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应用陆坡形态—迁移轨迹组合法寻找大型富砂深水扇

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摘要 在海外选区研究阶段,盆地勘探程度极低,资料贫乏,导致常规深水沉积分析工作很难开展。而陆坡形态与陆坡迁移轨迹富含丰富的地质信息,可借助二者的组合对深水沉积进行宏观分析。以二维地震资料为基础,应用陆坡形态—迁移轨迹组合法寻找大型富砂深水扇的有利发育区。A 盆地发育上升型、平直型、下降型三种陆坡迁移轨迹类型,其中平直—下降型迁移轨迹对应的陆坡进积距离更大,更有利于发育大型深水扇沉积;同时 A 盆地发育上凸型、下凹型、直线型和坡坪型四种陆坡类型,上凸型与下凹型陆坡的坡度更缓,宽度更大,更有利于重力流的砂泥分异,从而形成富砂深水扇沉积。将同一时期的大型、富砂深水扇的有利分布区相叠合,重叠区域即为该时期大型富砂深水扇的有利发育区,主要位于盆地东部拐角带与盆地西部。同时应用组合法还可建立盆地漂移期的沉积演化模式,分析漂移期沉积演化历史。

关键词 陆坡形态;陆坡迁移轨迹;组合法;深水扇

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0 引言

深水油气勘探逐渐成为全球油气勘探的热点之一,具有十分广阔的勘探前景。如今深水油气勘探的主战场集中在被动大陆边缘盆地,几乎所有的被动大陆边缘均有共同的地貌特征,大陆架—大陆坡—深海平原。对于深水石油勘探而言,陆坡上的沉积至关重要,陆坡上的重力流沉积是深水油气勘探的重要储层^[1],深水扇作为深水重力流的重要产物,以其规模大、砂质含量高的显著特点,已成为深水油气勘探的优质目标,受到了学术界和工业界的日益关注^[2-3]。随着高精度三维地震资料的广泛使用,在层序格架内,综合少量钻测井资料,对深水扇进行精细刻画已逐渐成为主流^[4-7]。近年来,随着层序地层与深水沉积过程研究的不断深入,陆坡迁移轨迹由于富含物源供给、相对海平面变化等多重信息受到了国内外学术界的广泛关注。众多学者开始研究陆坡迁移轨迹与深水重力流沉积尤其是深水扇的关系。

1 陆坡形态

针对陆坡形态,卓海腾等^[8]通过定量数据对南海北部陆坡形态进行拟合,将陆坡形态划分为三种类型,包括平直型、下凹型和 S 型,并综合构造、沉积物

供给、海流和内波、海平面变化等对造成陆坡形态差异的原因进行了探讨;王海荣等^[9]讨论了南海陆坡形态与红河物源供给及构造古地貌的关系;国外学者中,O'Grady *et al.*^[10]依据卫星采集的海底陆坡形态资料,把全球 50 余个被动大陆边缘划分为 5 类,分别为平缓—平滑型陆坡(Gentle and Smooth Margin)、S 型陆坡(Sigmoid Margin)、陡峭—粗糙型陆坡(Steep and Rough Margin)、深—陡型陆坡(Deep and Steep Margin)、阶梯型陆坡(Stepped Margin)。其中平缓型陆坡主要发育在物源供给充足、海底地形平缓的环境中。不同时期的陆坡形态对宏观判断物源供给强度具有一定的指示作用。Carvajal *et al.*^[11]突出了物源对于陆坡形态的控制,认为物源是陆架边缘生长的主力军,自层序地层学诞生以来,学者们往往过于强调海平面变化对于深水砂体沉积的控制作用,而忽视了物源供给的重要性。Carvajal *et al.*^[11]把陆坡划分为两种类型,第一种陆坡高度小于 1 000 m,陆架边缘的进积速率小于 60 km/My,加积速率小于 270 m/My,陆坡形态较为平缓,陆坡上的盆地能快速充填;第二种陆坡高度大于 1 000 m,陆架边缘的进积速率小于 40 km/My,加积速率小于 2 500 m/My,陆坡形态陡峭,陆坡上的盆地充填较慢,常发育重力滑脱构造。

