

文章编号:1009-9603(2022)05-0058-09

DOI:10.13673/j.cnki.cn37-1359/te.202108060

分频融合技术在致密砂岩储层预测中的应用

——以川东北通南巴背斜侏罗系为例

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摘要:为解决因波阻抗差异小导致的致密砂岩储层预测困难的问题,提出基于分频融合技术的河道刻画与储层“甜点”预测方法。该方法将目标砂体与地震频谱建立非线性映射关系,形成具有通频信息的混频数据体,并建立具有宏观地质意义的相控模型,进而开展高分辨率反演确定致密砂岩储层“甜点”分布。以通南巴背斜侏罗系千一段致密砂岩为研究对象,应用分频融合技术高精度刻画千一段沉积早期的河道分布。基于混频数据体的高分辨率反演结果表明,研究区千一段河道砂体孔隙度小于6%,背斜处孔隙度较高(4%~6%)。河道内砂体横向分布稳定,其中脆性砂体(自然伽马小于65 API)厚度变化较快,背斜处脆性砂体厚度一般大于20 m。储层预测结果显示千一段背斜带河道砂体具有厚度大、脆性好、孔隙度高、埋藏浅的特点,是千一段“甜点”发育区,也是未来致密储层改造的有利靶区。

关键词:分频融合;侏罗系;致密砂岩;“甜点”;通南巴背斜

中图分类号:TE122.2

文献标识码:A

Application of spectral decomposition and fusion technology in predicting of tight sandstone reservoirs: A case of Jurassic strata of Tongnanba anticline in northeastern Sichuan

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Abstract: In order to solve the difficult problem of tight sandstone reservoir prediction due to the small difference of wave impedance, this paper presents a prediction method for channel characterization and “sweet spot” based on the spectral decomposition and fusion technology. In this method, the nonlinear mapping relationship between the target sand body and the seismic spectrum was established to form a mixed data volume with direct frequency information, and a facies control model of macroscopic geological significance was constructed. In this way, the high-resolution inversion was performed to determine the distribution of “sweet spots” in tight sandstone reservoirs. By taking the tight sandstone in the Jurassic Qianyi Member of Tongnanba anticline as the research object, the early channel distribution of Qianyi Member was accurately described by spectral decomposition and fusion technology. The high-resolution inversion results based on mixed data volumes reveal that the porosity of channel sand bodies in Qianyi Member is less than 6%, and the porosity at the anticline is high (4%–6%). The horizontal distribution of sand bodies in the channel is stable, where the thickness of the brittle sand bodies (with gamma-ray (GR) less than 65 API) changes rapidly and is generally more than 20 m at the anticline. The reservoir prediction results indicate that the channel sand bodies in Qianyi Member of the anticline belt feature large thickness, good brittleness, high porosity, and shallow burial depth, which are not only the “sweet spots” development areas in Qianyi Member but also favorable target areas for tight reservoir stimulation in the future.

Key words: spectral decomposition and fusion; Jurassic; tight sandstone; “sweet spot”; Tongnanba anticline

收稿日期:2021-08-11。

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基金项目:“十三五”国家科技重大专项“深层礁滩相高含硫气藏稳产技术政策”(2016ZX05017-001),中国石化科技攻关项目“通南巴地区陆相天然气主控因素与储量评价研究”(P19012-4)。

分频融合技术是基于频谱成像原理对岩相组合形态进行描述,并对储层预测进行分析的技术,能够有效地提高储层几何形态描述与储层预测的精度^[1-2]。目前,分频融合技术已得到广泛应用并取得了良好的应用效果,尤其在河道识别、断裂精细刻画、碳酸盐岩缝洞型储层预测等方面取得了巨大的成功。曹鉴华利用分频融合技术成功地预测了河道体系的平面展布^[3];岳大力等基于分频融合技术对埕岛油田曲流带进行了预测并对曲流河沉积微相进行了精细解剖^[4];杨玉杰等采用分频融合技术精细分析了塔河油田东部奥陶系碳酸盐岩地层古水系的分布,提高了小尺度河道的识别精度^[5-7];侯海龙等将分频融合技术应用于碳酸盐岩储层预测^[8-10];代冬冬等采用分频融合技术对碳酸盐岩台地岩溶风化壳明河与暗河的分布进行了研究^[11-12]。前人对分频融合技术的应用主要集中在沉积现象的定性描述,在致密砂岩储层“甜点”的定量预测上极少进行研究。

