



细粒沉积岩物质来源及成因研究现状

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细粒沉积岩物质来源及成因研究现状

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摘要 【意义】细粒沉积岩物质来源研究作为细粒沉积岩“源—汇”系统理论中的首要环节,对恢复古环境、理解细粒沉积岩形成机理和预测非常规油气资源等方面具有重要意义。细粒沉积岩具有物质组成粒度较小、成分复杂、观察研究难度大的特点,且不同物质成分对应多样的物质来源和成因。纵观国内外现有的研究成果,目前仍旧缺乏针对细粒沉积物质来源及成因研究成果的系统性梳理和归纳总结。【进展】综合当前研究成果,将细粒沉积岩的物质来源归纳为陆源、内源和火山—热液源三大类。对常见细粒沉积物来源及成因进行了深入的归纳和总结,指出:(1)黏土矿物为陆源物质风化成因、成岩作用阶段其他矿物转化成因和黏土矿物之间转化成因、海底火山物质海解成因以及胞外聚合物生物介导作用成因;(2)石英主要源于陆源物质风化、盆内生物作用、火山凝灰物质脱玻化作用以及成岩作用;(3)长石源于陆源碎屑物质风化,火山—热液作用输入,近年来相关研究也发现长石能够由微生物化学作用形成;(4)碳酸盐矿物主要是内源物质,其能够在盆内由化学作用、生物—化学作用、生物作用和搬运再沉积作用形成,另外陆源物质和火山—热液源物质的输入不仅能直接为细粒沉积岩提供碳酸盐矿物,也会促使盆内碳酸盐矿物的形成;(5)黄铁矿主要由铁和硫两大成矿元素在盆内分别经过异化铁还原作用和铁穿梭机制主导还原作用、微生物还原作用和硫酸盐热化学还原作用形成;(6)有机质可划分为陆源的镜质体、惰质体和部分类脂体以及内源的部分类脂体、动物有机碎屑和次生有机质。【结论与展望】未来细粒沉积岩物质来源及成因的研究将围绕多学科、高精度等方面发展,当下仍亟待一套适用于细粒沉积岩物源研究的系统方案。细粒沉积岩物质来源和物质成因的系统性梳理与总结,增进了对细粒沉积物质来源和形成机制的理解,从而推动细粒沉积学理论的发展,为明确细粒沉积地层的展布特征、预测非常规油气资源的分布提供坚实的理论基础和科学依据。

关键词 细粒沉积岩;物质来源;物质特征;成因机制

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0 引言

在全球能源消费结构转型的背景下,美国“页岩革命”取得了显著成就,从常规油气向非常规油气过渡已成为全球石油工业的发展趋势(邹才能等, 2023;贾承造, 2024)。细粒沉积岩作为非常规油气资源重要的烃源岩和储集层,近年来在石油地质学领域的研究热度如日中天。细粒沉积岩是指粒度小于 62.5 μm 、含量大于 50% 的组分构成的沉积岩类(朱如凯等, 2025)。与碎屑岩、碳酸盐岩相比,细粒沉积岩具有粒度较小、物质成分复杂、观察研究难度

大的特点,因此其在物质来源、搬运—沉积机制、成岩作用乃至沉积环境、沉积相划分等方面的研究程度均远远落后于碎屑岩、碳酸盐岩的研究(Aplin and Macquaker, 2011)。

黏土矿物、石英、长石、碳酸盐矿物、黄铁矿、有机质等是细粒沉积岩中常见的物质成分。如此复杂的物质组成,难以避免其物源及物质成因的多样性和复杂性。例如,细粒沉积岩中的碳酸盐矿物,不仅可以由盆内的物理—化学作用、生物—化学作用、生物作用形成细粒级别的碳酸盐矿物(Dittrich *et al.*, 2003;姜在兴等, 2013;Shen *et al.*, 2022),也可以由陆

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源区白云岩、大理岩等碳酸盐矿物含量较高的岩石经过一系列地质作用形成(Valero, 1993),还能由水底热液直接向盆内输入细粒级别的碳酸盐矿物(南云, 2018; 柳益群等, 2019; 郭佩等, 2022)。

物质来源作为细粒沉积岩研究中的重要课题之一,对于发展和完善细粒沉积岩的相关基础理论有着重要意义,如提供古地理、古气候、古环境重建等信息可帮助了解细粒沉积岩的形成过程(Arthur and Sageman, 1994; Zou *et al.*, 2019; 张鸿禹和杨文涛, 2023)。纵观国内外现有的研究成果,目前仍旧缺乏针对细粒沉积物质来源及物质成因相关研究成果的系统性梳理以及归纳总结。因此,本文基于前人对细粒沉积岩相关的认识成果,系统总结近年来其物质来源的研究现状,理清陆源、内源、火山—热液源物质相关特征,总结黏土矿物、石英、长石、碳酸盐矿物、黄铁矿、有机质等细粒沉积岩常见物质组成特征及其来源,指出目前存在的问题及未来细粒沉积岩物质来源研究的发展趋势。

1 细粒沉积岩物质来源

1.1 陆源

陆源细粒沉积物质几乎在所有细粒沉积岩中均有记录,这类沉积物质是由陆源区母岩经过物理、化学、生物化学等风化作用形成的风化产物,经过河流、大气、冰川、生物等搬运介质搬运,并在搬运过程中进一步风化,最终沉积到盆地中形成的(Wang *et al.*, 2020)。通常陆相湖盆中的陆源细粒沉积物质主要来源于河流以及冲积扇的输入,陆源区的火成岩、变质岩、沉积岩均能够作为细粒沉积岩的母岩,其陆源物质输入量不仅受控于陆源区的风化剥蚀、供源数量和搬运距离,还受到气候条件和水体状态的影响,此外陆源细粒沉积岩对陆源物质输入的反应往往比海相细粒沉积岩更加强烈,物质组成、结构、构造与海相细粒沉积岩相比也更加复杂(朱红涛等, 2017; Liang *et al.*, 2018a; 黎茂稳等, 2022)。

陆源物质成分复杂,常见的有黏土矿物、石英、长石、碳酸盐矿物、有机质等物质和多种化学元素。其中,陆源黏土矿物是源区母岩经过风化、淋滤作用释放出硅、铝等元素形成的产物(路畅等, 2023)。陆源碎屑石英常呈次圆状—棱角状、粒级介于10~50 μm 、分布于细粒沉积岩中,通常风力搬运的陆源

碎屑石英表面可见碟形撞击坑、新月形撞击坑、麻点;流水搬运的石英表面可见水下磨光面、直线或弯曲状撞击沟、V形撞击坑(江新胜等, 2003; 汤海磊, 2020; 易婷, 2020; 赵迪斐, 2021)。陆源碳酸盐矿物常由构造活动较强、气候较干旱、富含碳酸盐矿物的近物源区输入,通常分选和磨圆程度较低(任韵清, 1986; Jiang *et al.*, 2007; Zheng *et al.*, 2015)。有机质中的镜质体、惰质体以及类脂体中的孢子体、角质体、树脂体等均是常见的陆源有机质(Mastalerz *et al.*, 2018; 代世峰等, 2021)。此外,陆源也能向盆内输入大量的元素,为盆内物质的形成提供物质基础。

1.2 内源

盆内来源的细粒沉积物质统称为内源细粒沉积物质,这类细粒沉积物是由湖或海盆内物理—化学作用、生物—化学作用以及生物作用沉积下来的(蒋宜勤等, 2015; 姜在兴等, 2021)。尽管目前对于细粒碳酸盐岩的物质来源和成因缺乏系统研究,但依旧可以明确内源仍然是其稳定来源(姜在兴等, 2021)。常见的内源细粒沉积物除碳酸盐矿物外,石英、Al、Fe、Mn的氧化物以及氢氧化物、硫酸盐、有机质等也都是内源的常见物质(姜在兴等, 2022)。另外,陆源物质输入、火山—热液活动与内源细粒物质来源关系密切(孔祥鑫, 2020):陆源的石灰岩、白云岩、大理岩、玄武岩、碳酸岩等岩石经过风化淋滤作用向湖盆内输入 Ca^{2+} 、 Mg^{2+} 等成分,为内源细粒物质形成提供必备条件(Valero, 1993; Gierlowski-Kordesch, 2010);火山活动形成的火山物质为湖盆内提供 Ca^{2+} 、 Al^{3+} 、 Fe^{3+} 、 Mg^{2+} 等成分,在一定程度上促进内源细粒沉积物质的生成(Liang *et al.*, 2018a)。

内源细粒沉积物按成因可分为盆内化学物质、生物源物质和再搬运沉积物质(操应长等, 2023)。盆内化学物质形成主要有化学作用和生物化学作用:化学物质是指盆内离子在高盐度、较高温度、较大 CO_2 分压环境下,直接从水体中析出并沉积的矿物类型,如江汉盆地潜江组页岩中大量的石盐和白云石等矿物均是化学作用成因(姜在兴等, 2023);生物化学作用是指通过生物生长活动改变沉积环境从而促进盆内矿物生成的作用,Dittrich and Obst(2004)发现湖泊中的细菌和藻类能够促进水体中的 Ca^{2+} 和 CO_3^{2-} 聚集,诱导方解石沉淀;此外Liang *et al.*(2018b)对我国济阳拗陷古近系页岩中碳酸盐矿物进行研究也认为碳酸盐矿物形成的关键机制是生物诱导的化

学沉淀。生物源物质是生物作用直接形成的细粒沉积物,如放射虫、海绵骨针、硅藻等对水体中的 SiO_2 分解、吸收形成生物机体,待死亡后 SiO_2 再次从生物机体中移出沉淀形成新的硅质矿物(Schimmelmann *et al.*, 2016; 郭旭升等, 2020; Gao *et al.*, 2021);另外,盆内蓝绿藻、硅藻、微藻、浮游沟鞭藻等可以形成有机质。值得注意的是,陆源也能向盆内输入各种动植物碎屑,其也属于生物源物质但并非内源物质,由于陆源生物源物质除了有机质外,其他陆源生物源物质含量相较于内源生物源物质相比含量非常低,因此本文将除了陆源有机质以外的陆源生物源物质不做探讨。再搬运沉积物质是盆内已经形成的沉积物质经过水动力作用破碎后重新沉积形成的,如碳酸盐质的内碎屑。

1.3 火山—热液源

火山—热液活动可形成水体外喷发的火山碎屑和通过断层、热液喷口输送到湖泊或海洋的热液沉积物(陈斐然等, 2024; 孙龙德等, 2024)。近年来,我国多个陆相含油气盆地内均发现主力烃源岩展布与火山—热液活动具有较好的耦合关系(Delmelle *et al.*, 2007; 陈斐然等, 2024),这与火山—热液活动向盆内输入大量主、微量元素促进有机质勃发密切相关(张文正等, 2009; 王书荣等, 2013)。但也有学者认为火山碎屑物质进入水体释放大量的Cu、Zn、HCl等有害物质导致生物大量死亡,不利于有机质发育(Zhang *et al.*, 2017)。

火山碎屑物质的搬运、沉积机制与陆源碎屑物质相似:风力搬运、碎屑流、重力流、异重流等流体都能将火山碎屑物质搬运至盆地沉积。李森等(2020)在对鄂尔多斯盆地长7段细粒沉积岩研究时发现中酸性火山灰喷发带来的火山晶屑形成的凝灰质层(图1a~d),石英、长石晶形程度较好、无明显搬运特征,整体呈层状正粒序构造,指示火山碎屑物质由风力作用搬运至湖盆内悬浮沉积的特征。

热液沉积物质按照形成方式可分为喷流式沉积物与喷爆式沉积物,当产出粒度小于 $62.5\ \mu\text{m}$ 时可归纳为细粒沉积物的范畴(Shearman *et al.*, 1983; 柳益群等, 2013; Jiao *et al.*, 2018; 焦鑫等, 2021; 郑庆华等, 2021)。喷流式沉积物是指热液进入水底经过沉积作用形成的沉积物(Edmond *et al.*, 1982),按照矿物组成可分为以硅酸盐、硅铝酸盐、碳酸盐矿物为主的“白烟囱”型和以黄铜矿、黄铁矿、方铅矿、闪锌矿等

为主的“黑烟囱”型(陈先沛等, 1992; 王江海, 1993)。我国在准噶尔盆地(贾斌等, 2015; 常海亮等, 2016)、三塘湖盆地(柳益群等, 2011; 焦鑫等, 2017)、鄂尔多斯盆地(He *et al.*, 2016; 贺聪等, 2017)等盆地均发现含有喷流式沉积物的细粒沉积岩,且均以具有正粒序层理的纹层状、条带状构造的“白烟囱”型为主(图1e~g)(柳益群等, 2011; He *et al.*, 2016; 贺聪等, 2017; 焦鑫等, 2017; 郑荣才等, 2018)。喷爆式沉积物是指固、液、气三相共存的深源岩浆、热液物质通过湖(海)底的喷流通道上升并喷发时,温度和压力的突然变化导致深源岩浆和热液物质剧烈喷发所形成的细粒沉积物类型。在这个过程中,原先形成的岩浆矿物会发生爆炸性破碎,形成微小的晶体碎片,这些微粒晶体矿物碎屑随后与水体混合并沉积下来,形成细粒沉积岩的组成部分(柳益群等, 2013)。李哲萱等(2020)通过研究准噶尔盆地吉木萨尔组陷芦草沟组黑色细粒沉积岩,发现其中发育一定量“斑状”方解石颗粒纹层,符合喷爆式沉积物的特性(图1h~j)。

整体而言,火山—热液源细粒沉积物质包含复杂的矿物组成,矿物剥蚀、搬运痕迹较弱,整体分选差、磨圆度低,具有轻微的定向排列的特征,常呈正粒序纹层状、条带状分布于细粒沉积岩中。但火山碎屑物质的发育规模往往大于喷流式沉积物和喷爆式沉积物,且物质组成更加多样,而喷流式沉积物和喷爆式沉积物常呈纹层状分布且物质组成单一。另外,喷爆式沉积物与火山碎屑物质、喷流式沉积物的矿物形态相比,更具备“碎斑状”的“爆破”特征。

2 细粒沉积岩典型物质的来源及其成因

2.1 黏土矿物来源及其成因

高岭石、蒙脱石、伊利石、绿泥石等是细粒沉积岩中常见的黏土矿物类型,不同的黏土矿物组合反映不同物质来源(路畅等, 2023)。细粒沉积岩中的部分黏土矿物为陆源成因,其类型、数量受母岩性质、源区气候、风化强度等因素控制(Biscaye, 1965; Dou *et al.*, 2014; 朱红涛等, 2017; 杨娅敏等, 2021)。其中古气候条件是制约母岩风化方向、风化强度和黏土矿物类型的关键要素,不同的温度和湿度的二元组合能够导致母岩风化强度、风化方向和黏土矿物类型发生改变。在不考虑气候条件、构造活动等

