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桂中坳陷下石炭统鹿寨组页岩段碳酸盐矿物发育特征及成因机制

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摘　要: 目前桂中坳陷下石炭统鹿寨组展现出较好的页岩气勘探前景, 但页岩中碳酸盐矿物含量较高, 异于国内主要页岩气层的碳酸盐矿物含量, 其碳酸盐矿物成因及其对页岩气产气的影响未知。文章以桂融页 1 井及其野外剖面为研究对象, 运用 X-全岩衍射、岩石薄片鉴定等手段, 发现鹿寨组页岩中碳酸盐矿物以方解石为主, 含量为 5%~80%, 平均为 30.33%, 并含少量白云石（0%~9%）, 平均为 2.1%, 碳酸盐矿物主要发育在炭质页岩、钙质泥岩、粉砂质钙质泥岩、生屑炭质泥岩、泥微晶灰岩和泥质灰岩中以及顺层分布的方解石脉、穿层的构造方解石脉中。在此基础上进一步开展阴极发光、碳氧同位素分析, 发现碳酸盐矿物成因主要为海水中原地正常沉积成因, 其次为海水中随海浪、风暴流打碎后异地搬运成因以及成岩期重结晶成因, 水平脉状方解石的形成可能为埋藏期差异压实收缩缝被地层流体充填后过饱和沉淀, 而垂向脉状方解石与多期构造活动有关。

关键词: 页岩气; 碳酸盐矿物; 成因机制; 鹿寨组; 桂中坳陷

创新点: 桂中坳陷下石炭统鹿寨组页岩气勘探取得较好发现, 但页岩中碳酸盐岩矿物含量较高, 其成因主要为海水中原地正常沉积, 其次是随海浪、风暴流打碎后异地搬运以及在成岩期重结晶形成, 其中水平方解石脉的形成与埋藏期差异压实有关, 垂向方解石脉的形成与多期构造活动有关。

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0　引　言

近年来, 中国页岩气工业取得了较大发展, 已成为世界上第三个实现页岩气工业化生产国家。但是产气页岩气层组及盆地均单一, 在国家油气能源压力渐涨、对外依存度高位徘徊的形势下, 急需要在更多盆地寻找和发现更多页岩气层组, 才能使页岩气在中国天然气工业中发挥更大作用[1]。而石炭系是

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世界上重要的“黑色层系”发育时期，北美地区的页岩气勘查开发首先是从石炭系海相页岩开始的，石炭系（密西西比系）Barnett 页岩已成为世界重要的页岩气开采层位之一[2–4]。中国石炭系海相页岩分布相对较少，主要发育在扬子板块边缘黔桂裂陷盆地[5–7]，大致分布在现今广西桂中—南盘江、贵州黔南—黔西南、湖南湘中等坳陷内[8]。围绕这些坳陷内石炭系的钻井（桂融页 1 井、黔紫页 1 井）已获得较好的页岩气显示[9–10]（图 1），2023 年桂融页 2 井经压裂后获石炭系工业气流，展现出良好的勘探前景，黔桂地区石炭系有望成为继五峰—龙马溪组页岩气之后中国下一个重要的勘探层系[11–16]。

尽管如此，该地区钻井揭示早石炭世相变快，页岩分布不稳定[17]，页岩中碳酸盐矿物较高，且常见碳酸盐岩夹层[16,18]，现场侵水实验和气测录井表明，页岩出气与页岩中碳酸盐矿物相关。对于页岩中碳酸盐矿物如何影响页岩气（油），国内学者已在其他盆地开展过相关研究，结果表明页岩中碳酸盐

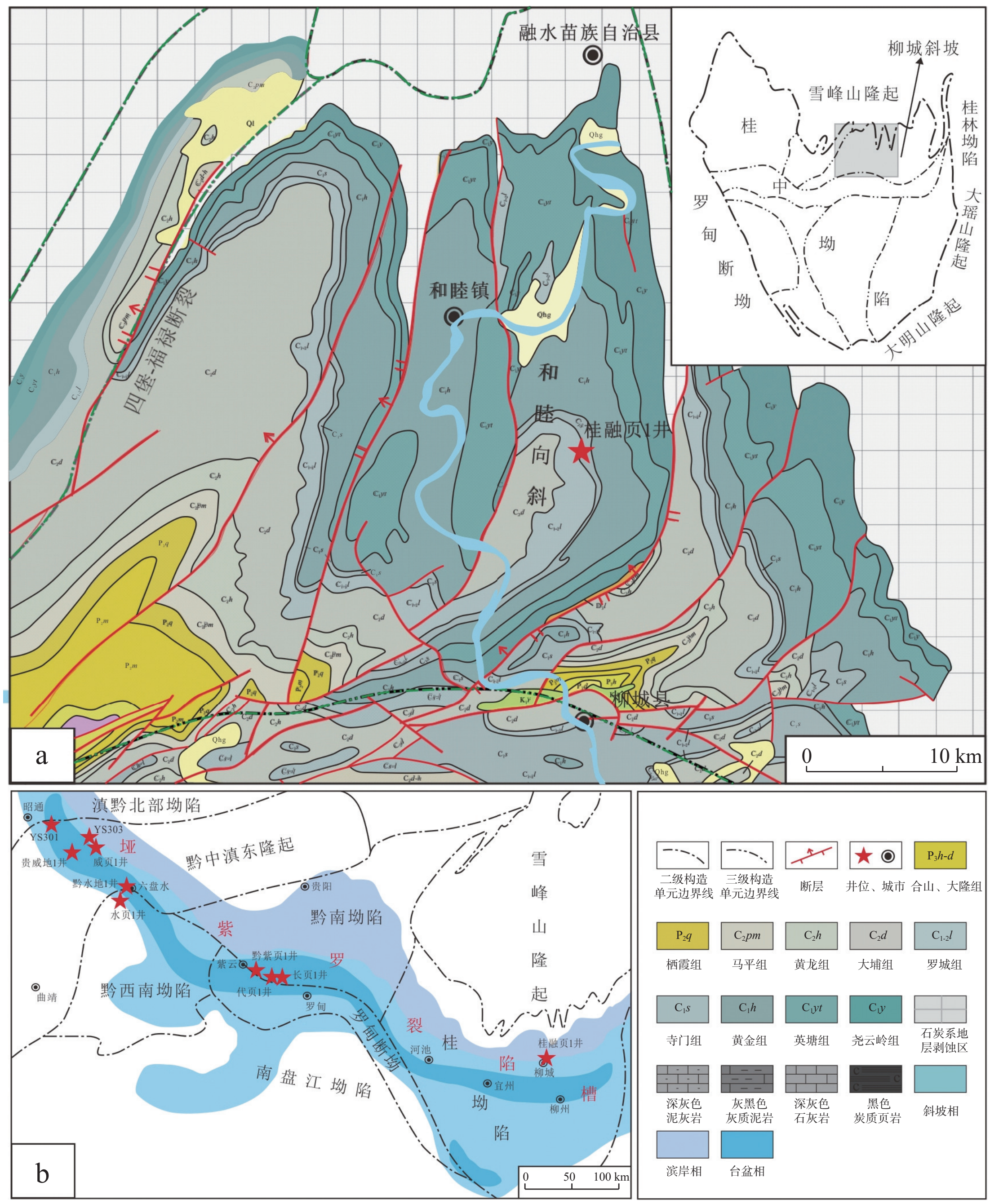

图 1　研究区构造位置（a）与早石炭世沉积位置图（b）（据覃英伦等[10]）

Fig. 1　Structural location (a) and sedimentary location during early Carboniferous (b) in the study area

