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# 四川盆地二叠纪栖霞—茅口期古地理格局转换及勘探启示

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**摘要** 层序岩相古地理的重建工作对认识盆地的构造—沉积演化、沉积建造时空分布和油气勘探具有重要意义。特殊的构造位置和演化历史造就了四川盆地二叠纪的构造—沉积分异的复杂性。前人对四川盆地二叠纪的原始地理格局认识差异较大,一定程度上制约了栖霞—茅口组有利勘探相带的预测。在综合油气勘探地震、钻井及盆地周缘的露头剖面资料上,通过沉积旋回和层序界面的识别,将栖霞组划分为SQ1和SQ2两个三级层序,茅口组划分为SQ3—SQ5三个三级层序;基于沉积相标志和地层层序的宏观分布特征,重建了四川盆地栖霞—茅口期各层序的岩相古地理。结果表明:岩相古地理相带宏观展布揭示了盆地构造形迹由栖霞期的东北向转变为茅口期的北西向;构造—沉积格局由栖霞期准稳定背景的“隆—坳”分异向茅口期非稳定背景的“台—槽”分异转换;准定期的栖霞组有利勘探相带以相对平坦地貌的水下微幅隆起控制为主,呈现出“一带一环”的白云岩浅滩分布,非稳定期的茅口组则在区域张裂构造背景及同沉积正断裂活动的影响下,有利勘探相带受“一槽一半岛”的控制;栖霞—茅口期的台地边缘性质是先成浅水地貌成因的边缘,有利勘探区主要分布在边缘内侧的岸后云质浅滩相带,不同于礁滩沉积铸造的有利勘探相带为滨岸高能礁滩体的镶边台地边缘。

**关键词** 四川盆地;栖霞组;茅口组;层序地层学;岩相古地理;构造—沉积分异

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## 0 引言

回顾中国碳酸盐岩的油气勘探历程,可主要划分为以下三个阶段:1)上世纪中后期以靖边气田为典型代表的寻找构造高部位的岩溶型碳酸盐岩油气藏;2)在步入21世纪后,以普光气田为典型代表的寻找台地边缘礁滩油气藏;3)2010年以来,逐渐拓展至寻找克拉通内幕白云岩油气藏新领域<sup>[1]</sup>。四川盆地是我国重要的油气能源基地,自20世纪60年代以来经历了复杂的勘探历程,当前的勘探正大举向克拉通内部拓展<sup>[2-3]</sup>。四川盆地二叠系栖霞—茅口组作为四川盆地的油气勘探重点层位,展现出巨大的勘探潜力和经济价值<sup>[4-8]</sup>。然而,由于不同学者选取资料

的侧重点及对古构造背景的认识有所不同,不仅使得二叠系层序地层的划分方案尚存在较大差异<sup>[9-17]</sup>,也造成了多种截然不同的岩相古地理编图方案和对当时构造—沉积格局的认识仍存在较大的分歧<sup>[18-23]</sup>。准确的层序地层划分与对比不仅是认识盆地地层充填过程与古地理格局重建的前提,也是认识碳酸盐岩台地发育演化模式和有利勘探相带预测的重要基础<sup>[24]</sup>。近年来,随着四川盆地钻探、取心资料以及野外工作的深入,为重新认识二叠系层序地层和古地理格局提供了良好的研究基础。鉴于此,作者基于野外露头、钻井岩心、测井资料及薄片等资料,在层序界面识别和层序划分的基础上,试图建立层序地层格架,明确地层充填过程,进而探讨盆地的构造—沉积格局。

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古地理演化及沉积相带展布,为寻找有利的油气勘探相带提供依据。

## 1 地质背景

四川盆地在构造上位于上扬子地区,是典型的多旋回性克拉通盆地<sup>[25-26]</sup>(图1)。经历了漫长的地质演化历史,一般划分为6个构造—沉积旋回:扬子旋回(震旦纪)、加里东旋回(寒武纪—志留纪)、海西旋回(泥盆纪晚期—二叠纪晚期)、印支旋回(三叠纪—侏罗纪)、燕山旋回(侏罗纪—白垩纪晚期)、喜马拉雅旋回(白垩纪晚期—第三纪)。三叠纪的栖霞—茅口组沉积期处于海西旋回阶段。

云南运动导致上扬子台地大范围抬升剥蚀,使得四川盆地及其邻区普遍缺失下二叠统地层。梁山组是海侵初期由陆到海转换的产物,为一套厚度不大的风化壳之上的陆源碎屑含煤组合,部分地区发育残积的铝土质页岩,在四川盆地及其邻区广泛发育<sup>[27]</sup>。栖霞组沉积期,上扬子地区发生了大规模的海侵,主要发育一套稳定的浅海碳酸盐岩沉积<sup>[28]</sup>。栖霞组底部以发育泥晶灰岩为主,局部地区可见纹层状、斑状白云质灰岩;中上部主要发育泥晶灰岩、颗粒灰岩、晶粒白云岩<sup>[29]</sup>。茅口组主要由泥晶灰岩、颗粒灰岩组成,其底部发育“眼球眼皮”灰岩<sup>[30]</sup>。中二叠世末,由于峨眉山大火成岩省事件、东吴运动和全球海平面下降事件,导致上扬子

