李俞锋，蒲仁海，樊笑微，等. 琼东南盆地北礁凹陷上新统等深流影响的水道沉积体系[J]. 海洋学报，2022, 44(10): 80–89, doi:10.12284/hyxb2022116

Li Yufeng, Pu Renhai, Fan Xiaowei, et al. Pliocene channel sedimentary system influenced by contour currents in the Beijiao Sag, Qiongdongnan Basin[J]. Haiyang Xuebao, 2022, 44(10): 80–89, doi:10.12284/hyxb2022116

琼东南盆地北礁凹陷上新统等深流影响的水道沉积体系

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摘要：等深流影响的水道沉积体系的沉积特征及其沉积过程是当前深水沉积学研究的热点、难点和前沿科学问题，但研究程度较为薄弱。该文以北礁凹陷上新统（地震反射 T20−T30）为研究对象，利用覆盖北礁凹陷局部的三维地震资料，采用均方根属性、相干属性、时间域构造，再结合地震切片等方法，研究北礁凹陷深水区上新统斜交斜坡（走向）的特殊水道沉积体系特征及其沉积过程。研究发现，该水道沉积体系分为早、晚两期，早期发育水道和片状、扇状溢堤沉积，晚期仅发育水道和片状溢堤沉积，其中扇状溢堤沉积仅发育在水道右侧弯曲处，片状溢堤沉积仅分布在水道左侧，水道始终与区域斜坡斜交，水道对称分布且无明显迁移现象。结合该时期北礁凸起发育等深流相关的丘状漂积体和环槽，认为该水道沉积体系特殊的形态主要受控于等深流与浊流交互作用的沉积结果：浊流流经水道，其上覆浊流溢出水道，形成溢岸浊流，在水道左侧，该溢岸浊流与等深流发生相向运动，被等深流“吹拂”到单侧，大面积分布，延伸千米，形成片状溢堤沉积；而在水道弯曲处（右侧），溢岸浊流与等深流发生相对运动，抑制溢岸浊流进一步扩展，形成相对小范围扇状溢堤沉积，该沉积结果与前人水槽实验结果相一致。

关键词：北礁凹陷；水道沉积体系；溢堤沉积；等深流；浊流

中图分类号：P736.21　　**文献标志码：**A　　**文章编号：**0253−4193(2022)10−0080−10

1　引言

深海并不是一个宁静的环境，存在各种地质营力，如浊流、等深流、海底风暴、内波、内潮等。这些地质营力并非完全是独立存在的，当两者或多者同时存在并发生交互作用时，可形成特殊的沉积体系，常在地震资料上表现出特殊的地震反射，如浊流与等深流交互作用（或相互影响）时，主要形成两种沉积体系类型：（1）向等深流下游方向单向迁移的水道沉积体系（图 1a），其中水道或峡谷堤岸较高，未发生越过堤岸的浊流溢堤沉积，即浊流仅沉积在水道内，如在南海北部神狐海域[1−4]，琼东南盆地北部斜坡[5−6]，巴西坎波斯盆地大陆边缘和巴西西南部边缘海峡谷[7−8]、格陵兰伊尔明厄盆地峡谷[9]、西非加蓬盆地峡谷[10]，下

收稿日期：2021−04−14；**修订日期：**2022−02−11。

基金项目：自然资源部海底矿产资源重点实验室公开基金（KLMMR-2018-B-07）；国家科技重大专题（2011ZX05025-006-02）；国家自然科学基金重大项目（41390451）。

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刚果盆地沿岸[11–12]; (2) 向等深流上游方向单向迁移的水道沉积体系(图 1b), 水道堤岸较低, 上部浊流越过单侧堤岸, 形成溢岸浊流沉积, 如在东非鲁伍马盆地[13–14]、琼东南盆地北礁凹陷中中新统[15]、非洲东部莫桑比克北部沿岸[16–19]。其中东非海域鲁伍马盆地受等深流的影响造成单侧天然堤规模很大, 单侧天然堤限制了浊流的活动范围, 往上游方向迁移, 而且等深流将浊流中的细粒部分携带至等深流的下游, 造成单侧天然堤持续建造, 整个浊流水道体系持续迁移[18–19]。

