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鄂尔多斯盆地东缘临兴中区太原组下段大型复合潮道砂体沉积演化特征及含气性耦合关系

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摘 要: 鄂尔多斯盆地东缘临兴中区太原组是煤层气与致密砂岩气协同勘探开发的核心层位.为明确该区煤系气富集规律,基于层序地层划分,结合地震、测井、岩心和露头资料,精细刻画了太原组下段大型复合潮道砂体的沉积演化特征,阐明了潮道砂体空间叠置关系及其与储层含气性的成因联系.研究结果表明:太原组下段为潮坪沉积体系,潮汐水道和砂坪为优势沉积微相,是致密砂岩气的主要储集单元;大型复合潮道砂体整体呈北厚南薄舌状、东西透镜状展布,沉积演化具有明显旋回性,遵循"奠基发展-鼎盛发育-衰退消亡"的垂向演变规律,且潮道砂体对下伏本溪组8+9#煤层存在强烈的冲刷作用.潮道砂体叠置型式可划分为多期叠置型、垂向叠置型、侧向叠置型和孤立型,其中多期叠置型和垂向叠置型砂体连通性优,含气性最佳,为区域优质储层.综合分析表明,沉积微相是控制含气单元与储层甜点空间分布的首要因素,砂体叠置型式为次要控制因素,而潮道砂体内部物性差异是导致储层含气性分异的本质原因.该研究成果可为临兴中区"深部煤层气和致密砂岩气"协同高效勘探开发提供重要地质依据.

关键词: 临兴中区;太原组下段;大型复合潮道;砂体叠置型式;含气性差异;沉积学;石油地质.

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Sedimentary Evolution Characteristics of Large-Scale Composite Tidal Channel Sandbody in the Lower Member of Taiyuan Formation in Linxing Middle Block, Ordos Basin and Their Coupling Relationship with Gas-Bearing Properties

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Abstract: The Taiyuan Formation in the Linxing Middle Zone, eastern margin of the Ordos Basin, serves as the key layer for the collaborative exploration and development of tight sandstone gas and coalbed methane (CBM). To clarify the enrichment patterns of coal measure gas in this region, this study finely characterizes the sedimentary evolution characteristics of large tidal sand bodies in the lower section of the Taiyuan Formation, clarifying the spatial stacking relationship of tidal sand bodies and their relationship with gas-bearing genesis, on the basis of the division of sequence stratigraphy, and in combination with seismic, logging, core, and outcrop data. It is suggested that the lower section of the Taiyuan Formation is a tidal flat sedimentary system, and tidal channels and sand flats are the main reservoir types of the Taiyuan Formation gas reservoir in this area. The large tidal sand bodies are distributed in a tongue-shaped pattern with thickness greater in the north and less in the south, and in an east-west lens shape in the northern part of the study area, showing a vertical evolution law from foundation development to peak development to decline and disappearance, which has a strong scouring effect on the underlying 8+9# coal seam. The stacking types of tidal sand bodies mainly include multi-stage stacking, vertical stacking, lateral stacking, and isolated types. Among them, multi-stage and vertical stacking sand bodies have excellent connectivity, greater thickness, and better gas content, making them potential high-quality reservoirs in the area. Comprehensive analysis suggests that the primary controlling factor for the distribution of gas-bearing units is sedimentary microfacies, followed by sand body stacking styles (multi-stage and vertical stacking styles are most favorable), while the physical conditions inside tidal channels are the essential factors resulting in differences in gas-bearing properties. The research results can provide a theoretical basis and technical support for the collaborative and efficient exploration and development of deep coalbed methane and tight sandstone gas in the Linxing Middle Block.

Key words: Linxing Middle Block; lower member of Taiyuan Formation; large-scale complex tidal channel; sandbody stacking type; gas-bearing differences; sedimentology; petroleum geology.

0 引言

在“双碳”战略目标引领下,我国非常规天然气产业迈入高速发展阶段,致密砂岩气、煤层气已成为国内油气增储上产的重要接替资源(沈玉林等,2012;戴金星等,2022;邹才能等,2024).鄂尔多斯盆地是我国非常规天然气勘探的核心盆地,近年来勘探重心逐步由盆地中心向盆缘过渡.中海油在鄂尔多斯盆地东缘临兴、神府区块相继实现致密砂岩气与深煤层气勘探重大突破,探明千亿立方米级特大型气田,发现国内首个千亿方深煤层气田,充分证实盆缘地区上古生界煤系气具备巨大勘探潜力(米立军和朱光辉,2021;徐长贵等,2024),研究区主力产气层位集中于上古生界石炭系本溪组、二叠系太原组与石盒子组,其中太原组致密砂岩与本溪组煤层构成了研究区煤系气的核心生储组合(杨华等,2004;李勇等,2023;王子轶等,2023).

临兴中区上古生界发育多套致密砂岩储层,资源禀赋优越(朱光辉等,2022).但随着勘探开发不断深入,储层非均质性强、多期砂体叠置关系复杂、单砂体空间展布规律不明等问题,严重制约了勘探开发成效(王波等,2022;李平等,2023).前期勘探证实,临兴-神府地区太原组下段砂岩厚度大、含气显示好,是极具潜力的优质产气层(冯文立等,2009;吴鹏等,2018).目前,学界针对临兴地区太原组储层的研究仍较为薄弱,对下段主力砂体的沉积环境、演化规律及含气控制机制认识不清.同时,本溪组8+9#优质煤系烃源岩与太原组砂体形成“近生近储”的有利成藏配置.

基于此,本文依托研究区226口钻井的测井、岩心、物性测试及三维地震、野外露头资料,对太原组下段开展精细地层划分、沉积演化及砂体构型研究,系统剖析砂体叠置样式与含气性的耦合关系,明确储层含气差异主控因素,为研究区煤系气协同勘探、甜点优选及高效开发提供理论支撑.

1 地质背景

鄂尔多斯盆地东缘上古生界太原组砂岩储层中已发现储量超过千亿立方米的大气田,是天然气开发的重要层位(杨华等,2012;吴鹏等,2018;蔡益栋等,2022).临兴中区地处鄂尔多斯盆地东缘晋西挠褶带中北部,整体为构造平缓的西倾单斜(图1a),区域构造稳定性好,断裂、褶皱不发育,为油气聚集提供了良好的构造条件(邓军等,2006;刘玲等,2019).研究区上古生界地层沉积连续、整合接

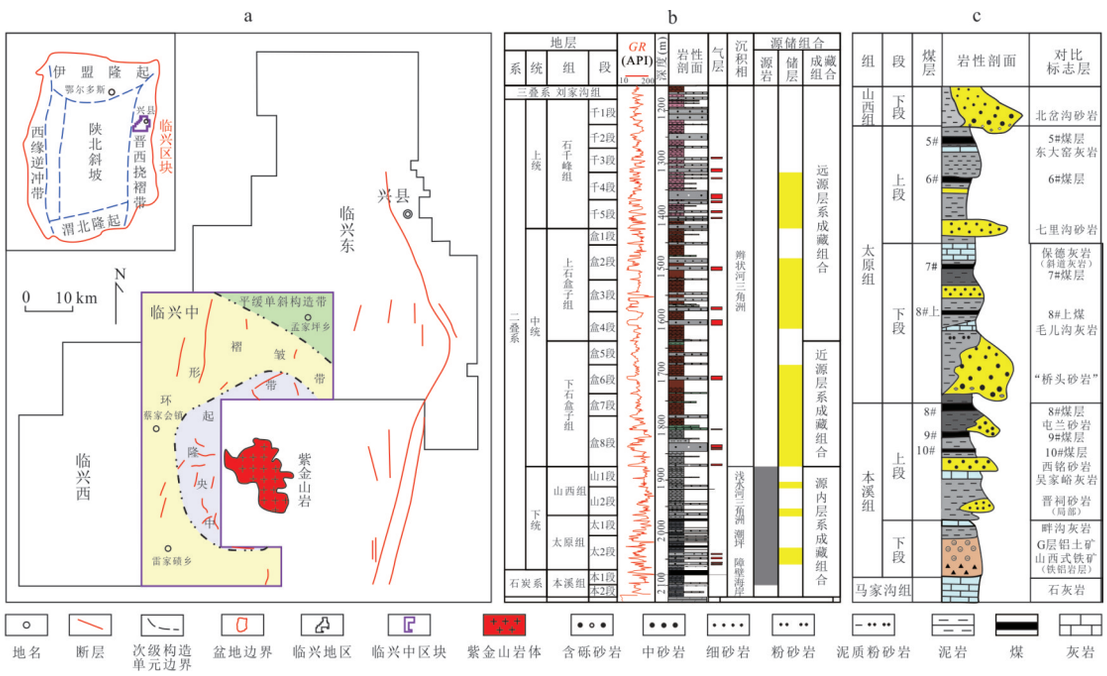

图 1　鄂尔多斯盆地临兴中区区域构造位置图 a(据蔡益栋等,2022 修改),上古生界地层综合柱状图 b 及太原组地层划分对比标志图 c(据吴鹏等,2018 修改)

Fig.1　Tectonic location (a, modified by Cai *et al.*, 2022), the Upper Paleozoic stratigraphic section (b) and stratigraphic division and correlation markers (c, modified by Wu *et al.*, 2018) of Taiyuan Formation in the Linxing Middle Block, eastern margin of Ordos Basin

触,自下而上依次发育本溪组、太原组、山西组、下石盒子组、上石盒子组及石千峰组,沉积环境由海陆过渡相逐步向陆相演化(图 1b).

