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川西北开江—梁平海槽与蓬溪—武胜台凹交汇区长兴组—飞仙关组沉积相展布与演化

王兆鹏[1,2,3]，邢凤存[1,2,3]，古强[1,2,3]，武赛军[4,5]，刘子琪[1,2,3]

1. 油气藏地质及开发工程全国重点实验室(成都理工大学)，成都　610059
2. 自然资源部深时地理环境重建与应用重点实验，成都理工大学，成都　610059
3. 成都理工大学沉积地质研究院，成都　610059
4. 中国石油勘探开发研究院四川盆地研究中心，成都　610041
5. 中国石油勘探开发研究院，北京　100083

摘　要　**【目的】**明确川西北晚二叠世长兴期—早三叠世飞仙关期开江—梁平海槽西侧台缘带与蓬溪—武胜台凹东侧台缘带在北部是否相连，确定川西北地区江油—剑阁及周缘地区长兴组—飞仙关组的沉积相展布模式，并分析沉积充填演化过程，以指示进一步的油气勘探工作。**【方法】**在最新的钻井、野外露头和地震资料，在地层和沉积相划分对比基础上，系统开展了广元—江油一带长兴期—飞仙关期岩相古地理展布及沉积充填演化过程分析。**【结果】**研究区长兴组—飞仙关组可识别出陆棚—盆地、斜坡、台地边缘、开阔台地、局限台地和蒸发台地等六类沉积相。基于多处台缘斜坡相带的沉积记录，明确了开江—梁平海槽西侧台缘带与蓬溪—武胜台凹东侧台缘带在川西北刺林包—上寺一带连接形成统一的台缘带。台缘带呈现北西向指状间互分布，而非简单的平滑带状分布。长兴期呈现北东—南西向的两槽夹一台的沉积格局，台缘带连接区发育多排并行的北西—南东向指状生物礁滩体。台缘带长一段沉积期发育生屑滩、长二段沉积期发育生物礁滩。飞一段和飞二段沉积期继承了长兴期台地—盆地的总体格局，但飞一段早期海泛期仅在台缘带局部发育鲕粒滩，飞一段晚期—飞二段沉积期台缘鲕粒滩逐渐发育、范围扩大，且总体具有向东迁移特征，台缘斜坡滑塌沉积普遍。飞三段沉积期海槽区逐渐填平，指状台缘带消失，形成统一的局限台地，仅在局部发育鲕粒滩。飞四段沉积期全区域填平、地貌平整，发育蒸发台地。研究揭示，该连通的台缘带在飞仙关组沉积期并未顺台地沿北西向指状延伸的方向迁移，而是具有向东迁移特征。**【结论】**该研究确定了开江—梁平海槽与蓬溪—武胜台凹长兴期至飞仙关期连通性并提出的六个沉积充填演化阶段，提出了长兴期—飞仙关期槽—凹交汇区沉积格局及沉积充填演化过程新认识，为上扬子晚二叠世—早三叠世岩相古地理演化研究及研究区油气勘探提供了思路与参考。

关键词　沉积充填；碳酸盐台地；沉积相；长兴组；飞仙关组；川西北地区

第一作者　王兆鹏，男，1998年出生，硕士研究生，沉积学(含古地理学)，E-mail: 1093711700@qq.com

通信作者　邢凤存，男，博士生导师，E-mail: xingfengcun@163.com

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0　引言

碳酸盐岩沉积充填演化过程是记录地球演化历史的重要载体，承载了地质历史时期古地理、古气候、古构造及重大地质事件信息，也孕育了丰富的油气等矿产资源(He *et al.*，2022；Liseroudi *et al.*，2022；Gou *et al.*，2024)。碳酸盐台地边缘形态受地质条件影响，存在点状、单排和多排台缘带共存等多种样式(郭凯等，2023；吴永宏等，2023；康婷婷等，2024)。随着研究不断深入，逐渐认识到碳酸盐岩台地边缘带的位置并非

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固定不变,而是具有不同程度的迁移性,不同构造背景的碳酸盐台地的台缘带形态、沉积充填演化过程具有差异性(Gréselle and Pittet, 2005; Wilson *et al.*, 2012; Basilone and Sulli, 2018)。目前,针对单一碳酸盐台地沉积充填演化过程研究较为深入(Grobe *et al.*, 2016; Varejão *et al.*, 2016; 邢凤存等, 2018; Qiao *et al.*, 2024; 李森等, 2025),而针对同期多排台缘带共存下的碳酸盐沉积充填演化过程研究还尚待探讨,目前尚未检索到公开发表文献针对同期两个斜交台缘带相连接的过渡区的沉积充填演化过程研究实例。

四川盆地晚二叠世长兴期—早三叠世飞仙关期自东向西同期发育城口—鄂西(左洺滔等, 2016; 董庆民等, 2019)、开江—梁平(魏国齐等, 2006; 张建勇等, 2011; 唐雨等, 2021; 杨雨等, 2023)及蓬溪—武胜(梁霄等, 2019)(或称为盐亭—潼南(李秋芬等, 2015, 2018)三个北西向—南东向带状深水区。三个深水区总体表现为向北延伸且水体加深(魏国齐等, 2006; 张建勇等, 2011; 李秋芬等, 2015, 2018; 左洺滔等, 2016; 董庆民等, 2019; 梁霄等, 2019; 唐雨等, 2021; 杨雨等, 2023)。目前针对三个深水区定名尚存争议,一般将城口—鄂西、开江—梁平深水区称为海槽(魏国齐等, 2006; 张建勇等, 2011; 左洺滔等, 2016; 董庆民等, 2019; 唐雨等, 2021; 杨雨等, 2023)或拉张槽(梁霄等, 2019),沉积相带上定为深水陆棚(李秋芬等, 2015; 梁霄等, 2019)或盆地(唐雨等, 2021; 杨雨等, 2023)等,蓬溪—武胜一带深水区存在台凹(张奇等, 2010)、拉张槽(梁霄等, 2019; 罗开平等, 2020; 文龙等, 2023)或海槽(李秋芬等, 2015, 2018)等多种叫法,该区沉积相有台内洼地(张奇等, 2010; 罗开平等, 2020)、深水—浅水陆棚(唐雨等, 2021; 孙自明等, 2023; 文龙等, 2023)及盆地(李秋芬等, 2015; 文龙等, 2023)等观点。在三个相对深水区两侧形成了同期5排碳酸盐台地(或台凹)边缘高能带(图1a),并在北部广元—江油、通江一带具有汇聚趋势,但是否相互连通存在争议(魏国齐等, 2006; 张建勇等, 2011; 李秋芬等, 2015, 2018; 左洺滔等, 2016; 董庆民等, 2019; 梁霄等, 2019; 唐雨等, 2021; 杨雨等, 2023)。前人针对川东北地区晚二叠世长兴期—早三叠世飞仙关期碳酸盐台地的沉积充填演化过程开展了系统研究(郑荣才等, 2008; 李秋芬等, 2015, 2018; 邢凤存等, 2017, 2018; 严张磊等, 2018; 周凯等, 2018; 徐敏等, 2021; 杨雨等, 2023),受资料情况和关注程度等影响,开江—梁平海槽(考虑名称争议,暂定此名)西侧台缘带与蓬溪武胜台凹(考虑名称争议,暂定此名)边缘高能带在北部是拼接到一起,还是直接向北西方向延伸到盆地之外未有定论(王一刚等, 2009; 乔占峰等, 2010; 陈洪德等, 2011; 郭彤楼, 2011; Zhou *et al.*, 2023),这也是长兴组—飞仙关组台缘礁、滩发现几十年来一直尚未解决的科学问题,导致该过渡区沉积格局及沉积充填演化过程认识不明确。该问题直接影响到对上扬子长兴组—飞仙关组沉积期碳酸盐台地沉积充填演化过程的完整性认识,同时制约了该地区长兴组—飞仙关组油气勘探部署。

本文以广元—江油为重点研究区(图1a),系统分析了长兴组—飞仙关组13条野外露头剖面(图1b)、区内最新的35口钻井及二维和三维地震资料(图1b)。针对开江—梁平海槽西侧台缘带和蓬溪—武胜台凹东侧边缘带在梓潼—剑阁—广元一带是否连通、具体形态特征及其沉积充填演化过程等问题开展了系统研究,以期为该地区乃至上扬子晚二叠世—早三叠世沉积充填提供素材,为该地区长兴组—飞仙关组油气勘探提供参考。

1　地质背景

研究区位于四川盆地西北部,北至广元、西至江油、东南至阆中(图1)。晚二叠世—早三叠世处于上扬子西北缘,开江—梁平海槽和蓬溪—武胜台凹的西北缘区域。研究区自震旦纪(邹才能等, 2014; 宋芳等, 2024),先后经历了加里东、海西、印支、燕山以及喜山运动等多期构造运动(刘树根等, 1995; 王金琪, 2003; 姚军辉等, 2011; 邹才能等, 2014; 宋芳等, 2024),其中海西期构造旋回和印支期构造旋回对研究区二叠纪、三叠纪之交槽台沉积格局的形成起到了重要作用。晚二叠世受峨眉地裂运动影响,形成了隆凹相间格局,对应发育碳酸盐台地和深水陆棚—盆地沉积组合,同期形成了5排台缘生物礁滩带(魏国齐等, 2006; 张建勇等, 2011; 李秋芬等, 2015; 唐雨等, 2021)。受二叠纪末生物大灭绝事件影响,早三叠世飞仙关期虽然继承了晚二叠世长兴期总体沉积格局,但高能相带主要发育鲕粒滩沉积(王一刚等, 2006; 姚军辉等, 2011; 彭志, 2015; 苏成鹏等, 2016; 张兵等, 2017)。本文主要研究了广元—剑阁一带St、Lg、Yb

