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在线阅读 View online: https://doi.org/10.16562/j.cnki.0256-1492.2025062001

ISSN 0256-1492
CN 37-1117/P

海 洋 地 质 与 第 四 纪 地 质
MARINE GEOLOGY & QUATERNARY GEOLOGY

第 45 卷 第 4 期
Vol.45, No.4

李想, 王毕文, 钟广法. 新西兰东部海域渐新世分支海底峡谷的三维地震表征及沉积演化 [J]. 海洋地质与第四纪地质, 2025, 45(4): 117-129.
LI Xiang, WANG Biwen, ZHONG Guangfa. Three-dimensional seismic characterization and sedimentary evolution of the Oligocene dendritic submarine canyons offshore eastern New Zealand[J]. Marine Geology & Quaternary Geology, 2025, 45(4): 117-129.

新西兰东部海域渐新世分支海底峡谷的三维地震表征及沉积演化

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摘要: 前人对海底峡谷进行的研究大多集中于大中型海底峡谷, 对于峡谷头部小型分支峡谷关注较少。本文基于高分辨率三维地震数据, 研究新西兰南岛东部陆坡邦蒂海底峡谷头部渐新世埋藏分支峡谷的地震地层特征及沉积演化。通过地震层序分析, 在渐新统地层内识别出 7 个地震层序界面, 据此将渐新统划分为 6 个地震层序。以层序为单位, 开展地震沉积单元分析, 识别出冲坑列、U 型谷及开放陆坡三种沉积单元。冲坑列由多个冲坑呈串珠状顺坡排列, 解释为超临界浊流成因底形, 其形成经历了从侵蚀型周期阶坎到部分沉积型周期阶坎的演化, 解释为断续型分支峡谷, 代表了分支峡谷的早期形态。U 型谷平面上表现为平直的顺坡分布的线状凹槽, 内部被浊流–半远洋交互沉积及少量碎屑流沉积充填, 解释为平直型分支峡谷。开放陆坡位于冲坑列和 U 型谷之间及以外区域, 以近平行反射为特征, 内部发育多边形断层, 解释为细粒半远洋沉积。断续型分支峡谷呈幕式发育, 随时间推移冲坑数逐期减少并被细粒沉积充填; 平直型分支峡谷上游表现出一定幅度的侧向迁移, 下游则以垂向加积为主。海平面变化、沉积物供给及陆坡坡度对峡谷演化具有重要影响。

关键词: 三维地震; 分支海底峡谷; 冲坑; 周期阶坎; 邦蒂海底峡谷; 新西兰
中图分类号: P736　　**文献标识码:** A　　**DOI:** 10.16562/j.cnki.0256-1492.2025062001

Three-dimensional seismic characterization and sedimentary evolution of the Oligocene dendritic submarine canyons offshore eastern New Zealand

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Abstract: Previous studies have focused largely on medium-to-large sized submarine canyons, with relatively little attention paid to small dendritic ones developed at canyon heads. We used high-resolution 3D seismic data to investigate the seismic stratigraphic characteristics and sedimentary evolution of the Oligocene buried dendritic tributary canyons located at the head of the Bounty Submarine Canyon System on the eastern continental slope offshore South Island, New Zealand. Through seismic sequence analysis, six seismic sequences separated by seven seismic horizons with reflection terminations were identified within the Oligocene strata. By seismic depositional element analysis, three depositional elements were identified, which are scour train, U-shaped valley, and open slope, respectively. The scour train, composed of multiple scours linearly arranged downslope, was identified as a train of supercritical turbidity-current bedforms. Within each sequence, the scours were vertically evolved from erosional to partially depositional cyclic steps. The train of scours comprises a discontinuous tributary canyon, possibly representing an early stage of dendritic canyons. The U-shaped valley appears as a downslope-extending straight depressions in plan view, filled with alternating turbidites and hemipelagites and minor debris-flow deposits, and was interpreted as a straight tributary canyon. Subparallel reflections with polygonal faults in the open slope environment were interpreted as fine-grained hemipelagic sediments. The development of the discontinuous tributary canyons is episodic. The scours gradually decreased in quantity and were filled by fine-grained sediments over time. The straight tributary canyon showed lateral migration in the upstream and aggradation in the downstream. The evolution of both tributary canyons was controlled by factors including sea-level change, sediment supply, and slope gradient.

Key words: three-dimensional seismic data; dendritic submarine canyons; scours; cyclic steps; Bounty Submarine Canyon; New Zealand

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资助项目: 国家自然科学基金项目“晚新生代台湾造山在花东海盆的沉积层序响应及沉积量”(42476073)
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收稿日期: 2025-06-20; **改回日期:** 2025-07-27.　周立君编辑

海底峡谷是大陆边缘重要的地貌形态和沉积单元，也是陆源沉积物从浅海向深海扩散的主要通道，其成因机制一直是海洋地质研究的热点之一[1-7]。前人研究大多集中于大型海底峡谷的地貌特征、沉积过程、形成演化及成因机制[4, 8-23]。相比之下，对于数量上占绝大多数的小型海底峡谷关注较少。邦蒂海底峡谷–水道系统是发育于新西兰南岛东部陆坡的一条大型海底水系，其头部发育典型的树枝状分支峡谷，为探讨小型海底峡谷的成因及演化提供了极佳案例。前人基于地震资料对该峡谷系统早渐新世不整合及第四纪水道进行过研究[24-30]，但对于其头部的分支海底峡谷还缺乏了解。本文基于三维地震数据，采用地震地层学和地震地貌学方法，研究邦蒂海底峡谷–水道系统头部渐新世埋藏分支峡谷的地貌和沉积特征，探讨其成因。

1　地质背景

邦蒂海底峡谷–水道系统位于新西兰南岛东部陆坡，全长约 1 800 km，是地球上最长的海底水系之一（图 1a）。其上游流经坎特伯雷盆地和大南盆地，沿邦蒂海槽向下游延伸至邦蒂海底扇，是南岛陆源沉积物输送至西南太平洋的主要通道[31-32]。前人地震地层学研究表明，该峡谷从渐新世开始持续发育至今[24, 26, 28-29, 33-34]。在现代海底地形图上，邦蒂峡谷

