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玛北地区页岩油压裂缝网分析及评价

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摘要：玛北地区作为中国页岩油开发的新区块，其开发潜力巨大。然而，压裂产生的缝网结构对油井排采效率的影响尚未得到充分研究。因此，精确表征压裂缝网的特征是提升油井产量的关键。本研究通过对玛北地区7口页岩油井焖井后压力数据的监测，应用Bourdet（布德）方法绘制压降特征曲线，以评估缝网形态。进一步结合压裂参数和试产数据，对压裂缝网特征进行了综合评价。研究聚焦于缝网的主裂缝长度、次裂缝宽度、密度和渗透率等关键参数，旨在系统揭示缝网的发育特征。研究表明，玛北地区页岩油的压裂缝网可划分为3类：Ⅰ类缝网，主裂缝长度短、次裂缝宽度中等、缝网密度和渗透率高，压降导数曲线呈现偏左下的“深V型”特征，表明该类缝网以导流能力为主导，能够有效提高油井排采效率；Ⅱ类缝网，主裂缝长度中等、次裂缝宽度宽、缝网密度中等、渗透率小，压降导数曲线呈现偏右上的“浅V型”特征，表明该类缝网以储集能力为主，尽管导流能力相对较弱，但仍具有一定的开发潜力；Ⅲ类缝网，主裂缝长度长、次裂缝宽度窄、缝网密度小、渗透率中等，整体缝网欠发育，其焖井压降导数曲线形态特征不明显，表明该类缝网在生产过程中见油晚，不利于油井高效开发。研究还揭示了一个重要规律：在破裂压力低的井中，若其他压裂条件相同，过高的每米加砂量易导致Ⅲ类缝网的形成。因此，为提高玛北地区页岩油开发效率，后续压裂设计中应着力避免形成Ⅲ类缝网。具体措施包括优化压裂参数（如合理控制每米加砂量），以提升缝网的导流与储集能力，最终实现页岩油的高效开发。

关键词：玛北地区页岩油；焖井；压降曲线；压裂缝网；压降导数
中图分类号：TE353　　**文献标识码：**A

Analysis and evaluation of shale oil fracture network in Mabei area

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Abstract: As a new block for shale oil development in China, Mabei area has huge development potential. However, the impact of fracture network structures generated by hydraulic fracturing on oil well drainage efficiency has not been fully studied. Therefore, accurately characterizing fracture networks is crucial for improving oil well production. This study monitored the pressure data after shut-in of 7 shale oil wells in Mabei area and used the Bourdet method to plot pressure drop characteristic curves to evaluate the fracture network morphology. By integrating fracturing parameters and production test data, this study aims to provide a scientific basis for the efficient development of shale oil in this area. The study selected seven wells of shale oil in the Mabei area as research subjects. Initially, detailed monitoring of shut-in pressure data from these wells was conducted. Subsequently, pressure drop characteristic curves were plotted using the Bourdet method, which effectively reflects the morphology and characteristics of fracture networks. By analyzing the morphology and characteristics of the pressure drop derivative curves, combined with fracturing parameters (such as breakdown pressure and sand volume per meter) and production test data (such as oil breakthrough time and production rates), a comprehensive evaluation of fracture network characteristics was performed. The study focused on key parameters such as main fracture length, secondary fracture width, density, and permeability, aiming to systematically reveal the development characteristics of fracture networks. The results showed that fracture networks of shale oil in Mabei area could be classified into three types. Type I fracture networks had short main fracture lengths, medium secondary fracture widths, high density, and high permeability. The pressure drop derivative curves showed deep V-shaped characteristics leaning to lower left, indicating that this type of fractured network was dominated by conductivity and could effectively improve oil well drainage efficiency. Type Ⅱ fracture networks had medium main fracture lengths, wide secondary fracture widths, medium density, and

