文章编号:1000-0550(2014)03-0442-08

中国南海西北次海盆西北陆缘洋陆过渡区深水沉积体系特征①②

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摘 要 高分辨率二维地震资料显示中国南海西北次海盆西北陆缘(水深 1 000 m 及以下)发育如下深水沉积体系:珠江口盆地南部隆起区缓坡带(水深约 1 000~1 500 m、坡度<1.2°)出露神狐南海山,该海山附近发育“海山相关等深流沉积体系”,可能受南海中层水循环(自西向东)底流控制;神狐南海山以南水深约 1 500~2 500 m 的陆坡区(坡度>2°)普遍发生坡移,发育“重力流滑塌体系”和“峡谷体系”,鲜见等深流沉积;下陆坡区(水深>2 500 m,坡度稍缓<2°)滑塌现象明显减少,主要发育“峡谷体系”以及“席状等深流沉积体系”,席状等深流沉积体系可能受分散的、流速较低的南海深层水循环底流控制。地震沉积记录显示,神狐南海山附近等深流侵蚀特征最早出现于晚中新世早期,其后至现今该区较稳定发育等深流沉积/侵蚀的加积序列,说明南海西北次海盆西北陆缘的稳定底流沉积/侵蚀可追溯至晚中新世早期。

关键词 深水沉积体系 底流 等深流沉积 中国南海

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中图分类号 TE121.3 **文献标识码** A

0 引言

近年来“深水沉积体系研究”持续得到广泛关注,其对于全球自然资源与能源勘探开发和古海洋古气候研究具有重大意义[1]。诸如“浊流沉积体系”、“块体流沉积体系”和“等深流沉积体系”等深水沉积体系普遍发育于大陆边缘陆架陆坡及深海半深海环境[2,3],这些沉积记录可反映古海洋条件的变化[4,5]。

中国南海西北次海盆的地理位置十分独特——因西沙海槽东端尾部、南海北缘洋陆过渡带和南海中央次海盆深海平原三者在此交汇(图 1)。迄今在南海北缘各新生代盆地已广泛开展重力流沉积体系研究工作并取得显著成果,如琼东南盆地和珠江口盆地[6]。目前等深流沉积体系的相关研究主要集中于东沙隆起以南和台湾岛以南陆坡区,尚属初步研究阶段[7~9]。国内外至今较少涉及有关西北次海盆西北缘洋陆过渡区的深水沉积体系研究[10~12]。

本文将报道中国南海西北次海盆西北缘洋陆过渡区(水深 1 000~3 000 m)的重力流、底流相关深水沉积体系,包括描述其地形地貌特征、空间展布特征、地震沉积特征并探讨其成因演化。

1 区域地质背景

研究区经纬度地理坐标区间为 18°~19° N,113°15'~114°30' E,水深范围主要集中于 1 000~3 000 m,属于中国南海西北次海盆西北缘洋陆过渡区。研究区北侧部分属于珠江口盆地北缘的南部隆起区(神狐隆起以南);南侧部分与西沙海槽和深海平原相邻(图 1,图 2)。海底地形显示 1 200~1 400 m 水深范围出露一座海山(图 2),因其位于神狐隆起以南,称其“神狐南海山”。

西北次海盆经历了南海的前期扩张(32~30 Ma),该扩张结束于 23 Ma[13]。早中新世(23 Ma)以来,南海北缘珠江口盆地已由海陆交互相过渡为滨浅海相沉积环境,局部更有深海—半深海相出现[14,15](图 3)。南海北部陆缘自晚中新世(11.5 Ma)以来已

①国家自然科学基金(批准号:91028009,41202086,41372112)、教育部博士点基金(编号:20100145110002)与国家重点油气专项(编号:2011ZX05025-002-02)联合资助
②第五届全国沉积学大会推荐论文
收稿日期:2013-07-28;收修改稿日期:2013-11-30