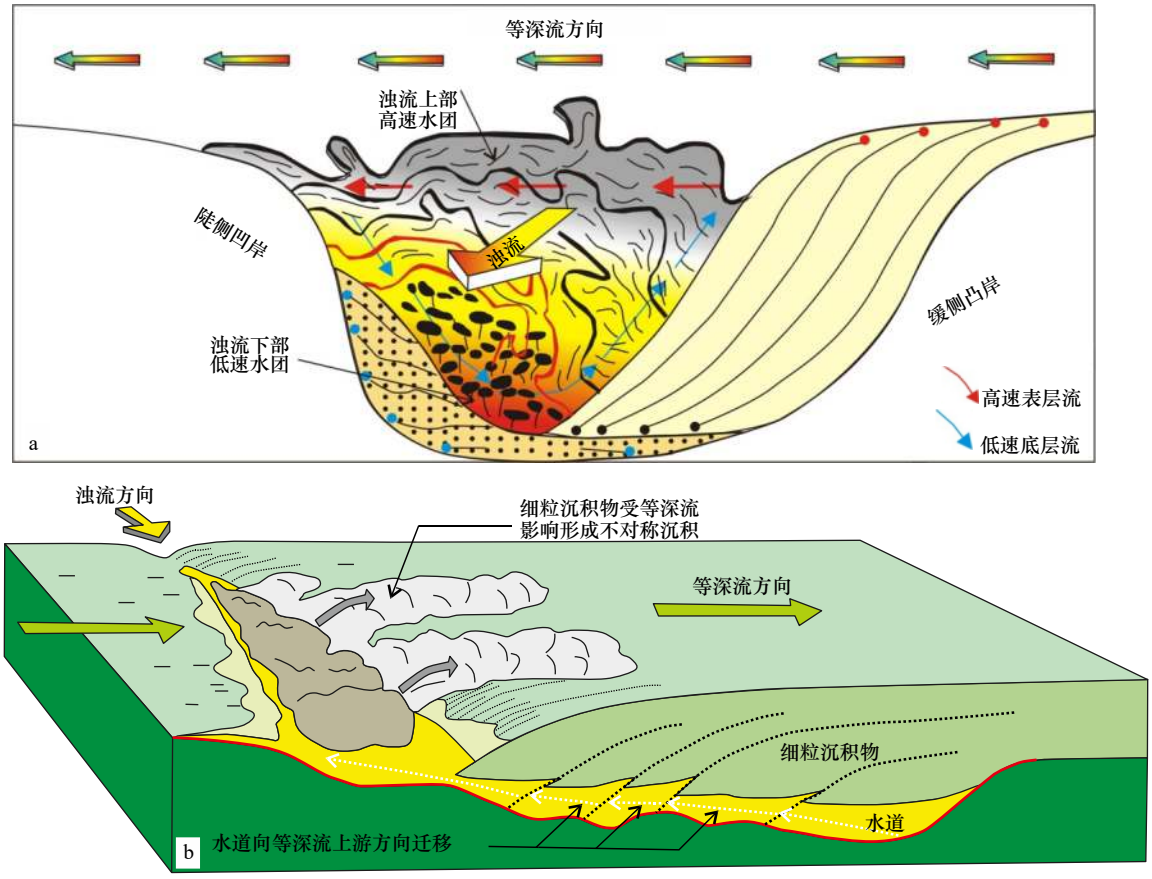

图 1　等深流与浊流交互作用的两种沉积类型

Fig. 1　Two types of sediment models for the interaction between contour currents and turbidity flows

a. 向等深流下游方向单向迁移的水道沉积体系模式(引自文献 [3]); b. 向等深流上游方向单向迁移的水道沉积体系模式(改自文献 [16–18])

a. Channel sedimentary system model for unidirectional downstream migrating of contour current flows (cited from reference [3]); b: channel sedimentary system for unidirectional upstream migrating of contour current flows (modified from references [16–18])

尽管它们形成的水动力条件有所差异, 但形态上有一定的相似性, 如均发育顺直或近于顺直的水道。等深流与浊流交互作用在深水中普遍存在[2, 20], 且两者交互作用形成的砂体, 往往是高孔高渗的储集体[21–22], 这已引起了地质学界的广泛关注。这两种水道往往在地质历史时期持续时间较长, 而本文中水道发育持续时间很短, 在上新世晚期, 其有何种沉积特征和差异, 有待深入研究, 对该问题的揭示, 有利于加深对等深流与浊流交互作用的理解。

2　区域地质背景

琼东南盆地位于南海西北部(图 2a), 是新生代伸展盆地[23], 具有南北高, 中间低的构造格局(图 2a)[24], 该盆地自新生代以来, 呈现南北高中间低、西浅东深的阶梯式地貌特征[24], 研究区处于南部隆起向中央坳陷的过渡带区——北礁凹陷与部分北礁凸起(图 2a), 地形地貌显示出南高北低的特点(图 2b)。本文中所用地震数据来自覆盖北礁三维地震的西部(局部)地震数据, 该资料的地震面元为 25 m×12.5 m, 垂向采样间隔为 2 ms, 纵向分辨率约 20 m。该盆地自晚中新世以来, 处于加速热沉降阶段[2, 24](图 3), 且盆地处于稳定阶段, 即构造断层不活跃[25]。北礁凹陷自中新世以来已处于半深海环境[26–27], 之后海水深度不断加深。