2 陆坡迁移轨迹

对于陆坡迁移轨迹,Carvajal *et al.*^[12-13]以详实的井资料论证了陆坡迁移轨迹与深水扇规模的关系。文中陆坡迁移轨迹主要有平直型、小角度上升型和高角度上升型。三种迁移轨迹对应的陆坡上均发育深水扇沉积,但深水扇沉积的规模具有明显不同,其中平直型和小角度上升型迁移轨迹所对应的深水扇规模更大(图1)。如图1所示,L代表C7沉积时期陆坡的最大进积距离,H代表该时期的地层加积厚度。通过数据统计认为陆坡进积/加积的比值越大(或陆坡最大进积距离越大),深水扇的规模越大(图2)。陆坡进积/加积的比值越大(或陆坡最大进积距离越大),意味着陆架上更多的陆源碎屑被搬运到了陆坡上,物源供给充足,因而更易形成大型深水扇。小角度上升型和平直型迁移轨迹的陆坡进积/加积的比值明显大于高角度迁移轨迹,故深水扇的规模更大。

Helland-Hansen *et al.*^[14],Henriksen *et al.*^[15],Bullimore *et al.*^[16]讨论了陆坡迁移轨迹与相对海平面升降之间的关系(图3),上升型迁移轨迹和下降型迁移轨迹主要是在相对海平面上升和下降阶段形成,相对海平面上升速率越快,上升型陆坡迁移轨迹的角度越大;平直型迁移轨迹是在海平面稳定或微微下降阶段所形成。Bullimore *et al.*^[17]的研究对于分析相对海平面变化以及深水层序地层演化具有一定的指导意义。

3 陆坡形态与迁移轨迹组合法

通过笔者对于陆坡形态和迁移轨迹的调研发现,现今国内外的研究只针对陆坡形态或陆坡迁移轨迹单个层面,并没有把两者结合起来系统研究。在此笔者探索性地提出利用陆坡形态—迁移轨迹组合法寻找大型富砂深水扇沉积。

首先,若要在深水中获得具有经济效益的油气发现,必须寻找大型深水砂体。以2D/3D地震资料为

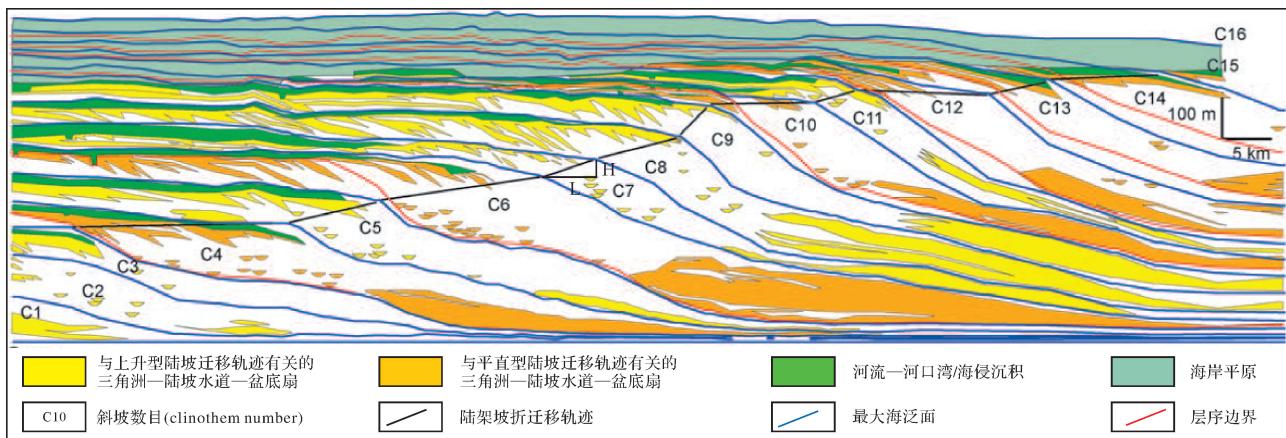


图1 不同类型陆坡迁移轨迹与深水扇规模的关系(据文献[12]修改)

Fig.1 Relationships between different types of shelf-edge trajectories and scale of deepwater fan (modified from the reference [12])

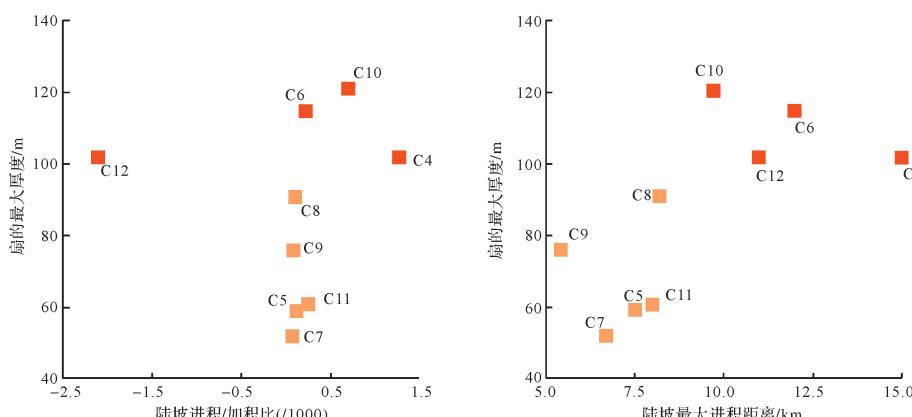


图2 陆坡进积/加积、最大进积距离与深水扇规模的关系(据文献[12]修改)