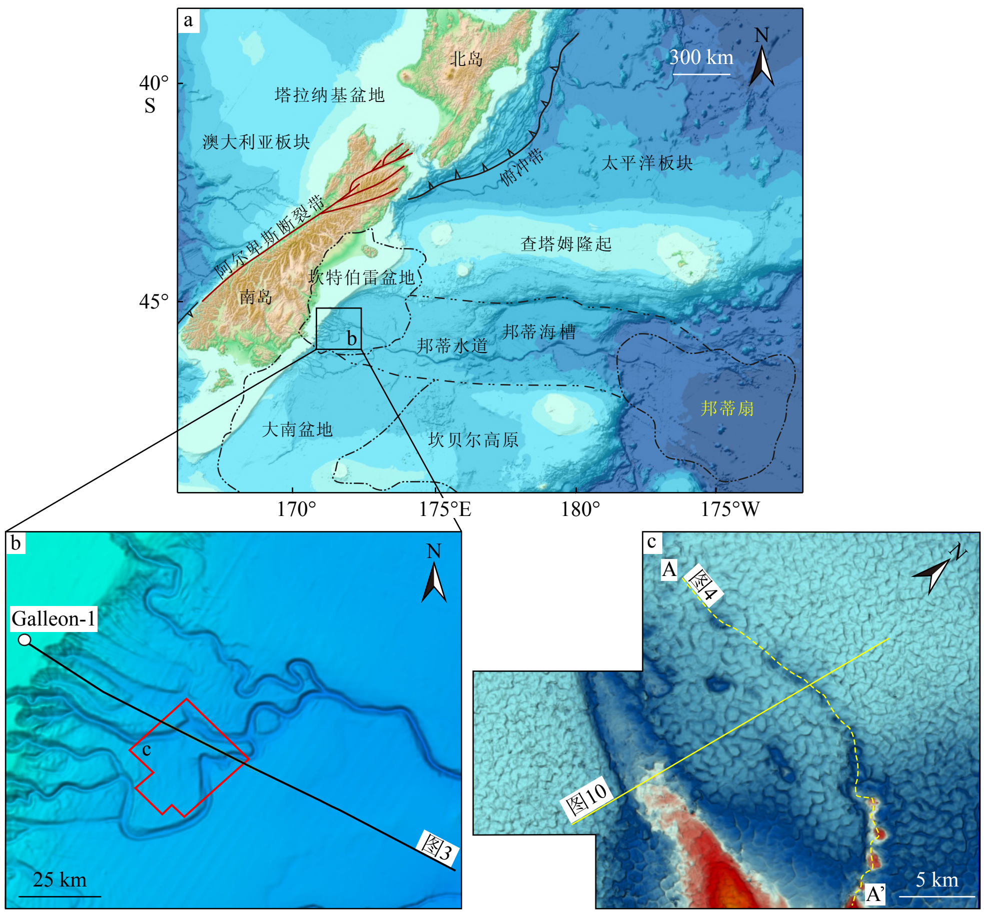

图 1　研究区地质背景

a: 新西兰周边海域海底地形图，展示主要地理和构造单元及邦蒂海底峡谷–水道系统的平面分布[35]; b: 邦蒂海底峡谷–水道系统上游海底地形放大图，红色边框为本文三维地震数据分布范围，黑色线段为图 3 所示过 Galleon-1 井地震剖面的位置; c: 研究区渐新世海底峡谷系统底界面埋深图，黄色虚线和实线分别为图 4 和图 10 所示剖面位置。

Fig.1　Geological background of the study area and surroundings

a: Seabed topographic map offshore of the eastern New Zealand, showing the distribution of major geographical and tectonic units and the Bounty submarine canyon-channel system[35]; b: Enlarged seafloor topographical map of the upper reach of the Bounty canyon-channel system. The red polygon shows the location of the 3D seismic data used in this study. The black solid line denotes the position of the seismic profile traversing the Galleon-1 well shown in Fig. 3; c: The structural map of the base of Oligocene submarine canyon system in the study area. Also shown are locations of the seismic profiles shown in Fig. 4 (yellow dotted line) and Fig. 10 (yellow solid lines).

头部呈树枝状，由多条发源于陆架边缘的分支峡谷组成（图 1b）。本文研究区位于邦蒂峡谷头部分支峡谷的上游，研究对象是渐新世埋藏分支峡谷（图 1c）。

坎特伯雷盆地面积 3.6 万 km^2，最大水深约 1 600 m，东邻邦蒂海槽，南接大南盆地，北界为查塔姆隆起[38]。该盆地是一个在冈瓦纳古陆裂解和太平洋板块俯冲控制下形成的中–新生代叠合盆地[30, 33, 36, 39-42]，其构造演化分为 3 个阶段（图 2）：同裂谷期（105～85 Ma）、裂后期（85～30 Ma）和汇聚边缘期（30 Ma 至今）[43-44]。

白垩纪同裂谷期，冈瓦纳大陆东缘发生显著地壳伸展，导致西兰洲从澳大利亚和南极洲分离，并在该陆块内形成了包括坎特伯雷盆地在内的一系列盆地[45-48]。坎特伯雷盆地具有典型的拉张型裂谷盆地特征。盆地早期以陆相沉积为主，包括冲积扇和辫状河相砂砾岩及湖相泥岩。随着时间推移，早期陆相沉积逐渐过渡为浅海相[43]。

晚白垩世至早渐新世裂后期，坎特伯雷盆地进入被动大陆边缘热沉降演化阶段，构造活动显著减弱，沉积环境由陆源碎屑沉积体系过渡为深水碳酸

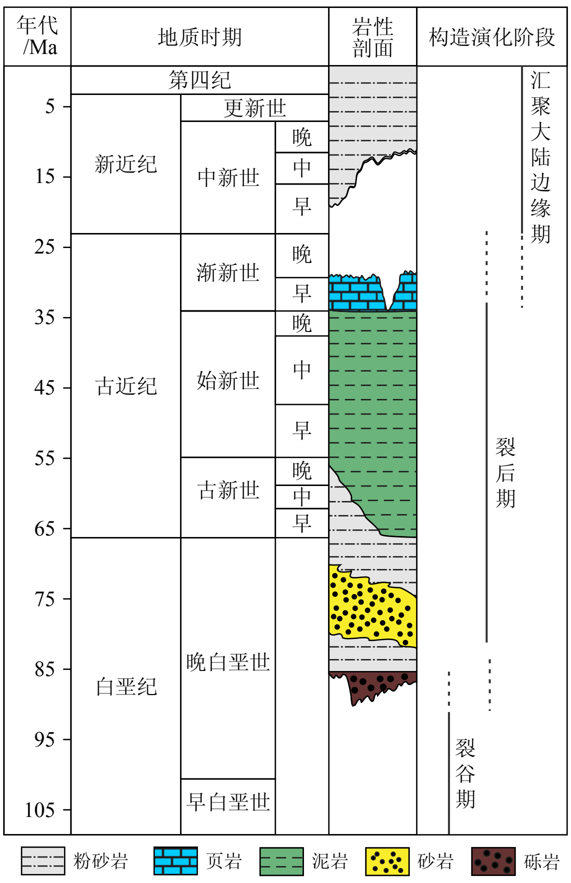

图 2　坎特伯雷盆地构造-地层柱状图[33, 35-37]

Fig.2　Tectonic-stratigraphic column in the Canterbury Basin[33, 35-37]

盐沉积体系[49]，主要由深水钙质泥岩和碳酸盐岩组成[32, 50-51]。晚始新世至早渐新世，研究区以细粒钙质沉积物为主[49, 52-53]。始新统和渐新统之间发育一个区域不整合面，上覆渐新统至中中新统的地层由灰岩、粉砂岩以及砂岩组成[24, 39, 49, 54-56]。

早中新世开始，受太平洋板块斜向俯冲影响，坎特伯雷盆地受到走滑挤压，转换为太平洋汇聚大陆边缘的一部分[57]。中中新世以来，南阿尔卑斯隆升导致陆源碎屑增加[49]。上新世至更新世时期，盆地西部发育由冲积扇砾岩–陆架砂岩–半深海泥岩组成的沉积单元，东部形成浊流沉积体系[43, 58]。

2　数据和方法

本文所用的三维地震数据由新西兰石油和矿产部提供。三维数据覆盖区面积约为 700 km^2（图 1b），水深 1 300～1 400 m。该三维数据的面元大小为 15 m×12.5 m，采样间隔为 2 ms，目标层段主频约为 30 Hz，对应的垂向分辨率（调谐厚度）约为 17 m（目标层段的声波速度约为 2 000 m/s）。本文地震数据采用 SEG 正极性显示，正反射系数界面表示为波峰，用黑色显示；负反射系数界面表示为波谷，用红色显示。