基本转变为深水沉积环境[16,17]。

南海温盐环流自中中新世—上新世开始稳定发生[18,19]。现代南海温盐循环主要发生在三个深度:水深小于 350 m 为南海表层水循环,水深在 350~1 350 m之间为中层水循环(南海局部地区该水团范围可达1 500 m或更深),水深大于 1 350 m 为深层水循环[10,20~22]。其中南海表层水循环的方向受季风影响呈现季节性变换(冬季顺时针夏季逆时针)[23,24]。中层水和和深层水循环研究程度较低[25~27],已有资料显示中层水循环大致呈顺时针方向[10,28,29]而深层水循环则相反[7,8]。

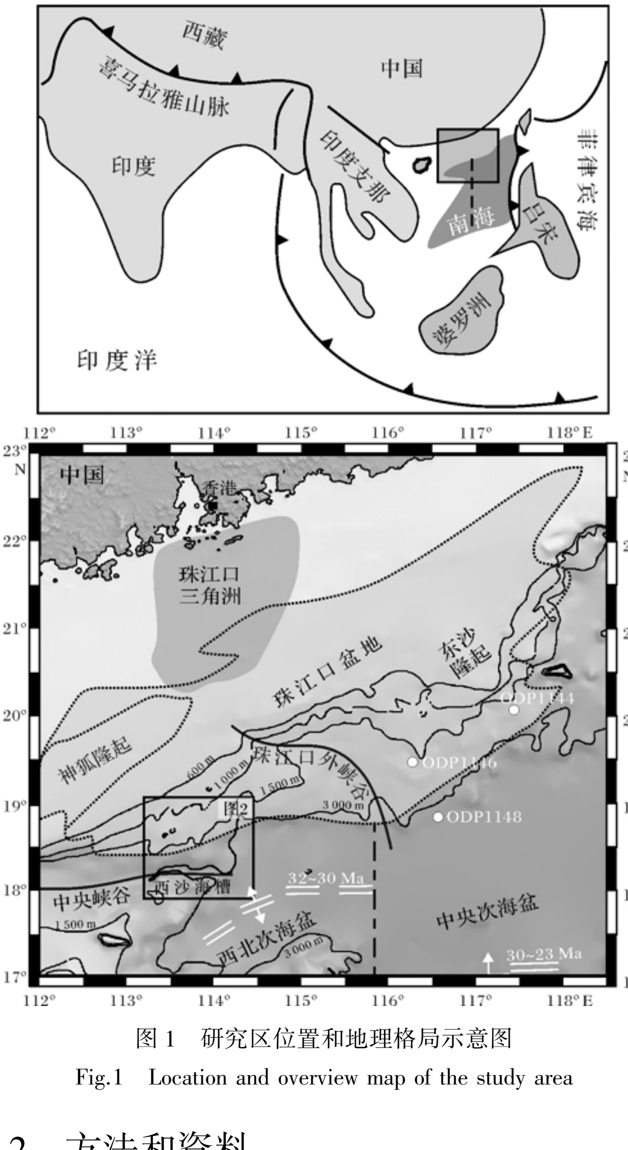

图 1　研究区位置和地理格局示意图

Fig.1　Location and overview map of the study area

2　方法和资料

本文使用的高分辨率 2D 地震数据资料由中海油湛江分公司采集处理后提供。地震数据总覆盖面积>4 200 km^2,剖面总长度>1 500 m,平均剖面间距

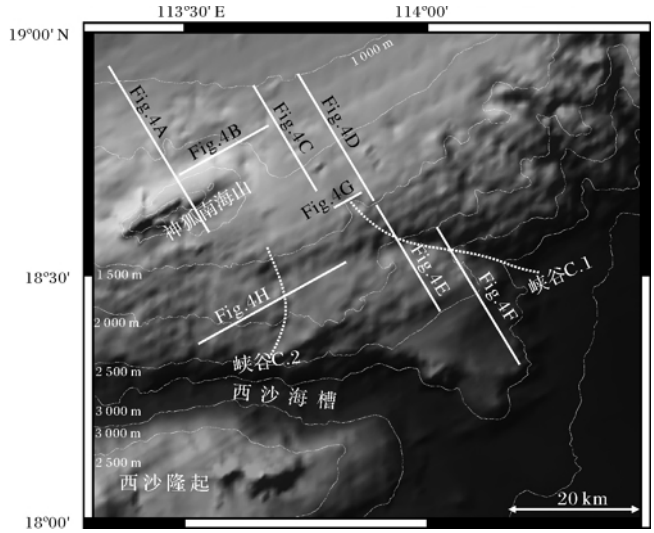

图 2　研究区地震剖面及主要地理单元位置示意图

Fig.2　Bathymetry of the study area showing the locations of the seismic profiles