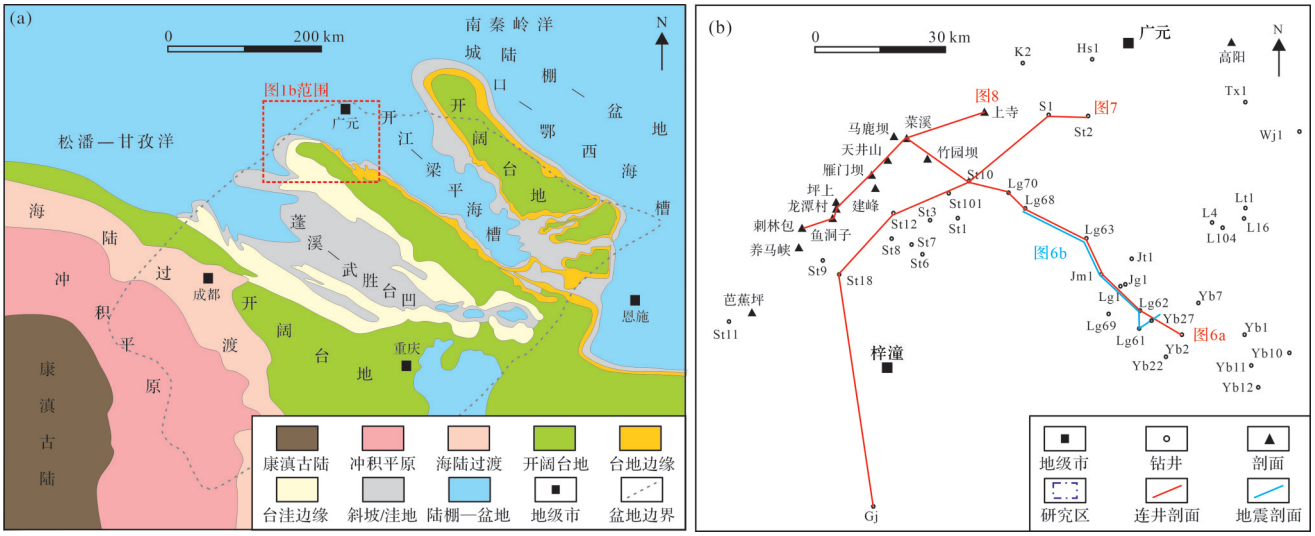

图1 研究区位置、资料点和对比剖面位置图

(a)研究区地理位置及长兴组沉积期岩相古地理概要图(据李秋芬等,2015;文龙等,2023修改);(b)研究区剖面、地震测线和钻井位置图

Fig.1 Location of the research area and map of data points and comparative profiles

(a) geographical location of the study area and schematic lithofacies paleogeography map of the Changxing Formation during its depositional period (modified from Li *et al*., 2015; Wen *et al*., 2023); (b) location map of sections, seismic lines, and drilling wells in the study area

等井位及其附近的部分野外剖面(图1b)。

前人针对川西北地区长兴组—飞仙关组层序地层划分已基本达成共识,将其划分为4个三级层序(乔占峰等,2010;郭彤楼,2011;彭志,2015;邢凤存等,2017;苏成鹏等,2016;王高峰等,2016;胡欣等,2017;张兵等,2017),图2展示了St1井层序地层和体系域划分方案。

2 沉积相类型

综合前人研究,基于区内野外、钻井和地震等资料(图1b),将研究区长兴组—飞仙关组划分出蒸发台地、局限台地、开阔台地、台地边缘、台缘斜坡及陆棚—盆地等六种沉积相类型(图3,4、表1)。前人已经针对这些沉积相类型进行了系统分析(王一刚等,2009;乔占峰等,2010;张奇等,2010;陈洪德等,2011;郭彤楼,2011;左洺滔等,2016;邢凤存等,2017,2018;周凯等,2018;徐敏等,2021),沉积相类型基本达成共识,本文不再赘述各沉积相类型特征。

前人已经证实在Yb井区(郭彤楼,2011;邢凤存等,2017;严张磊等,2018)和Lg井区(王高峰等,2016;胡欣等,2017)长兴组发育碳酸盐台地边缘生物礁滩(图5),St井区尚存争议。本次研究揭示露头区发育珊瑚礁灰岩(图3b,c),珊瑚具有明显的原地生长结构,钻井和野外露头也揭示了苔藓虫(图3d)和绿藻(图3f,g)等造礁生物发育。综合地震解释、钻井及野外露头厚度资料,对长兴组地层厚度进行了编图(图5)。由于沉积期后没有受到明显剥蚀,地层厚度能够有效指示古地貌特征,前人研究也揭示地层厚度显著增大的区域指示了生物礁滩发育部位(张奇等,2010;张建勇等,2011;彭志,2015;苏成鹏等,2016;王高峰等,2016;严张磊等,2018;罗开平等,2020;文龙等,2023)。类比Yb和Lg井区现已钻遇的台缘生物礁的杂乱、底平顶凸和地层增厚的典型地震反射特征(图5,6),在St井区也发现了明显的杂乱起伏的生物建隆结构(图5)。同时,目前钻遇生物礁的Lg70、Lg68、Lg63、Lg62、Jm1、Yb2、Yb1、Yb10等钻井长兴组地层厚度均大于250 m,而St井区和露头区也有大于250 m的带状凸起地貌,且这些地貌上的带状凸起区与地震杂乱反射区对应,由此认为St井区存在生物礁。前人近期研究也证实了St井区该地区长兴组生物礁的存在(朱可丹等,2023),综上,结合地震反射和地层厚度凸起区能够有效确定生物礁发育区(图5)。

3 台凹—海槽过渡区连通性分析

对于开江—梁平海槽西侧台缘带与蓬溪—武胜台凹东侧台缘带在北部进行连通性研究,进而刻画台缘带具体形态特征,首先需要确定台地边缘带或

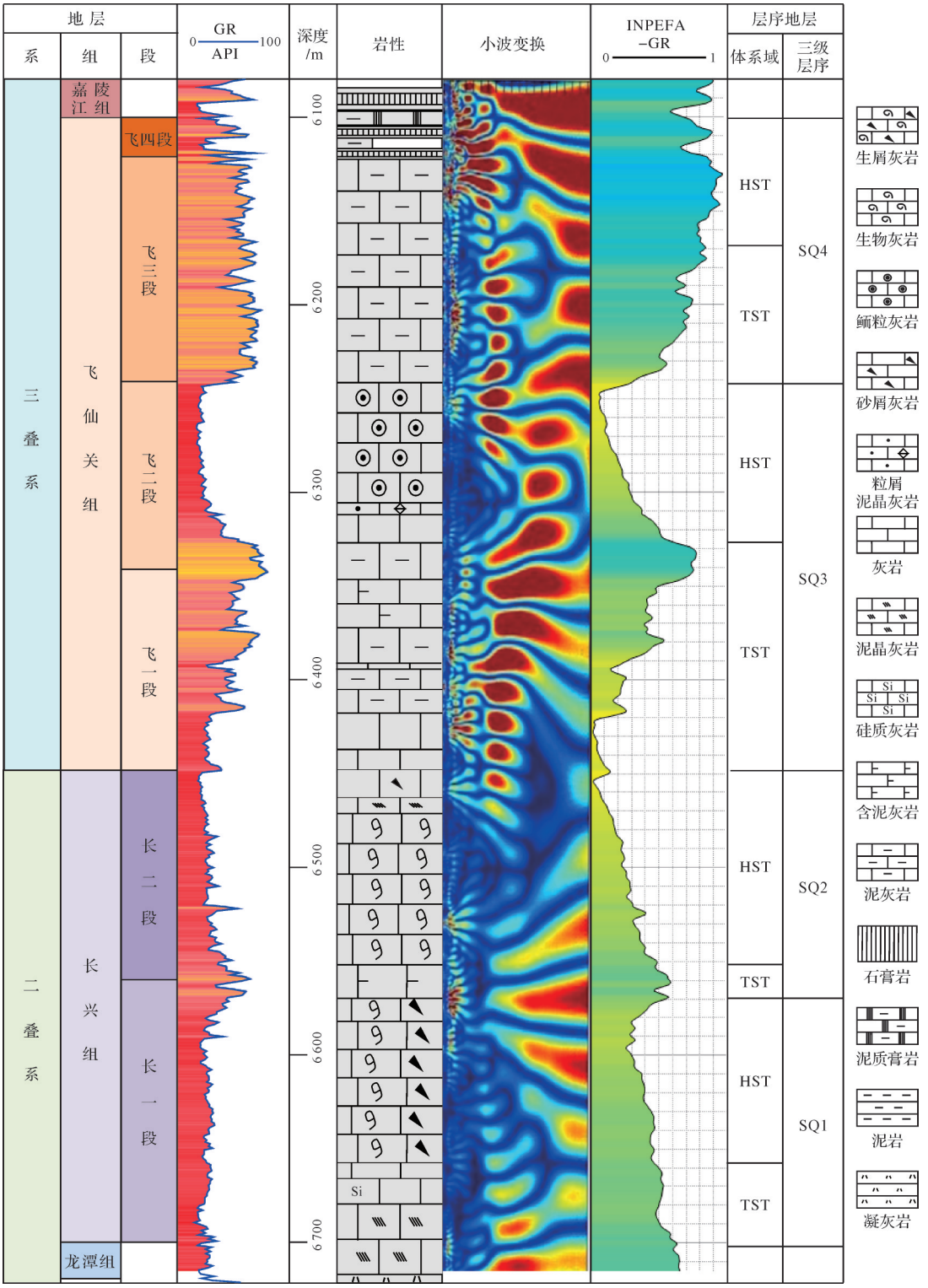

图2　St1井长兴组—飞仙关组层序地层综合柱状图

Fig.2　Sequence stratigraphy comprehensive column of the Changxing Formation-Feixianguan Formation in well St1