本文采用通用的地层划分方案,以本溪组顶部 8+9#煤层顶界面为太原组底界,以山西组底部“北岔沟砂岩”为太原组顶界,并依据沉积旋回特征将太原组划分为上下两段(李文厚等,2021;米立军和朱光辉,2021;杜佳等,2022;李勇等,2023)(图 1c).其中,太原组上段以泥岩、泥灰岩、煤层夹粉砂岩等细粒沉积为主,底部连续分布的斜道灰岩为上下段分界的标志性地层;太原组下段为研究区主力产气层,底部发育厚层灰白色细-粗粒石英砂岩、岩屑石英砂岩,夹粉砂岩与煤线,与区域知名的桥头砂岩为同期沉积(陈钟惠等,1989),是区内致密气勘探的核心目标层(吴鹏等,2018).研究区太原组地层厚度整体稳定,地势北东高、南西低,潮坪-障壁海岸相沉积特征显著(吴洛菲,2018).

2　沉积微相识别及其配置关系

2.1　沉积体系与沉积微相

关于太原组下段主力砂体的沉积环境,前人曾先后提出河流相、潮汐三角洲-障壁相、浅水三角洲相等多种认识(陈钟惠等,1989;桂学智等,1993;姜烨等,2001;王华等,2001;平立华等,2006;王付斌等,2007;冯文立等,2009;沈玉林等,2009;席胜利等,2009;兰朝利等,2011;宋雪娟等,2011;李勇等,2013;郑文波等,2015).尽管存在分歧,总体而言,普遍认为太原组沉积期处于陆表海环境,频繁的海侵-海退过程导致辫状河、浅水三角洲、潮坪、浅海沉积体系在时空上叠加共存,砂体沉积受古构造、海平面变化及物源供给共同控制.

本次研究基于测井、岩心及野外露头观察描述,结合研究区沉积背景,综合太原组下段砂体物质成分、沉积构造、空间展布等沉积特征,明确太原组下段主体为碎屑滨岸沉积体系下的潮坪沉积,其判别依据如下:

(1)典型潮汐成因构造:太原组砂岩中普遍发育脉状层理、透镜状层理和羽状交错层理等受潮汐影响的沉积构造以及反映泥坪、泥炭沼泽沉积的典型成因相标志组合如灰黑色泥岩、碳质泥岩、煤层及根土岩等(图 2a~2e).野外露头古水流测量显示双向特征(图 2d,2e),为典型潮汐水流作用的结果.

(2)高成熟度砂岩与滞留沉积:太原组砂岩类



图 2 临兴中区太原组下段典型沉积成因标志

Fig.2 Typical sedimentary facies markers of the lower member of Taiyuan Formation in Linxing Middle Block

a～c 为具脉状层理和透镜状层理的泥坪相沉积，LX-14，2 049.52～2 053.80 m；LX-6，～1 846 m；d 和 e. 羽状交错层理，显示双向古水流特征，保德镇朱家川桥头砂岩露头；f. 岩性以石英砂岩为主，见腕足类化石；g. 底部为具低角度交错层理和大量滞留沉积物的潮道砂体，中部为具块状层理的细砂岩，顶部为粉砂质泥岩，LX-17 井，1 887 m；h 为 g 中红色方框的特写，见大量泥砾

型以石英砂岩、岩屑石英砂岩为主，颗粒分选以中、好为主，磨圆为次圆、次棱角状，表明其经过潮汐水流的反复冲洗，成分与结构成熟度均较高，局部亦可见少量腕足类化石等（图 2f）. 以 LX-17 井为例（图 2g，2h），太原组下段砂体的底部发育不规则冲刷面，其上可见由泥砾、砾石、植物茎秆及煤屑等构成的滞留沉积物，代表了强水动力条件下潮汐水道的下切侵蚀；向上过渡为具块状层理的中-细砂岩，粒度减小，分选变好，显示出砂坪沉积特征；顶部则被泥坪沉积所覆盖.

（3）垂向沉积序列：岩心与露头剖面均显示出潮下带-潮间带-潮上带的垂向分带特征（图 3）. 潮下带以潮汐水道作用为主，砂体发育且具有侵蚀能力，*GR* 曲线形态以箱型、钟型为主；潮间带的底部常以砂坪或低能潮汐水道为主，向上逐渐发育混合坪、泥坪，*GR* 曲线以复合钟型和指型为主；潮上带发育泥岩、泥灰岩和泥炭沼泽，并见煤层.

综上分析，太原组下段沉积微相类型主要为潮汐水道和砂坪（潮下带）、混合坪（潮间带）和泥坪/泥灰坪/泥炭沼泽（潮上带）.

2.2 沉积微相空间配置关系

基于 226 口钻孔中砂体、泥岩、泥灰岩和煤层等岩性厚度统计和综合分析，本文恢复了太原组下段沉积微相平面展布格局（图 4）. 结果显示，太原组下段砂体厚度区间为 0.2～37.7 m，平均厚约 10.24 m，呈北厚南薄舌状、东西透镜状展布（以潮道或砂坪为主；图 4a，4c），厚度分异显著，巨厚砂岩仅分布于研究区中部和北部，向南、向东迅速减薄，相变为混合坪或泥坪沉积，泥岩、灰岩及煤层发育（图 4c）. 潮汐水道和砂坪为有利储集微相，构成了太原组底部的大规模储气砂体. 前人曾将其解释为障壁砂坝（宋雪娟等，2011；吴鹏等，2018），但障壁砂坝外侧

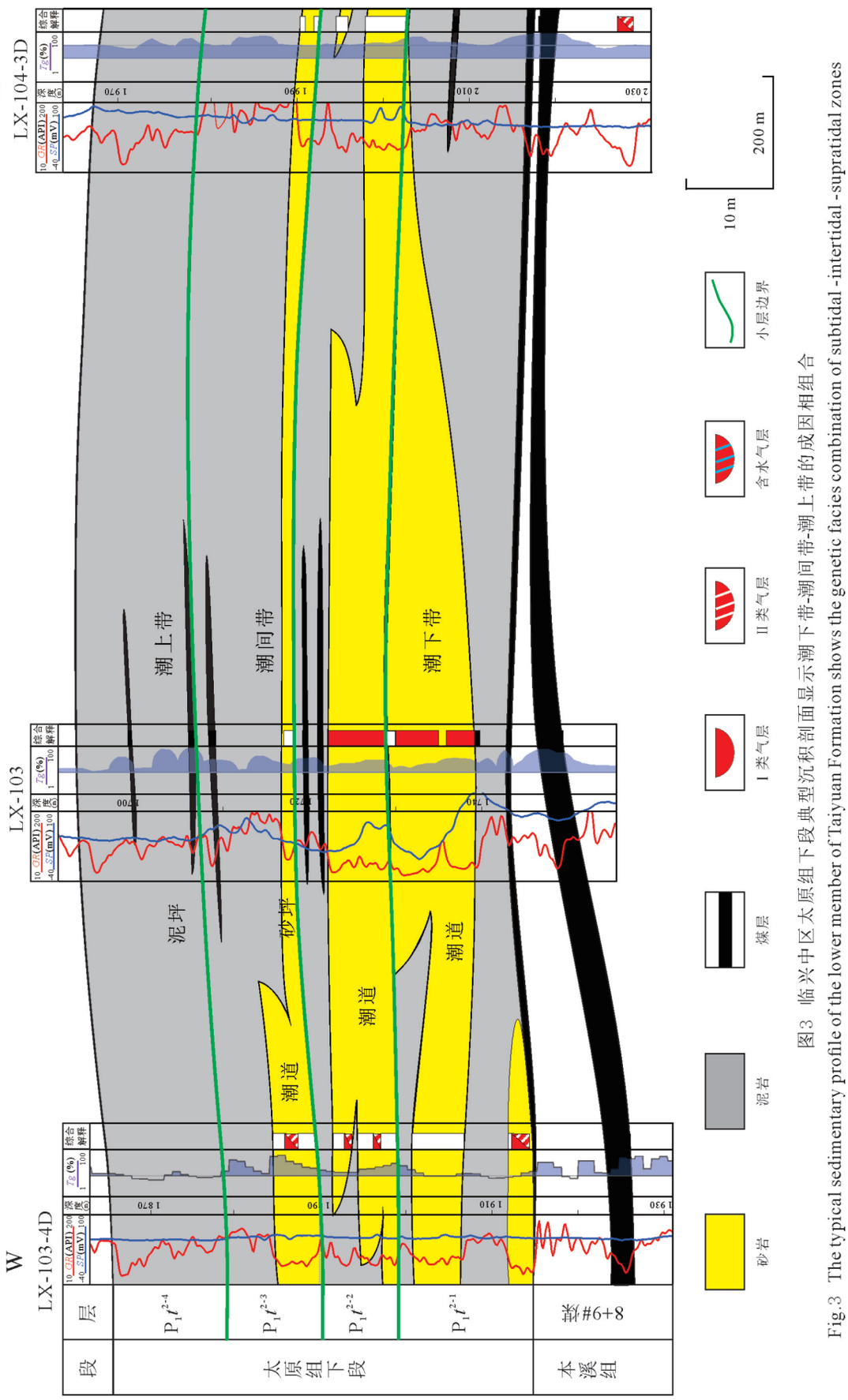

图3　临兴中区太原组下段典型沉积剖面显示潮下带-潮间带-潮上带的成因相组合

Fig.3　The typical sedimentary profile of the lower member of Taiyuan Formation shows the genetic facies combination of subtidal -intertidal -supratidal zones