矿物控制了东营凹陷页岩油发育[19−20],对页岩油产出具有积极作用,而四川盆地中龙马溪组少量发育的碳酸盐矿物使得页岩致密化,限制了页岩出气[21−22],而桂中鹿寨组页岩中碳酸盐矿物成因及其如何影响出气并没有相关研究。为此,本文以野外剖面、钻井岩芯为研究对象,在综合运用X-全岩衍射、薄片鉴定等手段,在明确碳酸盐矿物类型的基础上,进一步开展阴极发光、碳氧同位素地球化学分析,着重探讨碳酸盐矿物成因机制,建立成因模式,以期为后期不同类型碳酸盐矿物分布预测、含气性分析以及桂中坳陷下石炭统页岩气“甜点”优选提供理论参考。

1 地质背景

桂中坳陷为滇黔桂盆地东北部的二级构造单元[23],北临雪峰山隆起,西部与黔南坳陷、罗甸坳陷相接,东部与桂林坳陷、大瑶山隆起为邻,南部为大明山隆起(图 1),是一个在加里东运动基础上形成的晚古生代大型海相残留坳陷[6,11]。桂中坳陷地处滨太平洋与特提斯—喜马拉雅两大构造的复合部位[24],其形成经历了 4 个构造演化阶段[12,23,25],包括:(1)海西期:区域拉张下沉,海水由南往北入侵,裂陷盆地发育;(2)印支期:造山活动增强,结束海相沉积环境,发育前陆盆地;(3)燕山期:坳陷遭受挤压隆升,发育大量褶皱和断裂;(4)喜马拉雅期:坳陷及周缘全面抬升,遭受严重剥蚀。

研究区位于桂中坳陷北部三级构造单元柳城斜坡,发育北北东向“雁列”式排列断层,残留向斜在平面上沿断裂呈条带状展布(图 1a)。早石炭世时期,研究区继承了滇黔桂地区“台—盆”相间的古地理格局,富有机质页岩主要沉积于东西向深水裂陷台盆相中,目的层下石炭统鹿寨组即为此沉积环境下的产物[10](图 1b)。陈粤等[13]研究表明鹿寨组由下往上可分为三段,鹿寨组一段岩性主要为黑色硅质页岩、泥页岩、钙质页岩、泥质硅质岩、含硅泥岩,北部常夹泥灰岩条带;鹿寨组二段岩性主要为深灰色薄—中层状泥灰岩夹灰黑色薄层状硅质泥岩;鹿寨组三段岩性主要为灰黑色泥页岩、灰黑色粉砂质泥岩、泥质粉砂岩、粉砂岩,灰色、灰白色石英砂岩,属于海陆过渡相沉积。富有机质页岩主要发育在鹿寨组一段。钻探显示:研究区鹿寨组一段主要发育灰黑色炭质页岩、深灰色钙质泥岩、深灰色钙质粉砂质页岩和泥灰岩夹层,厚度达到 280 m;测井解释和岩芯观察表明:下部 40 m 灰黑色炭质页岩碳酸盐矿物低,往上碳酸盐矿物增加,岩芯滴酸起泡明显,气测录井表明鹿寨组一段均有良好显示(图 2)。

2 碳酸盐矿物发育特征

据覃英伦等[10]X-全岩衍射分析数据(图 3)表明:桂融页 1 井石炭系鹿寨组页岩层段主要由石英、长石、方解石、黄铁矿、白云石、黏土等构成,碳酸盐矿物主要由方解石组成,含少量白云石,其中方解石占 5%~80%(方解石＞50%,为页岩中灰岩夹层),平均占比为 30.33%,白云石占 0~9%,平均占比为 2.10%。测井解释表明:鹿寨组一段底部为灰黑色炭质泥岩(图 2),碳酸盐矿物含量低(＜10%),往上渐变为深灰色钙质泥岩、泥灰岩互层,碳酸盐矿物含量明显升高,整体上该套页岩滴酸均起泡,碳酸盐矿物整体含量较高。

而具体到发育碳酸盐矿物的岩石类型,通过野外剖面观测、桂融页 1 井岩芯取样、岩石薄片鉴定,发现有纯泥岩类、含粒泥岩类及碳酸盐岩类三大类岩石类型。泥岩类包括灰黑色炭质页岩(LF5)、深灰色钙质泥岩(LF3)(图 4A、B、C),碳酸盐矿物呈泥晶状大量分散于泥岩中(图 5A);含粒泥岩类包括深灰色粉砂质钙质泥岩(LF6)(具有明显砂纹、包卷、交错层理)(图 4E)及灰黑色生屑炭质泥岩(具“漂浮状”生屑)(LF7)(图 4F)等,深灰色粉砂质钙质泥岩中碳酸盐矿物呈胶结物存在于岩石中(图 5E),灰黑色生屑炭质泥岩的碳酸盐矿物主要在生物碎屑中,为泥晶—细晶结构(图 5G);碳酸盐岩类主要为泥微晶灰岩和泥质灰岩(LF2)(具有水平纹层)(图 4D),碳酸盐矿物主要存在于灰岩水平纹层中,以泥微晶结构为主(图 5C)。桂融页 1 井下部以灰黑色炭质页岩和生屑钙质泥岩为主,中部含粉砂,往上逐渐过渡为碳酸盐岩(图 2),反映下部水体较深,为深水陆棚沉积,往上变为浅水陆棚或混积陆棚沉积(图 2),早石炭世该区水体整体具有由深变浅特征。此外,中部泥岩中不仅含碳酸盐矿物,还含较大颗粒石英(图 5E),既有化学碳酸盐矿物沉淀又有陆源石英供给,反映出该区页岩沉积受到