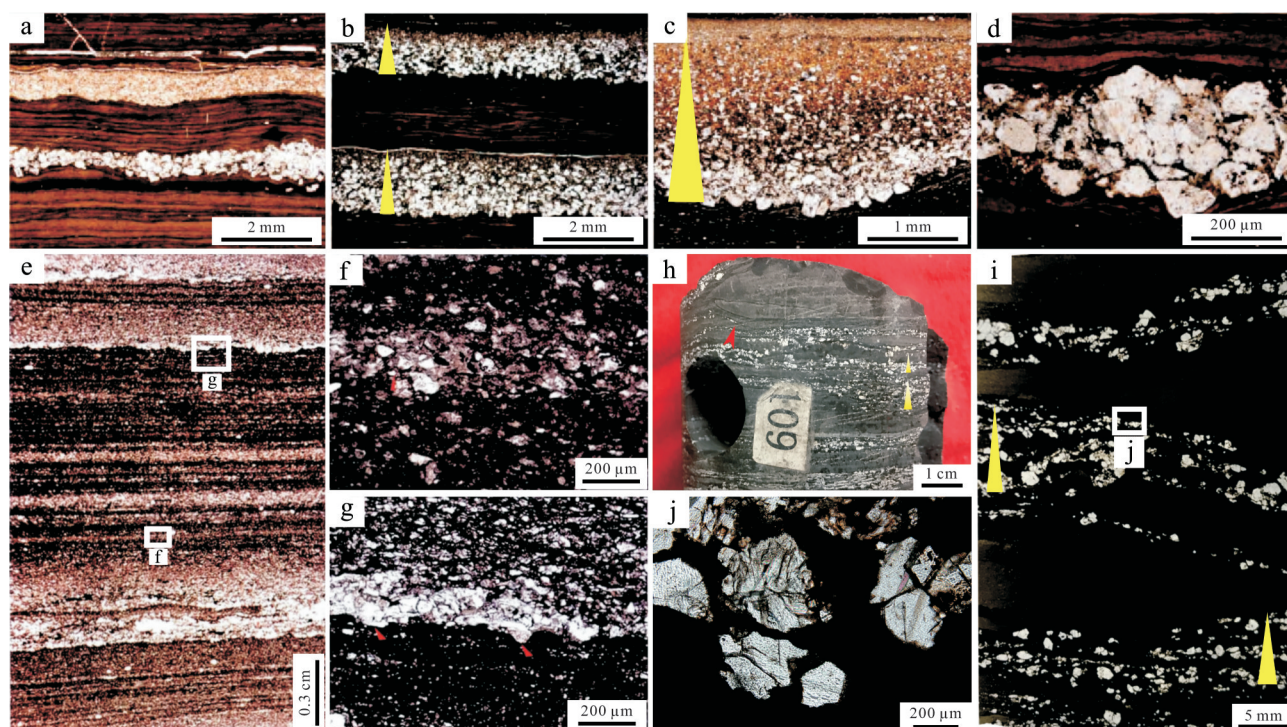


图1 火山—热液源沉积物特征图

(a)水平纹层状页岩发育两期凝灰质层,下层为长英质晶屑火山灰层,上层为玻屑火山灰层,鄂尔多斯盆地长7段,YY1井,228.44 m,单偏光(据李森等,2020修改);(b)水平纹层状页岩发育两期正粒序火山晶屑,鄂尔多斯盆地长7段,YY1井,229.60 m,单偏光(据李森等,2020修改);(c)正粒序火山晶屑,鄂尔多斯盆地长7段,YY1井,236.50 m,单偏光(据李森等,2020修改);(d)图a中下层晶屑火山灰,鄂尔多斯盆地长7段,YY1井,228.44 m,单偏光(据李森等,2020修改);(e)纹层状火山碎屑(白色)岩与白云岩(深褐色)互层,三塘湖盆地芦草沟组,M11井,2 944.80 m,单偏光(据焦鑫等,2017修改);(f)为e中f框的放大,长英质颗粒(白色)呈棱角状,个别具鸡骨状结构(红箭头)(据焦鑫等,2017修改);(g)为e中g框的放大,火山碎屑岩(上半部)与白云岩(下半部)呈明显的剥蚀面接触(红箭头),火山碎屑岩显示正粒序(据焦鑫等,2017修改);(h)喷爆岩,可见大量斑状方解石,红色箭头指示碎斑状颗粒数量逐渐减少至消失,准噶尔盆地吉木萨尔凹陷芦草沟组,J32井,3 733.20 m,岩心手标本照片(据李哲萱等,2020修改);(i)对应h岩心手标本岩石薄片照片,准噶尔盆地吉木萨尔凹陷芦草沟组,J32井,3 733.20 m,单偏光(据李哲萱等,2020修改);(j)对应图i中j框位置,发育碎斑状方解石,裂隙发育,准噶尔盆地吉木萨尔凹陷芦草沟组,J32井,3 733.20 m,单偏光(据李哲萱等,2020修改)

Fig.1 Characteristic of volcanic-hydrothermal sediments

(a) horizontally bedded shale with two periods of tuffaceous layers, the lower layer is a feldspar crystal tuff layer, and the upper layer is a glassy tuff layer, Chang 7 member, Ordos Basin, well YY1, 228.44 m, planed-polarized light (PPL) (modified from Li *et al.*, 2020); (b) horizontally bedded shale with two periods of normal-graded volcanic crystal fragments, Chang 7 member, Ordos Basin, well YY1, 229.60 m, PPL (modified from Li *et al.*, 2020); (c) normal-graded volcanic crystal fragments, Chang 7 member, Ordos Basin, well YY1, 236.50 m, PPL (modified from Li *et al.*, 2020); (d) tuff of the lower crystal fragments in Figure a, Chang 7 member, Ordos Basin, well YY1, 228.44 m, PPL (modified from Li *et al.*, 2020); (e) interbedded laminated volcanoclastic rock (white) and dolomite (dark brown), Lucaogou Formation, Santanghu Basin, well M11, 2 944.80 m, PPL (modified from Jiao *et al.*, 2017); (f) enlargement of the f frame in e, showing angular feldspar grains (white), some with a chicken-bone structure (red arrow)(modified from Jiao *et al.*, 2017); (g) enlargement of the g frame in e, showing a clear erosional contact between the volcanoclastic rock (upper half) and the dolomite (lower half), with the volcanoclastic rock displaying normal grading (modified from Jiao *et al.*, 2017); (h) explosion breccia, with a large number of patchy calcite, red arrows indicating the gradual decrease to disappearance of patchy particles, Jimusaer Depression, Junggar Basin, Lucaogou Formation, well J32, 3 733.20 m, core photo (modified from Li *et al.*, 2020); (i) corresponding rock thin section photo of the hand specimen in h, Jimusaer Depression, Junggar Basin, Lucaogou Formation, well J32, 3 733.20 m, PPL (modified from Li *et al.*, 2020); (j) corresponding to the j frame in Figure i, showing developed patchy calcite with developed fractures, Jimusaer Depression, Junggar Basin, Lucaogou Formation, well J32, 3 733.20 m, PPL (modified from Li *et al.*, 2020)

因素的情况下,母岩性质则是影响黏土矿物生成的主要因素,通常沉积岩的抗化学风化能力强于火成岩类(杨雅秀,1994),而火成岩中的原生矿物按照鲍温反应系列(图2)(赵亚杰,2016),从橄榄石到石英,其抗风化能力又逐渐增强(陆景冈,1997)。

高岭石主要由花岗岩、花岗闪长岩等酸性、中性岩浆岩在温暖潮湿的气候条件下形成(Chamley, 1980;明洁,2013),蒙脱石主要由陆源的中性岩浆岩

和基性岩浆岩在干湿交替的气候条件或强季节性强降水环境下经过风化作用形成(de Segonzac, 1970; Chamley, 1989; Sheldon and Tabor, 2009; Liu *et al.*, 2016)。Robert(2004)认为半干旱地区蒙脱石结晶程度较高,因此其能够作为区域降水量的指示特征;此外,Jiménez-Espinosa and Jiménez-Millán(2003)认为与赤铁矿伴生形成的蒙脱石能够指示半干旱的气候条件。伊利石是典型的陆源黏土矿物,主要由陆地

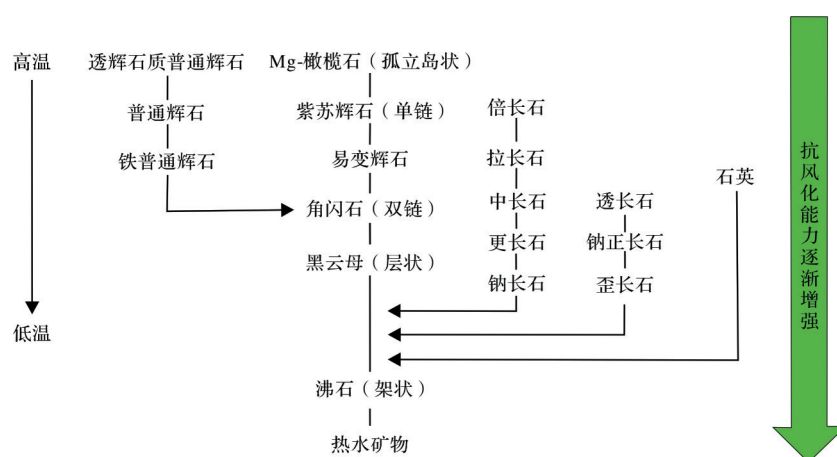


图2 鲍温反应系列图及抗风化能力(据赵亚杰,2016修改)

Fig.2 Bowen's Reaction Series diagram and weathering resistance (modified from Zhao, 2016)

上的各种母岩经过风化作用形成(刘华华等,2016),干冷条件下淋滤作用较弱,伊利石的保存条件较好(明洁,2013)。当气候向湿热条件转变时,伊利石的保存条件变差,逐渐向高岭石转变。绿泥石主要是在干燥寒冷气候条件下由低级变质岩、岩浆岩以及先前的沉积岩在化学风化作用受到抑制的条件下风化形成(汤艳杰等,2002;王银等,2021)。

另外,细粒沉积岩在成岩时期发生矿物之间的相互转化也是黏土矿物的重要成因之一。成岩演化时期,在一定的温压条件下有机质脱羧形成大量有机酸并释放 CO_2 对环境中的长石、云母进行溶解形成高岭石(Berger *et al.*, 1997);此外,当成岩时期具有钾源流体的情况下,偏基性的斜长石溶蚀后可直接沉淀形成伊利石(郇金来等,2011)。除了其他矿物转化形成黏

土矿物,成岩演化时黏土矿物之间也会发生转化,其遵循的规律一般是高岭石→蒙脱石→伊/蒙混层→伊利石、高岭石→伊利石(王秀平等,2014),通常这一过程也与长石的溶解共同发生,长石不断溶解为环境中供给 K^+ ,促进黏土矿物转化。随着研究的不断深入,黏土矿物演化及其组合已经成为表征细粒沉积岩成岩作用阶段及成熟度的指标,已有学者对黏土矿物类型和组合特征以及成熟度之间的关系进行了匹配与划分(图3)(Merriman, 2005)。

也有学者认为黏土矿物的来源与海底火山物质海解有关,大量学者研究发现在火山活动强烈的海底,如太平洋中部、马里亚纳海槽等地区的蒙脱石含量较高,其主要由海底火山活动形成的基性火山物质在海底风化形成(Jeong and Yoon, 2001; 邓韬等,

盆地成熟度	黏土矿物组合特征	烃类成熟阶段	伊利石结晶度	镜质体反射率/%	成烃阶段	成岩阶段
未成熟	蒙脱石+高岭石+伊利石+绿泥石	未成熟	~1.00	0.5 0.7 1.3	生物气	早成岩阶段
成熟	高岭石+伊/蒙混层+伊利石+绿泥石	成熟			重质—轻质油阶段	中成岩A期
	伊蒙混层+伊利石+绿泥石	高成熟			湿气阶段	中成岩B期
过成熟或低变质	伊利石+绿泥石	过成熟早期	0.42	2.0 2.5	干气阶段	晚成岩阶段
		过成熟晚期	0.30	3.0	干气阶段	
		变质期	0.25	4.0	生烃终止	变质阶段

图3 黏土矿物与细粒沉积岩成岩演化等指标关系(据 Merriman, 2005 修改)

Fig.3 The relationship between clay minerals and the diagenesis indicators of fine-grained sedimentary rocks (modified from Merriman, 2005)

2023;黄璞等,2025)。靳宁等(2007)在研究帕里西维拉海盆北部表层沉积物的黏土矿物物质来源时,发现蒙脱石丰富的区域往往与火山玻璃丰富的区域相匹配,认为蒙脱石的物源与成因和火山活动有着密切关系,且研究区弱碱性、弱氧化性的沉积环境更适合火山物质蒙脱石化作用的发生和蒙脱石的保存。

随着研究的不断深入,前人对现代土壤、湖泊以及海洋的细粒沉积物进行研究发现,常见的蒙脱石、海泡石、坡缕石、伊利石等黏土矿物均能够由胞外聚合物(Extracellular Polymeric Substances, EPS)通过生物介导作用形成(Calvo *et al.*, 1995; Ueshima and Tazaki, 2001; Burne *et al.*, 2014; Zeyen *et al.*, 2015)。王杰等(2024)在研究微生物对沙土强度的影响时,发现胶质芽孢杆菌生长活动形成的有机酸和EPS对环境中的硅酸盐矿物能产生一定的生物风化作用,部分硅酸盐矿物在风化溶蚀、络合作用下逐渐分解,形成充填在颗粒之间的黏土矿物。

目前缺乏直接利用镜下形态特征分辨黏土矿物具体物源的研究方法,主要因为黏土矿物类型多样,产状和微结构特征复杂,单纯利用镜下识别不仅难度大、误差大,且缺乏定量数据反馈的能力。因此,大多数黏土矿物溯源方法仍是通过乙二醇饱和处理、加热处理、XRD特征谱线分析、Biscaye方法等得到研究区黏土矿物的类型和相对含量,结合区域地质背景与研究区周边可能的黏土矿物物源区做对比,综合分析识别黏土矿物的物质来源(Zhang *et al.*, 2012; Li *et al.*, 2017; Jadhav *et al.*, 2022; Liu *et al.*, 2022a)。另外,由于黏土矿物性质极不稳定,易受到氧化还原条件、水动力条件、水体pH值等环境条件影响以及有机质吸附作用、成岩作用、热液作用、地下水活动等后期改造作用影响,从而改变黏土矿物性质和其指示物质来源的信号(Hu *et al.*, 2023a; Zanoni *et al.*, 2023),因此目前涉及黏土矿物的物质来源研究往往围绕表层细粒沉积物和现代细粒沉积物展开(Liu *et al.*, 2016; Chen *et al.*, 2023a; Chen *et al.*, 2023b; Hu *et al.*, 2023b; 张会娜等, 2023)。

2.2 石英来源及其成因

石英作为细粒沉积岩重要的矿物组成,在细粒沉积学理论研究以及非常规油气资源勘探开发中具有重要的研究意义。早期的研究常认为细粒沉积岩中的石英主要来源于陆源碎屑(Blatt and Schultz, 1976; Milliken, 1994),然而随着研究的不断深入,

这一观点逐渐被推翻,Chen *et al.*(2009)认为洋盆中的石英多来源于火山—热液活动;Schieber *et al.*(2000)认为页岩中的石英除了陆源提供,浮游生物的蛋白石骨架溶解也能提供石英;Zhao *et al.*(2017)发现石英不仅来源于浮游生物,还可能来源于黏土矿物转化;Metwally and Chesnokov(2012)研究指出石英来源于黏土矿物转化和长英质矿物的溶解以及交代作用;另外,Milliken *et al.*(2016)研究发现美国晚白垩世的Eagle Ford页岩区域,自生石英的比例高达85%;Ye *et al.*(2022)研究认为我国四川盆地五峰组—龙马溪组页岩中自生石英的含量可达到50%。综合上述观点,可将石英类型总结为:陆源碎屑石英、生物石英、火山—热液源石英、黏土矿物转化石英、长英质矿物溶蚀石英、交代石英等。

细粒沉积岩中的陆源碎屑石英具有较强的抗风化能力,在整体搬运过程中保存良好,常呈次圆状—次棱角状,粒级分布介于10~50 μm (图4a)(易婷, 2020; 赵迪斐, 2021; 冯冰等, 2024)。电子显微镜下,陆源碎屑石英颗粒无色透明,正交光下干涉色较淡,如一级灰白、一级黄白、一级淡黄等;另外,由于搬运作用、成岩作用的影响,陆源碎屑石英表面常有裂纹和溶蚀现象,部分石英边缘可见次生加大边(图4b)(Thyberg *et al.*, 2010; 钟秋, 2021)。通常,利用石英颗粒表面微形态特征能够分析其搬运方式(Vos *et al.*, 2014):风力搬运的陆源碎屑石英表面常见碟形撞击坑(图4c)、新月形撞击坑(图4d)、麻点等特征(图4e);水力搬运的陆源碎屑石英表面常见水下磨光面(图4f)、直线或弯曲的撞击沟(图4g)、V形撞击坑(图4h)等水力搬运特征(江新胜等, 2003; 汤海磊等, 2020; 黄日辉等, 2023; 丁家翔等, 2025; 田娅琪等, 2025)。

形成陆源碎屑石英的母岩在地质历史时期所经历的温度条件不同,阴极发光特征也不同,因此利用阴极发光特征能够分析陆源碎屑石英的母岩类型(Ye *et al.*, 2022)。母岩为火成岩(经历温度>573 $^{\circ}\text{C}$)的石英阴极发光以蓝紫色为主(Zinkernagel, 1978; 魏月华, 2022)(图5a);母岩为变质岩(经历温度300 $^{\circ}\text{C}$ ~573 $^{\circ}\text{C}$)的石英阴极发光以棕色、褐紫色为主(图5b)(王子腾, 2020; 张俊锋等, 2022; 袁圣强等, 2023);母岩为沉积岩(经历温度<300 $^{\circ}\text{C}$)的石英阴极发光表现为不发光(图5c)(王子腾, 2020)。此外,利用SEM-CL图像和单色阴极发光光谱特征也能分析石