为 5 m 左右,频率约 60 Hz。本文所使用地震剖面位置见图 2。使用 2D 地震数据研究海底地形地貌时,本文默认海水的 P 波速度为 1 500 m/s。

3　结果和讨论

3.1　等深流沉积体系

(1) 海山相关等深流沉积体系

"等深流环槽(contourite moat)"用于定义那些通常与伸长状—丘状的孤隔型漂积体(elongated-mounded separate drift)共生发育在突起地形(如出露的海山)边缘的底流侵蚀特征[30]。海底地形特征和 2D 地震资料共同显示,神狐南海山北侧发育典型等深流环槽,环槽南侧(海山北坡)发育黏附型漂积体(plastered drift),环槽北侧发育伸长状—丘状漂积体(图 4A,B)。"等深流水道(contourite channel)"定义为由底流侵蚀形成的平行陆坡方向展布的侵蚀特征[30]。研究区东北部陆坡(水深 1 500 m 附近,坡度<1.14°)的 NNE—SSW 方向 2D 地震剖面上可见平行陆坡方向展布的水道(宽度 0.5~2 km,下切深度 10~20 m)(图 4C,D)。对该区域地震反射界面进行闭合解释后,地震沉积记录显示上述侵蚀/沉积特征在地层界面 T40(11.5 Ma)至现今的海底地层中发育稳定加积序列(图 4A~D)。底流侵蚀能力较弱时形成下切深度小于 10 m 的侵蚀现象称为"犁沟(furrow)"[30]。研究区等深流环槽以北的伸长状—丘状漂积体沉积物表面发育有平行陆坡方向排列的等深流犁沟(图