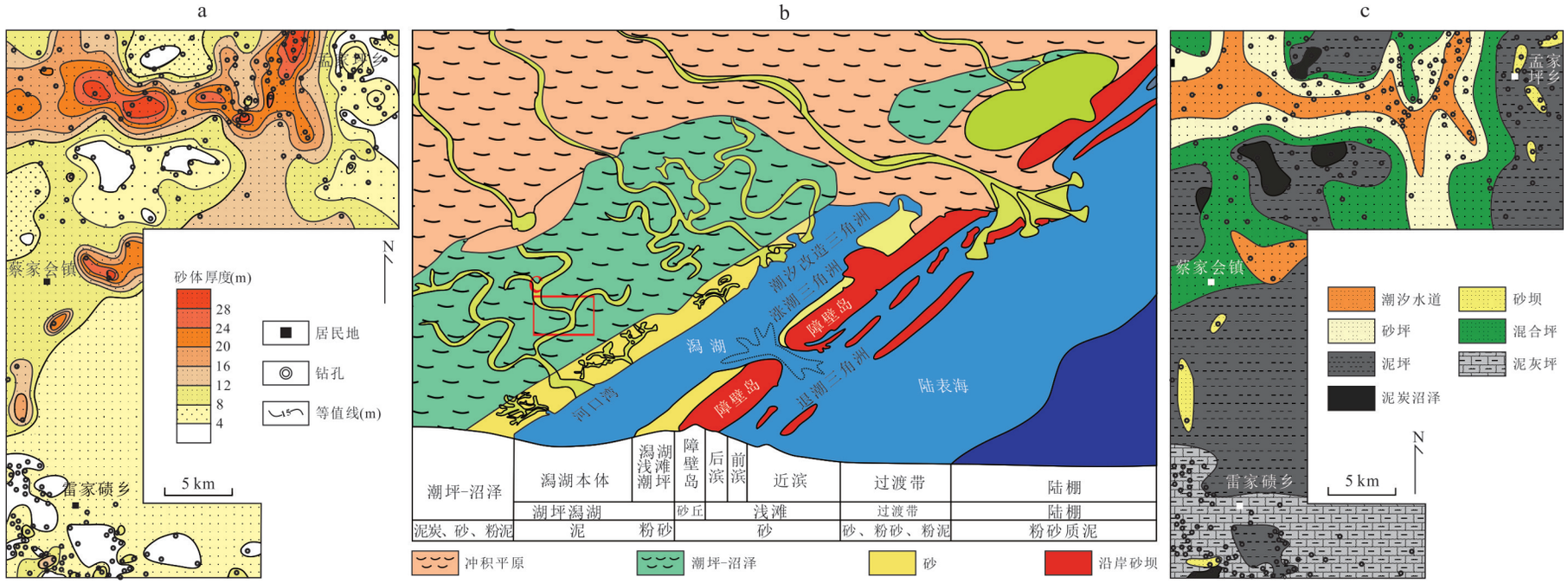

图4 临兴中区太原组下段沉积环境及沉积微相分布

Fig.4 Sedimentary environment and facies distribution of the lower member of Taiyuan Formation in Linxing Middle Block

a. 太原组下段砂体厚度图; b. 研究区沉积环境为潮坪沉积体系,且毗邻陆地方向一侧发育; c. 太原组下段沉积微相平面配置关系

受潮汐改造,不利于大规模聚煤(焦养泉等,2015).而研究区该砂体内部及顶底部均有煤层发育,且平面上南北两侧亦见较厚煤层(图 3),这与潮坪环境特征更为契合.太原组沉积期,华北地台构造稳定、基底平缓,海平面小幅升降即可引发大规模海侵-海退(郭英海和刘焕杰,2000),潮汐作用影响范围大,加之区域古地形呈北高南低,会在靠陆地一侧形成垂交岸线、延伸可达几十公里的线形潮道砂体(陈钟惠等,1989;图 4b).

3　大型复合潮道砂体时空演化特征

3.1　小层划分与对比

小层精细划分与对比是储层精细刻画、甜点评价及油气开发部署的基础(蓝宝锋等,2024;彭虎等,2024).依据层序地层学原理,在段级别界面的约束下,依据岩性组合、测井相、沉积相等,在太原组下段内部进一步识别并划分了 4 个小层(图 5),自下而上分别为太原组下段 1 小层($P_1t^{2\text{-}1}$)、太原组下段 2 小层($P_1t^{2\text{-}2}$)、太原组下段 3 小层($P_1t^{2\text{-}3}$)和太原组下段 4 小层($P_1t^{2\text{-}4}$).其中 $P_1t^{2\text{-}1}$和 $P_1t^{2\text{-}2}$的 *GR* 曲线向左偏移显著,表现为微齿化箱型、漏斗型和钟型等形态,显示砂岩含量增多;$P_1t^{2\text{-}3}$底部 *GR* 曲线表现为低幅齿化箱型和钟型,顶部曲线变化幅度收窄变弱,反映泥岩含量增加;$P_1t^{2\text{-}4}$的 *GR* 曲线总体表现为中-低幅锯齿状、低平指状,沉积环境更趋于低能,水动力条件明显减弱.

在小层划分基础上,通过构建连井网络对比剖面(图 6),实现了小层划分对比的一致性.各小层总体可对比,但因频繁海侵-海退导致的相变,岩性组合存在差异.$P_1t^{2\text{-}1}$和 $P_1t^{2\text{-}2}$总体相对富砂,且砂岩在研究区的中部、北部一带较厚,单砂体厚度分别可达 11.4 m 和 16.8 m,向南部和东西两侧变薄.上述小层高伽马特征被视为太原组早期处于潮汐-障壁

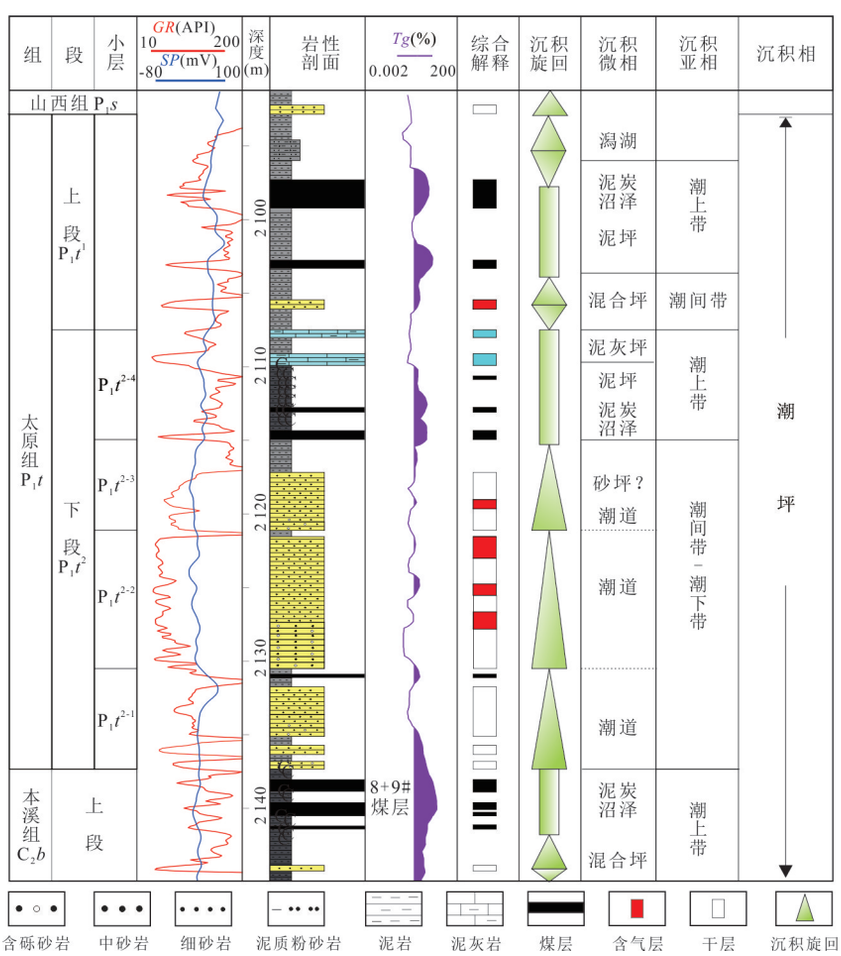

图 5　临兴中区太原组下段小层划分及综合柱状图

Fig.5　Composite columnar section showing strata and sedimentary cycles of various sub-members in the lower member of Taiyuan Formation, the Linxing Middle Block

