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古地貌对渤海湾盆地B区块太古宇暴露型潜山变质岩风化带储层裂缝发育的影响

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摘要:古潜山是中国渤海湾盆地油气勘探开发的重要领域,渤中凹陷B区块是近年来中国东部发现的规模最大的凝析气田,该区块为太古宇暴露型潜山,古地貌在储层形成及发育过程中具有重要作用。受古地貌控制,变质岩潜山遭受风化作用时间及强度存在差异,进而影响了风化带储层的发育,尤其是影响了潜山风化带裂缝的形成。在岩心描述、成像测井裂缝解释结果、潜山古地貌恢复及古地貌划分基础上,详细讨论了古地貌对潜山风化带储层裂缝发育的影响。结果表明:①古地貌相对高部位风化淋滤作用较强,裂缝密度较大,古地貌直接影响了风化带裂缝的发育,削弱了内幕带储层的岩石力学性质,在一定程度上间接地控制了内幕带裂缝的发育;②古地貌对潜山风化带的影响深度存在差异,控制了潜山不同深度带的裂缝形成,B区块古地貌呈现明显的东、西区差异,西区风化裂缝带厚度(平均为277 m)明显大于东区(平均为193 m),西区古地貌影响的风化裂缝带深度也大于东区;③古地貌与各组系(期次)的裂缝密度呈明显相关性,即风化带的裂缝发育不仅受古地貌控制,还与各期的构造活动有关,特别是早期的构造活动(印支期)与古地貌共同控制了风化带早期裂缝的形成;④B区块发育3大高幅隆脊残丘区,残丘区裂缝最发育,地貌幅度控制着风化带裂缝的发育,对北西-南东向印支期裂缝的控制作用较强,残丘缓翼水-岩反应更充分,风化淋滤作用强,岩石力学强度降低,更易在各种应力下产生裂缝,并发生规模溶蚀,利于风化带优质储层的形成。

关键词:风化带;古地貌;暴露型潜山;太古宇变质岩;储层裂缝;渤海湾盆地
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The effects of paleogeomorphology on the development of fractures in reservoirs of weathering metamorphic zone in an exposed Archean burial hill, Block B, Bohai Bay Basin

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Abstract: Burial hill is one of the important targets for oil and gas exploration and development in the Bohai Bay Basin where Block B in an exposed Archean burial hill is recently found to be hosting the largest gas condensate field in eastern China. The paleo-geomorphology is suggested to have played an important role in the formation and development of reservoirs in the field that caused differences in duration and intensity of weathering upon the burial hill of metamorphic rocks and thus shaped the development of reservoirs and even the formation of fractures in the weathering zone of the burial hill. Based on core description and image logging interpretation of fractures as well as the restoration and division of the ancient landform of the burial hill, the control of paleogeomorphology on the formation of fractures in the reservoirs of burial hill is discussed in detail. The following results are obtained: ① The weathering and leaching effect is relatively stronger at the higher parts of the paleogeomorphology, resulting in denser fractures. The paleogeomorphology directly

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affects the development of fractures in the weathering zone, weakens the rock properties of the reservoir in the inner zone, and indirectly controls the development of fractures in the inner zone to a certain extent. ② The depth ranges of effects of paleogeomorphology on weathering zone of buried hill are different in different areas, which controlled the formation of fractures in different depth of the burial hill. The paleogeomorphology in the east part of Block B is very different from that in the west part, with the thickness of the weathering fracture zone in the west part (277 m) significantly larger than that in the eastern part (193 m). The depth of the weathering fracture zone affected by the paleogeomorphology in the west part is also greater than that in the east part. ③ There is a clear correlation between paleogeomorphology and the fracture density of each fracture group/system (stage), i. e. , the fracture development in the weathering zone is not only controlled by paleogeomorphology, but also related to the tectonic activities of each period, especially the early tectonic activities (Indosinian period) which controls jointly with paleogeomorphology the formation of early fractures in the weathering zone. ④ Block B contains 3 large high-pitched ridge remnant mound areas with well-developed fractures. Fractures, especially the NW-SE-trending fractures of Indosinian period in the weathering zone are controlled by geomorphologic amplitude. More complete water-rocks reaction occurs in the gentle flanks of the remnant mounds, where the weathering and leaching effect is strong enough to reduce the mechanical properties of the rocks and facilitate the formation of fractures under various stresses and large-scale dissolution, all providing favorable conditions for the formation of high-quality weathering zone reservoirs.

Key words: weathering zone, paleogeomorphology, exposed burial hill, Archean metamorphic rocks, reservoir fracture, Bohai Bay Basin

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近年来,古潜山已成为渤海油气勘探的重要领域。中国渤海湾盆地是潜山油气藏发现的集中地,经过多年潜山油气勘探,已取得一系列的突破性进展,包括冀中坳陷任丘潜山油气藏、黄骅坳陷千米桥潜山油气藏、济阳坳陷桩西潜山油气藏和辽河坳陷兴隆台潜山油气藏[1-10]。其中,位于渤中坳陷的B区块是近年来中国东部发现的规模最大的凝析气田[11-14]。B区块主力储层为太古宇变质岩潜山储层,储层纵向上具有明显的分层性,上段主要为孔隙性储层,储/地比0. 18~0. 68,孔隙度0. 6 %~17. 0 %(平均7. 1 %),渗透率(0. 05~90. 30)$\times 10^{-3}$ μm^2,储渗性能相对较好。下段主要为构造作用形成的裂缝性储层,储/地比0. 52,孔隙度0. 2 %~10. 9 %(平均2. 8 %),渗透率(0. 04~0. 05)$\times 10^{-3}$ μm^2(平均0. 05 $\times 10^{-3}$ μm^2)[15]。前人研究普遍认为B区块太古宇潜山储层具有双孔介质特征,潜山储层受岩石类型及矿物含量、古地貌、风化淋滤作用及构造运动等因素影响,形成机理十分复杂[16-23]。

由于B区块为太古宇暴露型潜山(图1),研究目的层太古宇变质岩在地质历史时期长期暴露于地表,岩石遭受了风化、剥蚀,使抗风化能力差的长石类矿物发生蚀变,极大加剧了岩石的破碎程度,物理风化作用后,化学淋滤溶蚀作用对储集层进行更进一步的改善[24-28]。对于风化壳储层来说,古地貌是风化壳发育程度的重要控制因素[29-32]。受古地貌控制,变质岩潜山上覆地层时代不同,地层遭受风化淋滤作用时间存在差异,进而影响风化带储层的发育程度,特别是影响了潜山风化带裂缝的发育[33-38]。中国针对覆盖型潜山储层裂缝特征及其发育影响因素研究已见相关文献报道[16,39],但针对暴露型潜山储层裂缝研究鲜有报道。基于研究区特殊地质条件及现有研究程度,本文在岩心系统观察描述、成像测井裂缝解释及太古宇潜山顶界古地貌划分研究基础上,详细深入地讨论了太古宇顶界古地貌对暴露型潜山风化带储层裂缝形成与发育的影响。