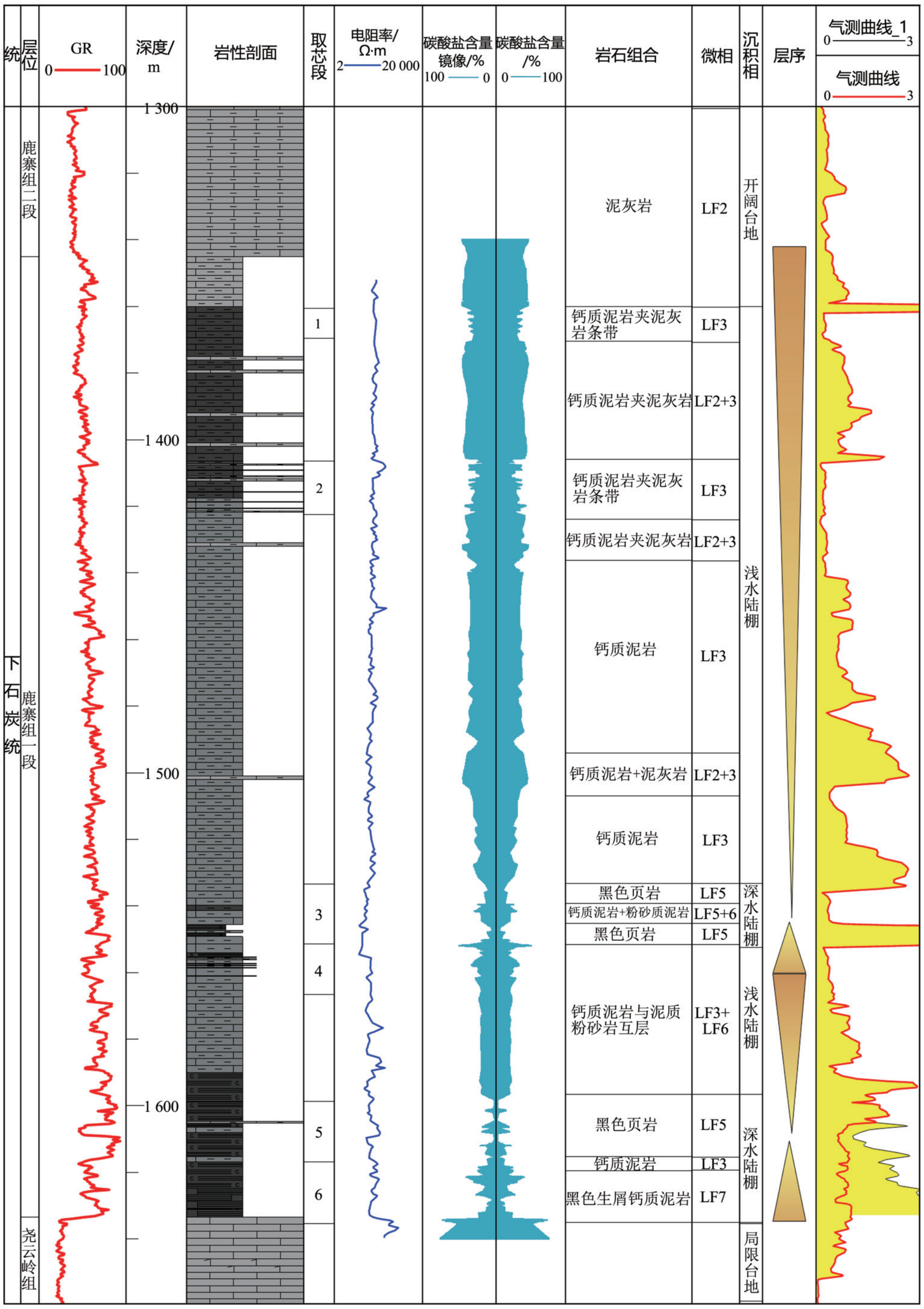

图 2　桂融页 1 井鹿寨组一段碳酸盐含量—沉积相综合柱状图 (部分数据据覃英伦等[10])

Fig. 2　Comprehensive histogram of carbonate contents and sedimentary facies in Member 1 of the Luzhai Formation of Guirongye Well 1 (Part of the data is based on Qin Yinglun, etc.[10])

古陆物源供给影响。

碳酸盐矿物除均匀发育在岩石中外，还集中分布在方解石脉中，主要发育两类脉体：一是具有顺层水平状分布脉体(图 4G，图 4H)；二是穿层斜交或垂直脉体(图 4I，图 4J)，主要呈细—中晶结构(图 5I，图 5K)。

3　碳酸盐矿物阴极发光特征

上述几类岩石中碳酸盐矿物具有不同阴极发光特征：块状钙质泥岩(LF3)及水平纹层状泥晶碳酸盐矿物 (LF2) 基本不发光(图 5B，图 5D)。粉砂质钙质

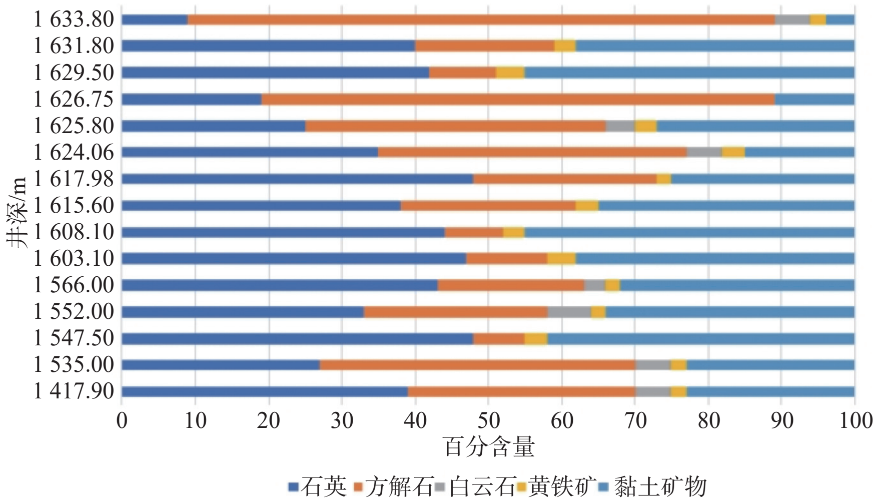

图 3 桂融页 1 井鹿寨组一段页岩全岩矿物

Fig. 3 Whole rock mineral composition of shale in Member 1 of the Luzhai Formation of Guirongye Well 1

泥岩(LF6)中部分碳酸盐矿物具有弱红光,部分不发光,发光碳酸盐矿物为钙质胶结物和一些钙质生屑(图 5E),炭质页岩中"漂浮"碳酸盐生屑 (LF7) 一般会发弱红光 (图 5H),透镜状、脉状晶粒方解石具有弱阴极发光性(图 5J)。

一般来说,碳酸盐岩阴极发光与碳酸盐中 Fe、Mn 含量有关[26],而 Fe、Mn 含量与沉积—成岩环境有关,因此可用碳酸盐矿物阴极发光一定程度反映碳酸盐矿物成因,上述碳酸盐矿物表现出不同发光性,表明融页 1 井碳酸盐矿物具有多种成因。黄思静[26] 研究结果表明当碳酸盐矿物在海水中正常沉积,具有低 Mn 含量,碳酸盐矿物一般显示为不发光。而碳酸盐矿物显示弱的发光表明碳酸盐矿物经历了成岩作用或异地搬运。桂融页 1 井块状钙质泥岩(LF2)和水平纹层状泥微晶碳酸盐岩 (LF3) 基本不发光反映出桂融页 1 井大多数碳酸盐矿物为海水中正常沉积成因,而其余发光碳酸盐矿物经历了明显沉积期或成岩期改造,以下通过碳氧同位素地球化学特征进一步分析。