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low permeability. The pressure drop derivative curves showed shallow V-shaped characteristics leaning to upper right, indicating that this type of fractured network was mainly storage-oriented. Although their conductivity was relatively weak, they still held certain development potential. Type Ⅲ fracture networks, characterized by long main fracture lengths, narrow secondary fracture widths, low density, and medium permeability, were overall underdeveloped. Their shut-in pressure drop derivative curves lacked distinct morphological characteristics, indicating that this type of fractured network had late oil breakthrough during the production process and was unfavorable for efficient oil well development. The study also revealed an important pattern. In wells with low breakdown pressure, under the same fracturing conditions, excessively high sand volume per meter tended to lead to the formation of Type Ⅲ fracture networks. Therefore, to improve shale oil development efficiency in Mabei area, subsequent fracturing designs should focus on avoiding the formation of Type Ⅲ fracture networks. Specific measures include optimizing fracturing parameters, such as reasonably controlling sand volume per meter, to enhance the conductivity and storage capacity of fracture networks, thereby achieving efficient shale oil development. In conclusion, this study provides valuable insights into the characteristics of fracture networks in the Mabei shale oil area and offers practical recommendations for optimizing hydraulic fracturing operations to maximize well productivity. Future research can expand the sample size and incorporate numerical simulations and field experiments to further validate these findings and refine the strategies for efficient shale oil development.

Keywords: shale oil in Mabei area; shut-in; pressure drop curve; fracture network; pressure drop derivative

随着油气勘探开发的深入,页岩油等非常规油气资源已占中国累计探明储量的41%,逐渐转变为“新常规”,持续延长石油工业的生命周期[1-3]。相比于常规油气藏,页岩油藏具有自生自储、储层致密、自然产能低的特点[4-6],通常采用“大斜度井+大规模水力压裂”的方式开发[7-11]。玛北地区位于中国准噶尔盆地玛湖凹陷北部,是一个新页岩油区块,其烃源岩以二叠系风城组碱湖优质烃源岩为主[12],埋藏深度普遍大于4 500 m,储层厚度介于200～800 m。相较于中国其他页岩油区块,该区块具有埋藏深、厚度大、储层压实作用强的显著特征[13-14]。区内压力系数介于1.2～2.0,属异常高压层系;孔隙度小于5%,渗透率小于$0.1\times10^{-3}\ \mu m^2$,属于典型的低孔低渗储层;岩性复杂多样,以云质泥岩和云质粉砂岩为主,表现出强烈的非均质性[15-16]。

玛北地区页岩油井长期排采跟踪数据显示:相邻井压裂后焖井一段时间,其初期的排采特征存在显著差异。根据前人对页岩油的研究[17-20],在压裂后焖井过程中,页岩储层内的润湿相流体在毛管力作用下,沿岩石内部缝网进入微小孔隙,并将孔隙中的原油置换出来,从而使油从微小孔隙转移至大孔隙或缝网中。缝网作为页岩油主要运移通道,对排采动态具有重要影响。目前,关于玛北地区页岩油井初期排采特征、缝网形态与压裂参数之间的关系,尚未开展系统性研究,厘清其关系对于提升该区油气产量至关重要。

近年来,诸多学者针对裂缝网络(缝网)形态开展了深入研究。刘博等[21]提出了基于微地震监测技术的分析方法,通过融合微地震数据与压裂施工数据等信息进行缝网表征;闫鑫等[22]提出地表测斜仪技术,并基于复杂缝网模型,采用模拟退火方法反演获取缝网参数;唐慧莹等[23]利用有限元中的内聚力模型对现场压裂井裂缝形态进行模拟;李海涛等[24]基于MCMC(马尔科夫链蒙特卡洛)算法建立了DTS(数据传输服务)反演模型,对各级有效人工裂缝进行模拟。以上方法虽然能对缝网进行分析,但操作复杂且数据处理困难,难以有效诊断次裂缝的特征。王飞等[25]根据页岩油焖井压降变化与缝网的相关性,通过数值模拟建立了主、次裂缝特性参数与焖井压降特征曲线的对应关系,该方法兼具高效性与便捷性,仅需分析压裂后焖井压降数据。本研究选用玛北地区页岩油缝网进行分析。为控制变量、避免结果分析过于复杂,施工过程中严格控制其他工程参数,仅改变每米加砂量这一变量。在此基础上,探讨缝网形态与每米加砂量、初期排采特征的关系,旨在筛选出更具开发效益的缝网形态,为后期玛北地区页岩油的高效开采提供理论依据与工程指导。

