

含裂缝的硬脆性泥页岩理化及力学特性研究

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[摘要] 硬脆性泥页岩的理化及力学特征对深入研究深部地层泥页岩井壁稳定机理、裂缝性泥页岩漏失等问题具有至关重要的意义。采用泥浆化学、微观结构扫描及岩石力学试验手段, 对某工区易失稳泥页岩地层的理化及力学特性进行了系统的研究和分析。结果表明, 该工区泥页岩属于硬脆性泥页岩, 粘土矿物以伊利石为主, 基本不含蒙脱石, 具有低膨胀易分散的特性, 微观结构显示微裂缝发育; 流体浸泡导致裂缝扩展延伸, 降低了泥页岩的强度, 随着时间的增加, 强度降低得越显著。

[关键词] 硬脆性泥页岩; 裂缝; 岩石力学特性; 水敏性

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泥页岩井壁稳定一直是困扰石油勘探开发的一大难点问题, 目前随着我国页岩气资源勘探开发战略步伐的加快, 研究人员更加关注泥页岩基本物理力学特性的研究, 因为页岩气勘探开发过程中遇到的泥页岩井壁稳定问题、裂缝性泥页岩漏失问题、页岩气评价及开发问题, 都与泥页岩在赋存的地质环境、地层流体分布情况、地应力及工程因素条件下泥页岩所表现出的物理力学性能有着密不可分的关系。虽然针对泥页岩的力学特性研究成果并不鲜见^[1~5], 但是对含裂缝的硬脆性泥页岩的力学规律研究还不多, 仍是该领域研究的难点。笔者重点开展了某地区深部硬脆性泥页岩的理化特性分析, 及含裂缝的硬脆性泥页岩力学特性及破坏模式的规律性认识分析, 丰富了相关领域的研究。

1 泥页岩组构及理化特性分析

泥页岩本身的矿物组成、结构构造以及理化特征是泥页岩力学及化学性能至关重要的控制因素, 因此, 准确地测定分析泥页岩的成分、结构、理化性能, 探讨它们的相互关系, 对于研究泥页岩地层的失稳机理具有重要的意义。

1.1 泥页岩组构分析

开展了某工区易垮塌层位的泥页岩全岩试验及粘土矿物 X 射线衍射试验, 结果表明该区域泥页岩非粘土矿物以石英为主, 斜长石、方解石次之, 含少量白云岩及菱铁矿。粘土矿物总量 50% 左右, 相差不大。粘土矿物以伊利石为主, 伊/蒙间层次之, 含高岭石及绿泥石, 伊/蒙间层粘土的间层比较低 (5%~20%), 各层间粘土矿物组成相差不大。工区泥页岩的平均岩石成分比例及粘土矿物含量比例见图 1。

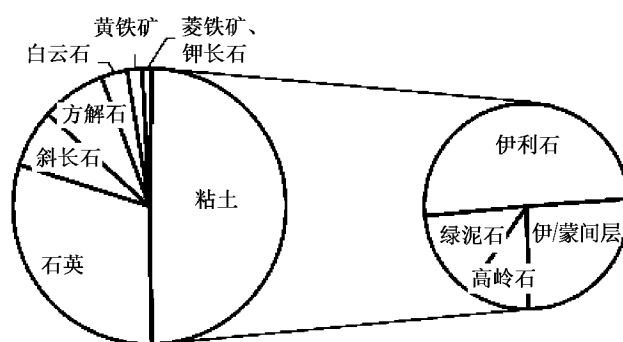


图 1 岩石成分比例及粘土矿物含量比例示意

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进一步开展了泥页岩的微观结构分析，以揭示粘土矿物晶体的排列方式及胶结结构。对研究工区泥页岩岩心制作切片进行电镜扫描，从电镜扫描结果图 2 和图 3 可以看出，研究工区的泥页岩表面有较多微裂缝和微孔，填充物为片状粘土矿物，局部发育溶蚀孔隙，孔隙中有不溶残余物。图 3 结果为岩样用现场井浆浸泡 3d 后开展的电镜扫描试验结果，可以发现，岩石表面微缝呈片状定向分布。由于硬脆性泥岩主要由伊利石和间层粘土矿物组成，其中的蒙脱石以与间层粘土矿物伴生的形式存在，很少含膨胀层粘土矿物，其地层的泥岩压实程度较高，水平层理、微裂隙发育。这种成层特性及微观构造，一方面，使泥页岩在外力的作用下极易沿微裂缝或层理面破坏，造成井壁失稳，如泥页岩微裂隙发育或构造应力集中的话，也易发生硬脆性泥页岩的破裂和剥落导致井壁失稳；另一方面，在该区钻井过程中，钻井滤液沿微裂缝或节理面侵入地层深部后，虽然不会迅速发生膨胀和变软，但往往加剧泥页岩的水化和分散，扩大泥页岩水化面积，降低了泥页岩的结合强度和层理面之间的结合力，使泥页岩沿层理面或微裂隙裂开，进一步造成井壁失稳。一旦钻井液滤失量偏高时，就很容易发生井壁掉块、坍塌等井内复杂情况。