1　区域地质概况

B区块位于渤中坳陷西南部,东南方向为渤南低凸起,西部为埕北低凸起,南接黄河口坳陷,北接渤中坳陷主洼地带,为渤中坳陷西南次洼和南次洼夹持,处

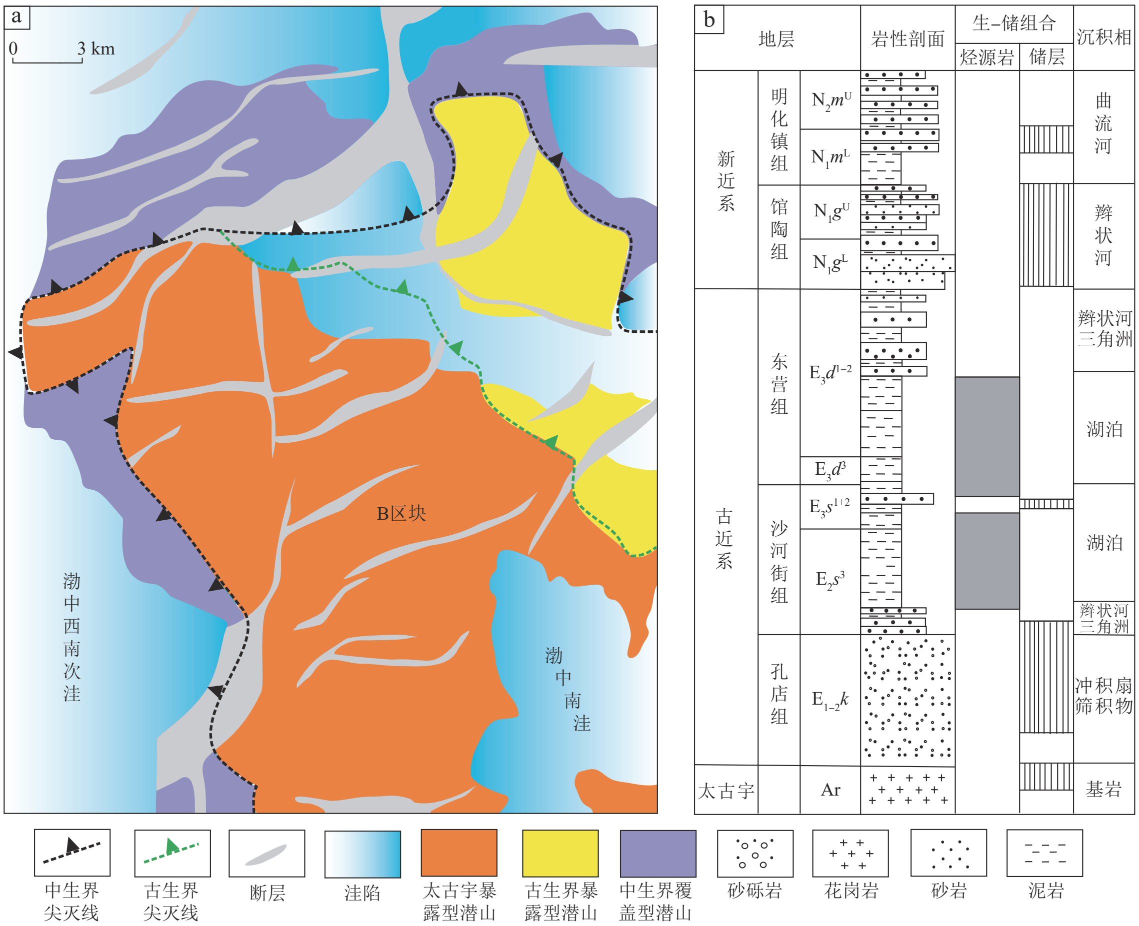

图1　研究区构造地理位置(a)及气田生-储组合简图(b)(据文献[16]和[20]修改)

Fig. 1　Structural location of the study area (a) and schematic diagram of the source-reservoir assemblage of gas fields (b) (modified after references [16] and [20])

于B19构造脊上(图1),与3个生烃坳陷组成具有洼中隆起特征的背斜构造带[15,40]。其地层自上而下依次发育平原组、明化镇组、馆陶组、东营组、沙河街组以及太古宇变质岩基底,除了上述地层外,构造带南部还发育孔店组砂砾岩地层,构造带北部发育中生界[41-42]。其中沙(沙河街组)三段、沙一段及东(东营组)三段为主要的3套烃源岩层,明化镇组、馆陶组、孔店组等主要发育碎屑岩储层,中生界岩性主要为砂砾岩和凝灰岩,太古宇为变质岩[43-44],纵向上按岩性及风化程度差异划分为砂砾岩带、强风化带、次风化带及内幕带。

B区块太古宇潜山储层埋藏深度在4 200~5 500 m。垂向上潜山储层具有明显的二元结构,即表层风化裂缝带和内幕裂缝带,风化带与内幕带的物性差异在钻时、电阻率等电测曲线上有明显体现[45-46]。上部风化裂缝带地层厚度约为150~316 m,储层厚度约为36~201 m,分布较稳定。内幕带裂缝段地层厚度一般在120~740 m,储层厚度20~255 m,纵向致密段、隔夹层较多,非均质性强[18,47-48]。

2　岩心缝洞发育特征

B区块太古界变质岩潜山8口取心井共观察到裂缝276条,23处有一定规模的网状裂缝发育段(部分岩心可见溶蚀孔/洞)。根据岩心裂缝观察结果,以裂缝成因为依据将裂缝划分为构造裂缝和非构造裂缝。

2.1　构造裂缝

构造裂缝广泛存在于地层中,主要与构造或断层活动有关。岩心上观察到的构造裂缝主要为张性破裂缝和剪切破裂缝。剪切破裂缝一般可见缝面擦痕和阶步,缝面见泥质充填,沿缝面可见少量的溶蚀孔洞,此类裂缝具有一定的有效性。B区块潜山变质岩的剪切破裂面大多为低角度斜交缝破裂(图2a)。构造张性缝部分呈现未充填或半充填,部分为方解石或泥质全充填,此类裂缝偶见切割限制关系(图2b,c)。

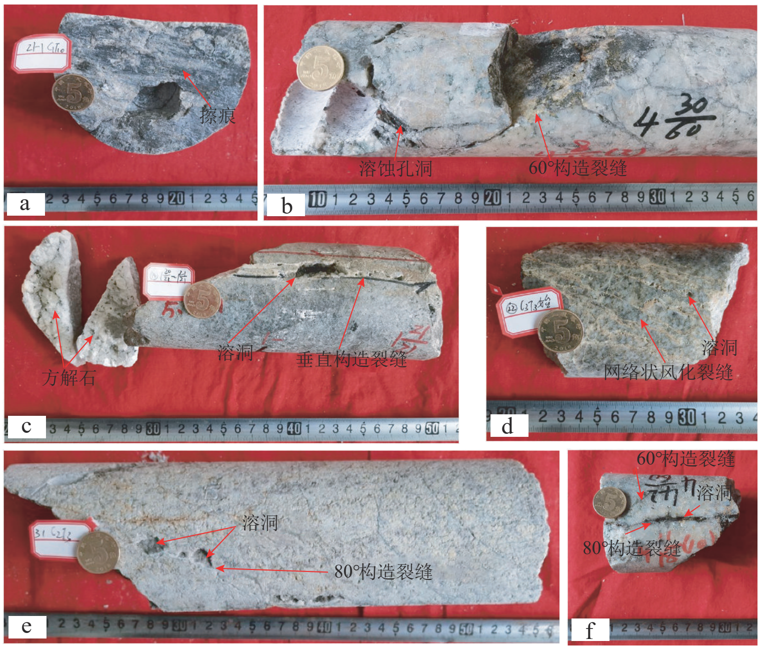

图 2　渤海湾盆地 B 区块太古宇不同类型裂缝及溶蚀孔洞典型照片

Fig. 2　Typical photos showing different types of fractures and dissolved pores in the Archean of Block B, Bohai Bay Basin

a. B14 井,埋深 4 368. 42 ~ 4 368. 46 m,低角度裂缝缝面,裂缝倾角 30°,泥质充填,缝面见擦痕; b. B7 井,埋深 4 681. 45 ~ 4 681. 67 m,发育 1 条倾角为 60°构造裂缝,缝宽 0. 1 ~ 2. 0 mm,泥质、沥青质半充填,沿缝有溶蚀,发育溶蚀孔洞,大小 1 mm×5 mm;c. B12 井,埋深 5 274. 83 ~ 5 275. 31 m,发育 1 条垂直构造裂缝,方解石半充填,沿缝发育溶洞,大小 10 mm×30 mm,方解石半充填,可见岩心破碎;d. B12 井,埋深 5 524. 84 ~ 5 524. 94 m,发育网络状风化裂缝,产状凌乱,主体为 80°,宽度 1 ~ 2 mm,沿缝发育溶洞,大小 3 mm×5 mm;e. B14 井,埋深 4 371. 80 ~ 4 372. 04 m,沿 80°构造裂缝发育多个溶洞,方解石半充填,大小 10 mm×13 mm;f. B7 井,埋深 4 683. 11 ~ 4 683. 21 m,1 条 80°和 1 条 60°构造裂缝,方解石半充填,沿 80°构造缝见溶洞,大小 2 mm×3 mm

2. 2　非构造裂缝

研究区的非构造裂缝主要为风化裂缝,主要是指风化作用使岩石发生崩解,形成裂缝。风化裂缝具有延伸短、分支多、分布较为杂乱的特点(图 2d)。研究区 8 口取心井取心段的风化裂缝发育段厚度为 4. 91 m,其在现有取心段上的发育率为 6. 67 %。风化裂缝多被砂泥质充填,纵向上地层深度越深,风化裂缝的发育程度越弱。

2. 3　溶蚀孔/洞

岩心上可见的溶孔/洞直径一般在 0. 1 ~ 15. 0 mm,这些孔/洞多与裂缝伴生,表现为大缝大孔。岩心上可见溶蚀孔/洞一般无充填物或者被方解石、泥质等半充填(图 2e,f),有效性普遍较好。

