

江西修武盆地早寒武世热液活动 对有机质富集的影响

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摘要:下寒武统是中国海相页岩气勘探的主要目的层,不同层段页岩含气性变化较大,如何寻找勘探目标是亟待解决的重要问题。以江西修武盆地XN1井为例,通过岩心描述、测井数据分析、矿物和元素组成分析、总有机碳含量测试等手段,对下寒武统王音铺组和观音堂组页岩进行研究。结果表明,水体下部的氧化还原环境和水体表层的生物生产力控制着有机质的富集。热液活动使水体还原性增强,生物生产力提高,从而控制有机质的富集,进一步影响页岩气的富集。早寒武世SQ1沉积时期研究区水体还原性变化大,SQ2和SQ3沉积时期水体普遍具有强还原性,均远高于SQ4和SQ5沉积时期;以SQ3沉积时期生物生产力最高,SQ2和SQ1沉积时期生物生产力相差不大,均高于SQ4和SQ5沉积时期的生物生产力。研究区SQ1沉积时期的硅质来源变化较大,SQ2和SQ3沉积时期大部分层段存在热液成因硅且含量较高,SQ4沉积时期开始出现大段的陆源碎屑沉积,也存在热液成因硅,SQ5沉积时期的硅质矿物基本来源于陆源碎屑沉积。SQ2和SQ3为研究区下寒武统页岩气有利发育层段。

关键词:有机质富集 热液活动 氧化还原环境 生物生产力 沉积环境

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Effect of hydrothermal activity on the enrichment of sedimentary organic matter at Early Cambrian in the Xiuwu Basin

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Abstract: The Lower Cambrian is the main target intervals of marine shale gas exploration and exploitation in China. Shale gas content varies greatly in different intervals and how to determine favorable targets is an important problem to be solved urgently. Taking Well XN-1 in Xiuwu Basin as an example, according to core description, logging data analysis, mineral and elemental composition analysis and total organic carbon (TOC) content tests, the shale in Lower Cambrian Wangyinpu Formation and Guanyintang Formation was studied. Results show that water redox conditions and bioproductivity control the enrichment of sedimentary organic matter. Hydrothermal activities are helpful for the increase of reducibility of seawater and enhancing bioproductivity, and thus controls the enrichment of sedimentary organic matter and the enrichment of

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shale gas is further affected. The water reducibility during the deposition of SQ1 at early Cambrian varies greatly, and it is generally strong during the deposition of SQ2 and SQ3 of the Wangyinpu Formation. The reducibility of all the three sequences is stronger than that during the deposition of SQ4 and SQ5. The bioproductivity during the deposition of SQ3 is the highest and little difference in the bioproductivity has been found between SQ1 and SQ2, both of which show higher values than that of SQ4 and SQ5. Siliceous origin of SQ1 varies greatly in the study area; most siliceous minerals of SQ2 and SQ3 are hydrothermal origin, whose content is high; content of hydrothermal origin siliceous minerals drops in SQ4 and terrigenous siliceous content increases; siliceous minerals of SQ5 originate from normal terrigenous clastic deposition. SQ2 and SQ3 are favorable targets of shale gas in the Lower Cambrian.

Key words: enrichment of organic matter; hydrothermal activity; redox conditions; bioproductivity; deposition environment

美国最早进行页岩气勘探研究,2005年以来,得益于水平井钻井技术和水力压裂技术的发展,开发成本大幅降低,使页岩气资源在北美得到了大规模勘探与开发^[1-2]。中国蕴藏着潜力巨大的页岩气资源,2010年以来相继在威远、长宁、昭通、涪陵、富顺—永川等区块进行了商业开发,2015年中国页岩气产量达 $0.45 \times 10^{10} \text{ m}^3$ ^[3-8]。