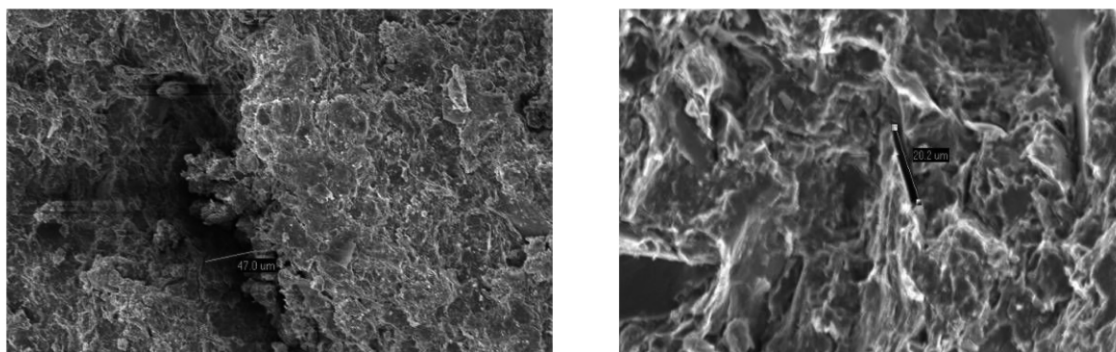


图 2 深度 3658. 68m 泥页岩电镜扫描结果

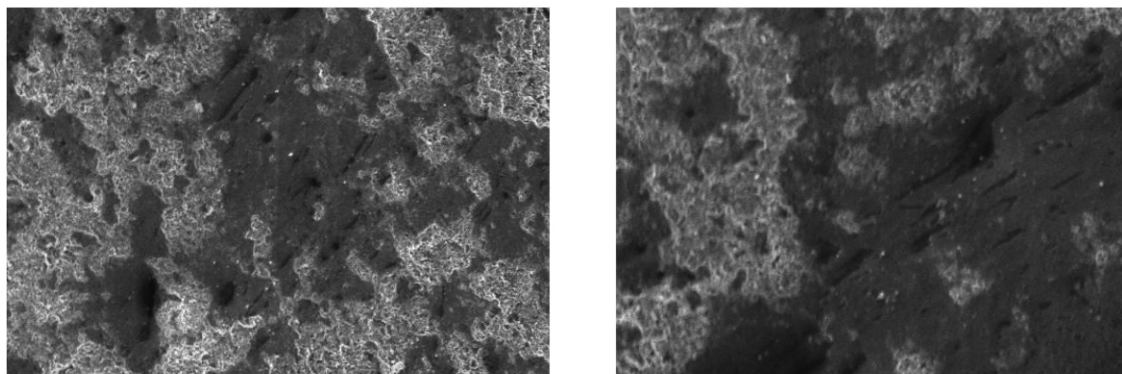


图 3 深度 3947. 29m 泥页岩钻井液浸泡后电镜扫描结果

1.2 泥页岩膨胀分散试验特性

开展了泥页岩水化膨胀试验，发现该地区泥页岩线性膨胀率在 4.18%~6.78% 之间，且随着井深的增加而呈降低趋势，表明其膨胀性粘土矿物含量逐渐较少，属于定向弱膨胀泥页岩。通过滚动回收试验对工区的泥页岩开展水化分散能力测试，发现泥页岩分散性较强，回收率平均在 38.26% 左右，岩屑容易分散，回收率较低。综合而言，该地区泥页岩属于弱膨胀易分散的泥页岩类型。