1 焖井压力分析

玛北地区目前已完成7口页岩油井的压裂后焖井监测,并对其焖井压力数据进行分析,压力曲线形态显示:X208X井、M56X井、M48H井和M57H井焖井前期压力快速下降,后期下降趋势逐渐变缓,呈现“L型”;M51X井、M54X井焖井前期压力呈“L型”,后期压力缓慢上升;M55H井焖井前期压力快速下降,后期压力先快速上升,后缓慢上升(图1)。焖井主要目的是利用岩石能够自发渗吸纳压裂液,达到补能的作用,压力的变化反映主裂缝、次裂缝和基质的关联。王飞等[25]模拟出焖井过程中压降与主裂缝、次裂缝和基质的关系,随着焖井时间增加,主裂缝、次裂缝泄压,基质增能。焖井前期压降快,反映在压裂沟通主裂缝并快速泄压;焖井中期主裂缝压降趋于稳定,次裂缝泄压,压降幅度变缓;焖井后期,主、次裂缝压降趋于稳定,压降幅度基本不变。这一理论模型描述的压降过程整体呈现“L型”。除M55H井外,其余各

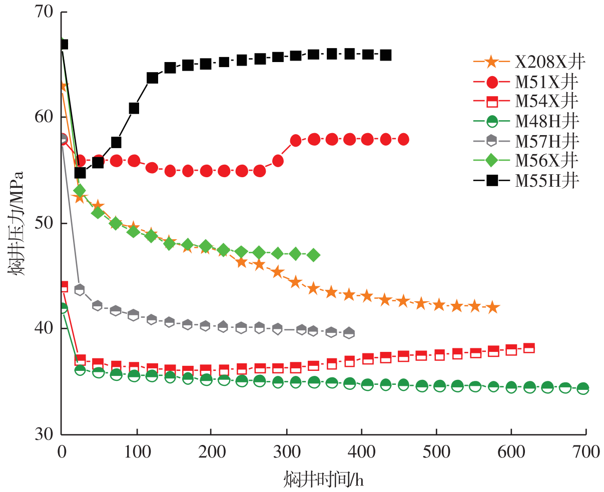
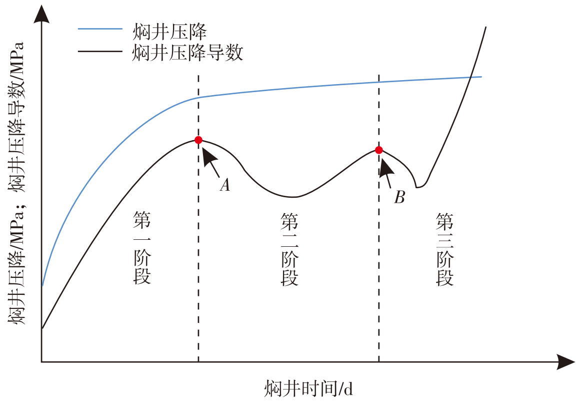


图1　玛北地区7口页岩油井焖井期间压力变化监测

Fig. 1　Pressure change monitoring during shut-in of 7 shale oil wells in Mabei area



注：*A*为压降导数曲线第一个波峰对应值；*B*为压降导数曲线第二个波峰对应值。

图2　焖井压降和压降导数双对数曲线示意图

Fig. 2　Schematic diagram of double logarithmic curves of shut-in pressure drop and pressure drop derivative

