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川北元坝地区茅口组顶面古地貌恢复与岩溶发育特征

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摘要:川北元坝地区茅口组碳酸盐岩岩溶储层发育,但该套储层非均质性强,储层预测有较大困难,需要进一步恢复岩溶古地貌、古水系,从而掌握储层分布规律,指导下一步油气勘探开发。文章选用残厚法恢复了元坝地区茅口组顶面岩溶古地貌,并结合现代岩溶学和岩溶动力学理论,划分了岩溶台地、岩溶缓坡地、岩溶平原和岩溶盆地4类二级地貌单元。应用现代岩溶分类方法,根据微地貌组合形态,划分了6类三级地貌单元,并对古水系进行了刻画。分析认为元坝地区茅口组顶面岩溶古地貌属岩溶地貌形成演化的初期阶段,不同地貌位置岩溶发育有较大差异,岩溶缓坡地属地下水径流区,水动力条件最强,孔洞最发育,是下一步储层勘探方向。

关键词:古水文条件;碳酸盐岩;岩溶古地貌;元坝地区;茅口组

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0 引言

中二叠统茅口组是四川盆地重点勘探层系之一,但大量研究及钻探工作集中于川中和川南地区^[1-4]。近年来,川北元坝地区茅口组相继获得高产工业气流,表明该区茅口组同样具有勘探潜力^[5-8]。前期研究认为茅口组沉积末期发生的暴露岩溶作用是岩溶储层形成的主要原因。

岩溶古地貌是岩溶作用和各类地质作用综合的结果,地貌形态对岩溶地下水运动及其形成的溶蚀孔、洞、缝发育起着控制作用^[9-11]。因此,开展岩溶古地貌、古水系研究对岩溶储层成因、分布及预测评价具有重要意义。前人已对川北元坝地区茅口组古地貌开展了一定的研究工作,但整体研究精度不

高,没有进行三级地貌单元和古水系的刻画,缺乏对元坝地区茅口组顶面岩溶古地貌的精细表征^[8, 12]。本次研究在前人工作的基础上,结合现代岩溶地质理论和分类方法,充分利用最新地质成果和地震解释资料,恢复元坝地区茅口组顶面岩溶古地貌,并对微地貌、古水系进行精细刻画,为下一步储层成因分析、储层预测评价提供基础,以便更好地指导元坝地区茅口组勘探开发。

1 研究区地质背景

川北元坝地区区域构造上位于四川盆地川北低平褶皱区与川中平缓褶皱区结合部(图1),整体为一个大型低缓构造带,区内地层产状平缓,构造变形弱,

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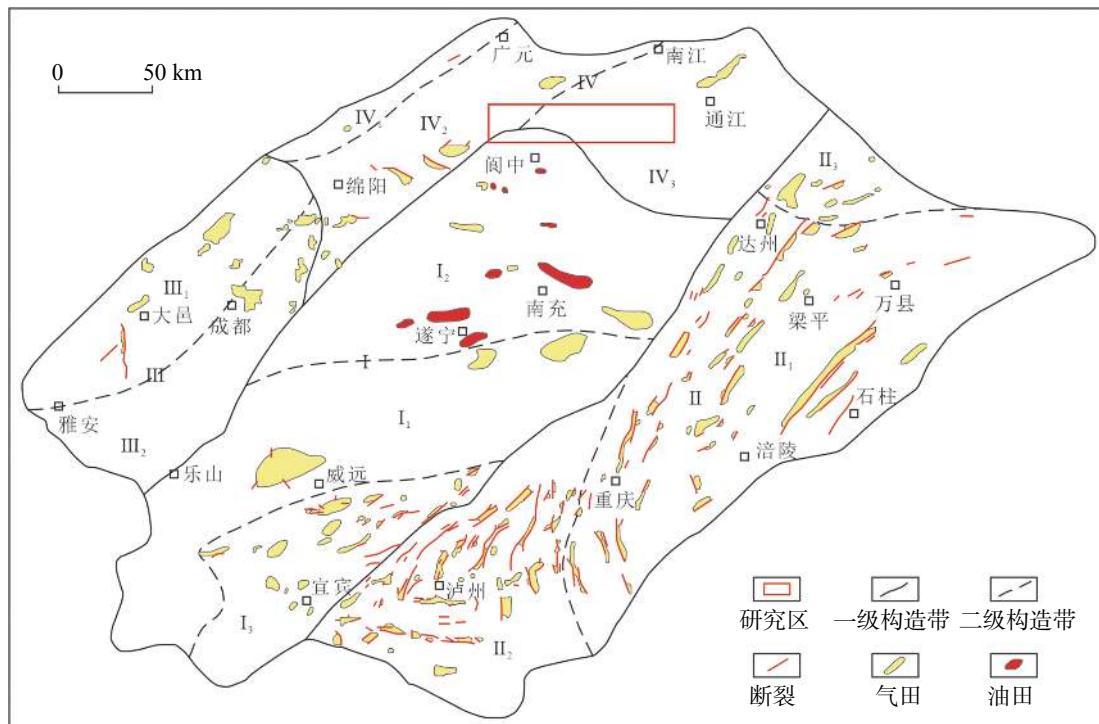


图1 研究区构造位置图(据参考文献[1],有改动)