2 流体浸泡条件下的力学特性

为了探索硬脆性泥页岩的失稳规律,开展了井下 3948.5m 处的泥页岩岩心在流体浸泡条件下的力学特性试验,以研究不同流体浸泡条件下的岩石力学参数,测试结果见表 1。试验中对岩心浸泡前后的裂缝分布及岩心质量变化情况进行了记录。浸泡前后岩心质量变化不大,最大未达到 0.2%,这是由于该泥页岩基本不含蒙脱石因而吸水性不强的缘故;也发现质量增加的程度和岩石本身裂缝的发育程度相关,如 9 号和 21 号岩心的裂缝最为发育,浸泡前后质量增幅相对明显。

表 1 浸泡前后岩石试验参数

编号	围压 /MPa	弹性模量 /GPa	泊松比	抗压强度 /MPa	浸泡温度 /℃	浸泡时间 /d	岩心描述	岩心质量 变化/%
1	30	36.77	0.21	186.13	120	3	前 表观完整 后 表观完整	—
5	30	30.86	0.24	141.26	120	6	前 3 组纵向半贯通缝 后 3 组半贯通缝 > (2/3) 岩心高度	0.001
7	50	31.35	0.24	197.82	120		前 2 组纵向半贯通缝 后 2 组半贯通缝 > (2/3) 岩心高度	0.006
4	30	31.54	0.27	112.65	120	18	前 完整 后 纵向出现 4 组裂缝	0.07
6	50	29.44	0.26	162.99	120		前 端面缝 1 条 后 纵向出现 4 组裂缝	0.07
9	30	裂缝过于发育贯通,加载轴压时未能记录应力应变数据就发生了破坏			室温	19	前 7 组半贯通缝、单缝 后 9 组显著贯通竖缝	0.17
21	30	30.46	0.22	68.85	室温	5	3/4 岩心高度的贯通竖缝	0.12

试验同时对于岩心裂缝浸泡前后的变化情况进行了记录,可以发现随着时间的推移,泥页岩裂缝呈增加的趋势,原本表观完整的岩心(如 4 号岩心),在浸泡一段时间后,内部微裂缝出现了发育和延展,浸泡后岩心表观甚至可见裂缝。不同裂缝系统中,9 号及 21 号岩心的强度最低,结果表明岩心裂缝越发育,贯穿深度越大,裂缝系统对其强度影响越显著。另外,对 21 号岩心浸泡前后开展了层析 CT 扫描分析,该扫描技术从微观角度高精度地描述了裂缝形态及

流体在裂缝孔隙的分布形式,保持了岩心的完整性,使后续进行岩石力学试验成为可能,同时克服了常规电镜扫描对岩心进行切片的破坏性试验,保证了岩心的唯一特性。由图 4 可以发现,岩心浸泡后裂缝吸水现象显著,裂缝缝宽增大,裂缝缝面的粗糙度则会发生降低。

从图 4 可以发现,流体浸泡后,岩心内部出现不同程度的裂缝水浸、扩展。这是由于工作液的侵

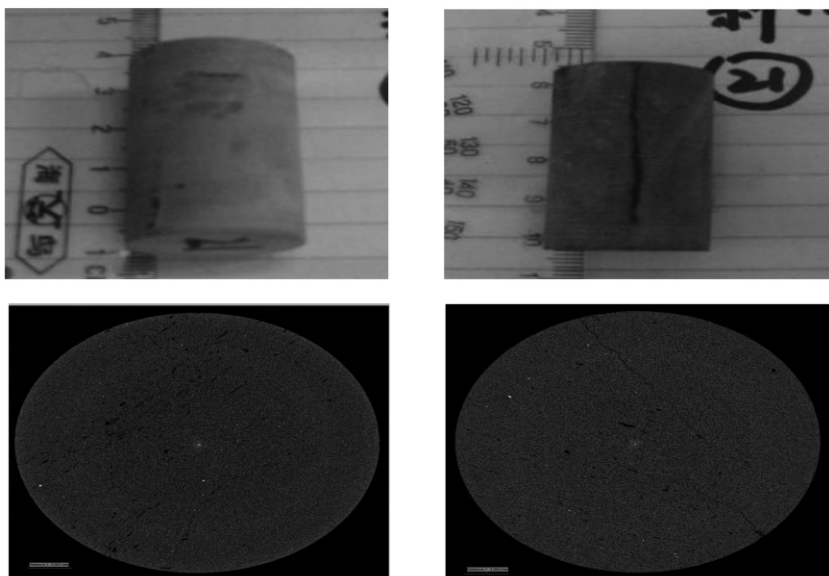


图 4 21 号岩心浸泡前(左)后(右)的岩心表观裂缝及 CT 扫描结果

入、溶蚀和冲刷硬脆性泥页岩结构弱面中的粘土矿物，降低了裂缝弱面的表面摩擦强度，导致内部微裂缝和主裂缝的贯通，这也往往造成钻井过程中含结构面井壁围岩强度的降低，带来钻井过程中井壁垮塌危险，甚至伴生阻卡和卡钻事故复杂情况。