Fig.2 Relationships between slope progradation/aggradation, maximum progradational distance and scale of deepwater fan (modified from the reference[12])

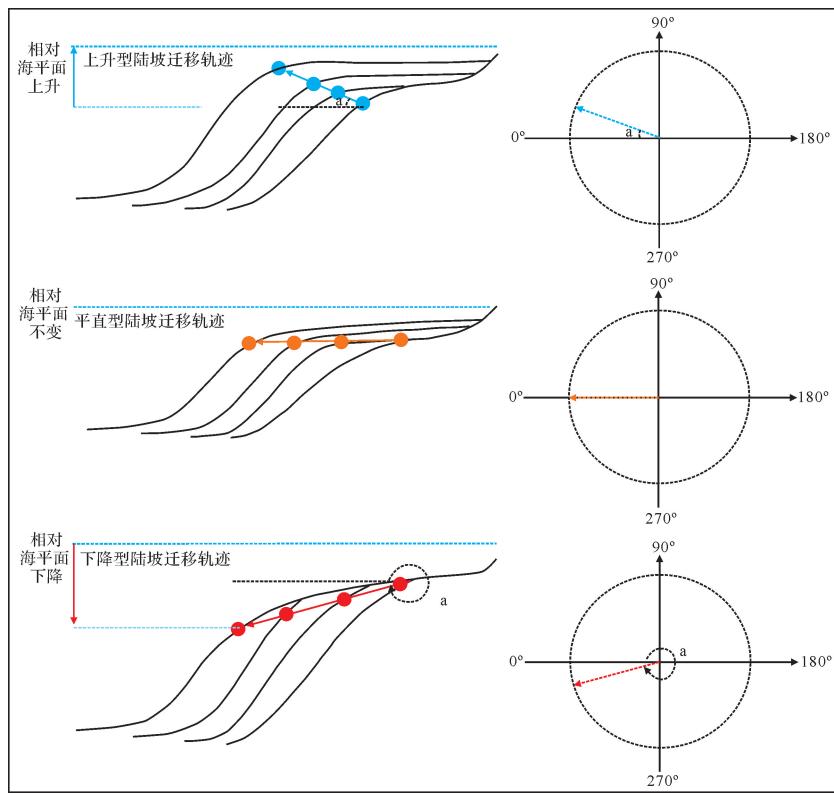


图3 陆坡迁移轨迹与海平面的关系(据文献[7]修改)

Fig.3 Relationships between shelf-edge trajectories and sea level (modified from the reference[7])

基础,通过对不同时期陆坡迁移轨迹的研究寻找大规模深水扇的有利分布区。一般而言,平直型、下降型和小角度上升型迁移轨迹的陆坡最大进积距离(或进积/加积)更大,物源供给更为充足,其下部更易发育大型深水扇沉积^[12]。对于深水扇而言,仅仅规模大还不够,深水扇的储集物性也极为重要。深水扇不等于砂岩储集层^[18],从岩性上来看,深水扇可分为富砾、富砂和富泥型深水扇^[19-20]。深水扇的储集物性一方面与陆架上的物源供给类型具有密切关系,另一方面与陆坡形态也紧密相关。Shanmugam^[21]认为,深水重力流的平面演化依次经历了滑移、滑塌、碎屑流和浊流四个阶段(图4)。从重力流的流变过程来看,重力流作为一种突发性的事件流和密度流,在其流动过程中由初始的滑动、滑塌、变形形成粗细混杂的碎屑流,到流动过程中不断被混进的海水稀释、液化、黏性降低、流态发生变化,由碎屑流逐渐转变为了浊流。砂泥混合的重力流需要经历砂泥分异过程才能析出优质砂岩储集层,未经分异的水道复合体及来不及分异就“冻结”的深水扇都难以形成优质储集层^[18]。坡度缓、宽度大的陆坡形态更有利于重力流的砂泥分异从而较易形成储集物性好的碎屑流和浊