台地茅口组与上覆乐平统地层之间普遍呈平行不整合接触<sup>[31-33]</sup>。

## 2 三级层序地层格架

### 2.1 层序界面识别

识别层序界面是划分层序的基础,本研究在36个野外露头和400余口测井资料的基础上,结合地震格架剖面,开展了梁山—栖霞—茅口组系统的层序界面识别。层序界面识别标志主要有古风化壳、岩溶作用面、火山事件面、不整合面和岩性—岩相转换面。

#### 2.1.1 梁山组顶底界面

在云南运动造成的区域风化壳的基础上,随着海侵的到来,海水从盆地西北、东南两个方向侵入,形成了以含煤碎屑岩沉积为主的梁山组地层,覆盖在石炭系或更老地层之上,是海侵初期由陆到海转换的产物<sup>[27-28]</sup>。四川盆地梁山组与下伏地层的不整合界面,是典型的I型层序界面<sup>[17,34]</sup>。该界面是一个地层穿时面,覆盖的地层包括石炭系、泥盆系、奥陶系、寒武系多套地层。随着海平面上升,上扬子地区全部被海水淹没,沉积环境转变为栖霞组的广阔的碳酸盐岩台地沉积。梁山组碎屑沉积偶夹灰岩向上逐渐过渡为栖霞组台地碳酸盐岩沉积(图2a),是连续海侵过程的产物,因此梁山组与栖霞组的界面并非三级层序界面<sup>[10,15,17,28]</sup>。

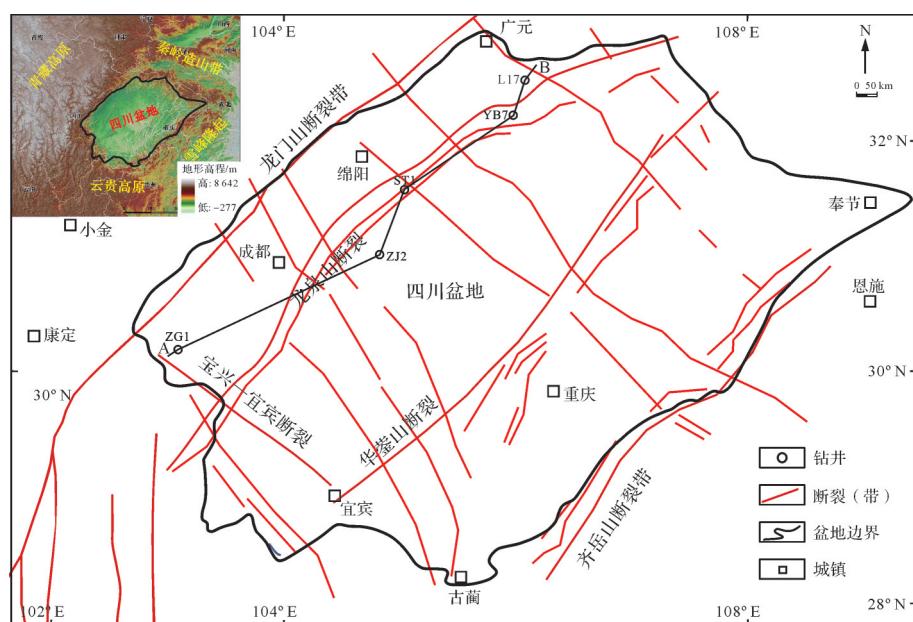


图1 四川盆地位置及二叠纪构造纲要

Fig.1 Geotectonic outline and location of Sichuan Basin

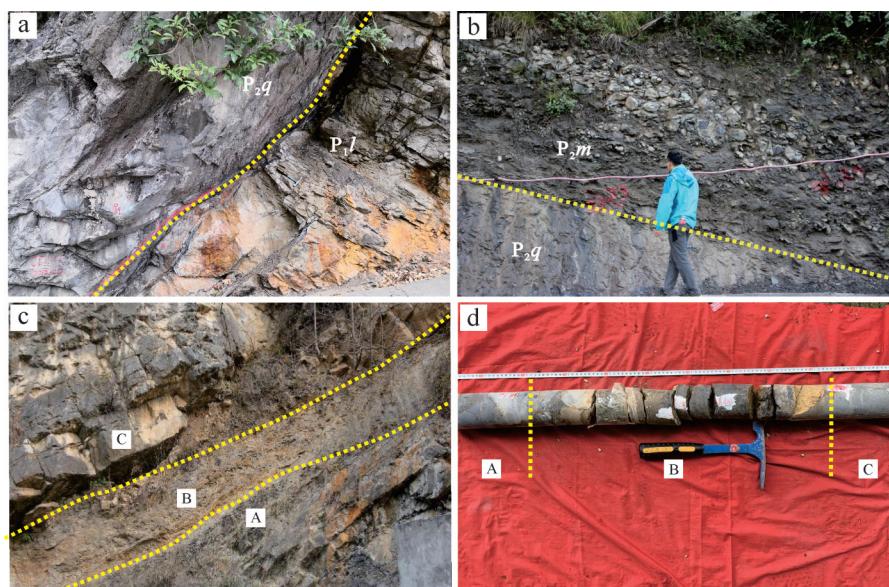


图2 四川盆地栖霞—茅口组层序界面特征

(a)旺苍双汇剖面梁山组与栖霞组界面;(b)綦江藻渡剖面栖霞组与茅口组界面;(c)广元车家坝剖面(A.茅口组孤峰段硅质岩;B.王坡页岩;C.吴家坪组灰岩);(d)YDD3井茅顶特征(A.茅口组;B.茅口组顶部风化壳;C.峨眉山玄武岩)