试验发现岩心破坏模式受裂缝系统的影响也有特点。图 5~8 中，实线和虚线均代表浸泡后岩心表面裂缝分布，其中虚线表示导致岩心最终发生破坏的裂缝。其中 4、5、6、9 号岩心受纵向贯通缝存在的影响发生了劈裂破坏，在不同组合的裂缝系统中，纵向延伸至岩心试件端面的裂缝往往对岩心的破坏形式起着决定性的影响。9 号岩心由于浸泡时间较长，裂缝过于发育，在没有记录下数据时就发生了破坏。7 号岩心则发生了明显的剪切破坏和表面裂缝引起的剥落掉块的复合破坏模式。1 号岩心结构完整，发生了整体式的劈裂破坏。

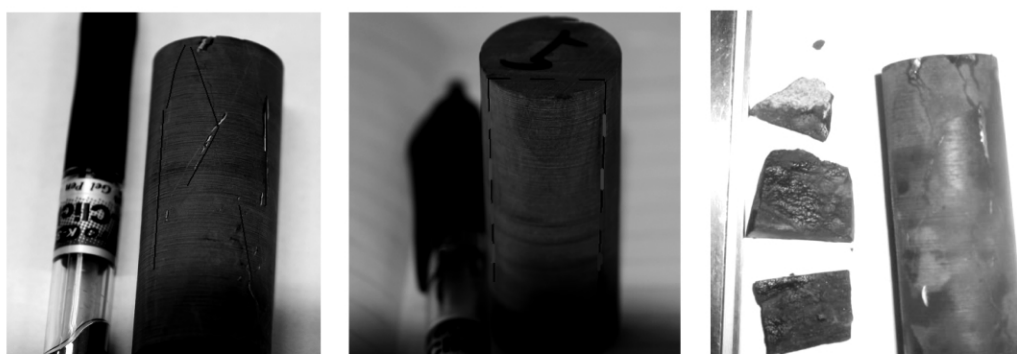


图 5 5 号岩心清水浸泡后裂缝分布及破坏模式

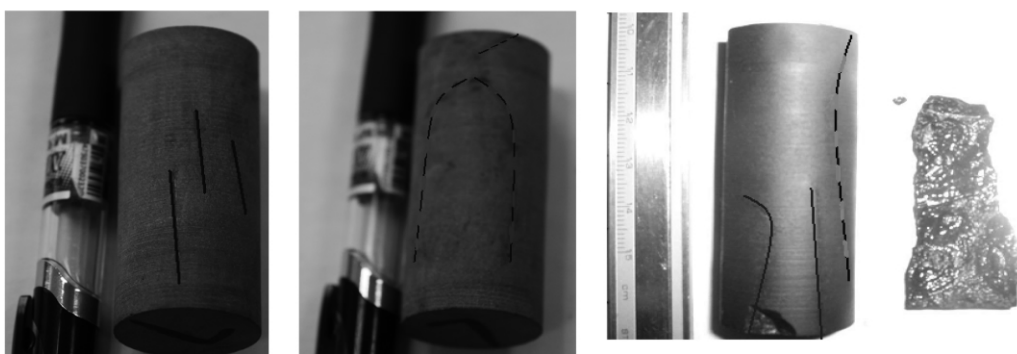


图 6 7 号岩心清水浸泡后裂缝分布及破坏模式

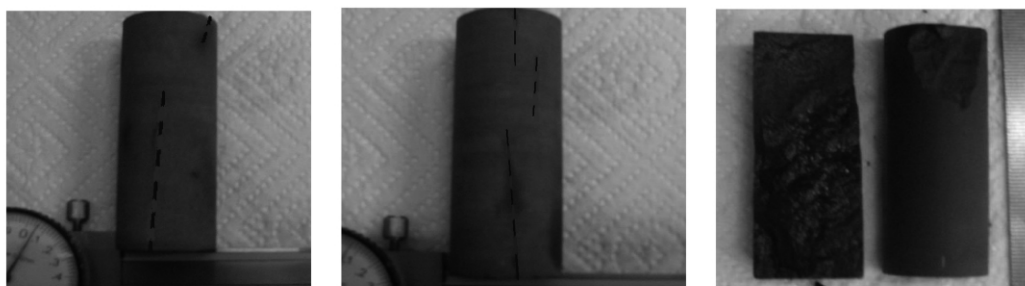


图 7 4 号岩心清水浸泡后裂缝分布及破坏模式

通过分析泥页岩抗压强度变化规律（图 9）、破坏模式及层析 CT 扫描结果，可以发现：①随着浸泡时间的增加，泥页岩的微裂缝扩展发育，同时流体侵入也润滑了结构面，双重影响导致含裂缝的硬脆



