

测井地质学研究的深度、尺度、跨度与维度

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摘要: 万米级深部地层、千米级深水、非常规油气勘探和老油田剩余油开发已逐渐成为油气勘探开发的主要方向。这些油气藏类型多样、地质条件复杂、勘探开发难度大, 测井地质学研究面临方法技术体系与勘探开发对象不匹配等挑战。分析了油气勘探开发测井地质学在深度、尺度、跨度和维度4个方向的发展, 研究结果表明: ① 测井地质学研究正逐步朝多学科深度融合和多维度方向发展。地质、测井、地震、工程和人工智能的融合可以提高油气勘探开发效率, 降低成本和风险。② 在万米级深度深层-超深层领域, 测井与地质结合可以揭示储层成因机理, 研究储层品质主控因素, 完成储层的综合评价。③ 测井地质学研究能够识别非常规油气储层毫米级纹层地质特征, 分析微纳米尺度孔喉内部含油性和可动性的细微变化。④ 测井技术在空间尺度上可以探测井筒、井旁和远井区域范围, 实现“点-线-面-体”地质信息刻画。在时间跨度上, 可通过分析压裂前、后和注水开发前、后测井信息的变化, 实现油气精细开发。⑤ 通过人工智能技术赋能, 未来地质、测井、地震和工程等多学科维度的深度融合将进一步拓展测井地质学的应用领域与范围, 推动测井地质学的发展, 为油气勘探开发提供有力技术支撑。

关键词: 微纳米尺度; 万米深度; 时-空跨度; 学科维度; 测井地质学

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Evolution of research on well logging geology in terms of depth, scale, span, and dimension

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Abstract: Hydrocarbon exploration and exploitation have progressively shifted toward 10 000-meter-deep onshore plays, 1 000-meter-deep offshore plays, unconventional plays, and residual oil in mature oilfields. The emerging frontiers are characterized by diverse reservoir types, complex geological conditions, and considerable difficulties in exploration and development, posing challenges such as incompatibilities between existing methodological and technical systems and exploration and exploitation targets to research on well logging geology. This study presents a summary of the evolution of research on well logging geology in terms of depth, scale, span, and dimension for hydrocarbon exploration and exploitation. The results indicate that logging geology research is gradually advancing towards in-depth interdisciplinary integration and multidimensional development. The integration of geology, logging, seismology, engineering, and

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artificial intelligence (AI) can enhance the efficiency of hydrocarbon exploration and exploitation while reducing costs and risks. In the development of deep to ultra-deep onshore plays at depths of about 10 000 m, the combination of logging and geology allows revealing the genetic mechanisms of reservoirs and analyzing major factors controlling reservoir quality, thereby achieving a comprehensive reservoir evaluation. For unconventional hydrocarbon reservoirs, research on well logging geology enables the identification of the geological characteristics of millimeter-scale laminae, as well as analyses of subtle variations in oil-bearing properties and oil mobility within micro- to nano-scale pore throats. On the spatial scale, logging technology allows for the detection of wellbores, near-well areas, and far-well regions, achieving the characterization of point-line-plane-volume full-space geological information. On the temporal scale, logging technology enables the analysis of changes in log data before and after fracturing or water injection, thus contributing to fine-scale hydrocarbon development. Driven by AI empowerment, the future integration of multidisciplinary dimensions, that is, geology, well logging, seismology, and engineering, will further expand the application domains and scope of well logging geology, accelerating its development. This will offer robust technical support for future hydrocarbon exploration and exploitation.

Key words: micro- to nano-meter scale, depth of about 10 000 m, spatiotemporal span, multidisciplinary dimension, well logging geology

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上天、入地和下海是人类探索自然的三大壮举^[1]。科学钻探作为“入地”的重要手段,是伸入地球内部探测信息的“望远镜”^[2]。在漆黑且高温的地下探井中,受限于经济技术成本,取心作业通常较为困难。通过将先进的测井仪器置入探井,可获取岩层声学、电磁学和核物理等岩石物理属性,这一过程可类比为对地球深部“做B超”“拍CT”或“扫核磁”。地球物理测井通过采集声、电、核及核磁等数据资料,为科学钻探与油气资源探测等提供了关键技术保障^[2]。作为深入漆黑地下、洞察深部岩层信息、探寻石油天然气、地热和铀矿等资源的重要手段^[3–4],测井也被形象地称为地质学家洞察地下油气藏的“眼睛”^[5–6]。

在全球“双碳”背景下,“减煤、稳油、增气、强新”已成为国家能源发展新战略^[7–8]。为响应中国“稳油和增气”目标,“两深一非一老”(万米级深地、千米级深水、非常规油气和老油田剩余油)正逐步成为中国未来油气增储上产的主要领域^[9–14]。

当前,中国陆上油田已迈入“地下珠峰”找油找气时代,进军“深地”不仅是国家战略所需,深层–超深层油气更是保障国家能源安全的重要战略储备^[15]。加快陆上深层–超深层油气勘探开发,既是中国油气接替的战略需求,也是当前和未来油气勘探开发的重点和热点^[16–17]。