本文采用地震地层学和地震地貌学研究方法。首先，根据地震反射终止关系（上超、下超、削截、顶超等）识别不整合面，沿不整合面横向追踪至对应的整合面，确定层序界面。通过与新西兰海域经大量钻井资料标定的区域地震层位划分方案[28, 36]进行对比（图 3），确定关键地震层序界面的地质年代。其次，以层序为单位，采用地震相[59]和地震属性[60-61]分析方法，识别和划分地震沉积单元，分析其成因及演化。地震相分析主要依据振幅、连续性、内部结构和外部几何形态等地震反射参数。地震属性分析主要基于均方根振幅（RMS）和振幅方差（或相干）属性，前者反映地层的岩性[62]，后者用于刻画不同地震沉积单元的边界[22, 63-65]。依据划分好的层序格架，分别制作沿层序边界的层位切片和层序内部的地层切片[66]。

3　结果

3.1　地震层序分析

根据反射终止标志，在渐新世层段识别出 7 个地震层序界面，自下而上依次命名为 H1–H7（图 4）。

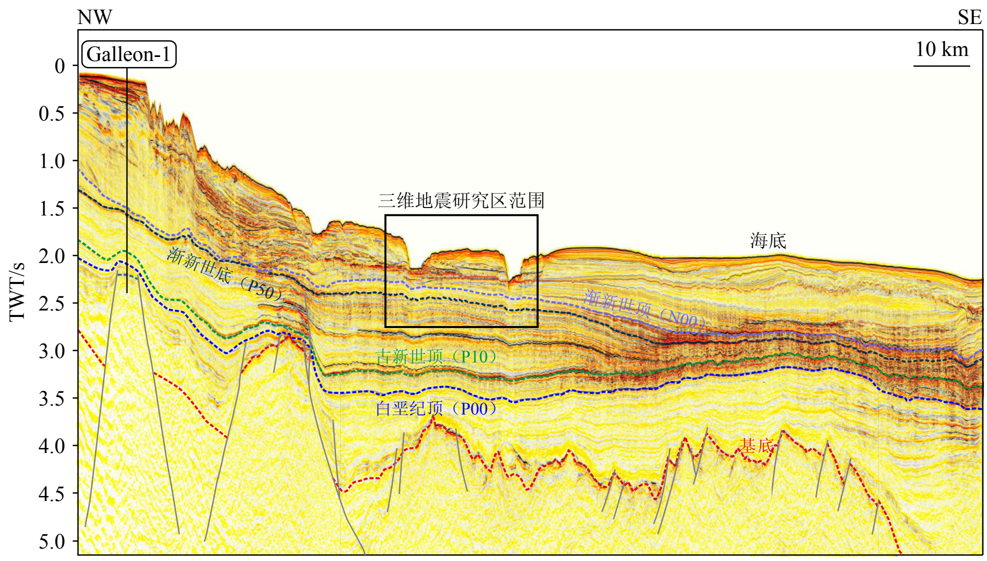

图 3　过 Galleon-1 井 NW-SE 走向的区域地震剖面

此剖面展示新西兰海域经过大量钻井年代数据标定过的关键区域地震层序界面[24, 37]，灰色实线表示断层；TWT 为双程旅行时（下同）；剖面位置见图 1b。

Fig.3　A NW-SE regional seismic profile passing the Galleon-1 well and the study area

This profile shows some age-dated regional seismic horizons (colored dashed lines) in waters offshore of the New Zealand[24, 37]. Solid gray lines indicate faults. TWT denotes two-way travel time (same for the following figures). See profile location in Fig. 1b.

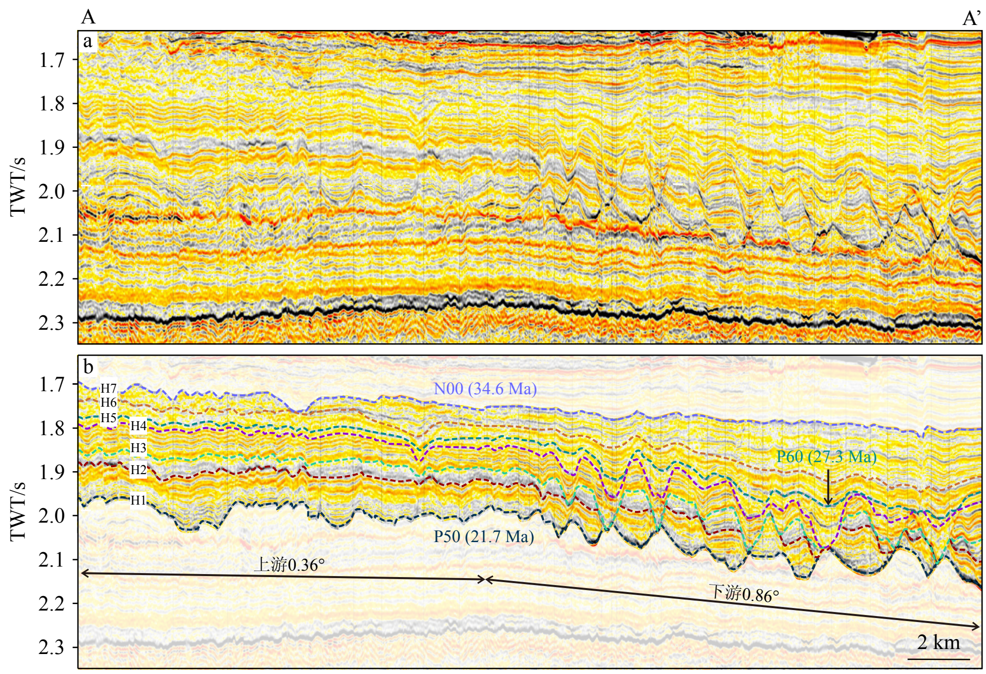

图 4　研究区渐新统地震层序划分

a：未解释的地震剖面，b：解释的地震剖面；剖面位置见图 1。

Fig.4　The Oligocene seismic sequences in the study area

a: Uninterpreted, b: interpreted seismic profile. See Fig.1 for the profile location.

这些层序界面总体表现为中–强振幅、中–高连续性反射，其下伏地层普遍被削截，而上覆地层则常常表现为上超终止关系。对比新西兰海域区域地震层序划分方案[28, 43, 67]，本文识别的层序界面 H1 与前人划定的 P50 反射界面一致，对应于始新统与渐新统的分界面（约 34.6 Ma）。层序界面 H5 与 P60 反射界面吻合，对应于上、下渐新统分界面（约 27.3 Ma）。层序界面 H7 与 N00 反射界面相当，对应于上渐新

统与下中新统分界面(约 21.7 Ma)(图 3-4)。根据层序界面 H1–H7 将渐新统划分为 6 个地震层序, 自下而上依次命名为层序 S1–S6。

3.2　地震沉积单元分析

在层序划分基础上, 以层序为单位开展地震沉积单元识别及特征分析。根据剖面反射特征和平面属性特征, 识别出 3 种地震沉积单元类型, 分别为 U 型谷、冲坑列及开放陆坡。

3.2.1　U 型谷

研究区发育一个北西−南东走向、顺坡变宽的凹槽状地貌, 长约 17 km, 宽约 3～5 km。层序界面埋深图显示, H1−H5 界面凹槽上游左侧地势相对较高(图 5a)。凹槽横截面呈宽缓的 U 字型, 其下伏地层普遍被削截(图 6a-c)。地震相分析显示, U 型谷内部主要充填亚平行−发散反射, 含少量杂乱反射。其中层序 S1–S4 的振幅总体上强于 S5–S6。U 型谷上游具有侧向加积特点, 自层序 S1 至 S4, 谷底向西南方向横向迁移了约 2 km; 中下游则以垂向加积为主(图 6)。沿层相干切片显示, U 型谷内部不发育多边形断层(图 5b)。均方根振幅切片显示, U 型谷中泓线及其右壁呈现明显的北西−南东向的条带状强振幅特征(图 7)。