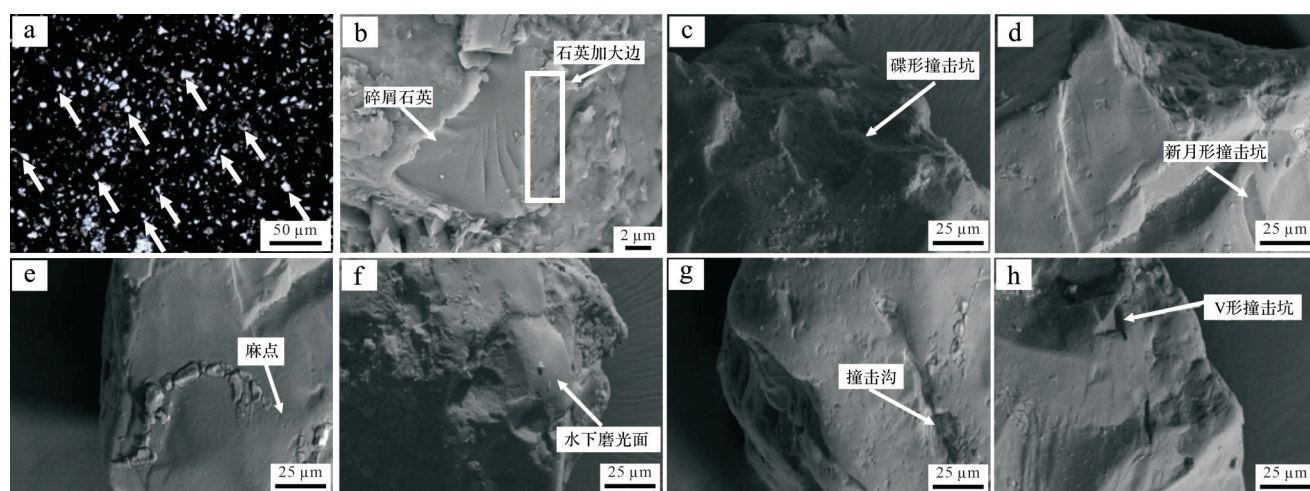


图4 陆源碎屑石英微观特征

(a)陆源碎屑石英(白色箭头所指),分选较好,呈次棱角状—次圆状均匀分布在细粒沉积岩中,黔北正安地区,龙马溪组,安页2井,单偏光(据冯冰等,2024修改);(b)陆源碎屑石英伴生的石英加大边(白框内),沁水盆地山西组—太原组,扫描电镜(据冯冰等,2024修改);(c)风力搬运陆源碎屑石英表面微型态—碟形撞击坑,扫描电镜(据黄日辉等,2023修改);(d)风力搬运陆源碎屑石英表面微型态—新月形撞击坑,扫描电镜(据黄日辉等,2023修改);(e)风力搬运陆源碎屑石英表面微型态—麻点坑,扫描电镜(据黄日辉等,2023修改);(f)水力搬运陆源碎屑石英表面微型态—水下磨光面,扫描电镜(据黄日辉等,2023修改);(g)水力搬运陆源碎屑石英表面微型态—撞击沟,扫描电镜(据黄日辉等,2023修改);(h)水力搬运陆源碎屑石英表面微型态—V形撞击坑,扫描电镜(据黄日辉等,2023修改)

Fig.4 Microscopic characteristics of detrital quartz from terrestrial sources

(a) terrestrial detrital quartz (indicated by white arrows), well sorted, with subangular to subrounded shapes evenly distributed in fine-grained sedimentary rocks, in the Zheng'an area of northern Guizhou, Longmaxi Formation, well Anye-2, PPL (modified from Feng *et al.*, 2024); (b) terrestrial detrital quartz accompanied by quartz overgrowth (within the white frame), in the Qinshui Basin, Shanxi Formation-Taiyuan Formation, Scanning Electron Microscope (SEM) (modified from Feng *et al.*, 2024); (c) aeolian transported terrestrial detrital quartz with surface micro-morphology - disc-shaped impact craters, SEM (modified from Huang *et al.*, 2023); (d) aeolian transported terrestrial detrital quartz with surface micro-morphology - crescent-shaped impact craters, SEM (modified from Huang *et al.*, 2023); (e) aeolian transported terrestrial detrital quartz with surface micro-morphology - pitted craters, SEM (modified from Huang *et al.*, 2023); (f) hydraulic transported terrestrial detrital quartz with surface micro-morphology - subaqueous polished surfaces, SEM (modified from Huang *et al.*, 2023); (g) hydraulic transported terrestrial detrital quartz with surface micro-morphology - impact grooves, SEM (modified from Huang *et al.*, 2023); (h) hydraulic transported terrestrial detrital quartz with surface micro-morphology - V-shaped impact craters, SEM (modified from Huang *et al.*, 2023)

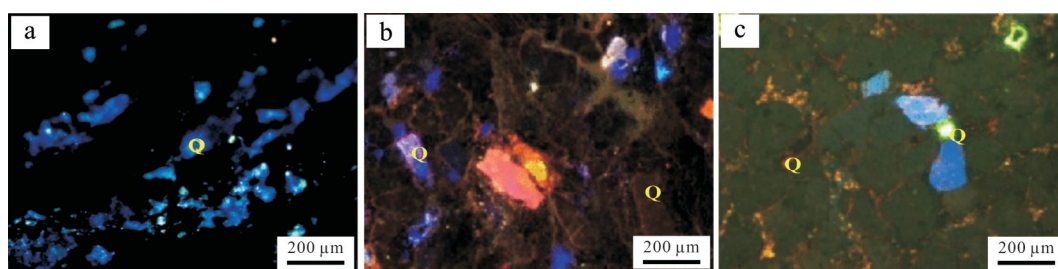


图5 陆源碎屑石英阴极发光特征

(a)陆源碎屑石英阴极发光呈蓝色,其母岩为岩浆岩,澜沧群沉积岩(据魏月华,2022修改);(b)陆源碎屑石英阴极发光呈棕褐色,偶见蓝紫色,母岩为变质岩和少量岩浆岩,苏峪口剖面(据王子腾,2020修改);(c)校育川剖面,陆源碎屑石英阴极发光呈棕褐色和不发光,偶见蓝紫色,证明母岩为变质岩、沉积岩和少量岩浆岩(据王子腾,2020修改)

Fig.5 Cathodoluminescence characteristics of detrital quartz from terrestrial sources

(a) cathodoluminescence of terrestrial detrital quartz appears blue, its parent rock is igneous, Lancang Group sedimentary rocks (modified from Wei, 2022); (b) cathodoluminescence of terrestrial detrital quartz appears brown, occasionally blue-purple, parent rock is metamorphic rock and a small amount of igneous rock, Suyu Kou section (modified from Wang, 2022); (c) at the Xiaoyu Chuan section, the cathodoluminescence of terrestrial detrital quartz appears brown and non-luminous, occasionally blue-purple, indicating that the parent rocks are metamorphic rocks, sedimentary rocks, and a small amount of igneous rocks (modified from Wang, 2022)

英是否属于陆源碎屑:通常陆源碎屑石英表现为SEM-CL图像上的强发光和单色阴极发光光谱的双峰值,主峰为625~650 nm,次峰出现于420~450 nm处(Peltonen *et al.*, 2009; 赵建华等, 2016; 刘洪林等, 2019; 管全中, 2020)。

生物石英主要源于盆内的硅质生物躯壳,如放射虫、海绵骨针、硅藻等硅质生物,属于内源沉积物质。硅质生物生长活动时从水体中汲取 Si^{4+} ,将其在体内转化为性质不稳定的蛋白石-A,生物死亡后其沉积在水体底部,在早成岩阶段在温度、压力等作

用下,不稳定的蛋白石-A逐渐向稳定的蛋白石-CT转化,最终转化形成稳定的隐晶质、微晶以及粗晶石英(王濡岳等,2021;李怡等,2024)。生物石英一般具有两种常见的形式:一种是继承了生物原始结构、形态的石英(图6a,b)(赵建华等,2016;钟秋,2021;彭俊文,2022;卢龙飞等,2022;李怡等,2024;王拔秀等,2024),另一种是受到水—岩作用溶解后经过重结晶作用形成的无生物结构的隐晶/微晶质石英集合体,常与沥青质体伴生(图6c)(卢龙飞等,2022)。通常,生物石英在阴极射线照射下弱发光或不发光(图6d)(钟秋,2021),单色阴极发光光谱主峰介于580~620 nm,次峰介于390~430 nm(刘洪林等,2018)。

火山—热液活动也是细粒沉积岩石英的重要来源,火山喷发带来的凝灰质物质是细粒沉积岩的重要物质组成,常呈条带状、纹层状分布(图7a)(罗凡等,2024),其包含丰富的、性质极不稳定的火山玻璃(王俊怀等,2014;张建国等,2022;何文军等,2023),在早成岩作用浅埋藏阶段,火山玻璃经历脱玻化转变为微晶石英(郝兵,2021)、长石等矿物以及非晶形态的二氧化硅。扫描电镜下可见火山—热液源石英呈微型条带状聚集(图7b),也可见石英形成于孔、洞之中(图7c)(刘国恒等,2016)。火山—热液源石英主要以两种形式存在,一种呈非晶形态,不规则球粒状、无棱角发育(图7d,e)(刘国恒等,2016;何文军等,2023);另一种常与长石、白云石、残留的火山物质共生的石英,其晶型较好,多呈短柱状而并非经典的六方柱状分布(图7c,f)。当利用石英的晶体形态难以判断其为火山—热液源石英时,可以利用石英

附近的非晶态物质能谱分析判断,一般硅铝比显示为与上地幔中的硅铝比相一致的7~9,或远高于大陆地壳中的硅铝比(3.8)时,则证明石英为火山—热液来源(刘国恒等,2016)。

除了上述陆源、内源、火山—热液源所直接或间接向细粒沉积岩提供的石英外,成岩作用也是石英形成的重要方式之一,但其物源溯源难度大,因此难以划分至本文的三大物源方案之中。成岩过程中随着温度、压力的不断增大,黏土矿物逐渐从蒙脱石、伊/蒙混层、高岭石向伊利石转化(高波等,2025)。该过程中黏土矿物不断从环境中汲取 K^+ ,并向环境中释放 Si^{4+} (Hower *et al.*, 1976),由于细粒沉积岩的渗透率极低,其释放的游离 Si^{4+} 无法流动和扩散,因此逐渐沉积在原地,随着成岩作用的进行,一部分 Si^{4+} 逐渐转化为自生石英充填于黏土矿物之间(图8a,b)(Liang *et al.*, 2018a; 操应长等,2023)。这一过程涉及大量钾的供应,通常钾来源于长石的溶解,当有机质进入生油窗时,有机质脱羧形成大量有机酸并释放 CO_2 对环境中的长石进行溶解,该过程不仅能直接向环境内输送硅质还能提供大量 K^+ ,促进黏土矿物转化释放大量硅质(邱隆伟等,2001;张永旺等,2021)。四川盆地自流井组常见大量生物介壳边缘发育石英,其是由介壳边缘的长石溶解、黏土矿物转化释放的硅质对介壳边缘的方解石交代所形成的成岩自生石英(图8c)(朱毅秀等,2021)。另外,在碱性的成岩条件下,陆源碎屑石英颗粒表面常被溶蚀产生孔隙,边缘溶蚀呈港湾状,当溶蚀的 Si^{4+} 浓度达到饱和时,可形成石英次生加大边(图8b)或以自生石英晶体独立存在(万友利等,2014)。

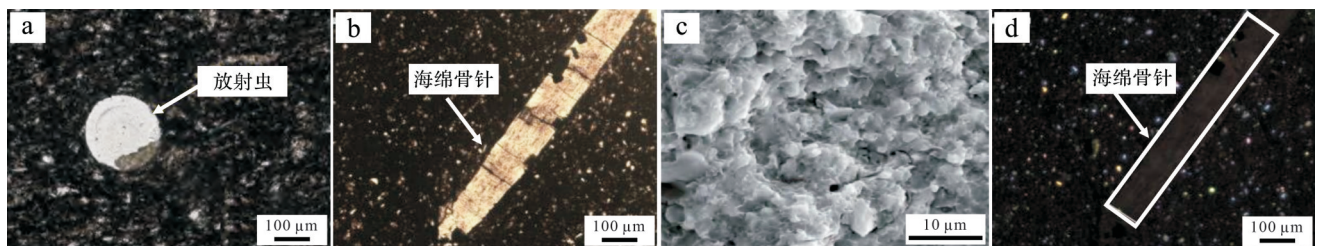


图6 生物石英微观特征

(a)放射虫石英,下扬子地区,高家边组,鼓地1井,1 222.00 m,单偏光(据钟秋,2021修改);(b)海绵骨针石英,重庆盆地东北部下志留统龙马溪组,单偏光(据王拔秀等,2024修改);(c)微晶石英集合体,表面光滑细腻,多为隐晶质,四川盆地五峰组—龙马溪组,扫描电镜(据卢龙飞等,2022修改);(d)图(b)的阴极发光照片,白框对应(b)中的海绵骨针,阴极射线照射下表现为不发光(据钟秋,2021修改)

Fig.6 Microscopic characteristics of biotic quartz

(a) radiolarian quartz, in the Lower Yangtze region, Gaojiabian Formation, well Gudi-1, 1 222.00 m, PPL (modified from Zhong, 2021); (b) spicule quartz, in the northeastern Chongqing Basin, Lower Silurian System Longmaxi Formation, PPL (modified from Wang *et al.*, 2024); (c) microcrystalline quartz aggregates, smooth and delicate surfaces, mostly cryptocrystalline, Sichuan Basin Wufeng Formation-Longmaxi Formation, SEM (modified from Lu *et al.*, 2022); (d) cathodoluminescence photograph of Figure (b), the white frame corresponds to the spicules in (b), non-luminous under cathode ray irradiation (modified from Zhong, 2021)

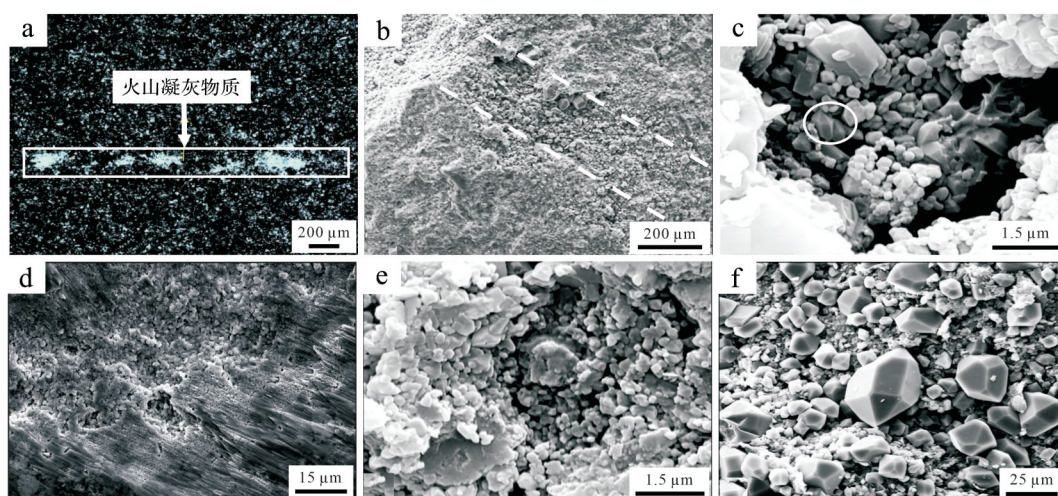


图7 火山—热液作用石英特征

(a)火山凝灰物质,呈纹层状分布,鄂西咸丰地区,五峰组—龙马溪组,EXY1井,1 512.80 m,正交偏光(据罗凡等,2024修改);(b)凝灰质细粒沉积岩,图中白色条带中间为石英聚集形成的条带,马朗坳陷芦草沟组,LU1井,3 062.18 m,扫描电镜(据刘国恒等,2016修改);(c)凝灰岩,白圈为凝灰岩脱玻化形成自生石英,与长石共生形成于孔、洞之中马朗坳陷芦草沟组,LU1井,3 060.63 m,扫描电镜(据刘国恒等,2016修改);(d)含云凝灰物质脱玻化形成非晶形态的二氧化硅,玛湖坳陷粉尘风城组,MY1井,4 952.18 m, P_f^{-1} ,扫描电镜(据何文军等,2023修改);(e)凝灰物质脱玻化作用形成非晶态,不规则球粒状二氧化硅,马朗坳陷芦草沟组,LU1井,3 060.63 m,扫描电镜(据刘国恒等,2016修改);(f)凝灰物质脱玻化形成晶型较好的,短柱状石英,与白云石、长石、残余火山物质共生,马朗坳陷芦草沟组,LU1井,3 062.18 m,扫描电镜(据刘国恒等,2016修改)

Fig.7 Microscopic characteristics of hydrothermal-volcanic quartz

(a) volcanic ash material, distributed in a laminated pattern, in the western Hubei Xianfeng area, Wufeng Formation-Longmaxi Formation, well EXY1, 1 512.80 m, cross-polarized light (XPL) (modified from Luo *et al.*, 2024); (b) tuffaceous fine-grained sedimentary rock, the white band in the middle of the picture is a band formed by the aggregation of quartz, Malang Depression Lucaogou Formation, well LU1, 3 062.18 m, SEM (modified from Liu *et al.*, 2016); (c) tuff, the white circle is the self-formed quartz formed by the devitrification of tuff, coexisting with feldspar in pores and caves in the Malang Depression Lucaogou Formation, well LU1, 3 060.63 m, SEM (modified from Liu *et al.*, 2016); (d) devitrification of tuff material containing cloud ash to form non-crystalline forms of silicon dioxide, Mahu Depression dust wind city group, well MY1, 4 952.18 m, P_f^{-1} , SEM (modified from He *et al.*, 2023); (e) devitrification of tuff material to form amorphous, irregular spherical silicon dioxide, Malang Depression Lucaogou Formation, well LU1, 3 060.63 m, SEM (modified from Liu *et al.*, 2016); (f) self-formed quartz formed by the devitrification of tuff material, with better crystallinity, short columnar quartz, coexisting with dolomite, feldspar, and residual volcanic material, Malang Depression Lucaogou Formation, well LU1, 3 062.18 m, SEM (modified from Liu *et al.*, 2016)