随着常规油气资源占比逐渐下降,致密油气、页岩

油气和煤岩气等非常规油气在保障中国国家能源安全方面具有日益重要的战略地位^[18–20]。近年来,全球深水油气领域重大新发现展示了海上深水盆地广阔的油气勘探前景^[21–23],走向深水、加大深水油气勘探开发力度,对推动海洋强国建设与保障国家能源安全具有重要意义^[24]。另外,实现老油田的经济有效开发,也是保障中国油气稳产、社会平稳运行和民生幸福的重要支柱^[25–26]。

随着油气勘探开发主阵地逐步逐渐转向“两深一非一老”,新增油气储量主要集中于深层–超深层、非常规油气和海域等复杂领域,面临油气藏类型多样、地质条件复杂、勘探开发成本高等一系列科学技术难题^[6,27–28]。测井评价同样面临技术理论体系与勘探开发对象不匹配的问题,具体表现为数据问题突出、模型泛化性差、多维多尺度数据整合能力弱等挑战^[14,29–30]。为支撑深地、深海和非常规油气勘探进程,并助力延长老油气田寿命,亟需攻关面向复杂勘探开发目标的测井评价技术,充分释放“两深一非一老”领域增储上产潜力^[6,28]。

本文据此梳理了“两深一非一老”背景下测井地质学发展的4个“度”,即万米深度、微纳米尺度、广时–空跨度和多学科维度。测井地质学综合研究有助于揭示深层–超深层领域万米级深度储层的成因机理,并实现储层综合分类评价。在非常规油气领域,

测井地质学研究能够识别和刻画毫米级纹层信息变化,进一步探测微纳米孔喉内部含油性和可动性变化。测井技术还可捕捉井筒、井旁和远井区域范围内“点-线-面-体”特征变化,分析压裂前、后裂缝发育特征,从而实现广时-空跨度下的地质信息刻画。最后,本文总结了测井地质学未来发展方向,指出其将朝着地质、测井、地震、工程和人工智能等多学科深度融合的维度演进。相关研究成果有望为“两深一非一老”油气勘探开发提供技术支撑,并推动测井地质学学科的持续发展。

1 “两深一非一老”与测井地质学

在“两深一非一老”背景下,中国油气产业呈现出向“三个维度”发展的趋势,即勘探深度向万米深度地层挺进,油气储集空间尺度拓展至纳米尺度,老油气田开发建设实现百年时间跨度^[28]。

“两深一非一老”领域油气勘探开发潜力巨大,但仍面临沉积地质特征复杂和勘探开发成本高等难题^[13]。陆上深层-超深层和海上深水等领域取心困难,而地球物理测井技术是深入漆黑地下、洞察万米深井岩层信息的关键手段,在寻找和发现油气资源中发挥着不可替代的作用^[31-32]。

非常规油气具有岩性致密、物性差和非均质性强等特点,岩石物理响应机理复杂,导致“甜点”识别和评价难度大。因此,亟需将地质分析与测井解释评价相结合,以实现非常规油气的规模效益开发^[33-37]。百年跨度老油田含水率高,如何有效提高采收率已成为亟待解决的问题^[28]。测井技术作为油气勘探开发过程重要一环,是释放“两深一非一老”增储上产潜力的重要技术支撑^[38]。

在陆上深层-超深层领域,测井地质学研究也逐渐实现向万米深度的跨越,在深层-超深层领域可用于沉积储层特征精细描述与刻画^[4,39]。在海上深水领域,尽管测井测试等作业难度较大,但通过全系列常规测井、成像、核磁和声波等测井采集可实现深水油气储层岩性识别、储层参数计算和流体识别^[23,40-41]。在非常规油气领域,测井地质学研究正逐步跨入微纳米尺度领域。核磁共振测井能够揭示微纳米孔喉内部含油性的差异,而成像测井可以拾取毫米级沉积纹层^[42-45]。

在百年跨度老油田领域,测井地质学研究逐渐发展为广时-空跨度研究。测井是洞察地下油气藏的“眼睛”,是识别和评估油气藏的核心利器,承担着透视

地下深处奥秘的重要使命。它贯穿了油气勘探开发的全过程:在勘探阶段,是地质家的“眼睛”;在开发阶段,则作为“增储上产”的“臂膀”,是发现剩余油、评价水淹层等任务提供了有力技术保障^[3,46]。

2 万米深度

深层-超深层油气资源潜力巨大,已成为中国石油工业上游未来发展的关键领域^[17]。在陆上深层-超深层领域,地球物理测井技术大有可为,可在缺少岩心的情况下,提供大量地质信息^[4,47-49]。面对万米深度所处的超高温、超高压和超强应力条件,亟需攻克耐温(>260℃)和耐压(>200 MPa)的测井仪器开发,以及油基泥浆等复杂井筒环境测井处理和储层与流体评价等一系列“卡脖子”技术^[50-53]。

当斯通利波穿过渗透性地层时,孔隙中流体的流动会引起斯通利波衰减和频散,该现象与地层的渗透率和裂缝发育情况密切相关^[54-55]。基于此原理,中国石油勘探开发研究院李宁创新团队自主研发的渗透率测井仪,于2025年1月11日晚8时,在深地塔科1井埋深9 885~10 088 m裸眼段测得连续深度渗透率曲线,首次实现了万米深度储层渗透率的直接、连续测量。这一成果彰显了测井技术在科学技术向地球深部进军和在深层-超深层油气勘探开发等方面具有重要意义^[56]。