2. 4　岩心缝、洞发育关系

裂缝与溶蚀孔/洞的发育在纵向上具有一定相关性。裂缝和溶蚀孔/洞在顶部砂砾岩带的发育数量较少,自强风化带到次风化带再到内幕带,裂缝条数和溶蚀孔/洞个数逐渐减少,这在一定程度上印证了裂缝与溶蚀孔/洞的伴生关系,也揭示了该地区风化作用与溶蚀作用存在一定关联(图 3)。

8 口井岩心观察结果表明,岩心裂缝和溶蚀孔/洞在不同地层段的充填情况也存在差异(图 3)。纵向上,顶部砂砾岩带观察到的裂缝数量较少,且全为充填裂缝,即均为无效裂缝;从强风化带到次风化带、内幕带,无效裂缝(指全充填裂缝)数量递减,有效裂缝(指半充填或未充填裂缝)数量则呈现先增后减的趋势,裂缝有效率也呈现先增后减趋势。溶蚀孔/洞在顶部砂砾岩带数量极少,仅观察到少量有效溶蚀孔/洞,溶蚀孔/洞数量从强风化带到内幕带呈现递减趋势,并且溶

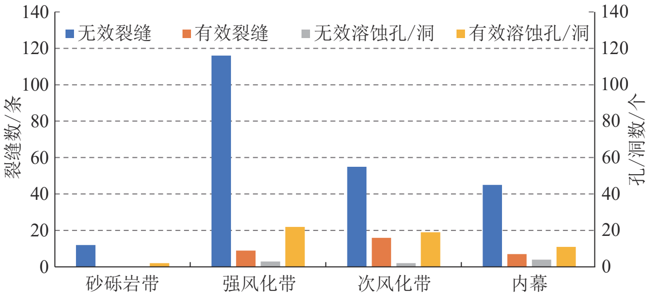

图 3　B 区块纵向不同分带裂缝、溶蚀孔/洞充填情况

Fig. 3　Bar chat showing the filled fractures and dissolved vugs in different vertical zones of Block B

蚀孔/洞有效率也呈现先增大后减小的规律，与裂缝有效率变化趋势一致。

3 古地貌与风化带储层裂缝发育关系

研究区太古宇变质岩在地质历史时期长期暴露于地表，岩石遭受风化、剥蚀，抗风化能力差的长石类矿物发生蚀变，极大加剧了岩石的破碎程度，物理风化作用后，化学淋滤溶蚀作用对储集层进行了再次改造[24-29]。对于受暴露风化作用而形成的储层来说，古地貌是储层发育程度的重要控制因素[29-32]。受古地貌控制，变质岩潜山储层遭受风化淋滤作用的时间及强度存在差异，进而影响了风化带储层的发育程度，特别是影响了潜山风化带裂缝的形成及发育[33-38]。由于研究区太古宇潜山变质岩纵向上具有二元结构[45-46]，根据风化作用强度差异可划分为风化带和内幕带，风化带以发育风化裂缝为主，内幕带以发育构造裂缝为主。因此，太古宇顶界古地貌对暴露型潜山风化带裂缝的形成与发育具有重要的影响作用。

3.1 古地貌划分与储层发育的关系

3.1.1 古地貌划分

B区块太古宇潜山古地貌整体呈残丘型地貌格局（图4），中部古地形高，周缘地形低，中部存在4个主要的高古地形分布区：B4井区、B8井区、B16井区和

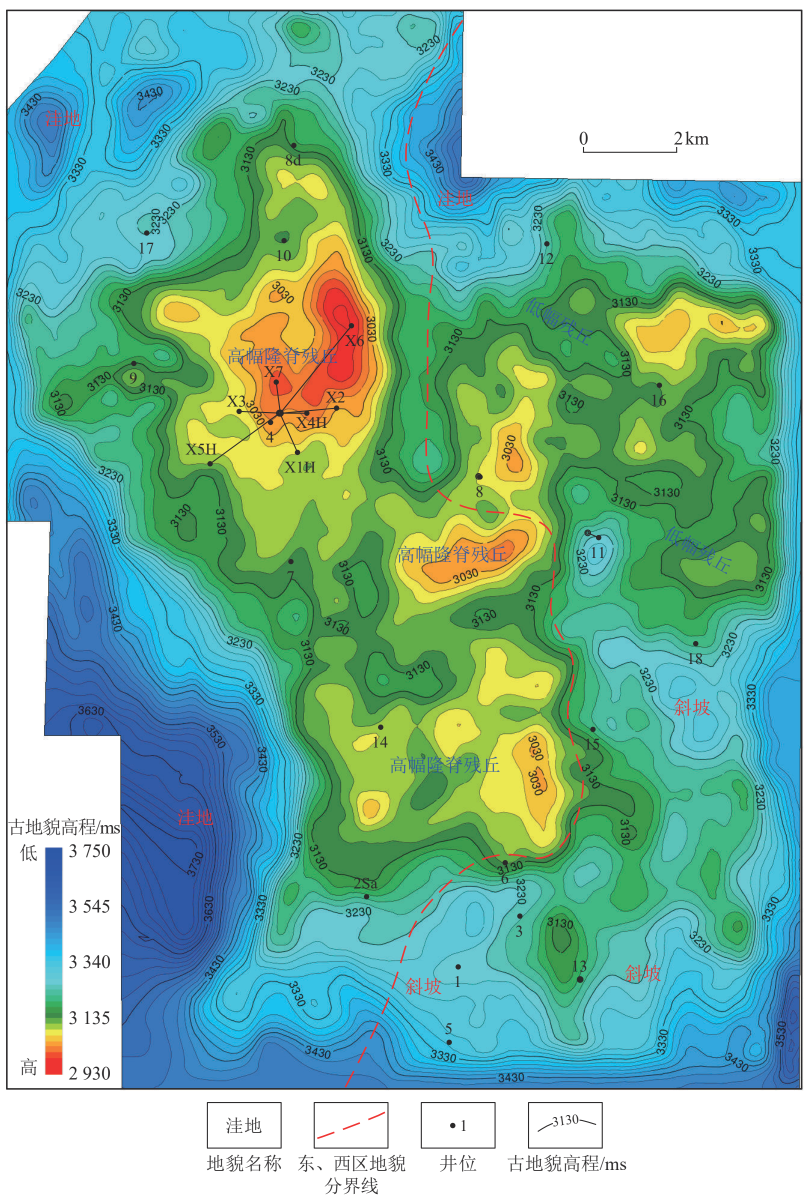

图4 B区块潜山顶界微古地貌划分

Fig. 4 Division map of micro-paleogeomorphology at the top boundary of burial hill in Block B

B14井区。结合古地貌实际形态,将研究区地貌按高程划分为4种主要类型(图4)。①高地:古地形高的区域,高程在2 950 ~3 080 ms,可根据高地上残丘形态进一步划分为高幅隆脊残丘及其侧翼;②高地-斜坡过渡带:古地形开始变缓的区域,高程在3 080~3 140 ms,根据地貌形态进一步划分为低幅残丘及其侧翼,高幅/低幅残丘可进一步细分为残丘顶峰、残丘陡翼和残丘缓翼;③斜坡:古地形明显降低的区域,高程在3 100~3 300 ms;④洼地:地势低洼的区域,高程大于3 300 ms。

3.1.2　古地貌特征及与储层发育关系

根据B区块16口井风化带和内幕带的储层厚度实钻资料,研究了古地貌高程与不同分带储层厚度的关系。古地貌位置越高遭受风化剥蚀的时间就越长,风化淋滤作用的强度也就越大,相应地风化带储层储地比越高,储层厚度越大(图5,图6)。内幕带储层厚度和储地比与古地貌高程的相关性明显降低(图6),但在古地貌相对高的部位,储层厚度偏大,储地比也相对较高,表明古地貌位置不仅对潜山顶部风化带储层的发育具有明显的控制作用,同时也在一定程度上影响了潜山深部储层(内幕带)的发育(图6)。

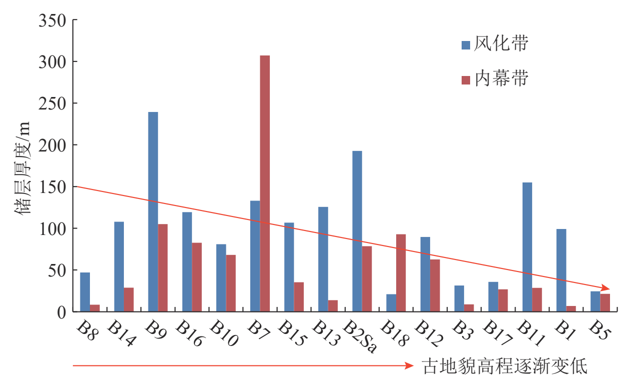

图5　B区块潜山顶界古地貌高程变化与不同分带储层厚度关系

Fig. 5　Relationship between the paleogeomorphic elevation of the top boundary of burial hill and the thickness of reservoirs in different zones of burial hill in Block B