流沉积;而坡度较陡的陆坡(以直线型陆坡为主)上,重力流多以滑移滑塌为主,快速堆积在坡底,形成滑塌体沉积,储集物性一般较差^[8](物源为高含砂率的三角洲或滨岸沉积除外)(图5)。因此可以通过不同历史时期的陆坡形态来宏观判断富砂深水扇的有利分布区。通过以上分析,将同一时期大型深水扇与富砂深水扇的有利分布区相叠合,重叠区域即为大型富砂深水扇的有利发育区。该方法操作简单,效率较快,结合陆架物源类型分析,尤其适用于勘探程度较低,缺乏深水钻井资料、地震资料以二维为主的海外选区研究阶段。

4 应用实例

4.1 应用陆坡迁移轨迹寻找大型深水扇

以A盆地为例,该盆地为西非北段典型的被动大陆边缘盆地,勘探程度极低,仅有稀疏的、分辨率较差的二维地震资料,无深水钻井资料。在该资料基础上,通过对陆坡迁移轨迹的研究预测大型深水扇的有利发育区。

A盆地发育3种陆坡迁移轨迹类型,分别为上升型、下降型和平直型陆坡迁移轨迹,三种迁移轨迹的

发育时期分别为渐新世—全新世和土伦—三冬期,最大进积距离分别为3.5 km、8.6 km、9.7 km,进积速率分别为0.15 km/Ma、0.86 km/Ma、0.97 km/Ma(表1)。可见平直型—下降型陆坡迁移轨迹所对应的陆

坡进积距离更大,因此在土伦—三冬期,平直—下降型迁移轨迹所对应的陆坡上,更易发育大型深水扇沉积。该时期平直—下降型迁移轨迹主要分布在盆地的西部和东部拐角地带,因此该区域更有利形成大

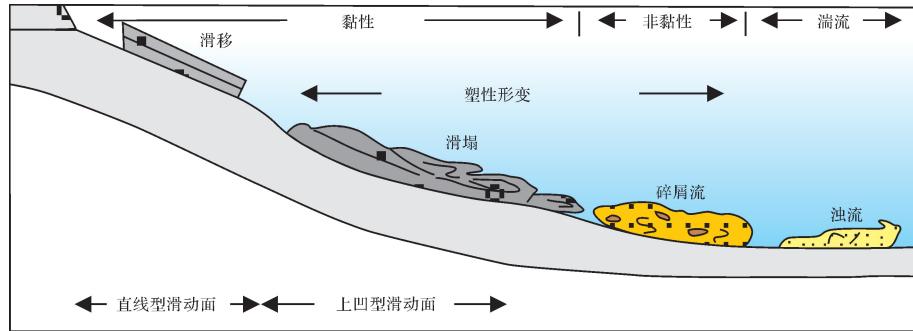


图4 深水重力流演化的四个阶段(据文献[10]修改)

Fig.4 Four stages of deep-water gravity flow evolution (modified from the reference[10])

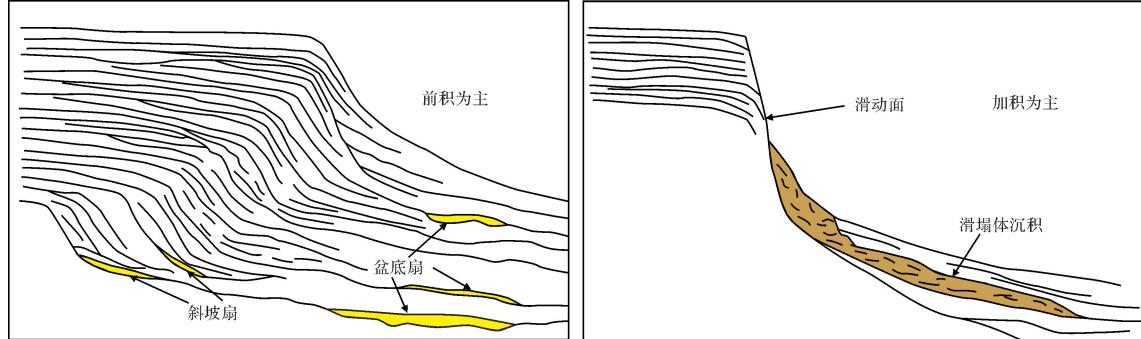
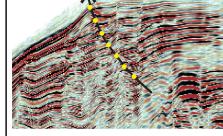
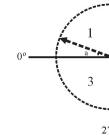
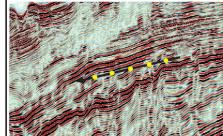
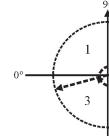
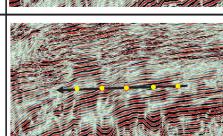
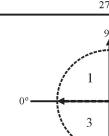