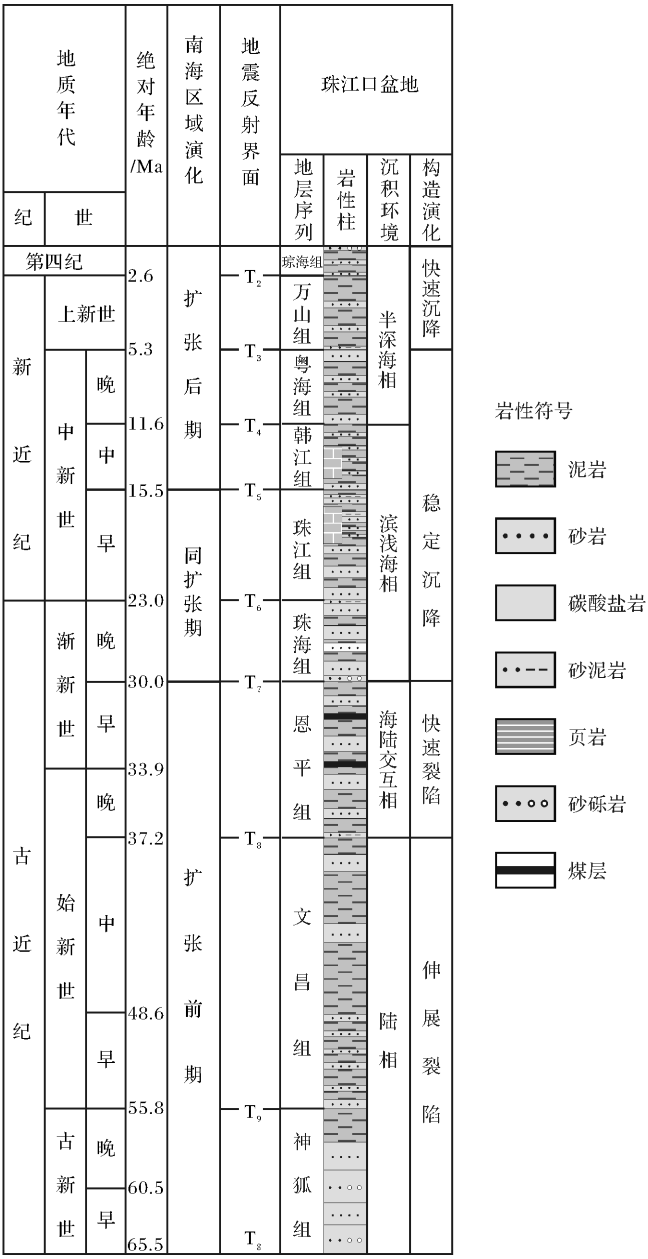

图3 古新世以来南海珠江口盆地地层序列及演化历史

Fig.3 Schematic overview of the stratigraphic sequence and tectonic evolution in the Pearl River Mouth Basin, of South China Sea since the Palaeocene

4A)。上述沉积单元共同构成神狐南海山附近“海山相关等深流沉积体系”。

在北半球海山突起地形附近,自西往东的水流受到科氏力作用(右偏)在海山北侧受到地形限制,水流速度大幅增加,水流侵蚀能力大于沉积沿海山北侧边缘形成环槽;环槽北侧陆坡接受水流沉积作用,发育伸长状—丘状漂积体[30,31]。当环内水流因地形变化速度减缓时,会在海山北侧山坡形成黏附型漂积体[32]。远离海山的底流未被强烈加速,在环槽北侧漂积体沉积物上形成常规的等深流水道和犁沟。同一时刻在海山南侧区域,受到科氏力作用右偏的水流未受到地形限制,易形成沉积区(图4A)[30]。该现象亦指示自西向东的水流方向。因此,我们推测“海山相关等深流沉积体系”主要受反气旋方向(由西向东)南海中层水循环的底流行为控制。

研究区海山附近等深流侵蚀特征最早被发现于晚中新世早期(地层界面T40之上)(图4)。在其后至现今海底地层中,该区都发育较稳定的等深流沉积/侵蚀特征加积序列,指示南海西北次海盆西北缘陆坡区的稳定底流沉积/侵蚀过程可追溯至晚中新世早期。

(2) 席状等深流沉积体系

在坡度较缓且地形较平整的大陆边缘下陆坡区,大范围流速较缓的底流易产生沉积作用形成“席状漂积体(sheeted drift)”[33]。通过本研究区东南部水深大于2 500 m缓坡区(平均坡度约1.5°)的2D地震资料,可识别出厚度超过70 ms TWT的席状漂积体沉积物。地震剖面显示其具有连续性强、平行/亚平行的中等振幅反射特征;外部形态以平整、平滑为主要特征。峡谷的出现会直接破坏席状漂积体沉积物平整一致的外形(图4E),断层密集区席状漂积体发生局部变形(图4F)。该套漂积体沉积构成神狐南海山以南下陆坡“席状等深流沉积体系”。

席状等深流沉积多发育在缓而平坦的陆坡,如深海平原,该体系主要受分散的、流速较低的深层面状底流控制[32]。结合太平洋深层水经吕宋海峡入侵南海北部后所形成南海深层水团的行为模式以及该深层水团沿南海北部陆缘的流动路径[7,25],推测本区深层底流可能属于自东往西流向的南海深层水循环(图5)。

3.2 重力流滑塌体系和峡谷体系

2D地震剖面显示神狐南海山以南水深约1 500~2 000 m陆坡区(坡度2°~4°)具有坡移(mass-wasting)滑塌(slump/sliding)现象(图4E)。滑塌沉积物外形呈阶梯状起伏,各起伏单元内部具平行/亚平行、中等—高振幅的地震反射特征,起伏单元之间的地震反射轴被清晰的滑移面切断。