3.2　古地貌对风化带储层裂缝发育的控制

3.2.1　古地貌与潜山纵向各带裂缝发育关系

依据古地貌高程(或风化带厚度)与潜山强风化带、次风化带、内幕带及单井全段的裂缝密度之间的关系(图7,图8)可以看出:①B区块古地貌相对高部位风化淋滤作用较强,裂缝密度相对较大,古地形直接影响了风化带裂缝的发育(图7a—c),削弱了内幕带储层的岩石力学性质,在一定程度上间接影响了内幕带裂缝的发育(图7d)。②古地貌高程与裂缝之间的相关性并不特别显著(图7a—d),但这并非意味着古地貌对裂缝的发育控制作用弱,而是说明在笼统分析高程与裂缝发育之间的关系时如果不考虑不同古地貌位置的影响会导致统计结果不准确。从另一个角度来看,这也表明裂缝发育同时还受控于其他因素。③风化带厚度可以在一定程度上反映古地貌控制下的风化作用强弱,风化厚度越大,强风化带裂缝越发育(图8a),而对次风化带及下部内幕带的裂缝发育影响明显减弱(图8b)。

3.2.2　古地貌东、西区裂缝发育的差异性

B区块古地貌呈现明显的东、西区差异(图4),古地貌对潜山风化带的影响深度存在差异,控制了不同深度带的裂缝形成。西区风化裂缝带厚度明显高于东区,西区古地貌影响的风化裂缝带深度也大于东区,西区风化带裂缝发育深度最大距潜山顶界面可超过450 m。研究区古地貌高点主要位于西区(4井区附近),西区古地貌不仅控制了风化带的储层厚度(平均厚度277 m),也明显控制了该区裂缝系统的形成,古地貌位置越高风

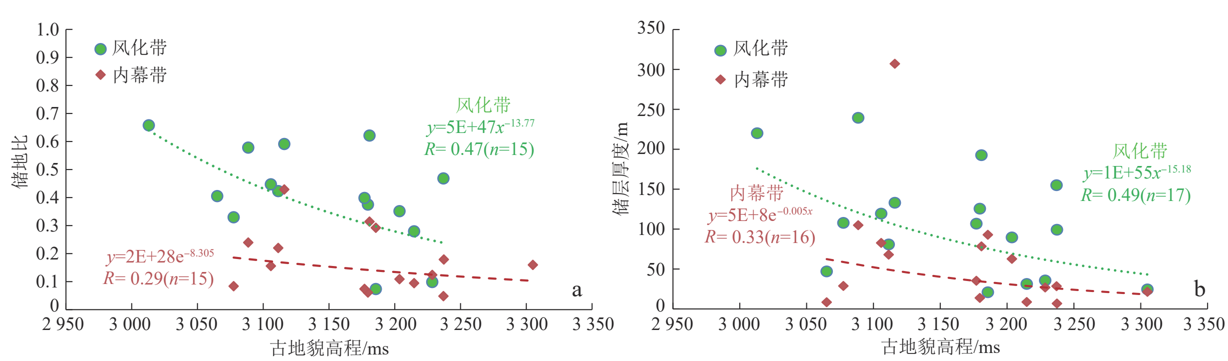

图6　B区块潜山顶界不同分带古地貌高程与储/地比(a)、储层厚度(b)的关系

Fig. 6　Relationship of the paleogeomorphic elevation with net-gross ratio (a) and reservoir thickness (b) of different zones on the top boundary of buried hill in Block B

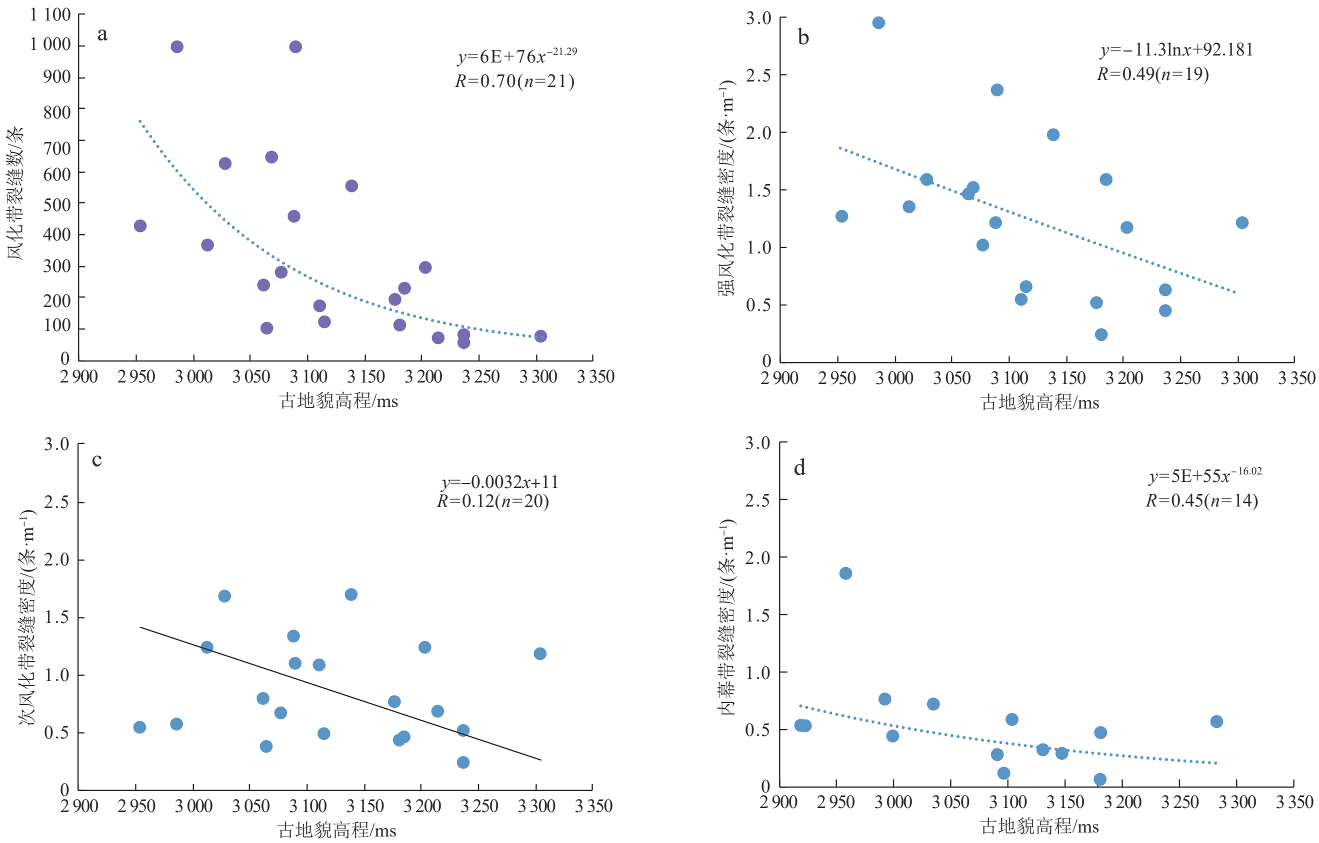

图7 B区块潜山古地貌高程与裂缝发育特征之间的关系

Fig. 7 Relationship between paleogeomorphic elevation and fracture density of buried hill in Block B

a. 风化带裂缝数;b. 强风化带裂缝密度;c. 次风化带裂缝密度;d. 内幕带裂缝密度

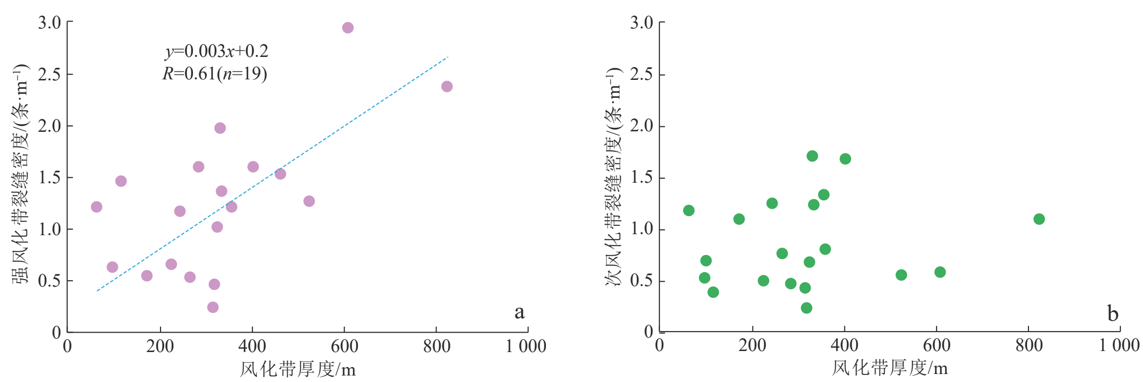

图8 B区块潜山风化带厚度与强风化带(a)、次风化带裂缝密度(b)的关系

Fig. 8 Relationship between thickness and fracture density of intensively weathered zones (a) and less intensively weathered zones in buried hill in Block B