Fig.2 Sequence boundary characteristics of Chihsia-Maokou Formations in Sichuan Basin

### 2.1.2 栖霞—茅口组内部界面

在不整合面不发育或难以识别的地层中,划分和对比层序地层的关键是准确识别岩性—岩相转换面。综合对比多类型测井曲线发现,利用以自然伽马(GR)曲线为主,电阻率(RT)曲线与冲洗带电阻率(RXO)曲线结合的测井响应序列,能够较为准确的对四川盆地栖霞—茅口组内部进行层序地层划分和对比。GR曲线可以灵敏反映泥质含量和岩石粒序粗细的变化趋势。栖霞组从底部以发育泥质含量较高的泥晶灰岩和颗粒灰岩转换为上部的白云岩、颗粒灰岩,形成了栖霞组内部的一个岩性—岩相转换面。该转换面在大部分钻井以白云岩的出现为标志。栖霞组和茅口组之间,是第二个岩性—岩相转换面,该界面表现为栖霞组浅灰色颗粒灰岩向茅口组一段的区域性发育的泥质含量较高的“眼球眼皮”灰岩(图2b)。茅口组一段和茅口组二段C亚段,是一套泥质含量较高的灰岩,构成一个层序。其与上覆的茅口组二段的B、A亚段和茅口组三段在岩性—岩相上亦存在明显从转换关系,泥质含量明显降低,颗粒含量相对较高,是茅口组内部的第一个岩性—岩相转换面。茅口组四段则以出现大量硅质结核和硅质条带为特征,颗粒含量降低、泥质含量增多,与下伏的三段亦是一个岩性—岩相转换面。这些岩性—岩相转换面是非常明显的,在野外露头和绝大部分钻井上都很容易识别,属于Ⅱ型层序界面。

### 2.1.3 茅口组顶界面

受东吴运动、峨眉地幔柱上升和海平面快速下降的影响,在火山尚未喷发之前,茅口组便暴露地表而遭受风化剥蚀,与上二叠统地层之间沉积了一套风化残积物,即“王坡页岩”(图2c),是可作区域对比的等时界面。随后,由于峨眉山玄武岩喷发,在川西南地区厚度巨大的玄武岩不整合覆盖于茅口组之上(图2d)。茅口组顶部的风化壳或与火山岩喷发不整合接触面可作为层序界面的识别标志,该界面属于I型层序界面。

## 2.2 层序地层划分

依据上述层序界面的识别标志,四川盆地中二叠统的单井测井曲线中的自然伽马曲线(GR)和电阻率曲线(RT/RXO)和野外露头开展了详细的层序地层分析,确立了层序地层划分方案,梁山—栖霞组识别出SQ1和SQ2两个三级层序,茅口组识别出三个三级层序:SQ3、SQ4和SQ5(图3)。

前文已经对各层序的岩性—岩相进行了阐述,在此对研究用到的主要资料点测井曲线进行详述:SQ1层序的GR呈现持续递减趋势,RT/RXO曲线呈钟型;SQ2层序的GR曲线转变为平滑齿状低值,RT/RXO曲线呈指状高值;SQ3层序的GR值明显由SQ2层序的低值转变为指状高值;SQ4层序的GR曲线转变为箱型低值;SQ5层序的GR值相对较高,曲线呈漏斗型。研究区中二叠统400余口资料井中超过90%