海底地形图显示在中国南海西北次海盆西北陆缘普遍发育深切峡谷(图2,5)。本文所研究地震剖面展示了其中位于神狐南海山东南方向的峡谷C.1(图4G)和神狐南海山以南的峡谷C.2(图4H)。峡

谷C.1在水深 2 000 m 及以上处呈 NNW—SSE 走向,在2 000 m以下其走向转变为 WNW—ESE 走向,直至水深 3 500 m 处该峡谷下切下陆坡后汇入深海平原(图2,5)。图4G的地震剖面位于水深1350m左

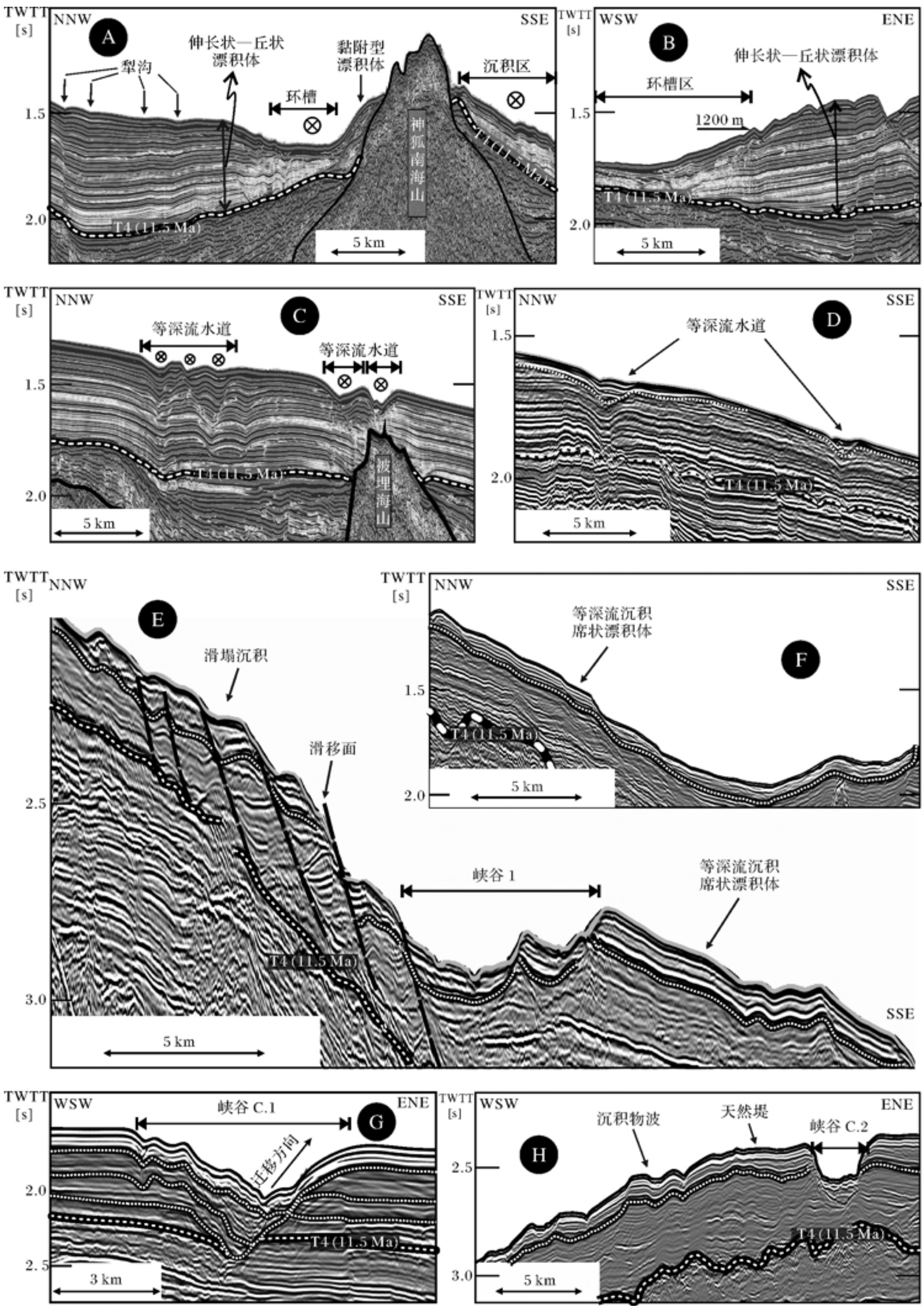

图4　A,B:海山相关等深流沉积体系,包括环槽、伸长状—丘状漂积体、黏附型漂积体、犁沟;C,D:等深流水道;E:重力流滑塌沉积、峡谷 C.1 和等深流沉积席状漂积体;F:等深流沉积席状漂积体;G:峡谷 C.1 具不对称 V 字型下切形态和明显 ENE 方向迁移;H:峡谷 C.2 具对称 U 字型下切形态,两侧发育具明显加积特征的丘状天然堤沉积,西侧天然堤沉积物上发育沉积物波。

Fig.4　A,B: seamount related contourite sedimentary system, including the moat, elongated-mounded drift, plastered drift, contourite furrows; C,D: contourite channels; E: the deposits and canyon of gravity flow slump (C.1) and contourite sheeted drift; F: contourite sheeted drift; G: C.1 shows an asymmetric V-shaped morphology with an obvious ENE migrating pattern; H: C. 2 presents a flat-bottomed