I—川中平缓区(I₁-威远、龙女寺状隆起构造带, I₂-川中梯状低平构造带, I₃-白贡低中褶皱构造带) II—川东高陡褶皱区(II₁-川东高陡构造带, II₂-川东高、中复合构造带, II₃-川东北叠瓦式复合构造带) III—川西推覆褶皱区(III₁-灌县、名山高、中构造带, III₂-龙泉山、熊坡推覆带) IV—川北低平褶皱区(IV₁-龙门山山前推覆带, IV₂-梓潼平缓构造带, IV₃-通江低平构造带)

Fig. 1 Map of tectonic locations in the study area^[1]

断裂不发育^[13]。中二叠世末期,东吴运动主幕导致构造差异抬升,海水大范围退去,使得茅口组整体遭受长达1~3 Ma的暴露剥蚀过程。元坝地区茅口组地层可划分为3个长期旋回,分别对应茅一段、茅二段和茅三段(图2)。茅一段为一套浅海碳酸盐台地相沉积,岩性以泥灰岩、生屑泥晶灰岩、泥晶生屑灰岩为主,常以“眼皮眼球状”构造为主要识别标志;茅二段在台地/台缘相区主要发育泥晶生屑灰岩、亮晶生屑灰岩及少量生屑泥晶灰岩,斜坡相区以生屑泥晶灰岩、泥晶生屑灰岩为主;茅三段在台地/台缘相区主要发育泥晶生屑灰岩、亮晶生屑灰岩,斜坡/陆棚相区厚度较薄,以硅质泥岩、炭质泥岩为主^[12]。

2 岩溶古地貌恢复方法

常用的古地貌恢复方法包括印模法和残厚法^[14],关键在于寻找标志层,即通过标志层与恢复面的差值来反映岩溶古地貌的高低起伏,一般通过钻井层位数据或地震深度层位数据来计算分析。元坝地区钻井分布较少,基于钻井资料的层位数据难以满足微地貌精细刻画的需要,但该区三维地震全覆盖,

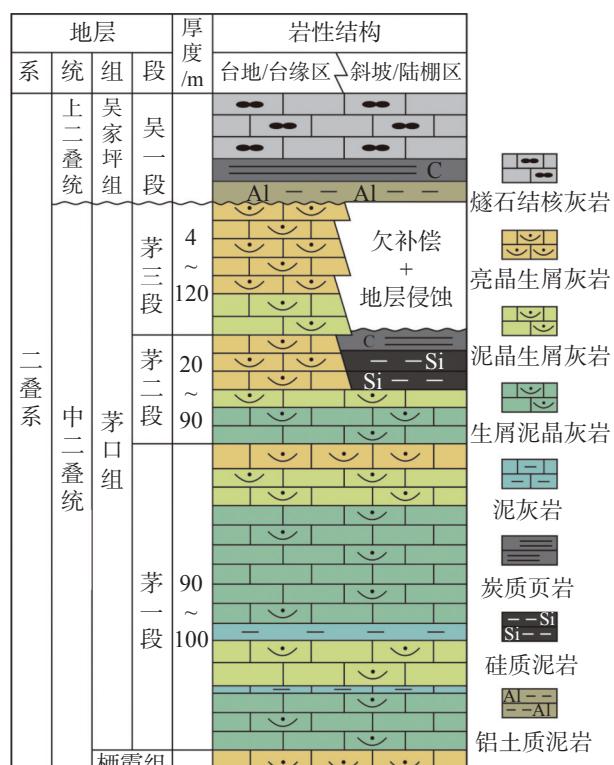


图2 元坝地区茅口组综合柱状图

(据文献[1],有改动)

Fig. 2 Bar chart of Maokou formation in Yuanba area^[1]

重点层位解释的精度相对较高,本文利用地震层位数据来恢复古地貌。

印模法和残厚法的区别在于:①印模法的关键在于选择目的层上覆基准面,茅口组上覆最近的标志层为吴家坪组一段灰岩夹泥岩。但吴家坪组一段厚度变化大,难以作为上覆基准面。研究发现元坝地区吴家坪组二段沉积期为一个完整的海侵—海退旋回,吴家坪组二段顶面距茅口组顶面较近,受构造活动的影响相对较小,分布广泛,但厚度不稳定,未起到填平补齐作用。可见,利用印模法恢复岩溶古地貌在本区并不适用。②残厚法的关键在于选择目的层下伏基准面。研究发现元坝地区为整体抬升过程,褶皱、断裂不发育,茅口组一段沉积区域分布稳定,属泛海沉积。因此以茅口组一段顶面作为下伏基准面,利用残厚法恢复茅口组顶面岩溶古地貌是可行的。为更好地刻画岩溶微地貌形态,本次采用“残厚趋势面与印模残差组合法”^[15]进行古地貌恢复。

3 不同级别岩溶古地貌类型划分与刻画

3.1 二级地貌类型划分指标体系与刻画

根据元坝地区茅口组顶面岩溶古地貌特征,结合茅口组顶面至茅口组一段顶面的厚度,建立岩溶古地貌类型划分指标体系(表1)。根据茅口组顶面至茅口组一段顶面的厚度这一定量指标,结合古地理环境、古水动力条件,将研究区划分为4类二级地貌类型:岩溶台地、岩溶缓坡地、岩溶平原和岩溶盆地,具体刻画结果如图3。