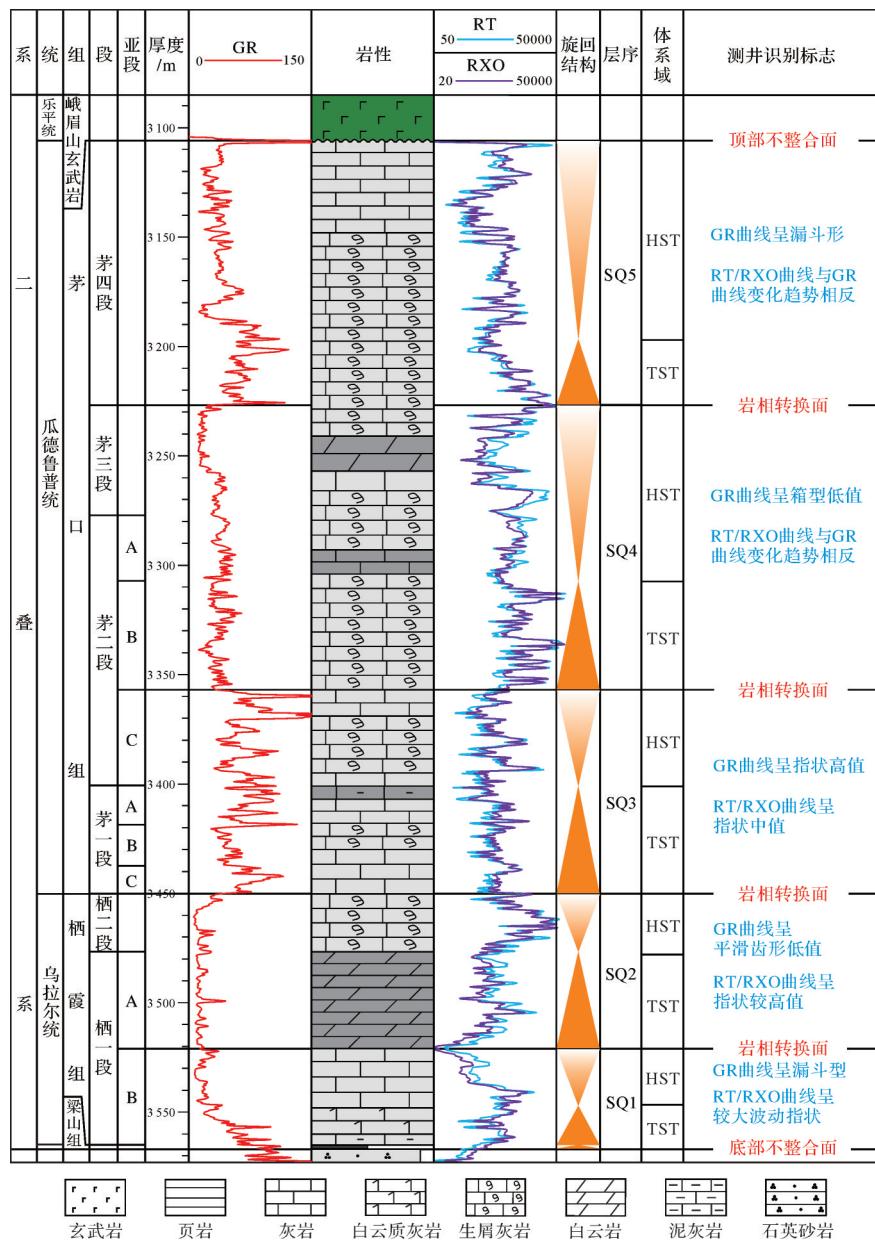


图3 四川盆地栖霞—茅口组ZG1井层序划分方案

Fig.3 Sequence division scheme of well ZG1

的井都有类似特征,自然伽马曲线和电阻率曲线具有全区可对比性,据此建立了层序地层格架(图4)。SQ1—SQ3层序地层厚度相对均一,为稳定克拉通沉积背景,SQ4—SQ5层序地层厚度差异较大,反应茅口组沉积的中—晚期发生构造—沉积分异作用。然而部分测井曲线对比不太一致的井,大多与茅口组中晚期构造—沉积分异有关,即部分钻遇在深水相井的测井曲线的岩性—岩相转换与浅水台地区的存在不一致,但是从沉积旋回上看,仍然能够识别出5个旋回,即能够通过旋回性与浅水相的钻井进行对比。

### 3 层序岩相古地理

本文根据15条野外剖面实测、21条野外剖面观测和32口钻井的岩心观察,对沉积相标志进行分析,建立了沉积相划分方案。在岩心—测井沉积相分析基础上,对400余口测井资料开展了测井相分析。在层序格架内依据优势相和特殊相法则确定了各资料点每个层序的沉积相类型及特征,结合层序厚度约束,编制了各层序的层序岩相古地理图(图5)。

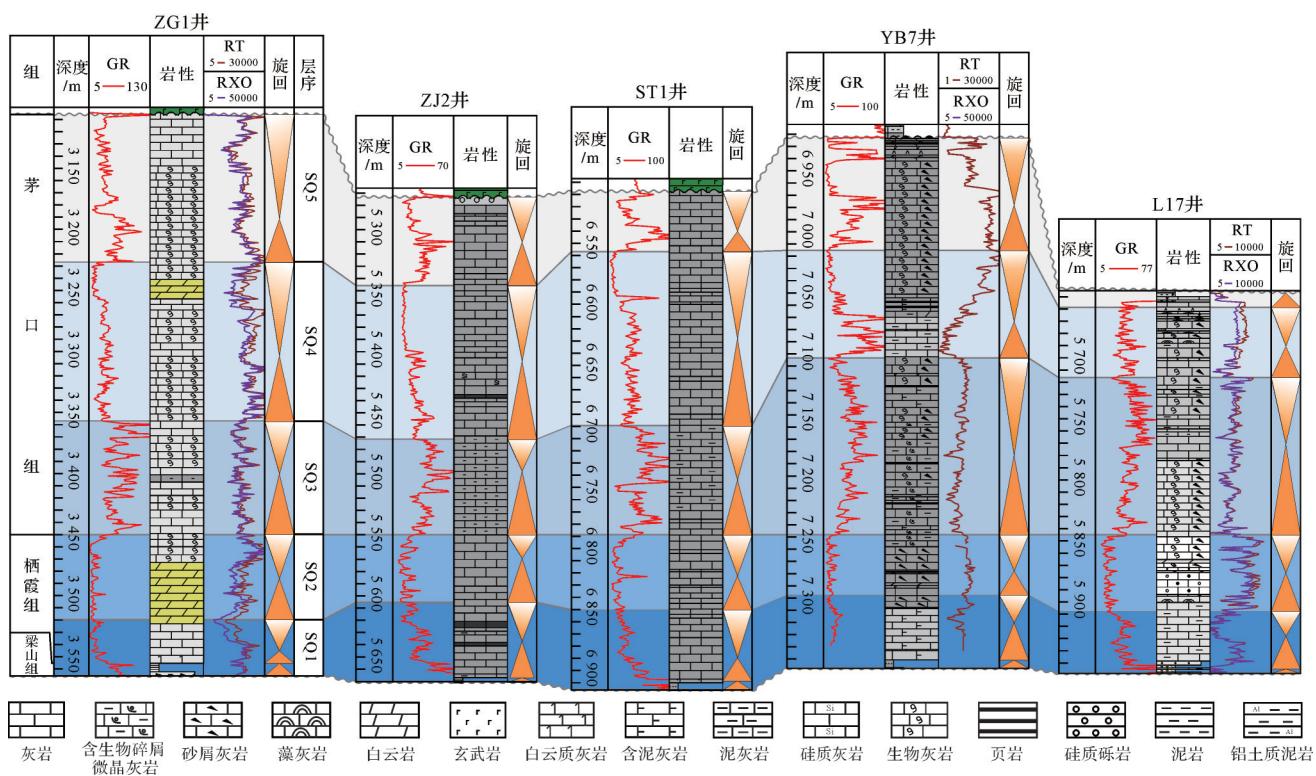


图4 四川盆地栖霞—茅口组层序对比图(连井线位置见图1)