川东北地区通南巴背斜侏罗系河道砂岩为致密储层,横向空间分布与纵向叠置上表现出强烈的非均质性,对该类储层“甜点”预测困难成为制约其有效动用开发的关键问题。为此,笔者应用分频融合技术精确确定研究目标砂体的展布范围,建立具有宏观地质意义的相控模型,在相控范围内建立起

储层砂体厚度、物性与地震波阻抗之间的映射关系,通过叠后高分辨率反演定量预测脆性砂岩储层厚度与孔隙度的分布,明确“甜点”储层发育区,为川东北地区侏罗系致密砂岩储层天然气勘探提供技术支撑。

1 区域地质背景

川东北地区通南巴背斜位于米仓山与大巴山冲断带叠合区,由通南巴背斜、池溪凹陷与通江凹陷构成^[13-17]。米仓山向南挤压形成通南巴背斜 NEE—SWW 向主体构造,大巴山逆冲推覆带向西挤压形成通南巴背斜 NNW—SSE 走向的断层和褶皱^[18],最终定型形成现今的构造格局^[19-20](图 1)。千佛崖组沉积时期,川东北地区邻近造山带,侏罗系整体为一套以河流-三角洲沉积为主的典型陆源碎屑沉积。早侏罗世,受燕山运动 I 幕影响,南秦岭碰撞造山带发生逆冲推覆,大巴山构造带剧烈隆升,川东北地区在万源—通江—巴中一线,由北向南西方向发育河流冲积平原-辫状河三角洲-滨浅湖沉积体系,岩性主要为灰色石英砂岩、泥岩以及深灰色砂岩,至千佛崖组沉积晚期,开始出现紫红色砂泥岩,但砂岩的成分成熟度和结构成熟度低,交错层理、底冲刷构造常见,为明显的河流相特

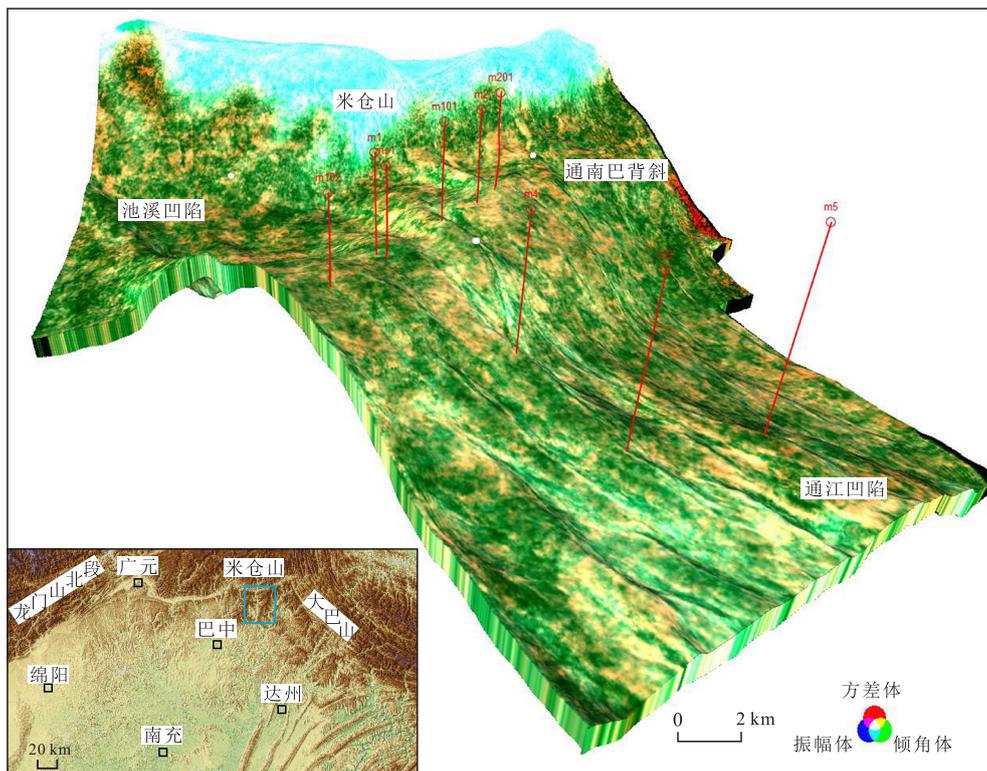


图1 研究区位置及地貌特征

Fig.1 Geographical location and geomorphic characteristics of study area

征。通南巴背斜位于米仓山山前构造带,物源供给充足,广泛发育河流碎屑岩沉积,湖盆水体明显变浅,以长距离分流河道为显著特点^[21]。分流河道砂岩储层具有明显的低孔低渗透特征,孔隙度小于3.2%,渗透率小于1 mD。