下寒武统为中国海相页岩气勘探的主要目的层,因与下志留统页岩的沉积环境不同,导致页岩中有机质富集的原因有所差别。江西修武盆地地下寒武统王音铺组和观音堂组页岩的总有机碳含量(TOC)普遍大于2%,热演化程度较高,有机质类型均为I型,表明其下寒武统页岩具有较好的生烃物质基础^[9]。前人对修武盆地地下寒武统页岩气的成藏条件和勘探潜力进行了初步分析^[9-10],但缺乏对页岩沉积环境的分析及有利发育层段的预测方法。为此,笔者从分析氧化还原环境和生物生产力对有机质富集的控制作用及研究区硅质矿物来源入手,论证热液活动对氧化还原环境及生物生产力的影响,进而分析其对有机质富集的影响,最终明确修武盆地地下寒武统页岩气有利勘探层段,进一步指导研究区下一步的页岩气勘探开发。

1 区域地质特征

1.1 地层发育特征

修武盆地位于扬子地区中部,受早—中侏罗世构造运动挤压形成向斜,由修水—武宁向斜和罗洞向斜组成^[10],页岩气区块位于修水—武宁向斜西部(图1)。修武盆地由下至上依次沉积震旦系、寒武系、奥陶系、中—下志留统、上泥盆统、上石炭统、中—上二叠统、下三叠统、白垩系、古近系和第四系。研究目的层为下寒武统王音铺组和观音堂组。王音铺组下伏地层是上震旦统皮园村组,岩性为灰色硅质白云岩;王音铺组岩性为黑色硅质页岩,上覆地层是观音堂组,岩性为深灰色硅质页岩;

观音堂组上覆地层是中寒武统杨柳岗组,岩性为灰色微晶灰岩。各组地层之间均为整合接触。

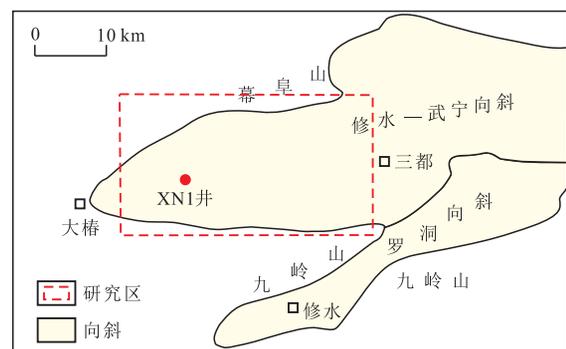


图1 修武盆地区域构造位置

Fig.1 Regional structural location of the Xiuwu Basin

1.2 沉积演化特征

修武盆地在震旦纪末期发生海退,发育皮园村组。早寒武世王音铺组沉积时期发生大规模海侵,沉积环境演变为深水环境,形成TOC值较高的富有机质页岩;观音堂组沉积时期水体逐渐变浅,TOC值逐渐下降,至观音堂组沉积晚期演变为浅水陆棚环境。中—晚寒武世研究区由早寒武世的碎屑岩沉积体系演变为碳酸盐岩沉积体系。早—中奥陶世研究区重新演变为碎屑岩沉积体系,晚奥陶世—早志留世研究区水体重新变深,沉积了厚度约为20~30 m的富有机质页岩,中志留世研究区水体逐渐变浅,晚志留世研究区抬升为古陆。泥盆纪和石炭纪抬升期与沉降期相互交叉,研究区沉积量较少,二叠纪、早—中三叠世为主要沉降期,研究区沉积环境为浅海相碳酸盐台地,在晚三叠世修武盆地开始隆起遭受剥蚀至今^[11],现存的地层由向斜轴部至向斜两翼依次出露下三叠统至震旦系。白垩系和古近系为盆地抬升剥蚀后形成的陆相冲积扇沉积^[12]。

1.3 层序地层特征

前人根据SLATT等提出的层序地层学理论^[13],依据野外剖面、岩心、测井资料以及氧化还原指数(U/Th)、盐度指数(Ca/(Ca+Fe))、与海岸线距离指数(Ti/Al)将修武盆地地下寒武统划分为由海侵体系域

(TST)和海退体系域(RST)组成的二级层序^[14],并进一步划分为5个三级层序(图2),其中王音铺组包括3个三级层序(SQ1,SQ2和SQ3),观音堂组包括2个