图5 陆坡形态与深水重力流沉积(据文献[8]修改)

Fig.5 Slope geometries and deep-water gravity flow deposits (modified from the reference[8])

表1 A 盆地陆坡迁移轨迹分类

Table 1 Classification of shelf-edge trajectories in A basin

迁移轨迹类型	发育时期	样例	角度	进积距离/km	进积速率/(km/Ma)
上升型	渐新世以后			3.5	0.15
下降型	土伦—三冬期			8.6	0.86
平直型	土伦—三冬期			9.7	0.97

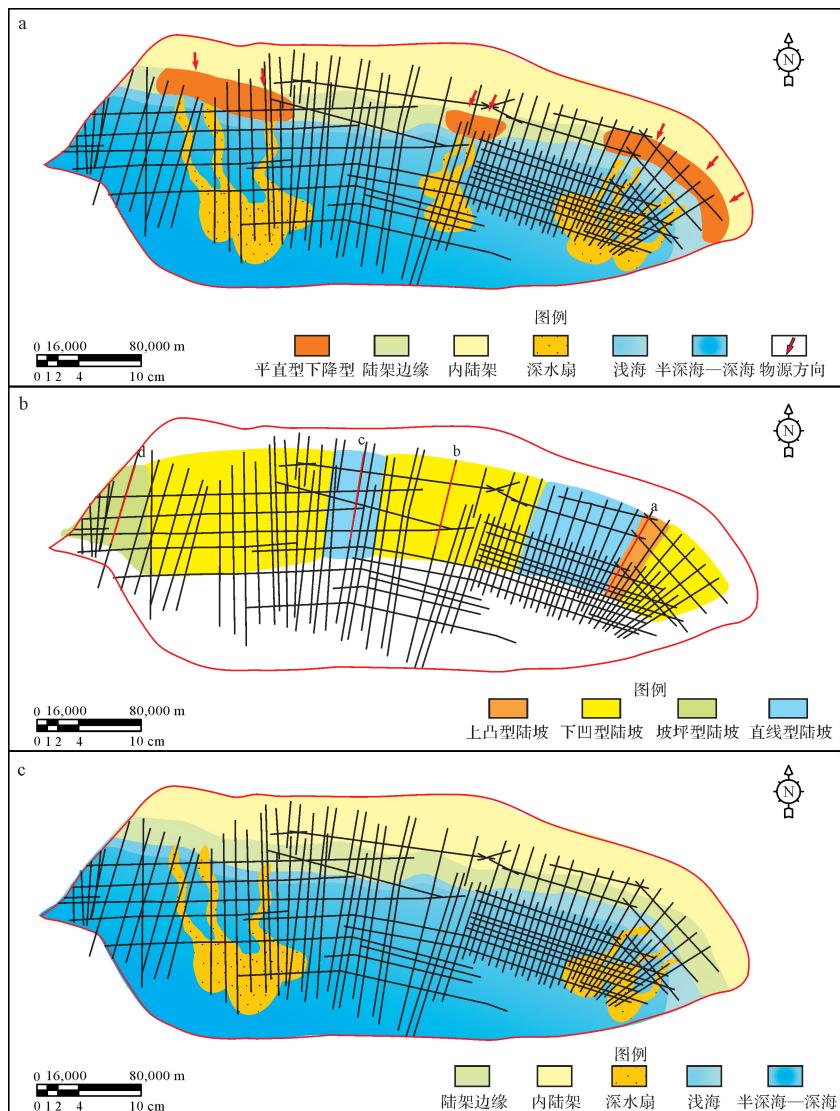


图 6 A 盆地陆坡形态—迁移轨迹组合法成果图

a. 大型深水扇分布图;b. 陆坡形态分布图;c. 大型富砂深水扇分布图

Fig.6 Combination of slope geometries and shelf-edge trajectories result diagram of A Basin

型深水扇沉积(图 6A)。

4.2 应用陆坡形态寻找富砂深水扇

对于深水扇而言,除了规模其储集物性也是至关重要的。由于陆坡形态与深水重力流沉积过程有直接联系,因此通过对陆坡形态的研究对深水扇的储集物性进行宏观分析。若被动陆缘漂移期的构造演化较为简单,早期的陆坡形态与现今陆坡形态类似,则可采用将今论古的思路,通过对现今陆坡的研究类比古陆坡,从而宏观分析富砂深水扇的有利发育区。