2 砂岩储层预测技术

2.1 河道刻画

邹才能等认为,“相控论”是油气勘探由构造油气藏向岩性油气藏转变的关键,基于高分辨率三维地震数据的高精度沉积相带(储层岩性组合)刻画与储层预测是“相控论”可以成功实践的基础^[22]。针对致密砂岩储层的高精度刻画提出了一种基于目标岩性体(储层)频谱特征,应用分频融合技术刻画储层岩性展布范围与几何形态的方法,其理论基础是同一沉积相带具有“同期次”、“同频谱”的特征,即在同一沉积时期(储层岩性对比不能穿时)的岩性组合具有相同或者相近的频谱分布。不同频率段的振幅调谐体可以定量表征储层在岩性组合与厚度上的差异。地震的低频可以有效地表征单一厚层岩性的分布,如以厚层砂岩为主要沉积物的河床滞留沉积;中高频段对砂泥岩交互的薄储层表征较好,如三角洲前缘亚相。目标岩性组合的不同频率振幅调谐体应用RGB混色融合技术进行融合,形成具有通频信息的融合数据体,该融合数据体突出不同主频数据体对沉积体的分辨能力,克服单一频率对地质异常体反映的片面性,尤其对具有明显几何形态的特殊地质异常体,如盐丘、河道、断裂等具有良好的分辨效果^[23-25]。

采用分频融合技术对沉积体几何形态与展布范围的刻画主要包括3个方面:首先,分析明确岩性组合(研究目标)的地震频谱响应特征,确定岩性组合的有效频带分布与主频。其次,通过谱分解技术建立起目标岩性组合的不同频率的振幅调谐体。最后,采用RGB混色融合技术描述沉积体几何形态与展布范围。

通南巴背斜千一段发育两期河道,地震反射特征表现为强振幅反射,钻井揭示两期河道的测井相主要为厚层箱状特征。早期(第1期)河道以m102井为代表,储层目标岩性的低频为10 Hz,主频(中频)为20 Hz,高频为40 Hz;晚期(第2期)河道以m101与m1井为代表,储层目标岩性的频率相同,低频为20 Hz,主频(中频)为40 Hz,高频为60 Hz(图2)。因此,同一沉积时期的储层具有相同或者相近

的频谱分布,而不同沉积时期的储层频谱差异较大。以千一段沉积早期河道为例,采用低频10 Hz反映河道主体(河床滞留沉积),主频20 Hz反映河流整体全貌沉积(该频率兼顾低频与高频的部分特征),以高频40 Hz补充砂泥岩互层的分布,通过RGB混色融合技术形成新的通频融合数据体,完成河道边界的刻画(图3)。河道主要为曲流型河道,呈蜿蜒曲折的流路,呈NE—SW向展布,具有埋藏浅、分布广、面积大的特点。南部通江凹陷河道在研究区内分布极为有限,河道长度较小,根据平面展布形态初步认为该河道为高弯度曲流型。

2.2 致密砂岩储层“甜点”预测

以分频融合技术为基础的致密砂岩储层“甜点”预测是一种基于相控的高分辨率反演的储层预测方法。该方法有效解决了因储层致密性导致的储层与围岩或非储层之间在层速度、密度与阻抗等地球物理参数差异较小,基于阻抗的叠后储层反演预测困难的问题。通过分频融合技术将目标地质体从时间域转换到频率域,刻画目标地质体的展布范围,建立目标储层相控模型。该模型一方面明确储层与非储层之间的边界,约束反演过程中的模型插值范围,提高储层反演的预测精度;另一方面建立具有通频信息的混频地震数据体,压制非储层地震响应的同时提高信噪比,改善目标地质体地震反射的连续性,提高地震资料品质^[26-27]。但由于相控范围内岩性较为单一,岩性的阻抗差异不大,基于阻抗差异进行岩性的区分存在困难,为此通过储层敏感参数特征曲线重构,在分频融合技术确定的有利岩相范围内,进一步提高岩性差异的分辨率,识别脆性砂岩的厚度^[28-30],有效区分相控模型内储层岩性的细微差异。