台凹边缘高能带、台缘斜坡带以及深水陆棚—盆地区的分布。研究区生物礁滩、鲕粒滩等高能相带在研究区台地边缘或(台凹边缘)具有显著分布(图3),其周缘均有台缘斜坡和深水沉积证据(图4)。研究揭示,长兴组斜坡区普遍发育中薄层状含生屑泥晶灰岩,层位起伏,且普遍可见燧石团块(图4a),长兴组台前深水陆棚—盆地区一般是以硅质岩或者硅质岩与泥质灰岩或者泥晶灰岩为主的薄层—薄板状互

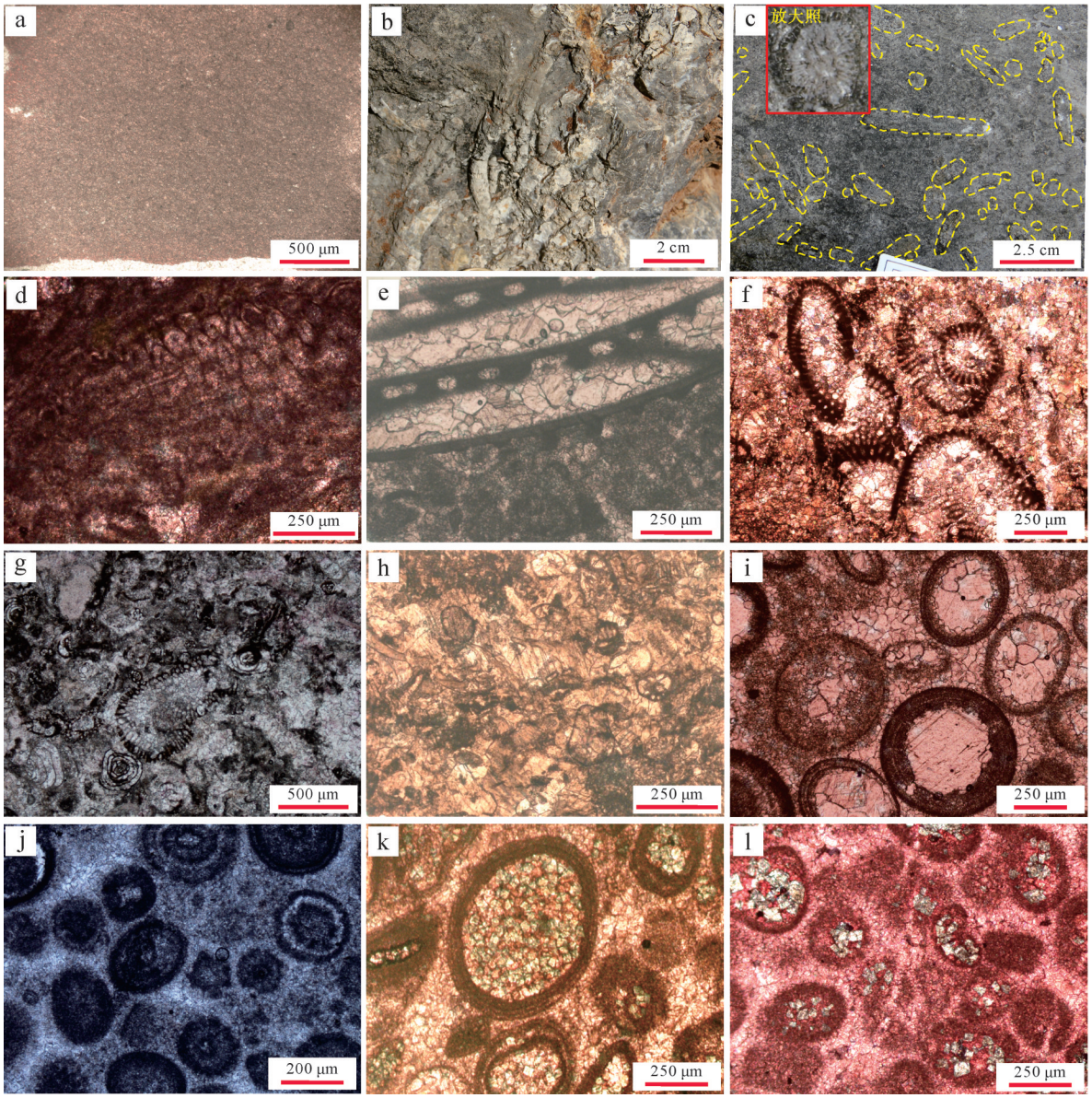

图3 研究区长兴组—飞仙关组台地—台地边缘沉积典型照片

(a)泥微晶灰岩,开阔台地,长兴组,St6井,单偏光;(b)生物灰岩,珊瑚定向生长,台地边缘,长兴组,菜溪剖面;(c)生物灰岩,珊瑚总体定向生长(图件中黄色圈),台地边缘,长兴组,鱼洞子剖面;(d)生物灰岩,苔藓虫,台地边缘,长兴组,St1井,正交偏光,茜素红染色;(e)生屑灰岩,上部为蜓化石,台地边缘,长兴组,St8井,单偏光;(f)生物灰岩,绿藻定向生长,台地边缘,长兴组,St7井,正交偏光;(g)生屑灰岩,可见腹足、绿藻、有孔虫,台地边缘,长兴组,龙潭村剖面,单偏光;(h)亮晶生屑灰岩,部分生屑呈漂浮状,台地边缘,长兴组,St7井,单偏光;(i)亮晶鲕粒灰岩,鲕粒内部发生溶蚀和重结晶作用,台地边缘,飞二段,St1井,单偏光,茜素红染色;(j)亮晶鲕粒灰岩,台地边缘,飞一段,龙潭村剖面,单偏光;(k)含云质亮晶鲕粒灰岩,鲕粒内部发生白云石化,台地边缘,飞仙关组,St18井,单偏光,茜素红染色;(l)含云质亮晶鲕粒灰岩,鲕粒内部发生白云石化,台地边缘,飞一段,St10井,单偏光,茜素红染色

Fig.3 Carbonate platform and platform margin typical photographs of the Changxing Formation-Feixianguan Formation in the study area

(a) micritic limestone, open platform, Changxing Formation, well St6, plane-polarized light (PPL); (b) bioclastic limestone with oriented growth of corals, platform margin, Changxing Formation, Caixi section; (c) bioclastic limestone with generally oriented growth of corals (yellow circles in the figure), platform margin, Changxing Formation, Yudongzi section; (d) bioclastic limestone with bryozoans, platform margin, Changxing Formation, well St1, cross-polarized light (XPL), stained with alizarin red; (e) bioclastic limestone with fusulinids in the upper part, platform margin, Changxing Formation, well St8, PPL; (f) bioclastic limestone with oriented growth of green algae, platform margin, Changxing Formation, well St7, XPL; (g) bioclastic limestone containing gastropods, green algae, and foraminifera, platform margin, Changxing Formation, Longtancun section, PPL; (h) sparry bioclastic limestone with some bioclasts floating in the matrix, platform margin, Changxing Formation, well St7, PPL; (i) sparry oolitic limestone with dissolution and recrystallization within ooids, platform margin, Second member of Feixianguan Formation, well St1, PPL, stained with alizarin red; (j) sparry oolitic limestone, platform margin, First member of Feixianguan Formation, Longtancun section, PPL; (k) dolomitic sparry oolitic limestone with dolomitization within ooids, platform margin, Feixianguan Formation, well St18, PPL, stained with alizarin red; (l) dolomitic sparry oolitic limestone with dolomitization within ooids, platform margin, First member of Feixianguan Formation, well St10, PPL, stained with alizarin red