将该 U 型谷解释为平直型分支海底峡谷, 其北西−南东走向与区域陆坡倾向一致, 表明物源主要来自西北方向。峡谷内部的强振幅、亚平行−发散地震相暗示该峡谷充填由较粗粒的浊流沉积与细粒半远洋沉积交互组成。少量的杂乱反射可能指示碎屑流沉积的存在。峡谷上游沉积充填从层序 S1 开始持续向西南方向迁移, 直至层序 S6 完全被充填废弃。峡谷下游相对稳定, 以垂向加积为主。强振幅反射和侧向迁移特征指示活跃的浊流活动。峡谷充填的强振幅反射特征及内部多边形断层不发育, 可能暗示峡谷内部主要被相对粗粒的沉积物充填(多边形断层一般发育于细粒泥质沉积物中)。

3.2.2　冲坑列

研究区发育北西−南东走向、顺陆坡倾向排列

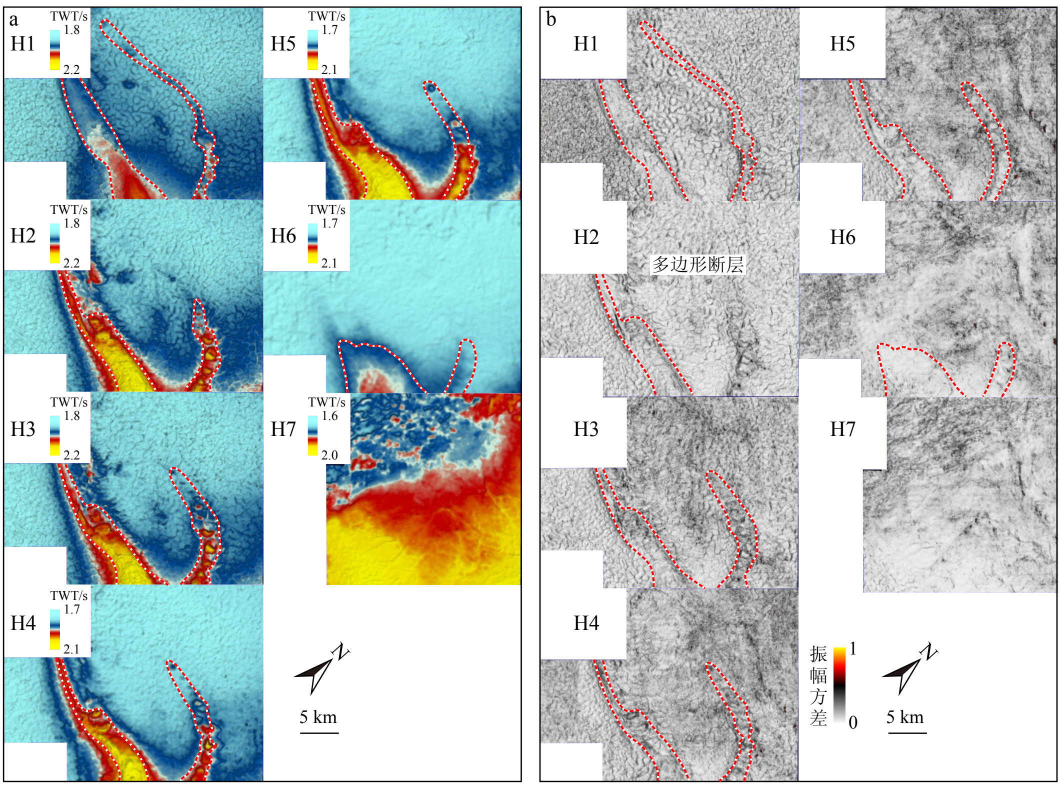

图 5　层序界面 H1–H7 的埋深图和沿层相干切片

a: 层序界面 H1–H7 的埋深图, b: 层序界面 H1–H7 的沿层相干切片图; 红色虚线表示峡谷谷底边界。注意从 H1 至 H5 多边形断层发育程度逐渐减弱, H6、H7 缺乏多边形断层。

Fig.5　Structural maps and coherence horizon slices of horizons H1-H7

a: Structure maps of horizons H1-H7, b: Coherence horizon slices of horizons H1-H7. The red dashed lines indicate canyon floor boundaries. Note that the density of polygonal faults decreased from horizons H1 to H5, and few polygonal faults were observed in horizons H6-H7.

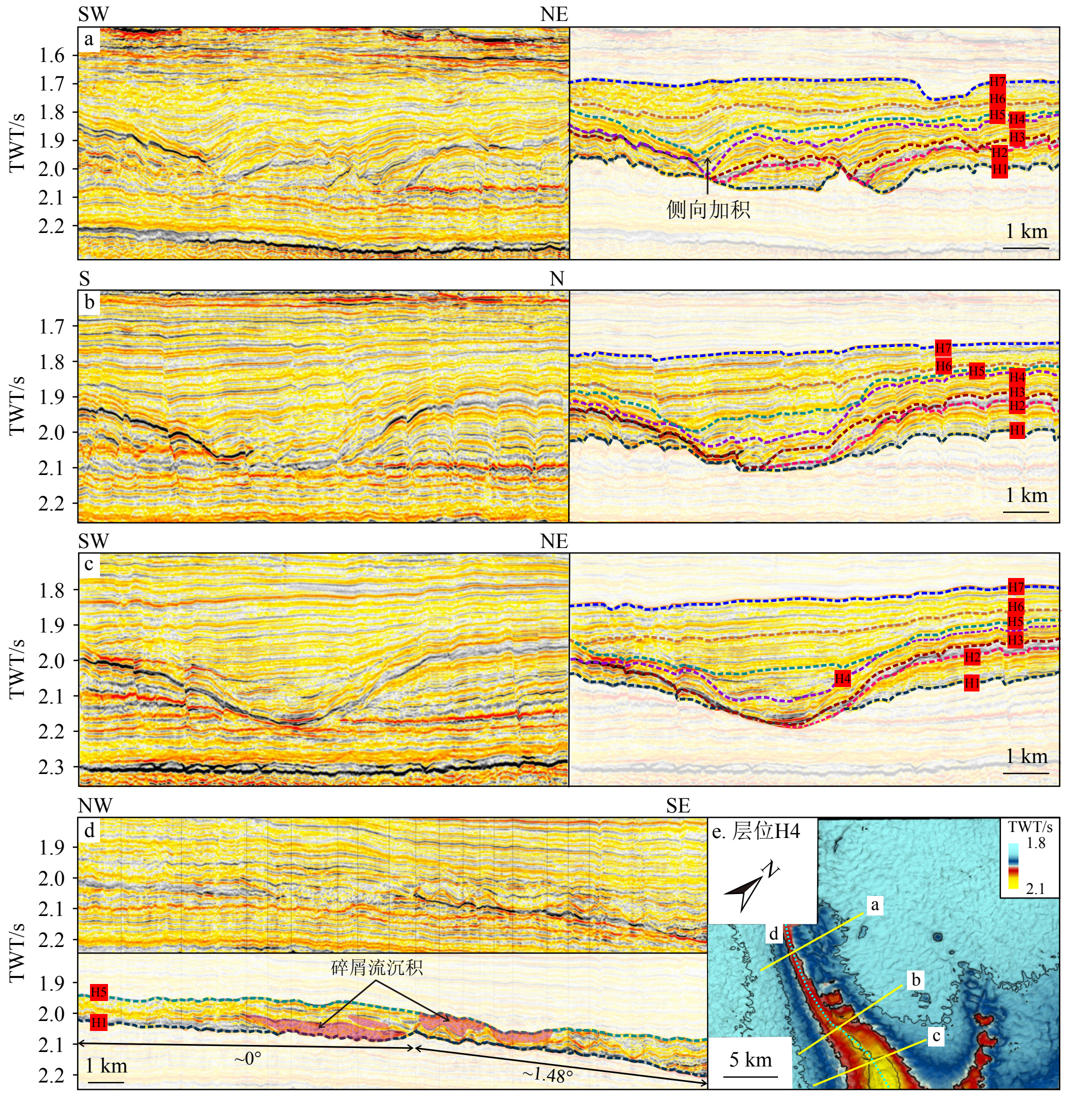

图 6　U 型谷地震反射特征

a-c: 穿过 U 型谷上、中、下游的地震横剖面(左侧)及对应的地质解释(右侧), d: 谷底中泓线地震剖面(上)及对应的地质解释(下), e: 层位 H4 埋深图及测线位置。