现今南海水体主要被分为 3 层, 由上至下分别为表层水、中层水、深层水[28]。南海表层水夏季逆时针流动, 冬季顺时针流动, 受季风影响明显, 主要分布在

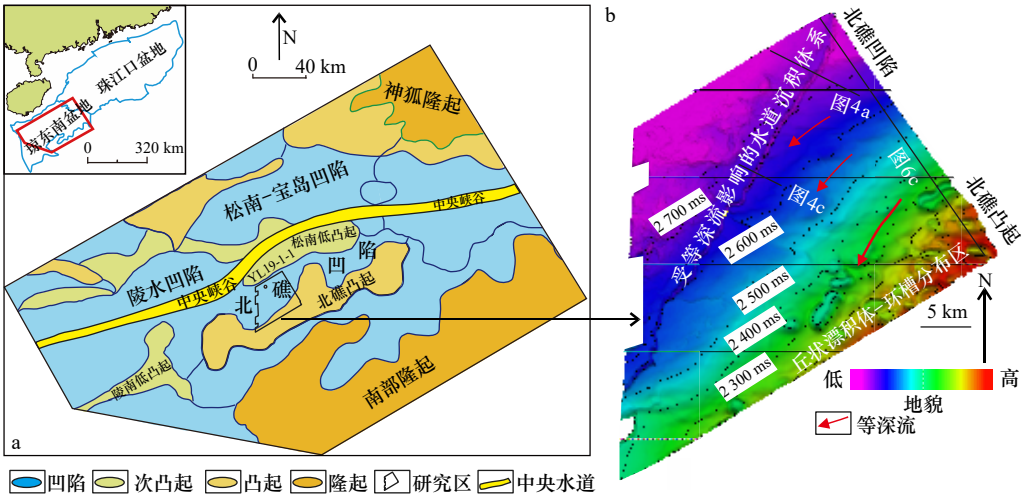

图 2 琼东南盆地构造单元(改自文献 [24])(a)与北礁凹陷三维地震勘测上新统上段(含水道沉积体系)的古地貌图(b)

Fig. 2 Tectonic unit of the Qiongdongnan Basin (modified from reference [24]) (a) and paleogeomorphic map of the upper Pliocene (aquifer channel sedimentary system) from three dimensional seismic survey of Beijiao Sag (b)

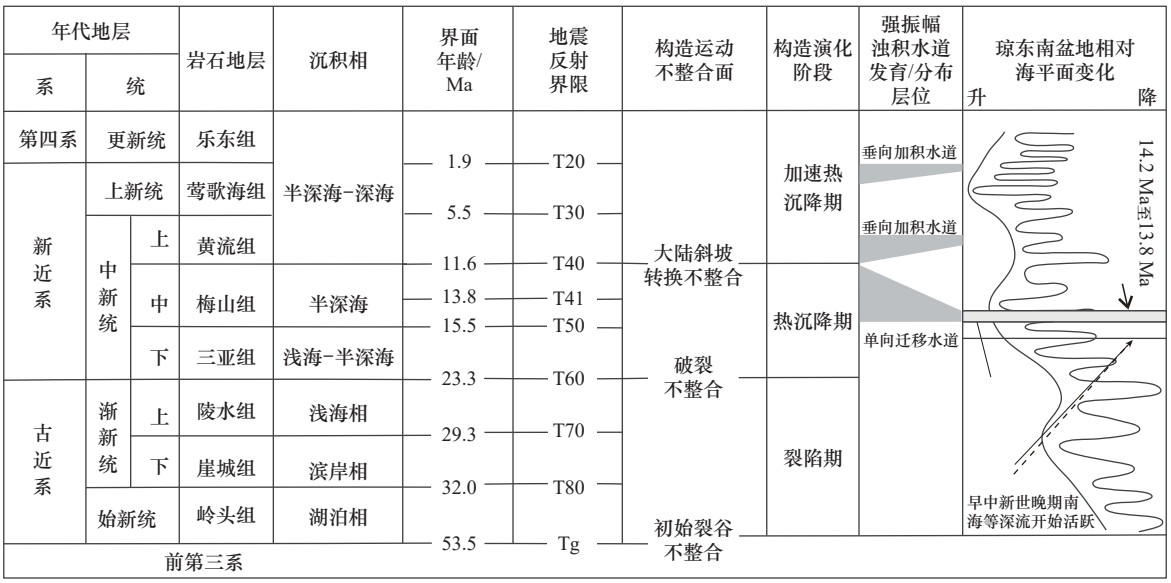

图 3 琼东南盆地深水区地层综合柱状图

Fig. 3 Comprehensive stratigraphic histogram in the deep-water area of the Qiongdongnan Basin

此图展示了沉积相(引自文献 [29])、构造运动及演化(引自文献 [24])、强振幅水道发育/分布层位(引自文献 [15])及海平面变化(引自文献 [27])

It shows characteristics of sedimentary facies (cited from reference [29]), tectonic movement and evolution (cited from reference [24]), development or distribution location of channels with high amplitudes (cited from reference [15]), and eustatic sea level change (cited from reference [27])

水深 350 m 以浅的范围；中层水呈顺时针流动，深度主要分布在 350～1 350 m；深层水逆时针流动，主要分布在 1 350 m 以下的范围内[2, 29–30]。中层水–深层水影响着南海北部斜坡水道的迁移方向以及丘状漂积体、环槽的发育与分布，它们也常被称为中层与深层相关等深流[3, 30]。

3 水道沉积体系剖面特征

由西非下刚果盆地地震资料和广西田林、内蒙古桌子山野外露头剖面可知，深水水道沉积体系被划分为水道、堤岸、决口扇及废弃水道 4 个沉积单元，并认为该体系是深水油气勘探的优势区[31]。南海北礁凹陷黄流组底部水道沉积体系结构单元被划分为侵蚀界面、底部滞留沉积以及上部的水道–堤岸复合体[26]，且该凹陷的梅山组单向迁移水道沉积体系被划分为底部侵蚀界面和其上部水道砂–堤岸泥过渡复合体两个结构单元[15]。北礁凹陷三维区上新统(T20–T30)上部发育了一套典型的水道沉积体系