4 碳酸盐矿物碳氧同位素特征

前人研究泥岩中或灰岩中泥晶碳酸盐矿物成因类型包括:在海底或沉积物中形成的原地正泥晶灰岩,即原地泥晶灰岩;离散的骨架物质和磨蚀的岩屑沉积形成的异化泥晶灰岩,即异地泥晶灰岩;成岩作用形成的假泥晶,即晶粒方解石颗粒表面可能略有污浊[27]。原地泥晶灰岩主要为盐度和水温变化引起的物理化学沉淀,与生物密切相关,异地泥晶灰岩主要为侵蚀和磨蚀作用下所形成的泥晶灰岩,与生物成因密切相关,而成岩作用形成的假泥晶受成岩作用控制,与生物作用无关。

以此为依据,进一步将鹿寨组碳酸盐矿物归为三类:将钙质泥岩中(LF3)和页岩中纹层状(水平状)泥微晶灰岩 (LF2) 碳酸盐矿物归为原地碳酸盐矿物类;将与砂混积呈现为砂纹层状 (LF6) 和页岩中"漂浮"碳酸盐生屑 (LF7) 碳酸盐矿物归为异地碳酸盐矿物类;将页岩中透镜状、脉状晶粒碳酸盐岩和裂缝中发育方解石脉归为成岩期晶粒碳酸盐矿物类。按以上三类在自然资源部实物地质资料中心取样,共计取样 80 件,在自然资源部岩溶地质资源环境检测中心进行碳氧同位素测试,并将测试结果绘图(图 6)。

碳酸盐矿物碳氧同位素可很好区分碳酸盐矿物并判断其成因[28−29]。不同类型碳酸盐矿物碳氧同位素具有显著分异特征,同时又表现出一定规律性。统计测试结果发现:原地碳酸盐矿物类 $\delta^{13}C$ 为 2.70 ‰~5.81 ‰,平均 4.68 ‰,$\delta^{18}O$ ‰为 −8.89 ‰~−5.97‰,平均−7.54‰;异地碳酸盐矿物类 $\delta^{13}C$ 为 2.62 ‰~4.39 ‰,平均 3.30 ‰,$\delta^{18}O$ ‰为 −8.89 ‰~−7.67‰,平均−8.04 ‰;成岩期晶粒碳酸盐矿物类 $\delta^{13}C$ ‰为 −1.18 ‰~5.73 ‰,平均 2.78 ‰,$\delta^{18}O$ 为 −12.76‰~−5.75‰,平均−9.77‰。无论原地碳酸盐矿物还是异地碳酸盐矿物碳氧同位素分布区间基本与早石炭世海水正常沉积碳氧同位素一致[30],但整体上 $\delta^{13}C$ 和 $\delta^{18}O$ 平均值具有原地碳酸盐矿物类>异

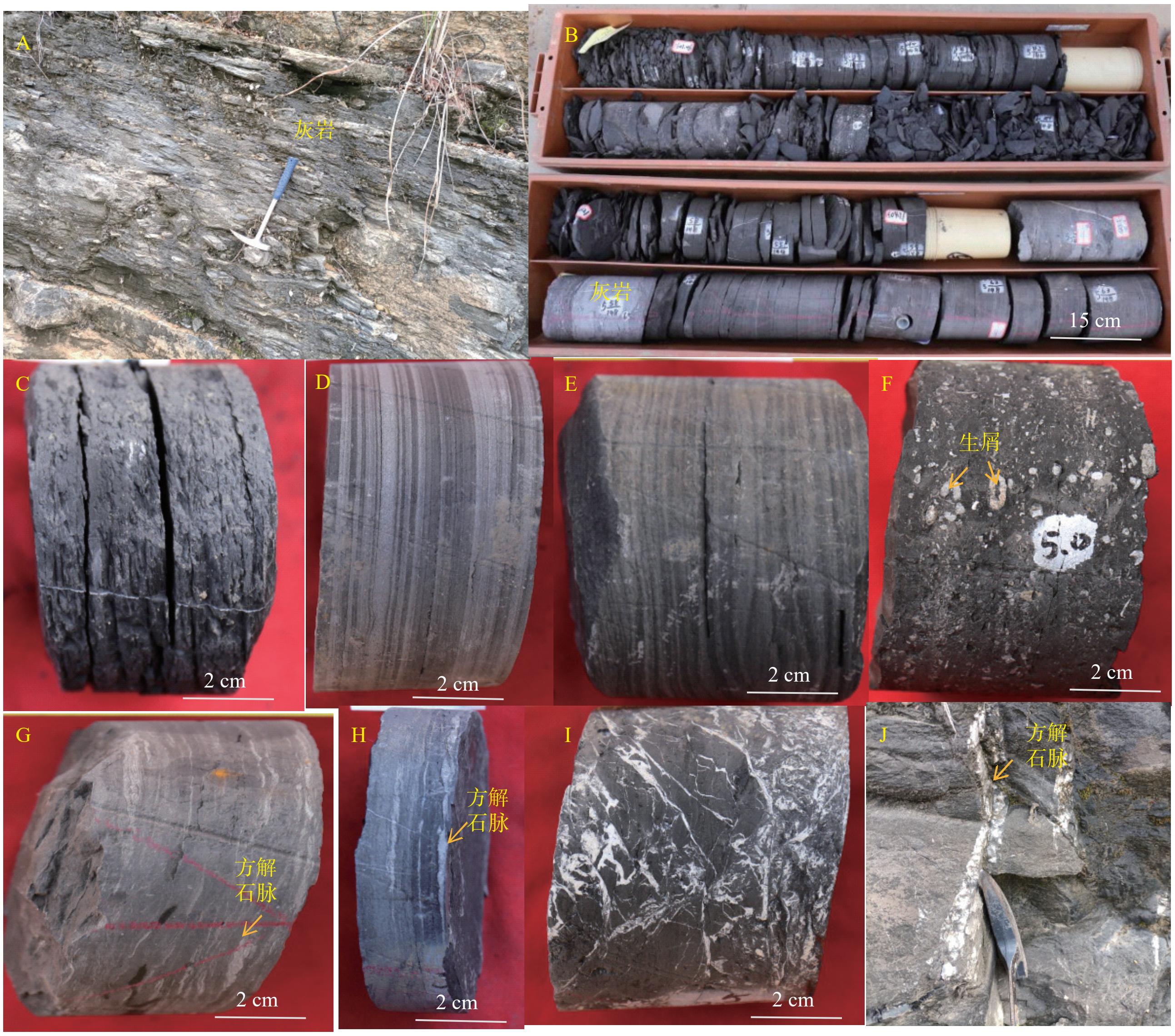

图 4　桂中坳陷鹿寨组一段碳酸盐矿物产出宏观特征

A.深灰色钙质页岩夹泥晶灰岩条带及透镜体，融水大良剖面　B.深灰色钙质泥岩夹泥晶灰岩，1 602.3~1 606.4 m，桂融页 1 井　C.灰黑色钙质泥岩，1 544 m，桂融页 1 井　D.灰色泥晶灰岩与深灰色泥灰岩互层，见水平纹层，1 414.32 m，桂融页 1 井　E.深灰色粉砂质钙质泥岩，具交错层理，1 539.66 m，桂融页 1 井　F.含生屑炭质泥岩，生屑成“漂浮状”，1 603.66 m，桂融页 1 井　G.具透镜状方解石脉钙质泥岩，1 412.1 m，桂融页 1 井　H.具水平脉状方解石钙质泥岩，1 534.4 m，桂融页 1 井 I.深灰色钙质泥岩发育网裂缝，被方解石全充填，1 416.9 m，桂融页 1 井　J.钙质泥岩中垂直层面构造方解石脉，融水大良剖面