Fig.6　Seismic reflection characteristics of the U-shaped valley

a-c: Cross-sections (left panel) and corresponding interpretation (right panel) across the upper(a), middle (b) and lower (c) reaches of the U-shaped valley; d: Seismic profile along the canyon thalweg (upper panel) and corresponding interpretation (lower panel); e: Time structural map of horizon H4 and the location of seismic profiles.

的串珠状冲坑列，由 2～16 个冲坑首尾相连组成，冲坑列的总长度约 28.5 km(图 4-5)。单个冲坑的直径为 0.5～1.5 km，冲坑间距 0.3～1.2 km。自层序 S1 至 S6，冲坑数量逐渐减少。单个冲坑在平面上呈不规则圆形或椭圆形负地貌，剖面上冲坑底界表现为强振幅下切面，其下伏地层被削截。沿中泓线的纵剖面显示，冲坑总体呈迎流面较缓、背流面较陡的不对称形态(图 8)。冲坑内部充填沉积的地震反射有以下 3 种类型：① 冲坑充填沉积物主要分布在冲坑的迎流面，呈逆坡倾斜、厚度顺流减薄的发散反射结构，反射振幅中–强，反射连续性中–高(图 8d-f)，相邻发散反射单元被顺坡倾斜的侵蚀面分隔(图 8c-f)；② 冲坑充填沉积物发育于部分冲坑的底部，以弱振幅、低连续性的杂乱或透明反射结构为特征(图 8c-d)。③ 冲坑充填沉积物发育于晚期冲坑相连形成的带状凹陷，总体表现为中–弱振幅、中–高连续性发散反射结构(图 8a)。均方根振幅切片表明，冲坑迎流面为红色或黄色强振幅区，杂乱充填区多呈蓝色弱振幅(图 9a)，晚期带状凹陷区与两侧相邻地层的振幅差异很小(图 5、图 7)。

把该串珠状冲坑解释为超临界浊流成因的周期阶坎底形，它们具有迎流面缓、背流面陡的不对

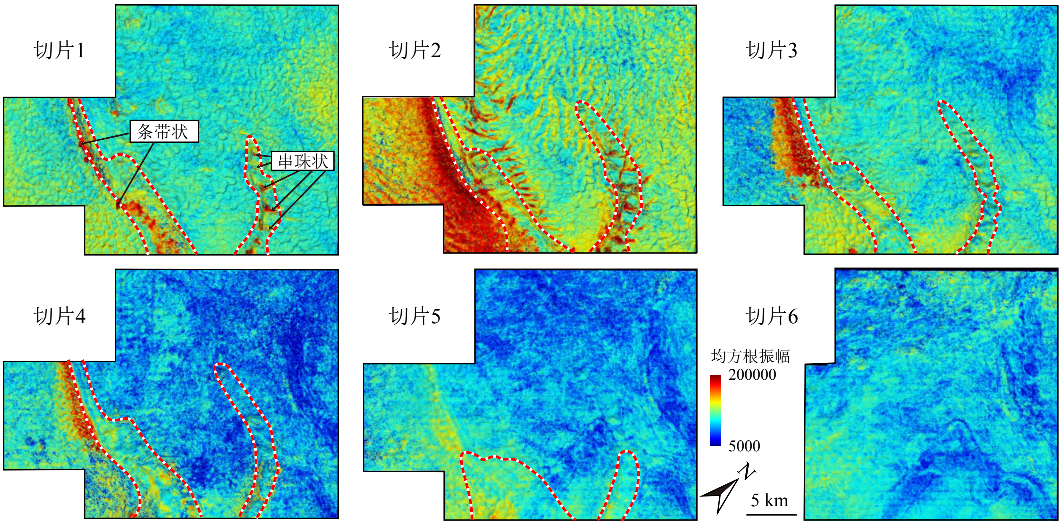

图 7　各层序内部均方根振幅地层切片

展示研究区分支海底峡谷的平面演化。切片 1 为层序界面 H1 和 H2 之间平分层序 S1 的地层切片, 切片 2 为界面 H2 和 H3 之间平分层序 S2 的地层切片, 其余依此类推。红色虚线表示峡谷谷底边界。

Fig.7　Root-Mean-Square (RMS) amplitude stratal slices within each seismic sequence

The stratal slices demonstrate the planar evolution of the dendritic submarine canyons in the study area. Slice 1 equally divides sequence S1; slice 2 equally divides sequence S2, and so forth for other slices. The red dashed line indicates the canyon floor boundary.

称特征。单个冲坑内部迎流面的发散反射解释为后积层理[68], 分隔相邻后积层理的顺坡倾斜的侵蚀面解释为复合侵蚀面(图 8), 迎流面沉积、背流面侵蚀的底形解释为部分沉积型周期阶坎[68], 其强振幅反射特征指示其粗粒浊积物特征[60, 69-70]。冲坑底部局部区域的杂乱、弱振幅反射可能代表与水跃有关的快速堆积。而冲坑列发育晚期的中–弱振幅发散反射可能代表冲坑废弃后以半远洋细粒沉积为主的填平补齐沉积[71]。整个冲坑列解释为由多个周期阶坎底形首尾相连组成的断续型海底峡谷, 可能代表了分支海底峡谷的一种早期形态。需要说明的是, 上述复合侵蚀面在地震剖面上容易与断层相混淆, 但根据以下特征不难将二者区分: 首先, 复合侵蚀面仅分布于冲坑的背流面, 不像断层有一定的横向延伸范围; 其次, 复合侵蚀面的产状系统地顺坡倾斜, 且相邻复合侵蚀面之间的间距基本一致, 而断层很难出现这种完全同向倾斜且间距近等的现象; 第三, 复合侵蚀面仅分布于发育周期阶坎底形的层序中, 而断层很少完全限制在某个特定的层序内。

3.2.3　开放陆坡

U 型谷和串珠状冲坑列之间或以外的区域, 地形较为平缓, 平均坡度约为 0.4°, 局部偶尔可见零散的冲坑(图 5)。总体表现为中–弱振幅、连续的平行–亚平行反射地震相, 切片上对应的均方根振幅较弱。相干切片显示, 该单元分布着密集的多边形网格状构造(图 5)。这些构造形态在剖面上的倾角约为 30°～80°, 间距 150～700 m, 发育地层的厚度为 390～710 m, 并呈现出自西向东逐渐减薄的趋势。多数断层向上终止于 H6 层位, 仅少数可延伸至海底, 其底界多限于上始新统(图 10)。

该单元解释为峡谷间或峡谷外的开放陆坡沉积, 其连续平行–亚平行反射结构和低 RMS 振幅属性指示形成于稳定中–低能沉积环境下的细粒沉积物, 解释为陆坡半远洋沉积[59, 72]。多边形网格状构造解释为多边形断层系统[50]。地震剖面显示, 研究区多边形断层主要发育于上始新统至中–下渐新统(图 6, 图 10)。区域地质资料表明, 该时段陆坡沉积物主要由钙质泥岩和泥晶碳酸盐岩组成, 其粒度细、含水率高、早期固结弱[32, 36, 44], 为多边形断层发育提供了优越的条件。