测井资料可用于分析储层沉积特征和反映储层成岩相特征,并进一步刻画裂缝发育规律,从而实现储层的综合评价与预测^[57-58]。万米深层-超深层经历复杂成岩作用改造,基质物性普遍较差(孔隙度多低于10%),且裂缝发育程度不一,油气主要富集于裂缝和基质物性较好“甜点”区,勘探开发难度大^[59-62]。优质储层的发育程度是制约深层-超深层油气勘探开发的关键^[63]。塔里木盆地库车坳陷白垩系巴什基奇克组是超深层碎屑岩油气资源勘探开发主力产层^[64],岩性以中-细砂岩和砂砾岩为主,属于超深层、高温、高压、低孔和裂缝型砂岩储层,具有孔喉细小、孔喉连通性差、非均质性强和裂缝较发育等特征^[17,61,65-66]。

库车坳陷巴什基奇克组是典型的扇三角洲-辫状河三角洲沉积体系,发育水下分流河道和河口坝等沉积微相。以博孜8井埋深8 081.0~8 090.2 m井段为例,其箱形自然伽马(GR)曲线特征指示该段为典型水下分流河道沉积形成的单砂体,岩性以中砂岩为主,中间可见粉砂岩层段。沉积微相通常对储层品质具有先天控制作用,而成岩作用是控制致密砂岩储层质量的

关键,裂缝发育和地应力则对致密储层品质起改善与调整作用^[57,67-68]。测井解释孔隙度和薄片分析表明,砂体顶部由于泥质含量增加,抗压实能力较弱,在超过8 000 m的深埋过程中受高应力差影响被强烈压实,原生孔隙几乎完全丧失;砂体底部邻近下伏泥岩,流体活动强烈,泥岩中的Ca²⁺和Mg²⁺易在河道砂体底部沉淀形

成碳酸盐胶结物,对储层物性产生破坏^[39,69](图1);单砂体内优质储层主要分布于砂体中部,该段颗粒粒度粗、泥质含量低、水平两向应力差低,部分原生孔隙得以保存,因而孔隙度最高,在埋深8 000 m以深仍能保有8%的面孔率(图1)。