Fig. 4　Petrological macroscopic characteristics of carbonate minerals in Member 1 of Luzhai Formation in the depression of central Guangxiormation in Guizhong Depression

A.Dark gray calcareous shale with micrite stripes and lenses, Rongshuidaliang profile　B.Dark gray calcareous mudstone with micite, 1,602.3–1,606.4 m, Guirongye Well 1　C.Gray-black calcareous mudstone, 1,544 m, Guirongye Well 1　D.Horizontally laminated micrite alternating with calcareous mudstone, 1,414.32 m, Guirongye Well 1　E.Cross-stratified calcareous silty mudstone, 1,539.66 m, Guirongye Well 1　F.Carbonaceous mudstone containing "floating" bioclastics, 1,603.66 m, Guirongye Well 1　G.Calcareous mudstone with lens-shaped and vein-shaped calcite, 1,412.1 m, Guirongye Well 1　H.Calcareous mudstone with horizontally vein-shaped calcite, 1,534.4 m, Guirongye Well 1　I.Dark gray calcareous mudstone with developed net fractures, completely filled with calcite, 1,416.9 m, Guirongye Well 1　J.Calcite veins are constructed in vertical plane of calcareous mudstone, Rongshuidaliang profile

地碳酸盐矿物类＞成岩期晶粒碳酸盐矿物类的特征，后两者比原地碳酸盐矿物碳氧同位素更负偏，且脉状晶粒方解石 $\delta^{13}C$ 大多小于−9.5‰，而泥晶方解石、异地碳酸盐生屑则大多大于−9.5‰(图 6)，该界限可能为海水环境与成岩环境界限。

5　页岩中碳酸盐矿物成因机制

（1）块状钙质泥岩和水平纹层状泥晶灰岩中碳酸盐矿物基本不发光反映了桂融页 1 井大多数碳酸

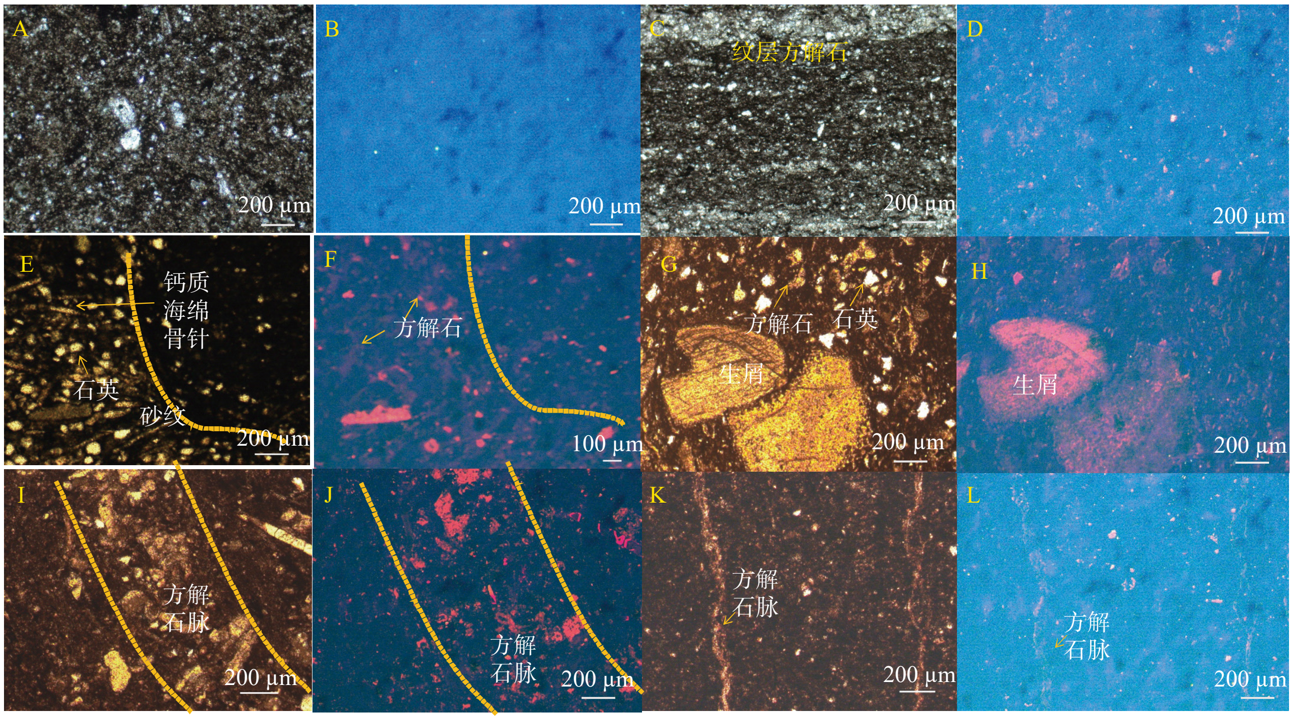

图 5 桂融页 1 井鹿寨组碳酸盐矿物发育微观特征及其阴极发光

A.钙质泥岩，碳酸盐矿物呈泥晶状大量分布于泥岩中，1 544 m B.为 A 阴极发光，显示不发光，1 544 m C.为图 4D 水平纹层泥灰岩镜下照片，深色钙质泥岩与浅色泥微晶方解石呈条带状互层 D.阴极发光为不发光，1 414.32 m E.为图 4E 具交错层理粉砂质泥岩镜下特征，左下为粉砂质泥岩纹层，由石英、黏土、方解石混积，右上主要为黏土和方解石，为钙质泥岩纹层，1 539.66 m F.为 E 阴极发光，部分方解石具有弱红阴极发光，部分不发光，发光碳酸盐矿物为钙质胶结物和一些钙质生屑，1 539.66 m G.图 4F 含生屑炭质泥岩镜下特征，生屑含量可达到 20%，有珊瑚、海百合、钙质海绵骨针等，生屑具有泥晶—细晶结构，泥岩中含少量石英，1 603.66 m H.G 中生屑阴极发光中具有弱红光，1 603.66 m I.为图 4G 具透镜状方解石钙质泥岩镜下特征，两条黄色线内为脉体，方解石呈细晶结构，1 412.1 m J.I 中脉体方解石具弱红色阴极发光，1 412.1 m K.为图 4I 网裂缝镜下特征，方解石全充填，1 416.9 m L.为 K 阴极发光，左侧裂缝发很弱光，右侧裂缝基本不发光，1 416.9 m