三级层序(SQ4和SQ5),每个三级层序同样可以细分为TST和RST,对每个三级层序的储层特征进行分析,认为SQ2和SQ3在5个层序中具有较高的脆

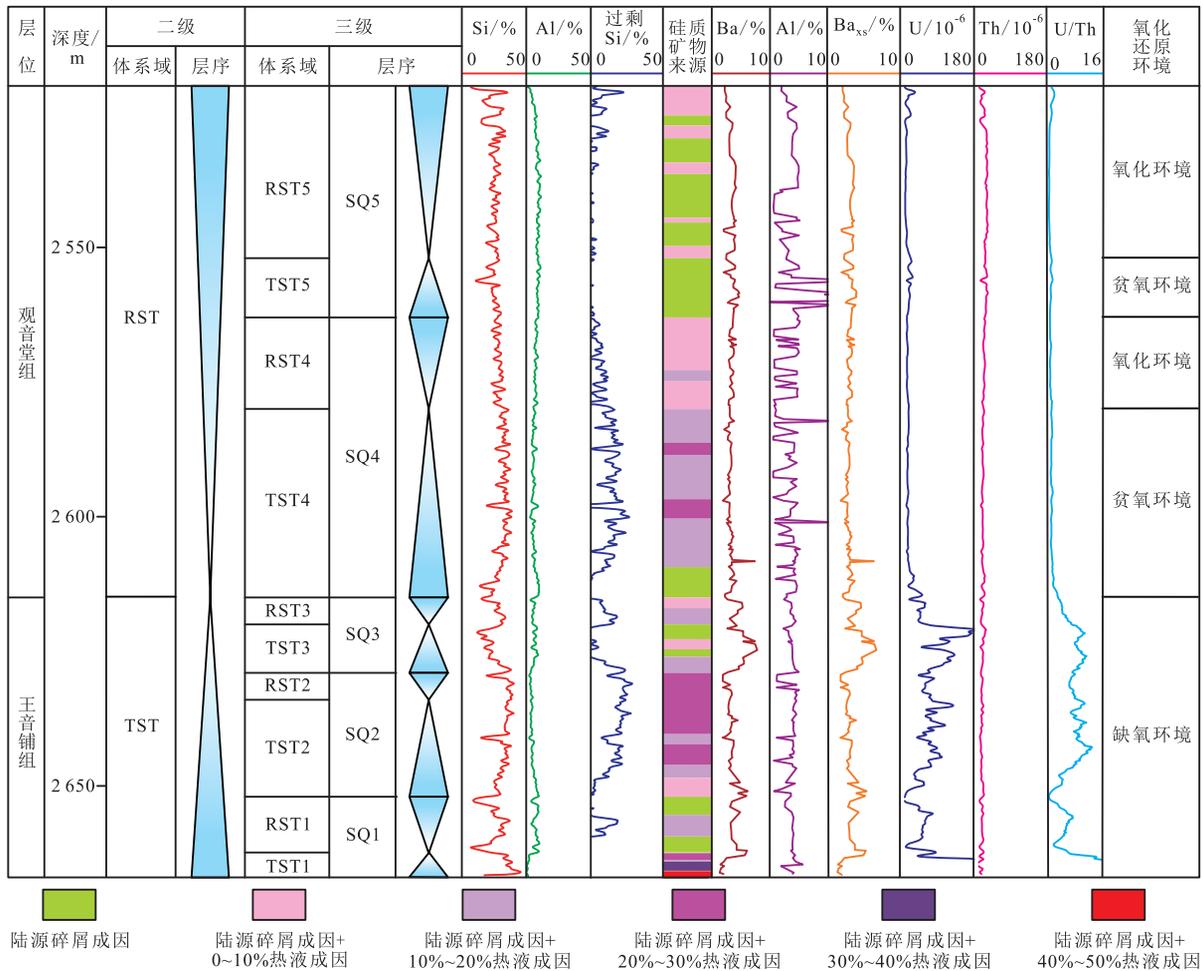


图2 XN1井下寒武统页岩氧化还原环境、生物生产力及硅质矿物来源分析

Fig.2 Analysis of redox conditions, bioproductivity and the origin of the siliceous minerals in the Lower Cambrian shale drilled by Well XN1