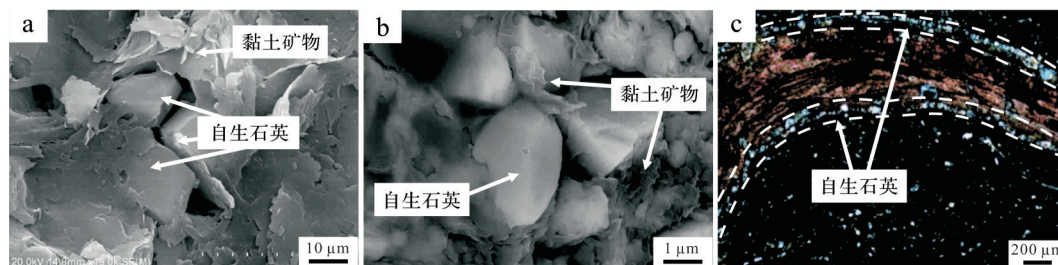


图8 成岩作用石英微观特征

(a)成岩自生石英,充填于黏土矿物之间,济阳坳陷沙四上亚段,NY1井,3 456.50 m,扫描电镜(据Liang *et al.*, 2018a修改);(b)成岩自生石英,充填于黏土矿物之间,鄂尔多斯盆地延长组,G293井,2 565.00 m,扫描电镜(据操应长等,2023修改);(c)硅质交代钙质形成的自生石英,石英在介壳边缘向内部生长(箭头所指虚线内),川北元坝地区侏罗统大安寨段,YL4井,3 758.20 m,正交偏光(据朱毅秀等,2021修改)

Fig.8 Microscopic characteristics of diagenetic quartz

(a) diagenetic self-formed quartz, filling between clay minerals, Jiyang Depression Sha four upper sub-segment, well NY1, 3 456.50 m, SEM (modified from Liang *et al.*, 2018a); (b) diagenetic self-formed quartz, filling between clay minerals, Ordos Basin Yanchang Formation, well G293, 2 565.00 m, SEM (modified from Cao *et al.*, 2023); (c) self-formed quartz formed by silicification of calcareous material, quartz growing from the edge of the shell to the inside (indicated by the dashed line in the arrow), in the Yuanba area of northern Sichuan, Jurassic Da'anzhai segment, well YL4, 3 758.20 m, XPL (modified from Zhu *et al.*, 2021)

2.3 长石来源及其成因

长石族矿物是细粒沉积岩储层中的重要骨架颗粒,大量的钻井岩心资料表明长石矿物广泛存在于古生代—新生代的相关细粒沉积地层中。例如:我

国鄂尔多斯盆地上三叠系延长组(解馨慧等,2024)、渤海湾盆地沧东凹陷古近系孔二段(冯家乐等,2024)、四川盆地中侏罗世千佛崖组(彭军等,2024)、松辽盆地白垩系青山口组(于利民,2023)、三塘湖盆

地二叠系芦草沟组(秦恩鹏等,2023)等。作为细粒沉积岩重要的物质组成,长石在构造背景和物源区性质判识、沉积环境分析、古环境重建等方面有着不可忽视的研究意义。

通常,细粒沉积岩中的长石大部分来源于陆源物质风化,即陆源区母岩,特别是花岗岩和片麻岩,经过长期风化作用形成,伴随多种搬运介质搬运并进一步风化,最终形成细粒沉积岩的组成部分。相较于石英而言,长石族矿物的抗风化能力较弱,因此其在细粒沉积岩中的含量往往小于石英,而钾长石与钠长石相比具备更强的风化能力,这就导致细粒沉积岩中的斜长石含量随着陆源区距离的增加而逐渐减小,而钾长石的相对含量逐渐增加,通过这一特征并结合具体研究的实际地质条件、地质背景,能够对细粒沉积岩陆源区进行初步的判识(Lerman *et al.*, 1995)。但Schieber(1996)和Schieber *et al.*(2000)研究北美泥盆系富有机质细粒沉积岩时,将与长石同属于硅酸盐矿物的石英作为研究对象,发现其含量不具备上述传统沉积学理论所支撑的由陆源区向沉积中心递减的现象,并且石英颗粒多具备自生结构特征,而几乎无搬运特征,应是其他作用形成。因此,同上一小节石英的来源与成因一样,除了聚焦于传统陆源碎屑提供外,还应考虑其他来源。

随着研究的不断深入,众多学者一致认为火山—热液活动是细粒沉积岩中长石矿物的重要物质来源之一。一方面,火山活动形成的火山碎屑物质和水下热液活动能够直接为细粒沉积岩“源—汇”系统提供长石矿物,如我国准噶尔盆地、三塘湖盆地等盆地均

发现以钠长石、方沸石为主的“白烟囱”型喷流式沉积物(常海亮等,2016;柳益群等,2011);另一方面火山—热液活动也能够为细粒沉积岩中长石的形成提供物质基础(焦鑫等,2021),经成岩作用阶段形成长石,如玛湖凹陷风城组常见由火山活动带来的火山玻璃、玻屑、火山尘等在沉积埋藏后,经碱性流体作用下重结晶形成的长石(何文军等,2023)。

除此之外,近年来微生物形成长石的相关研究也越来越受到重视。碱性铁还原菌等微生物在其铁还原酶的作用下(Shi *et al.*, 2007),破坏蒙脱石结构Fe(III)进而导致蒙脱石中大量的Al、Si等元素释放到环境中,而微生物表面的大分子有机物(即胞外聚合物,EPS)携带大量负电荷的官能团,能够有效吸附环境中的 Al^{3+} 、 Si^{4+} 等元素,形成纳米级无定形Al-Si复合体,再经历脱水、熟化等作用最终形成长石(图9)(Konhauser and Urrutia, 1999)。

2.4 碳酸盐矿物来源及其成因

碳酸盐矿物在碳酸盐质细粒沉积岩和混积细粒沉积岩中具有较高的含量分布,如我国渤海湾盆地始新统、南襄盆地渐新统湖相地层发育灰质细粒沉积岩(张建国等,2022;Sun *et al.*, 2023;Xia *et al.*, 2024;李阳等,2025),江汉盆地古近系、渤海湾盆地沧东凹陷始新统、准噶尔盆地、三塘湖盆地中二叠统发育云质细粒沉积岩(周立宏等,2018;Zhao *et al.*, 2018;邓远等,2020;潘永帅等,2022;张建国等,2022;肖贝等,2024;俞映月等,2024),其往往受陆源碎屑供应、盆内环境条件以及火山—热液活动等多种因素共同控制形成(图10)。

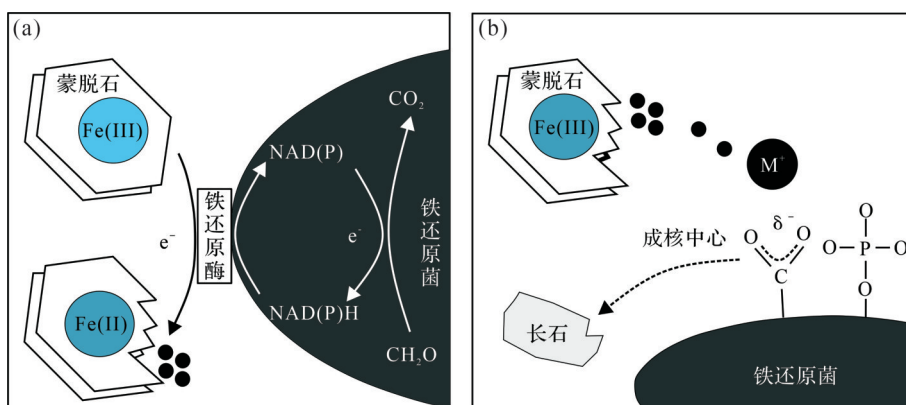


图9 微生物介导长石形成机制(据Konhauser and Urrutia, 1999修改)

(a)微生物体内有机质氧化产生的电子经过铁还原酶传递给胞外铁蒙脱石,导致蒙脱石结构被破坏;(b)蒙脱石释放的元素经过胞外聚合物吸附最终形成长石

Fig.9 Mechanism of feldspar formation mediated by microorganisms (modified from Konhauser and Urrutia, 1999)

(a) organic matter within microorganisms is oxidized to produce electrons that are transferred to extracellular iron-bearing montmorillonite through iron-reducing enzymes, leading to the destruction of the montmorillonite structure; (b) elements released from montmorillonite are adsorbed by extracellular polymers and ultimately form feldspar

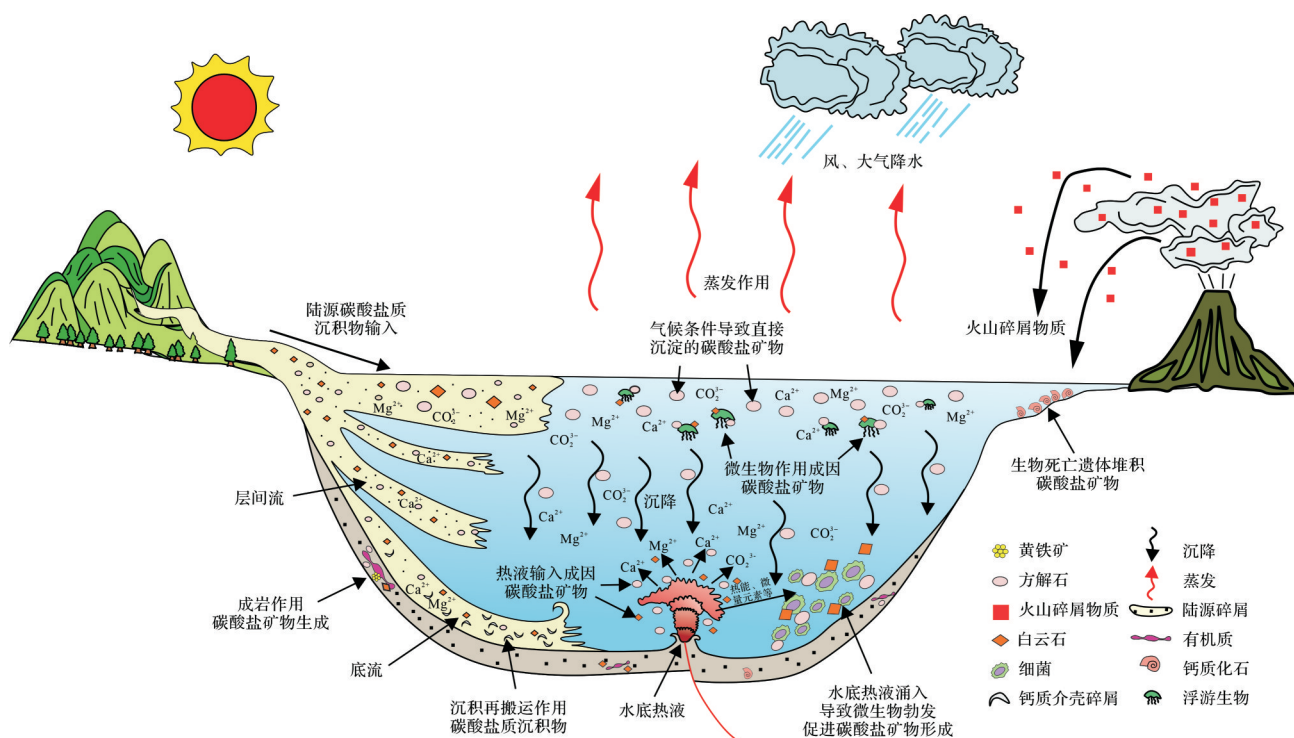


图10 碳酸盐质细粒沉积物形成模式

Fig.10 Formation patterns of carbonate fine-grained sediments

早期研究往往认为碳酸盐矿物主要由化学作用直接沉淀形成,但近年来学者们发现化学作用形成碳酸盐矿物的条件十分苛刻。当气候条件导致的蒸发作用非常强烈或者热液涌入水体导致离子浓度局部过饱和时,才能通过化学作用形成大量碳酸盐质细粒沉积物。通常这类碳酸盐质细粒沉积岩有机质含量较低,如江汉盆地潜江凹陷古近系发育大量低有机质韵律夹钙芒硝层状泥晶白云岩(图11a)(吴世强等, 2020),其形成原因可能与沉积时期亚热带干旱气候和封闭性高盐度湖水(张永生等, 2005; 徐崇凯等, 2018)导致的化学作用有关。另外,化学作用也常发生在成岩作用阶段:一方面,有机质成岩演化时,向环境中释放有机酸和 CO_2 对原有的碳酸盐矿物溶解,形成的流体经重结晶作用形成晶型较好的方解石(陈森然等, 2024),常呈亮晶方解石纹层状分布(图11b~d)(韩豫等, 2024; 张欢等, 2024);另一方面,细粒沉积岩经过压实脱水,蒙脱石和伊利石等黏土矿物发生转化为环境卤水中释放大 Mg^{2+} ,形成富镁的高盐度白云石化流体,当白云石化流体与方解石进行深埋接触交代时,方解石逐渐转化为白云石,常呈中—粗晶、自形—半自形存在于细粒沉积岩中(图11e, f)(滕建彬, 2018; 朱光有和李茜, 2023; 李茜等, 2024)。

近年来,众多学者围绕微生物在碳酸盐矿物形

成中起到的作用,开展了大量研究工作,发现碳酸盐矿物的形成和盆内微生物化学作用密切相关(Stabel, 1986; Dupraz *et al.*, 2009; Macquaker *et al.*, 2010)。水体中的浮游生物、细菌,如浮游藻、蓝细菌等通过新陈代谢降低 CO_2 分压,导致水体pH值升高, HCO_3^- 向 CO_3^{2-} 方向转化,促进碳酸盐矿物形成(图12a, b)(Kelts and Hsü, 1978; Ditttrich and Obst, 2004; Bluszcz *et al.*, 2009)。通常,这类碳酸盐矿物具有明显的季节性差异,夏季水体生物勃发、蒸发作用强,易形成较厚的、颜色较浅的碳酸盐质细粒沉积纹层;而冬季水体生物大量死亡、蒸发作用弱,易形成较薄的、颜色较深的、由碳酸盐矿物、黏土矿物和生物死亡后形成的有机质共同组成的纹层(图13a)(Ma *et al.*, 2017; 王铭乾等, 2025)。另一方面,生物分泌的大分子有机物附着在生物表面形成的胞外聚合物(EPS)在碳酸盐矿物的形成中也扮演着重要角色(Dupraz *et al.*, 2009; Krause *et al.*, 2012; Suosaari *et al.*, 2022)。EPS含有带负电荷的官能团,能够结合水中的金属阳离子形成以生物细胞壁为基底的方解石、白云石等碳酸盐矿物(图12c)(Pacton *et al.*, 2007; De Muynck *et al.*, 2010; Decho and Gutierrez, 2017; 冯晓等, 2024),当矿物形成后,成核基底有机质和EPS降解形成遗留的小孔(图13b)。因此,微生