以通南巴背斜千一段第1期河道为例,选取北部埋藏较浅且大面积展布的曲流河道为研究目标。该河道以砂岩为主,自然伽马为44~75 API,河道主体即河床滞留沉积自然伽马小于55.2 API,砂体横向分布稳定,呈强振幅连续反射特征,纵波阻抗与自然伽马交会分析显示基于阻抗反演无法识别岩性的差异(图4a),而岩性与自然伽马曲线有良好的相关性,通过以声波曲线为载体,利用自然伽马曲线对声波曲线进行重构,建立新的波阻抗曲线,该曲线与岩性之间具有明显的线性相关性(图4b)。

在阻抗反演的基础上计算自然伽马小于65 API的砂岩厚度,结果显示河道内脆性砂体厚度变化较快,非均质性强(图5a),背斜构造带处河道砂岩储层厚度较大,一般大于20 m,北部池溪凹陷的储层

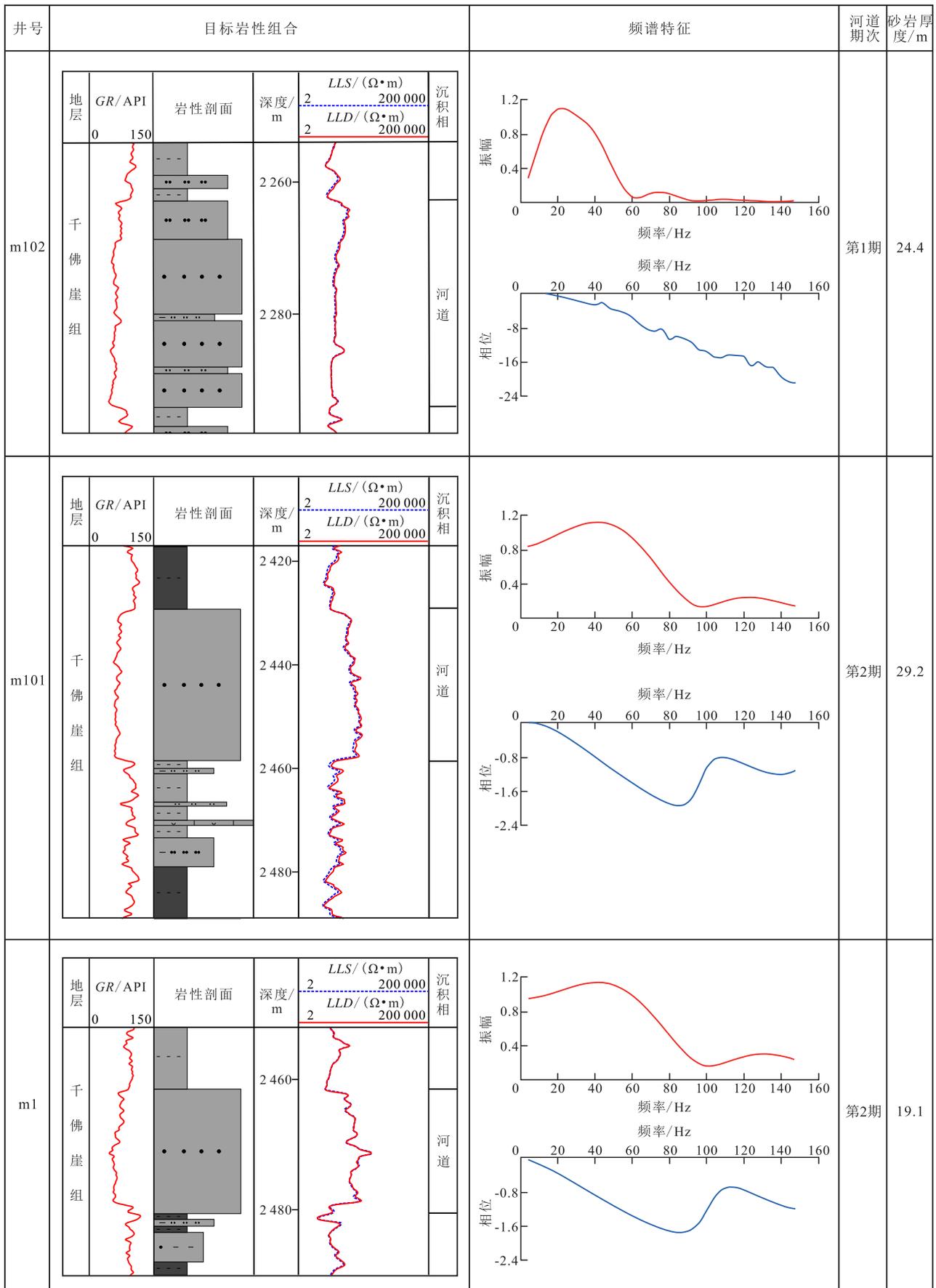


图2 通南巴背斜千一段河道沉积频谱特征

Fig.2 Spectral characteristics of channel deposit in Qianyi Member of Tongnanba anticline