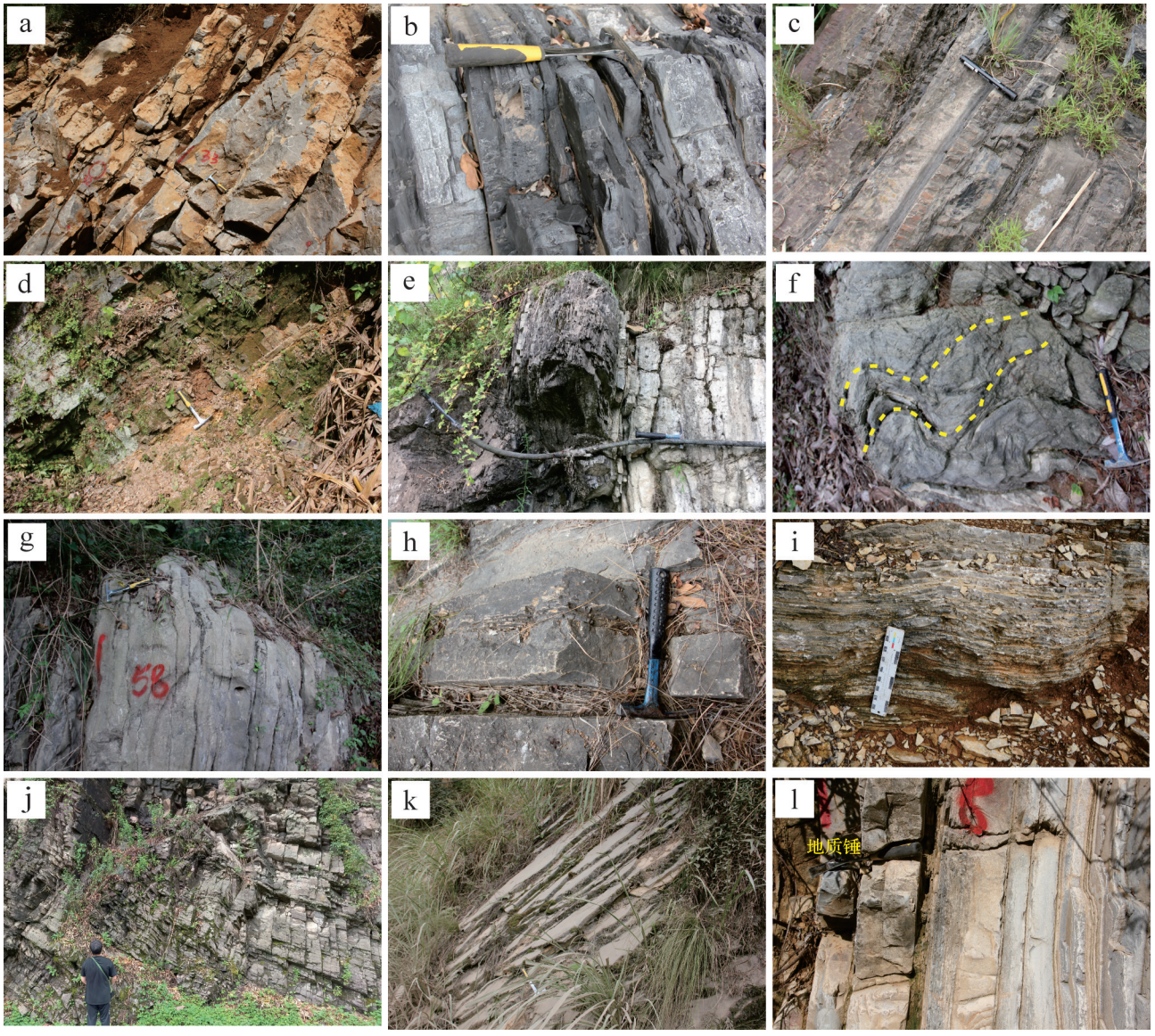

图4　研究区长兴组—飞仙关组台缘斜坡和深水陆棚—盆地沉积典型野外照片

(a)中—薄层含生屑泥晶灰岩,层面波状起伏,可见燧石团块,台缘斜坡,长兴组,菜溪剖面;(b)薄层泥晶灰岩与薄层硅质岩互层,水平层理发育,深水陆棚,大隆组,上寺剖面;(c)薄层泥晶灰岩与薄层硅质岩互层,水平层理发育,深水陆棚,大隆组,建峰剖面;(d)薄层硅质岩,深水陆棚,长兴组,竹园坝剖面;(e)中—薄层泥晶灰岩,层面波状起伏,台缘斜坡,飞仙关组,雁门坝剖面;(f)薄板状泥晶灰岩,准同生期液化变形,台缘斜坡,飞一段,刺林包剖面;(g)薄板状灰岩,水平层理发育,台缘斜坡,飞仙关组,菜溪剖面;(h)薄层灰岩夹薄板状泥灰岩,水平层理发育,台缘斜坡,飞仙关组,雁门坝剖面;(i)薄层灰岩与泥岩互层,准同生期液化变形,台缘斜坡,飞仙关组,刺林包剖面;(j)薄板状泥晶灰岩与泥质灰岩薄互层,深水陆棚,飞仙关组,芭蕉坪剖面;(k)薄板状钙质页岩,深水陆棚,飞一段底部,竹园坝剖面;(l)薄层泥晶灰岩与薄板状泥质灰岩构成薄互层,夹页岩,深水陆棚,飞仙关组底部,上寺剖面

Fig.4　Typical outcrop photographs of carbonate platform margin slope and deep-water continaental shelf-basin of the Changxing Formation-Feixianguan Formation in the study area

(a) medium to thin-bedded bioclastic-bearing micritic limestone with undulating bedding planes and chert nodules, platform-margin slope, Changxing Formation, Caixi section; (b) interbedded thin-bedded micritic limestone and thin-bedded chert with well-developed horizontal bedding, deep-water shelf, Dalong Formation, Shangsi section; (c) interbedded thin-bedded micritic limestone and thin-bedded chert with well-developed horizontal bedding, deep-water shelf, Dalong Formation, Jianfeng section; (d) thin-bedded chert, deep-water shelf, Changxing Formation, Zhuyuanba section; (e) medium to thin-bedded micritic limestone with undulating bedding planes, platform-margin slope, Feixianguan Formation, Yanmenba section; (f) thin-platy micritic limestone with penecontemporaneous liquefaction deformation structures, platform-margin slope, First member of Feixianguan Formation, Cilinbao section; (g) thin-platy limestone with well-developed horizontal bedding, platform-margin slope, Feixianguan Formation, Caixi section; (h) thin-bedded limestone intercalated with thin-platy marlstone, with well-developed horizontal bedding, platform-margin slope, Feixianguan Formation, Yanmenba section; (i) interbedded thin-bedded limestone and mudstone with penecontemporaneous liquefaction deformation structures, platform-margin slope, Feixianguan Formation, Cilinbao section; (j) thin interbeds of thin-platy micritic limestone and argillaceous limestone, deep-water shelf, Feixianguan Formation, Bajiaoping section; (k) thin-platy calcareous shale, deep-water shelf, basal part of the First member of Feixianguan Formation, Zhuyuanba section; (l) thin interbeds of thin-bedded micritic limestone and thin-platy argillaceous limestone, with shale intercalations, deep-water shelf, basal Feixianguan Formation, Shangsi section

表1 研究区长兴组—飞仙关组沉积相分类表

Table 1 Sedimentary facies of the Changxing Formation-Feixianguan Formation in the study area

沉积相	沉积亚相	发育层位	代表岩性
蒸发台地	潮坪	飞四段	膏岩,含膏灰岩,膏质泥岩,等
局限台地	台内滩	飞三段	鲕粒灰岩、生屑灰岩、生屑含云质灰岩,等
	潮坪		白云岩、泥质白云岩、泥岩,等
开阔台地	台内滩	长兴组,飞一段—飞二段	鲕粒灰岩、生屑灰岩、生屑含云质灰岩,等
	滩间海		泥晶灰岩、生屑泥晶灰岩,等
台地边缘	台缘滩	长兴组,飞一段—飞二段	生屑白云质灰岩、生屑灰岩、生屑云岩、鲕粒灰岩,等
	台缘礁	长二段	生屑灰岩、藻灰岩,等
	礁滩间	长兴组,飞一段—飞二段	泥晶生屑灰岩、生屑泥晶灰岩,等
台缘斜坡		长兴组,飞一段—飞二段	燧石结核灰岩、泥晶生屑灰岩、泥晶灰岩、砾屑灰岩,等
陆棚盆地		长兴组,飞一段—飞二段	泥岩、硅质灰岩、泥晶灰岩,等

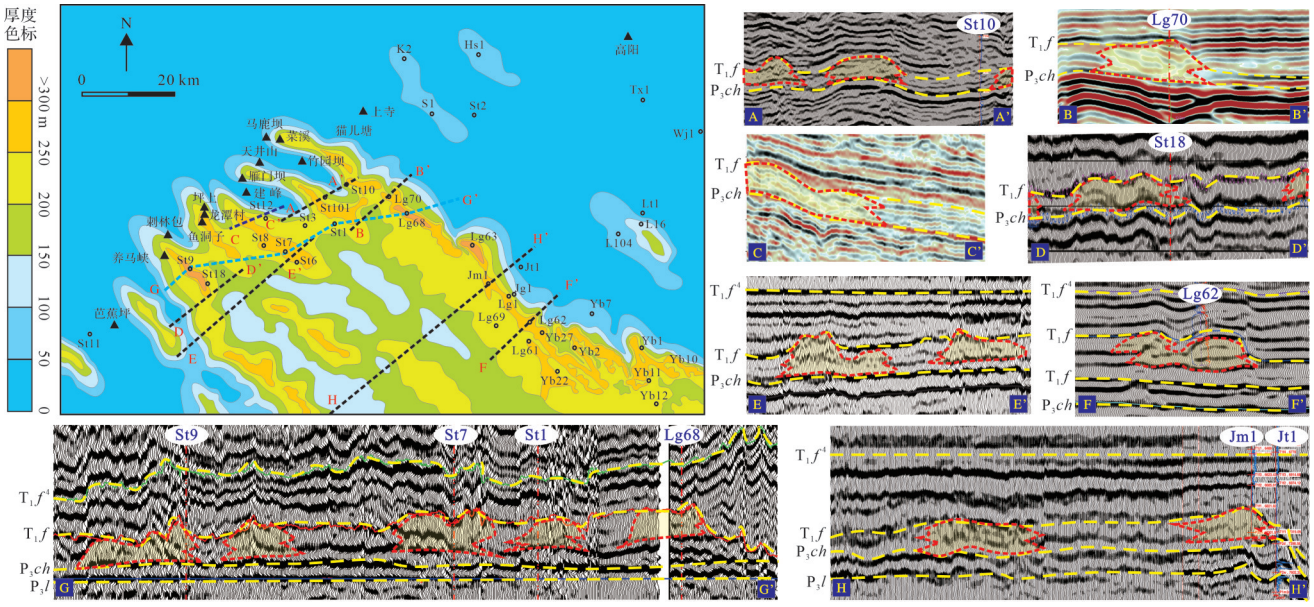

图5 研究区长兴组地层厚度及生物礁滩地震响应

Fig.5 Thickness of the Changxing Formation and seismic response of the reef and beach in the study area