U-shaped morphology with an aggradational levee-system on the both sides. The levee sediments on the WSW side show continuous wave-shaped reflectors.

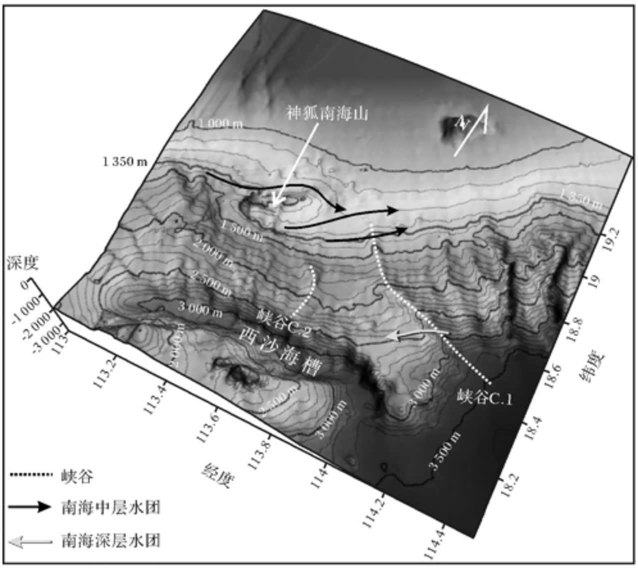

图5　中国南海西北次海盆西北缘洋陆过渡区底流活动示意图

Fig.5　Schematic diagram of bottom current activities on the northwestern margin slopes of the Northwest Sub-Basin, South China Sea

右,坡度为0.9°的区域(图4G),该剖面显示峡谷C.1下切形态呈不对称V字型(宽度6.5 km,下切深度140 m),具明显的ENE方向迁移特征。峡谷C.2在水深约1 800 m及以上处呈NNW—SSE的走向,向下其走向转变为ENE—WSW方向,至水深约2 500 m处该峡谷下切进入西沙海槽(图2,5)。图4H地震剖面位于水深1 870 m左右的陆坡,该剖面显示峡谷C.2底部平坦,下切形态呈U字型,无明显迁移特征;其两侧发育丘状天然堤沉积,加积特征较明显,且西侧天然堤体系出现波状沉积(图4H)。

3.3　等深流沉积体系对重力流滑塌体系和峡谷体系的影响

本区坡移现象主要发育于较陡陆坡区域,周边地震活动较少,未见浅层天然气或气体水合物的指示。据此我们认为较陡的坡度(>2°)是导致本区滑移活动的决定性因素[1]。与此同时,在较陡陆坡基本未见等深流沉积记录,可能因坡度较陡,沉积环境不稳定而导致常规底流活动没有能力在该区留下侵蚀/沉积记录,或导致等深流沉积记录被频繁的重力流活动强烈破坏而无法被识别[5,34],进而不利于等深流沉积体系的发育和保存。