以 A 盆地为例,陆坡形态可分为上凸型陆坡(2° ~ 3°)、下凹型陆坡(3° 左右)、坡坪型陆坡(8° ~ 17° 左右)和直线型陆坡(4° ~ 11°)(表 2)。陆架边缘至坡

脚(坡度接近 0°)皆为陆坡范围,本次研究将陆坡宽度进行三等分,分别为上陆坡、中陆坡、下陆坡。陆坡坡度向海方向逐渐降低,陆架破折到坡脚连线的坡度为陆坡的整体坡度。上凸型陆坡在四种陆坡类型中规模最大,坡度最缓,呈现向上凸的形态特征。其中上陆坡坡度 2.68° ,总体 2.3° ,陆坡宽度 55.4 km,陆架与陆坡间较为平滑,陆架坡折不易识别。下凹型陆坡上陆坡坡度 7.3° ,下陆坡 2.3° ,上陆坡坡度较大,向下坡度逐渐变缓,总体为 2.97° 左右,陆坡宽度 49.3 km,较上凸型陆坡而言,下凹型陆坡坡度增大,宽度减小,陆架坡折形态明显。坡坪型陆坡形态上与坡坪型断层较为相似,纵向上可分为三段,上陆坡坡度 16.7° ,

中陆坡 5.7° , 下陆坡 15.1° , 整体 8.0° , 陆坡宽度仅为 38.4 km 。直线型陆坡整体形态近于直线, 上陆坡坡度 10.7° , 整体 4.26° , 陆坡宽度较窄, 仅 35.2 km , 陆架坡折非常突兀(图7)。四种陆坡类型中, 上凸型陆坡坡度小, 宽度大, 更有利于深水重力流的砂泥分异, 从而有利于发育富砂深水扇, 下凹型陆坡次之, 而直线

型和坡坪型陆坡坡度大, 宽度小, 一般情况下, 不利于富砂深水扇的发育。以 2D 地震资料为基础, 研究表明上凸型陆坡仅在 A 盆地的东部拐角地带小范围分布, 下凹型陆坡主要分布在盆地的东部和西部(图 6B)。上凸型陆坡和下凹型陆坡分布的区域更有利 于发育富砂深水扇沉积。