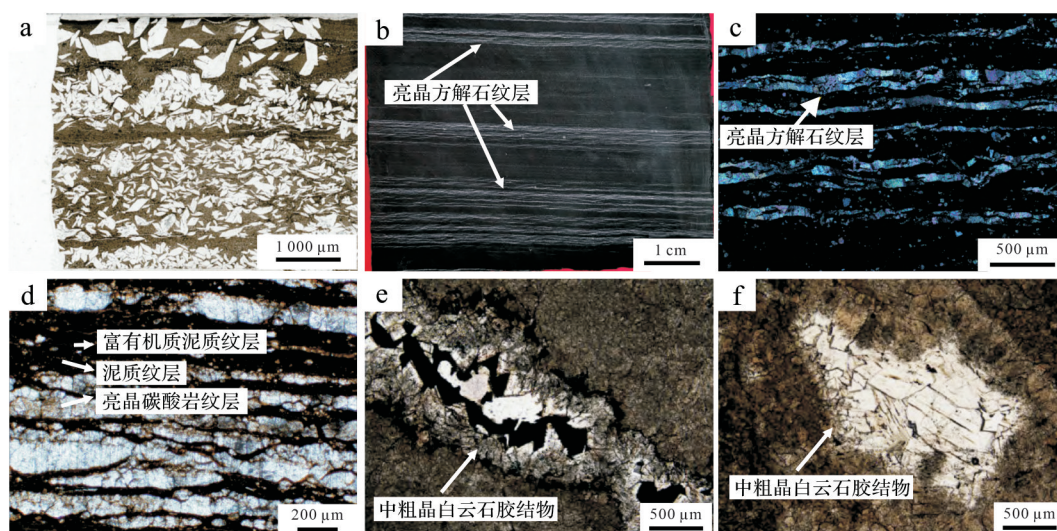


图 11 化学作用成因碳酸盐质细粒沉积物微观特征

(a)层状钙芒硝,芒硝结晶程度较好,江汉盆地潜江凹陷古近系,蚌页油 2 井,3 647.32 m,单偏光(据吴世强等,2020 修改);(b)纹层状灰质黏土岩,箭头所指为亮晶方解石纹层,川南地区五峰组—龙马溪组,W213 井,3 741.42 m,岩心照片(据韩豫等,2024 修改);(c)亮晶方解石纹层与黏土纹层互层,川南地区五峰组—龙马溪组,W213 井,3 741.42 m,正交偏光(据韩豫等,2024 修改);(d)亮晶方解石纹层与黏土纹层互层,渤海湾盆地东营凹陷沙三下亚段—沙四上亚段,正交偏光(据张欢等,2024 修改);(e)埋藏成因形成的中—粗晶白云石胶结物,发育在孔隙边缘,具有明显的次生加大边,四川盆地震旦系灯影组,单偏光(据李茜等,2024 修改);(f)埋藏成因形成白云石胶结物,四川盆地震旦系灯影组,单偏光(据李茜等,2024 修改)

Fig.11 Microscopic characteristics of chemically formed calcareous fine-grained sediments

(a) lamellar natrite, with well-formed crystals of natrite, in the Paleogene of the Qianjiang Depression of the Jiangnan Basin, well Bangye Oil 2, 3 647.32 m, PPL (modified from Wu *et al.*, 2020); (b) laminated argillaceous limestone, with bright calcite laminae indicated by the arrow, in the Wufeng Formation - Longmaxi Formation of the southern Sichuan area, well W213, 3 741.42 m, core photo (modified from Han *et al.*, 2024); (c) alternating bright calcite laminae and argillaceous laminae, in the Wufeng Formation - Longmaxi Formation of the southern Sichuan area, well W213, 3 741.42 m, XPL (modified from Han *et al.*, 2024); (d) alternating bright calcite laminae and argillaceous laminae, in the lower submember of the Sha San and the upper submember of the Sha Si of the Dongying Depression, XPL (modified from Zhang *et al.*, 2024); (e) medium- to coarse-crystalline dolomite cement formed by burial genesis, developed at the edge of pores, with distinct secondary enlargement margins, from the Sinian Doushantuo Formation in the Sichuan Basin, PPL (modified from Li *et al.*, 2024); (f) dolomite cement formed by burial genesis, from the Sinian Doushantuo Formation in the Sichuan Basin, PPL (modified from Li *et al.*, 2024)

物活动导致 EPS 微域的 pH 值局部增加,能够诱导形成无定形方解石与 EPS 大分子混合物产生纳米级方解石球体(图 13c,d),如渤海湾盆地东营凹陷沙河街组中的纳米级簇状、哑铃状方解石(Dupraz *et al.*, 2009;韩舒筠等,2018);也能够诱导方解石围绕微生物沉淀,其核心为球状、哑铃状微生物(图 13e)(王金艺和金振奎,2022;李茜等,2024)。除此之外,微生物硫酸盐还原作用和甲烷生成作用也能影响白云石的形成,这种生物成因的白云石化作用通常主要用于解释非碱性微咸水—咸水湖相深水富有机质含泥白云岩或云质细粒沉积岩中的白云石成因,常与菱铁矿、黄铁矿伴生形成(滕建彬等,2022;Guo *et al.*, 2023)。

另外,盆内生物作用可直接为细粒沉积岩提供碳酸盐矿物。软体动物贝壳、轮藻、珊瑚等生物死亡后遗体堆积直接可以形成方解石、文石、一水合碳酸钙等碳酸盐矿物(滕建彬等,2022)。这类碳酸盐矿物一定程度上保留着生物的原始形态(图 13f~h)

(Becker *et al.*, 2003;崔航等,2022;李倩文等,2022),广泛发育于巴西桑托斯盆地阿普特阶/巴雷姆阶 Itapema 组(Anjos *et al.*, 2019)、美国堪萨斯州下二叠统(Watabe and Kaesler, 2004)以及我国四川盆地自流井组(辛利伟等,2024)、千佛崖组(蒋代琴等,2024)、茅口组(刘树根等,2020)、松辽盆地青山口组(王鑫等,2024)、嫩江组(王成善等,2008)、羌塘盆地中侏罗统布曲组(刘中戎等,2025)、准噶尔盆地芦苇沟组(胡素云等,2019)、渤海湾盆地沙河街组(王永炜等,2017)等细粒沉积地层中。

除了生物化学作用、生物作用外,盆内的沉积物质再搬运沉积作用也是方解石、白云石等碳酸盐质细粒沉积物的重要成因机制(姜在兴等,2021)。例如:东营凹陷南坡陈官庄地区沙河街组四段上亚段的混积细粒沉积岩中可见大量碳酸盐质砾屑颗粒(图 14a)(彭军等,2022),即原先形成的沉积物质经过风暴侵蚀、破碎后重新沉积形成碳酸盐质沉积物。

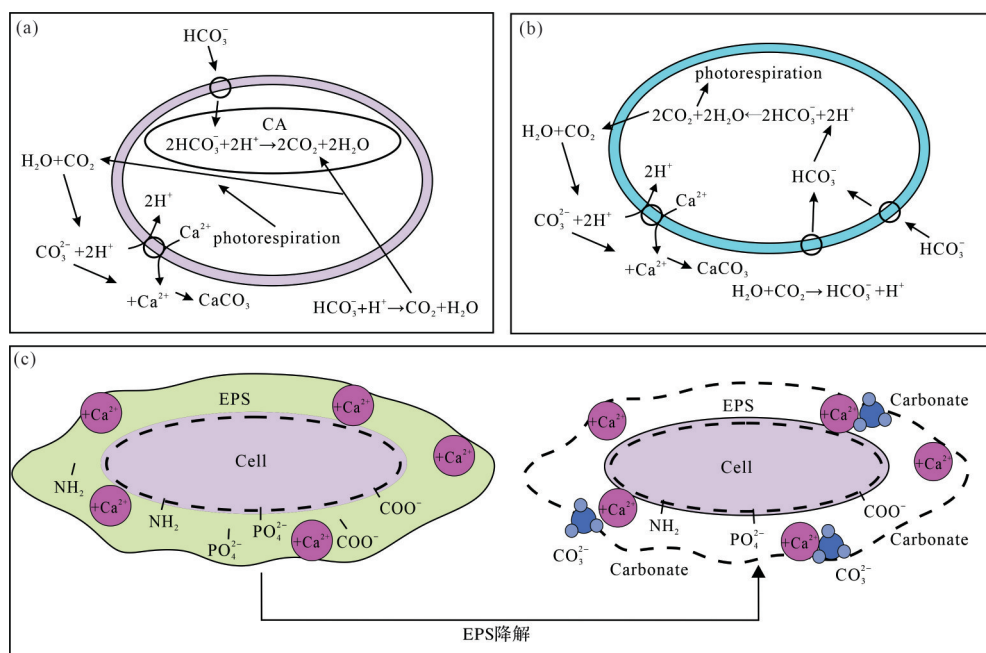


图 12 微生物化学作用形成碳酸盐矿物理论模型

(a) 浮游藻生物化学作用形成方解石理论模型 (据 Dittrich and Obst, 2004 修改); (b) 蓝细菌生物化学作用形成方解石理论模型 (据 Dittrich and Obst, 2004 修改); (c) 微生物胞外聚合物促使碳酸盐矿物沉淀理论模型 (据冯晓等, 2024 修改); EPS: 胞外聚合物

Fig.12 Theoretical models for the formation of carbonate minerals by microbial chemical action

(a) theoretical model for the formation of calcite by planktonic algae through biochemical action (modified from Dittrich and Obst, 2004); (b) theoretical model for the formation of calcite by cyanobacteria through biochemical action (modified from Dittrich and Obst, 2004); (c) theoretical model for the precipitation of carbonate minerals induced by microbial extracellular polymers (modified from Feng *et al.*, 2024)

陆源物质的输入同样也会对碳酸盐矿物的形成产生影响(姜在兴等, 2021)。陆源区灰岩、白云岩、大理岩、玄武岩、碳酸岩等在风化淋滤过程中释放大量 Ca^{2+} 、 Mg^{2+} 能为盆内碳酸盐矿物的形成提供丰富的物质基础(Valero, 1993)。通常情况下, 陆源区以丰富的碳酸盐矿物组成的岩石为主时, 盆区内具备形成大量碳酸盐岩的条件。当陆源区既有碳酸盐矿物又有硅质碎屑基岩时, 盆内形成的碳酸盐岩规模会受到源区风化强度、物质输入类型以及构造特征等因素控制; 当陆源区的碳酸盐矿物组成的岩石含量极少时, 盆内缺乏 Ca^{2+} 、 Mg^{2+} 等离子的供给, 往往很难形成规模性的碳酸盐矿物(姜在兴等, 2021)。另外, 富含碳酸盐矿物的陆源区受到强构造活动、较为干旱的气候条件等因素的影响, 能够直接为较近的盆内输入大量分选、磨圆较差的陆源碳酸盐质碎屑(任韵清, 1986; Jiang *et al.*, 2007; Zheng *et al.*, 2015), 在东营凹陷沙三下亚段, 可见大量分选、磨圆较差的云质碎屑与长英质矿物、黏土矿物共同沉积(图 14b, c)(孔祥鑫, 2020)。

除了内源与陆源, 火山—热液活动也是碳酸盐

矿物的重要物质来源(柳益群等, 2011)。火山—热液活动可向盆内提供 Ca^{2+} 、 Mg^{2+} 等离子并提高环境中 CO_2 含量以及水体的 pH 值, 从而营造出更加适合碳酸盐矿物形成的环境(Landmann *et al.*, 1996; 蒋宜勤等, 2015; 张奎华等, 2025)。一方面, 水底热液的注入能够提高周围区域 Ca^{2+} 、 Mg^{2+} 、 Fe^{2+} 、 CO_3^{2-} 等离子浓度和水体温度, 促进富含 Fe、Mg 的方解石、白云石等碳酸盐矿物直接沉淀(柳益群等, 2011), 通常这类白云石晶体中的流体包裹体均一温度在 $167\text{ }^{\circ}\text{C} \sim 283\text{ }^{\circ}\text{C}$, 呈负偏态分布, 55% 的温度在 $160\text{ }^{\circ}\text{C} \sim 200\text{ }^{\circ}\text{C}$, 表明白云石在高温下形成, 另外常伴生硅灰石、钠长石、重晶石、钠沸石、菱镁矿、地开石或立方黄铁矿等正常湖相沉积物中罕见的热液矿物(Becker *et al.*, 2003)。另一方面, 水底热液向四周流散, 在提高水底温度的同时也带来丰富的微量元素, 促进微生物的勃发, 进而促进碳酸盐矿物和有机质大量生成(魏世林等, 2024)。我国三塘湖盆地条湖—马朗坳陷芦苇沟组二段(秦恩鹏等, 2023)、玛湖坳陷风城组(肖杰, 2020)、准噶尔盆地吉木萨尔凹陷(蒋宜勤等, 2015)等受火山—热液活动影响的细粒

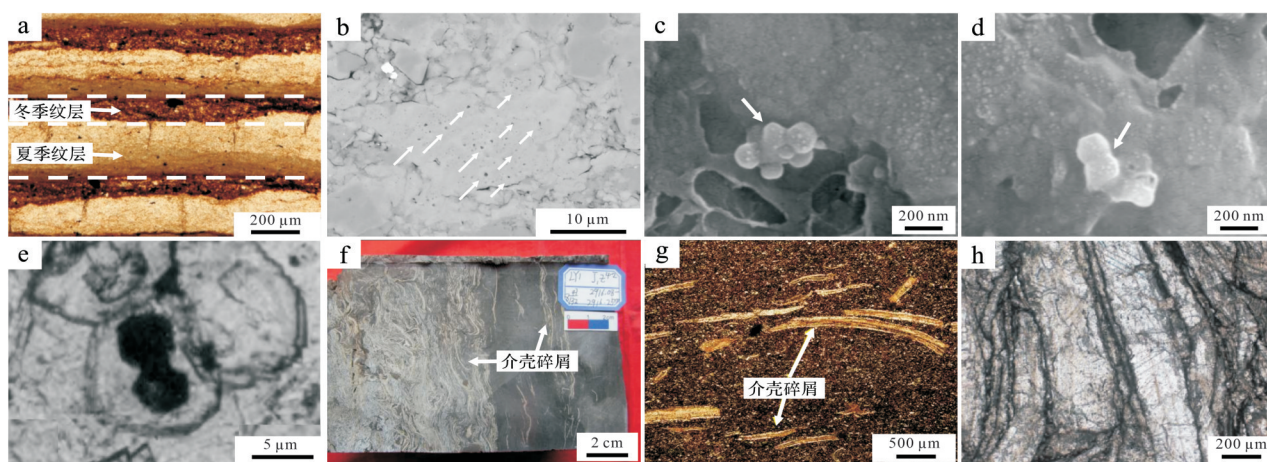


图13 生物化学成因及生物成因碳酸盐矿物微观特征

(a) 季节性韵律性碳酸盐质细粒沉积岩, 夏季浅色微晶方解石纹层和冬季褐色泥晶方解石纹层相互互层, 束鹿凹陷 Es_3^1 , ST1H 井, 4 206.60 m, 单偏光(据王铭乾等, 2025 修改); (b) EPS 介导作用形成的微亮晶方解石, 白色箭头所指为有机质降解遗留的小孔, 束鹿凹陷 Es_3^1 , ST1H 井, 4 206.20 m, 氩离子抛光扫描电镜(据孔祥鑫, 2020 修改); (c) 簇状方解石, 由多个纳米级球状方解石组成(白色箭头), 东营凹陷沙河街组, 扫描电镜(据韩舒筠, 2018 修改); (d) 哑铃状方解石, 由两个纳米级球状方解石组成(白色箭头), 东营凹陷沙河街组, 扫描电镜(据韩舒筠, 2018 修改); (e) 微生物化学作用形成的微生物白云石, 其内部保留微生物的原始形态(据王金艺和金振奎, 2022 修改); (f) 介壳泥岩, 介壳排列杂乱无序, 川北阆中地区大安寨二亚段, 2 916.12~2 916.25 m, 岩心照片; (g) 含介壳粉砂质黏土岩, 见介壳碎片呈漂浮状分布在细粒沉积岩中, 仪陇—营山地区侏罗系大安寨段, 平安 1 井, 3 173.60 m, 单偏光(据崔航等, 2022 修改); (h) 介壳形成的亮晶方解石组成的介壳灰岩, 元坝地区大二亚段, Y2 井, 3 903.99 m, 单偏光(据李倩文等, 2022 修改)

Fig.13 Microscopic characteristics of biochemically and biologically formed carbonate minerals

(a) seasonal rhythmic carbonate fine-grained sedimentary rocks, with light-colored microcrystalline calcite laminae in summer and brownish micritic calcite laminae in winter, Shu Lu Depression Es_3^1 , well ST1H, 4 206.60 m, PPL (modified from Wang *et al.*, 2025); (b) microcrystalline calcite formed by EPS-mediated action, with small holes left by the degradation of organic matter indicated by the white arrow, Shu Lu Depression Es_3^1 , well ST1H, 4 206.20 m, argon ion polishing scanning electron microscope (AIP - SEM) (modified from Kong, 2020); (c) clustered calcite, composed of multiple nanoscale spherical calcite (indicated by the white arrow), in the Shahejie Formation of the Dongying Depression, SEM (modified from Han *et al.*, 2018); (d) dumbbell-shaped calcite, composed of two nanoscale spherical calcite (indicated by the white arrow), in the Shahejie Formation of the Dongying Depression, SEM (modified from Han *et al.*, 2018); (e) microbially formed dolomite through microbial chemical action, with the internal preservation of the original microbial morphology (modified from Wang and Jin, 2022); (f) shelly mudstone, with shells arranged in a disorderly manner, in the Second member of the Da'an Zhai of the northern Sichuan Langzhong area, 2 916.12~2 916.25m, core photo; (g) shelly silty claystone, with shell fragments floating in fine-grained sedimentary rocks, in the Jurassic Da'an Zhai section of the Yilong-Yingshan area, well Ping'an 1, 3 173.60 m, PPL (modified from Cui *et al.*, 2022); (h) shelly limestone composed of bright calcite formed by shells, in the Second member of the Yuanba area, well Y2, 3 903.99 m, PPL (modified from Li *et al.*, 2022)