性矿物含量、有效孔隙度、TOC及含气量^[15]。

2 有机质丰度的影响因素

有机质中主要发育连通性孔隙,并且控制页岩总含气量,故TOC是页岩气评价的重要指标^[16-19]。页岩中残留的TOC一方面取决于有机质成熟度,成熟度越高,残留的TOC越低;另一方面,在同一层段有机质成熟度差别不大的情况下,取决于有机质的丰度。故对有机质丰度的影响因素进行分析。

2.1 氧化还原环境

通常采用元素地球化学指标来判断沉积环境^[20-21]。U在强还原环境下以不溶的U⁴⁺存在,而造成U在沉积物中的富集,而在氧化环境下则以可溶的U⁶⁺存在;加之Th不受水体氧化还原环境的影

响,因此用U/Th值可反映沉积氧化还原环境^[22]。一般来说,U/Th > 1.25代表缺氧环境,U/Th值为0.75~1.25,代表贫氧环境,U/Th < 0.75代表氧化环境^[23]。由图2可见,研究区XN1井SQ1,SQ2和SQ3沉积时期U/Th值高达4~18,水体具有强还原性;SQ4中的TST4沉积时期U/Th值迅速下降至0.75~1.25,水体变为贫氧环境,RST4沉积时期U/Th值进一步降至0.75以下,为氧化环境;SQ5中TST5沉积时期,发生海侵,水体加深,U/Th值又升至0.75~1.25,水体变为贫氧环境,RST5沉积时期,发生海退,水体变浅,U/Th值又降至0.75以下,为氧化环境。

由图3可知,研究区下寒武统页岩的U/Th值与TOC具有较好的正相关性。早寒武世SQ1—SQ3沉积时期至SQ4—SQ5沉积时期,水体由强还原环境变化为贫氧—氧化环境,相应的TOC大幅下降,说

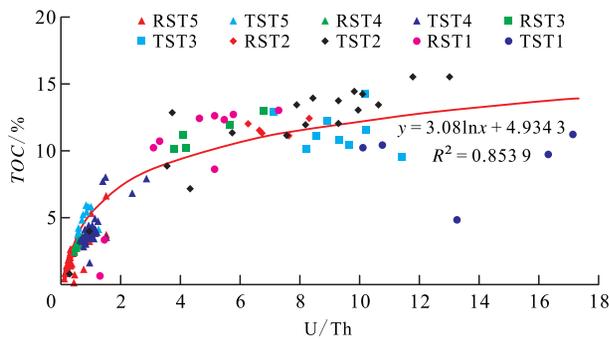


图3 XN1井下寒武统页岩TOC与U/Th的相关性

Fig.3 Correlation between TOC and the U/Th in the Lower Cambrian shale drilled by Well XN1

明水体的氧化还原环境对原始沉积有机质的保存起着重要作用。

2.2 生物生产力

最早开始并广泛使用的能够反映古海洋生物生产力的指标是Ba元素的含量。腐烂的有机质表面存在高浓度的且由H₂S氧化而成的SO₄²⁻离子,与海水中的Ba²⁺反应生成沉淀,导致高生物生产力地区BaSO₄的含量较高^[24]。岩石中的微量元素由陆源输入成分和自生成分2部分组成,只有自生成分能够反映古沉积环境特征。仅来源于生物作用的Ba称为过剩Ba(Ba_{xs}),其含量一般用Ba的总含量减去陆源碎屑Ba的估算含量,其表达式为

$$C_{Ba_{xs}} = C_{Ba_{样品}} - C_{Al_{样品}} \left(\frac{Ba}{Al} \right)_{PAAS} \quad (1)$$

式中: C_{Ba_{xs}} 为过剩Ba含量,%; C_{Ba_{样品}} 和 C_{Al_{样品}} 分别为所测样品中Ba和Al的体积分数,%; (Ba/Al)_{PAAS} 为标准澳大利亚页岩中Ba和Al的比值,其值为0.0077^[25]。