(图 4a), 根据其外部形态和内部结构可分为早、晚两期: 早期水道沉积体系可划分为侵蚀界面、底部滞留沉积(即水道)、溢堤沉积(片状与扇状)4 个结构单元; 晚期水道沉积体系可划分为侵蚀界面、块体搬运沉积体或滑塌体充填的水道、片状溢堤沉积 3 个结构单元(图 4b1, 图 4c1)。早期侵蚀界面呈“V”型, 明显分隔开连续强振幅的水道砂和弱振幅的远洋泥; 早期水道与下伏地层呈明显的削截关系, 振幅强度较大, 可能预示砂体粒径较大, 与泥岩形成较大的波阻抗差有关; 中振幅溢堤沉积仅位于水道的左侧(图 4b, 图 4b1), 或者在水道两侧均分布(图 4c, 图 4c1)。晚期水道沉积体系在早期基础上继承性发育, 晚期水道比早期水道规模大, 中振幅杂乱发射的滑塌体充填在水道中, 类似于滑塌体充填的中央峡谷[32], 早期–晚期水道均以垂向加积为主, 均呈现出对称性, 未出现单向迁移现象, 强振幅连续性好的溢堤沉积发育在水道的左侧, 其右侧不再发育强振幅的溢堤沉积(图 4b1, 图 4c1), 晚期溢堤沉积呈现出(异常)强振幅而非下伏早期溢堤沉积的中振幅, 可能是晚期溢堤沉积体(粉砂岩–泥岩)中含有低频浅层气所致(如图 4a 中青色虚线框)。

4　水道平面展布特征

北礁凸起与北礁凹陷过渡区形成的局部斜坡走向为 NEE 向, 而该沉积体系(主要为水道)的走向为 NE 向, 两者斜交(图 2b), 这与大多数水道与斜坡垂直形态迥异。早期水道沉积体系沉积相平面展布由近顺直水道、扇状溢堤沉积和片状溢堤沉积组成(图 5a, 图 5a1), 它们以强–中振幅为特征, 与远洋泥质弱振幅形成鲜明的对比。晚期水道沉积体系以异常强振幅片状溢堤沉积及近顺直水道为特征(图 5b, 图 5b1)。早期水道较窄(图 4b), 宽约 200 m, 晚期水

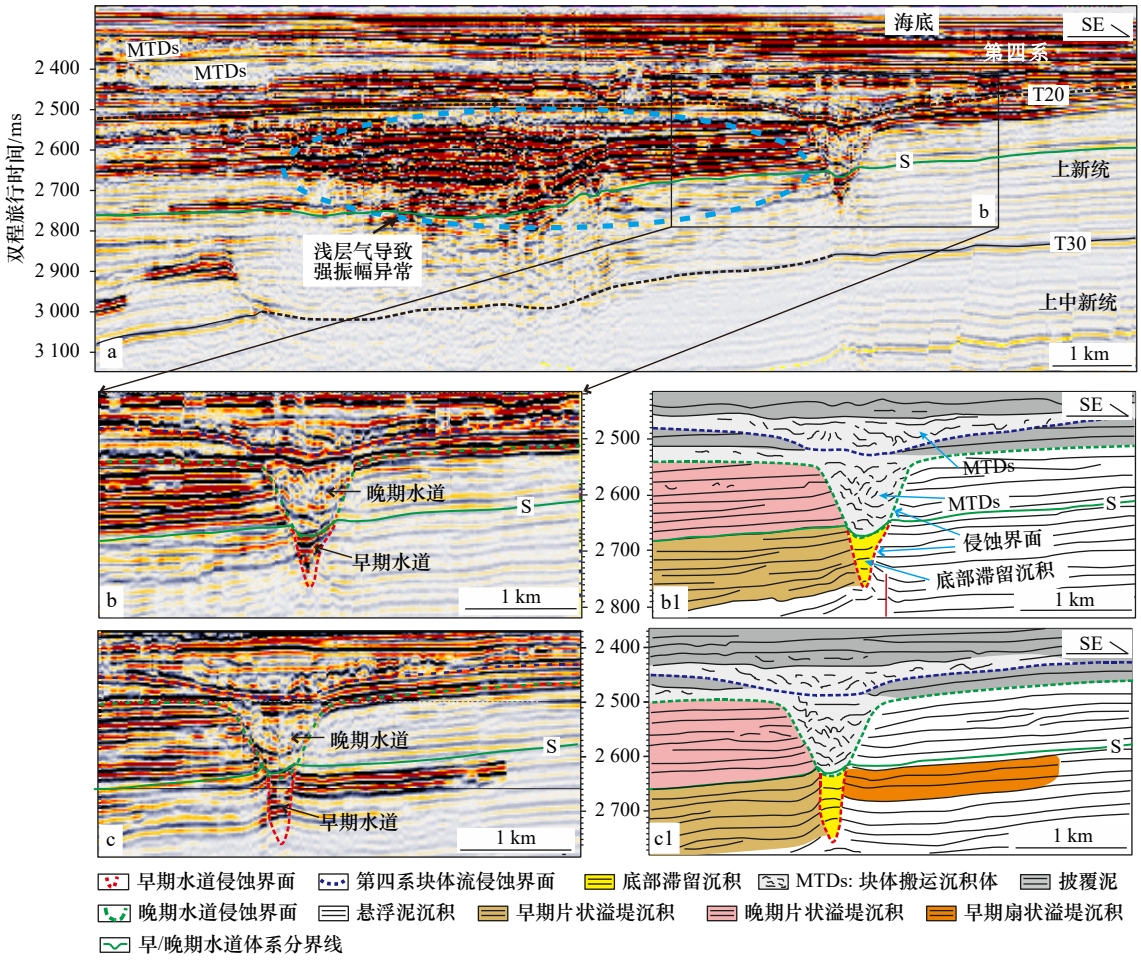

图 4　琼东南盆地北礁凹陷上上新统早–晚期水道沉积体系剖面特征(a–c)及其沉积单元划分(b1, c1)