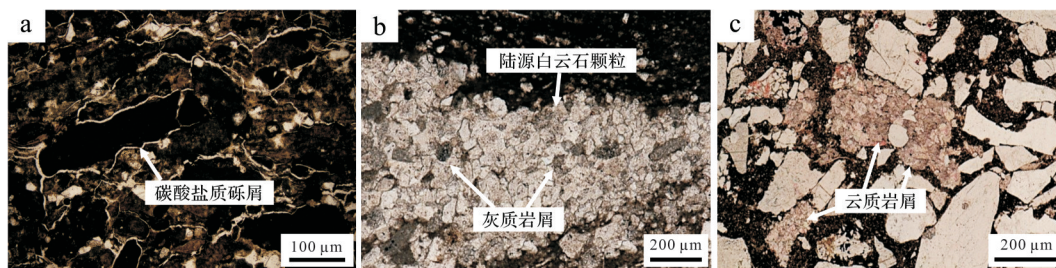


图14 机械作用成因碳酸盐质沉积物特征图

(a) 含粉砂砾屑泥晶灰岩, 可见碳酸盐砾屑, 东营凹陷南坡陈官庄地区沙河街组四段上亚段, G3 井, 1 940.23~1 940.25 m, 单偏光(据彭军等, 2022 修改); (b) 陆源白云石颗粒夹灰质岩屑, 束鹿凹陷 Es_3^1 , ST3H 井, 3 907.20 m, 单偏光(据孔祥鑫, 2020 修改); (c) 白云石晶体组成的云质岩屑与周围磨圆度低的陆源长英质矿物共同沉积, 东营凹陷 Eq_3^1 , Y891 井, 单偏光(据孔祥鑫, 2020 修改)

Fig.14 Microscopic characteristics of mechanically formed carbonate sediments

(a) silty calcareous mudstone with gravel, visible carbonate gravel, in the upper submember of the Fourth member of the Shahejie Formation of the southern slope of the Dongying Depression, Chen Guanzhuang area, well G3, 1 940.23~1 940.25 m, PPL (modified from Peng *et al.*, 2022); (b) terrestrial dolomite grains interbedded with argillaceous rock fragments, in the Shu Lu Depression Es_3^1 , well ST3H, 3 907.20 m, PPL (modified from Kong, 2020); (c) dolomitic rock fragments composed of dolomite crystals and low-roundness terrestrial feldspathic minerals co-deposited, in the Dongying Depression Eq_3^1 , well Y891, PPL (modified from Kong, 2020)

沉积岩中常见火山—热液活动影响下形成的白云石、方解石呈层状发育(图 15a, b), 部分碳酸盐矿物与有机质共同发育(图 15c, d)。除此之外, 火山—热液活动还能直接向盆内输入碳酸盐物质, 在我国准

噶尔盆地吉木萨尔凹陷细粒沉积岩中常见喷爆式方解石、白云石等碳酸盐矿物呈不规则碎斑状与细粒沉积物共同沉积(图 15e, f)(柳益群等, 2018; 柳益群等, 2019; 李哲萱等, 2020)。

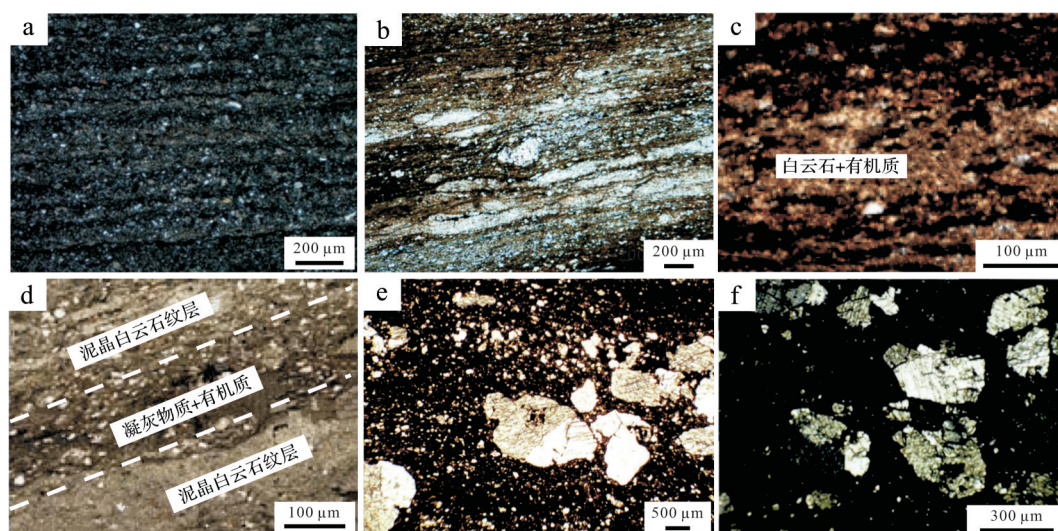


图 15 火山—热液作用碳酸盐质沉积物微观特征

(a)纹层状白云质凝灰岩,显微层状构造,玛湖凹陷风城组, FN1 井, 4 338.19 m, 正交偏光(据肖杰, 2020 修改); (b)含凝灰质藻云岩(浅褐色)夹凝灰质纹层(白色), 准噶尔盆地吉木萨尔凹陷, J174 井, 3 224.30 m, 单偏光(据蒋宜勤等, 2015 修改); (c)纹层状白云质凝灰岩, 白云石颗粒与长英质混杂, 见有机质呈层状发育, M78 井, 3 048.00 m, 单偏光(据潘永帅等, 2022 修改); (d)纹层状凝灰质白云岩, 凝灰质与有机质层和泥晶白云石纹层互层, 三塘湖盆地条湖—马朗凹陷芦二段, 凝灰质白云岩, L1 井, 3 079.13 m, 单偏光(据潘永帅等, 2022 修改); (e)碎斑状喷爆式方解石, 呈不规则颗粒以及集合体形态产出, 准噶尔盆地吉木萨尔凹陷芦草沟组, 上油层段, J174 井, 3 197.00 m, 单偏光(据柳益群等, 2019 修改); (f)碎斑状喷爆式方解石, 方解石呈不规则角砾状发育, 可见粒内破裂现象, 基质主要成分为白云石、铁白云石、方解石、钠长石、正长石和石英等, 准噶尔盆地吉木萨尔凹陷, 单偏光(据柳益群等, 2018 修改)

Fig.15 Microscopic characteristics of carbonate sediments formed by volcanic-hydrothermal action

(a) laminated dolomitic tuff, with microlaminated structure, in the Fengcheng Formation of the Mahu Depression, well FN 1, 4 338.19 m, XPL (modified from Xiao, 2020); (b) algal dolostone containing tuffaceous material (light brown) interbedded with tuffaceous laminae (white), in the Jimusaer Depression of the Junggar Basin, well Ji 174, 3 224.30 m, PPL (modified from Jiang *et al.*, 2015); (c) laminated dolomitic tuff, with dolomite grains intermingled with feldspathic minerals, showing organic matter developed in layers, well M 78, 3 048.00 m, PPL (modified from Pan *et al.*, 2022); (d) laminated tuffaceous dolomite, with tuffaceous and organic layers and micritic dolomite laminae, in the Tiaohu-Malan Depression of the Santanhu Basin, tuffaceous dolomite, well L1, 3 079.13 m, PPL (modified from Pan *et al.*, 2022); (e) brecciated explosive calcite, irregular granular and aggregate forms, in the Licaogou Formation of the Jimusaer Depression of the Junggar Basin, upper oil layer, well J174, 3 197.00 m, PPL (modified from Liu *et al.*, 2019); (f) brecciated explosive calcite, calcite developed in an irregular angular breccia, with grain internal fractures, the matrix mainly composed of dolomite, ankerite, calcite, albite, orthoclase, and quartz, etc., in the Jimusaer Depression of the Junggar Basin, PPL (modified from Liu *et al.*, 2018)

2.5 黄铁矿来源及其成因

近年来黄铁矿在细粒沉积岩相关研究中得到广泛重视,其作为盆内金属硫化物的主要载体,在细粒沉积岩中广泛存在,具有指示沉积环境、成岩演化等作用(Wilkin *et al.*, 1996; Wignall *et al.*, 2010; Gomes *et al.*, 2022)。通常细粒沉积岩中的黄铁矿以边缘较平直、晶体形态多样的自形黄铁矿(图 16a, b)(邓乃尔等, 2024)、大小均匀的微粒组成的草莓状黄铁矿(图 16c, d)(何贤科等, 2024; 李怡等, 2024)以及交代其他矿物所形成的交代型黄铁矿(图 16e, f)为主(Ohfuji and Rickard, 2005; 刘江艳等, 2021; Tribovillard *et al.*, 2022)。

铁元素和硫元素作为黄铁矿的重要成矿元素,是研究黄铁矿物质来源的关键。铁来源多样,包含河流输入、大气输入、冰川融解所带来的陆源铁元素、盆内沉积物质再循环的铁元素以及火山—热液活动输入的铁元素(Raiswell and Canfield, 2012; 刘治

成等, 2024; Liang *et al.*, 2024),其在盆内以溶解铁、胶体铁、颗粒铁三种形式存在(Norman *et al.*, 2014; Tagliabue *et al.*, 2017)。Fe³⁺转化为Fe²⁺按照生物参与与否可将该过程划分为生物途径和非生物途径,其中生物途径以异化铁还原为主:地杆菌科(Geobacteraceae)、希瓦氏菌属(Shewanella)等特定细菌通过代谢活动利用细胞外的铁氧化物作为电子最终受体产生能量,将Fe³⁺还原成Fe²⁺(Lovley, 1997)。而非生物途径以铁穿梭机制为主,在这个过程中Fe³⁺从沉积盆地的边缘较浅的水域被运输到盆地的更深处,穿越化学跃层还原成Fe²⁺(Mänd *et al.*, 2021; Wang *et al.*, 2024)。

在研究黄铁矿物质来源时,相较于铁元素,学者们往往更加关注硫元素的来源和还原机制(Rickard, 2021)。硫元素的来源与铁元素相似(Liang *et al.*, 2024),其还原作用主要依赖微生物硫酸盐还原作用(MSR)和硫酸盐热化学还原作用

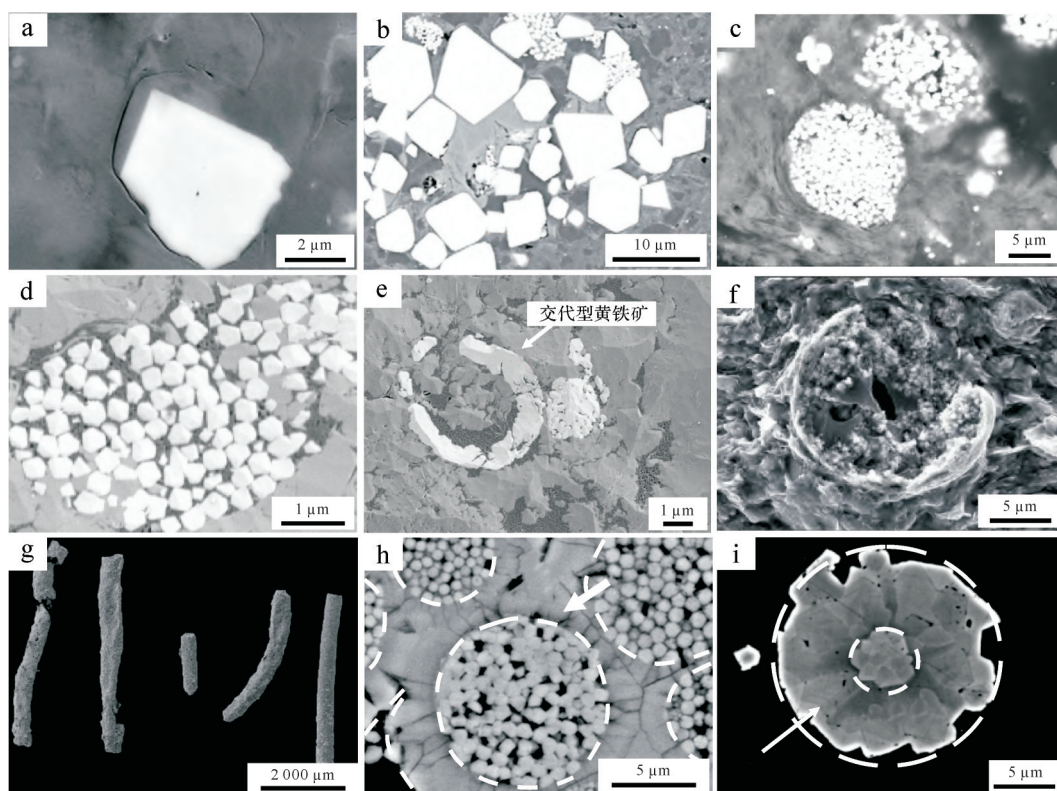


图 16 不同类型黄铁矿及其微观特征

(a)自型单晶黄铁矿,边缘平直,四川盆地泸州I区Y101-01井,五峰组龙一₁亚段,3 744.51 m,扫描电镜(据邓乃尔等,2024修改);(b)自型黄铁矿,边缘平直,四川盆地泸州I区Y101-03井,五峰组龙一₁亚段,3 744.51 m,扫描电镜(据邓乃尔等,2024修改);(c)草莓状黄铁矿,西湖凹陷平湖斜坡北段,KB1井,P8砂组,背闪射扫描电镜(据何贤科等,2024修改);(d)草莓状黄铁矿,形成时期早于自生石英,粒径约3 μm,川南地区,L202-84B,龙一₁,4 322.26 m,扫描电镜(据李怡等,2024修改);(e)交代型黄铁矿,黄铁矿交代生物腔体,形成保留部分生物结构的黄铁矿,川南地区,L204-35JX,五峰组,3 845.64 m,扫描电镜(据李怡等,2024修改);(f)交代型黄铁矿,黄铁矿交代生物外壁与体腔,可见黏土矿物围绕藻类生物体腔生长,鄂尔多斯盆地,CY1井,长7₂亚段,扫描电镜(据刘江艳等,2021修改);(g)AOM-SR作用影响下的管状、棒状黄铁矿集合体,扫描电镜(据Wang *et al.*, 2015修改);(h)经过AOM-SR作用影响的过度生长黄铁矿(箭头所指的白色虚线内),具再生生长结构,扫描电镜(据Lin *et al.*, 2017修改);(i)过度生长型草莓状黄铁矿,白色箭头所指的虚线区域内为经TSR作用后过度生长的黄铁矿,大唐坡组灰色页岩,埃迪卡拉纪,华南地区,扫描电镜(据Cui *et al.*, 2018修改)

Fig.16 Different types of pyrite and their microscopic characteristics

(a) autogenetic single-crystal pyrite with straight edges, in the Yulin I area of the Sichuan Basin, well Y101-01, Wufeng Formation - Long₁₁ submember, 3 744.51 m, SEM (modified from Deng *et al.*, 2024); (b) autogenetic pyrite with straight edges, in the Yulin I area of the Sichuan Basin, well Y101-03, Wufeng Formation - Long₁₁ submember, 3 744.51 m, SEM (modified from Deng *et al.*, 2024); (c) strawberry-like pyrite, in the northern section of the Pinghu Slope in the Xihu Depression, well KB1, P8 sand group, backscattered electron scanning microscope (BSEM) (modified from He *et al.*, 2024); (d) strawberry-like pyrite, formed earlier than authigenic quartz, with a grain size of about 3 μm, southern Sichuan area, L202-84B, Long₁₁, 4 322.26 m, SEM (modified from Li *et al.*, 2024); (e) metasomatic pyrite, pyrite replacing biological cavities, forming pyrite that retains part of the biological structure, southern Sichuan area, L204-35JX, Wufeng Formation, 3 845.64 m, SEM (modified from Li *et al.*, 2024); (f) metasomatic pyrite, replacing the outer wall and body cavity of organisms, with clay minerals growing around the body cavity of algae, Ordos Basin, well CY1, Chang₇₂ submember, SEM (modified from Liu *et al.*, 2021); (g) tubular and rod-shaped pyrite aggregates affected by AOM-SR, SEM (modified from Wang *et al.*, 2015); (h) overgrown pyrite affected by AOM-SR (indicated by the white dashed line within the arrow), with a regrown structure, SEM (modified from Lin *et al.*, 2017); (i) overgrown strawberry-like pyrite, the area within the dashed line indicated by the white arrow is the overgrown pyrite after TSR, in the grey shale of the Datangpo Formation, Ediacaran Period, South China, SEM (modified from Cui *et al.*, 2018)