在取心较为困难的万米深层,通过解读蕴含丰富

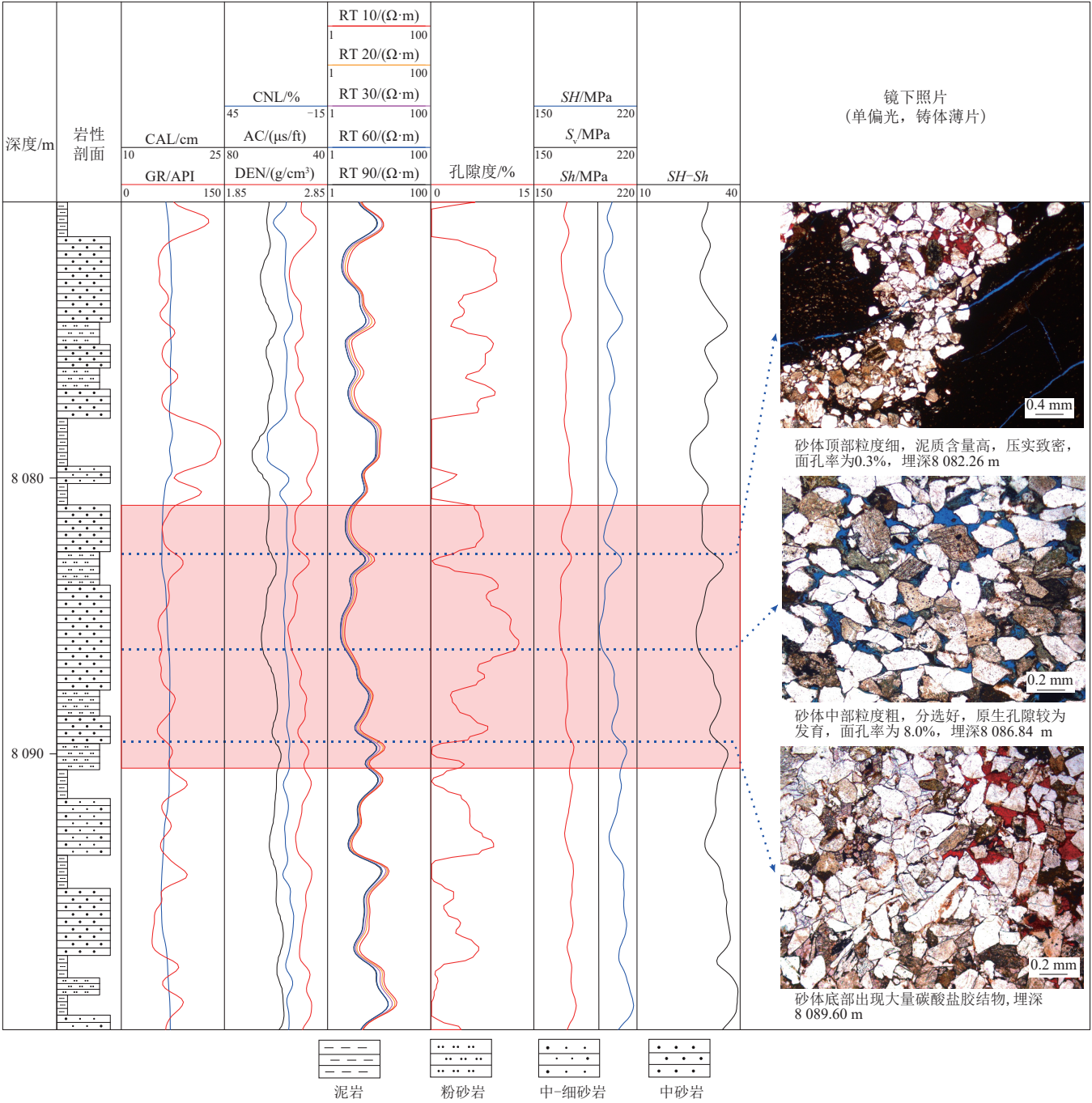


图1 塔里木盆地库车坳陷博孜8井白垩系巴什基奇克组超深层砂体内部孔隙差异机理分析

Fig. 1 Porosity variation mechanisms for the ultra-deep sand bodies of the Cretaceous Bashiji Formation, well Bozi 8, Kuqa Depression, Tarim Basin

SH. 水平最大主应力;S_v. 垂向应力;Sh. 水平最小主应力;SH-Sh. 水平方向上最大和最小主应力差
(图中红色区域表示巴什基奇克组超深层河道砂体。)

地质信息的测井曲线,可以实现沉积储层信息精细识别与评价,揭示万米深层储层成因机理并实现储层综合评价。

3 微纳米尺度

得益于水平井钻井和体积压裂技术的持续进步,非常规油气规模效益勘探开发已成为现实,并将在未来能源格局中扮演日益重要的角色^[36,70-73]。然而,由于非常规油气普遍具有储层致密、黏土矿物含量高、微纳米孔发育和连续性分布等特点,测井和物探技术均面临“甜点”检测识别较难的挑战^[44,50,74-77]。致密油气、页岩油气和深层煤岩气等非常规油气资源勘探开发对测井解释评价提出了更高精度的要求,亟需发展与之配套的创新性测井评价技术,以解决非常规油气复杂

储层识别与评价难题^[37,78-80]。

成像测井技术在沉积储层领域应用广泛^[81-82]。通过对成像测井资料进行精细处理,可以获得切片图像和纽扣电极图像。其中,切片图像为井壁展开图像在某一方向(如南北方向)上的投影,类似于沿岩心某一方向进行切割,因而可起到“虚拟岩心”作用^[32,42]。此类切片处理能够有效增强沉积纹层信息的识别精度(图2);成像测井仪的纽扣电极间距为2.5 mm,由其构成的电导率测量系统理论上可提供同等分辨率的井壁图像。在纽扣电极图像中,纹层结构更为清晰,其电导率的高低变化直接反映了纹层发育的规模与特征(图2)^[32,42,83-84]。