Fig.4 Sequence correlation map of Chihsia-Maokou Formations in the Sichuan Basin

### 3.1 SQ1层序岩相古地理特征

受云南运动及风化剥蚀的影响,四川盆地在中二叠统沉积之前基本准平原化,在盆地周缘形成微隆起,内部形成坳陷,为克拉通坳陷盆地<sup>[35-36]</sup>。随着海侵的到来和持续扩大,海水主要从盆地东北部、南部两个方向侵入,形成了以含煤碎屑岩沉积为主的梁山组地层,披覆在石炭系或更老地层之上,梁山组是海侵初期由陆到海转换的产物<sup>[27-28]</sup>。随着海侵作用的加速,海平面迅速上升,上扬子地区全部被海水淹没,四川盆地在栖霞组沉积期形成了广阔的碳酸盐岩台地沉积。受四川盆地在二叠系沉积前古地貌呈西南高、北东低的影响<sup>[14,37-39]</sup>,有一定程度的自南部—东部向西—西南方向的超覆。由于隆起的围限作用和整体的浅水地貌,盆地内部主体属于局限台地一半开阔台地沉积环境,岩性以灰色泥晶灰岩、含生屑颗粒灰岩为主(图5a)。川西地区为浅的水下隆起,形成了台缘浅滩环境;受康滇古陆的影响,盆地西南缘的栖霞组底部的灰岩中混杂有陆源石英。盆地北缘和西缘快速向斜坡和深水盆地转换。从峨眉—邛崃—雅安—都江堰—江油—剑阁一线的条带状台缘浅滩展布来看,该时期盆

地的构造形迹主体呈北东向。该时期古地理格局整体上较为稳定,是碳酸盐台地逐渐建设成型阶段。

### 3.2 SQ2层序岩相古地理特征

SQ2沉积期基本继承了SQ1沉积期的构造古地理格局,仍然表现为浅水陆表海的背景。该时期海平面总体呈缓慢下降趋势<sup>[40]</sup>,沉积相带的分异特征更为明显。台地上气候适宜、营养充分、阳光充裕,有利于碳酸盐岩生长,是栖霞组沉积期乃至中二叠世的主要成滩期。西部的峨眉—邛崃—雅安—都江堰—江油—剑阁一线仍然发育条带状台的台缘浅滩,在浅滩内侧为局限环境背景下的席状云质浅滩体;在克拉通内部发育水体能量相对较高的云质浅滩带,宏观形态上呈“C”型分布。通过分析栖霞组沉积前的古地貌特点,该浅滩带明显受控于奥陶系、志留系地层的尖灭线,即与不整合面上的岩性差异造成地貌坡折有关(图5b)。