层(刘康林等,2011),水平层理发育(图4b~d);飞仙关组台缘斜坡区往往以中薄层泥晶灰岩为主(图4e~h),可见准同生期液化变形构造(图4f),其深水陆棚—盆地区以薄板状泥晶灰岩、泥质灰岩、页岩或者三者的互层为主,水平层理发育(图4i,j,l)。基于钻井、野外露头识别台地(或台凹)高能相带(图3)、台缘斜坡和深水陆棚—盆地(图4),结合地震生物礁滩解释和古地貌等特征(图5)及沉积相剖面对比分析(图6~8),能够有效确定台地边缘或台凹边缘高能相带—台缘斜坡—深水陆棚—台地的分布与形态特征。

综上,认为研究区普遍存在台缘斜坡和深水陆棚—盆地沉积记录,能够确定开江—梁平海槽西部台缘带和蓬溪—武胜台凹东侧高能边缘带在广元—江油一带是连通的(图9)。

4 沉积相时空展布和演化

4.1 沉积相剖面分布

本文选取顺台缘带(图6)、跨海槽(台凹)—台地(图7)、顺台缘斜坡带(图8)等3条沉积相对比剖面,对研究区长兴组—飞仙关组沉积相时空展布特征进行了分析。

过菜溪剖面—Tb1井的北西—南东方向的连井剖面显示了顺台缘带的沉积相展布情况(图6)。垂向上,长兴组总体具有从台缘斜坡—深水陆棚沉积,

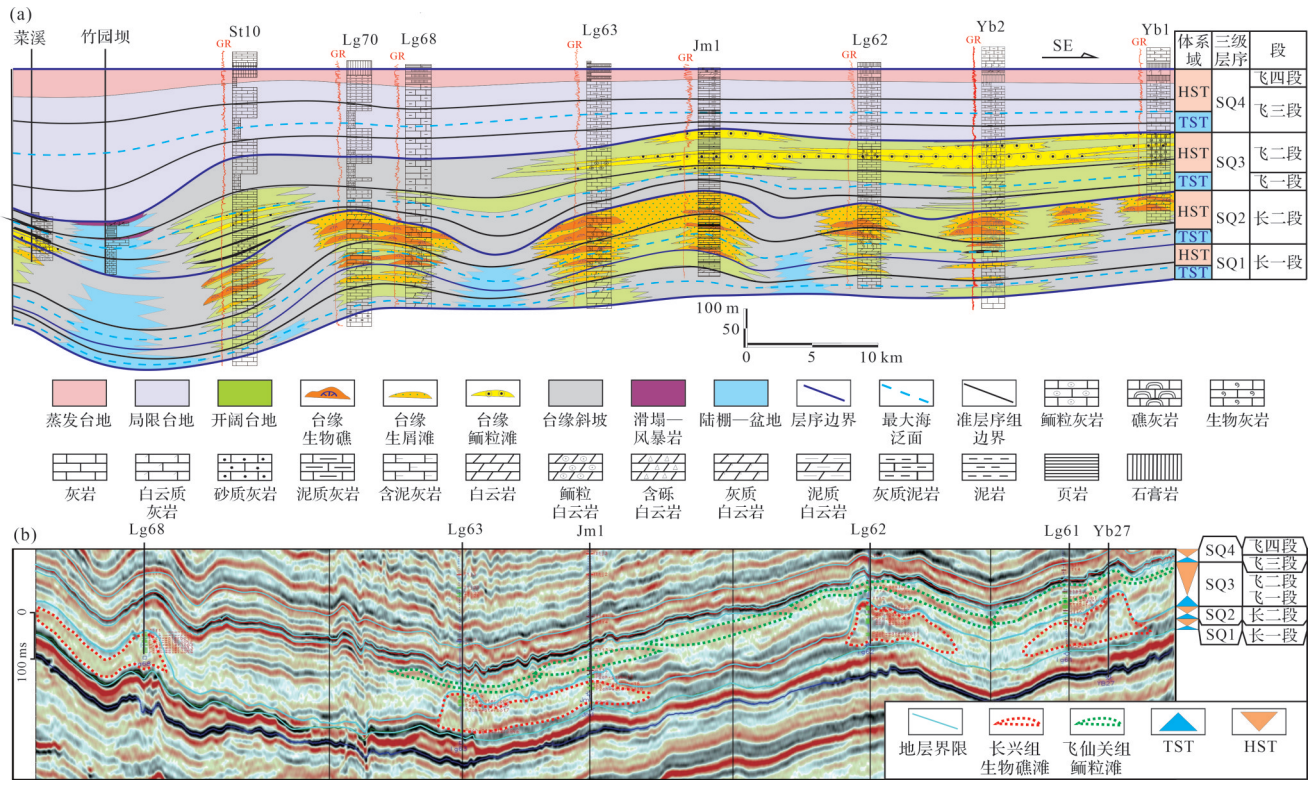

图6　过菜溪剖面—Yb1井长兴组—飞仙关组层序地层和沉积相对比剖面图

备注:剖面位置见图1b;地震测线位置见图1b

Fig.6　Comparative profile of sequence stratigraphy and sedimentary facies from Changxing Formation-Feixianguan Formation across the Laixi section to well Yb1

逐渐向上过渡到台缘生物礁滩和开阔台地沉积,长一段(SQ1) TST以斜坡和深水陆棚沉积为主,向上HST逐渐发育台缘生屑滩;长二段(SQ2) TST,台缘生屑滩被淹没和不发育,随着SQ2 HST水体逐渐变浅,逐渐形成由孤立—连片的台缘生屑滩—台缘生物礁滩组合;飞仙关早期SQ3 TST阶段,海泛淹没了长兴期台地,形成台缘斜坡或者开阔台地沉积,此阶段鲕粒滩发育有限,随着SQ3 HST阶段,水体逐渐变浅,台缘鲕粒滩逐渐由孤立分布向上连片,并具有一定的向东迁移趋势;SQ4(飞三段和飞四段)阶段,地貌逐渐填平补齐,形成稳定的局限台地和蒸发台地沉积(图6a)。横向上,长兴组台缘生物礁滩具有明显的孤立分布特点,并与台缘斜坡和台前深水沉积东西向间互出现,向上礁滩逐渐连接到一起。相比长兴期,飞仙关期鲕粒滩也具有早期孤立分布、向上横向逐渐连续的特点,但总体上,与台缘礁滩位置相比,具有向东错位分布的特点,飞仙关组鲕粒滩主要位于原长兴组生物礁滩高能带所处位置的东部。

过蓬溪—武胜台凹、台地和开江—梁平海槽的北东—南西向沉积相对比剖面(图7)显示,垂向上,水体总体向上变浅,两侧深水区具有从深水陆棚向上台缘斜坡、局限台地、蒸发台地演化过程,中部台地区总体具有从开阔台地向局限台地和蒸发台地演化过程;长兴期(SQ1—SQ2)—飞二段沉积期(SQ3)在台地边缘或(台凹边缘)发育高能相带,长一段沉积期发育生屑滩、长二段沉积期发育生物礁滩、飞二段沉积期发育鲕粒滩。飞仙关组早期继承了长兴组总体沉积格局,在长兴组台缘生物礁滩带之上发育了飞仙关组早期台缘鲕粒滩沉积,而到飞二段中晚期,随着填平补齐过程,鲕粒滩具有向东迁移的特点。需要说明的是,每个三级层序TST沉积期往往生物礁滩、鲕粒滩发育程度明显弱于HST,总体上HST晚期生物礁滩、鲕粒滩最为发育。横向上,长兴组—飞二段沉积相带分异明显,西南部的蓬溪—武胜台凹区Gj井区水体较深,向东北水体逐渐变浅,过渡到台凹边缘带,到ST18—ST10井一带主要为开阔台地和台地边缘带,S1和S2井主要为开江—梁平海槽台缘斜坡—陆棚—盆地,飞三期—飞四期已经趋于单一局限台地和蒸发台地沉积。

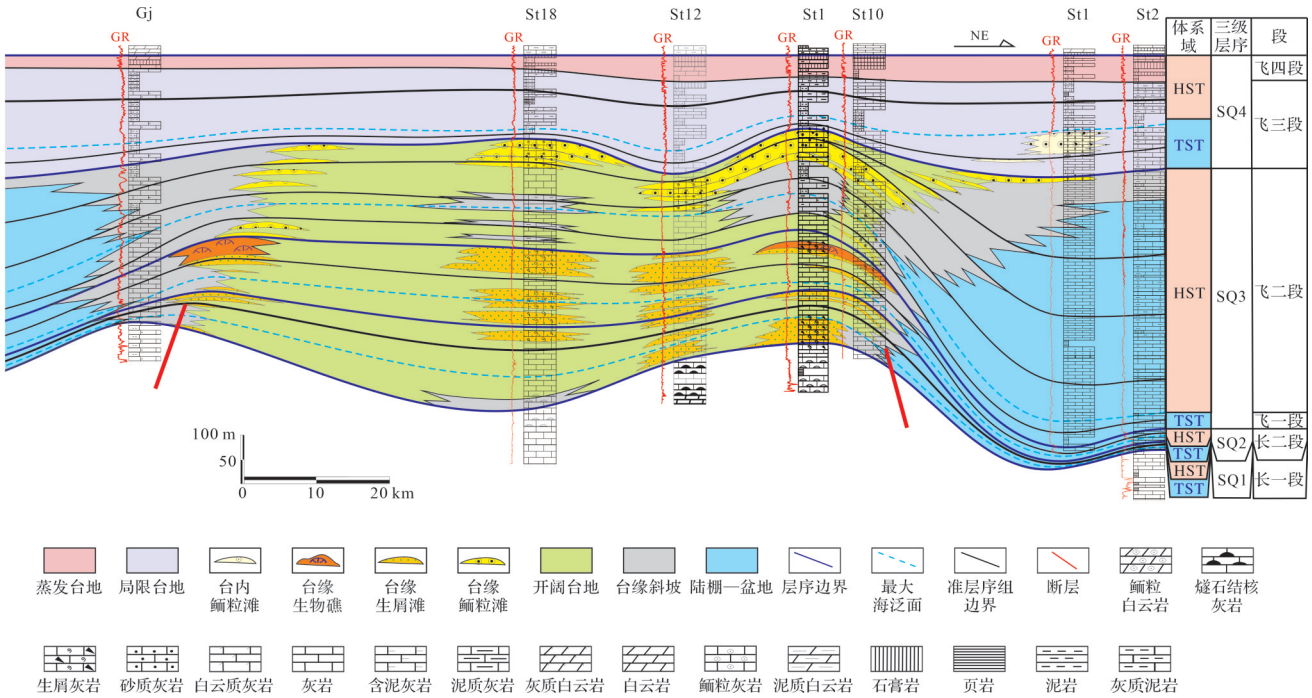

图7 过Gj井—St2井长兴组—飞仙关组层序地层和沉积相对比剖面图

备注:剖面位置见图1b

Fig.7 Comparative profile of sequence stratigraphy and sedimentary facies from the Changxing Formation-Feixianguan Formation across well Gj to well St2