页岩储层主体以微米级孔隙、纳米级孔隙和页理缝为主。其中,纳米级孔隙是基础,微米级孔隙是“桥梁”,页理缝则是页岩油气聚集的末端^[85]。实验技术

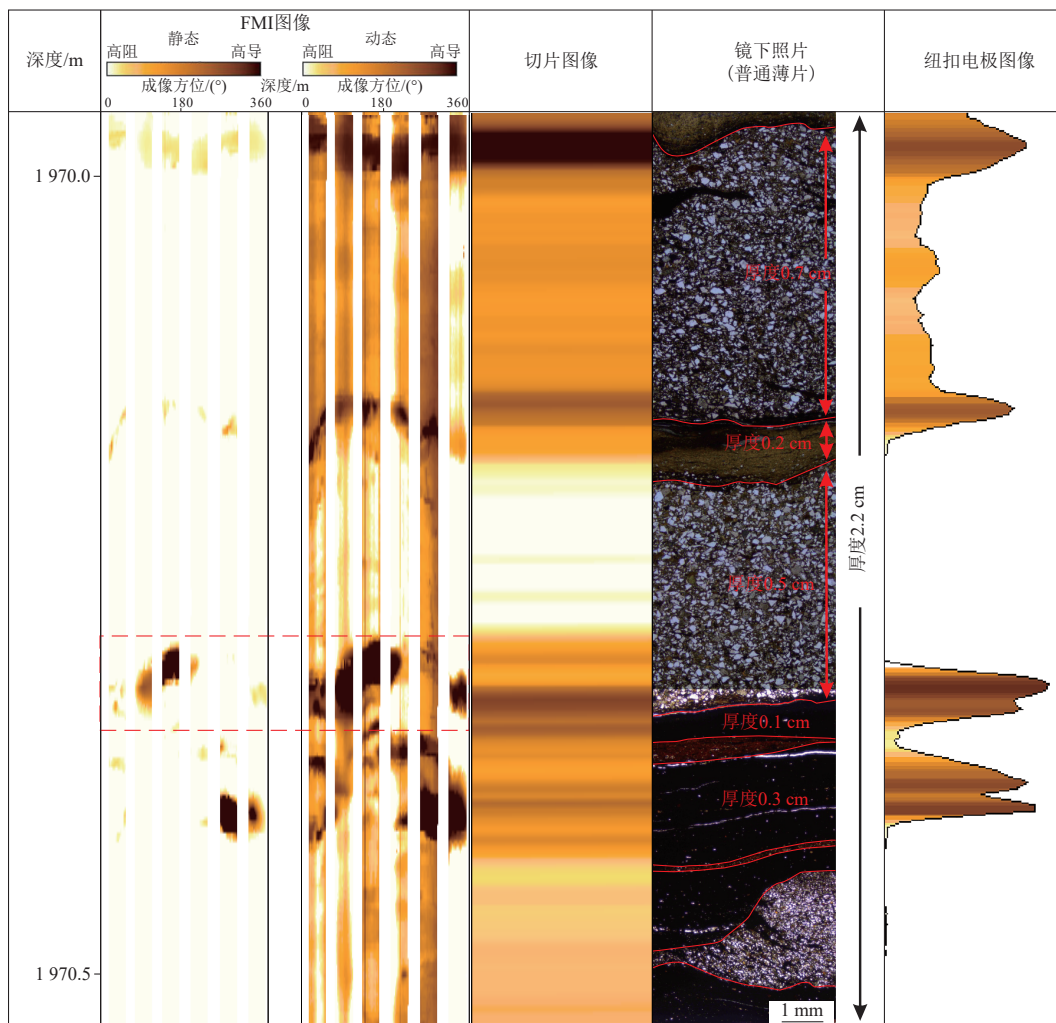


图2 基于成像测井切片和纽扣电极处理的鄂尔多斯盆地上三叠统延长组7油组页岩毫米级纹层信息拾取

Fig. 2 Information on millimeter-scale laminae in the 7th member of the Yanchang Formation in the Ordos Basin extracted using formation micro-imaging (FMI) log slicing and button electrode-based image processing

(图中红色虚线框表示镜下照片对应的薄片深度段;红色实线表示不同纹层界面,数值表示单个纹层厚度。)

方面,扫描电镜、微纳米CT扫描、QEMSCAN—拉曼矿物分析和核磁共振分析等测试技术融合可以实现微纳米尺度孔隙—裂缝等表征,分析流体赋存状态和可流动性^[86-92]。二维核磁测井可以识别与探测微纳米尺度孔喉分布信息,并进一步揭示孔喉内部的流体赋存和可动状态(图3)^[43]。

核磁共振测井可以探测非常规油气储层微米级和纳米级孔喉内部流体信息变化,并计算孔隙度、含油饱和度 and 可动油饱和度等参数^[85,93]。利用二维核磁共振

测井可较好地地区分微纳米级孔喉中的油、水和固体有机质信号^[94-98]。

通过成像测井与岩心分析,可识别出毫米级纹层结构的变化。以准噶尔盆地玛湖凹陷下二叠统风城组细粒沉积岩为例,如图3所示,该套页岩自上而下依次发育纹层状、层状和块状结构。对应的岩心和成像测井切片均清晰呈现了纹层信息变化,而薄片和扫描电镜分析则可进一步探究不同纹层尺度下岩心内部的微纳米孔喉信息。在此基础上,借助二维核磁共振测井