U/Th值与过剩Ba含量具有负相关性(图4),这是由于在贫氧一厌氧环境下,BaSO₄中的硫酸根离子被硫化细菌还原,使BaSO₄大量溶解而损失一部分生物Ba^[26]。研究区王音铺组还原性强于观音堂组(图2),生物Ba溶解量较多的SQ1和SQ2沉积时

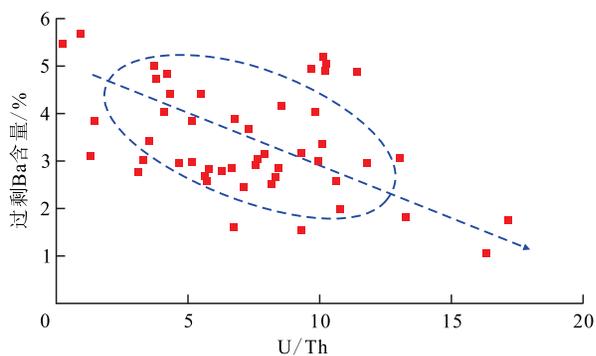


图4 XN1井下寒武统页岩过剩Ba含量与U/Th的相关性

Fig.4 Correlation between the excess Ba and U/Th in the Lower Cambrian shale drilled by Well XN1

期的过剩Ba含量与溶解量较少的SQ4和SQ5沉积时期基本一致,而且在水体还原性相近的情况下,SQ3沉积时期的过剩Ba含量高于SQ1和SQ2沉积时期。说明早寒武世王音铺组沉积时期生物生产力高于观音堂组沉积时期,其中SQ3沉积时期的生物生产力最高,SQ1和SQ2沉积时期次之,均高于SQ4和SQ5沉积时期。

综上所述,研究区早寒武世王音铺组沉积时期水体还原性强于观音堂组沉积时期,其中SQ1沉积时期水体还原性变化大,SQ2和SQ3沉积时期水体普遍具有强还原性,均远高于SQ4和SQ5沉积时期。SQ3沉积时期的生物生产力最高,SQ2和SQ1沉积时期生物生产力相差不大,均高于SQ4和SQ5沉积时期,从而造成了不同层段有机质丰度的差异,SQ2-SQ3,SQ1,SQ4和SQ5沉积时期TOC值分别为0.7%~15.8%,0.1%~13.9%,0.15%~8%和0.1%~8.3%。

3 热液活动对有机质富集的影响

3.1 过剩Si含量的计算

修武盆地下寒武统页岩中的硅质矿物平均含量为40%~75%,研究页岩中硅质矿物来源有重要的古沉积和古构造意义^[27]。硅质矿物一般来源于陆源碎屑沉积、生物沉积和热液沉积^[27]。下寒武统与上奥陶统一志留统是中国南方海相页岩气勘探的有利目的层系,四川盆地上奥陶统一志留统页岩中的硅质矿物含量与TOC相关性较好,且在扫描电镜下发现硅质生物碎屑,这说明上奥陶统一志留统页岩中的硅质矿物以生物成因为主^[28]。由图5可知,修武盆地下寒武统页岩硅质矿物含量与TOC也具有相关性。

HOLDAWAY等提出了页岩中陆源碎屑成因的硅质矿物和其他成因的硅质矿物(即过剩Si)占硅质矿物总含量百分比的计算方法^[29]。首先计算页岩层系中过剩Si的含量,若过剩Si含量为负值,则说明该层系为陆源碎屑成因,若过剩Si含量为正值,则说明该层系存在非陆源碎屑成因的Si。过剩Si含量是指高于正常陆源碎屑沉积环境下的SiO₂含量,其计算公式为

$$C_{Si_{过剩}} = C_{Si_{样品}} - \left[\left(\frac{Si}{Al} \right)_{背景} \times C_{Al_{样品}} \right] \quad (2)$$