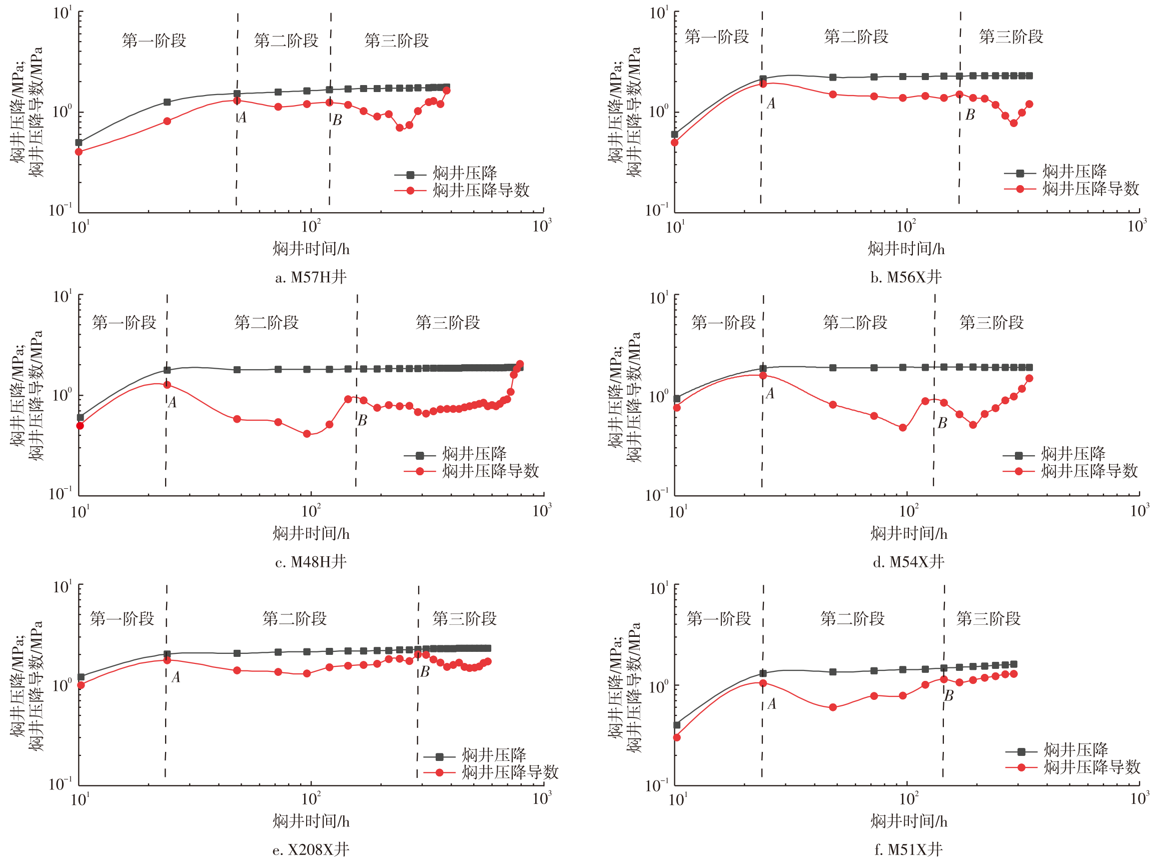
井压降过程均经历了理论模型描述的3个阶段，符合主裂缝、次裂缝和基质中的压降变化。其中，M51X井、M54X井、M55H井焖井后期压力上升，考虑可能与焖井过程中页岩油进入井筒有关。由于页岩油储层低孔低渗，具有很高的毛管力，焖井后期在毛管力的作用下，基质进行自发渗吸，渗吸的压裂液将储层中的原油驱替至裂缝网络中，随后又进入到井筒中。由于监测压力是监测井筒内的压力变化（监测压力=储层压力-液柱压力），受井筒内液柱压力变化的影响。根据3口井开井短时间内见纯油且无明水，而后才开始恢复正常，排出压裂液和油，判断焖井过程中原油可能进入井筒，导致井筒液柱压力降低，监测压力升高。