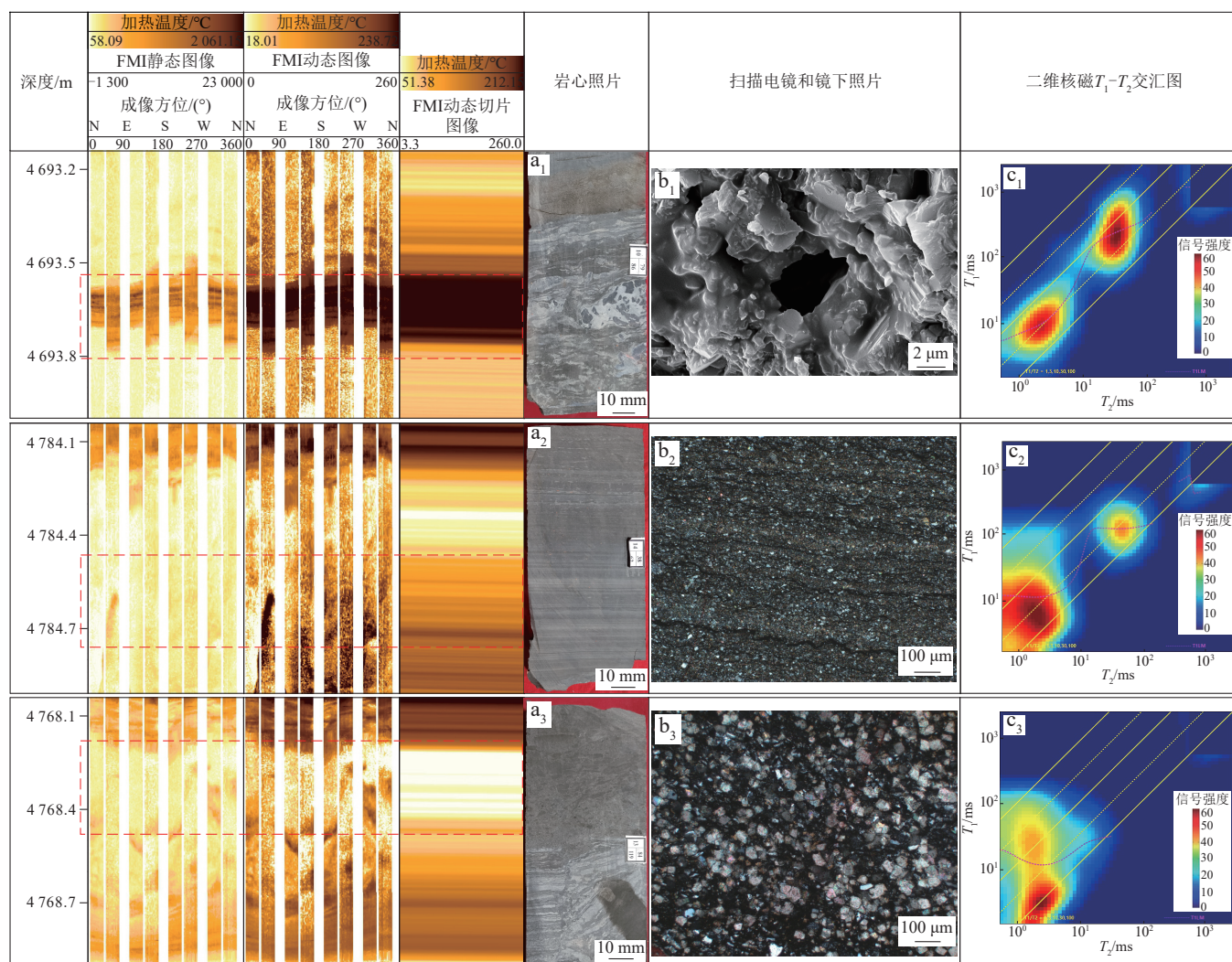


图3 准噶尔盆地玛湖凹陷下二叠统风城组页岩微纳米孔隙内含油性和可动性评价

Fig. 3 Assessment of oil-bearing properties and oil mobility in micro- and nano-scale pores within shales of the Fengcheng Formation, Mahu Sag, Junggar Basin

a₁. 玛页1井,埋深4 690.62~4 691.11 m,风城组,岩心;a₂. 玛页1井,埋深4 781.49~4 781.76 m,风城组,岩心;a₃. 玛页1井,埋深4 765.14~4 765.49 m,风城组,岩心;b₁. 玛页1井,埋深4 690.82 m,风城组,扫描电镜,可见油膜;b₂. 玛页1井,埋深4 781.49 m,风城组,普通薄片,正交光;b₃. 玛页1井,埋深4 765.15 m,风城组,普通薄片,正交光;c₁. 玛页1井,埋深4 690.62~4 691.11 m,风城组,核磁测井流体解释成果图;c₂. 玛页1井,埋深4 781.49~4 781.76 m,风城组,核磁测井流体解释成果图;c₃. 玛页1井,埋深4 765.14~4 765.49 m,风城组,核磁测井流体解释成果图

T_1 . 纵向弛豫时间; T_2 . 横向弛豫时间

(图中红色虚线框表示岩心照片对应深度段,岩心深度沿井筒方向向下移动3 m进行归位;图c₁—c₃中色标值为弛豫时间信号强弱相对值,无量纲;图c₁—c₃中的紫色虚线表示纵向弛豫时间几何均值(T_{1LM});图c₁—c₃中黄色实线和虚线从下往上“实—虚—实—虚—实”分别表示 $T_1/T_2=1, 3, 10, 30, 100$ 。)

纵向弛豫时间(T_1)-横向弛豫时间(T_2)交会可探索微米孔喉内部含油性的变化规律。结果显示,自上而下,玛湖凹陷风城组页岩微观孔喉的含油性和可动性逐渐变差(图3c₁-c₃)。

4 广时-空跨度

地质分析数据往往不连续,多为“点”数据,而测井

技术可以实现地质参数单井连续定量计算,从而将研究工作从“点”拓展至“线”和“面”,乃至井轴360°范围内的空间“体”^[29,45]。

在空间跨度上,不同的测井序列具有不同的探测深度和纵向分辨率。通过将常规测井、成像测井、声波测井和远探测测井等技术相结合,可以实现“点-线-面-体”全空间信息刻画^[3,80,99-100]。成像测井可探测径向深度约为5 cm、轴向360°范围内的地质