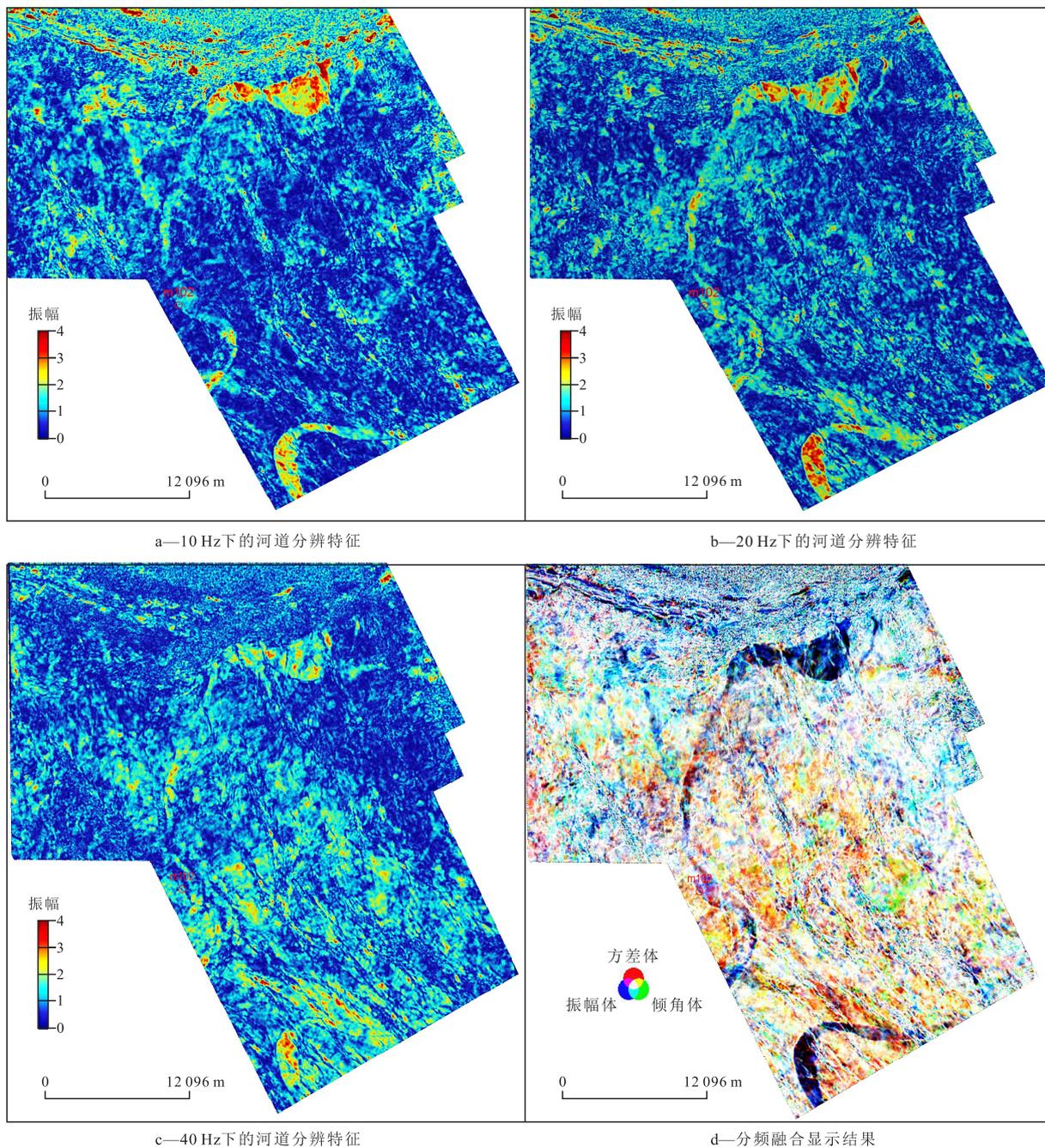


图3 千一段第1期河道不同频率下的分辨特征与分频融合显示结果

Fig.3 Channel resolution characteristics and spectral decomposition and fusion display results at different frequencies in first-stage channel of Qianyi Member

厚度较小(图6a)。致密砂岩储层的物性对甜点分布至关重要,千一段河道砂岩内孔隙度与原始纵波阻抗相关性较好(相关系数为0.73)(图4c),通过原始阻抗反演可获得孔隙度预测的分布范围,反演结果显示河道砂岩孔隙度小于6%(图5b),具有致密性、非均质性强及局部孔隙发育的特点,孔隙发育主要集中于背斜带附近(图6b)。结合砂体厚度分布与孔隙度分布分析,背斜带高部位河道砂体厚度大、脆性好、孔隙度相对较高、埋藏浅,是千一段“甜

点”发育区。

3 结论

分频融合技术可以更好地将目标砂体与地震频谱建立起非线性映射关系,可以提供更加准确和更高精度的砂体平面展布范围,建立起具有宏观地质意义的相控模型用以约束反演过程中的插值范围,使储层预测的反演结果具有相控和高分辨率的