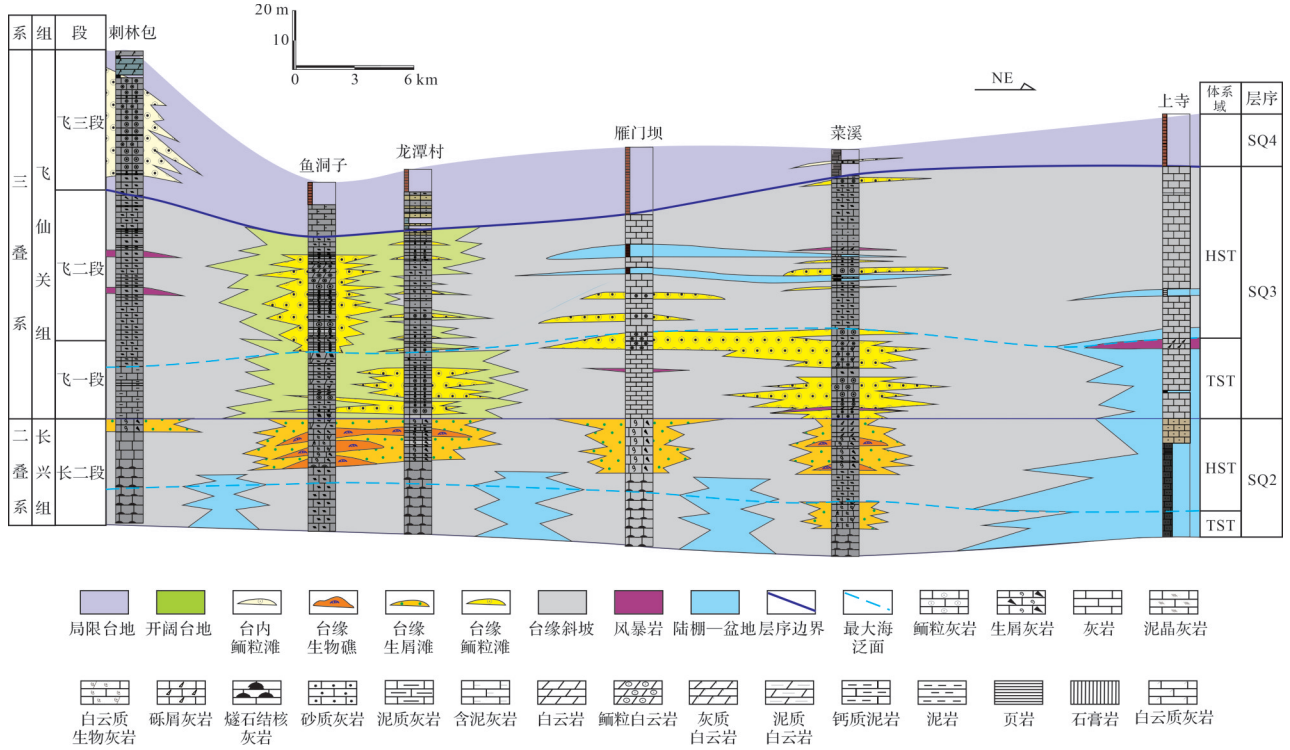

图8 过刺林包剖面—上寺剖面长兴组—飞仙关组层序地层和沉积相对比剖面图

备注:剖面位置见图1b;长二段未展示到底界,飞三段未展示到顶界

Fig.8 Comparative profile of sequence stratigraphy and sedimentary facies of the Changxing Formation-Feixianguan Formation across the Cilinbao section to Shangsi section

过刺林包剖面—上寺剖面位于北侧台缘斜坡区(图8),主要横跨台缘交汇带。该相带上长兴组垂向上主要表现为由台缘斜坡逐渐过渡为台缘礁滩的演化序列,而飞仙关组则主要表现为鲕粒滩逐渐发育的特点,但飞二段中晚期,鲕粒滩在研究区仅局部分布,以台缘斜坡沉积为主。飞三段沉积期,则在西部的刺林包剖面存在台内鲕粒滩。横向上,长兴组台缘礁滩和飞仙关组台缘鲕粒滩表现为与台缘斜坡间互分布特点,飞一段—飞二段(SQ3)沉积期在台缘斜坡区发育风暴岩沉积。

4.2　沉积相平面展布

根据野外、钻井和地震等资料,重建了研究区长兴期—飞仙关期沉积相平面展布(图9)。长一段沉积期(图9a),研究区中南部发育开阔台地,环开阔台地向西、向北、向东过渡为台地边缘(或台凹边缘)带—台缘斜坡—深水陆棚—台地沉积,在St9井—St18井及周缘、St8井—St12井及周缘、St6井及周缘、St1井—St101井及周缘以及St10井处均不连续地分布着生屑滩(或生物礁),台地东北侧台缘带上从Lg70井到Yb12井处连续成片分布着台缘生屑滩,总体上,西北部台缘生屑滩成北西向指状与台缘斜坡—深水陆棚—台地间互。长二段沉积期继承了长一段沉积期开阔台地、台缘礁滩、台缘斜坡到陆棚—盆地总体格局,沉积相发育部位基本一致,台缘带和台内高能带范围有所扩大,台缘带已从生屑滩演化为生物礁滩(图9b)。飞仙关早期开江—梁平海槽西北侧大部分地区总体继承了长兴组的开阔台地—台地边缘—台缘斜坡—深水陆棚—盆地的沉积格局。飞一段早期受海泛影响,仅在St18井—St12井—Lg68井一线出现鲕粒滩,其在东侧部分发生白云石化(图9c)。飞二段沉积期台缘鲕粒滩发育范围逐渐扩大并连片,达到飞仙关期最大鲕粒滩范围,鲕粒滩中部高部位不同程度白云石化(图9d)。飞仙关中晚期SQ4阶段(飞三段—飞四段)受填平补齐影响,开江—梁平海槽区和蓬溪—武胜台凹区逐渐被充填,沉积相带逐渐趋于统一,地势差异不再显著。飞三段沉积期发育局限台地沉积,仅剩少量台内点滩,位于Lg63井—Jg1井—Lg1井附近、刺林包附近以及L104井—L16井—Lt1井附近,为灰质鲕粒滩(图9e);飞四段沉积期,研究区进一步填平补齐,其沉积环境整体进入蒸发台地阶段(图9f)。综合以上分析,建立了长兴组和飞仙关组重点层段沉积相发育模式(图10)。

4.3　沉积充填演化过程与模式

研究区晚二叠世长兴期—早三叠世飞仙关期沉积充填演化过程表现为二叠纪末受东吴运动影响,区域应力由伸展转变为挤压(刘树根等,1995;郭彤楼,2011;邹才能等,2014;宋芳等,2024),长兴组沉积期,继承了峨眉地裂运动造成的隆凹格局,SQ1(长一段)TST阶段,海平面上升,发育深水陆棚—台缘斜坡—深水陆棚—台地,生屑滩不发育;随着SQ1 HST水体逐渐变浅,台地边缘或(台洼边缘)带逐渐形成生屑滩,由于早期断裂和地貌控制,生屑滩横向孤立分布(图11,阶段1),平面上形成指状分布(图9a)。SQ2(长二段)TST阶段,受海泛影响,SQ1 HST发育台地边缘或(台洼边缘)高能带被淹没,仅有少量生屑滩分布,SQ2 HST阶段,随着海平面逐渐下降,台地边缘或(台洼边缘)生屑滩逐渐发育,台缘生屑滩由孤立的点状逐渐合并(图11,阶段2),HST中晚期形成台缘生物礁滩沉积。晚二叠世末期发生全球最大的显生宙生物大灭绝,飞仙关组早期继承了长兴组晚期台地—盆地格局,受早期海泛(冯增昭等,1997;童金南等,2019)影响,SQ3 TST(飞一段)台地边缘或(台洼边缘)高能带被淹没,鲕粒滩不发育(图11,阶段3),SQ3 HST(飞二段)随着海平面逐渐下降,在继承长兴组礁滩带高地貌背景下,形成了零星的鲕粒滩加积沉积(图11,阶段4),HST中晚期逐渐形成鲕粒滩的连片分布(田力等,2014;古强等,2021),且具有向东迁移特点,与长兴组生物礁形成了"长兴组生物礁滩在西、飞仙关组鲕粒滩在东"的高能相带垂向错位叠置的特点(图11,阶段5),进而形成了TST和HST早期继承长兴组地貌和沉积格局的加积结构,HST中晚期地貌逐渐填平补齐,台地边缘或(台洼边缘)带和台前斜坡整体向东迁移的沉积结构序列,并使得早期深水的海槽和台凹区逐渐填平水体变浅。SQ4沉积期,早期深水的海槽和台凹区已经基本填平,发育了整一的局限台地和蒸发台地(图11,阶段6),仅在SQ4 TST局部存在少量台内鲕粒滩沉积(图9e)。