表 2 A 盆地陆坡形态分类

Table 2 Classification of slope geometries in A basin

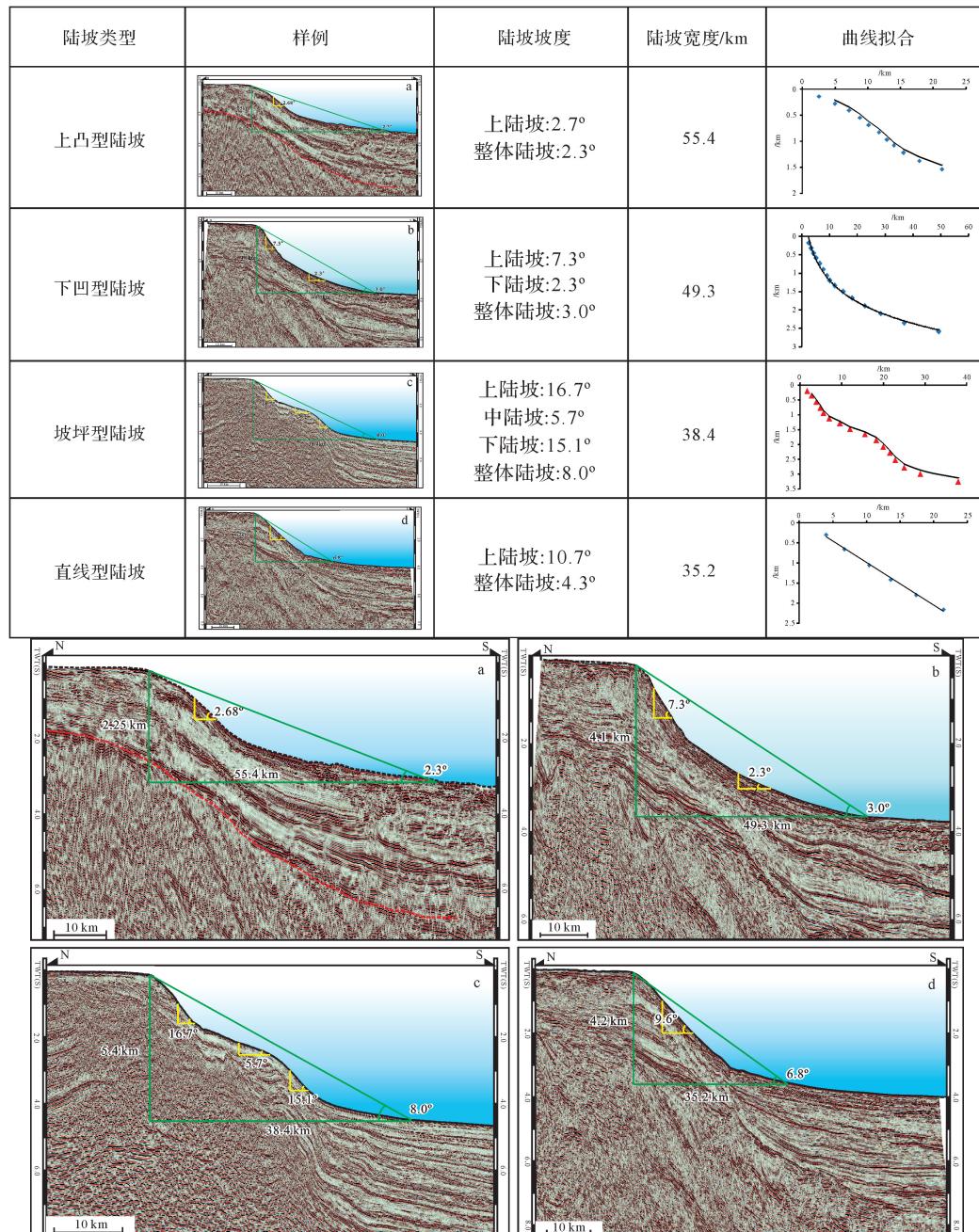


图 7 陆坡形态分类

a.上凸型陆坡;b.下凹型陆坡;c.坡坪型陆坡;d.直线型陆坡(剖面位置见图 6B)

Fig.7 Classification of slope geometries

4.3 应用组合法确定大型富砂深水扇有利发育区

综合以上研究成果,将土伦—三冬阶大型深水扇与富砂深水扇的有利分布区相叠合,重合区域即为大型富砂深水扇的有利分布区,主要集中在A盆地的东部拐角地带和西部区域(图6C)。该方法在低勘探程度、二维地震资料为主的资料背景下,宏观预测出大型富砂深水扇的有利分布区,为A盆地的海外战略选区提供了一定的技术支撑。

4.4 应用组合法分析盆地沉积演化模式

应用组合法还可宏观分析被动大陆边缘漂移期的沉积演化模式。以A盆地为例,土伦—三冬期,相对海平面下降,物源供给充足,此阶段发育平直及下降型陆坡迁移轨迹,在下凹和上凸型陆坡上,发育大型深水扇沉积,在直线和坡坪型陆坡上易发育滑塌沉积(图8a);渐新世之后相对海平面迅速上升,物源供给不足,此阶段以高角度上升型陆坡迁移轨迹为主,上凸和下凹型陆坡上主要发育小规模的退积扇体,由于陆坡变陡,滑塌沉积较为发育(图8b)。

5 结论

(1) 应用陆坡形态—迁移轨迹组合法快速宏观寻找大型富砂深水扇的有利发育区。首先平直型—下降型迁移轨迹所对应的陆坡上更有利于发育大型深水扇;其次坡度缓、宽度长的陆坡上有利于重力流的砂泥分异,从而发育富砂深水扇;通过组合法,把盆地同一时期二者的分布区域相叠合,重叠区即为该时期大型富砂深水扇的有利分布区。以A盆地为例,A盆地发育上升型、平直型、下降型三种陆坡迁移轨迹类型,其中土伦—三冬期所发育的平直—下降型迁移轨迹对应的陆坡迁移速率更快,更有利于大型深水扇沉积;同时A盆地发育上凸型、下凹型、直线型和坡坪型四种陆坡类型,上凸型与下凹型陆坡的坡度更缓,宽度更大,有利于发育富砂深水扇沉积。将同一时期的大型、富砂深水扇的有利分布区相叠合,重叠区域即为该时期大型富砂深水扇的有利发育区,主要位于A盆地东部拐角带与盆地西部。