### 3.3 SQ3层序岩相古地理特征

茅口组沉积早期,华南发生了整个二叠纪甚至晚古生代以来的区域最大海泛事件<sup>[41]</sup>。海侵方向主要来自东南,即由鄂西和黔北向西北方向侵入,其次

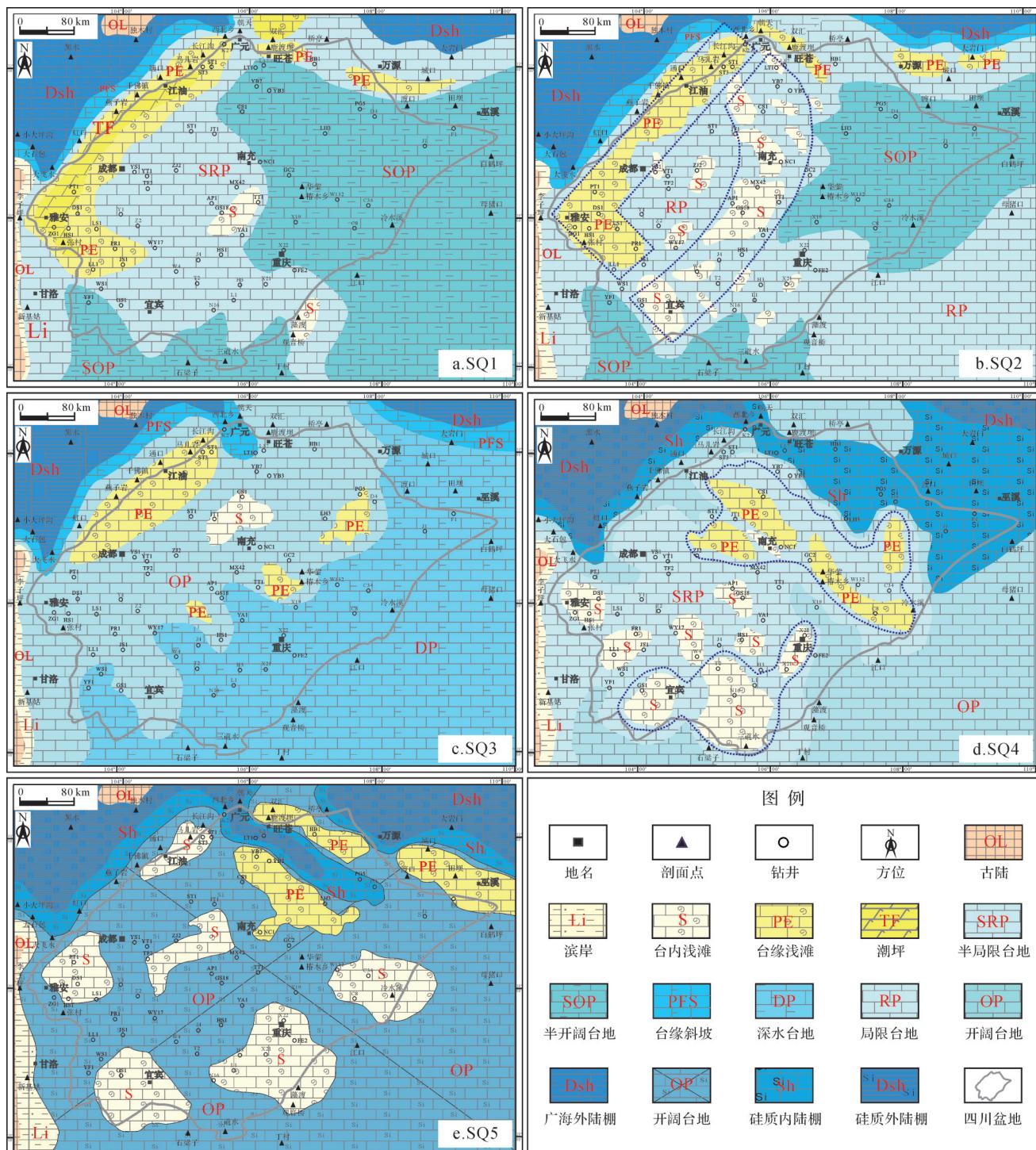


图5 四川盆地栖霞—茅口期岩相古地理图

Fig.5 Lithofacies paleogeographic maps of Chihsia-Maokou periods in the Sichuan Basin

由秦岭洋经川北侵入,再次则由西向东通过龙门山古岛链侵入<sup>[42]</sup>。四川盆地整体上由SQ2沉积期的浅水局限台地一半开阔台地转化为开阔台地—淹没台地,但依然保持了与栖霞组类似的北东向相带展布格局。该时期的一个显著特点是大面积地发育瘤状

灰岩,由其形态特征而俗称“眼皮眼球”灰岩。“眼皮眼球”灰岩在川西北地区的颜色较浅,往川东南方向颜色变深。川东南地区颜色较深的“眼皮眼球”灰岩有机质含量较高,作为一种自生自储的特殊类型具有一定的勘探潜力(图5c)。

### 3.4 SQ4层序岩相古地理特征

茅口组SQ4沉积期,岩相古地理图揭示的沉积相带展布发生了明显的改变,由此前的北东向展布转换为北西向展布(图5d),指示出盆地构造体制及其形成的构造形迹的转变。伴随全球海退的发生,海平面的缓慢下降,四川盆地大部分地区再次成为水体相对较浅、能量较高的开阔台地—半开阔台地。台地上发育众多大小不一的浅滩。该时期另外一个显著特点是,相对水深的含硅质结核灰岩开始出现在北部的剑阁—巴中—宣汉一带,呈槽型分布。该深水槽西南翼的台地发育北西向条带状的台缘浅滩。同时,在研究区南部屏山—古蔺—赤水—泸州—江津一带沿基底断裂带展布方向发育一呈半岛状分布的台内浅滩带。

### 3.5 SQ5层序岩相古地理特征

全球海平面从罗德期(茅口组中部)开始缓慢下降,直至卡匹敦晚期(茅口组顶部)快速下降,全球海平面下降到了地质历史时期的最低点<sup>[33]</sup>。同时受峨眉地幔柱上升的影响,茅口组沉积末期华南的古地理格局发生巨变,古陆规模和浅水面积扩大,右江盆地四周隆起形成新的孤岛和古陆,康滇古陆向东扩张,同时,江南古陆和云开古陆也隆升出水面,深水盆地向西南方向收缩<sup>[41]</sup>。四川盆地的茅口组虽然仍广泛发育开阔台地和浅滩,但生物碎屑和颗粒含量明显降低,而泥质含量却升高,特别是以发育大量硅质条带和硅质结核为特征。在西北乡—巴中一带深水相带更为发育,指示了明显的构造—沉积分异,这可能是峨眉山大火成岩省前期隆升造成的远端张性裂陷槽(图5e)。

## 4 构造—沉积格局转换及勘探启示

中二叠世早期,中国南方整体处于海侵背景,栖霞期海水逐渐向加里东形成的古隆起地貌超覆。川西地区继承了前期龙门山边缘裂陷的古构造格局,受裂陷盆地边缘同沉积断层的控制,形成克拉通边缘低幅水下隆起,向裂陷盆地一侧快速变为陆棚—斜坡相沉积。在克拉通边缘浅水地貌的基础上发育台缘浅滩相,同时在克拉通内部发育受加里东期古地貌“后效作用”影响的半环形斜坡上的台内浅滩相。总体上,沉积相带呈北东向展布,为水体相对较浅的陆表海背景,构造—沉积分异作用相对较弱,表现为稳定背景的隆—坳分异。至层序SQ4期,沉积