Fig. 5 Microscopic characteristics and cathodoluminescence of carbonate minerals from the Luzhai Formation in Guirongye Well 1

A. Calcareous mudstone with large quantities of micrite carbonate minerals are distributed in it B. Cathodoluminescence is non-luminous, at 1,544 m C. a photomicrograph of horizontally laminated muddy limestone of Fig.4D, with dark calcareous mudstone and light micrite calcite showing stripped interlayer D. Cathodoluminescence is non-luminous, at 1,414.32 m E.The microscopic feature of the cross-stratified silty mudstone of Fig.4E; the lower left part shows silty mudstone lamination mixing with quartz, clay, and calcite, and the upper right part mainly consists of clay and calcite, showing calcareous mudstone lamination; part of the calcite emit weak and red cathodoluminescence but part of the calcite are non-luminous F. Luminescent carbonate minerals are calcareous cements and some calcareous bioclastics, at 1,539.66 m G.The microscopic feature of bioclastic carbonaceous mudstone from Fig.4F with the contents of bioclastics reaching 20%; the mudstone includes corals, sea lilies, calcareous sponges and a small amount of quartz; the bioclastics emits weak red luminescence under cathodoluminescence H.At 1,603.66 m I.The microscopic feature of lens-shaped calcite calcareous mudstone of Fig.4G; the veins are in the two yellow lines and the calcite shows fine crystal structure;the vein calcite emits weak red cathodoluminescence J.At 1,412.1 m K.The microscopic feature of the net fractures from Fig.4I; completely filled with calcite; The left fracture emits weak luminescence while the right fracture is basically non-luminous under cathodoluminescence L.At 1,416.9 m

盐为海水中沉积成因的特征，属于原地碳酸盐矿物类，碳氧同位素也与石炭纪正常海水沉积一致[30]，其碳酸盐矿物形成受到海洋物理化学和生物作用控制，同时由于其发育厚度极薄且在纵向上快速变化，泥晶碳酸盐矿物水平纹层主要与海平面变化频繁波动导致碳酸盐岩饱和面（CCD 面）变化有关（表 1，图 7）。

（2）在含粒泥岩中，与砂混合的碳酸盐矿物表现为不发光或发弱红光，具有复杂性，不发光的碳酸盐矿物为海水正常沉积，而发光碳酸盐矿物可能为成岩作用碳酸盐矿物，具有重结晶，或沉积在动荡水环境（可见交错层理），碳酸盐矿物具有异地搬运，这两类碳酸盐矿物均可发光；炭质页岩中“漂浮”碳酸盐生屑一般会发弱红光，表明这些生屑本身可能沉积水体较浅，或为生屑滩沉积，然后经历风暴作用，搬运至深水黑色炭质页岩中沉积（图 7），因此生屑基本均会发红色光。此外，异地碳酸盐矿物岩

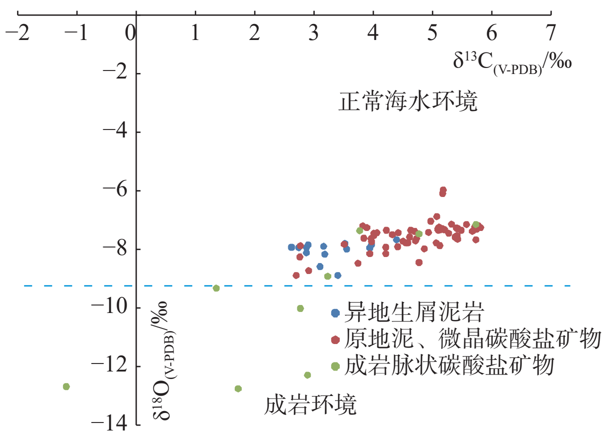

图 6　桂中坳陷鹿寨组页岩中不同类型碳酸盐矿物碳氧同位素特征

Fig. 6　Characteristics of carbon and oxygen isotopes of different types of carbonate minerals in the shale of Luzhai formation in the depression of central Guangxi

石碳氧同位素值比原地碳酸盐矿物岩石碳氧同位素稍偏负(图 6),这证明了异地碳酸盐矿物岩石里面除本身海水正常沉积碳酸盐矿物外,还混合有碳氧负偏的碳酸盐矿物。

(3)透镜状、脉状晶粒碳酸盐矿物阴极发光,可见晶粒方解石具有弱发光性,且碳氧同位素具有明显负偏,反映出其是在后期成岩流体中重结晶形成的。在早期海洋中沉积大量的泥质沉积物、碳酸盐矿物,一方面,在埋藏环境下,受到压实作用的影响,泥质沉积物排出部分流体,体积收缩形成成岩收缩缝;另一方面,受到异常压力的影响,超压体系内剩余压力超过压实系统的承受能力,在诸如页岩页理缝这样较为脆弱的应力面形成透镜体状裂缝(图 8)。与此同时,深部的地层水进入裂缝,这些成岩流体对碳酸盐饱和后在页理缝或原有的孔缝之间进行充填并起到支撑作用,最后形成在泥页岩中充填的呈透镜体状发育的水平脉状晶粒碳酸盐矿物。而垂向的构造裂缝碳酸盐矿物,有的不发光,有的弱发光,可能是多期流体成因,反映出桂融页 1 井可能存在多

表 1　桂中坳陷鹿寨组碳酸盐矿物发育特征及成因

Table 1　Development characteristics and genesis of carbonate minerals of the Luzhai Formation in the depression of central Guangxi

发育位置	发育类型	碳酸盐矿物含量	发育形态	阴极发光	碳氧同位素	成因分析	发育规模
纯泥岩	钙质泥岩	10%~50%	泥晶状分散于泥岩中	基本不发光	$\delta^{13}C$为2.70‰~5.81‰, $\delta^{18}O$为−8.89‰~−5.97‰	海水中原地正常沉积成因	大规模发育在目的层中
	炭质泥岩	＜10%	泥晶状分散于泥岩中	基本不发光	/	海水中原地正常沉积成因	小规模发育在目的层中
含粒泥岩	粉砂质泥岩	10%~50%	呈胶结物存在于石英颗粒间	部分方解石具有弱红光,部分不发光,发光为钙质胶结物和一些钙质生屑	$\delta^{13}C$为2.62~4.39‰, $\delta^{18}O$为−8.89‰~−7.67‰	海水中随海浪打碎后异地搬运成因	小规模发育在目的层中
	含生屑炭质泥岩	5%~10%	发育在生物碎屑中为泥晶—细晶结构	碳酸盐生屑具有弱红光		海水中随风暴流打碎后异地搬运成因	小规模发育在目的层中
夹层碳酸盐岩	泥晶灰岩	＞80%	发育在灰岩水平纹层中,以泥微晶结构为主	基本不发光	$\delta^{13}C$为2.70‰~5.81‰, $\delta^{18}O$‰为−8.89‰~−5.97‰	海水中原地正常沉积成因	小规模发育在目的层中
	泥灰岩	50%~75%	发育在灰岩水平纹层中,以泥微晶结构为主	基本不发光		海水中原地正常沉积成因	中等规模发育在目的层中
页岩中方解石脉体	顺层透镜状方解石脉	100%	呈细—中晶结构	晶粒方解石具有弱阴极发光	$\delta^{13}C$为−1.18‰~5.73‰, $\delta^{18}O$为−12.76~−5.75‰	埋藏期差异压实收缩缝被地层流体充填后过饱和沉淀	极小规模发育在目的层中
	穿层构造方解石脉	100%	呈细—中晶结构	晶粒方解石具有弱阴极发光		与多期构造活动有关	小规模发育在目的层中