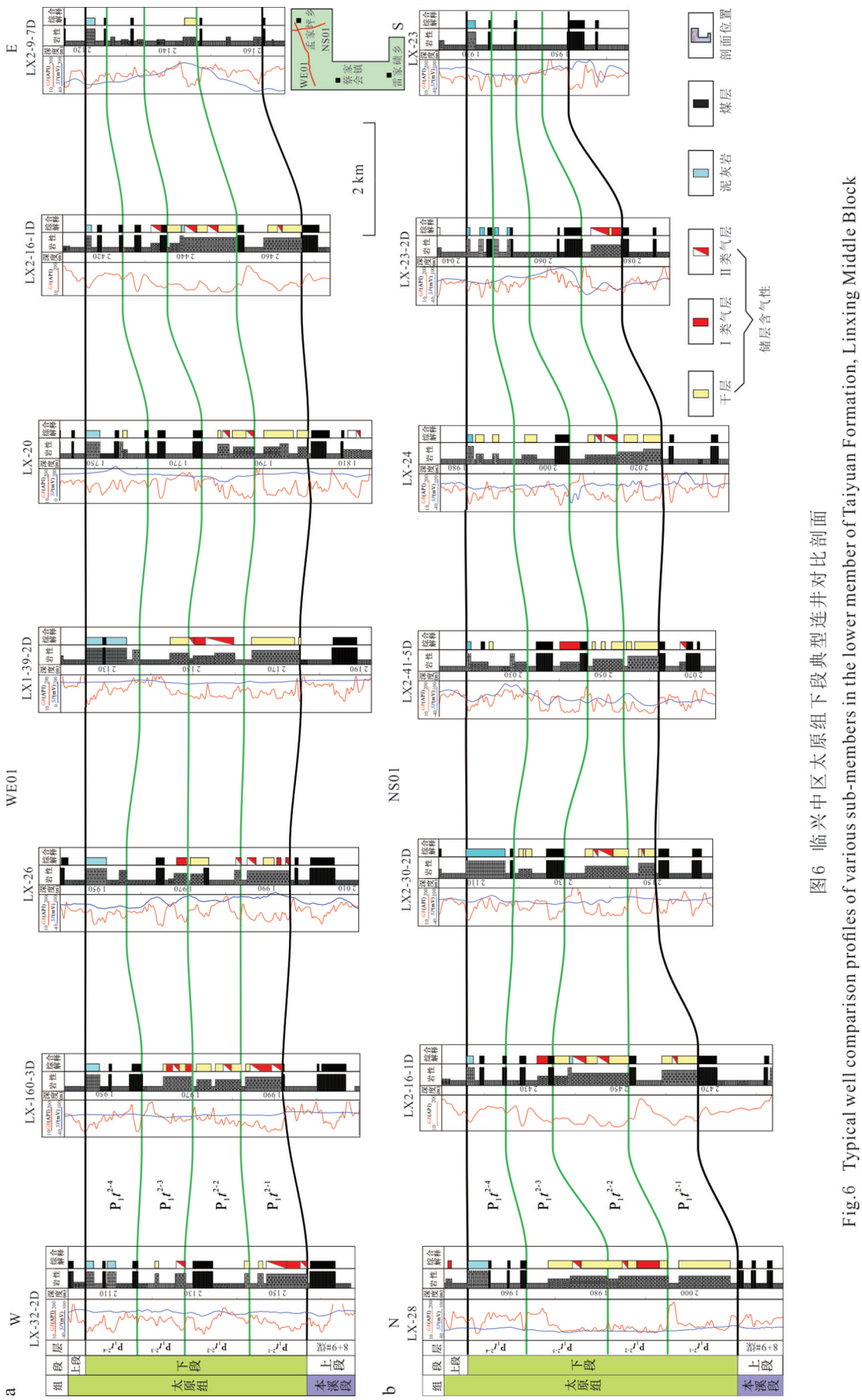

图6 临兴中区太原组下段典型连井对比剖面

Fig.6 Typical well comparison profiles of various sub-members in the lower member of Taiyuan Formation, Linxing Middle Block

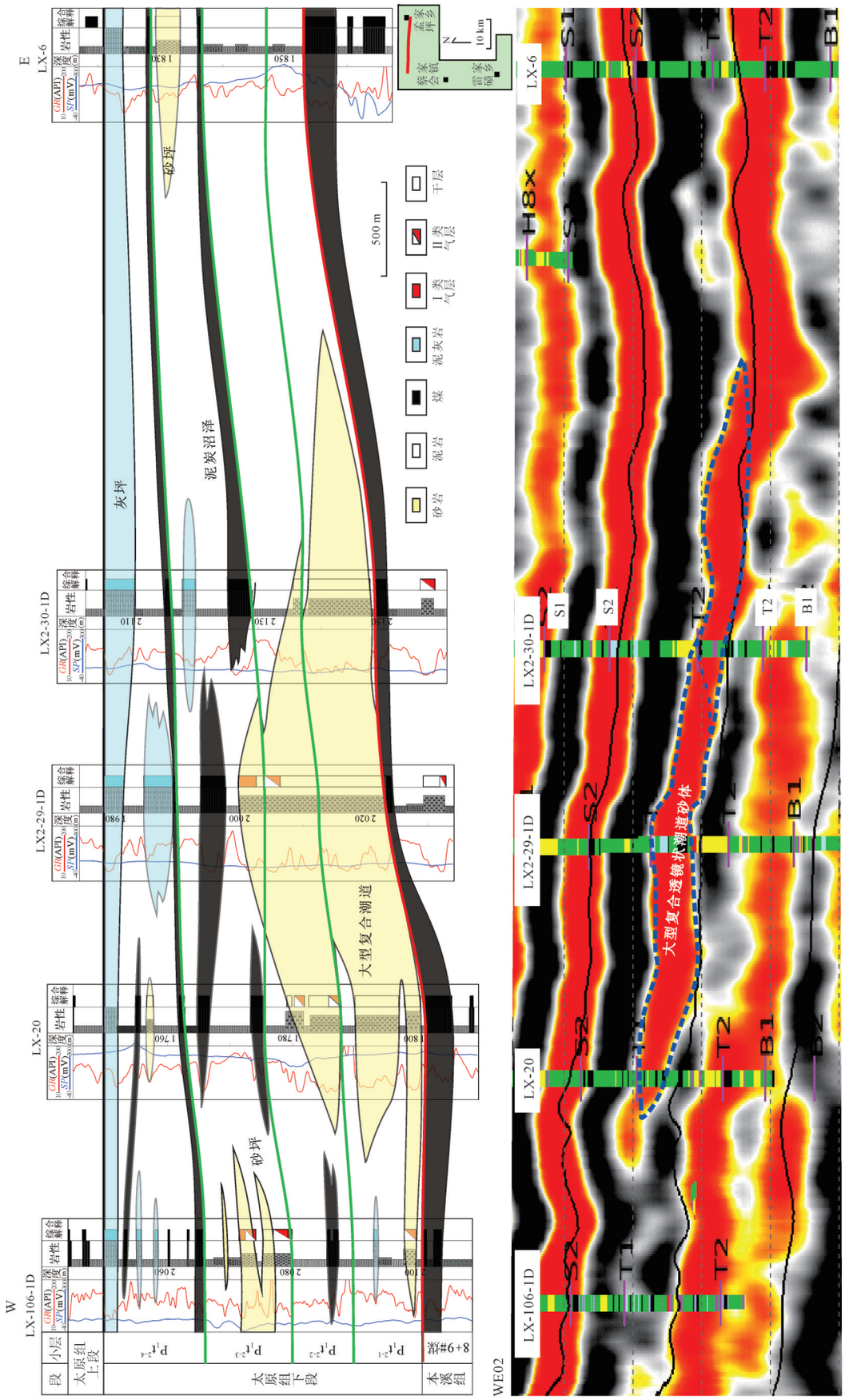

图7　临兴中区太原组下段大型复合潮道连井剖面

Fig.7　Profile of large-scale complex tidal channel sandbody in the lower member of Taiyuan Formation, Linxing Middle Block