化带储层裂缝越发育。东区古地貌对风化带储层和裂缝形成的控制作用相对西区明显变弱,风化带平均厚度为193 m,潜山上部裂缝密度明显低于西区(图9),古地貌对风化带储层裂缝发育的控制作用明显减弱。

3.2.3 古地貌对不同走向(不同期次)裂缝发育的控制

由于不同构造活动的作用方式及强度的差异,裂缝的形成与发育通常会呈现出多期次、多组系(走向不同)特征[49]。B区块古地貌与各组系(期次)的裂缝密度呈较明显相关性(局部异常点为受构造等其他因素主控)(图10),表明风化带的裂缝不仅受古地貌控制,还与各期构造活动有关。研究区潜山主要经历了4个演化阶段[40,50]:第一阶段为古生代物质基础形成阶段,属于沉积建造期,构造运动以整体垂直隆升为主,构造欠发育;第二阶段为印支期至燕山早期持续挤压隆升与潜山构造雏形阶段;第三阶段为燕山中期块断隆升及

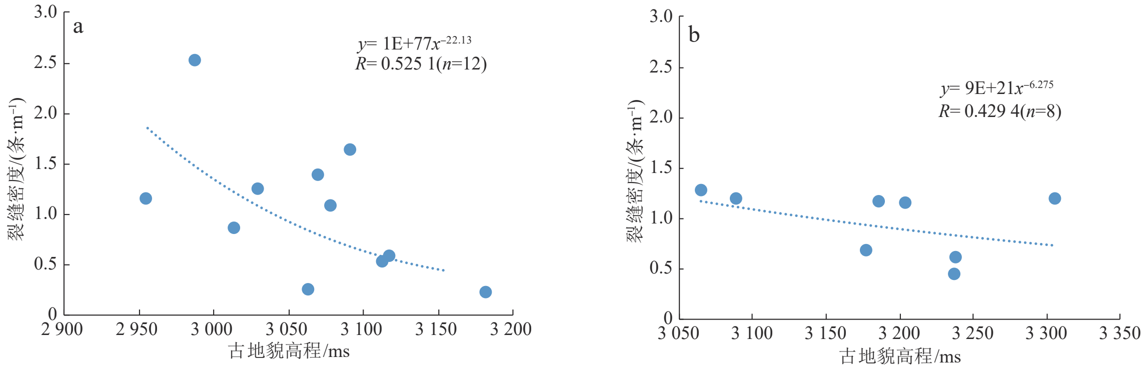

图 9　B 区块西区(a)、东区(b)不同单井古地貌高程与砂砾岩带+强风化带裂缝密度关系

Fig. 9　Relationship between the paleogeomorphic elevations in different single wells and the fracture density of the coarse-grained clastic rock zone + strong weathering zone in the west (a) and east (b) parts of Block B

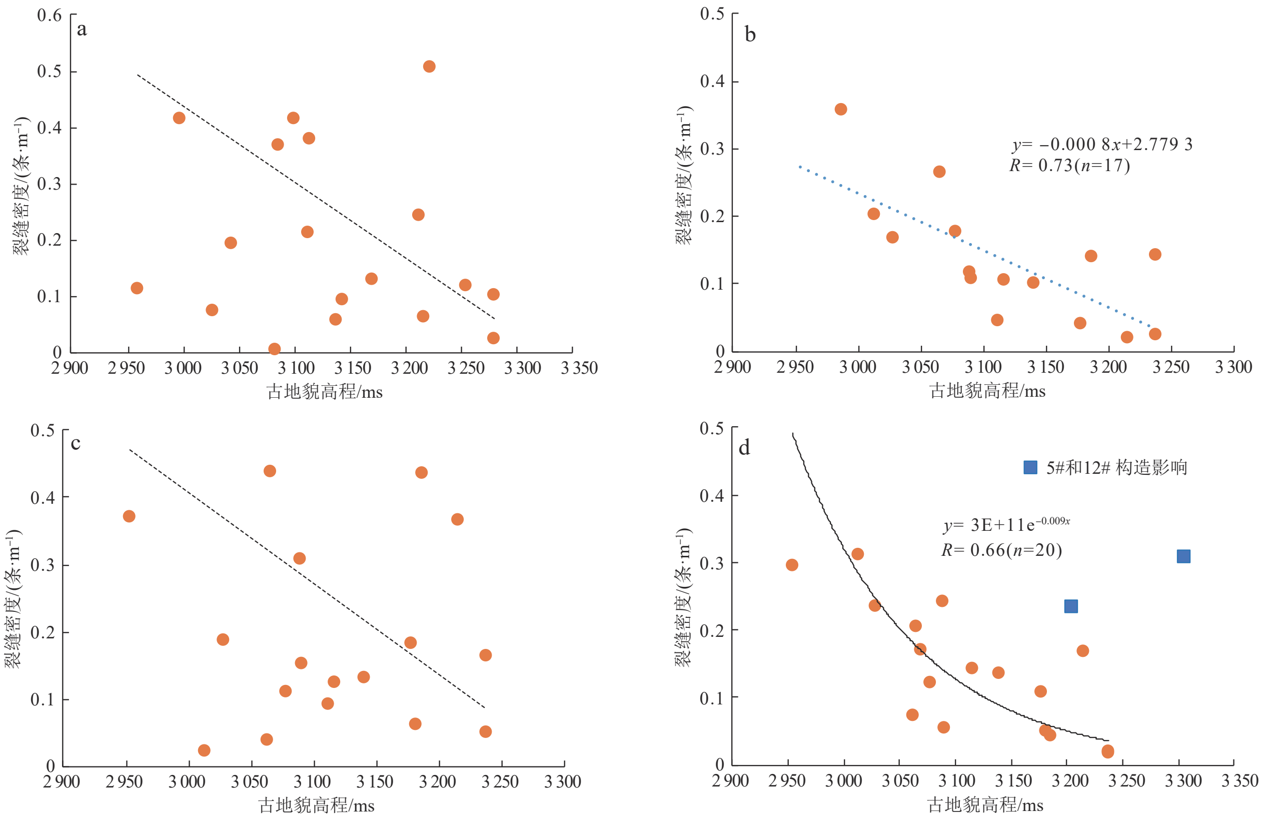

图 10　B 区块风化带不同走向裂缝密度与古地貌高程相关性

Fig. 10　Correlation between density of fractures of different trends and paleogeomorphic elevation of weathering zones in Block B

a. 北东-南西向；b. 近南北向；c. 近东西向；d. 北西-南东向

潜山初始格局形成阶段；第四阶段为新生代以来改造与快速埋藏阶段。研究区太古界变质岩潜山沉积建造后遭受风化作用，形成了风化带储层及其裂缝，在此基础上，裂缝接受印支期及之后的构造运动的改造、继承性发展，并可能产生新的破裂，根据成像测井解释出的不同走向(反映不同期次)裂缝与古地貌关系来看，近南北向和北西-南东向的裂缝发育与古地貌相关程度最高(图 10b，d)，因此早期的构造活动(印支期)与古地貌共同控制了风化带早期裂缝的形成与发育。

3.2.4　古地貌单元对裂缝发育的控制

根据前述古地貌单元的划分，对研究区 21 口井纵向各带的裂缝发育进行分析研究发现，残丘区(包括残丘缓翼、残丘陡翼或顶峰)风化带裂缝最发育(裂缝线密度均值为 1.10 条/m)，斜坡区裂缝发育程度(裂缝线密度均值为 0.72 条/m)明显不如残丘区(图 11a)。其次，同为残丘地貌的各井裂缝发育程度仍有差异，地貌单元与裂缝发育的关系(图 11a—c)分析表明，残丘缓