3.3　分支峡谷系统的沉积演化

综上所述, 研究区发育的 U 型谷和串珠状冲坑列代表了分支海底峡谷的两种类型, 其中冲坑列与超临界浊流的幕式侵蚀–沉积充填作用有关, 而 U 型谷则代表了正常的相对成熟的海底峡谷。

U 型谷代表的平直型分支海底峡谷的演化可以大致划分为两个阶段: 层序 S1–S4 发育期, 平直型峡谷上游以侧向加积为主, 整体从东北向西南迁移了 2 km(图 6a), 峡谷下游则以垂向加积为主。层

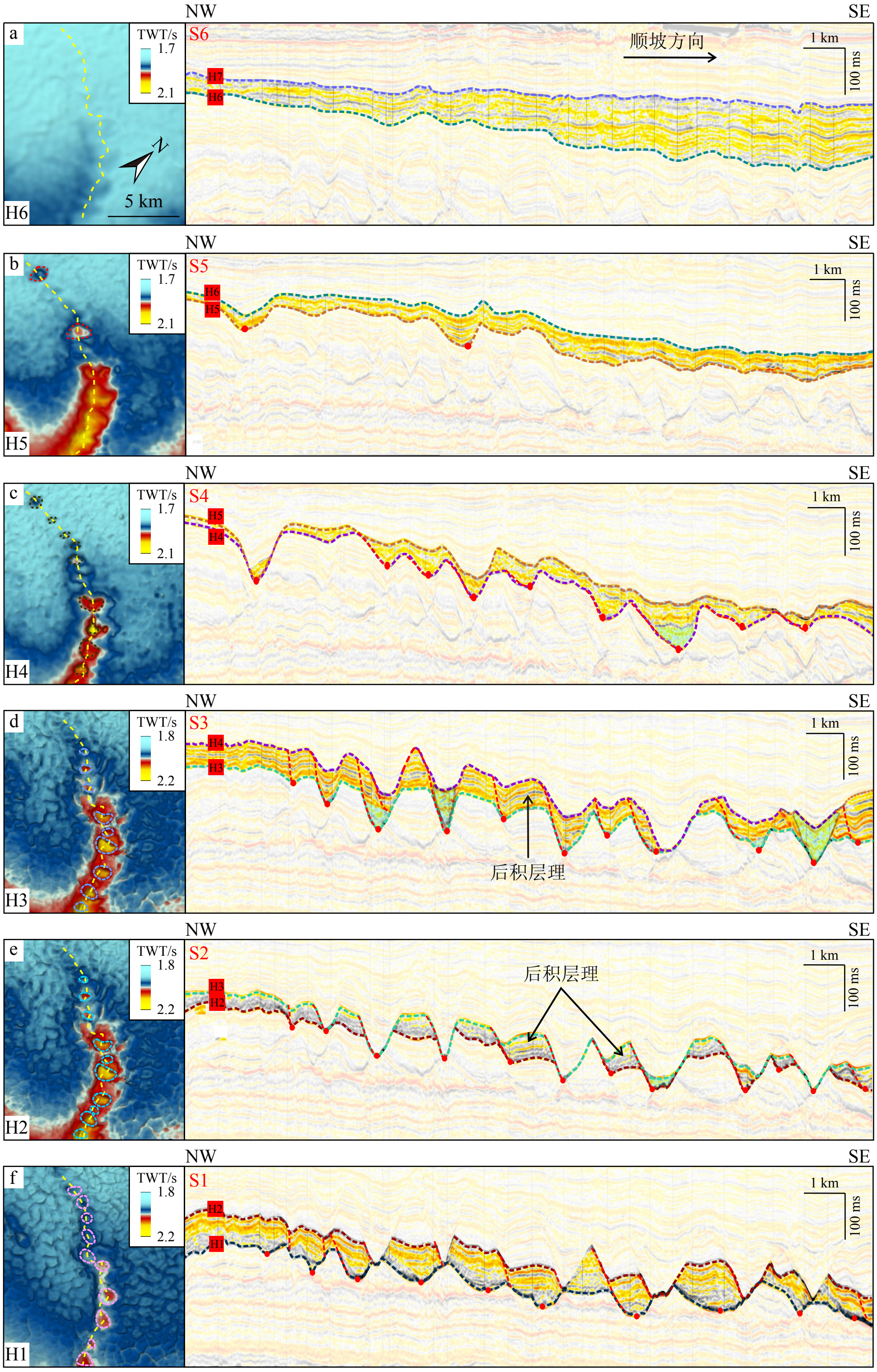

图 8　冲坑列中泓线地震反射特征

a-f 依次为层位 H6−H1 埋深图的局部放大(左)及层序 S6−S1 的中泓线剖面解释(右)。埋深图中的彩色圆形虚线代表冲坑。地震剖面图中的红色圆点表示每个冲坑的最低点,绿色充填区域为杂乱充填,红色虚线为复合侵蚀面。

Fig.8　Seismic reflection characteristics of the scour train thalwegs

a-f: Enlarged structural maps of horizon H6-H1 (left) and corresponding interpreted seismic profiles (right) for sequence S6-S1, respectively. The colored circular dotted lines in the structural maps represent scours. The red dots indicate the deepest points of individual scours. Green shaded area represents the chaotic fill-typed seismic facies, and the red dashed lines represent the composite erosion surfaces.