(TSR) (Machel, 2001; Ryu *et al.*, 2006; Cai *et al.*, 2022)。其中MSR主要发生在浅埋藏带,按照反应的埋藏深度、参与硫酸盐还原反应物质、反应产物不同可以分为细菌硫酸盐还原作用(BSR)和甲烷厌氧氧化—硫酸盐还原作用(AOM-SR)。BSR主要受到氧化还原界面、生物含量、硫酸盐浓度等方面控制(Ryu *et al.*, 2006; Nara *et al.*, 2010)。开放环境中,氧化还

原界面通常在水—沉积物界面以下;而在封闭环境中,氧化还原界面往往在水体中(Jørgensen *et al.*, 1992)。当细菌处于氧化还原界面以下、温度高于0℃且不超过80℃时,由细菌作为介导发生硫酸盐—碳氢化合物氧化还原反应形成黄铁矿中的硫元素(公式(1))(Rickard, 2019)。由于BSR主要发生于沉积水体中以及浅埋藏带中,因此形成的草莓状黄

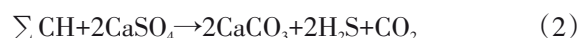
铁矿粒度通常较小(平均小于 $7.7\ \mu\text{m}$)(图 16c, d)(Wilkin *et al.*, 1996; Rickard, 2019)。



AOM-SR 不受氧化还原界面的控制, 主要在更深部的硫酸盐—甲烷转换带(SMTZ)发生硫酸盐的还原作用(图 17)(Treude *et al.*, 2005; Lin *et al.*, 2016; Liu *et al.*, 2022b; Liang *et al.*, 2024)。深部生成的甲烷沿着沉积物的孔隙向上运移扩散, 与向下扩散的硫酸盐相遇, 在还原细菌的作用下形成硫化氢(Reeburgh, 2007), 因此该方式形成的黄铁矿通常受到沉积物孔隙通道的限制而呈管状或者棒状(图 16g)(Wang *et al.*, 2015; Lin *et al.*, 2017; Mänd *et al.*, 2021)。另外, 随着埋深的改变, 经历 AOM-SR 作用形成的草莓状黄铁矿也会不断生长直至形成自型黄铁矿(Liu *et al.*, 2022b; 陈杨等, 2025)。BSR 与 AOM-SR 发生的反应深度不同, 经历过 BSR 作用所形成的黄铁矿在埋藏过程中经历 SMTZ 也会发生过度生长的现象(图 16h)(Lin *et al.*, 2017), 因此 AOM-SR 形成的黄铁矿粒度平均大于 $20\ \mu\text{m}$ (Miao *et al.*, 2021)。

TSR 并不涉及生物作用, 属于达到一定温度(大于 $140\ ^\circ\text{C}$)才能够开始进行的硫酸盐还原作用, $200\ ^\circ\text{C}$ 左右是其反应作用效率最高的温度(Orr,

1974; Ohmoto, 1986; Machel *et al.*, 1995; Cai *et al.*, 2001; Cai *et al.*, 2009; Cai *et al.*, 2015)。该反应的发生深度一般大于 MSR 的发生深度, 是温度控制下的有机质还原硫酸盐作用(公式 2)(Jørgensen *et al.*, 1992; Treude *et al.*, 2005; Reeburgh, 2007)。TSR 反应形成的黄铁矿在细粒沉积岩中以过度生长的自形黄铁矿、继承交代矿物形态的交代型黄铁矿(图 16e)以及过度生长的草莓状黄铁矿(图 16i)为主(Wilkin *et al.*, 1996; Cui *et al.*, 2018)。前人研究表明, 除了深度和温度控制 TSR 反应的发生外, 有机质的类型、环境 pH 值、硫酸盐类型也控制着该反应发生的强度(Tyson, 2006; Amrani *et al.*, 2008; Ma *et al.*, 2008; Walters *et al.*, 2015; 罗厚勇等, 2017)。



2.6 有机质来源及其成因

细粒沉积岩中蕴含着丰富、多样的有机质, 但目前并没有针对细粒沉积岩的有机质统一划分方案, 大多数学者仍采取的是煤岩学中的有机质划分理论, 将细粒沉积岩中的有机质划分为镜质体、惰质体、类脂体、动物有机碎屑以及次生有机质 5 大显微组分(Cardott *et al.*, 2015; Mastalerz *et al.*, 2018; Liu *et al.*, 2022c)。利用镜下观察有机质显微组分特征是最直接有效的物源研究方法, 其各特征总结如下。

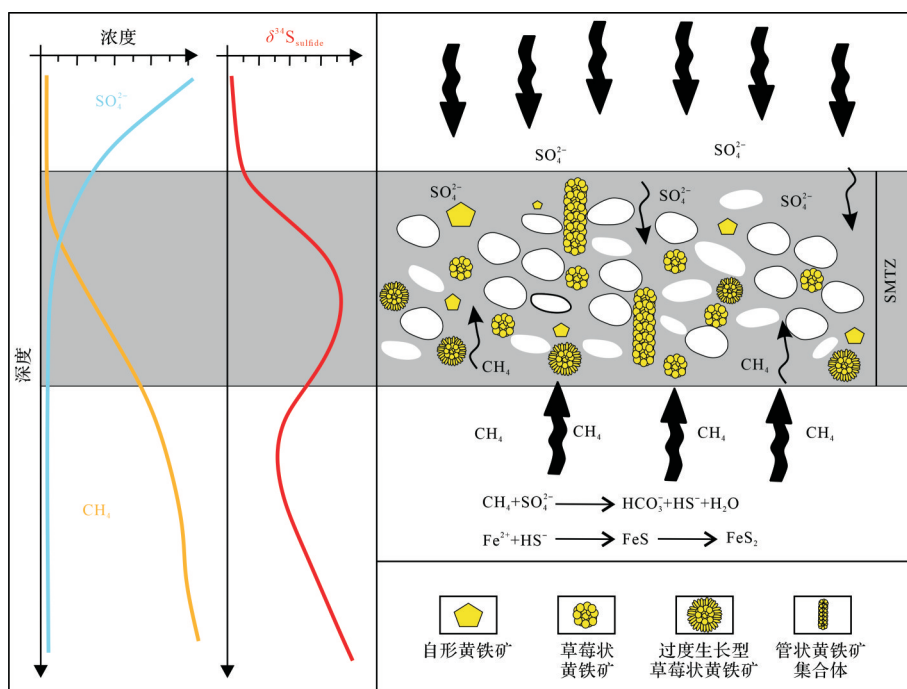


图 17 甲烷厌氧氧化—硫酸盐还原作用(AOM-SR)模式图(据 Liang *et al.*, 2024 修改)

Fig.17 Schematic diagram of anaerobic oxidation of methane coupled to sulfate reduction (AOM-SR)

(modified from Liang *et al.*, 2024)

镜质体是随陆源碎屑一起搬运到盆内的陆源高等植物的茎、叶、木质纤维组织凝胶化形成的有机显微组分,常在煤系细粒沉积地层中出现,物源可以追溯到靠近盆内水体的沼泽以及邻近的陆源区域,按照形态可分为结构镜质体和无结构镜质体。结构镜质体具有较清晰的轮廓和更深的颜色,具长条状、网格状、块状等形态(图 18a,b)(焦淑静等,2019;刘忠等,2023)。而无结构镜质体由于其粒度较小,常以颗粒状分散于细粒沉积岩基质中,很少具备明显的细胞结构(图 18c,d)(何燚,2021;刘贝,2023),镜下鉴别十分困难,因此难以对其显微组分进行准确划分(Mastalerz *et al.*, 2018)。

惰质体来源与镜质体相似,均来自陆源高等植物,但不同的是惰质组在沉积前经历过丝炭化作用的氧化,因此其组分性质更加稳定,其最常见的显微组分是植物细胞形态保存较好的丝质体,纵断面呈纤维状,常顺层排列(图 19a~c)(焦淑静等,2018;贾

云倩等,2021),横断面常呈整齐的筛网结构,并被其他矿物充填(图 19d)(焦淑静等,2019)。除此之外,半丝质体、碎屑惰质体等也是细粒沉积岩中常见的惰质体类型。

类脂体是细粒沉积岩中最常见的显微组分,其物质来源复杂,既包含来源于陆源的高等植物的孢子体、角质体、树脂体;也包含来源于盆内的浮游藻类、低等植物在厌氧菌的参与下形成的藻类体、沥青质体(无定形体)以及类脂碎屑体(代世峰等,2021)。孢子体能够保存孢子以及花粉的形态特征,扫描电镜下常见的是呈扁平状、线状、蠕虫状、环状的小孢子(图 20a)(焦淑静等,2019;代世峰等,2021);角质体是由植物表皮的角质层形成的显微有机组分,表现出较强的韧性,常呈弯曲状、条带状分布在细粒沉积岩中(图 20b,c)(Stopes, 1935;焦淑静等,2018);树脂体是植物分泌物所形成的显微有机组分,常呈椭圆形、圆形分布在细粒沉积岩中,其表面平坦、轮廓

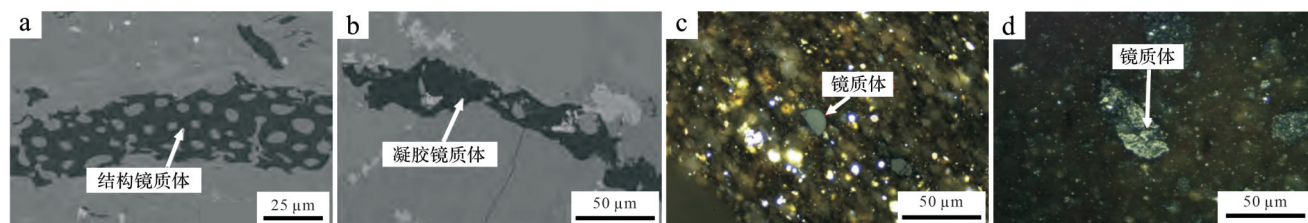


图 18 细粒沉积岩中镜质体微观特征

(a) 网格状结构镜质体,细胞结构保留完好,武宁盆地武南区块,石炭—二叠系太原组—山西组(据刘忠等,2023 修改);(b) 条带状凝胶镜质体,武宁盆地武南区块,石炭—二叠系太原组—山西组(据刘忠等,2023 修改);(c) 无结构碎屑镜质体,美国 Illinois 盆地 New Albany 页岩,油浸反射光(据刘贝,2023 修改);(d) 无结构碎屑镜质体,川东—黔东南龙潭组, M1 井(据何燚,2021 修改)

Fig.18 Microscopic characteristics of vitrinite in fine-grained sedimentary rocks

(a) reticulated structure of vitrinite, with well-preserved cellular structure, in the Wuning Basin, Wuning South Block, Carboniferous-Permian Taiyuan Formation-Shanxi Formation (modified from Liu *et al.*, 2023); (b) banded gel vitrinite, in the Wuning Basin, Wuning South Block, Carboniferous-Permian Taiyuan Formation-Shanxi Formation (modified from Liu *et al.*, 2023); (c) structureless detrital vitrinite, in the New Albany Shale of the Illinois Basin, USA, oil-immersion reflected light (modified from Liu, 2023); (d) structureless detrital vitrinite, in the Longtan Formation of the eastern Sichuan-southeastern Guizhou area, well M1 (modified from He, 2021)

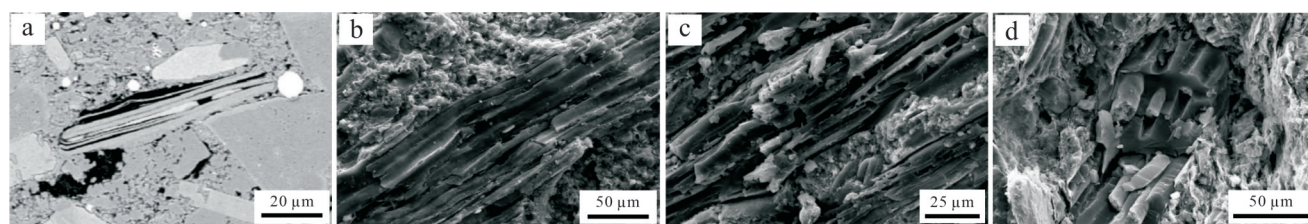


图 19 细粒沉积岩中惰质体微观特征

(a) 顺层状排列的惰质组丝质体,威远地区, X3 井, 龙一₁, 2 653.40 m, MAPS 扫描图像, 250 nm 分辨率(据贾云倩等, 2021 修改);(b) 顺层分布的惰质组丝质体纵断面, 新疆芦草沟组, 扫描电镜(据焦淑静等, 2018 修改);(c) 顺层分布的惰质组丝质体纵断面, 三塘湖盆地芦草沟组, 扫描电镜(据焦淑静等, 2019 修改);(d) 惰质组丝质体横断面, 矿物后期充填细胞空腔, 华北石炭二叠系, 扫描电镜(据贾云倩等, 2021 修改)

Fig.19 Microscopic characteristics of inertinite in fine-grained sedimentary rocks

(a) lamellar arrangement of inertinite fibrous matter, in the Weiyan area, well X3, Long1, 2 653.40 m, MAPS scanning image, 250 nm resolution (modified from Jia *et al.*, 2021); (b) laminar distribution of longitudinal section of inertinite fibrous matter, in the Lucaogou Formation of Xinjiang, SEM (modified from Jiao *et al.*, 2018); (c) laminar distribution of longitudinal section of inertinite fibrous matter, in the Lucaogou Formation of the Santanhu Basin, SEM (modified from Jiao *et al.*, 2019); (d) transverse section of inertinite fibrous matter, with minerals filling the cell cavities later, in the Carboniferous-Permian of North China, SEM (modified from Jia *et al.*, 2021)

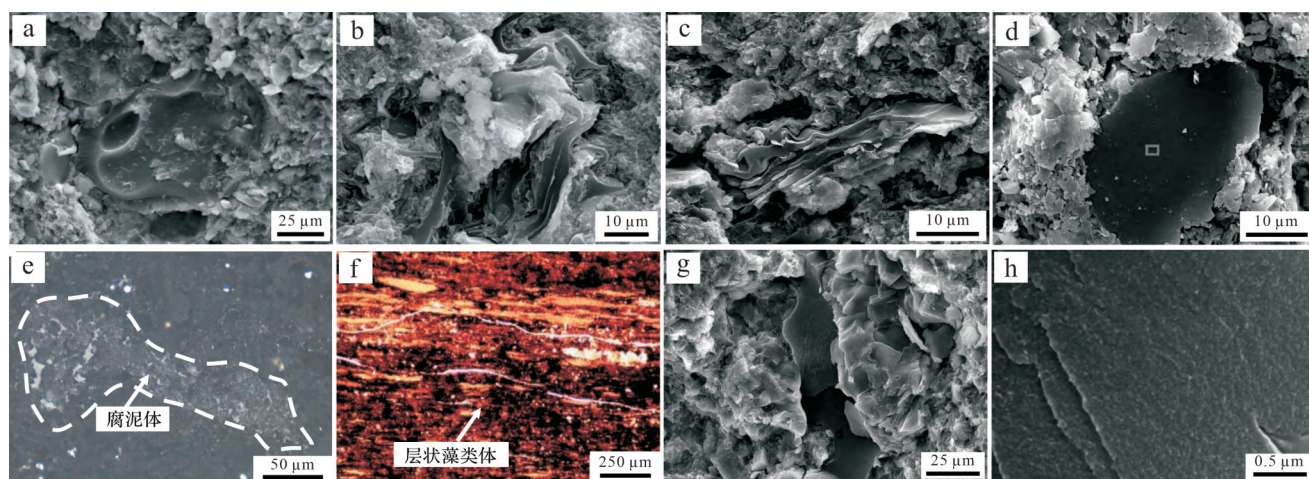


图20 细粒沉积岩中类脂体微观特征

(a)切面呈圆环的孢子体,三塘湖盆地芦草沟组,扫描电镜(据焦淑静等,2019修改);(b)弯曲状角质体,三塘湖盆地芦草沟组,扫描电镜(据焦淑静等,2019修改);(c)层状角质体,新疆芦草沟组,扫描电镜(据焦淑静等,2018修改);(d)椭圆形树脂体,轮廓清晰,华北石炭系—二叠系,扫描电镜(据焦淑静等,2018修改);(e)单个无定形状藻类体,还保存着一定的藻类轮廓,内部由细小的有机质与黏土矿物组成,四川盆地五峰组—龙马溪组(据刘思逸等,2022修改);(f)呈条带状分布的层状藻类体,四川盆地渝西地区,Z202井,龙马溪组,3 877.09 m,单偏光(据谢国梁等,2021修改);(g)条状沥青质,自然断面光滑平坦,新疆芦草沟组,扫描电镜(据焦淑静等,2018修改);(h)图g的局部放大,可见沥青质内部的球粒结构,新疆芦草沟组,扫描电镜(据焦淑静等,2018修改)