2　压裂缝网特征

页岩油焖井压降曲线是反映井筒-主次裂缝网格-基质系统的压力-流量连续性耦合关系的特征曲线。王飞等[25]根据一口典型页岩油压裂水平井压后焖井情况，模拟出焖井过程中主裂缝、次裂缝和基质中的压降动态。压降过程中储层整体呈现主、次裂缝泄压，基质增能趋势，对应压降及导数曲线不同阶段（图2）。通过对主缝半长、导流能力、次裂缝缝网密度、渗透率、缝宽和基质含油性单因素敏感性模拟，识别了不同焖井压降曲线特征，该缝网诊断方法适用此次研究。

根据焖井压降数据，采用BOURDET等[26]所定义的压降和压降导数绘制出压降特征曲线。由于M55H井压降时间短，因此对其余6口井焖井压降特征曲线进行分析。6口井的压降导数曲线整体呈现“W型”，具有完整的3个阶段（图3）。第一阶段反映主裂缝的变化，压降速度快，为焖井早期，该阶段压降导数形态与主裂缝长度相关，主裂缝长度越长该阶段压降导数曲线持续时间越长，结束时刻*A*点值越大[24]。从图4中可以看出，M57H井第一阶段持续时间最长，反映M57H井主裂缝长度最长，其余井持续时间相同情况下，根据*A*点值大小，对应主裂缝长度关系为M57H井>M56X井>X208X井>M54X井>M48H井>M51X井。第二阶段反映次裂缝的变化，压降速度减缓，为焖井中期，该阶段压降导数形态与次裂缝缝网密度、宽度和渗透率有关。次裂缝缝网密度越大，第二阶段“V型”越深；次裂缝渗透率越大，第二阶段“V型”出现得越早，结束时刻*B*点值越小；次裂缝宽度越小，“V型”越窄，持续时间越短。根据第二阶段“V型”深度，对应次裂缝缝网密度大小关系为M54X井>M48H井>M51X井>M56X井>X208X井>M57H井；根据第二阶段“V型”出现的时间和*B*点值，对应次裂缝渗透率大小关系为M54X井>M48H井>M51X井>M57H井>M56X井>X208X井；根据第二阶段“V型”宽度、持续时间，对应次裂缝宽度大小关系为X208X井>M56X井>M48H井>M51X井>M54X井>M57H井。第三阶段由基质控制，压降速度缓慢，为焖井晚期，含油性较低时，特征曲线整体向上倾斜，呈现斜“Z型”。第三阶段过程中，M57H井、M48H井压降导数明显向上倾斜，整体呈现“Z型”，反映含油性差，其余井第三阶段未出现“Z型”，但曲线倾斜度呈现M54X井>M56X井>X208X井>M51X井的关系，对应其含油性的大小。

综合分析表明，研究井的缝网主要分为3类。Ⅰ类具有主裂缝长度短，次裂缝宽度中等、缝网密度和渗透率大，压降导数曲线呈现整体偏左下的“深V型”特征，以缝网导流能力为主[27-28]，代表井为M54X井、M48H井、M51X井；Ⅱ类具有主裂缝长度中等，次裂缝宽度宽、缝网密度中等、渗透率小，压降导数曲线呈现整体偏上的“浅V型”特征，以缝网储集能力占主导，代表井为M56X井、X208X井；Ⅲ