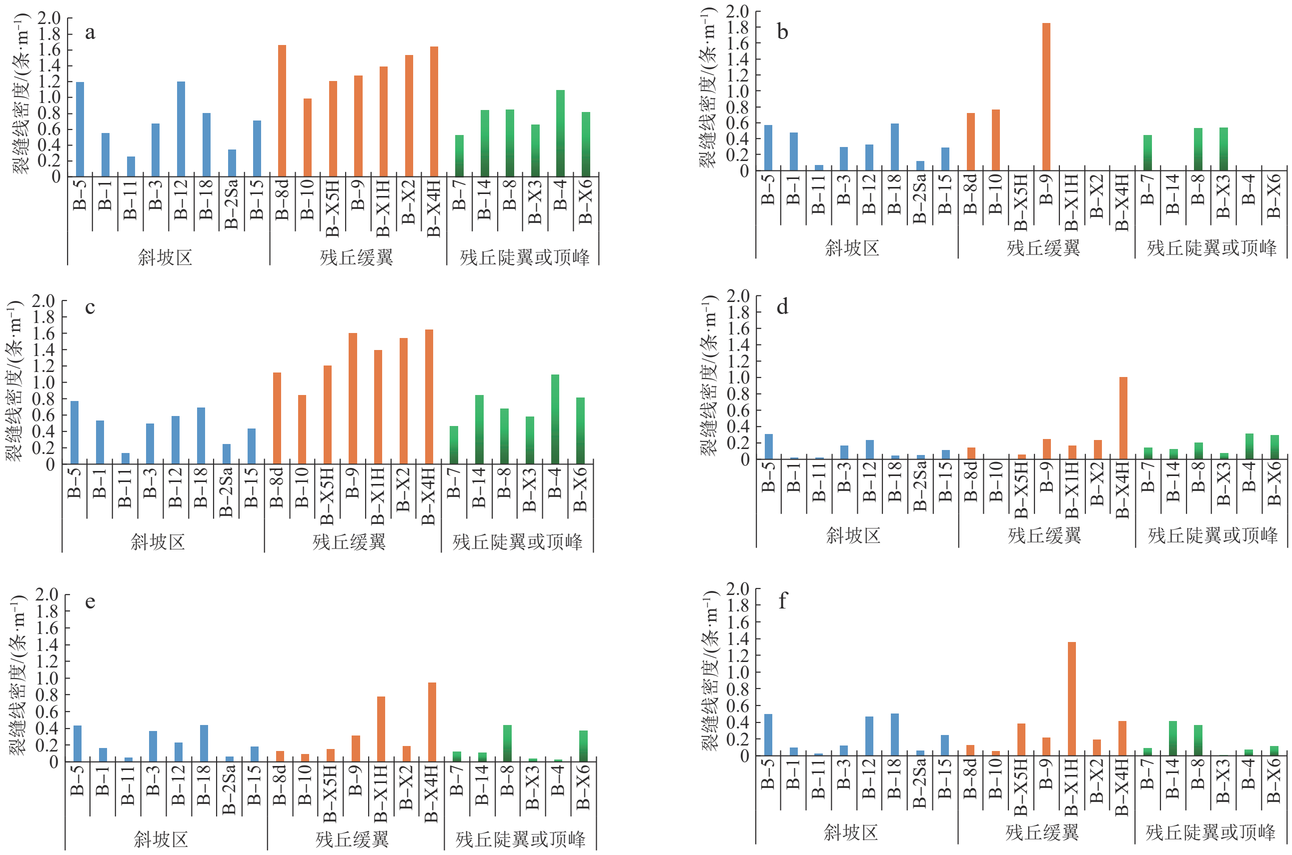

图11 B区块不同地貌单元、纵向分带及不同走向裂缝密度分布

Fig. 11 Density distribution of fractures in different geomorphic units and vertical zones and of different trends in Block B

a. 风化带裂缝密度;b. 内幕带裂缝密度;c. 单井裂缝密度;d. 风化带北西向裂缝密度;e. 风化带近东西向裂缝密度;f. 风化带北东向裂缝密度

翼水-岩反应更充分,风化淋滤作用强,岩石力学强度降低,更易在各种应力下产生裂缝,并发生规模溶蚀,利于优质风化带储层的形成;残丘缓翼各带的裂缝密度明显高于残丘陡翼、顶峰及斜坡。因此,不同地貌单元控制着风化带裂缝的发育程度(图11a—c)。再者,纵向上受风化作用影响较弱的内幕带,其裂缝(以构造裂缝发育为主)的发育程度在一定程度上也受到不同地貌单元的影响,但控制作用明显变弱,裂缝发育程度普遍低于风化带,裂缝线密度基本上小于0.6条/m(图11b)。此外,分析研究区风化带不同走向的裂缝发育程度发现(图11d—f),残丘缓翼的裂缝线密度更高,但规律性不如图11a,这一特征表明,风化带不同古地貌单元对裂缝形成的控制作用要明显强于构造作用对裂缝发育的影响。

4 结论

1) 暴露型潜山风化作用强,古地貌相对高部位裂缝更为发育,古地貌直接控制了风化裂缝的形成与发育,削弱了内幕带储层的岩石力学性质,在一定程度上间接地控制了内幕带裂缝的发育。古地貌对B区块潜山风化带的影响深度存在差异,控制了潜山不同深度带的裂缝形成,B区块古地貌呈现明显的东西区差异,西区风化裂缝带厚度明显大于东区,西区古地貌影响的风化裂缝带深度也大于东区。

2) B区块古地貌与各组系(期次)的裂缝密度呈明显相关性,表明风化带的裂缝不仅受古地貌控制,还与各期构造活动有关。特别是早期的构造活动(印支期)与古地貌共同控制了风化带早期裂缝的形成。

3) B区块发育3大高幅隆脊残丘区,残丘区裂缝最发育,地貌幅度控制着风化带裂缝的发育,对北西向印支期裂缝的控制作用较强;残丘缓翼水-岩反应更充分,风化淋滤作用强,岩石力学强度降低,更易在各种应力作用下产生裂缝,并发生规模溶蚀,利于风化带优质储层的形成。

参 考 文 献

[1] 张巨星,蔡国刚. 辽河油田岩性地层油气藏勘探理论与实践[M]. 北京:石油工业出版社,2007:19-22.
ZHANG Juxing, CAI Guogang. Theory and practice of oil and gas

reservoir exploration in lithologic strata in Liaohe Oilfield [M]. Beijing: Petroleum Industry Press, 2007: 19-22.

[2] CUONG T X, WARREN J K. Bach ho field, a fractured granitic basement reservoir, Cuu Long Basin, offshore se Vietnam: A "buried-hill" play [J]. Journal of Petroleum Geology, 2009, 32 (2): 129-156.

[3] 沈万杰，苏惠，巩磊，等. 东濮凹陷三叠系砂岩潜山油气藏裂缝特征[J]. 断块油气田，2009，16(4)：19-21.
SHEN Wanjie, SU Hui, GONG Lei, et al. Fracture characteristics of buried-hill reservoirs of Triassic sandstone in the North of Dongpu Depression [J]. Fault-Block Oil and Gas Field, 2009, 16(4): 19-21.

[4] 李军生，庞雄奇，宁金华，等. 太古宇潜山油气成藏控制因素分析——以辽河断陷大民屯凹陷法哈牛-曹台地区为例[J]. 油气地质与采收率，2010，17(4)：17-19，23.
LI Junsheng, PANG Xiongqi, NING Jinhua, et al. Analysis of controlling factors on hydrocarbon accumulation in Archaeozoic buried hill——a case study with Fahaniu-Caotai area in Damintun depression of Liaohe rift basin [J]. Petroleum Geology and Recovery Efficiency, 2010, 17(4): 17-19, 23.

[5] 杜振京. 埕岛东部潜山油气成藏分析[J]. 油气地质与采收率，2012，19(4)：31-33.
DU Zhenjing. Analysis of hydrocarbon accumulation of buried hill in east Chengdao area [J]. Petroleum Geology and Recovery Efficiency, 2012, 19(4): 31-33.

[6] 吴伟涛，高先志，李理，等. 渤海湾盆地大型潜山油气藏形成的有利因素[J]. 特种油气藏，2015，22(2)：22-26.
WU Weitao, GAO Xianzhi, LI Li, et al. Favorable conditions formed in large-scale buried-hill reservoir in Bohai Bay Basin [J]. Special Oil & Gas Reservoirs, 2015, 22(2): 22-26.

[7] LI T J. The curve application in the recognition of Archean metamorphic buried-hill rocks in Liaohe depression [J]. Open Journal of Natural Science, 2016, 4(1): 81-91.

[8] 陈少平，刘丽芳，黄胜兵，等. 湖相碳酸盐岩——渤中凹陷油气勘探新领域[J]. 中国海上油气，2019，31(2)：20-28.
CHEN Shaoping, LIU Lifang, HUANG Shengbing, et al. Lacustrine carbonate rock: A new domain of oil and gas exploration in Bozhong sag of Bohai Sea [J]. China Offshore Oil and Gas, 2019, 31(2): 20-28.