相带展布发生了90°的转变,由原来的北东向转变为北西向为主,表现最为明显的体现在研究区北部的“西北乡—巴中—宣汉”一带的北西向深水相带。岩相古地理编图揭示出的沉积相带展布的变化,指示了栖霞组沉积期向茅口组沉积期演化过程中构造—沉积格局的转换。栖霞组沉积前为构造相对稳定背景下的陆表海“隆—坳”分异,而茅口组沉积期则为构造背景相对活跃的“台—槽”分异。导致这种转换最为关键的因素很可能是峨眉地幔柱的隆升活动造成的,促使了上扬子地台内部的隐伏基底断裂发生张性复活,从而造成同沉积断裂作用或沉陷作用,并形成深水区(图6),这在地震剖面所揭示的地层结构上也有相应的响应<sup>[23]</sup>。因此,在全球海平面下降的背景下,在扬子地区内部“剑阁—巴中—宣汉”一带发育了一套深色的泥晶灰岩、泥质灰岩、泥岩、硅质岩建造,地层上可以扬子北缘的孤峰组对比,与茅口组顶部地层为同时异相沉积<sup>[23,43-45]</sup>。

四川盆地及邻区由栖霞期准稳定背景的隆—坳分异向茅口期非稳定背景的台—槽分异转换,造成了两个不同时期的主要勘探有利相带上的差异。这种构造背景的相互转换是我国小型克拉通的一个典型现象<sup>[8]</sup>,造成了不同层位构造—沉积分异模式的差异和勘探思路的变换。栖霞组的勘探目标主要是局限环境的席状分布的层状白云岩,有利相带主要为川西龙门山“L”型白云质台缘浅滩和克拉通内部的“C”型台内环状白云质台内浅滩,简称为“一带一环”(图5b深蓝色虚线圈定区)。在栖霞组“L”型白云质台缘浅滩带和“C”型台内环状白云质台内滩范围内已有多口钻井均获得勘探新突破,包括盆地西北缘的ST1井栖霞组获气87.6万方、ST3井和ST8井均获得工业气流,西南缘的PT1井栖霞组获66.86万方气,川中高磨地区的GS18井、MX42井和MX31X1井等亦获得高产工业气流。

茅口组的勘探目标则主要以层序SQ4的浅滩为主,茅口组的有利勘探相带主要有北部“剑阁—巴中—宣汉”台内深水槽西南翼的台地边缘浅滩和盆地南部“屏山—古蔺—赤水—泸州—江津”一带半岛状分布的浅滩,其控制因素简称为“一槽一半岛”(图5d深蓝色虚线圈定区)。这一认识推动了茅口组勘探由早期以顶部岩溶储层向中部滩相储层的转变,并实现了多个滩相储层的勘探突破,包括北部的YB7井、WT1井、CS1井、GC2井等以及位于南部“半岛”滩范围内的YJ2井。