式中: C_{Si_{过剩}} 为过剩Si含量,%; C_{Si_{样品}} 和 C_{Al_{样品}} 分别为所测样品中Si和Al的体积分数,%; (Si/Al)_{背景} 为常数,采用页岩平均比值3.11。

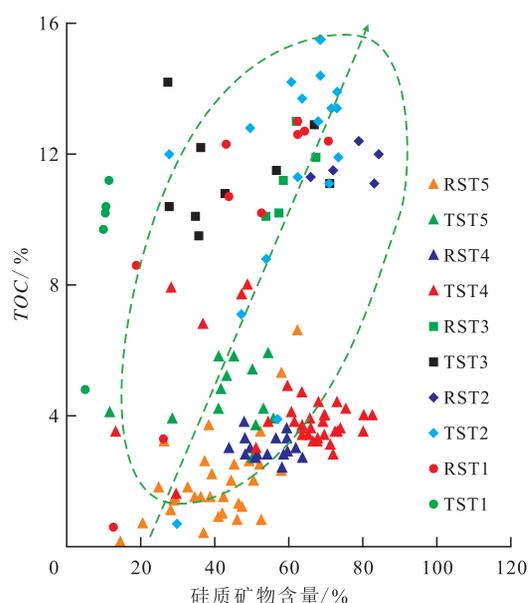


图5 XN1井下寒武统TOC与硅质矿物含量的相关性

Fig.5 Correlation between the siliceous mineral content and TOC in the Lower Cambrian shale drilled by Well XN1

由计算结果(图2)可知,研究区王音铺组和观音堂组大部分层段存在过剩Si。

3.2 硅质矿物来源分析

硅质页岩中Fe和Mn富集与热液参与有关^[30-31], Al富集大多与陆缘物质的介入有关, WEDEPOHL等提出利用Fe-Mn-Al三角图判别页岩中硅质矿物是来源于热液还是生物的方法^[32-34]。由于过剩Si含量为正值,说明该层系存在非陆源碎屑成因的硅,在过剩Si含量为正值层段用Fe-Mn-Al三角图判断过剩Si是热液成因还是生物成因。

由图6可以看出,研究区王音铺组和观音堂组存在过剩Si层段的数据较为集中,都在热液成因区,说明修武盆地寒武统页岩中的过剩Si为热液成因。由图2可见,不同层段热液成因的硅含量不同。SQ1层序硅质矿物来源变化较大,有全部为正常陆源碎屑成因的层段,也有热液成因Si含量较高的层段;SQ2和SQ3层序大部分层段为热液成因Si,含量为10%~30%;SQ4层序开始出现大段大部分为陆源碎屑成因Si的层段,也存在热液成因Si的层段,但含量相对SQ2—SQ3层序下降,为0~20%;SQ5层序基本为正常陆源碎屑成因Si。

3.3 对氧化还原环境的影响

还原的酸性热液流体进入海底后形成缺氧环境^[35-36],为有机质的保存提供有利条件。何金先等通过对上扬子地区下寒武统黑色页岩研究发现^[37],由于高的生物生产力造成生物呼吸作用和有机质

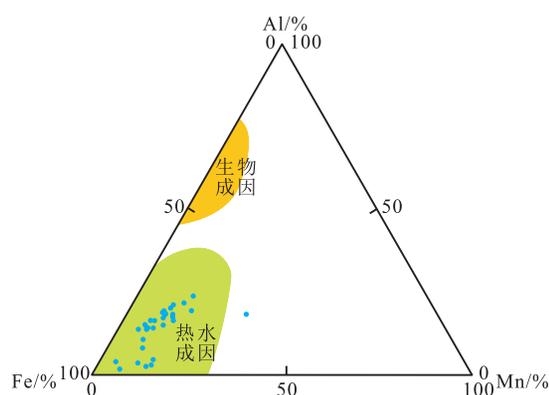


图6 XN1井下寒武统页岩含有过剩Si层段的Fe-Mn-Al含量及硅质矿物来源分析

Fig.6 Fe-Mn-Al content and origin analysis chart for the siliceous mineral of the Lower Cambrian drilled by Well XN1