a. M57H井

b. M56X井

c. M48H井

d. M54X井

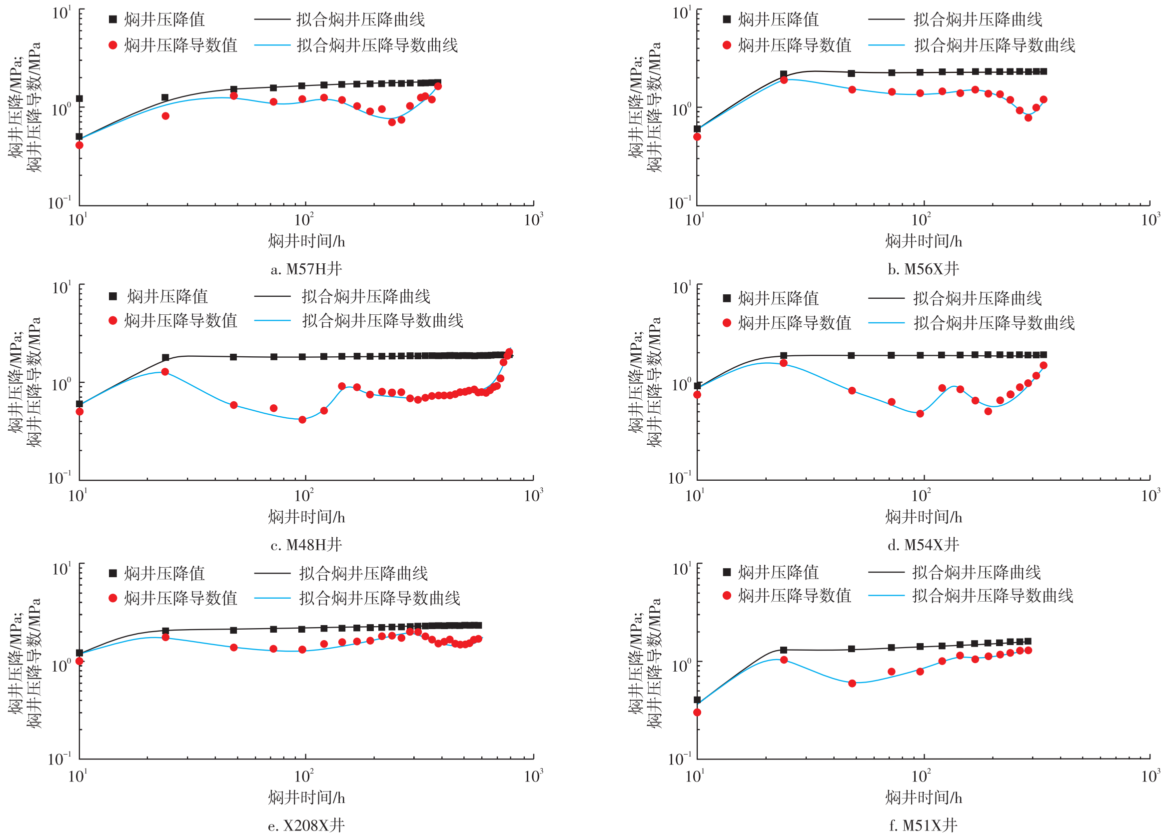
e. X208X井

f. M51X井

注:*A*为焖井压降导数曲线第一个波峰对应值;*B*为焖井压降导数曲线第二个波峰对应值。

图3　玛北地区6口页岩油井焖井压降特征曲线

Fig. 3　Characteristic curves of shut-in pressure drop of 6 shale oil wells in Mabei area



a. M57H井

b. M56X井

c. M48H井

d. M54X井

e. X208X井

f. M51X井

图4　玛北地区6口页岩油井焖井压降特征曲线拟合结果

Fig. 4　Fitting results of characteristic curves of shut-in pressure drop of 6 shale oil wells in Mabei area