图 8 9 号岩心浸泡 19d 后的岩心裂缝分布及破坏模式

性泥页岩强度发生一定程度的降低。②岩石的破坏形式受岩石本身所含裂缝的影响,多以沿最不利的裂缝弱面发生劈裂破坏为主。当岩心含有多组裂缝时,其中贯通程度最显著,尤其是贯通长度大的一组裂缝对岩心的破坏模式起控制作用。发生整体式崩落破坏及剪切破坏的 1 号和 7 号岩心,其抗压强度高于含有贯穿至端面的裂缝岩心的抗压强度。③当岩心含有延伸至端面的裂缝时,破坏往往沿着这类裂缝而发生,对贯通裂缝在岩心端面投影情况的统计发现:当裂缝分布在靠近岩心轴心的范围内

时,该类裂缝岩心的强度比完整岩心的强度明显降低;而裂缝分布在靠近岩心试件圆柱表面时,该类裂缝岩心的强度与裂缝分布在靠近岩心轴心范围内的岩心相比,前者强度降低的程度比后者要小,如裂缝靠近岩心轴心范围分布的 4 号岩心(抗压强度 112.65MPa)与裂缝靠近柱面分布的 5 号岩心(抗压强度 141.26MPa)的抗压强度相比,4 号强度降低得更为明显。

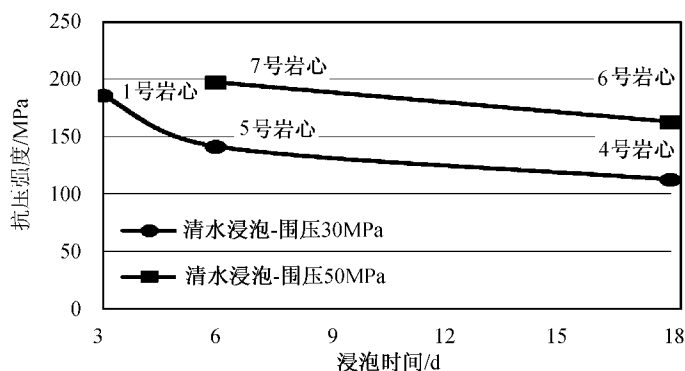


图 9 浸泡条件下的泥页岩抗压强度变化曲线

3 结 论

- 1) 研究工区的硬脆性泥页岩粘土矿物以伊利石为主,基本不含蒙脱石,具有低膨胀易分散的水化特性。
- 2) 通过岩石力学室内试验发现,工作液沿裂缝侵入是导致泥页岩强度降低的根本原因。
- 3) 含裂缝系统的泥页岩较少发生整体式劈裂或剪切破坏,而是容易沿着其中一组最不利的裂缝发生破坏,裂缝面在岩心端面的投影越靠近轴心,其对岩心整体强度的影响越显著。
- 4) 对于硬脆性泥页岩地层的钻井施工,需要考虑泥页岩力学特性的时空效应,合理地确定安全泥浆密度窗口,同时提高钻井液的裂缝封堵能力以改善井筒流体侵入的不利影响,将有利于井筒的稳定。

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98 Palaeobathymetric Reconstruction Based on Natural Gamma Ray Spectrometry Logging Data

—By Taking Bachu Formation in Region 4 of Tahe Oilfield for Example

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Abstract: Paleobathymetric reconstruction was one of the important foundations of basin analysis, sequence stratigraphic study as well as paleogeomorphology recovery. Based on geochemical characteristics and rules of migration and accumulation of Th, U, K, a semi-quantitative method with 4 steps was introduced to restore paleo-depth of water and checking. The method was used in Block 4 of Tahe Oilfield for example. Log analysis shows that there is hardly any oxygen of water in the second and third members of Bachu Formation, and the latter one corresponds to the condensate section which has the strongest reductibility. The upper mudstone (II) is deposited on the ocean floor between 1 to 10 m and the average depth of water is 4 m. The lower mudstone (IV) is deposited in between 1 to 20 m and the average depth of water is 5 m. This method is beneficial for rebuilding the paleobathymetry of sedimentary basin which is in short of paleontological data, also beneficial for improving the accuracy of restoring paleobathymetry, recovering the continuous curve of water depth, and deepening sequence stratigraphic subdivision and basin analysis.