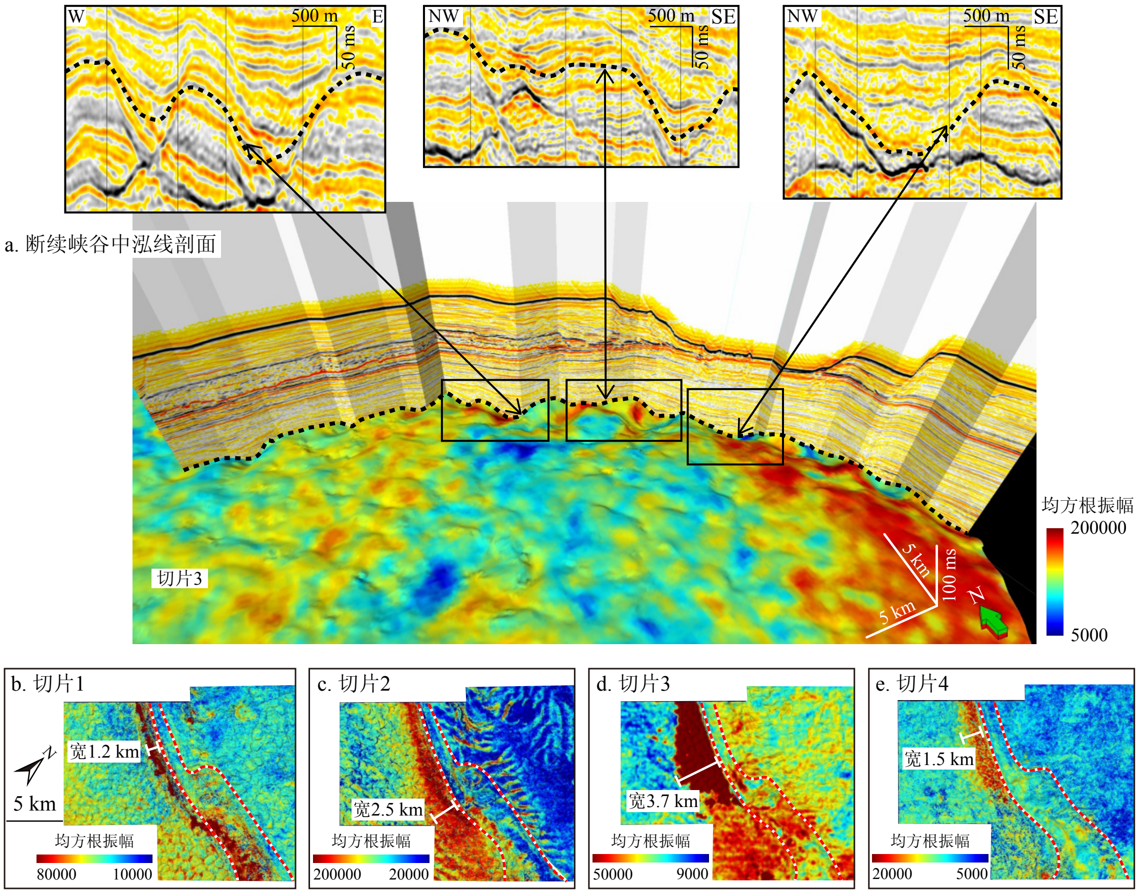

图 9　均方根振幅切片结合地震剖面展示断续峡谷和平直峡谷特征

a: 过断续峡谷的地震剖面与层位 H3 均方根振幅切片联合三维显示，三个放大地震剖面图显示冲坑及其充填特征；b-e: 平直峡谷切片 1-4 的局部放大图，红白虚线表示平直峡谷谷底范围。

Fig.9　Root-mean-square amplitude slices combined with seismic profiles showing the characteristics of the discontinuous and straight canyons

a: The 3D display of the seismic profiles along the discontinuous canyon thalweg combined with the RMS amplitude slice of Horizon H3. Enlarged seismic profiles showing details of selected scours; b-e: Enlarged stratal slices 1-4 showing the characteristics of straight canyon. The red lines with white dots lineates the straight canyon floor.

序 S5–S6 发育期，峡谷进入废弃阶段，表现为反射振幅减弱，沉积物以细粒半远洋沉积为主。

冲坑列所代表的断续型海底峡谷经历了 6 个层序的演化，每个层序中，冲坑列的演化始于层序底界所代表的大规模的超临界浊流的侵蚀下切，形成了首尾相连的冲坑列，其中每个冲坑代表了一个侵蚀型周期阶坎，接着是层序内部以部分沉积型周期阶坎为特色的冲坑充填阶段。每个层序从侵蚀型周期阶坎开始，到部分沉积型周期阶坎结束，代表一个完整的冲坑列从形成到充填的沉积旋回。相应地，六个层序反映冲坑列经历了六期形成与充填过程。自下而上，从层序 S1 至层序 S6，组成冲坑列的冲坑数量逐渐减少，冲坑规模也相应减小，直至最终在层序 S6 发育时期冲坑列完全废弃并被细粒沉积物填平（图 8）。

4　讨论

峡谷的起源一般认为与滑坡或浊流有关[73-74]。本文研究的两条渐新世分支峡谷中，平直型峡谷总体被浊流沉积充填，局部可见碎屑流沉积，其成因与浊流及部分碎屑流的侵蚀和沉积有关；而由冲坑列组成的断续型峡谷的形成和演化主要受超临界浊流的侵蚀和沉积过程控制。峡谷重力流的来源主要有河口异重流、海底滑坡引发的浊流和碎屑流、与风暴过程有关的浊流等类型[75]。由于本文研究的两条分支峡谷远离陆架河口区，可以基本排除异重流的可能性，同时考虑到平直型峡谷充填中见到部分碎屑流沉积，推测重力流可能主要由峡谷上游及两翼坡度较陡部位的海底滑坡转化而来。

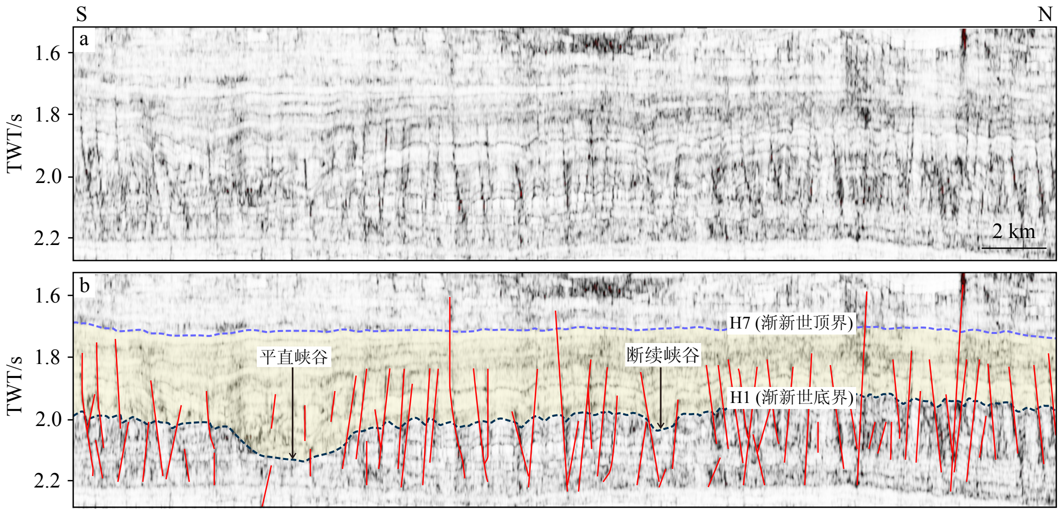

图 10 开放陆坡多边形断层的相干属性剖面图

a 和 b 分别为未解释和解释后的相干属性剖面，红线表示断层，黄色区域为渐新世地层。剖面位置见图 1。

Fig.10 Coherence attribute profiles showing polygonal faults in the open continental slope

a: Uninterpreted coherence profiles, b: Interpreted coherence profiles. Red lines indicate faults, and yellow shaded areas indicate the Oligocene interval. See Fig. 1 for profile location.

需要注意的是，本文分支峡谷的沉积演化受多种异旋回因素控制，包括构造活动、海平面变化、沉积物供应等。早渐新世，研究区整体处于构造稳定期，但西部的奥塔哥区域开始形成局部古隆起，可能为峡谷的形成提供了一定的沉积物来源。渐新世，全球海平面出现明显下降[20, 76]，导致陆源物质向海供应增加，也为峡谷系统的发育奠定了物质基础。海平面下降还有利于浊流的发育[77]，促成了峡谷的形成。前已提及，平直型峡谷充填主要由浊流与半远洋沉积交互组成，局部夹碎屑流沉积，而断续型峡谷则主要受超临界浊流控制，由一系列周期阶坎底形组成。断续型分支峡谷可能代表了峡谷的初始形态，而平直型峡谷的发育则相对成熟。尚不清楚平直型峡谷是否也经历了以冲坑列为代表的早期断续峡谷发育阶段。此外，这两条分支海底峡谷相距如此之近，为什么会呈现出如此不同的地貌形态和侵蚀–沉积特征，也有待未来收集更多的地质证据进行深入研究。

坡度对海底峡谷及重力流的发育至关重要，平直峡谷上游的侧向迁移可能与坡度有关。水槽实验研究显示，坡度较缓（＜0.5°）时水道更容易发生侧向迁移或摆动，当坡度大于 1.5°时则更容易形成直流水道[78]，实际海底观测也验证了这一结论[17, 79]。本文上游陆坡区的坡度不超过 0.5°（图 4、图 6），可能为峡谷侧向迁移产生有利条件。此外，组成断续峡谷的冲坑主要发育于坡度更陡的下游区域，此时浊流更容易加速获取更大能量，形成超临界浊流成因的侵蚀型冲坑。相比而言，上游坡度平缓的区域冲坑数量明显减少。

