地温约 140℃。包裹体测温数据明显高于地层埋藏温度,形成鞍

形白云石的流体可能经历了深部加热循环或存在外部高温流体的改造。

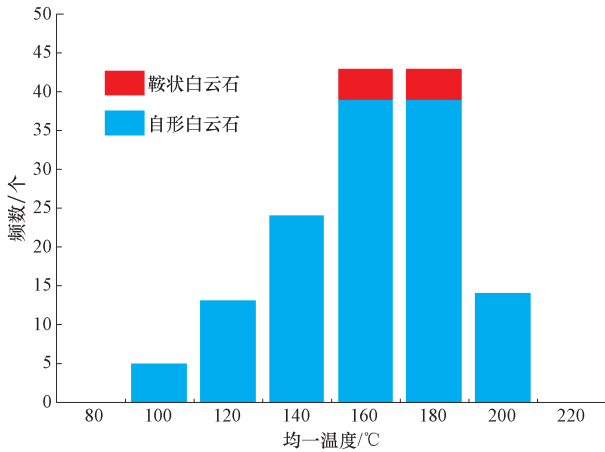


图6 隆鄂尼地区布曲组白云石包裹体均一温度

Fig. 6 Histogram of homogenization temperature of fluid inclusions in dolomites from the Buqu Formation of the Longeni area

表1 隆鄂尼地区自形白云石与鞍形白云石、方解石包裹体均一温度及盐度

Table 1 Homogenization temperature and salinity of fluid inclusions in the automorphic dolomite, saddle dolomite and calcite from the Buqu Formation of the Longeni area

样品	均一温度/°C		盐度均值/%
	分布范围	平均值	
自形白云石	139.5 ~ 180.7	150.4	20.1
鞍形白云石	152.8 ~ 174.1	163.7	23.3
方解石	64.3 ~ 114.9	84.8	5.1

3.3 碳、氧同位素特征

鞍形白云石微区碳氧同位素测试结果显示 $\delta^{13}\text{C}$ (PDB) 值为 $-4.81\text{‰} \sim 4.29\text{‰}$, $\delta^{18}\text{O}$ (PDB) 值介于 $-11.2\text{‰} \sim -7.51\text{‰}$ (表2)。研究区砂糖状白云岩全岩样品的 $\delta^{13}\text{C}$ (PDB) 值一般介于 $3.02\text{‰} \sim 4.23\text{‰}$, $\delta^{18}\text{O}$ (PDB) 值介于 $-8.94\text{‰} \sim -7.9\text{‰}$ [11]。白云石 $\delta^{13}\text{C}$ 值随温度变化的同位素分馏很轻微, $\delta^{18}\text{O}$ 值主要受流体氧同位素以及温度的影响 [16]。鞍形白云石的 $\delta^{13}\text{C}$ 值显示其碳来源主要为封闭系统中的宿主地层 [17-18], 较大的负偏可能受封闭环境下生物成因 CO_2 介入的影响 [19]。

4 讨论

鞍形白云石作为一种特殊的白云石类型, 形成过程中发生了晶格畸变, 其成因对于白云石化流体来源的研究具有十分重要的意义。Radke 和 Mathis [20] 首次从形态学、晶体光学、晶体化学等多个角度对具有鞍状形态的白云石类型进行了详细论述, 提出以鞍形白云石作为潜在地质温度计的观点。嗣后, 许多学者都引用了这一观点, 普遍认同鞍形白云石形成于深埋藏作

用下高温、高盐度卤水环境 [21-22], 其形成温度很大程度上与“生油窗”到“过成熟生干气”阶段的温度相一致 [23]。也有学者认为鞍形白云石形成于埋藏过程相对封闭系统中的化学压实作用 [18, 24]。近年来, 鞍形白云石与热液白云岩化作用的关系受到众多学者的重视 [25-29]。鞍形白云石的广泛发育可以作为构造热液白云岩储层的重要标志 [30-35]。