综上,揭示蓬溪—武胜台凹东部边缘与开江—梁平海槽西部台缘带在广元—江油一带连接在一起,形成连续的高能相带,台缘带明显具有指状间互特点,并非平滑状连片分布。该台缘过渡区经历了

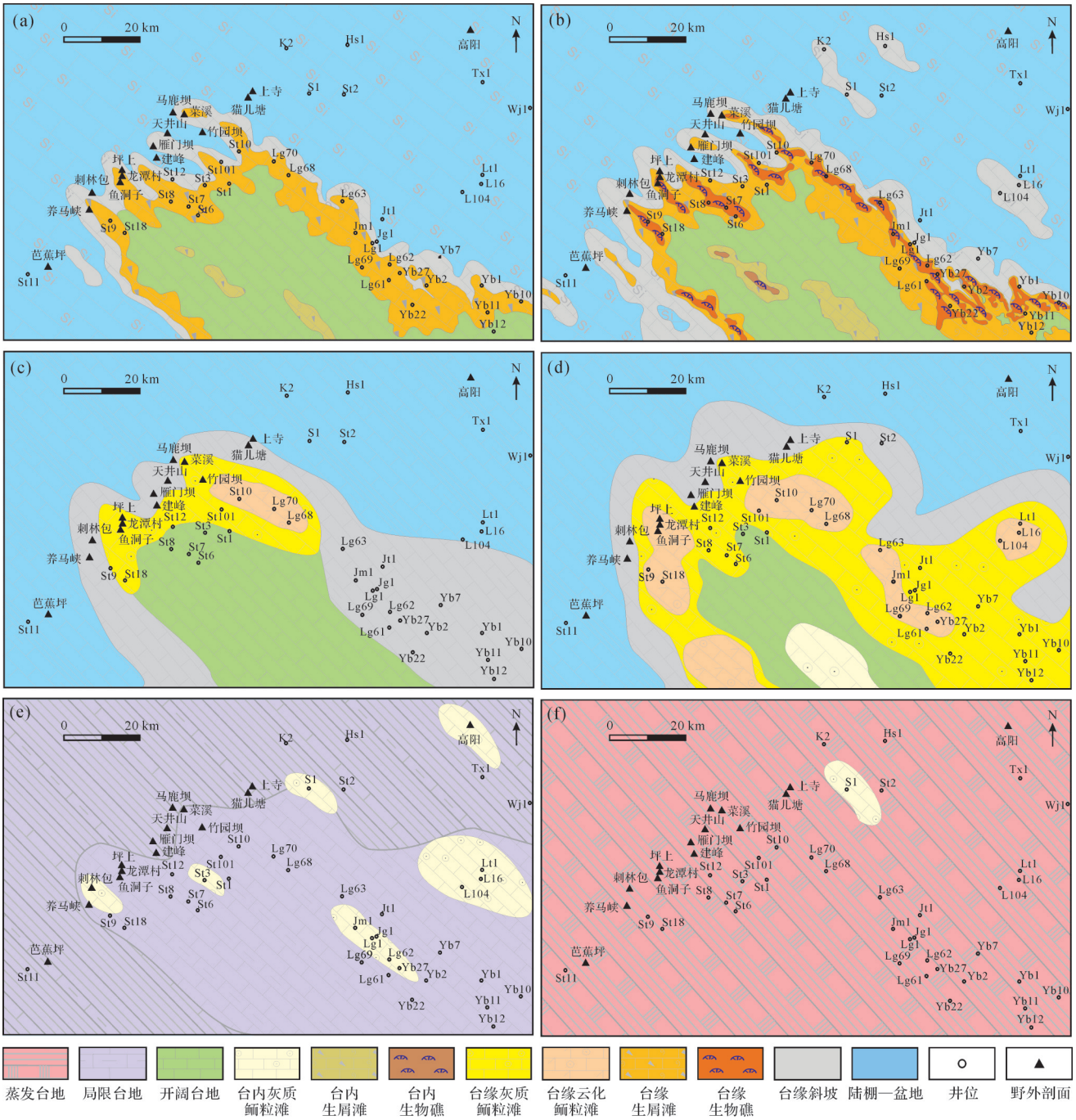

图9 研究区长兴组—飞仙关组沉积相展布图

(a)长一段沉积期(SQ1);(b)长二段沉积期(SQ2);(c)飞一段沉积期(SQ3 TST);(d)飞二段沉积期(SQ3 HST);(e)飞三段沉积期(SQ4 TST);(f)飞四段沉积期(SQ4 HST)

Fig.9 Sedimentary facies maps of Changxing Formation-Feixianguan Formation in the study area

(a) First member of Changxing Formation depositional period (SQ1); (b) Second member of Changxing Formation depositional period (SQ2); (c) First member of Feixianguan Formation depositional period (SQ3 TST); (d) Second member of Feixianguan Formation depositional period (SQ3 HST); (e) Third member of Feixianguan Formation depositional period (SQ4 TST); (f) Fourth member of Feixianguan Formation depositional period (SQ4 HST)

早期地貌起伏、晚期逐渐平整的演化过程,台缘带并未顺台缘带向北西方向填充,而是在早期继承性加积后,形成了具有明显的向东—东北方向迁移到填平补齐的沉积充填序列。

5 沉积充填演化过程对油气勘探启示

川西北地区长兴期—飞仙关期沉积充填演化序列研究为该区域后续的油气勘探提供了参考。研究

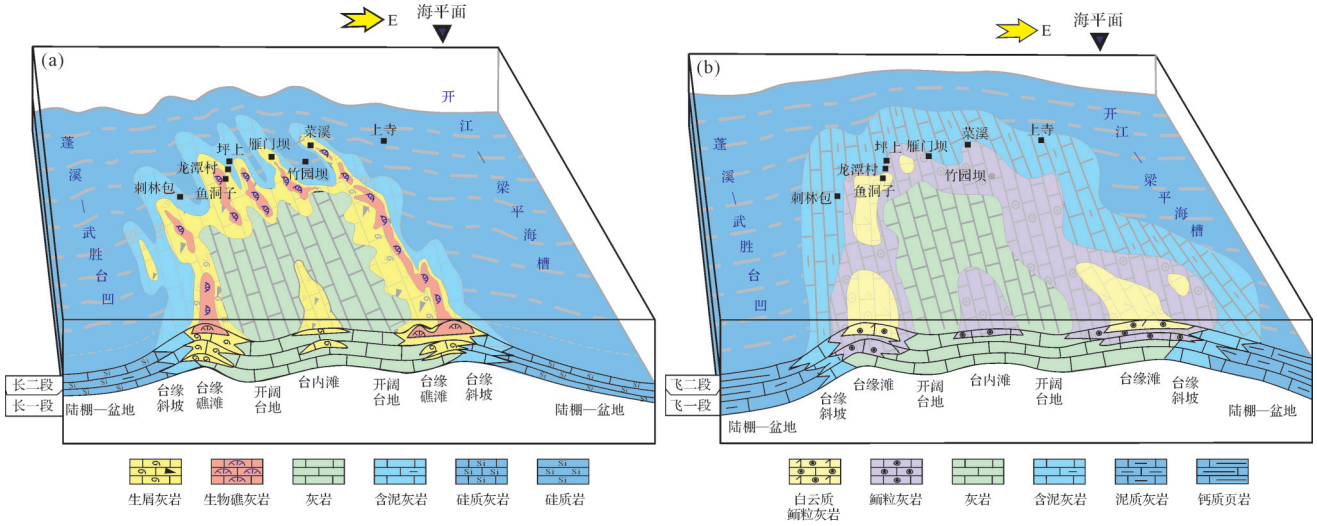

图 10　研究区长兴组—飞仙关组早期沉积模式图

Fig.10　Depositional models during the sedimentary period of the Changxing Formation-Feixianguan Formation in the study area

区重点储层的分布是制约油气勘探的核心要素,因此,本文主要侧重剖析沉积充填演化对潜在储层的时空分布控制作用。长兴组—飞仙关组储层相控明显,云化高能带有利(彭志,2015;苏成鹏等,2016;王高峰等,2016;张兵等,2017;周子龙和张廷山,2020),因此,生物礁滩和鲕粒滩的分布情况直接决定储层发育规律。综合本次研究认识,建议充分考虑沉积充填过程高能相带的演化规律,层段上重点关注长二段和飞二段,以台地边缘(或台凹边缘)高能相带为重点;不同演化阶段关注不同的储集体分布,长兴组重点关注台地边缘(或台凹边缘)生物礁滩带(李秋芬等,2015,2018;苏成鹏等,2016;王高峰等,2016;严张磊等,2018;邓思思等,2019;梁霄等,2019),总体具有北西向带状分布特点,横向上礁滩连续性有限,向北西向延伸更好。因此,储层分析过程中要注意避免龙门山造山挤压造成的逆冲断裂和褶皱影响,应多关注北西向高能相带。

飞仙关组油气勘探应重点关注鲕粒滩分布(郑荣才等,2008;郭彤楼,2011;黄可可等,2014;黄思静等,2016;邢凤存等,2017;罗开平等,2020;徐敏等,2021),飞一段鲕粒滩发育程度有限,该段储层预测应关注长兴组生物礁滩最高部位并寻找继承性发育的鲕粒滩带,而飞二段中晚期连片的鲕粒滩带是有利的储集相带,应重点关注。需要注意的是,该阶段虽然总体具有与长兴组高能生物礁滩与飞二段鲕粒滩的东西错位叠置特点,但鲕粒滩的迁移过程及云化需要引起足够重视,建议重点关注飞一段中上部—飞二段鲕粒滩储层,尤其是白云石化明显的高能相带发育区,可结合相图(图9~11)所展示的分布情况加以预测。从盖层发育条件来看,飞四段含膏岩性发育,是重点盖层发育层段,地貌继承性下膏岩分布规律还有待进一步分析。