Fig. 4　Profiles characteristics (a–c) and sediment units divisions (b1, c1) of the early and late channel sedimentary systems in the upper Pliocene in the Beijiao Sag, Qiongdongnan Basin

绿色实线“S”为早晚期水道沉积体系分界线

Solid green line “S” presenting the boundary between early and late channel sedimentary systems

道较宽，宽约 800 m，早期扇状溢堤沉积发育区大多分布在局部水道曲率较大位置处，晚期水道曲率较大位置（水道右侧）不再发育扇状溢堤沉积，可见，右侧扇状溢堤沉积的发育不仅与水道曲率有关，还与水道的规模有关（如宽度、深度等）。值得关注的奇特现象是：水道尽管与局部斜坡斜交，但未出现单向迁移现象，而表现垂向加积或叠置现象，呈对称分布；两期片状溢堤沉积均严格分布在水道左侧；早期扇状溢堤沉积严格分布在水道的右侧。初步认为是重力流受到等深流的影响形成的结果，首先该区是否存在等深流呢?见下文分析。

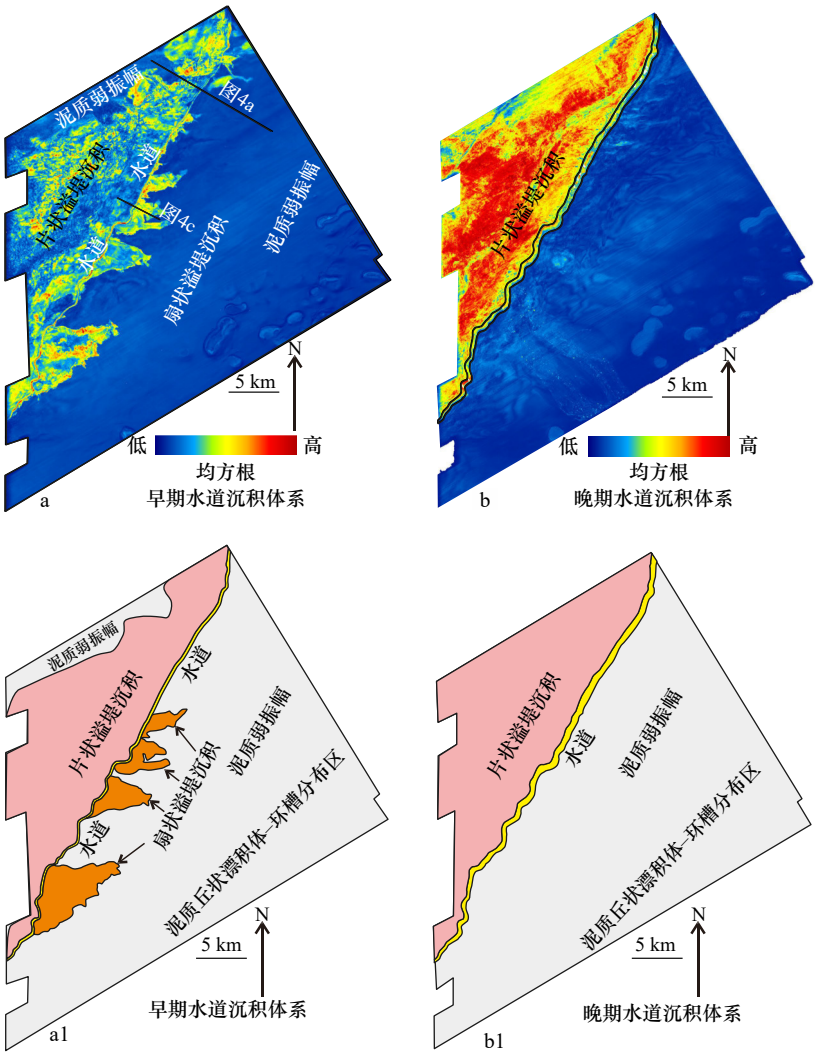

图 5 琼东南盆地北礁凹陷上新统早–晚期水道沉积体系均方根属性（a, b）及其沉积相解释（a1, b1）

Fig. 5 RMS attributes (a, b) and their sedimentary facies interpretation (a1, b1) of the early and late channel sedimentary systems in the Pliocene in the Beijiao Sag, Qiongdongnan Basin

a. 时窗为分界面 S 至 S 下移（+）40 ms; b. 时窗为分界面 S 至 S 上移（−）40 ms

a. Time window from boundary “S” to the downward shift (+) 40 ms of “S”; b. time window from boundary “S” to the upward shift (−) 40 ms of “S”