表1 元坝及邻区茅口组顶面岩溶古地貌类型划分表

Table 1 Classification of karst paleo-geomorphology in Yuanba area and on the top of Maokou formation

二级地貌类型	
类别	主要指标/m
岩溶台地	$215 \leq H_c < 265$
岩溶缓坡地	$185 \leq H_c < 215$
岩溶平原	$145 \leq H_c < 185$
岩溶盆地	$H_c < 145$

注: H_c 为茅口组顶面至茅口组一段顶面的厚度。

3.2 三级地貌类型划分与组合形态特征

根据现代岩溶地质学理论^[16-18],结合元坝地区茅

口组顶面岩溶古地貌特点,岩溶地貌个体形态及组合形态的划分指标体系如下:

3.2.1 岩溶正地形

(1) 溶丘: 山体高小于25 m(山体高差5~10 m为微丘), 高/基座直径小于0.5, 山体一般呈浑圆状(山体边坡一般大于30°)。

(2) 溶峰: 山体高小于25 m, 高/基座直径小于0.5, 山体一般呈锥状(山体边坡一般大于30°)。

(3) 垒脊: 由溶丘、溶峰组合呈条带状展布, 两侧一般为岩溶沟谷、槽谷。

3.2.2 岩溶负地形

(1) 岩溶槽谷: 呈长条形溶蚀谷地, 底部地势相对平坦, 并向一端倾斜, 其宽度一般大于5 m, 长一般大于50 m, 断面多呈“U”字形, 两岸地形坡度相对平缓, 上部较开阔。

(2) 岩溶沟谷: 属长条形溶蚀沟谷, 底部地势相对平坦, 并向一端倾斜, 其宽度一般小于5 m, 长一般大于50 m, 断面多呈“V”字形, 沟谷上一般无覆盖层。

(3) 洼地: 属负地形, 形状不规则, 一般为近圆形、椭圆形, 平面上多属“倒圆锥”形, 洼地底部多分布有落水洞, 其个体形态底部直径一般小于100 m。如溶丘与洼地底部相对高差小于10 m, 一般称为浅洼地(或“碟状”洼地)。

(4) 岩溶湖: 属负地形, 形状不规则, 一般为近圆形、椭圆形, 平面上多属“倒圆锥”形或蝶形, 其个体形态底部直径一般大于100 m, 地表径流易富集, 洼地底部不易渗漏。

3.2.3 微岩溶地貌组合形态及刻画

三级地貌主要以微地貌组合形态(正地形+负地形)来表征, 代表着一定范围内主要地貌特征, 经识别可以有6类组合形态, 即:

(1) 微丘洼地: 由微丘、浅洼地组成, 溶丘顶至洼地底相对高差一般大于5~10 m。

(2) 丘丛洼地: 主要由溶丘和洼地组成, 溶丘顶至洼地底相对高差10~20 m, 溶丘边坡一般小于30°。

(3) 微丘槽谷: 主要由微丘和槽谷组成, 微丘之间为槽谷, 微丘顶至槽谷底相对高差一般不超过10 m。

(4) 峰丛洼地: 主要由溶峰和洼地组成, 溶峰顶至洼地底相对高差20~30 m, 溶峰边坡一般大于30°。

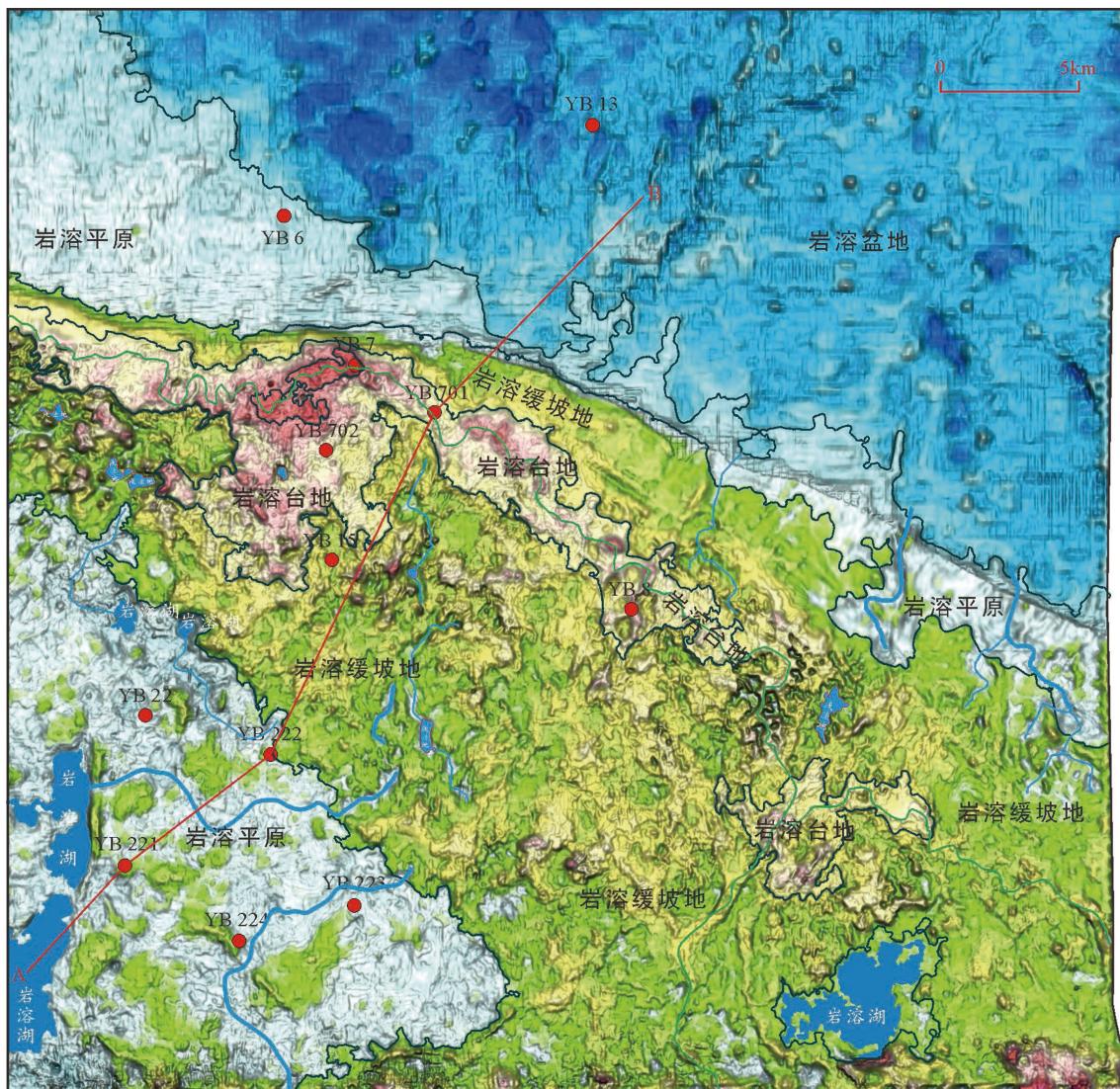


图 3 元坝及邻区茅口组顶面二级岩溶古地貌图

Fig. 3 Map of the second-tier karst paleogeomorphology in Yuanba area and on the top of Maokou formation

(5) 丘丛垄脊沟谷: 主要由溶丘和沟谷组成, 丘丛垄脊之间为沟谷, 垒脊与沟谷相间分布, 丘顶至沟谷底相对高差一般为 5~25 m。

(6) 残丘平原: 地势平缓, 地形微起伏, 丘与平原面相对高差 5~15 m。

在二级地貌单元刻画基础上, 结合元坝地区茅口组顶面岩溶古地貌的微地貌组合形态, 又可分为 6 类形态组合类型, 即三级地貌单元(表 2), 具体刻画如图 4。

4 不同类型地貌区古岩溶发育特征

根据茅口组顶面、茅口组一段顶面地震层位数据, 利用残厚法恢复的茅口组顶面岩溶古地貌, 整体

表现为中部地势相对较高, 地势自中部分别向北部、西南部缓慢降低。根据古地形、古地势特征及微丘洼地、丘丛洼地、微丘槽谷、峰丛洼地、丘丛垄脊沟谷和残丘平原在平面上的分布和相互之间的配置关系, 构建元坝及邻区茅口组顶部古岩溶面地表水系(图 5)。

总体而言, 受古地形、地势控制, 地表径流以岩溶台地向两侧分散径流为主, 古水系发育不完善, 无集中径流水系, 仅局部发育小沟流、岩溶湖。

茅口组顶面岩溶古地貌特征如下: 地形、地势自研究区中部 YB7 井—YB701 井—YB8 井一带, 分别向北、南西方向缓慢降低, 地势坡降不明显, 坡度一般小于 1°~2°, 局部坡度高达 5°, 山体顶多处于同一高程, 局部发育地表水系。丘洼相对高差一般小于

表 2 元坝及邻区茅口组顶面岩溶古地貌类型划分表

Table 2 Classification of karst paleo-geomorphology in Yuanba area and on the top of Maokou formation

岩溶古地貌类型			分布位置
二级地貌	三级地貌	主要微地貌形态	
岩溶台地	微丘洼地	微丘、浅洼地、沟谷	YB 701井-YB 702井-YB 8井一带
	微丘槽谷	微丘、浅洼地、槽谷、沟谷	YB 702井西南侧
	丘丛洼地	溶丘、洼地、沟谷	YB 7井一带、YB 701井东侧、研究区东部
	峰丛洼地	溶峰、洼地、沟谷	YB 8井一带
岩溶缓坡地	丘丛龙脊沟谷	溶丘、垄脊、沟谷、槽谷	研究区中部、YB 8井东南侧
	峰丛洼地	溶峰、洼地、沟谷	研究区中部西侧、YB 8井东南侧
	微丘洼地	微丘、浅洼地	YB 22井北侧
岩溶平原	残丘平原	溶丘、浅洼地、平原	YB 22井-YB 222井-YB 223井-YB 221井-YB 224井一带、研究区北部
	残丘平原	溶丘、浅洼地、平原	研究区北部