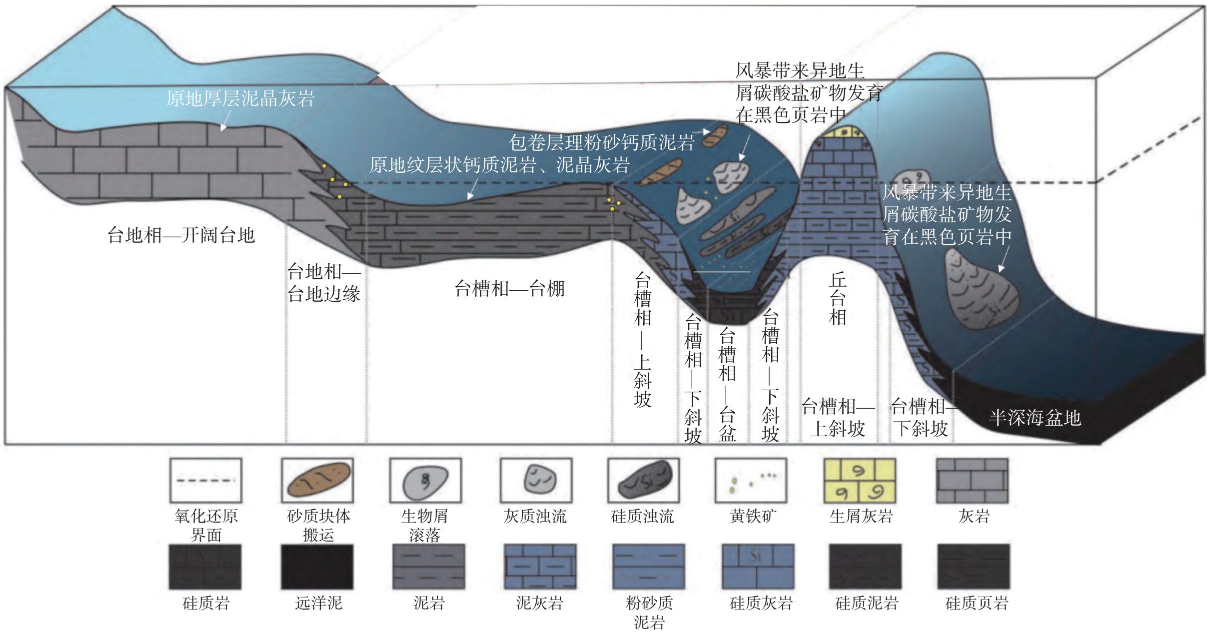

图 7　桂中坳陷鹿寨组原地、异地泥晶碳酸盐矿物成因机制 (据陶金雨等[17] 有修改)

Fig. 7　Genetic mechanism of in-situ and allochthonous micrite carbonate minerals in Luzhai Formation, Guizhong Depression (Revised based on Tao Jinyu, et al.[17])

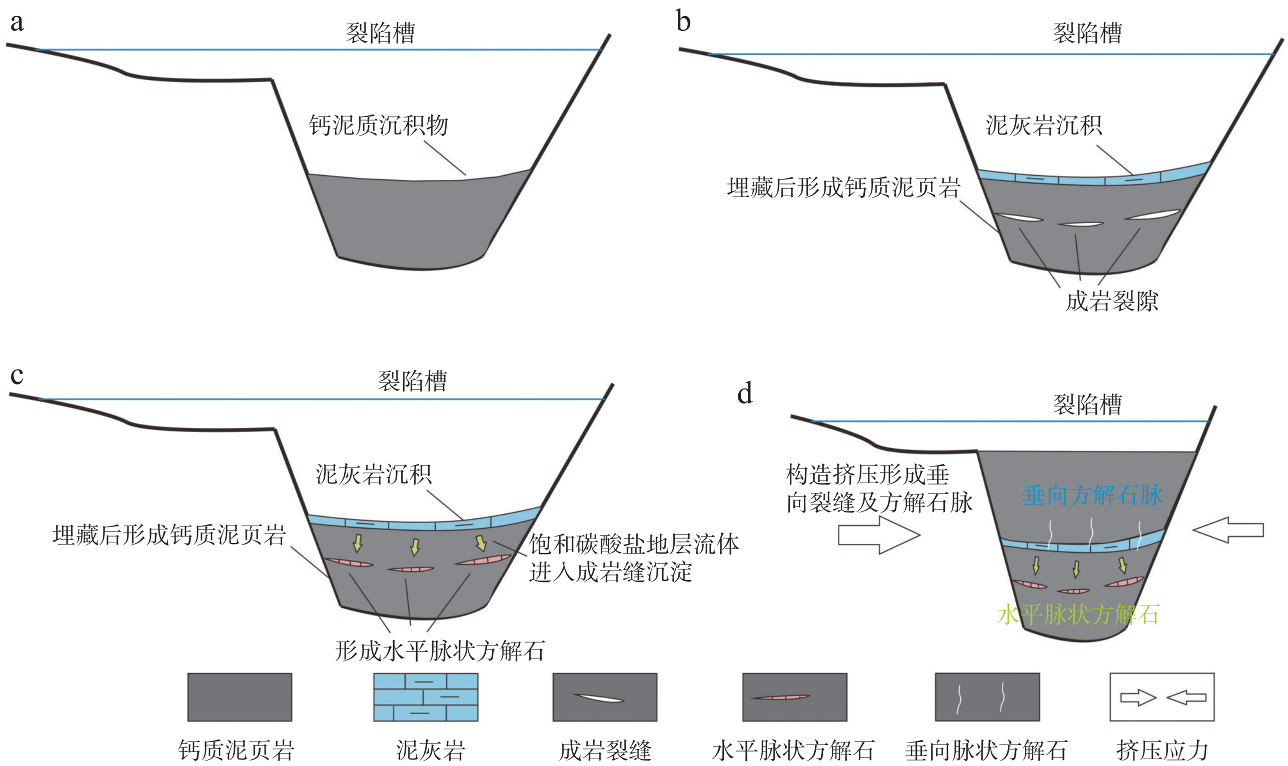

图 8　桂中坳陷鹿寨组脉状碳酸盐矿物成因机制

a.碳酸盐矿物与黏土混合沉积　b.埋藏期差异压实形成成岩裂缝　c.成岩裂缝被地层流体充填并生长水平脉状方解石，地层流体碳酸盐过饱和　d.受构造影响，垂向脉状方解石发育