5 环槽及丘状漂积体指示的等深流信息

等深流流动方向通常平行于大陆斜坡[30]。在南海北部荔湾凹陷已发现的最早活跃的等深流可追溯至早中新世晚期，这种等深流强度较大，可底蚀形成长条形脊[32]，同样，在北礁凹陷也发现在晚中新世早期活跃的等深流底蚀下伏梅山组地层，形成大面积分布的长条形残丘[26]，且这种凹凸不平的底形影响了上覆丘状漂积体和丘间环槽的分布[33]，这些信息都指示该区等深流强度较大，可影响沉积物形态。研究区伴随水道沉积体系发育的同时，该区不远处东南部北礁凸起上发育了大量的长条形凹凸不平的地貌——环槽（等深流水道）和丘状漂积体（图 2b），在北礁凹陷水道沉积体系发育的时期，与之相邻的北礁凸起上发

育了长条形丘状漂积体和环槽(图 6a, 图 6b), 丘状漂积体以高连续弱振幅(似“透明”)为主要特征, 它们之间为环槽发育区, 环槽内部也以高连续弱振幅为主要特征(图 6c)。相干属性显示, 北东向长条形环槽(等深流水道)北西侧为低相干(图 6a, 图 6b), 地震剖面显示削截反射(青色小圆点)主要发生在环槽的北西侧(图 6c), 表明等深流在长条形环槽中的流动主要侵蚀了环槽的北西侧, 即等深流在科式力作用下向北西方向偏转。在北半球, 若等深流在科式力作用下向西北方向偏转, 则可推测研究区等深流流动方向应为由东向西逆时针流动。研究区现今水深不小于 1 500 m (海水波速为 1 500 m/s, 双程旅行时间 ≥2 000 ms), 该深度属于逆时针流动的深层水水团相关等深流发育范围(细节见区域地质背景), 这与通过环槽侵蚀特征推测的本文等深流及其流动方向相一致。这种持续的等深流侵蚀现象从晚中新世早期持续至今(图 6c 中绿色虚线箭头), 表明在浊流发育时期, 也存在等深流的发育, 具备浊流与等深流交互作用的条件。

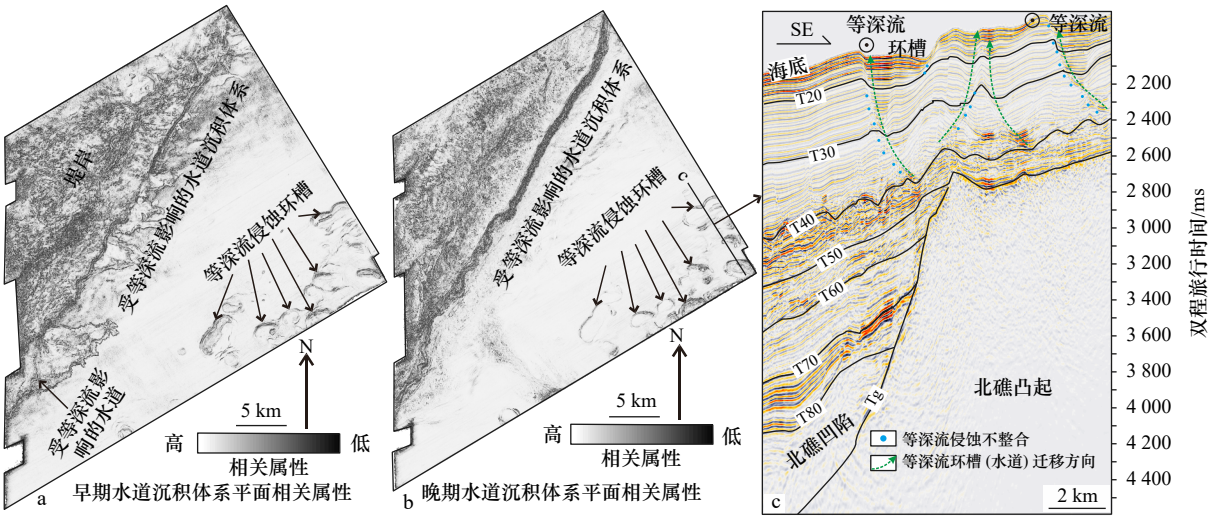

图 6　琼东南盆地北礁凹陷早–晚期水道沉积体系相干属性(a, b)及环槽与丘状漂积体发育特征(c)

Fig. 6　Coherence attribute of the early and late channel sedimentary systems (a, b) and the characteristics of moats and contourites (c) in the Beijiao Sag, Qiongdongnan Basin

6　水道沉积体系的成因初步探讨及沉积模式

沿斜坡的等深流与垂直斜坡浊流相遇, 两者发生交互作用, 在强等深流的作用下, 迫使相对低密度的上部浊流越过堤岸, 发生向等深流下游方向的溢岸浊流[8](图 7a)。这些溢岸浊流部分沉积在堤岸(天然堤)上, 部分形成溢堤沉积; 在地质历史中, 长期的交互作用, 使这类溢堤沉积持续性的发育, 甚至出现偏移现象, 最终溢堤沉积主要在等深流下游方向沉积[8](图 7b), 即在水道末端单侧沉积。前两种沉积模式均是前人的推测, 未进行水槽实验的验证, 随着水槽实验技术的成熟, 当等深流与浊流交互时, 观察到等深流确实能把浊流(尤其上部)平移向等深流的下游方向, 而在等深流上游方向, 等深流却抑制溢岸浊流的推进[34](图 7c), 在此情况下, 很容易诱导溢岸浊流的单侧沉积。