6　结论

(1) 明确了开江—梁平海槽西侧台缘带与蓬溪—武胜台凹东部高能边缘带在研究区相连通,形态上并非平滑的弧形过渡带,具有北西向延伸的指状形态。

(2) 研究区长兴期—飞仙关期主要经历了六个沉积充填演化阶段,长兴期—飞一段早期地貌起伏、沉积和地貌格局继承性明显,形成加积沉积结构,飞二段沉积期高能带整体向东迁移而非沿着长兴组北西向延伸的台缘带生长,飞三段—飞四段沉积期填平补齐形成统一的局限台地—蒸发台地沉积。

(3) 研究区长二段生物礁滩带和飞二段鲕粒滩带是重点关注储集体,需要注意沉积充填过程造成的沉积分异及白云石化程度。

(4) 沉积格局及沉积充填演化认识指示的构造意义、沉积充填演化机制及主控因素还有待今后进一步探讨。

致谢　感谢审稿专家给出的意见和建议。

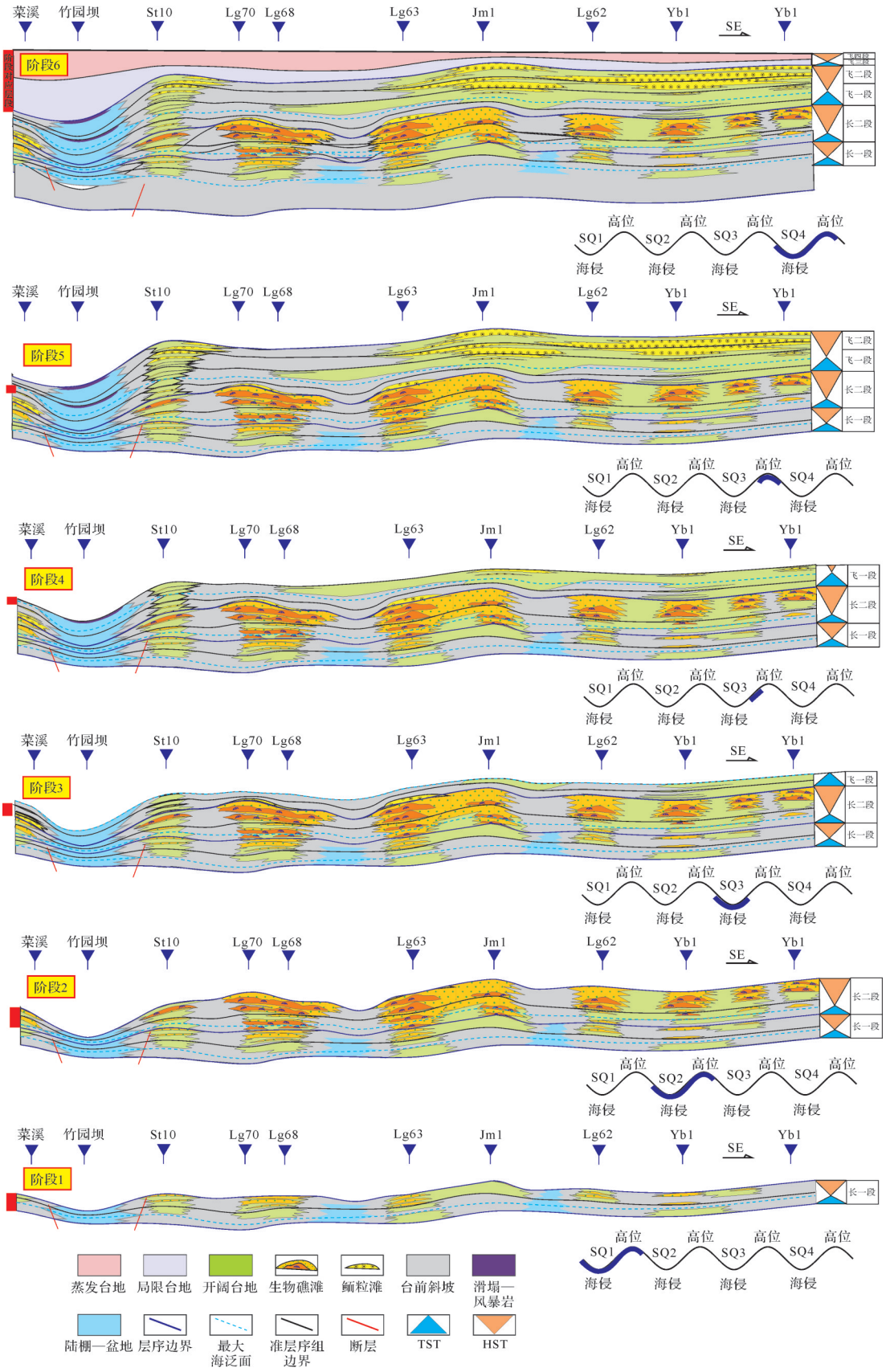

图 11 研究区长兴组—飞仙关组沉积充填阶段模式图

Fig.11 Sedimentary filling stage model of the Changxing Formation-Feixianguan Formation in the study area

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Distribution and Evolution of Sedimentary Facies from the Changxing Formation-Feixianguan Formation in the Intersection Area of Kaijiang Liangping Trough and Pengxi Wusheng Intra-Platform Depression, Northwestern Sichuan Basin

WANG ZhaoPeng[1,2,3], XING FengCun[1,2,3], GU Qiang[1,2,3], WU SaiJun[4,5], LIU ZiQi[1,2,3]

1. State Key Laboratory of Oil and Gas Reservoir Geology and Exploitation, Chengdu University of Technology, Chengdu 610059, China

2. Key Laboratory of Deep-time Geography and Environment Reconstruction and Applications of Ministry of Natural Resources, Chengdu University of Technology, Chengdu 610059, China

3. Institute of Sedimentary Geology, Chengdu University of Technology, Chengdu 610059, China

4. Sichuan Basin Research Center, PetroChina Research Institute of Petroleum Exploration & Development, Chengdu 610041, China

5. PetroChina Research Institute of Petroleum Exploration and Development, Beijing 100083, China

Abstract: [**Objective**] To clarify whether the western edge of the Kaijiang-Liangping trough is connected to the eastern platform margin of the Pengxi-Wushengtai Depression in the north of the Late Permian Changxing-Early Triassic Feixianguan period in northwestern Sichuan Basin, and to determine the sedimentary facies distribution pattern of the Jiangyou-Jiange Formation in northwestern Sichuan Basin and the Changxing Formation-Feixianguan Formation in the periphery area, and to analyse the evolution process of sedimentary filling to indicate further oil and gas exploration

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Corresponding author: XING FengCun, E-mail: xingfengcun@163.com

work.[**Methods**] Based on the latest drilling, field outcrop, and seismic data, this study systematically analyzed the distribution of lithofacies and paleogeography during the deposition of the Changxing Formation-Feixianguan Formation in the Guangyuan-Jiangyou area, based on the stratigraphic and sedimentary facies division and comparison.[**Results**] The intersection area of the Changxing Formation-Feixianguan Formation can identify six sedimentary facies: shelf basin, slope, platform edge, open platform, restricted platform, and evaporative platform. Based on the sedimentary records of the front slope of the platform, the western edge of the Kaijiang-Liangping trough and eastern edge of the Pengxi-Wusheng intra-platform depression were clearly merged to form a unified platform edge belt in the Cilinbao-Shangsi area in northwestern Sichuan Basin. The platform edge belt and front slope show a northwest finger shaped interdistribution, rather than a simple smooth belt distribution. The intersection area of the two troughs in the Changxing Formation presents a sedimentary pattern of two troughs interlocking from southwest to northeast. The connecting area of the platform margin zone developed a northwestern fingered reef beach, developing bioclastic shoals in the 1st member and biological reefs and shoals in the 2nd member of the Changxing Formation at the platform edge zone. During the sedimentary period of the 1st and 2nd members of the Feixianguan Formation, the sedimentary pattern of Changxing depositional period was inherited; however, in the 1st member of Feixianguan Formation, only local platform edge oolitic beaches were formed owing to sea flooding. In the stage of the late 1st to 2nd member Feixianguan Formation, platform edge oolitic beaches gradually developed and expanded in scope with an overall eastward migration. The slope in front of the platform was prone to sliding and sedimentation. During the sedimentation period of the 3rd member of the Feixianguan Formation, the sea trough gradually filled, and the finger shaped platform edge zone disappeared, forming a unified restricted platform. Only the local development of oolitic beach. The research area was filled and flattened during the depositional period of the 4th member of the Feixianguan Formation, forming an evaporative platform facies. The platform margin zone in this region did not migrate northwestward along the finger shaped platform margin zone, but rather exhibited eastward migration characteristics.[**Conclusions**] The determination of the Changxing-Feixianguan connectivity and the definition of five sedimentary filling evolution stages in the Kaijiang-Liangping trough and Pengxi-Wusheng intra-platform depression supplements a new understanding of the sedimentary pattern and filling evolution process in the intersection area of the Changxing-Feixianguan trough. It also provides ideas and references for oil and gas exploration in this area.

Key words: sedimentary filling; carbonate platform; sedimentary facies; Changxing Formation; Feixianguan Formation; northwestern Sichuan Basin