Fig. 8　Genetic mechanism of vein-shaped carbonate minerals of Luzhai Formation in the depression of central Guangxi

a.Carbonate minerals mixed with clay deposits　b.Diagenetic fractures are formed by differential compaction in burial period　c.The diagenetic fracture is filled by the formation fluid and grows horizontal calcite;the formation fluid is supersaturated with carbonate　d.Under the influence of structure, the vertical calcite veins developed

期构造活动。

前期研究认为碳酸盐矿物的存在会对页岩储层具有双重影响[19−22]。一方面，碳酸盐矿物占据储层孔隙空间使岩石孔隙度降低，储层质量变差；另一方面，碳酸盐矿物充当岩石骨架阻碍压实作用的进行，有利于保存原生孔隙并为后期溶解提供物质基础。在成岩过程中地层流体性质的变化常会引起碳酸盐的溶解和沉淀，碳酸盐矿物提供的晶间孔隙和有机孔隙、碳酸盐溶蚀孔具有较好储集性，另外碳酸盐层段易脆，容易产生微裂缝，这些裂缝也可成为较好的存储空间。对桂中坳陷不同成因类型碳酸盐矿物成因机制的分析，可用来进一步探讨和研究不同类型碳酸盐矿物对储层是贡献还是破坏，寻找有利的碳酸盐矿物类型，从而指导勘探“甜点段”的预测。

6　结　论

（1）桂中坳陷鹿寨组一段页岩层段具有较好含气性且碳酸盐矿物含量较高(方解石 5%~80%，平均占比为 30.33%，白云石 0~9%，平均占比为 2.10%)，明显异于四川盆地五峰—龙马溪组页岩。

（2）研究区碳酸盐矿物主要发育在纯泥岩、含粒泥岩及碳酸盐岩类岩石中以及顺层水平状分布方解石脉和穿层的构造方解石脉中，其中纯泥岩类包含灰黑色炭质页岩、深灰色钙质泥岩，含粒泥岩类包含粉砂质钙质泥岩、灰黑色生屑炭质泥岩，碳酸盐岩类包含泥微晶灰岩和泥质灰岩。

（3）碳酸盐矿物成因主要为海水中原地正常沉积成因，其次为海水中随海浪、风暴流打碎后异地搬运成因，以及成岩期重结晶成因。水平脉状方解石的形成可能为埋藏期差异压实收缩缝被地层流体充填后过饱和沉淀，垂向脉状方解石与多期构造活动有关。

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Development characteristics and genetic mechanism of carbonate minerals in shale member of the lower Carboniferous Luzhai formation in the depression of central Guangxi

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Abstract　The Carboniferous was significant for the development of "black strata" in the world. The exploration and development of shale gas in North America first began with the Carboniferous marine shale, and the Carboniferous (Mississippian) Barnett Shale has become one of the most important strata of shale gas production in the world. The distribution of Carboniferous marine shale in China is relatively limited, primarily developed in the Qian–Gui rift basin at the edge of the Yangtze plate. It is roughly distributed in depressions such as central Guangxi–Nanpanjiang in Guangxi, south Guizhou–southwest Guizhou, and central Hunan. In recent years, drilling activities in the Carboniferous depressions, such as Guirongye Well 1 and Qianziye Well 1 have yielded promising shale gas displays. In 2023, Guirongye Well 2 achieved industrial gas flow from the Carboniferous after the compression fracture was completed, indicating favorable exploration prospects. The Carboniferous strata in the Guizhou–Guangxi region are anticipated to become the next significant exploration target in China, following the shale gas of Wufeng–Longmaxi formation. However, drilling in this area revealed a rapid phase transition in the early Carboniferous, unstable distribution of shale, high levels of carbonate minerals within the shale, and the presence of common carbonate rock interlayers. On-site experiments on water invasion and gas logging suggest that shale gas production is influenced by carbonate minerals in the shale. The origins of these carbonate minerals in the shale of this region and their impact on gas production remain unclear.

To this end, the Luzhai formation shale of the early Carboniferous in the depression of central Guangxi was selected to analyze the origin of carbonate minerals within the shale. This study aims to provide theoretical reference for predicting distribution of various types of carbonate minerals in the subsequent shale formation, as well as for gas content analysis and the optimization of the lower Carboniferous shale gas "sweet spot" in the depression of central

Guangxi. The study area is situated in the Liucheng slope in the northern depression of central Guangxi. Field profiles and core samples from Rongye Well 1 were utilized as the research objects. Following the identification of carbonate mineral types, geochemical analyses of cathodoluminescence and carbon and oxygen isotopes were conducted. This was achieved through a comprehensive approach including X-ray whole-rock diffraction, thin section identification, and other analytical tests.

Research findings indicate as follows, (1) The study found that the carbonate minerals in the Luzhai formation shale are primarily composed of calcite, with a content ranging from 5% to 80%, averaging at 30.33%. Additionally, there is a small amount of dolomite, varing from 0% to 9%, with an average of 2.1%. Carbonate minerals are mainly developed in carbonaceous shale, calcareous mudstone, silty calcareous mudstone, bioclastic carbonaceous mudstone, mud-microcrystalline limestone, and muddy limestone. They are also present in calcite veins distributed along the layers and in structural calcite veins that traverse the layers. (2) Cathodoluminescence analysis shows that massive calcareous mudstone and horizontally laminated micrite carbonate minerals are generally non-luminescent. Some carbonate minerals in silty calcareous mudstone emit weak red light, while others do not. The luminescent carbonate minerals include calcareous cements and certain calcareous bioclastics. The "floating" carbonate bioclastics found in carbonaceous shale typically emit weak red light. Lens-shaped and vein-shaped calcite exhibits weak cathode luminescence. (3) Analyses of carbon and oxygen isotopes show that the $\delta^{13}C$ values of native carbonate minerals range from 2.70‰ to 5.81‰, with an average of 4.68‰. The $\delta^{18}O$‰ values range from –8.89‰ to –5.97‰, with an average of –7.54‰. For allochthonous carbonate minerals, the $\delta^{13}C$ values range from 2.62‰ to 4.39‰, with an average of 3.30‰, and the $\delta^{18}O$‰ values range from –8.89‰ to –7.67‰, with an average of –8.04‰. The $\delta^{13}C$‰ values of diagenetic vein-shaped carbonate minerals range from –1.18‰ to 5.73‰, with an average of 2.78‰, while the $\delta^{18}O$‰ values range from –12.76‰ to –5.75‰, with an average of –9.77‰.

Comprehensive exploration shows that the formation of carbonate minerals primarily results from normal sedimentation in seawater, followed by long-distance transport in seawater after being fragmented by waves and storm currents, and recrystallization during diagenesis. The formation of horizontal vein-shaped calcite may be attributed to supersaturated precipitation within differential compaction and contraction fractures filled by formation fluids during burial, while the vertical vein-shaped calcite is associated with multiple tectonic activities. Based on these findings, various models of carbonate mineral genesis have been established, providing theoretical reference for the optimal selection of sweet spots for shale gas in the lower Carboniferous depression of central Guangxi.

Key words shale gas, carbonate mineral, formation mechanism, Luzhai formation of the lower Carboniferous, depression of central Guangxi

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