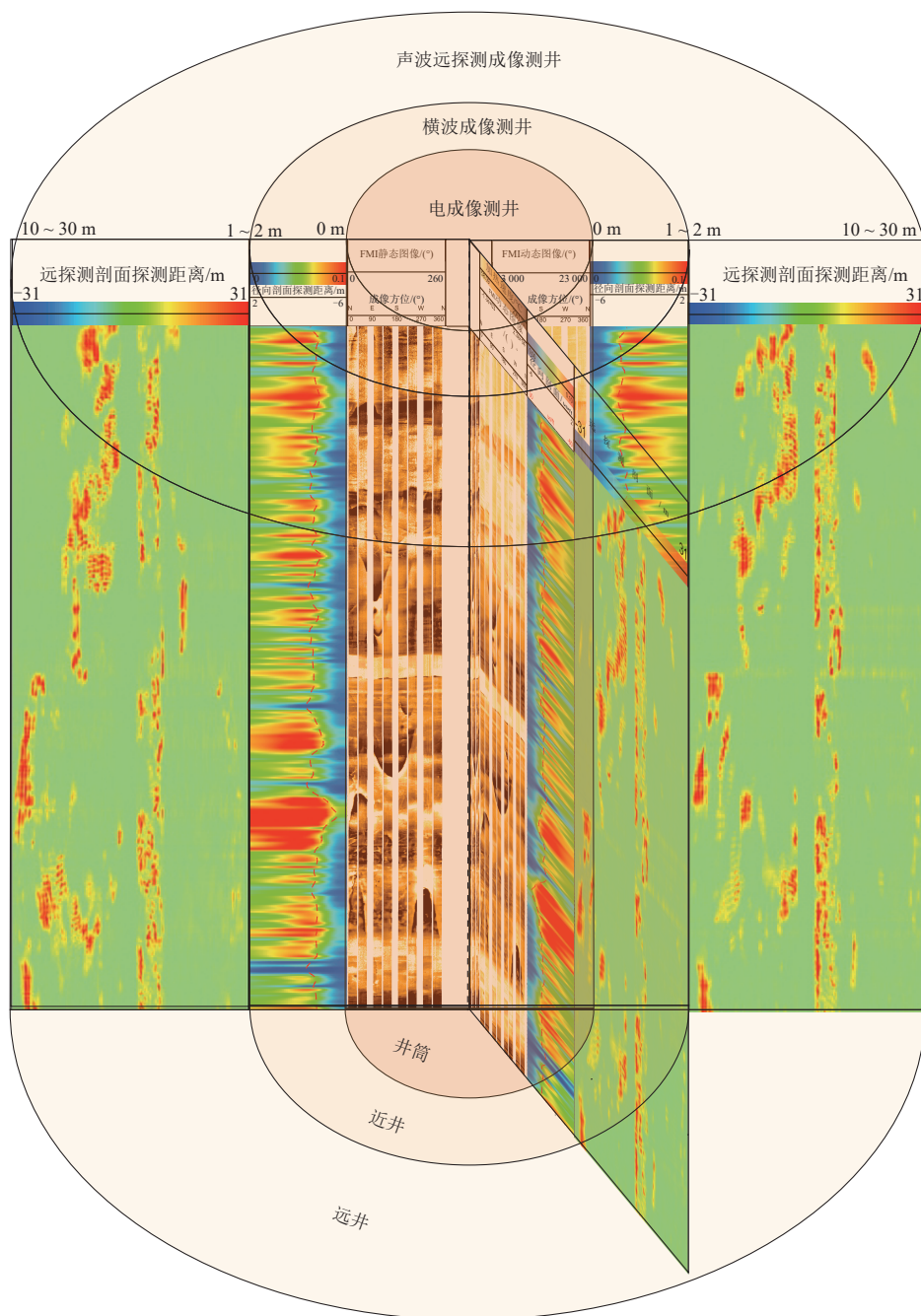


图4 井筒-井旁“点-线-面-体”地质特征识别与刻画(据文献[80]修改)

Fig. 4 Identification and characterization of point-line-plane-volume full-space geological information from wellbore to near-well areas (modified after reference [80])

(图中最上面一行数字表示沿着井周径向探测深度。)

体特征变化,而阵列声波测井和远探测声波测井可以探测从井筒到井旁数十米范围内的地质信息变化,进而可以实现地质体三维空间特征的精细描述(图4)^[32,80,101-103]。综合运用这些不同探测特性的测井序列,能够有效识别和刻画孔洞、裂缝等地质体的三维空间分布^[104-106]。

裂缝发育对储层具有明显的促溶、扩孔和增渗效应^[107]。裂缝的径向延伸长度是裂缝有效性评价的重点内容。从径向探测深度看,电成像测井(FMI)较浅,约5 cm,而方位电阻率成像测井(ARI)和偶极声波成像测井(DSI)的探测范围更大,可达井周2~3 m。因此,通过电成像、偶极声波成像和方位电阻率成像的“3I”联合分析,可实现裂缝有效性的综合评估^[45,108]。通常,诱导缝较浅,位于井眼周围的塑性变形层或进入弹性层内,仅在FMI图像上可见,而有效的天然裂缝则可在FMI,ARI和DSI图像上同时识别。闭合的裂缝虽在FMI图像中有显示,但在ARI图像上的特征已不明显,在DSI图像上则已无任何响应^[45]。

在时间跨度上,测井资料可以分时段采集,通过分析不同时间段岩石物理性质,揭示测井响应和地质特征在时-空维度上的动态演变^[109]。中国许多老油田开发已进入高含水后期,地下剩余油呈“整体高度分散、局部相对富集”状态^[110]。测井技术在老油田潜力剩余油储层挖掘方面至关重要,是恢复老油田产能和延长油田开采寿命的重要一环^[111]。裸眼井分析可以获得油藏未开采前地质信息,而套管井分析可以探究开采过程中固井质量、注入剖面 and 产出剖面等特征,二者贯穿于油气勘探开发的全过程^[46,112]。