Fig.20 Microscopic characteristics of lipinite in fine-grained sedimentary rocks

(a) sporinite with a cross-section in the shape of a ring, in the Lucaogou Formation of the Santanhu Basin, SEM (modified from Jiao *et al.*, 2019); (b) curvilinear cutinite, in the Lucaogou Formation of the Santanhu Basin, SEM (modified from Jiao *et al.*, 2019); (c) lamellar cutinite, in the Lucaogou Formation of Xinjiang, SEM (modified from Jiao *et al.*, 2018); (d) oval resinite, with clear contours, in the Carboniferous-Permian of North China, SEM (modified from Jiao *et al.*, 2018); (e) individual amorphous alginite, still retaining a certain outline of algae, composed of fine organic matter and clay minerals inside, in the Wufeng Formation-Longmaxi Formation of the Sichuan Basin (modified from Liu *et al.*, 2022); (f) lamellar alginite distributed in bands, in the Yuxi area of the Sichuan Basin, well Z202, Longmaxi Formation, 3 877.09 m, PPL (modified from Xie *et al.*, 2021); (g) strip-like bitumen, with a smooth and flat natural fracture, in the Lucaogou Formation of Xinjiang, SEM (modified from Jiao *et al.*, 2018); (h) a local magnification of Figure g, showing the granular structure inside the bitumen, in the Lucaogou Formation of Xinjiang, SEM (modified from Jiao *et al.*, 2018)

清晰(图20d)(Pickel *et al.*, 2017)。藻类体可划分为单个藻类体和层状藻类体,单个藻类体常呈无定形状、无定形团块状与细粒沉积矿物基质伴生(图20e)(刘思逸等,2022),层状藻类体在细粒沉积岩中常呈纹层状、条带状分布(图20f)(Kus *et al.*, 2017; Pickel *et al.*, 2017; 代世峰等,2021; 谢国梁等,2021); 沥青质体来自被降解的藻类、细菌以及浮游植物(Kus *et al.*, 2017; Reyes *et al.*, 2018; 谢国梁等,2021; Teng *et al.*, 2021),没有固定形态,自然断面样品上常见其表面光滑平坦(图20g),但在放大倍数的情况下可见沥青质内部的球粒结构(图20h)(焦淑静等,2018)。

动物有机碎屑常多来源于盆内,以笔石、几丁虫、牙形刺、有孔虫、苔藓虫等生物有机碎屑存在于细粒沉积岩中(Amrani *et al.*, 2008),尤其是古生界细粒沉积岩地层中(Reyes *et al.*, 2018),保存完好的动物有机碎屑能够较好地反映生物的形态和内部结构(图21a~d)(Petersen *et al.*, 2013; 焦淑静等,2018)。

次生有机质主要以固体沥青、焦沥青、微粒化沥青等形式存在于古生界及前寒武系细粒沉积岩中(Cardott *et al.*, 2015; Gao *et al.*, 2018; Luo *et al.*,

2021)。其成因复杂、种类多样(付小东等,2009),但可以明确的是次生有机质与类脂体中的沥青质体来源相同,均来自盆内的水生浮游生物以及藻类等(焦淑静等,2018)。按照沥青和油气生成的先后关系可将生油前形成的沥青定义为油前沥青,如类脂体中的沥青质体,而次生有机质则是生油后形成的油后沥青(Cardott *et al.*, 2015; Mastalerz *et al.*, 2018)。次生有机质没有固定的形状(图22a),部分展现出粒状镶嵌结构,具有明显的各向异性(图22b)(Gao *et al.*, 2018)。另外,次生沥青内部常发育经过改造作用后形成的纳米级圆形、椭圆形气孔(图22c,d)(焦淑静等,2018)。

3 结论与展望

3.1 结论

(1) 陆源细粒沉积物是陆源区母岩经过风化作用形成的风化产物,经过河流、大气、冰川、生物等搬运介质搬运并进一步风化,最终沉积到盆地中形成的细粒沉积物质;内源细粒沉积物是盆内生物—化

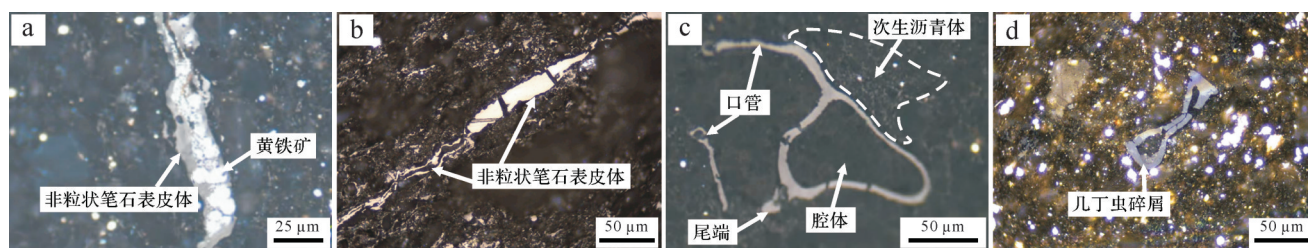


图21 细粒沉积岩中动物有机碎屑微观特征

(a)非粒状笔石有机碎屑,笔石内部腔体被黄铁矿化,发育大量草莓状黄铁矿,四川盆地五峰组—龙马溪组(据谢国梁等,2021修改);(b)非粒状笔石有机体,中国重庆市巫溪县志留系龙马溪组露头样品(据Liu *et al.*, 2022c修改);(c)几丁虫有机碎屑,墙体、口管、尾端形态完整,四川盆地五峰组—龙马溪组(据刘思逸等,2022修改);(d)几丁虫有机碎屑,美国Illinois盆地New Albany页岩(据Liu *et al.*, 2022c修改)

Fig.21 Microscopic characteristics of zooclastic organic debris in fine-grained sedimentary rocks

(a) non-granular graptolite organic debris, with the internal cavity of the graptolite mineralized by pyritization, developing a large number of strawberry-like pyrite, in the Wufeng Formation-Longmaxi Formation of the Sichuan Basin (modified from Xie *et al.*, 2021); (b) non-granular graptolite organic matter, Outcrop samples from the Silurian Longmaxi Formation in Wuxi county, Chongqing, China (modified from Liu *et al.*, 2022c); (c) chitinozoan organic debris, with complete morphology of the wall, oral tube, and tail end, in the Wufeng Formation-Longmaxi Formation of the Sichuan Basin (modified from Liu *et al.*, 2022); (d) chitinozoan organic debris, in the New Albany Shale of the Illinois Basin, USA (modified from Liu *et al.*, 2022c)

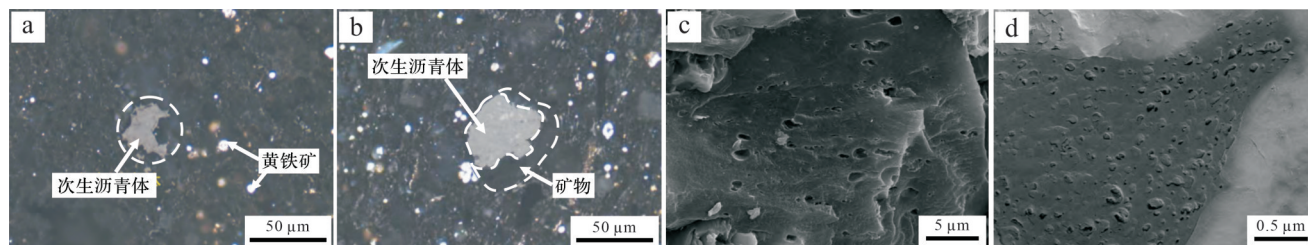


图22 细粒沉积岩中次生有机质微观特征

(a)次生有机质沥青体,呈无定形状,四川盆地五峰组—龙马溪组(据刘思逸等,2022修改);(b)次生有机质沥青体,可见沥青呈团块状镶嵌在矿物中,四川盆地五峰组—龙马溪组(据刘思逸等,2022修改);(c)次生有机质沥青体,可见圆形、椭圆形气孔发育,南方下寒武统(据焦淑静等,2018修改);(d)次生有机质沥青体,可见抛光面上气泡状孔隙发育,南方下寒武统(据焦淑静等,2018修改)

Fig.22 Microscopic characteristics of secondary organic matter in fine-grained sedimentary rock

(a) secondary organic matter bitumen, amorphous, in the Wufeng Formation-Longmaxi Formation of the Sichuan Basin (modified from Liu *et al.*, 2022); (b) secondary organic matter bitumen, visible bitumen inlaid in minerals in lumps, in the Wufeng Formation-Longmaxi Formation of the Sichuan Basin (modified from Liu *et al.*, 2022); (c) secondary organic matter bitumen, well-developed circular and elliptical vesicles are visible, in the lower Cambrian of the South (modified from Jiao *et al.*, 2018); (d) secondary organic matter bitumen, well-developed bubble-like pores are visible on the polished surface, lower Cambrian, South China, in the lower Cambrian of the South (modified from Jiao *et al.*, 2018)

学作用、化学作用、再搬运沉积作用以及生物作用形成的细粒物质;火山—热液细粒沉积物是火山喷发产生火山灰、火山尘形成的火山碎屑细粒沉积物质和通过断层或热液喷口输送到湖泊或海洋的上溢热液形成的热液细粒沉积物质。

(2) 细粒沉积岩物质成分相当复杂,常见的有黏土矿物、石英、长石、碳酸盐矿物、黄铁矿、有机质等。黏土矿物为陆源成因、成岩作用黏土矿物转化成因、其他矿物溶蚀成因和海底火山物质溶解以及胞外聚合物生物介导作用形成;石英不仅可以来自陆源物质风化,也能来自盆内生物作用、火山喷发带来的凝灰物质经过脱玻化作用以及成岩自生作用形成;长石大部分来源于陆源碎屑物质风化,也可以由火山—热液作用提供,近年来相关研究也证实长石能

够由微生物化学作用形成;碳酸盐矿物多为内源物质,受到盆内生物数量、陆源碎屑以及离子的供给、火山—热液微量元素的输入等多方面共同控制形成;黄铁矿中的铁和硫两大成矿元素来源复杂,河流输入、大气输入、冰川融解、盆内沉积物质再循环以及火山—热液均是铁元素和硫元素的来源,铁和硫在盆内经过异化铁还原和铁穿梭机制还原以及MSR和TSR作用形成黄铁矿;细粒沉积岩中的有机质类型复杂多样,可划分为陆源的镜质体、惰质体和部分类脂体以及内源的部分类脂体、动物有机碎屑和次生有机质。

3.2 展望

近年来细粒沉积岩的相关研究已经取得显著进展,但整体依旧处于探索阶段。纵观细粒沉积岩的

物源研究,多局限于某些特定区域,而缺乏全球范围内的整体性系统研究,导致细粒沉积岩仍缺乏普遍适用的研究方法。在研究细粒沉积岩物质来源时,依旧以传统方法为主,如:野外剖面观测、岩心观察、薄片分析、X射线衍射、地球化学分析、同位素分析等,这些方法虽然有效,但在处理复杂的物源问题时难免显得局限。

另外,目前细粒沉积岩的物源研究仍缺乏具有针对性的系统研究方案,多数学者在面对细粒沉积岩物源问题时仍采取传统粗粒度碎屑岩的部分方案,如岩石矿物三段元法、重矿学方法、地质年代学方法、沉积相分析法、地球化学方法、地质年代学方法等。这些方法在一定程度上有效,但应对细粒沉积岩这样粒度较小、观察难度较大、物源多样的复杂物源分析时难免捉襟见肘。例如,由于细粒沉积岩物质组成粒度较细,难以与传统物源研究方法匹配;对于多物源的细粒沉积岩利用传统物源研究方案,出现统计工作量大且难以达到准确溯源效果的弊端;传统物源研究手段应用到细粒沉积岩中容易出现成本较高、未考虑化学风化、搬运方式、迁移距离、沉积再分选等影响的缺陷。因此,未来细粒沉积岩物源研究的发展应集中在以下几个方面:

(1) 在细粒沉积岩物质来源的研究中注重多学科的研究方法,如地质学、地球化学、地球物理学、水文学、微生物学、分子生物学等学科研究,以及新技术的应用,如数值模拟、化学模拟、水模拟、生物模拟等手段,以更加精确、直观地了解不同细粒沉积物在“源—汇”系统中的迁移、转化和最终形成的微观形态和动态行为,同时更加全面地理解细粒沉积物在生物参与、不同的物理化学条件下的物理、化学和生物的成因机制。例如,利用水模拟、物理模拟、数值模拟等手段,模拟多种陆源碎屑沉积物质在侵蚀、搬运过程中的变化特征,深入探讨陆源细粒沉积物质在“源—汇”系统中的演化规律;通过研究细粒沉积物中的微生物群落的结构和功能,深入研究微生物在细粒沉积物尤其是黏土矿物、碳酸盐矿物的形成中起到的作用;利用先进技术手段,探究地球外部圈层和内部圈层如何控制陆源、内源、火山—热液源物质的耦合关系,进而控制富有机质细粒沉积岩的演化。

(2) 深入研究细粒沉积岩对古环境的响应,例如,基于“源—汇”系统理论,利用铁、锂、钼等多种非

传统同位素地球化学和XRF等技术,并辅以原型盆地恢复、岩相古地理重建等工作,明确古气候、古水深、古物源等环境变化如何控制细粒沉积物的发育和展布等。

(3) 加强“将今论古”这一地质学中重要的思维方法在细粒沉积岩物质来源及物质成因方面的应用,通过现代细粒沉积物物质来源及沉积过程的研究,反演古代细粒沉积岩的物质来源及沉积过程。例如,研究现代沉积环境中细粒沉积物的物源、类型及分布,解释远古地质时期相似的沉积环境下细粒沉积物物源及物质成因的可能等。

(4) 结合多种物源研究手段,在大量细粒沉积岩物源研究的基础上,对全球范围内的细粒沉积岩物源特征进行系统归纳和总结,针对细粒沉积岩物质成分粒度较小、观察难度较大、物源复杂多样的特点,形成一套具有针对性、普遍适配性的细粒沉积岩物质来源研究方案,弥补目前细粒沉积岩缺乏统一的物源研究方案这一空缺。

通过以上方向的深入探索,我们有望从多角度揭示更加细致的细粒沉积岩物质来源方向,增强对细粒沉积岩形成机制的理解,推动细粒沉积学基础理论以及实际应用的发展。

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Material Characteristics and Provenance Research of Fine-Grained Sedimentary Rocks

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Abstract: [Significance] The study of the provenance of fine-grained sedimentary rocks is a crucial first step in the "source-to-sink" system theory of fine-grained sedimentary rocks. It is important for restoring the ancient sedimentary environment, understanding the formation mechanism of fine-grained sedimentary rocks, and predicting the distribution of unconventional oil and gas resources. Fine-grained sedimentary rocks are characterized by small particle size, complex composition, and difficulty in observation and research, with different material components corresponding to a variety of sources and origins. A review of the existing research results worldwide shows that currently there is a lack of systematic organization and summary of research outcomes regarding the provenance and origins of fine-grained sedimentary materials. [Progress] This paper synthesizes current research findings and categorizes the sources of fine-grained sedimentary rocks into three major types: terrigenous, endogenic, and volcanic-hydrothermal. It provides an in-depth summary and conclusion on the common sources and origins of fine-grained sediments, pointing out: (1) Clay minerals are of detrital weathering origin, diagenetic transformation from other minerals, transformation among clay minerals themselves, hydrolysis of submarine volcanic materials, and biologically mediated by extracellular polymeric substances; (2) Quartz mainly originates from the weathering of terrigenous materials, intra-basin biological activity, devitrification of volcanic ash materials, and authigenic formation; (3) Feldspar originates from the weathering of terrigenous detritus, input from volcanic-hydrothermal activity, and recent studies have also indicated that feldspar can be formed through microbial chemical processes; (4) Carbonate minerals are primarily endogenic, formed through chemical, bio-chemical, biological, and re-transport and deposition processes within the basin, and the input of terrigenous and volcanic-hydrothermal materials not only directly provides carbonate minerals for fine-grained sedimentary rocks but also promotes the formation of carbonate minerals within the basin; (5) Pyrite is mainly formed by the two ore-forming elements, iron and sulfur, through dissimilatory iron reduction and iron shuttling mechanisms, microbial reduction, and thermogenic reduction of sulfate within the basin; (6) Organic matter can be divided into terrigenous vitrinite, inertinite, and some liptinite, as well as endogenic liptinite, zooclastic organic debris, and secondary organic matter. [Conclusions and Perspectives] Future research on the provenance and origins of fine-grained sedimentary rocks will develop in a multidisciplinary and high-precision direction, and there is still an urgent need for a systematic approach suitable for the study of the provenance of fine-grained sedimentary rocks. This paper aims to clarify the provenance and origins of fine-grained sedimentary rocks, enhance the understanding of the sources and formation mechanisms of fine-grained sediments, and thus promote the development of fine-grained sedimentology theory. It provides a solid theoretical foundation and scientific basis for identifying the distribution characteristics of fine-grained sedimentary strata and predicting the distribution of unconventional oil and gas resources.

Key words: fine-grained sedimentary rocks; provenance; material characteristics; mechanism of origin