根据白云石-水氧同位素分馏系数 [36] 绘制关系图解, 将鞍形白云石均一温度和 $\delta^{18}\text{O}$ 值进行投影, 结果显示沉淀鞍形白云石的流体 $\delta^{18}\text{O}$ (SMOW) 值介于 $5\text{‰} \sim 11\text{‰}$ (图7), 远大于现代海水和古海水 $-1\text{‰} \sim 1\text{‰}$ [37], 与岩浆水 $\delta^{18}\text{O}$ (SMOW) 值相似 [38]。隆鄂尼地区白云岩出露区周缘无深大断裂和火山岩分布, 白云岩镜下鉴定未见萤石、重晶石与菱镁矿等热液矿物, 表明鞍形白云石的形成不是岩浆水等外来热液流体作用的结果。鄂尔多斯盆地奥陶系马家沟组马五段埋藏白云岩成岩流体 $\delta^{18}\text{O}$ (SMOW) 平均值为 8‰ [39]。沉淀鞍形白云石的流体 $\delta^{18}\text{O}$ (SMOW) 值的大幅正偏可能是埋藏环境地层水高温浓缩所致。结合包裹体测温和盐度

表2 隆鄂尼地区布曲组鞍形白云石微区碳氧同位素分析结果
Table 2 Carbon and oxygen isotope analyses result of saddle dolomites from the Buqu Formation of the Longeni area

样品号	采样位置	岩性	测试方法	$\delta^{13}\text{C}$ (PDB)/ ‰	$\delta^{18}\text{O}$ (PDB)/ ‰
1	格鲁关那	鞍形白云石	微区	4.29	-10.02
2	格鲁关那	鞍形白云石	微区	3.36	-10.65
3	格鲁关那	鞍形白云石	微区	3.49	-10.31
4	德如日	鞍形白云石	微区	3.22	-7.51
5	格鲁关那	鞍形白云石	微区	-4.81	-11.2

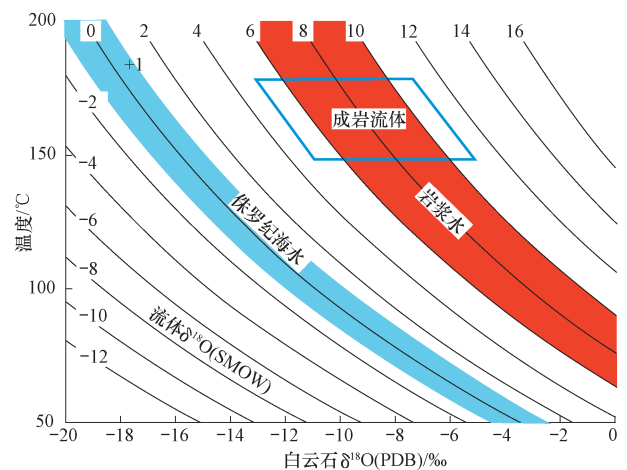


图7 应用分馏方程建立的温度与白云石以及流体氧同位素关系

Fig. 7 Plot of equilibrium relationship between $\delta^{18}\text{O}$ (PDB) of dolomite and homogenization temperature for various $\delta^{18}\text{O}$ (SMOW) of fluid using fractionation equation

(根据 Land [36] 分馏方程: $1000 \text{Ln}\alpha_{\text{白云石}-\text{水}} = 3.2 \times 10^6 T^{-2} - 3.3$ 绘制。)

分析,本文提出隆鄂尼地区鞍形白云石的成岩流体应为深埋藏环境下的地层水。由于缺乏蒸发环境的标志^[40],高盐度的地层水可能来自沉积期古海水与埋藏期地下热卤水的混合^[41]。地层水加热再循环的过程中受水岩作用影响,地表/近地表形成的白云岩调整改造(重结晶)为砂糖状白云岩,同时在孔隙或裂缝较为发育的部位沉淀鞍形白云石。

5 结论

1) 研究区鞍形白云石显微结构及包裹体特征显示其形成于封闭的流体系统,高温高盐度的流体环境。

2) 沉淀鞍形白云石的流体 $\delta^{18}\text{O}$ (SMOW) 值介于 5‰~11‰,成岩流体来自深埋藏环境下地层水的加热再循环。

3) 砂糖状白云岩与鞍形白云石的分布紧密相关,并且具有相似的阴极发光特征和包裹体均一温度,鞍形白云石的发育指示砂糖状白云岩的形成与埋藏环境下热液流体的调整改造有关。

致谢:成都理工大学博士研究生季长军与尹青,硕士研究生梁定勇、蔡占虎与金峰参加了野外剖面测量和采样工作,在此一并表示感谢!

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