将勘探开发过程中积累的大量测井数据体与地质分析资料和地震资料结合,可实现对储层构型的精细刻画,并对油藏进行静态描述与动态监测,以支撑高含水期老油田剩余油挖潜^[113-115]。老油田油气藏进入二次和三次开发后,剩余油空间分布及其随时间的动态变化对开发方案动态调整尤为重要^[109,116]。在注水开发过程中,储层的物性、含油性和油-水分布,都会随着注水程度改变而发生变化,因此利用测井资料识别与解释水淹层至关重要^[109,117]。在前期裸眼井测井采集的基础上,注水开发之后再次采集测井曲线(固井后需采集过套管电阻率),通过对比注水前、后的测井响应特征,结合测井曲线组合可有效识别水淹层,分析距注水口不同位置的油层电阻率变化特征,从而判断水淹层级别,避开高含水层段射孔^[116-117]。

此外,阵列声波测井能够获取地层岩石力学参数和裂缝发育特征。通过在压裂前和压裂后进行阵列声

波测井序列采集,可对比分析出压裂后裂缝的发育情况^[118-119]。图5中可以看到,压裂后的横波偏移成像与压裂前相比,没有发生明显的变化,说明压裂效果相对较差,没有形成规模的水力裂缝。

5 多学科维度

地球物理测井作为石油工业10大学科之一,是油气勘探开发流程中的关键环节,正发挥着日益重要的作用^[14,46]。然而,在“双碳”目标和人工智能技术赋能背景下,测井领域面临着勘探开发对象日趋复杂、多维度尺度数据整合能力不足等挑战^[14]。

在“两深一非一老”领域油气勘探开发驱动下,测井地质学研究正逐步迈向多学科深度融合的发展维度。当前,全球科技正朝着信息化、智能化和数智化方向发展,地质、测井、地震、工程和人工智能的融合可以提高油气勘探开发效率,降低成本和风险^[120-125]。以全序列测井资料大数据为基础,充分利用地质、地震、工程和生产动态等多源数据,能够优化测井储层解释模型,实现智能储层参数评价^[46]。例如,远探测声波测井技术的应用,有效促进了测井-地震、测井-钻井、测井-开发等多学科交叉融合,使测井探测范围从传统的“一孔之见”拓展为“一孔远见”^[102]。以煤岩气等非非常规油气勘探开发为例,其复杂储层特点决定了必须采用地质、测井、地震和工程等多学科融合的研究思路,并通过地质-工程一体化技术,优选地质和工程“甜点”,压裂构建“人工油气藏”^[19,126-129]。

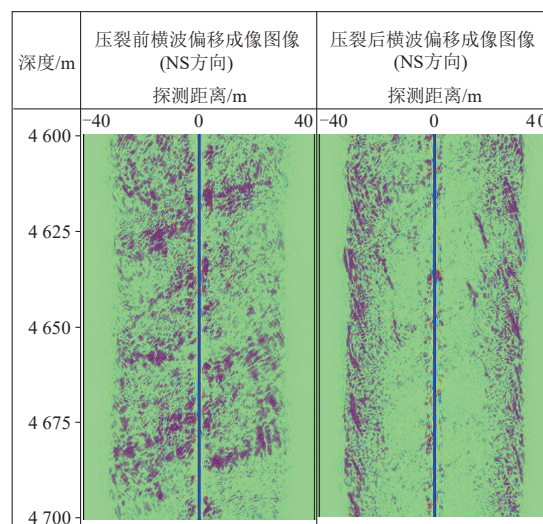


图5 时-空尺度上压裂前和压裂后声波测井特征

Fig. 5 Acoustic responses of fractures before and after hydraulic fracturing on the spatiotemporal scale
(图中蓝色直线表示井筒位置。)

随着“两深一非一老”领域油气勘探开发难度不断加大,结合大数据和人工智能等新方法技术融合,构建集测录井、地质、地震和油藏等多学科、多维度数据体于一体的智能大数据应用环境,已成为行业发展趋势。从多学科维度系统解决岩相解释、储层参数计算、裂缝判别和压裂效果分析等勘探开发关键难题,是未来技术发展的必然方向^[120,126,130-135]。

此外,地球物理测井资料在稀贵气体(如氢气和氦气)和天然气水合物等资源的精细评价中也具有应用潜力,例如可用于识别氢源岩,评估岩石矿物的释氢含量和氦气资源潜力^[136-138]。

6 结论

1) 测井地质学发展正在向万米深度跃进。在缺少岩心的万米深度,通过解读蕴含丰富地质信息的地球物理测井曲线,可以实现沉积储层信息精细识别与评价,揭示储层成因机理,明确储层品质主控因素并实现储层综合评价。

2) 测井地质学研究逐渐走向微纳米尺度。成像测井与核磁共振测井技术可以识别细粒沉积岩毫米级纹层信息,并探究微纳米尺度孔喉内部含油性和可动性细微变化。

3) 测井地质学也逐渐迈向广时-空跨度。空间尺度上,可以实现“点-线-面-体”空间信息刻画。时间跨度上,可通过分析压裂前、后和注水开发前、后测井信息的变化,实现油气精细开发。

4) 人工智能赋能背景下,未来地质、测井、地震和工程等多学科维度融合可进一步拓展测井地质学应用领域与范围。

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