本文所展示峡谷C.1和峡谷C.2表现出完全不同的外形形态和迁移模式。(1)处于神狐南海山东南侧水深约1 350 m处的峡谷C.1具不对称V字形和明显的ENE方向迁移。此迁移现象指示峡谷体系可能受到较强烈自西向东的底流改造作用而强制性东向迁移。此自西向东的底流与前文形成环槽和漂积体的水流方向一致,很可能同属南海中层水循环(图5)。在研究区邻近陆坡,Zhu *et al.*[10]和Li *et al.*[11]报道过类似现象。值得注意的是,峡谷的东向迁移现象亦能够在神狐南海山以南水深超过1 350 m陆坡区(约1 500 m)被发现,可能与局部地区南海中层水循环范围可达1 500 m或更深[22]有关。(2)处于神狐南海山南侧水深约1 850 m(坡度>2°)处的峡谷C.2呈对称U字型,两侧发育具加积序列的丘状天然堤沉积,暗示该处峡谷未受到强烈底流活动影响。丘状天然堤上的波状沉积物可能系浊流活动导致的沉积物波[35]。

4　结论

(1)中国南海西北次海盆西北缘洋陆过渡带(水深1 000~3 000 m)发育有"海山相关等深流沉积体系"、"席状等深流沉积体系"、"重力流滑塌体系"和"峡谷体系"一系列深水沉积体系。

(2)"海山相关等深流沉积体系"主要受属于南海中层水循环(反气旋方向)的底流行为控制。自西往东的水流受到科氏力作用后(右偏)在海山北侧受到地形限制,水流速度大幅增加,侵蚀大于沉积从而沿海山北缘形成环槽。环槽北侧陆坡接受水流沉积作用,发育伸长状—丘状漂积体。当水流因地形变化速度减缓时,在环槽南侧(海山北坡)发育黏附型漂积体。远离海山的底流未被强烈限制(加强),仅在环槽北侧的丘状—伸长状漂积体上形成常规的等深流水道和犁沟。"席状等深流沉积"易发育在缓而平坦的陆坡,主要受分散的、流速较低的深层面状底流控制,本区该深层底流可能属于自东往西流向的南海深层水循环。

(3)南海西北次海盆西北陆缘神狐南海山附近较缓陆坡区的稳定底流沉积/侵蚀过程可追溯至晚中新世早期(T40之后)。神狐南海山以南坡度较陡区沉积环境不稳定,频繁发生重力流活动而不利于等深流沉积发育和保存。

致谢　感谢第五届沉积学大会海洋地质与沉积学专题各位专家和审稿人提出的宝贵意见和建议。

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Characteristics of Deep-water Depositional Systems on the Northwestern Margin Slopes of the Northwest Sub-Basin, South China Sea

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Abstract: During recent years, the study of deep-water depositional systems has intensively attracted worldwide interests. Deep-water sediments can record plentiful paleoceanographic information, e.g., changes of climate and/or ocean circulation conditions, which is of crucial importance for paleoceanographic reconstructions. However, in and abroad studies involving deep-water sedimentary systems of the Northwest Sub-Basin in the South China Sea is rare.