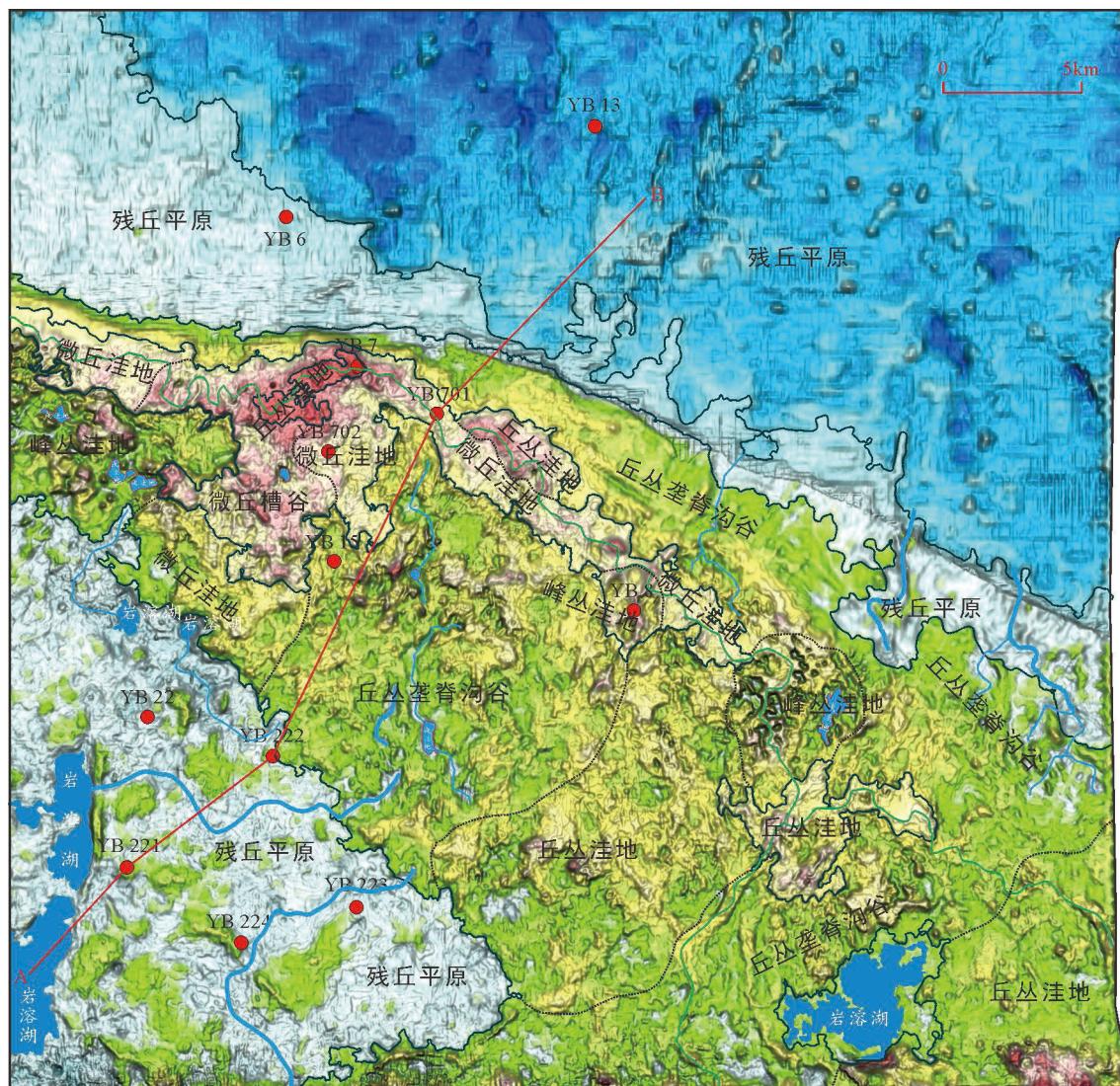


图 4 元坝及邻区茅口组顶面三级岩溶古地貌图

Fig. 4 Map of the third-tier karst paleogeomorphology in Yuanba area and on the top of Maokou formation