Key words: natural gamma ray spectrometry log; palaeobathymetric; Tahe Oilfield; Bachu Formation

104 Chemical and Mechanical Properties of Brittle Fractured Mud Shale

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Abstract: To study the chemical and mechanical characteristics of brittle fractured mud shale was important for solving problems of wellbore stability mechanism and drilling fluid leakage in deep mud shale formation. The physical, chemical and mechanical properties of brittle mud shale were systematically studied and analyzed by slurry chemical, microstructure scanning and rock mechanic experiments. The results show that mud shale in the area is brittle and cracked, and its clay minerals mainly contain illite and montmorillonite basically is free. Microstructure scanning shows that micro fractures are developed in mud shale; its soaking in fluid results in crack propagation, it reduce the strength as time increasing.

Key words: brittle fractured mud shale; crack; mechanical properties; water sensitivity

109 HPAM/St Solid Phase Mechanochemical Synthesis

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Abstract: To implement the PAM modifying with solid phase mechanochemistry, the PAM was grafted for hydrophobic monomer styrene under milling force. Through orthogonal experiment, the best conditions of solid phase mechanochemistry were determined: static pressure was 20kN, grinding was 20 times, rotation 40r/min, the proportion of St and HPAM was 1:99. Ultraviolet spectrophotometer was used for testing the content of styrene in reaction. The result shows that with the increase of styrene monomer, the content of styrene in reaction increases first and then decreases. When the static pressure is less than 20kN, the content of styrene in reaction becomes more; the pressure is more than 20kN, the result is on the contrary. When the grinding is less than 20 times, the content of styrene in reaction becomes more; the grinding is more than 20 times, the content is nearly unchanged. When the rotation is between 20~40r/min, the content is also nearly unchanged; when it is more than 40r/min, the content is declined.

Key words: solid phase mechanochemistry; PAM; graft copolymerization; hydrophobic monomer; styrene

112 Application of Pressure Test Analysis in G Oilfield Development Appraisal in Niger

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Abstract: G Oilfield of Niger belonged to a complicated fault block reservoir with both oil and gas in multiple pressure systems. Reservoir appraisal faced the challenges of uncertain gas cap area, uncertain reserves, hence it was difficult for making right development decisions in so short time. RFT pressure test data could be utilized determine fluid properties and fluid contacts and predicting reservoir distribution ranges through the evaluated pressure systems. Its successful use in G Oilfield indicates that the result of the pressure evaluation speeds up the progress of reservoir appraisal. It provides an important basis for development decision making when the oilfield is turned to the development stage.

Key words: RFT; pressure test; reservoir evaluation; fluid character; gas-oil contact; G Oilfield; Niger

116 Application of Fuzzy Recognition in Well and Layer Selection of Reservoir Chang 4+5 Fracturing in Hujianshan Area

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Abstract: Reservoir Chang 4+5 of Hujianshan Oilfield was a typical low permeability reservoir, therefore, wells needed to be fractured to obtain industrial oil flow. In order to avoid the blindness of traditional reservoir fracturing, based on the effect of single well fracturing of 178 wells, statistical analysis was performed, the major geologic and operating factors influencing fracturing were determined. On the basis stated above, fuzzy analysis method was used to establish a mathematical model for well selection in the studied area and according to the oilfield requirements, the identification standards for the model was determined. The application results show that the established selection criteria fits the practical data in oilfields well, it provides a basis for well and layer selections in the studied area.

Key words: Hujianshan Oilfield; fuzzy mathematics; fracturing; well and layer selection

121 The Effect of Alcohols on Interfacial Tension of Petroleum Sulfonate/Hydrophobically Associated Polymer Binary Combination Flooding System

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Abstract: The effects of alcohols with various carbon chain lengths and mixed alcohols on the interfacial tension of petroleum sulfonate/ hydrophobically associated polymer binary combination flooding system were studied. The study indicates that the alcohols have good synergistic effect with petroleum sulfonate. By adding the alcohols, the oil/water