分解对水中游离氧的消耗,导致早寒武世水体出现分层现象,表层生长大量浮游生物,底层水缺氧,对有机质的保存非常有利^[37-39]。

修武盆地早寒武世热液活动与水体氧化还原环境同样有相关性,由图2可见,XN1井下寒武统王音铺组沉积时期热液活动较频繁,且此时为海侵期,2方面的作用导致U/Th值较高,还原性较强;而观音堂组沉积时期热液活动较弱,此时为海退期,导致U/Th值较低,氧化性较强。

3.4 对生物生产力的影响

热液活动与生物生产力有着密切的关系。KOSCHINSKY等对Fiji盆地热液活动地区进行研究,发现距离热液活动区越近,其生物在水体中的数量和活动强度都会明显增加,较之普通的海洋表层,热液活动区会高1—3个数量级^[40]。KORZHINSKY等认为热液可以携带许多地壳表层罕见的元素^[41],而这些溶解状态的微量元素含有大量海洋生物必需的营养盐(Si, N, P, Fe, Zn)。生物死亡之后可呈“海雪”降落至海底,为烃源岩有机质富集提供物质来源^[42]。

修武盆地早寒武世热液活动与生物生产力也具有相关性,由图2可见,早寒武世王音铺组沉积时期热液活动较频繁,即使由于还原性较强造成过剩Ba溶解量较大,但剩余的过剩Ba含量也较高;而观音堂组沉积时期热液活动较弱,剩余的过剩Ba含量也较低。

4 有机质富集模式及页岩气有利发育层段预测

热液活动一方面形成页岩中的硅质矿物,另一

方面会对水体氧化还原环境和生物生产力产生影响,从而影响有机质丰度。

4.1 有机质富集模式

修武盆地下寒武统有机质富集模式为:在早寒武世,修武盆地位于扬子板块中部南缘,靠近扬子板块与华夏板块交界处,两板块之间相隔古华南洋;在早寒武世王音铺组沉积时期发生大规模海侵,由于洋壳扩张,在板块交界处构造拉张作用强烈,断裂较发育,地壳深部物质上涌,海水进入断裂将地壳深部物质携带出来,并受热形成富含矿物质(Si, N, P, Fe, Zn)的热液,在上升流的作用下,热液进入深水陆棚区,一方面进入海水表层,携带的营养盐类促进浮游生物生长繁殖,提高生物生产力;

另一方面在海底形成还原环境,有利于原始沉积有机质的保存,并与陆源粘土矿物、硅质碎屑和少量碳酸盐矿物及海水表层的生物有机质共同沉积下来,形成含有大量热液成因硅且TOC较高的下寒武统王音铺组页岩(图7a)。

在观音堂组沉积时期扬子板块与华夏板块交界处拉张活动减弱,热液来源减少,供应海水表层的营养盐类减少,造成生物生产力下降。由于观音堂组沉积时期海平面下降,使海底水体的还原性减弱,原始沉积有机质易遭受氧化破坏。由于发生海退使陆源的粘土矿物和硅质碎屑来源相对增加,形成了含有少量热液成因硅且TOC相对较低的下寒武统观音堂组页岩(图7b)。