北礁地区该体系发育时, 地貌呈南高北低的特点, 且水道由南向北逐渐加深(图 2b), 研究区紧邻南部隆起(图 2a), 再结合扇状溢堤沉积展布形态(图 5a1), 与琼东南盆地深水区主要来自北部和西北部物源不同, 初步推测浊流由南向北流动(图 8)。

该区 SW 向活跃的等深流与浊流相遇, 两者发生交互作用, 迫使溢岸浊流溢出水道(如图 7c 浊流左侧), 在水道左侧, 溢岸浊流与等深流发生相向运动, 溢岸浊流在等深流的扰动下, 发生片状分散, 缓慢沉积, 故在等深流下游方向沉积, 形成仅水道左侧分布的片状溢堤沉积(图 8)。在水道弯曲处, 浊流离心力较大, 上部浊流溢出水道, 在水道右侧, 溢出水道的溢岸浊流与等深流流向相反, 发生相对运动, 抑制溢岸浊流进一步流动(图 7c 右侧), 致使溢岸浊流速度快速下降, 近距离发生大量沉积, 形成紧靠水道的扇状溢堤沉积。而水道左侧, 弯曲处的溢岸浊流与等深流方向一致, 发生相向运动, 流速增加, 震荡加剧, 广泛分布(如图 7c 左侧雾状溢堤沉积), 颗粒不易集中快速堆积, 随着远离水道, 流速逐渐降低, 逐渐发生大范围的片状溢岸浊流沉积, 故水道左侧有片状溢堤沉积大面积分布。

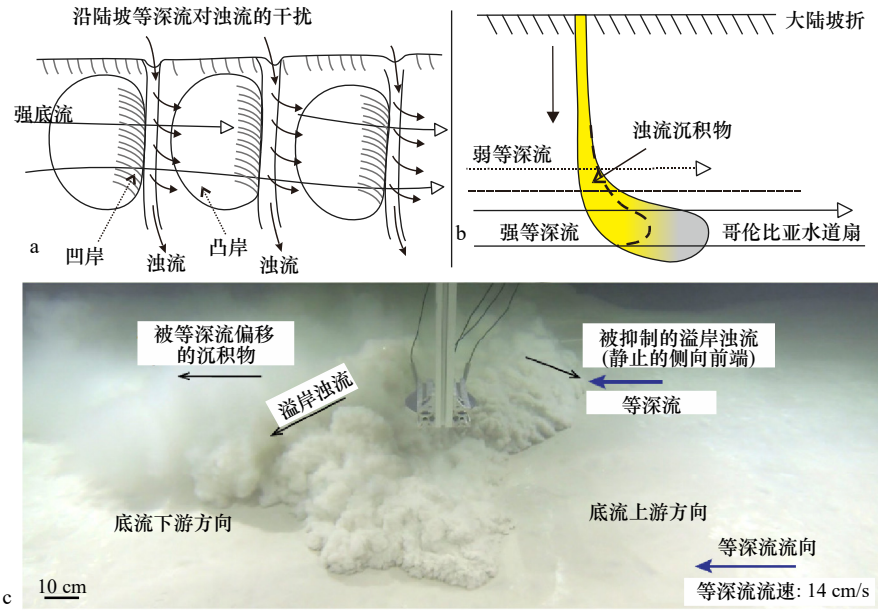

图 7 等深流与浊流交互作用下浊流溢出堤岸的沉积模式及其水槽实验

Fig. 7 Sedimentary models and flume-tank experiment of turbidity flows overflowing levees under the interaction of contour currents and turbidity flows

a. 沿斜坡等深流与跨斜坡浊流的交互作用平面形态(引自文献 [8]); b. 由于浊流受到等深流的影响发生溢岸浊流, 致哥伦比亚水道(扇)末端朵叶体向等深流下游方向迁移(引自文献 [8]); c. 等深流与浊流交互作用的水槽实验(引自文献 [34])

a. Interaction planform morphology of along-slope contour currents and across-slope turbidity flows (cited from reference [8]); b. lobe at the end of Columbia channel (fan) migrating downstream of contour currents, due to overspills from turbidity flows affected by contour currents (cited from reference [8]); c. flume-tank experiment of the interaction between contour currents and turbidity flows (cited from reference [34])

结合上述这样的水动力条件, 初步提出本文这一特殊水道沉积体系的沉积模式(图 8)。值得注意的是: 溢堤沉积是在离心力作用下溢出水道的浊流与等深流发生交互作用(等深流与离心力驱使下的浊流方向相反)这一水动力条件下形成的, 具有很强的筛选作用, 可带走泥质, 筛选出纯净的砂质, 是潜在水合物和浅层气的优质储集层; 另外, 该模式尽管能得到水槽实验的证实, 但个别小型扇状溢堤沉积在顺直水道处沉积, 可能与等深流影响下浊流扰动形成的 Kelvin-Helmholtz 波有关, 使浊流溢出水道, 形成小型扇体。