[9] 刘国平，董少群，李洪楠，等. 辽河盆地西部凹陷古潜山天然裂缝特征及其影响因素[J]. 石油与天然气地质，2020，41(3)：525-533.
LIU Guoping, DONG Shaoqun, LI Hongnan, et al. Characteristics of natural fractures and their influencing factors in the paleo-buried-hill reservoirs of the western sag in the Liaohe Basin, China [J]. Oil & Gas Geology, 2020, 41(3): 525-533.

[10] 程鑫，周立宏，操应长，等. 黄骅坳陷大港探区下古生界碳酸盐岩潜山差异演化及优质储层成因[J]. 石油与天然气地质，2021，42(3)：673-689.
CHENG Xin, ZHOU Lihong, CAO Yingchang, et al. Differential evolution and origin of high-quality reservoirs in the Lower Paleozoic carbonate buried hills in Dagang prospecting area, Huanghua Depression [J]. Oil & Gas Geology, 2021, 42(3): 673-689.

[11] 时培兵. 渤海湾盆地上太古界潜山储层裂缝特征[D]. 秦皇岛：燕山大学，2017：30-40.
SHI Peibing. The characteristics of Archeozoic buried hill reservoir fractures in the area of Bohai Bay Basin [D]. Qinhuangdao: Yanshan University, 2017: 30-40.

[12] 施和生，王清斌，王军，等. 渤中凹陷深层渤中19-6构造大型凝析气田的发现及勘探意义[J]. 中国石油勘探，2019，24(1)：36-45.
SHI Hesheng, WANG Qingbin, WANG Jun, et al. Discovery and exploration significance of large condensate gas fields in BZ19-6 structure in deep Bozhong sag [J]. China Petroleum Exploration, 2019, 24(1): 36-45.

[13] 宋国民. 渤中凹陷19-6构造区太古界潜山变质岩裂缝型储层特征与控制因素分析[D]. 长春：吉林大学，2021：33-50.
SONG Guomin. Characteristics and control factors of Archean buried-hill metamorphic fractured reservoirs in the BZ19-6 structural region, Bozhong sag [D]. Changchun: Jilin University, 2021: 33-50.

[14] 李威. 渤海湾盆地渤中19-6气田凝析气成因研究[J]. 同济大学学报(自然科学版)，2021，49(3)：458-466.
LI Wei. Origin of condensate gas in Bozhong 19-6 Gas Field in Bohai Bay Basin [J]. Journal of Tongji University (Natural Science), 2021, 49(3): 458-466.

[15] 徐长贵，于海波，王军，等. 渤海海域渤中19-6大型凝析气田形成条件与成藏特征[J]. 石油勘探与开发，2019，46(1)：25-38.
XU Changgui, YU Haibo, WANG Jun, et al. Formation conditions and accumulation characteristics of Bozhong 19-6 large condensate gas field in offshore Bohai Bay Basin [J]. Petroleum Exploration and Development, 2019, 46(1): 25-38.

[16] 薛永安，李慧勇，许鹏，等. 渤海海域中生界覆盖型潜山成藏认识与渤中13-2大油田发现[J]. 中国海上油气，2021，33(1)：13-22.
XUE Yongan, LI Huiyong, XU Peng, et al. Recognition of oil and gas accumulation of Mesozoic covered buried hills in Bohai Sea area and the discovery of BZ 13-2 Oilfield [J]. China Offshore Oil and Gas, 2021, 33(1): 13-22.

[17] 范廷恩，牛涛，范洪军，等. 渤中19-6凝析气田太古宇潜山储层发育主控因素及地质模式[J]. 海洋地质与第四纪地质，2021，41(4)：170-178.
FAN Tingen, NIU Tao, FAN Hongjun, et al. Archaeozoic buried-hill reservoir of Bozhong 19-6 condensate field: Main controlling factors and development model [J]. Marine Geology & Quaternary Geology, 2021, 41(4): 170-178.

[18] 叶涛，牛成民，王清斌，等. 渤海湾盆地大型基岩潜山储层特征及其控制因素——以渤中19-6凝析气田为例[J]. 地质学报，2021，95(6)：1889-1902.
YE Tao, NIU Chengmin, WANG Qingbin, et al. Characteristics and controlling factors of large bedrock buried-hill reservoirs in the Bohai Bay Basin——a case study of the BZ19-6 condensate field

[J]. Acta Geologica Sinica, 2021, 95(6): 1889-1902.

[19] 蒋有录, 叶涛, 张善文, 等. 渤海湾盆地潜山油气富集特征与主控因素[J]. 中国石油大学学报(自然科学版), 2015, 39(3): 20-29.
JIANG Youlu, YE Tao, ZHANG Shanwen, et al. Enrichment characteristics and main controlling factors of hydrocarbon in buried hill of Bohai Bay Basin[J]. Journal of China University of Petroleum (Edition of Natural Science), 2015, 39(3): 20-29.

[20] 侯明才, 曹海洋, 李慧勇, 等. 渤海海域渤中19-6构造带深层潜山储层特征及其控制因素[J]. 天然气工业, 2019, 39(1): 33-44.
HOU Mingcai, CAO Haiyang, LI Huiyong, et al. Characteristics and controlling factors of deep buried-hill reservoirs in the BZ19-6 structural belt, Bohai Sea area[J]. Natural Gas Industry, 2019, 39(1): 33-44.

[21] 谢玉洪. 渤海湾盆地渤中凹陷太古界潜山气藏BZ19-6的气源条件与成藏模式[J]. 石油实验地质, 2020, 42(5): 858-866.
XIE Yuhong. Gas resources and accumulation model of BZ19-6 Archean buried-hill large-scale gas reservoir in Bozhong Sag, Bohai Bay Basin[J]. Petroleum Geology and Experiment, 2020, 42(5): 858-866.

[22] 牛成民, 王飞龙, 何将启, 等. 渤海海域渤中19-6潜山气藏成藏要素匹配及成藏模式[J]. 石油实验地质, 2021, 43(2): 259-267.
NIU Chengmin, WANG Feilong, HE Jiangqi, et al. Accumulation factor matching and model of Bozhong 19-6 buried hill gas reservoir, Bohai Sea area[J]. Petroleum Geology and Experiment, 2021, 43(2): 259-267.

[23] 郑华, 康凯, 刘卫林, 等. 渤海深层变质岩潜山油藏裂缝主控因素及预测[J]. 岩性油气藏, 2022, 34(3): 29-38.
ZHENG Hua, KANG Kai, LIU Weilin, et al. Main controlling factors and prediction of fractures in deep metamorphic buried hill reservoirs in Bohai Sea[J]. Lithologic Reservoirs, 2022, 34(3): 29-38.

[24] 周心怀, 项华, 于水, 等. 渤海锦州南变质岩潜山油藏储集层特征与发育控制因素[J]. 石油勘探与开发, 2005, 32(6): 17-20.
ZHOU Xinhuai, XIANG Hua, YU Shui, et al. Reservoir characteristics and development controlling factors of JZS neo-Archean metamorphic buried hill oil pool in Bohai Sea[J]. Petroleum Exploration and Development, 2005, 32(6): 17-20.

[25] 杨磊. 中苏门答腊盆地石油地质特征与油气勘探潜力[J]. 新疆石油地质, 2011, 32(3): 329-331.
YANG Lei. Petroleum geology and exploration potential analysis in central Sumatra Basin[J]. Xinjiang Petroleum Geology, 2011, 32(3): 329-331.

[26] 董国栋, 张琴, 朱筱敏, 等. 中苏门答腊盆地新生代沉积演化及其油气意义[J]. 重庆科技学院学报(自然科学版), 2013, 15(3): 5-8.
DONG Guodong, ZHANG Qin, ZHU Xiaomin, et al. Cenozoic sedimentary evolution in the central Sumatra basin and its hydrocarbon significance[J]. Journal of Chongqing University of Science and Technology (Natural Sciences Edition), 2013, 15(3): 5-8.

[27] 徐长贵, 杜晓峰, 刘晓健, 等. 渤海海域太古界深埋变质岩潜山优质储集层形成机制与油气勘探意义[J]. 石油与天然气地质, 2020, 41(2): 235-247, 294.
XU Changgui, DU Xiaofeng, LIU Xiaojian, et al. Formation mechanism of high-quality deep buried-hill reservoir of Archaean metamorphic rocks and its significance in petroleum exploration in Bohai Sea area[J]. Oil & Gas Geology, 2020, 41(2): 235-247, 294.

[28] 卢欢, 牛成民, 李慧勇, 等. 变质岩潜山油气藏储层特征及评价[J]. 断块油气田, 2020, 27(1): 28-33.
LU Huan, NIU Chengmin, LI Huiyong, et al. Reservoir feature and evaluation of metamorphic buried-hill reservoir[J]. Fault-Block Oil and Gas Field, 2020, 27(1): 28-33.