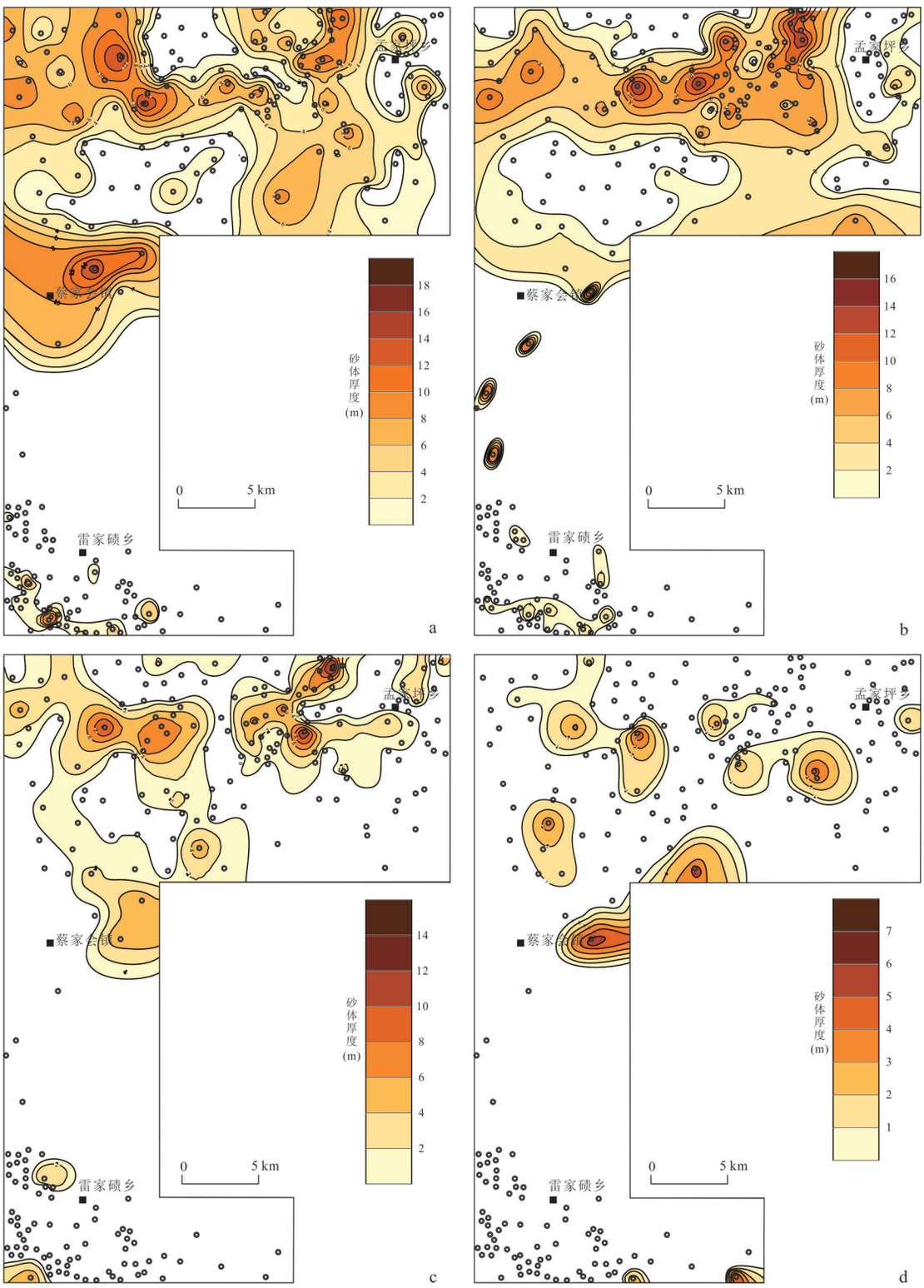

图 8 临兴中区太原组下段大型复合潮道砂体时空演化

Fig.8 Temporal and spatial evolution map of large-scale tidal sandbodies in the lower member of Taiyuan Formation, Linxing Middle Block

a. P_1t^{2-1}时期砂体厚度;b. P_1t^{2-2}时期砂体厚度;c. P_1t^{2-3}时期砂体厚度;d. P_1t^{2-4}时期砂体厚度

海岸沉积环境下的潮汐水道的典型标志.从 P_1t^{2-3} 小层开始,沉积水动力条件开始减弱,砂岩厚度明显变薄,上部主要发育泥岩、粉砂岩,局部夹薄煤层.至 P_1t^{2-4} 小层,沉积了较厚的泥岩、泥灰岩和

煤层等细粒沉积物,仅局部夹薄层砂岩.

3.2　砂体时空分布特征

3.2.1　垂向分布特征　太原组下段主要发育由$P_1t^{2\text{-}1}$、$P_1t^{2\text{-}2}$和$P_1t^{2\text{-}3}$小层构成的大型复合潮道(图6和图7),顶部则沉积较厚的泥岩、煤层和灰岩段($P_1t^{2\text{-}4}$),底部与泥岩或发育稳定的本溪组顶部8+9#煤层相接触.从单井特征看,太原组下段底部砂体十分发育,API值负向变化幅度超出基线值8~10倍,底部*GR*测井曲线形态以漏斗型、箱型为主,向上钟型增多,上部则为多个钟型或指型的叠合.从剖面特征看,该套砂体在不同钻孔所呈现的厚度差别较大,东西向连井剖面显示中部厚度大,最大可达37.7 m,但向两翼迅速变薄并相变为粉砂岩、泥岩等(图6a和图7);而南北向剖面则表现为北厚南薄的展布特征(图6b).故该砂体空间上呈现为不规则的复合透镜体,与其对应的地震剖面上亦显示该砂体呈明显透镜状特征(图7),表明其沉积环境有别于河流或三角洲相分流河道砂体.

3.2.2　平面演化特征　编制的各小层砂体厚度图(图8)显示,$P_1t^{2\text{-}1}$、$P_1t^{2\text{-}2}$和$P_1t^{2\text{-}3}$砂体的平面分布趋势总体特征相似,沉积具有继承性.其中,$P_1t^{2\text{-}1}$和$P_1t^{2\text{-}2}$时期砂体最为发育(图8a, 8b),平均厚度分别为5.61 m和5.99 m,而$P_1t^{2\text{-}3}$时期的砂体厚度则明显变薄,平均厚约4.2 m,分布范围进一步缩窄(图8c).至$P_1t^{2\text{-}4}$时期,以细粒沉积物为主,砂岩仅局部孤立发育(图8d).上述研究表明,太原组下段大型复合潮道的沉积过程具有旋回性,且随着水动力条件由强变弱,其发育呈现出由奠基发展阶段至鼎盛发育阶段($P_1t^{2\text{-}1}$→$P_1t^{2\text{-}2}$),再到衰退消亡阶段($P_1t^{2\text{-}3}$→$P_1t^{2\text{-}4}$)的演变过程.

4　大型复合潮道砂体含气性差异分析

4.1　大型复合潮道与下伏8+9#煤层空间配置关系

本溪组顶部的8+9#煤层是石炭系-二叠系主要的煤系烃源岩之一,是天然气聚集成藏的重要物质基础.编图显示8+9#煤层厚度变化于0.92~16.37 m,平均厚约7.11 m,富煤区主要分布于研究区的东北部、西部、北部以及南部(图9a).本溪组8+9#煤层的空间分布与上覆太原组下段大型复合潮道具有密切关系,即在潮道砂体发育且厚度最大的区域,8+9#煤层厚度显著减薄(图4a,图9a),特别是在研究区中东部的孟家坪乡一带尤为明显,表明二者具有明显的负相关关系.从典型砂体剖面看,该大型复合潮道在局部地段直接向下伏地层下切,在这些部位,底部煤层明显分叉变薄(图7,图9b),表明太原组下段大型复合潮道砂体对下伏8+9#煤层存在强烈的冲刷作用,这与前人研究一致(陈钟惠等,1989;陈钟惠和武法东,1993;王华等,2001).

野外露头调查发现太原组下段潮道砂体内部的冲刷面处存在大量煤屑,且越靠近砂体底部,煤屑数量越多、规模越大,其中最大的煤屑透镜体长约1 m,厚约0.3 m,具有磨圆性质(图9c).这是由于在这套透镜状厚砂体的强烈冲刷下切作用下,煤层被破坏,形成大量煤屑被搬运进入砂体,最终以滞留沉积物的形式堆积在冲刷界面处.上述研究表明,太原组大型复合潮道砂体直接就位于区域优质煤系烃源岩之上,空间上形成了有利的"生储盖"成藏组合;但受该砂体强烈的冲刷下蚀作用,局部地段的煤层被破坏,可能会对砂体含气性产生不利影响,这将在后续讨论中进一步加以举证分析.

4.2　沉积微相分布与含气性耦合关系

根据对太原组下段处于不同沉积时期($P_1t^{2\text{-}1}$、$P_1t^{2\text{-}2}$、$P_1t^{2\text{-}3}$和$P_1t^{2\text{-}4}$)的大型复合潮道砂体内部有效气层厚度的平面编图,分别圈定了含气单元及储层甜点,主要分布于研究区西北、北部(图10).在大型复合潮道的奠基发展-鼎盛发育阶段($P_1t^{2\text{-}1}$和$P_1t^{2\text{-}2}$时期),潮汐水道和砂坪分布范围广大,砂体厚度大(图8a, 8b),而含气单元的展布形态亦与之高度重合,且储层甜点数量增多,如代表性甜点TD1-1和TD2-1的有效气层厚度分别为6~10 m和4~8 m,发育规模(长度/宽度)分别为6.5 km/1.5 km和7.4 km/0.6 km,并显示出向东部迁移的趋势(图10a, 10b).至$P_1t^{2\text{-}3}$和$P_1t^{2\text{-}4}$时期,总体继承了早期沉积格局,但潮道和砂坪的发育规模均显著减小(图8c),沉积环境开始由潮下带向潮间带-潮上带过渡,该大型复合潮道进入衰退-消亡期,含气单元分布范围亦明显缩窄且彼此孤立分布,甜点仅分布于潮道中心,沿走向分布,如TD3-2的发育规模(长度/宽度)为7.0 km/0.7 km,但有效气层厚度减薄至2~4 m(图10c).至$P_1t^{2\text{-}4}$,潮间带-潮上带的低能沉积(泥坪和泥灰坪)几乎占据了整个研究区,由于砂体不甚发育(图8d),故含气性未见显示(图10d).