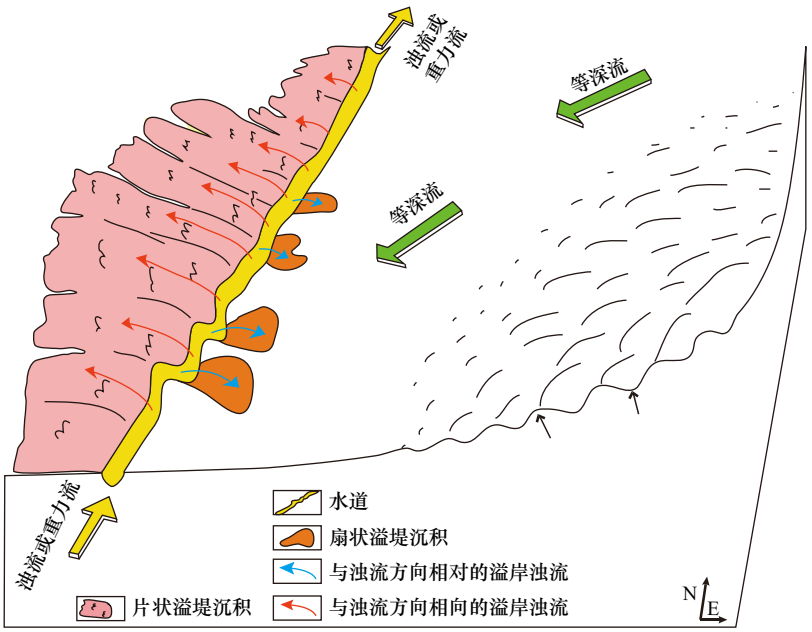

图 8 琼东南盆地北礁凹陷受等深流影响的水道沉积体系沉积模式

Fig. 8 Sedimentary model of the channel sedimentary system affected by contour currents in the Beijiao Sag, Qiongdongnan Basin

由于该体系仅发生在上新世中后期, 与单向迁移水道相比, 持续时间很短, 另外, 早/晚期水道均呈对称性, 说明水道两侧累计沉积厚度差异性不大, 水道总是由沉积多的一侧向沉积少的一侧单向迁移[5]的这种情况未发生, 所以此水道沉积体系未发现单向迁移现象, 而以垂向加积为主。

7　结论

研究区水道沉积体系发育在浅层(上新统地层中上部), 与局部斜坡斜交, 根据地震反射的内部结构和外部形态, 可把该水道沉积体系分为早、晚两期, 早期发育水道、片状与扇状溢堤沉积 3 个沉积单元, 晚期仅发育水道和片状溢堤沉积两个沉积单元。

水道早期规模较小, 以强振幅为特征, 晚期以中–强振幅、杂乱内部反射为特征, 可能被滑塌体充填, 水道与区域斜坡斜交, 近于顺直, 局部弯曲。扇状溢堤沉积紧临水道右侧且在曲率较大处呈扇形分布, 片状溢堤沉积仅在水道左侧分布, 早期以中振幅为主, 晚期以强振幅为主, 可能含浅层气所致, 均呈片状展布, 这些独特的展布特征很可能是受等深流的影响。

等深流影响浊流沉积是形成这种水道沉积体系的主要原因, 浊流与沿北礁凹陷局部斜坡流动的等深流相遇(斜交), 驱使上部浊流越过堤岸, 在水道左侧发生溢岸浊流, 在等深流下游方向, 形成片状溢堤沉积。水道局部曲率较大处的水道右侧, 在离心力作用下, 溢岸浊流与等深流流向相对, 受到等深流限制, 快速沉积, 故在水道右侧发育紧邻水道的扇状溢堤沉积, 由此提出了其沉积模式, 该沉积模式与前人水槽实验结果相一致。

致谢: 感谢两位匿名审稿专家提出的宝贵修改意见, 使本文质量得到很大提升。

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Pliocene channel sedimentary system influenced by contour currents in the Beijiao Sag, Qiongdongnan Basin

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Abstract: Depositional characteristics and process of deep-water channel sedimentary system influenced by contour currents is a current hotspot and new scientific issue in the study of deposits resulted from interaction between contour currents and turbidity flows. Using root mean square (RMS) attribute, coherenceseismic attribute, time structure and stratal slice, we focus on depositional characteristics and process of the channel sedimentary system in Pliocene strata in the Beijiao Sag, Qiongdongnan Basin. The results show that the channel sedimentary systems are divided into the early and late channel sedimentary systems. The depositonal units of the early system include channel, flake-shaped and fan-shaped overbank deposits. The units of the late systems incorporate: channel and flank-shaped overbank deposits. Fan-shaped overbank deposits are only distributed on the right side of the bend of the channel. Flake-shaped overbank deposits are only located on the left side of the channel. The channels are persistently oblique to the strike of the slope and they are symmetrical and characterized by vertical aggradations. Combined with the development features of mounded drifts and moats over the Beijiao uplift, it is inferred that the geometry of the channel sedimentary systems are mainly controlled by depositional products of the interaction between turbidity flows and contour currents. Contour currents flow across channels, forcing the upper part (low velocity and low density) of turbidity flows to deflect towards the left (downstream) side of channels and then form overspill currents. The direction of overspills is the same to that of contour currents, in this case, generating wide flake-shaped overbank deposits extending for several kmlometers. In the bend of channels, the direction of overspill currents is in contrast to that of contour currents, blocking or confining the range of the overbank deposits and then creating fan-shaped overbank deposits. This result are consistent with the previous results of flume-tank experiment.

Key words: Bejiao Sag; channel sedimentary system; overbank deposits; contour currents; turbidity flows