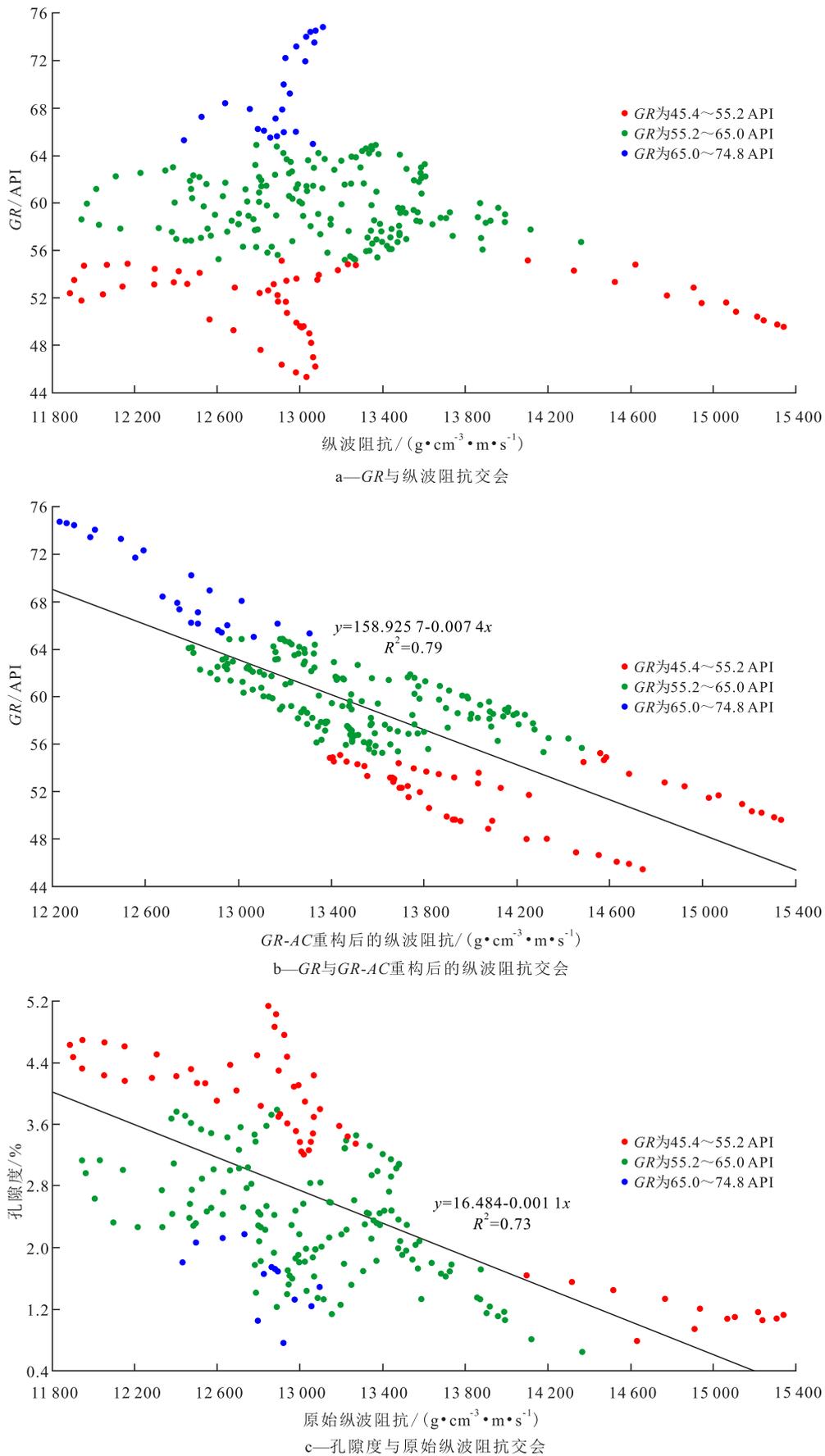


图4 自然伽马、孔隙度与纵波阻抗交会图

Fig.4 Cross plots of GR, porosity, and P-wave impedance curves

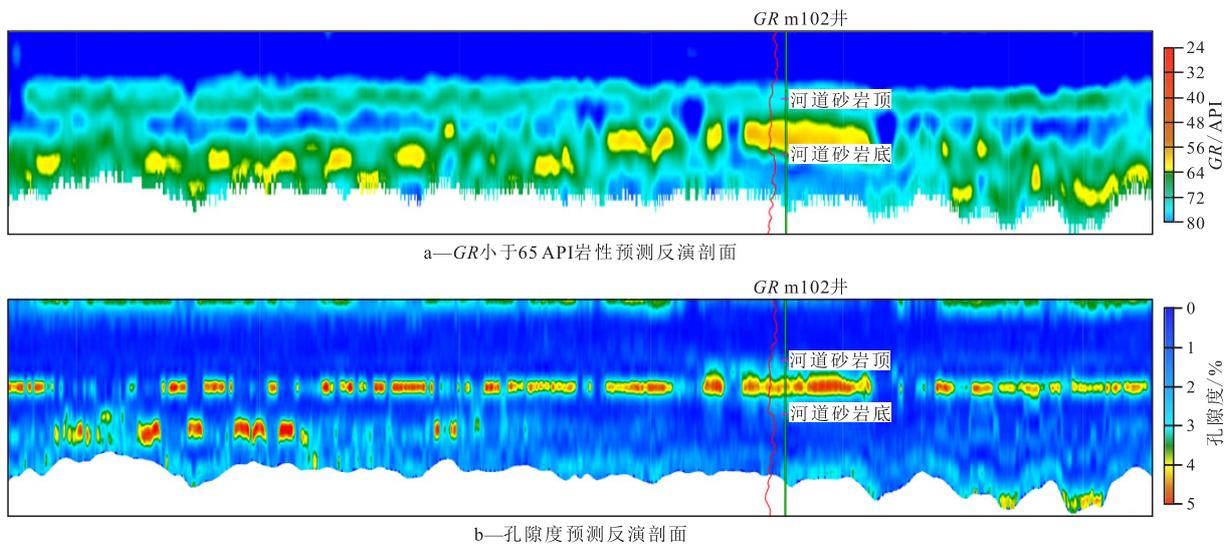


图5 河道岩性与孔隙度预测反演剖面