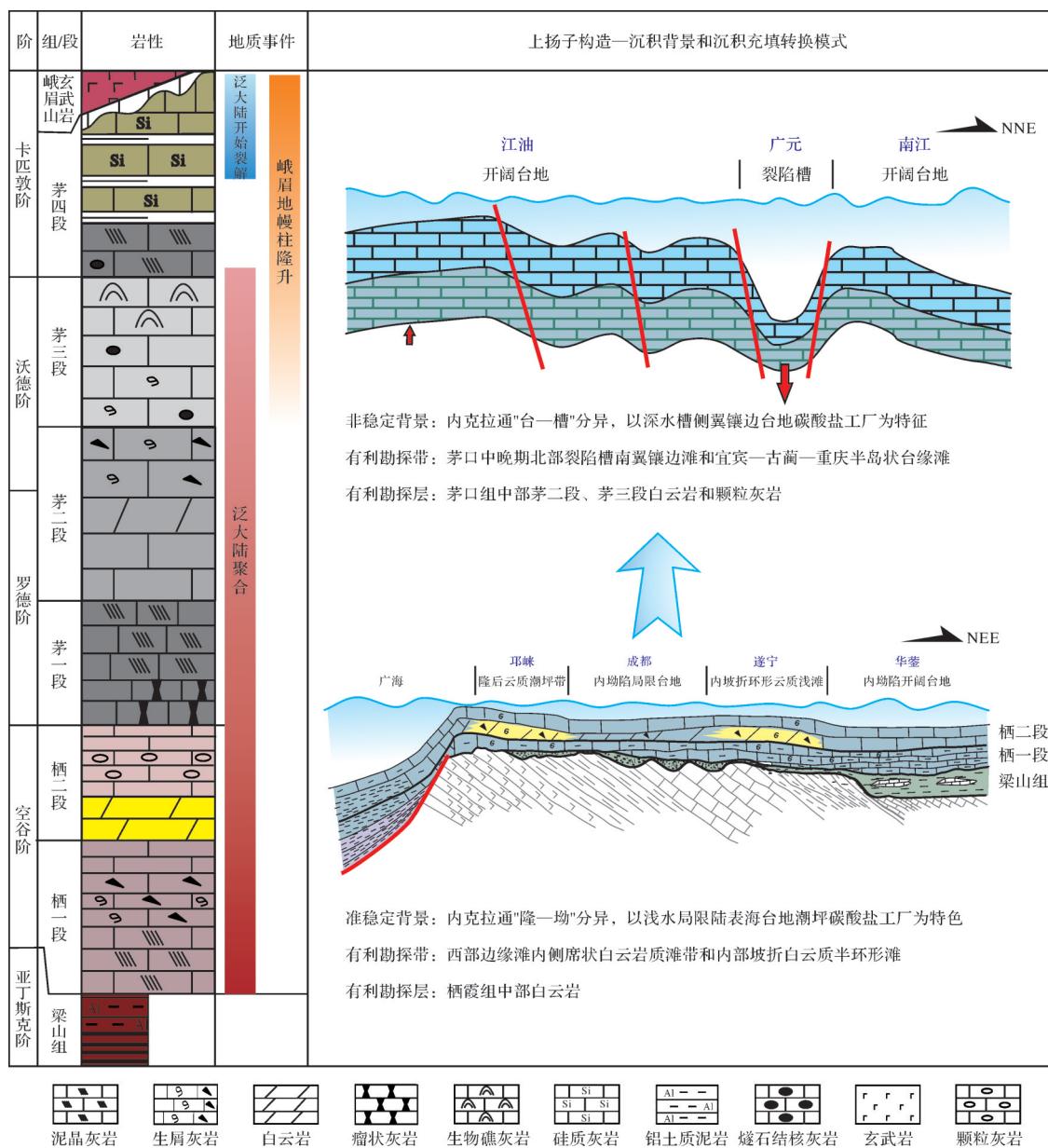


图6 四川盆地栖霞—茅口期构造—沉积分异演化模式

Fig.6 Tectonic sedimentary-differentiation evolutionary model of the Chihhsia-Maokou periods in the Sichuan Basin

另一方面,基于与四川盆地上二叠统长兴组的沉积建造的对比分析,揭示出栖霞—茅口组有利勘探相带具有明显的不同,长兴组的储层以镶边台地的边缘礁滩组合为特征,储层发育在面向深水一侧的高能相带,有利储层发育的相带具有明显的加厚现象。而栖霞—茅口组的台地边缘性质是先成浅水地貌成因的边缘,有利勘探区主要分布在边缘内侧的岸后云质浅滩相带,一般呈厚度较为均匀的席状分布,这完全不同于长兴组由礁滩沉积铸造的镶边台地边缘高能礁滩体。

5 结论

(1) 基于野外地质露头、钻测井资料和骨干地震剖面,将四川盆地中二叠统栖霞阶划分为SQ1和SQ2两个三级层序,茅口阶划分为SQ3—SQ5三个三级层序,每个三级层序内部可分为海侵体系域(TST)和高位体系域(HST),五个层序在横向上有很好的可对比性。

(2) 岩相古地理编图揭示中二叠世的构造—沉积格局由栖霞组沉积期准稳定背景的隆—坳分异型

向茅口组沉积期非稳定背景的台一槽分异转换,沉积相带在准稳定期以盆内低幅隆起地貌控制为主,非稳定期则受控于区域张裂构造背景及同沉积正断裂的活动。

(3) 栖霞组的有利勘探相带以SQ2下部的白云岩浅滩为主,呈现出“一带一环”的发育分布特征,茅口组有利勘探相带以中部层序SQ4的浅滩为主,受“一槽一半岛”的控制。

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# Paleogeographic Transition of the Permian Chihsia-Maokou Period in the Sichuan Basin and Indications for Oil-gas Exploration

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**Abstract:** The reconstruction of litho-paleogeography has an important role in understanding the evolution of sedimentary environments and the spatial distribution of sedimentary formations, and for hydrocarbon exploration. The unique location and evolution of structures caused complicated tectonic-sedimentary differentiation of the Permian in the Sichuan Basin. Previous studies have reported differences in their understanding of the original geographical pattern of the Permian in the Sichuan Basin. This has limited the prediction of favorable exploration facies belts in the Chihsia and Maokou Formations to a certain extent. In this study, the stratigraphy and sequence boundaries were interpreted from combined seismic and well log data and field data surrounding the Sichuan Basin. On this basis, the Chihsia Formation was divided into two third-order sequences, SQ1 and SQ2, and the Maokou Formation into three third-order sequences, SQ3, SQ4 and SQ5. Five paleogeographic maps were created based on the sedimentary facies evidence and characteristics of these 3rd-order sequences. These reveal that the tectonic features transitioned from the northeast of the Chihsia stage to the northwest of the Maokou stage. Tectonic-sedimentary differentiation features transition from the uplift and depression of the quasi-stable background in the Chihsia stage to platform/trough differentiation of the unstable background in the Maokou stage. The favorable exploration facies belt in the Chihsia Formation in the quasi-stable period was mainly due to the relatively flat landform, with slight uplift under water. The dolomite shoal facies is evident in a “belt and ring” structure. The unstable Maokou Formation was influenced by the regional extensional structural background and syndepositional normal fault activity. Favorable exploration facies belts occur in “trough and peninsula” structures. The platform margin between the Chihsia and Maokou periods marks the origin of shallow-water geomorphology. The favorable exploration areas are mainly in the backshore cloud shoal facies belt inside the margin. This differs from reef-sedimentary zones, where favorable exploration facies belts occur at the edge of the platform of a high-energy reef beach along the shore.

**Key words:** Sichuan Basin; Chihsia Formation; Maokou Formation; sequence stratigraphy; lithofacies paleogeography; tectonic-sedimentary differentiation