[29] DIEN P T, TAI P S, DZUNG L V, et al. Late-Mesozoic and Early Cenozoic events and petroleum system of the Cuu Long Basin[J]. Petro Vietnam Review, 1998, 1: 4-23.

[30] 张银德, 周文, 邓昆, 等. 鄂尔多斯盆地高桥构造平缓地区奥陶系碳酸盐岩岩溶古地貌特征与储层分布[J]. 岩石学报, 2014, 30(3): 757-767.
ZHANG Yinde, ZHOU Wen, DENG Kun, et al. Palaeogeomorphology and reservoir distribution of the Ordovician karstified carbonate rocks in the structurally-gentle Gaoqiao area, Ordos Basin[J]. Acta Petrologica Sinica, 2014, 30(3): 757-767.

[31] 魏新善, 任军峰, 赵俊兴, 等. 鄂尔多斯盆地东部奥陶系风化壳古地貌特征嬗变及地质意义[J]. 石油学报, 2017, 38(9): 999-1009.
WEI Xinshan, REN Junfeng, ZHAO Junxing, et al. Paleo-geomorphologic characteristic evolution and geological significance of the Ordovician weathering crust in eastern Ordos Basin[J]. Acta Petrolei Sinica, 2017, 38(9): 999-1009.

[32] HAN Changcheng, TIAN Jijun, HU Chenlin, et al. Lithofacies characteristics and their controlling effects on reservoirs in buried hills of metamorphic rocks: A case study of Late Paleozoic units in the Aryskum Depression, South Turgay Basin, Kazakhstan[J]. Journal of Petroleum Science and Engineering, 2020, 191: 107137.

[33] SORENSON R P. A dynamic model for the Permian Panhandle and Hugoton fields, western Anadarko Basin[J]. AAPG Bulletin, 2005, 89(7): 921-938.

[34] 季敏, 谭丽娟, 刘斌. 隐蔽油气藏研究的现状和发展趋势[J]. 断块油气田, 2009, 16(4): 45-47.
JI Min, TAN Lijuan, LIU Bin. The research status and development trend of subtle reservoir[J]. Fault-Block Oil & Gas Field, 2009, 16(4): 45-47.

[35] 黄保纲, 汪利兵, 赵春明, 等. JZS油田潜山裂缝储层形成机制及分布预测[J]. 石油与天然气地质, 2011, 32(5): 710-717.
HUANG Baogang, WANG Libing, ZHAO Chunming, et al. Formation mechanism and distribution of fractured buried hill

reservoir in JZS Oilfield[J]. Oil & Gas Geology, 2011, 32(5): 710-717.

[36] 张任风，张占松，张超谟，等. 渤中 19-6 气田潜山变质岩储层类型特征与电成像测井识别[J]. 东北石油大学学报，2019，43(5)：58-65.

ZHANG Renfeng, ZHANG Zhansong, ZHANG Chaomo, et al. Reservoir type characteristics and electrical imaging logging identification of buried-hill metamorphic rock in Bozhong 19-6 Gas Field[J]. Journal of Northeast Petroleum University, 2019, 43(5): 58-65.

[37] BONTER D A, TRICE R. An integrated approach for fractured basement characterization: The Lancaster Field, a case study in the UK[J]. Petroleum Geoscience, 2019, 25(4): 400-414.

[38] KONING T. Giant and major-size oil and gas fields worldwide in basement reservoirs: State-of-the-art and future prospects [J]. Georesources, 2020, (Special issue): 40-48.

[39] 李慧勇，牛成民，许鹏，等. 渤中 13-2 大型整装覆盖型潜山油气田的发现及其油气勘探意义[J]. 天然气工业，2021，41(2)：19-26.

LI Huiyong, NIU Chengmin, XU Peng, et al. Discovery of Bozhong 13-2 Archean large monoblock volatile buried hill oilfield and its oil and gas exploration significance [J]. Natural Gas Industry, 2021, 41(2): 19-26.

[40] 李慧勇，肖述光，李飞，等. 渤海郯庐断裂西支构造特征及对潜山形成的控制作用[J]. 地质科技通报，2021，40(5)：33-41.

LI Huiyong, XIAO Shuguang, LI Fei, et al. Structural characteristics of the western branch of the Tanlu fault in Bohai Sea and its control on the formation of buried hills[J]. Bulletin of Geological Science and Technology, 2021, 40(5): 33-41.

[41] 童凯军，赵春明，吕坐彬，等. 渤海变质岩潜山油藏储集层综合评价与裂缝表征[J]. 石油勘探与开发，2012，39(1)：56-63.

TONG Kaijun, ZHAO Chunming, LYU Zuobin, et al. Reservoir evaluation and fracture characterization of the metamorphic buried hill reservoir in Bohai Bay [J]. Petroleum Exploration and Development, 2012, 39(1): 56-63.

[42] 宋国民，张艳，李慧勇，等. 渤中凹陷 19-6 区太古界潜山变质岩岩石类型及鉴别特征[J]. 世界地质，2020，39(2)：344-352.

SONG Guomin, ZHANG Yan, LI Huiyong, et al. Types and identification characteristics of Archean metamorphic rocks of buried hill in 19-6 area of Bozhong sag [J]. Global Geology, 2020, 39(2): 344-352.

[43] 李慧勇，徐云龙，王飞龙，等. 渤海海域深层潜山油气地球化学特征及油气来源[J]. 天然气工业，2019，39(1)：45-56.

LI Huiyong, XU Yunlong, WANG Feilong, et al. Geochemical characteristics and sources of oil and gas in deep buried hills, Bohai Sea area[J]. Natural Gas Industry, 2019, 39(1): 45-56.

[44] 范洪军，罗江华，牛涛，等. 渤中 19-6 凝析气田太古界潜山储层裂缝特征及低渗主控因素[J]. 中国海上油气，2021，33(4)：85-93.

FAN Hongjun, LUO Jianghua, NIU Tao, et al. Fracture characteristics and low permeability main controlling factors of Archean buried hill reservoirs in BZ19-6 condensate field [J]. China Offshore Oil and Gas, 2021, 33(4): 85-93.

[45] ZABALZA I, LEGRAND N, NEFF P. An integrated history matching approach of a fractured basement reservoir-Block S2, Yemen [C]//Abu Dhabi International Petroleum Conference and Exhibition, Abu Dhabi, 2012. Houston: SPE, 2012: SPE-162398-MS.

[46] 薛永安，王奇，牛成民，等. 渤海海域渤中凹陷渤中 19-6 深层潜山凝析气藏的充注成藏过程[J]. 石油与天然气地质，2020，41(5)：891-902.

XUE Yongan, WANG Qi, NIU Chengmin, et al. Hydrocarbon charging and accumulation of BZ 19-6 gas condensate field in deep buried hills of Bozhong Depression, Bohai Sea [J]. Oil & Gas Geology, 2020, 41(5): 891-902.

[47] 周心怀，张如才，李慧勇，等. 渤海湾盆地渤中凹陷深埋古潜山天然气成藏主控因素探讨[J]. 中国石油大学学报(自然科学版)，2017，41(1)：42-50.

ZHOU Xinhuai, ZHANG Rucai, LI Huiyong, et al. Major controls on natural gas accumulations in deep-buried hills in Bozhong Depression, Bohai Bay Basin [J]. Journal of China University of Petroleum (Edition of Natural Science), 2017, 41(1): 42-50.

[48] 胡安文，牛成民，王德英，等. 渤海湾盆地渤中凹陷渤中 19-6 构造凝析油气特征与形成机制[J]. 石油学报，2020，41(4)：403-411.

HU Anwen, NIU Chengmin, WANG Deying, et al. The characteristics and formation mechanism of condensate oil and gas in Bozhong19-6 structure, Bozhong sag, Bohai Bay Basin [J]. Acta Petrolei Sinica, 2020, 41(4): 403-411.

[49] 周文. 裂缝性油气储集层评价方法[M]. 成都：四川科学技术出版社，1998.

ZHOU Wen. Evaluation methods of fracture reservoir in oil and gas pool[M]. Chengdu: Sichuan Science and Technology Press, 1998.

[50] 肖述光，吕丁友，侯明才，等. 渤海海域西南部中生代构造演化过程与潜山形成机制[J]. 天然气工业，2019，39(5)：34-44.

XIAO Shuguang, LYU Dingyou, HOU Mingcai, et al. Mesozoic tectonic evolution and buried hill formation mechanism in the southwestern Bohai Sea[J]. Natural Gas Industry, 2019, 39(5): 34-44.

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