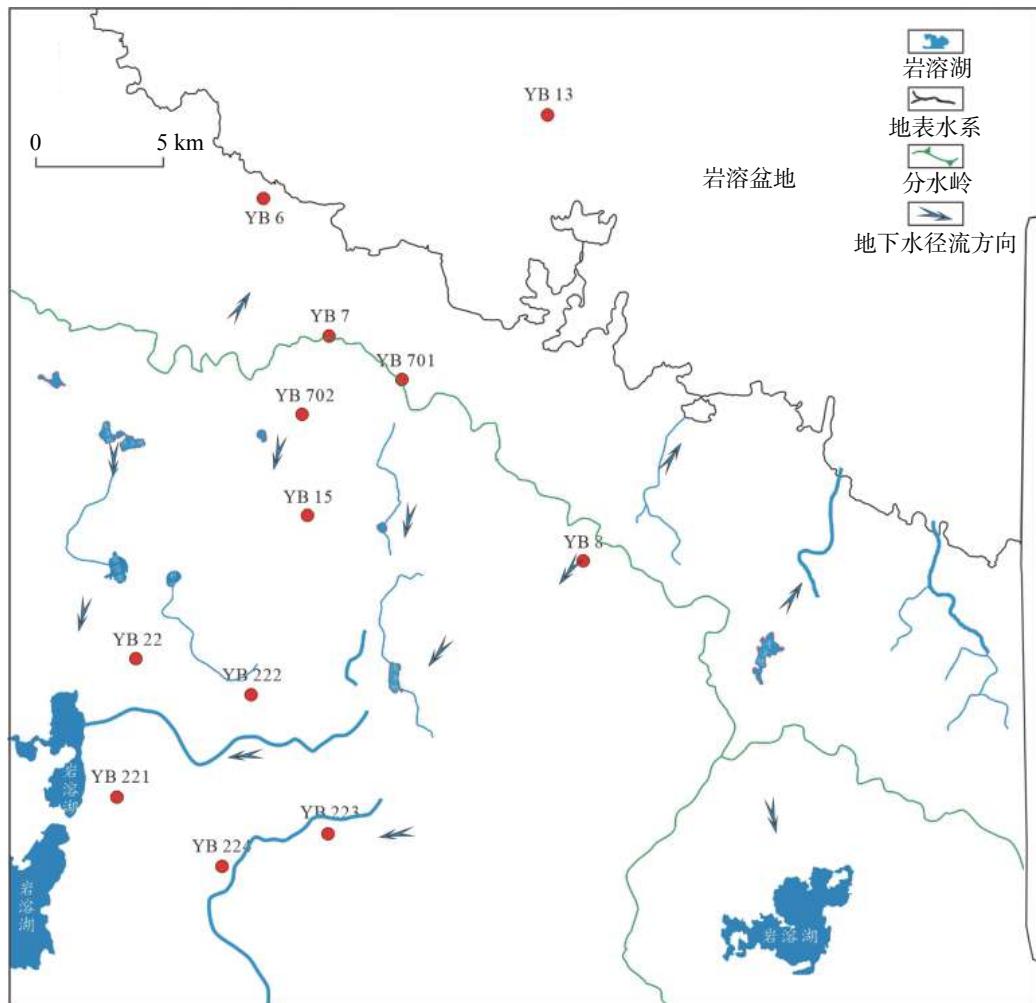


图5 元坝及邻区茅口组顶面古水系特征图

Fig. 5 Characteristics of paleo-water system in Yuanba area and on the top of Maokou formation

5 m, 局部可达 10~30 m, 整体属微地貌形态, 局部发育成熟的地貌。根据微地貌组合形态, 岩溶地貌主要为微丘洼地、丘丛洼地、微丘槽谷、峰丛洼地、丘丛垄脊沟谷、残丘平原 6 种地貌组合类型。

整体来看, 元坝及邻区茅口组顶面岩溶古地貌属岩溶地貌形成演化过程中初期岩溶地貌特征(局部发育成熟地貌), 其岩溶古地貌与岩溶作用特点是: 地势平缓(区域地势相对高差一般小于 120 m), 地形微起伏(小于 5~30 m), 丘(峰)洼相对高差一般小于 10~30 m, 属构造抬升剥蚀初期、滨岸(岛屿)岩溶地貌特征, 地表水系未完全成型(局部发育水系); 岩溶作用时间相对较短, 属表生裸露岩溶初期, 具有淡水、海水共同岩溶作用特点, 岩溶作用方式以淡水淋滤、渗滤为主, 难以形成集中侧向径流; 岩溶作用主要发生在浅部, 岩溶以溶蚀孔洞为主, 尚未形成具规模的岩溶缝洞(图 6)。

4.1 岩溶台地

岩溶台地位于元坝地区中部 YB7 井—YB702 井—YB701 井—YB8 井一带区域, 呈 NW—SE 穹隆状展布, 属元坝地区地势相对较高部位, 地形、地势平坦, 山体的夷平面高程相近, 地形微起伏, 相对高差一般小于 5~15 m。茅口组顶面至茅口组一段顶面的厚度为 215~265 m, 地表水系不发育, 负地形以浅洼地为主(局部发育深洼地)。岩溶地貌个体形态以微丘、浅洼地为主, 局部发育溶丘、溶峰、岩溶沟谷、槽谷, 根据地貌组合形态划分为微丘洼地、微丘槽谷、丘丛洼地、峰丛洼地地貌单元。此区域主要经历茅口组顶面暴露期岩溶作用。

该时期岩溶面地势平坦、地形微起伏, 属元坝地区高部位, 属地下水补给区。大气降水以垂向入渗为主, 岩溶作用主要沿裂缝进行淋滤、渗滤, 受地形坡降的影响, 岩溶地下水分别向北侧、西南侧岩溶缓