In this study, we analyzed high resolution 2-D seismic data that cover an area of >4 200 km^2, with the total length of >1 500 m. It reveals that there are mainly three deep-water depositional systems developed on the northwestern margin (water depth > 1 000 m) of the Northwest Sub-Basin, South China Sea. (1) There is a seamount named South Shenhu Seamount standing on the gentle slopes of the Pearl River Mouth Basin Southern Uplift Zone, where the water depths range from 1 000 m to 1 500 m and the slope is gentler than 1.2°. A "seamount related contourite depositional system" that consists of a moat (the depression close to an obstacle, produced by separate and faster bottom current cores and in genetic relation with mounded and elongated separated drifts), a mounded-elongated drift (typical type of contourites, which are mounded and elongated in shape along the slope, associating with moats), a plastered drift (produced by bottom currents with weakened dynamics due to topographic changes), contourite channels (alongslope aliened erosive features that are produced by bottom currents) and contourite furrows (alongslope aliened erosive features generate by bottom currents, with incisions of < 10 m) has been discovered developing in the vicinity of the South Shenhu Seamount. The moat runs along the northern foot of the seamount, with a mounded-elongated drift developed to its north side and a plastered drift to the south (plastered onto the northern flank of the South Shenhu Seamount). Alongslope aliened contourite furrows and channels developed on the mounded-elongated drift deposits. (2) Landslidings dominate the steep slopes (>2°) between 1 500 m and 2 500 m in the south of the South Shenhu Seamount, where gravity flow slump deposits and submarine canyons compose the "gravity flow slump system" and the "canyon system", respectively. An NNW-SSE oriented canyon (C.1) shows an asymmetric V-shaped morphology with ~140 m of incision and ~6.5 km in width on the mid-upper slope (~1 350 m in water depth and ~1° slope). The successive erosion bases within this canyon present an obvious ENE migration. Contourite deposits, however, are rare in this region. (3) On the northwestern lower slopes of the Northwest Sub-Basin (water depth >2 500 m and slope <

2°, canyons are still common. On slopes of ~1 790 m in depth and ~2° of slope, a canyon (C.2) shows a flat-bottomed and U-shaped morphology (~135 m of incision and ~4 km in width), with a slightly mounded aggradational levee-system developed on both flanks of the canyon. The levee sediments on the WSW side of the canyon show continuous wave-shaped reflectors but flat and parallel/sub-parallel reflectors on the ENE side. The development of gravity flow slump deposits are significantly reduced in this region, instead, contourite sheeted drifts (contourites deposited across continental margins where a gentle gradient and smooth topography favor a wide non-focused bottom current) compose the sheeted contourite depositional system.

The "seamount related contourite depositional system" is suggested to be generated by the anticyclone intermediate water circulation of the South China Sea. To the north side of the South Shenhu Seamount, bottom currents from west to east would be intensified after being deflected by an obstacle (the presence of the seamount). Thus the bottom current intensity is high and can erode the slope to form a moat. Due to Coriolis deflection, a mounded drift developed to the north of the moat and a small plastered drift to the south (plastered onto the northern flank of the South Shenhu Seamount). Currents away from the seamount are less/non-intensified, generating normal contourite channels and furrows on the drifted deposits north of the moat. Downslope gravity flow activities dominate steeper slopes, where the depositional environment is unsteady thus alongslope contourite deposits are missing. However, the eastward migrating downslope canyon of C.1 may indicate consistent bottom currents flowing from west to east, with intense dynamics. These high velocity currents might also belong to the intermediate water circulation. On gentle and flat slopes, e.g., the bathy plain, sheeted contourite deposits are commonly developed under the control of unfocused and low velocity bottom current in deep layer. The "sheeted contourite depositional system" in the studied area, thus, is proposed to be generated by unfocused bottom currents within the westwards South China Sea deep water circulation. Furthermore, sediment waves and aggradational levees are taken place on flanks of the canyon at the deeper depths, e.g., C.2, which suggests a dominated mechanism for their origin to be overflows of turbidity currents.

Indicated from the first channelized features of consistent contourite channels on seismic reflections, the stable development of the contourite depositional system in the study area could be traced back to ~10 Ma, when local SCS bottom currents initially formed. In agreement with the general transgressional pattern in the northern margin area of the SCS, the followed contourite depositional system developed an aggradational pattern. This study provides new data for further understanding how the environmental factors, e.g., seafloor topographies, sea level/climate changes, tectonic activities and sediment sources, influencing the evolution of the SCS deep-water depositional systems.

Key words: deep-water depositional system; bottom current; contourites; South China Sea