大型复合潮道砂体内部含气单元、储层甜点与沉积微相的空间叠合关系分析显示(图10),含气单

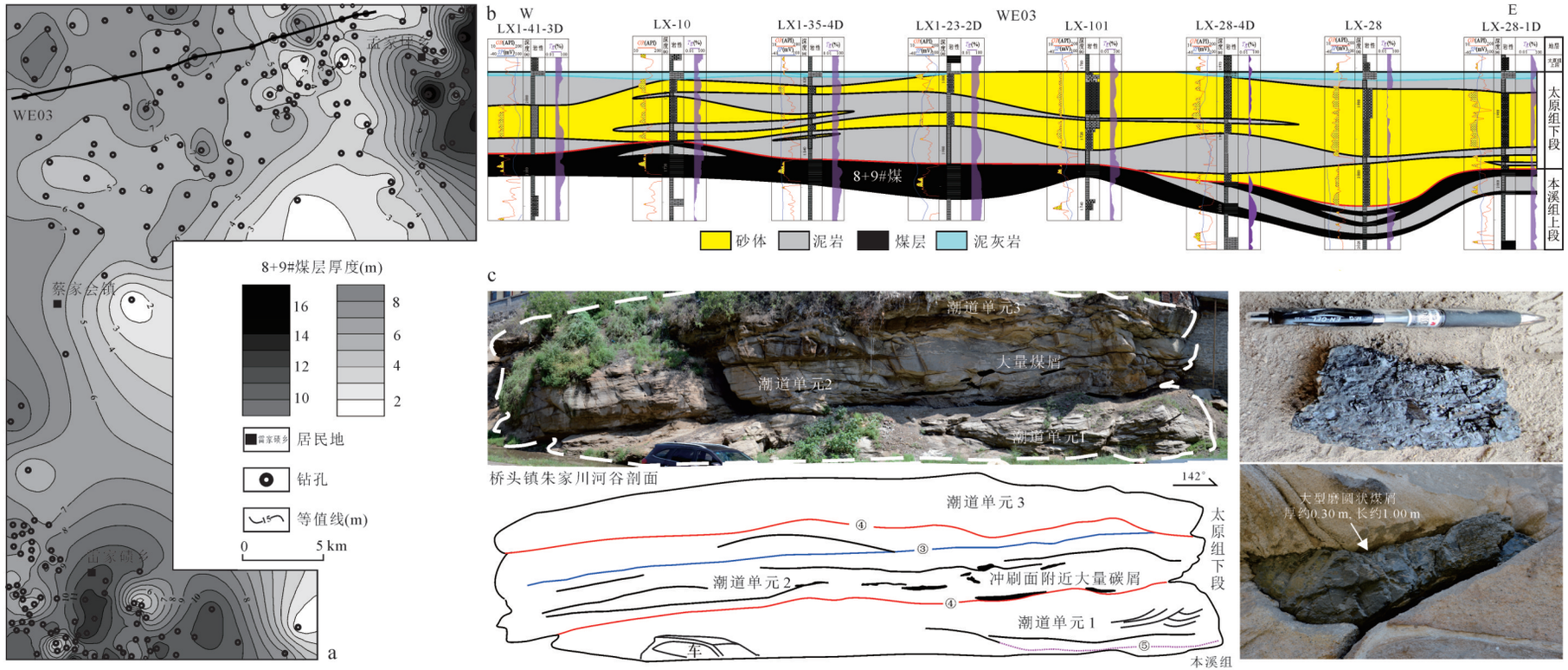

图9 临兴中区太原组下段大型复合潮道与下伏8+9#煤层的空间配置关系

Fig.9 The spatial configuration relationship between the large-scale complex tidal channel sandbody of the lower member of Taiyuan Formation and the underlying 8+9# coal seams of the Benxi Formation in Linxing Middle Block

a. 本溪组8+9#煤层厚度; b. 大型复合潮道与下伏本溪组8+9#煤层空间叠置关系, 剖面位置见图a; c. 大型潮道砂体露头内部构成特征

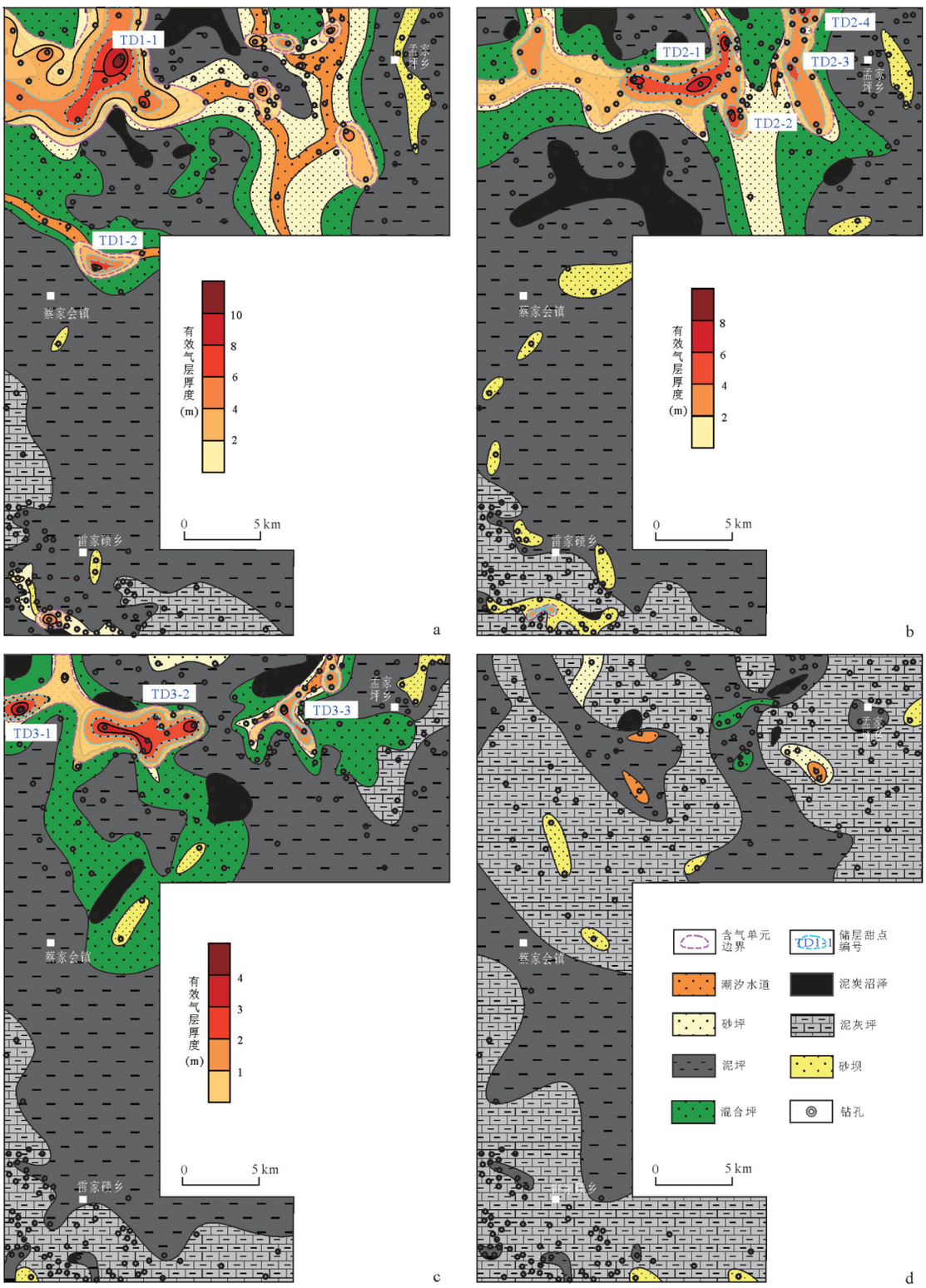

图 10　临兴中区太原组下段沉积微相与含气单元、储层甜点的空间耦合关系

Fig.10　Spatial distribution characteristics of sedimentary facies and gas bearing units of the lower member of Taiyuan Formation in Linxing Middle Block

a. $P_1t^{2\text{-}1}$时期;b. $P_1t^{2\text{-}2}$时期;c. $P_1t^{2\text{-}3}$时期;d. $P_1t^{2\text{-}4}$时期

元与储层甜点的长轴方向常与潮汐水道的优势展布方向相一致,且在潮汐水道的中心处,有效气层厚度最大(4~8 m),含气性最为优越;其次是在潮道的边缘和砂坪,有效气层厚度介于 2~4 m.从典型