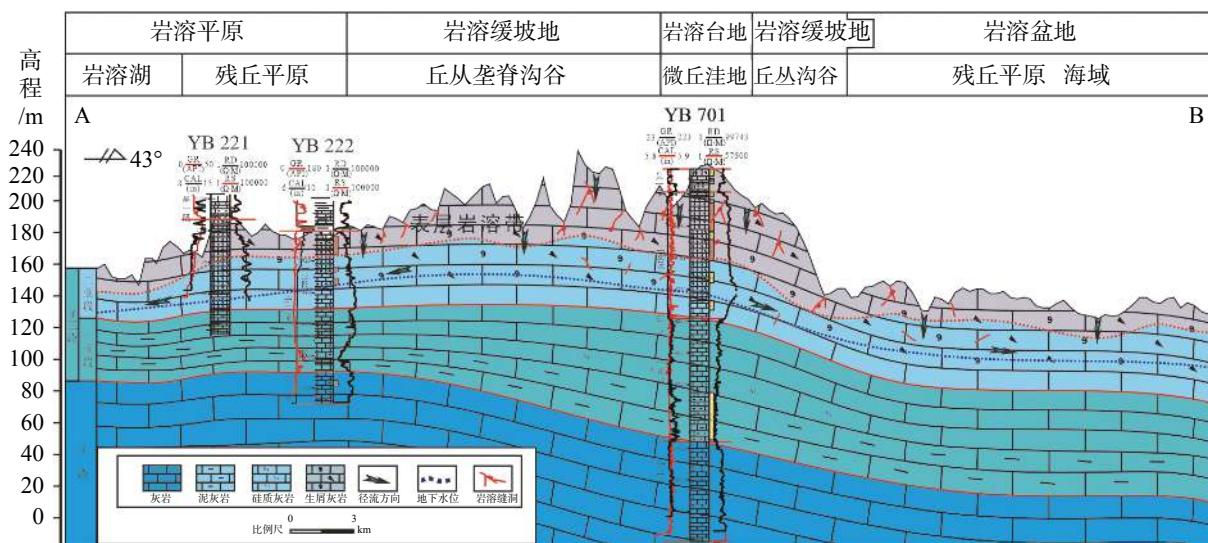


图 6 YB 221 井-YB 222 井-YB 701 井古岩溶连井剖面图(剖面位置见图 3、图 4)

Fig. 6 Sections of ancient karst wells—Well YB221, Well YB222 and Well YB701 (refer to Fig. 3 and Fig. 4 for profile positions)

坡地径流排泄。由于岩溶台地至两侧岩溶缓坡地坡降影响(地形坡度较小),地下水侧向径流缓慢,此时期岩溶作用主要位于浅部0~40 m范围,岩溶以溶蚀孔洞为主。

4.2 岩溶缓坡地

岩溶缓坡地位于岩溶台地北侧、西南侧,地形、地势有一定的微起伏,地势整体向南西或向北倾斜,地势相对高差一般小于30~35 m,地形坡度相对较小,属元坝地区低缓斜坡部位。茅口组顶面至茅口组一段顶面的厚度为180~215 m,属微地貌形态。地表水系局部发育,负地形以沟谷、槽谷和浅洼地为主,根据地貌组合形态划分为丘丛垄脊沟谷、微丘洼地、溶丘洼地、峰丛洼地地貌单元。此区域主要经历茅口组顶面裸露期岩溶作用。

该时期岩溶面地势相对平缓,地形起伏相对较小,岩溶缓坡地较岩溶台地相对较低,属地下水补给、径流区。地下水补给除接受大气降水垂向入渗外,还接受岩溶台地的侧向径流补给,因而整体岩溶作用强度比岩溶台地较强,但受地形地势、地层展布控制,岩溶作用除垂向淋滤、渗滤溶蚀外,存在侧向径流溶蚀(属分散径流,未形成集中径流)。岩溶作用也主要发生在浅部0~80 m范围,受水动力强度和暴露时间的影响,岩溶以溶蚀孔洞、溶蚀裂缝为主,溶蚀缝洞规模较小。

4.3 岩溶平原

岩溶平原位于YB22 井—YB222 井—YB223 井—

YB221 井—YB224 井一带及研究区东南部区域,地形、地势平坦,山体较少,微丘、浅洼地相对高差较小(相对高差小于5 m),属元坝地区低部位、地下水径流排泄区。茅口组顶面至茅口组一段顶面的厚度为145~185 m,属微地貌形态。地表水系不发育,负地形以浅洼地、槽谷地为主,根据地貌组合形态划分为残丘平原地貌单元。此区域主要经历茅口组顶面裸露期岩溶作用。

此时期岩溶面地势平坦、地形起伏较小,属元坝地区较低部位地区,属研究区地下水径流、排泄区。地下水主要接受岩溶缓坡地的侧向径流排泄,整体水岩作用周期相对较长,但由于地下水径流缓慢,岩溶作用强度相对较弱。YB22 井—YB 222 井—YB223 井—YB221 井—YB224 井分布在该区,岩溶作用主要位于浅部,岩溶发育较弱,溶蚀缝洞规模较小。

4.4 岩溶盆地

岩溶盆地位于研究区东北部区域,地势平坦,残丘较少,微丘、浅洼地相对高差较小(相对高差小于5 m),属元坝地区低部位、地下水径流排泄区。茅口组顶面至茅口组一段顶面的厚度小于145 m,属微地貌形态。地表水系不发育,负地形以浅洼地、槽谷地为主,根据地貌组合形态划分为残丘平原地貌单元。此区域主要经历茅口组顶面裸露期岩溶作用。