(2) 应用组合法可研究盆地漂移期的沉积演化模式。如A盆地,土伦—三冬期,相对海平面下降,物源供给充足,陆坡迁移速率较快,以平直及下降型陆坡迁移轨迹为主,在下凹和上凸型陆坡上,发育大型深水扇沉积,在直线和坡坪型陆坡上发育滑塌沉积;渐新世之后相对海平面迅速上升,物源供给减弱,陆坡迁移速率减慢,以高角度上升型陆坡迁移轨迹为

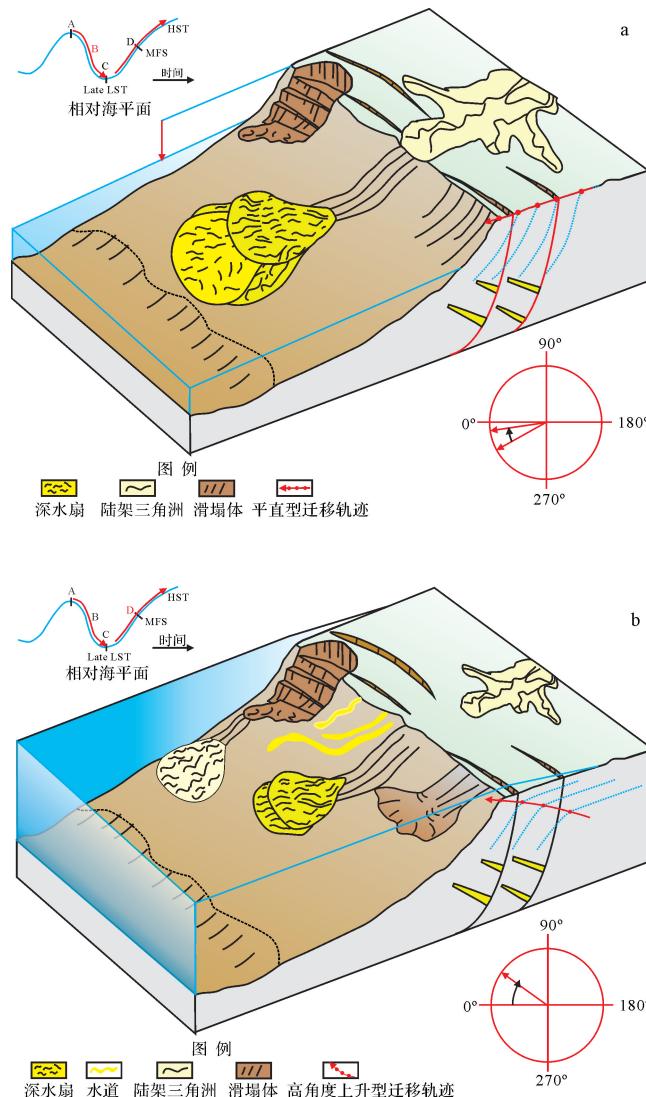


图8 A盆地沉积演化模式

a.土伦期—三冬期;b.中新世—全新世

Fig.8 Sedimentary evolution model in A Basin

主,在下凹和上凸型陆坡上,发育小型退积深水扇沉积,在直线和坡坪型陆坡上发育滑塌沉积。

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Application from Combination of Slope Geometries and Shelf-Edge Trajectories to Find Large-Scale, Sand-Rich Deepwater Fan

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Abstract: In overseas selection stage, extremely low exploration degree and poor data of basin lead to work hard to carry out regular deepwater sedimentary analysis. Slope geometries and shelf-edge trajectories have abundant geological information. In this paper, on the basis of 2D seismic data, apply combination of slope geometries and shelf-edge trajectories to look for favorable distribution of large-scale, sand-rich deepwater fan. A basin develops three types of shelf-edge trajectories, including increasing shelf-edge trajectories, flat shelf-edge trajectories, decreasing shelf-edge trajectories. Progradational distance of linear-decreasing shelf-edge trajectories corresponding slope is longer, more beneficial to develop of large-scale deepwater fan deposits. At the same time, A basin develops four types of slope, including up convex slope, down concave slope, linear slope, and ramp-flat slope. Up convex slope and down concave slope have smaller slope angle and bigger slope width, more beneficial to sand mud differentiation and thus form deepwater fan deposits with better physical property of reservoir. Overlap favorable distribution of deepwater fan with large-scale and good physical property of reservoir during the same period. Overlapping area is the favorable distribution of large-scale, sand-rich deepwater fan, mainly located in the eastern corner and western area in the basin. Also, applying combination method of slope geometries and shelf-edge trajectories can establish sedimentary evolution model of basin during drifting period and analyze history of sedimentary evolution.

Key words: slope geometries; shelf-edge trajectories; combination method; deepwater fan