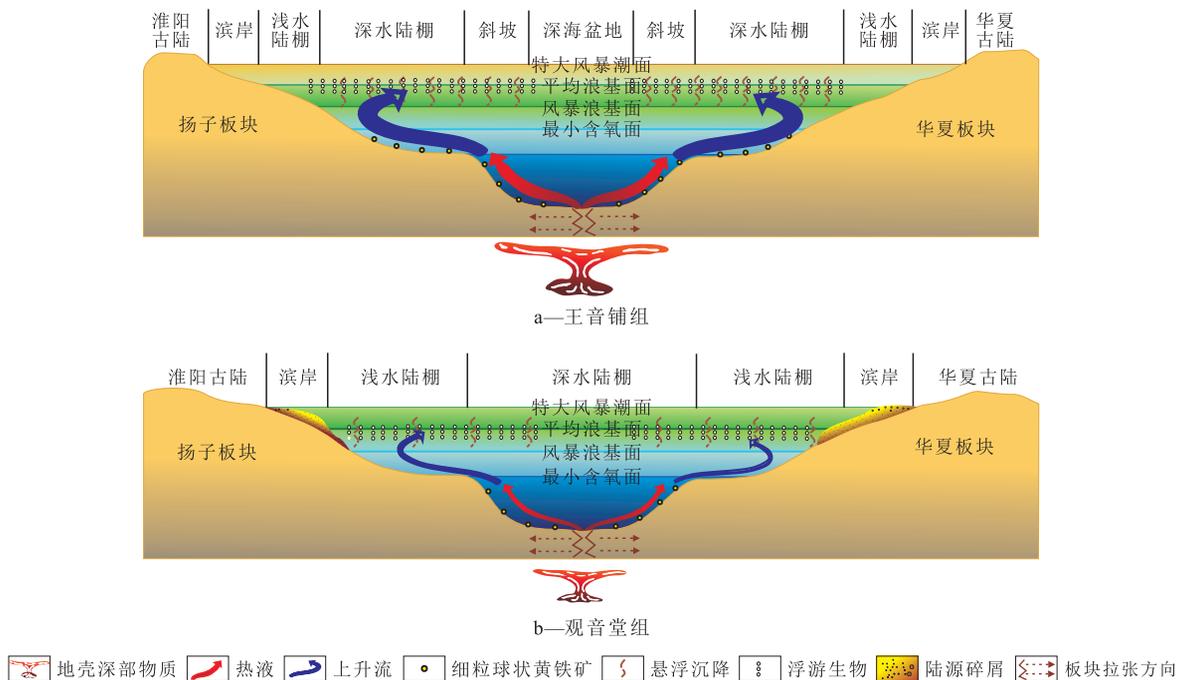


图7 修武盆地下寒武统王音铺组和观音堂组有机质富集模式

Fig.7 Scheme of sedimentary organic matter enrichment model for the Lower Cambrian Wangyinpu Formation and Guanyintang Formation in the Xiuwu Basin

4.2 有利层段预测

早寒武世扬子板块与华夏板块普遍发育热液活动,一方面提高水体表层的生物生产力,使有机质的来源增多;另一方面使水体下部形成缺氧还原环境,有利于有机质的保存。热液活动的强弱对有机质的富集可产生较大影响,进一步控制了TOC和含气量。研究区SQ2和SQ3的热液活动在下寒武统5个层序中较强(图2),由于SQ2和SQ3在5个层序中具有较高的脆性矿物含量、有效孔隙度、TOC及含气量,这说明可以通过分析早寒武世热液活动强弱来预测下寒武统页岩气的有利勘探层段。研究表明,研究区SQ2和SQ3是最有利的页岩气发

育层段。

5 结论

水体下部的氧化还原环境和水体表层的生物生产力控制着有机质的富集,早寒武世SQ1沉积时期修武盆地水体还原性变化大,SQ2和SQ3沉积时期水体普遍具有强还原性,均远高于SQ4和SQ5沉积时期;SQ3沉积时期的生物生产力最高,SQ2和SQ1沉积时期生物生产力相差不大,均高于SQ4和SQ5沉积时期。

修武盆地下寒武统王音铺组和观音堂组页岩

的硅质矿物除来源于陆源碎屑沉积之外,还有大量热液成因。SQ1的硅质矿物来源变化较大,部分层段中热液成因Si含量较高,SQ2和SQ3大部分层段具有热液成因Si,并且含量较高,SQ4开始出现大段的陆源碎屑沉积,也存在热液成因Si的层段,但其含量相对SQ1,SQ2和SQ3下降,SQ5的硅质矿物基本来源于陆源碎屑沉积。

热液活动使水体还原性增强,并提高生物生产力,从而控制有机质丰度,进一步影响页岩气的富集。修武盆地下寒武统热液活动较强的SQ2和SQ3即为页岩气有利发育层段。

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