Fig.5 Prediction inversion profiles of channel lithology and porosity

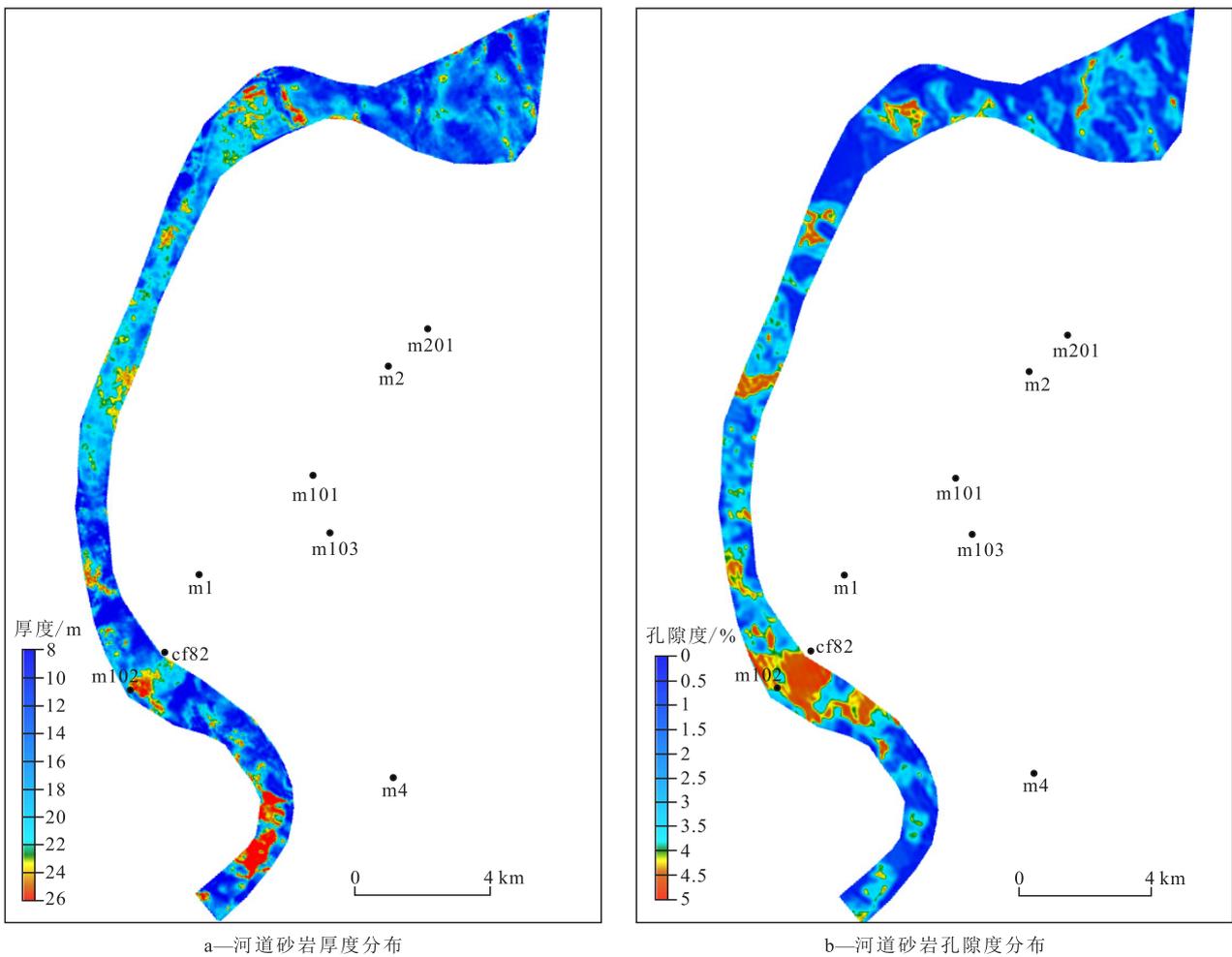


图6 致密河道砂岩储层定量预测

Fig.6 Quantitative prediction of tight channel sandstone reservoirs

特征。该技术有效提高了储层预测的分辨率,对致密砂岩储层勘探有着重要支撑作用。

川东北地区通南巴背斜千一段的有利勘探目

标主要为河道砂岩储层,河道内砂体横向分布稳定,非均质性强。储层预测结果显示千一段背斜带河道砂体厚度大(>20 m)、脆性好($GR < 65$ API)、孔

隙度相对较高(4%~6%)、埋藏浅(小于2 500 m),是千一段“甜点”发育区。

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编辑 林 璐