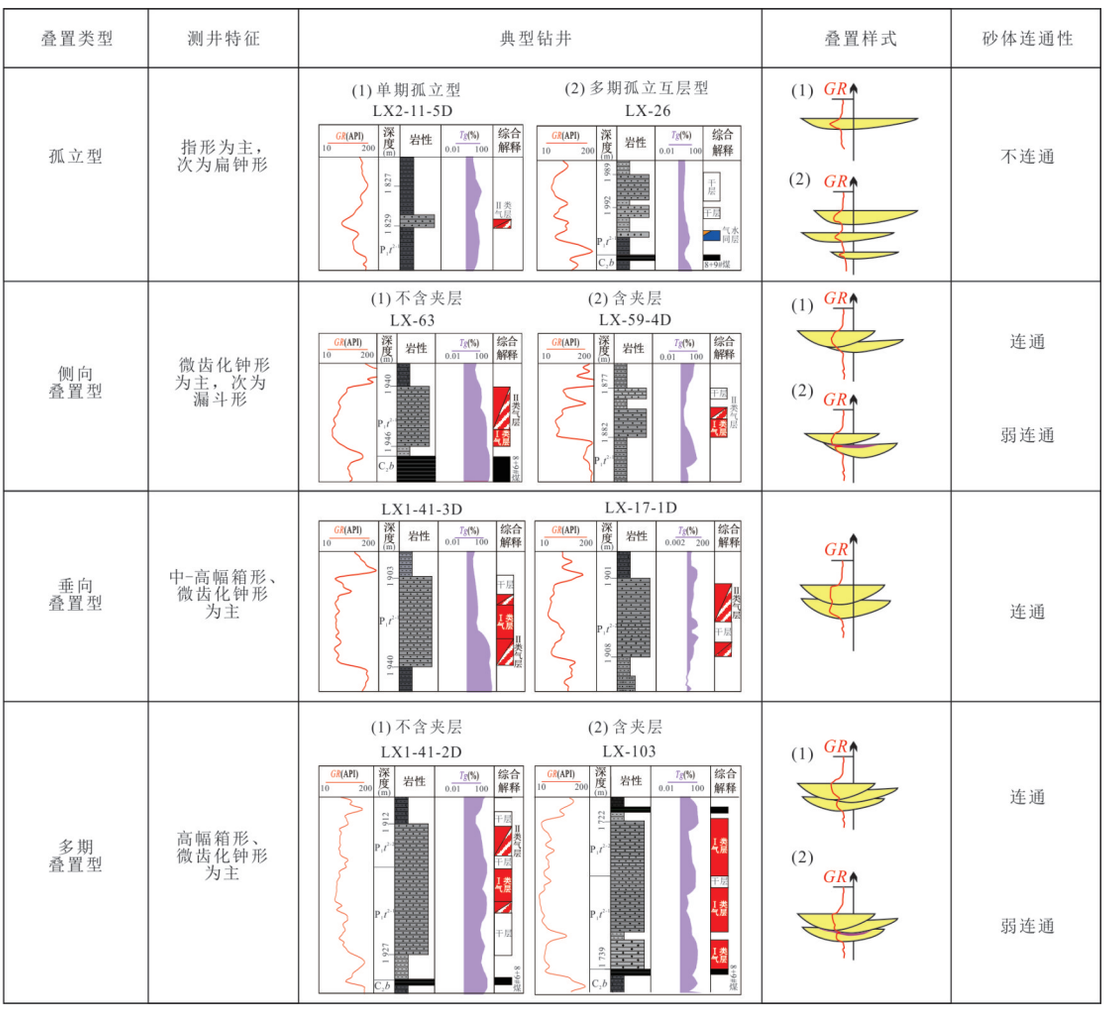

图 11 临兴中区太原组下段大型复合潮道的砂体叠置型式及特征

Fig.11 The large-scale complex tidal channel sandbody stacking types and its characteristics of the lower member of Taiyuan Formation in Linxing Middle Block

剖面看(图 7),位于潮下带内的大型复合潮道砂体厚度大且横向上分布稳定、延伸较远,是最为有利的含气储层;而潮间带内的砂坪和小型潮道厚度减小(图 11),且砂体间泥质夹层增多,不利于气体的垂向运移,故有效气层厚度也较薄;潮上带内主要为细粒沉积物,储层不发育.上述分析结果一致表明,沉积微相是制约含气单元及储层甜点空间展布的第一控制要素,且在不同沉积演化时期,含气性分布具有明显差异,故在致密气勘探实践中应对目的层砂体进行分层评价与预测.

4.3 砂体叠置型式与含气性差异分布

4.3.1 砂体叠置型式及特征 基于对单砂体形态、厚度及垂向叠置关系的精细分析,在大型复合潮道内部识别出 4 种砂体叠置类型(图 11 和图 12),分别为孤立型、侧向叠置型、垂向叠置型以及多期叠置型.

(1)孤立型(LT):该类型砂体一般呈单期或多期的孤立透镜状分布于潮道边缘,厚度变化于 0.7~3.0 m,均厚约 1.7 m,横向延伸距离小于 600 m,连通性差,表明潮道水动力条件较弱,沉积物供给不足.

(2)侧向叠置型(LST):该类型砂体是由相邻两期潮道在横向上切割叠置所形成,砂体厚度变化于 1.1~6.7 m,均厚约 3.2 m.该类型砂体厚度变化稳定,横向延伸距离 0.7~1.7 km,连通性较好,反映潮道侧向迁移明显.

(3)垂向叠置型(VST):该类型砂体是由相邻两期或多期潮道在垂向上相互叠置形成,夹层极少,砂体厚度变化于 3.6~10.6 m,均厚约 5.8 m.此类砂体具有纵向连通性好,但横向上延伸距离较短(0.8~1.1 km),连通性相对较差的特点,反映河道侧向迁移少,沉积过程以垂向加积作用为主.该类

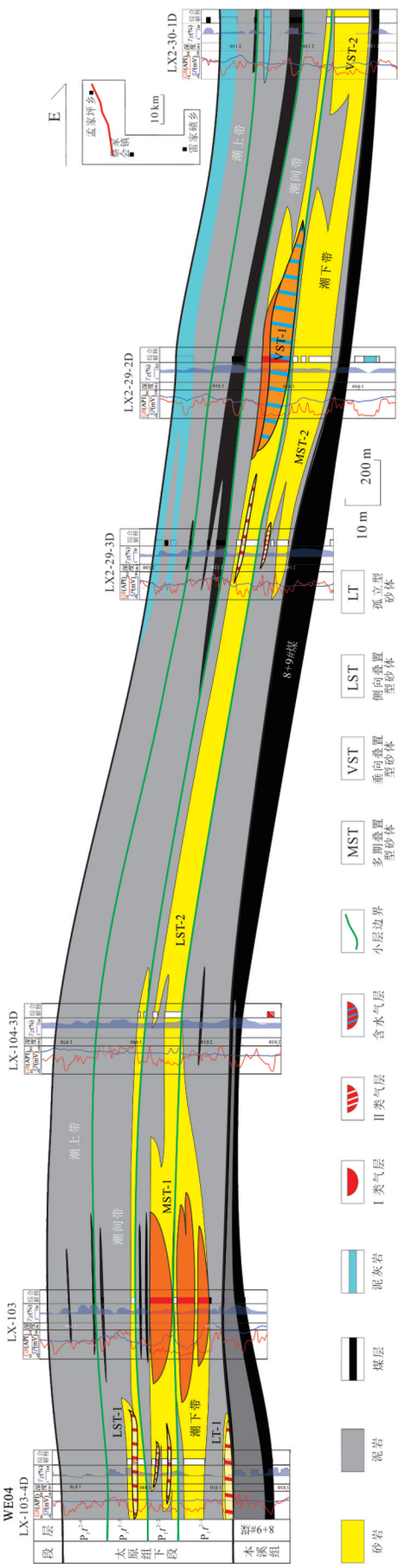

图12　临兴中区太原组下段大型复合潮道内部不同叠置型式砂体的连通性及含气性特征

Fig.12　Connectivity and gas bearing characteristics of large-scale complex tidal channel sandbody with different stacking types of the lower member of Taiyuan Formation in Linxing Middle Block

表 1　临兴中区太原组下段大型复合潮道内部不同叠置型式砂体含气性统计

Table 1　Statistical data of gas content in large-scale complex tidal channel sandbodies of different stacking types in the lower member of Taiyuan Formation in Linxing Middle Block

叠置类型	Ⅰ类气层(m)	Ⅱ类气层(m)	含水气层(m)	干层(m)
孤立型	1.53	10.62	0.90	29.48
侧向叠置型	11.76	27.87	0	49.51
垂向叠置型	56.45	57.63	7.05	109.03
多期叠置型	101.66	115.30	7.86	335.94
总计	171.40	211.42	15.81	523.96

注:上述厚度均为累计厚度.

型砂体由于整装性较好,具备构成良好储层的潜力.

(4)多期叠置型(MST):该类型砂体是由多期潮道在垂向上和横向上相互切割叠置所形成,故具有较好的连通性.砂体厚度变化于 5.0～13.2 m,均厚约 7.8 m,夹层厚度多小于 0.6 m 且数量少,砂岩厚度占比超过 90%,*GR* 测井曲线呈微齿化箱型、钟型.该叠置类型砂体呈厚层状分布,且横向上具有一定的延伸距离(0.7～1.6 km),表明潮道亦具有侧向迁移特征,沉积过程以垂向加积和侧向加积作用为主.与其他 3 类砂体相比,多期叠置型砂体是区内潜在的优质储层.

4.3.2　不同叠置型式砂体含气性分析　对 63 口代表性钻孔中太原组下段大型复合潮道内部 4 种叠置类型砂体的含气性进行统计,结果显示砂体累计总厚为 922.59 m,其中干层总厚度为 523.97 m,占砂体总厚度的 56.8%(表 1,图 13a).从砂体叠置类型看,多期叠置型砂体的Ⅰ类气层、Ⅱ类气层的累计厚度均为最大,其次是垂向叠置和侧向叠置型,其有效气层(包括Ⅰ类气层和Ⅱ类气层)累计厚度分别为 216.96 m、114.08 m 和 39.63 m,而孤立型砂体中的Ⅰ类气层几乎不发育,Ⅱ类气层累计厚度仅为 10.62 m.整体上,太原组下段砂体的总有效气层厚度占比为 41.3%,其中垂向叠置和侧向叠置型的有效气层厚度占比较高,分别为 49% 和 43.2%,其次为多期叠置型,占比为 38.7%,而孤立型最低,为 28.6%.上述结果表明砂体叠置类型是含气性优劣的关键影响因素.