此时期岩溶面地势平坦、地形起伏较小,属元坝地区最低部位地区,为地表水汇流区,属研究区地下水径流、排泄区。地下水主要接受岩溶平原的侧向

径流排泄, 整体水岩作用周期长, 岩溶作用强度弱。

5 结 论

(1)以茅口组一段顶面作为下伏基准面, 采用残厚法恢复了元坝地区茅口组顶面岩溶古地貌。根据古地貌识别和划分, 可将茅口组顶岩溶地貌化分为4个二级地貌单元: 岩溶台地、岩溶缓坡地、岩溶平原和岩溶盆地和6个三级地貌单元: 微丘洼地、丘丛洼地、微丘槽谷、峰丛洼地、丘丛垄脊沟谷、残丘平原;

(2)不同岩溶地貌特征、古水动力条件分析表明, 岩溶缓坡地属地下水径流区, 水动力条件最强, 岩溶发育条件最好, 孔洞最发育, 是下一步储层勘探方向。

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Reconstruction of karst paleo-geomorphology and paleo-water system on the top of Maokou formation in Yuanba area, northern Sichuan Basin

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Abstract The carbonate karst reservoir of Maokou formation is developed in the Yuanba area, northern Sichuan Basin. However, it is difficult to predict this set of reservoir because of its strong heterogeneity. Therefore, for the guidance of future oil and gas exploration and development, it is necessary for us to further restore karst paleo-geomorphology and paleo-water system so as to master the law of reservoir distribution. In order to better depict the micro karst landform, the "the trend surface of residual thickness and impression residual" are combined to restore the ancient landform. According to the characteristics of karst paleo-geomorphology on the top of Maokou Formation in Yuanba area and the thickness from the top of Maokou formation to the top of its first section in Yuanba area, an index system for the classification of karst paleo-geomorphology types is established. Based on the thickness mentioned above, the paleogeographic environment and paleo-hydrodynamic conditions, the study area is divided into four second-tier geomorphic units—karst platform, gentle karst slope, karst plain and karst basin. Then, in terms of modern karst classification, a third-tier geomorphic units are subdivided into six types —micro hill depression, hill-cluster depression, micro hill trough, cluster-peak depression, hill-cluster ridge valley and monadnock plain, according to the micro geomorphic combination form of karst paleo-geomorphology on the top of Maokou Formation in Yuanba area. Based on the characteristics of paleo-topography as well as the plane distribution and mutual configuration relationship of the six third-tier geomorphic units, the surface water system of the paleo-karst surface at the top of Maokou

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then described the carbonate sedimentary facies. Based on abundant drilling data, we conducted a case study by the establishment of identification marks of beach facies, the correlation of inter-well sedimentation, ratios of shoal thickness to stratum thickness and the planar distribution of sedimentary facies. This study indicates that the distribution of sedimentary facies in layer a of Mao2 submember from southwest to northeast in eastern Sichuan is respectively open platform, platform margin, slope and basin, among which the platform margin is approximately east-west banded in the area of Linshui-Fengdu-Zhongxian. The low-energy beaches both in the platform and in the slope are mainly distributed in the area with ratios of shoal thickness to stratum thickness of 0.3-0.5; the high-energy beach in the platform is developed in the area with ratios of 0.5-0.6; and the marginal platform beach is mainly distributed in the area with ratios of 0.6-0.8. The results of well gas test show that beach facies have a certain controlling effect on oil-gas productivity, and the marginal platform beach has more exploration potential than the high-energy beach in the platform. The study shows that in the area where carbonate strata are eroded, compared with the thickness of beach, the use of the ratios of shoal thickness to the whole stratum to accurately analyze the type and distribution range of granular beach so as to judge the development of granular beaches in the layer section.

Key words eastern Sichuan, carbonate beach facies, layer a of Mao2 submember, distribution of sedimentary facies, platform margin

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formation in Yuanba and its adjacent areas is constructed. In general, controlled by the ancient topography, the surface runoff is mainly the scattered runoff from the karst platform to both sides. The ancient water system is not well developed with no centralized runoff system, and only small gullies and karst lakes are locally developed. On the whole, the ancient karst landform on the top of Maokou formation in the study area belongs to the initial stage of the formation and evolution of karst landform. The relative elevation difference of the regional terrain which is slightly undulating is generally less than 120 m. The relative elevation difference of hills (peaks) and depressions is generally less than 10-30 m, which belongs to the initial stage of tectonic uplift and denudation and is characterized by coastal (island) karst landform, and the surface water system is not fully formed. The karstification time of the study area is relatively short, belonging to the initial stage of epigenetically exposed karst which is characterized by the joint karstification of atmospheric fresh water and seawater. The karstification mode is mainly the leaching and infiltration of atmospheric fresh water, which is difficult to form concentrated lateral runoff. Karstification mainly occurs in the shallow part, and karst is dominated by dissolution holes. Large-scale karst fractures and caves have not been formed. There are great differences in karst development in different geomorphic locations, among which the karst platform belongs to the groundwater recharge area; the atmospheric precipitation is mainly vertical infiltration; and the lateral runoff of groundwater is slow. The karst plain belongs to groundwater runoff and discharge area, where groundwater runoff is slow, and the intensity of karstification is relatively weak. The karst basin belongs to groundwater drainage area with long water-rock interaction cycle and weak karstification intensity. The gentle karst slope belongs to groundwater runoff area with the strongest hydrodynamic force and the most developed holes, which is suitable for the future reservoir exploration.

Key words paleo-hydrogeological condition, carbonate rocks, karst paleo-geomorphology, Yuanba area, Maokou formation

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