型具有主裂缝长度长,次裂缝宽度窄、缝网密度小和渗透率中等的特征,属于缝网欠发育型,代表井为M57H井。

基于以上定性分析,根据王飞等[25]建立的物理和数学模型,通过MaFraUst软件对压降特征曲线进行拟合,反演计算压裂缝网参数。具体的拟合步骤为:输入储集层基本物性参数;设置不同裂缝特征参数组合,进行压后焖井数值模拟;将模拟所得的焖井压降曲线与实际压降曲线进行对比,通过反复调整参数并重新模拟,直至模拟曲线与实际曲线吻合良好,即完成拟合。各井的焖井压降特征曲线拟合结果见图4。缝网参数反演结果为:Ⅰ类缝网的主裂缝半长介于66～83 m,次裂缝缝网密度介于8.61～9.03 m^{-2},次缝缝宽介于0.77～0.83 cm,次缝渗透率介于(0.11～0.23)$\times 10^{-3}$ μm^2;Ⅱ类缝网的主裂缝半长介于84～87 m,次裂缝缝网密度介于8.57～8.60 m^{-2},次缝缝宽介于0.83～0.86 cm,次缝渗透率介于(0.065～0.075)$\times 10^{-3}$ μm^2;Ⅲ类缝网的主裂缝半长为116 m,次裂缝缝网密度为8.42 m^{-2},次缝缝宽为0.80 cm,次裂缝渗透率为0.095$\times 10^{-3}$ μm^2。

3　压裂缝网评价

通过压降导数曲线对缝网形态进行分析,并结合前期压裂施工参数与后期排采参数对缝网进行评价(表1)。压裂施工期间,所有井均采用2500型压裂车,泵注排量介于6.7～16.4 m^3/min。分析表明:Ⅰ类缝网井具有中等加砂量,高破裂压力的特征;Ⅱ类缝网井具有低加砂量,中等破裂压力的特征;Ⅲ类缝网井具有高加砂量,低破裂压力的特征。后期排采过程中,Ⅰ类和Ⅱ类缝网井见油时间快,见油时返排率低,Ⅲ类缝网见油时间长,见油时返排率高。综上所述,Ⅲ类缝网井见油慢,开发效果相对较差,生产中需谨慎控制此类缝网的形成。此次研究展现缝网形态与破裂压力、加砂量具有一定关联。然而,破裂压力受岩石脆性、孔隙压力、天然裂缝发育情况及地应力等多种因素影响[29-30]。由于缺乏研究井相关的地质力学参数(岩石脆性、孔隙压力、裂缝以及地应力等)资料,因此未对此进入深入探讨。

表1　缝网特征评价

Table 1　Evaluation of fracture network characteristics

井号	缝网类型	压裂车型	泵排/(m^3/min)	加砂量/(m^3/m)	破裂压力/MPa	见油时间/d	见油返排率/%
M54X	Ⅰ类	2500型	7.0～16.1	25.43	106.38	1	0.12
M48H		2500型	6.7～16.4	25.96	107.59	3	0.47
M51X		2500型	7.4～16.0	25.86	106.92	1	0.03
X208X	Ⅱ类	2500型	7.5～16.3	23.24	100.12	1	0.29
M56X		2500型	7.3～16.0	23.89	100.08	1	0.05
M57H	Ⅲ类	2500型	8.0～16.2	32.98	96.45	13	1.98

4　结论

1)玛北地区页岩油压裂后焖井阶段,井底压力压降过程主要整体呈现“L型”特征,可分为3个阶段。其中,M51X井、M54X井、M55H井在焖井后期出现的压力上升现象,主要与基质渗吸和油水置换有关。

2)研究区内6口井的压降导数曲线整体呈现“W型”,基于压降导数曲线形态进行分析,将研究区缝网划分为3类。Ⅰ类具有主裂缝长度短,次裂缝宽度中等、缝网密度和渗透率大,压降导数曲线呈现整体偏左下的“深V型”特征,属于以缝网导流能力为主的缝网,代表井为M54X井、M48H井、M51X井;Ⅱ类具有主裂缝长度中等,次裂缝宽度宽、缝网密度中等、渗透率小,压降导数曲线呈现整体偏上的“浅V型”特征,属于以缝网储集能力占主导的缝网,代表井为M56X井、X208X井;Ⅲ类具有主裂缝长度长,次裂缝宽度窄、密度小、渗透率中等的特点,属于缝网欠发育,代表井为M57H井。

3)缝网类型受压裂施工参数影响显著,破裂压力低的井,压裂过程中每米加砂量大,易形成Ⅲ类缝网。然而,Ⅲ类缝网油井见油时间长,见油后返排率高,不利于实现油井高效排采。

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