由于沉积作用的不均一性,致使砂体规模、连通性以及物性条件等产生明显差别,这也造成了不同叠置类型砂体内部含气性的差异.首先,沉积微

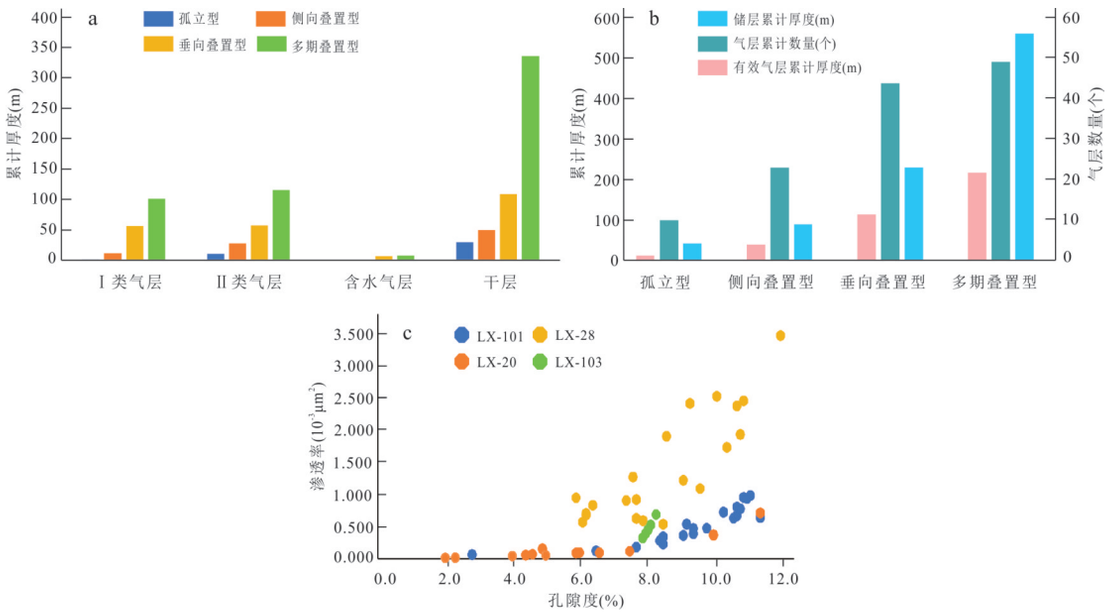

图 13　临兴中区太原组下段大型复合潮道内部不同叠置型式砂体含气性统计直方图与孔渗分布特征

Fig.13　Statistical histograms of gas content and pore permeability distribution characteristics of large-scale complex tidal channel sandbodies with different stacking types in the lower member of Taiyuan Formation in Linxing Middle Block

a. 不同叠置类型砂体含气性分布；b. 不同叠置类型砂体主要参数对比；c. 不同叠置型式砂体孔渗分布特征，LX-101 为垂向叠置型，见气层、差气层，砂坪相或潮道边缘；LX-20 为侧向叠置型，全部为干层，潮道边缘相；LX-28 为多期叠置型，见气层、差气层，潮道中心；LX-103 为垂向叠置型，为气层，近潮道中心，钻孔位置见图 14

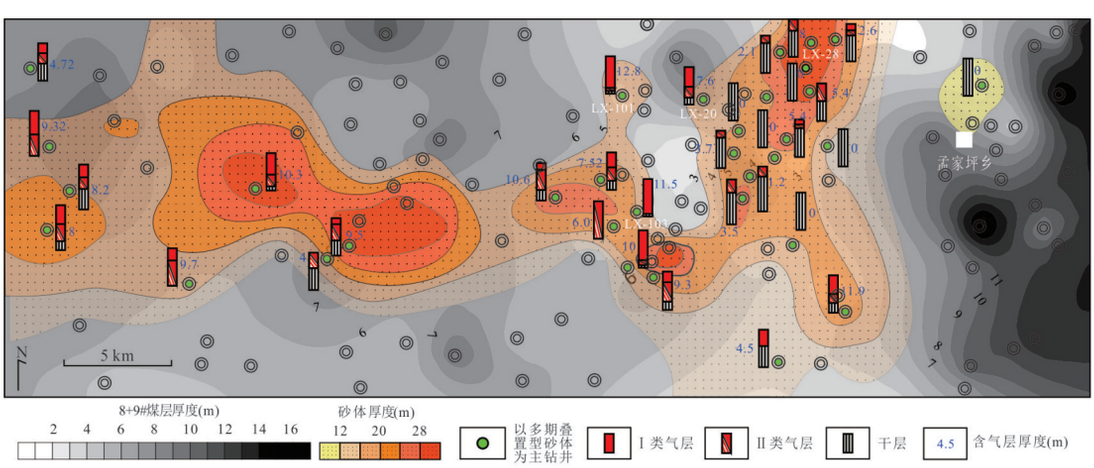

图 14　临兴中区北部太原组下段大型复合潮道内部多期叠置型砂体的含气性分布及与下伏 8＋9#煤层的空间叠合关系

Fig.14　Gas bearing distribution of multi-stage stacked sandbodies in the lower member of the Taiyuan Formation in the northern part of Linxing Middle Block and their spatial superposition relationship with the underlying 8＋9# coal seam

相控制着砂体的发育规模(图 10)，而后者与含气性具有正相关性，当砂体规模越大时则越有利于含气层的发育，如多期和垂向叠置型砂体的厚度大，发育的气层数量和有效气层厚度也更大(图 13b)．其次，砂体叠置型式直接决定了砂体内部在纵向与横向上的连通性，多期与垂向叠置型砂体较侧向叠置和孤立型砂体的含气性明显更好，这是因为受多期潮道在垂向与侧向上的下切与侵蚀作用，打破了低渗透物性边界的制约，使单砂体间贯通起来，扩大了储集空间，有利于形成联系紧密的更大规模含气系统．

以典型剖面 WE04 为例，太原组下段大型复合潮道的砂体叠置类型以多期叠置和垂向叠置型为主(图 12)，最大厚度分别为 16.70 m 和 9.75 m，构成了该复合潮道的主体．侧向叠置型砂体厚约 4.52～6.40 m，横向上具有稳定延伸；孤立型砂体则较少，仅厚约 2.81 m．在多期叠置型砂体 MST-1 核

部,垂向上含3层Ⅰ类气层,厚度分别为3.28 m、4.96 m和6.42 m,边缘部位则仅见少量Ⅱ类气层.MST-2虽然也具备较厚砂体,但含气性差,全部为干层.同样地,垂向叠置型砂体VST-1与VST-2也具有类似的分布规律.而侧向叠置和孤立型砂体仅含少量Ⅱ类气层.上述结果表明多期叠置和垂向叠置型砂体因其具备较厚的储层规模且在垂向上具有良好的连通性,因而是含气性最为优越的砂体叠置型式.但在相同叠置型式砂体内部,含气性分布仍具有较大差异,以多期叠置型砂体为例,含气层的孔渗性明显要比干层更好(图13c),表明物性条件是砂体内部影响含气性分布的本质因素.

研究表明,含气性好的多期叠置型砂体主要位于研究区西部;而东部地区(即太原组潮道最厚、下伏8+9#煤层最薄的区域)的多期叠置型砂体则多为干层或仅含差气层(图14).这可能指示了由于底部烃源岩遭受上覆砂体强烈的冲刷作用,近生近储的成藏过程被迫中断,导致该区段内气体规模锐减.另外,西部砂体的物性总体要较东部更好,表明区内沉积、成岩非均质性较强,下一步研究将重点予以关注.

5　结论

(1)鄂尔多斯盆地东缘临兴中区太原组下段石英砂岩的成分与结构成熟度均较高,并具有典型的双向古水流特征,剖面上显示出潮坪沉积成因相组合特色,且在砂体两侧均发育有较厚的煤层,由此确认其为潮坪沉积体系.潮汐水道和砂坪为有利沉积微相,且潮汐水道对下伏本溪组8+9#煤层具有强烈的冲刷作用.

(2)太原组下段可划分为4个小层($P_1t^{2\text{-}1}$至$P_1t^{2\text{-}4}$).大型复合潮道砂体平均厚约10.24 m,空间上呈北厚南薄舌状、东西透镜状展布,其沉积过程具有旋回性,遵循"奠基发展-鼎盛发育($P_1t^{2\text{-}1}$、$P_1t^{2\text{-}2}$)→衰退-消亡($P_1t^{2\text{-}3}$、$P_1t^{2\text{-}4}$)"的旋回性规律.

(3)研究区太原组下段大型复合潮道的砂体叠置型式可划分为多期叠置型、垂向叠置型、侧向叠置型和孤立型.多期和垂向叠置型砂体厚度大、连通性好、含气性优,是区内潜在优质储层.含气性差异受多因素控制:沉积微相是首要控制因素,决定了含气单元的整体分布;砂体叠置型式是次要控制因素,影响了含气系统的规模与连通性;砂体内部物性(孔渗)差异是导致含气性分异的本质原因.研究成果对临兴中区深部煤层气与致密砂岩气的协同勘探具有重要指导意义.

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