5 结论

基于地震层序分析，将研究区渐新统划分为 6 个地震层序。地震相和属性切片分析揭示了研究区发育 U 型谷、冲坑列和开放陆坡三种沉积单元。其中，U 型谷较为平直，上游较窄、下游变宽，解释为平直型分支峡谷，在渐新世经历了从形成、持续发育到废弃的完整演化过程，其内部沉积物主要由浊流–半远洋交互沉积及少量碎屑流沉积组成；冲坑列由多个冲坑呈串珠状顺坡排列，解释为超临界浊流成因底形，其形成经历了 6 期从侵蚀型冲坑到部分沉积型周期阶坎的演化，可能代表了分支峡谷的一种早期形态；开放陆坡位于冲坑列和 U 型谷之间或以外区域，以近平行反射为特征，内部发育多边形断层，解释为细粒半远洋沉积。两类分支峡谷都经历了从侵蚀下切到充填废弃的演化过程，主要受浊流过程主导，其沉积演化过程主要与海平面变化、沉积物供给与坡度等因素有关。

致谢： 感谢两位匿名专家的评审。本文系第二十七届中国科协年会学术论文。

参考文献 (References)

[1] Shepard F P. Submarine canyons: multiple causes and long-time persistence[J]. AAPG Bulletin, 1981, 65(6)：1062-1077.

[2] Normark W R, Posamentier H, Mutti E. Turbidite systems: state of the art and future directions[J]. Reviews of Geophysics, 1993, 31(2)：91-116.

[3] Clark J D, Kenyon N H, Pickering K T. Quantitative analysis of the geometry of submarine channels: implications for the classification of submarine fans[J]. Geology, 1992, 20(7)：633-636.

[4] Jobe Z R, Lowe D R, Uchytil S J. Two fundamentally different types of submarine canyons along the continental margin of Equatorial Guinea[J]. Marine and Petroleum Geology, 2011, 28(3)：843-860.

[5] Deptuck M E, Steffens G S, Barton M, et al. Architecture and evolution of upper fan channel-belts on the Niger Delta slope and in the Arabian Sea[J]. Marine and Petroleum Geology, 2003, 20(6-8)：649-676.

[6] Covault J A, Sylvester Z, Hubbard S M, et al. The stratigraphic record of submarine-channel evolution[J]. The Sedimentary Record, 2016, 14(3)：4-11.

[7] Weimer P, Slatt R M. Petroleum systems of deepwater settings[M]. Tulsa: Society of Exploration Geophysicists, 2004.

[8] Normark W R. Growth patterns of deep-sea fans[J]. AAPG Bulletin, 1970, 54(11)：2170-2195.

[9] Mutti E, Ricci Lucchi F. Turbidites of the northern Apennines: introduction to facies analysis[J]. International Geology Review, 1978, 20(2)：125-166.

[10] Walker R G. Deep-water sandstone facies and ancient submarine fans: models for exploration for stratigraphic traps[J]. AAPG Bulletin, 1978, 62(6)：932-966.

[11] Deptuck M E, Sylvester Z, Pirmez C, et al. Migration–aggradation history and 3-D seismic geomorphology of submarine channels in the Pleistocene Benin-major Canyon, western Niger Delta slope[J]. Marine and Petroleum Geology, 2007, 24(6-9)：406-433.

[12] Covault J A, Romans B W, Graham S A, et al. Terrestrial source to deep-sea sink sediment budgets at high and low sea levels: insights from tectonically active Southern California[J]. Geology, 2011, 39(7)：619-622.

[13] Prather B E, Deptuck M E, Mohrig D, et al. Application of the Principles of Seismic Geomorphology to Continental-Slope and Base-of-Slope Systems: Case Studies from Seafloor and Near-Seafloor Analogues [C]//SEPM Special Publication. Tulsa: Society for Sedimentary Geology (SEPM), 2012: 5-9.

[14] Kolla V, Bourges P, Urruty J M, et al. Evolution of deep-water Tertiary sinuous channels offshore Angola (west Africa) and implications for reservoir architecture[J]. AAPG Bulletin, 2001, 85(8)：1373-1405.

[15] Kolla V, Posamentier H W, Wood L J. Deep-water and fluvial sinuous channels: characteristics, similarities and dissimilarities, and modes of formation[J]. Marine and Petroleum Geology, 2007, 24(6-9)：388-405.

[16] Posamentier H W. Deep-water turbidites and submarine fans[M]//Facies Models Revisited. Tulsas: SEPM Society for Sedimentary Geology, 2006: 399-520.

[17] Jobe Z R, Howes N C, Auchter N C. Comparing submarine and fluvial channel kinematics: implications for stratigraphic architecture[J]. Geology, 2016, 44(11)：931-934.

[18] Mahon E M, Wallace M W. 3D seismic geomorphology of Early Cenozoic incised channels, Gippsland Basin, SE Australia: evidence for submarine origin[J]. Sedimentary Geology, 2022, 430：106092.

[19] Gouott B S B, Yem M, Atangana J Q Y, et al. Seismic geomorphology of a Late Cretaceous submarine channel system in the Kribi/Campo sub-basin, offshore Cameroon[J]. Marine and Petroleum Geology, 2022, 145：105865.

[20] Haq B U, Hardenbol J, Vail P R. Chronology of fluctuating sea levels since the Triassic[J]. Science, 1987, 235(4793)：1156-1167.

[21] Sylvester Z, Pirmez C, Cantelli A. A model of submarine channel-levee evolution based on channel trajectories: implications for stratigraphic architecture[J]. Marine and Petroleum Geology, 2011, 28(3)：716-727.

[22] Bouchakour M, Zhao X M, Ge J W, et al. Evolution of submarine channel morphology in intra-slope mini-basins: 3D-seismic interpretation from offshore Niger delta[J]. Marine and Petroleum Geology, 2022, 146：105912.

[23] Mitchell W H, Whittaker A C, Mayall M, et al. New models for submarine channel deposits on structurally complex slopes: examples from the Niger delta system[J]. Marine and Petroleum Geology, 2021, 129：105040.

[24] Barrier A, Nicol A, Browne G H, et al. Early Oligocene marine canyon-channel systems: implications for regional paleogeography in the Canterbury Basin, New Zealand[J]. Marine Geology, 2019, 418：106037.

[25] Abbey C J. The Waitaki Canyon - An investigation of the Late Quaternary development of a shelf-indenting submarine canyon using high-resolution boomer seismic data[D]. Master Dissertation of University of Otago, 2017.

[26] Harishidayat D, Raja W R. Quantitative seismic geomorphology of four different types of the continental slope channel complexes in the Canterbury Basin, New Zealand[J]. Applied Sciences, 2022, 12(9)：4386.

[27] Mitchell J, Nell H. OS20/20 Canterbury—Great South Basin TAN1209 voyage report[R]. Wellington: National Institute of Water and Atmospheric Research (NIWA), 2012.

[28] Sahoo T R, Kroeger K F, Thrasher G, et al. Facies distribution and impact on petroleum migration in the Canterbury Basin, New Zealand[C]//International Conference and Exhibition, Melbourne, Australia 13-16 September 2015. Tulsa: American Association of Petroleum Geologists (AAPG), 2015.

[29] Zhao T, Zhang J, Li F Y, et al. Characterizing a turbidite system in Canterbury Basin, New Zealand, using seismic attributes and distance-preserving self-organizing maps[J]. Interpretation, 2016, 4(1)：SB79-SB89.

[30] O'malley M D. A multi-channel seismic interpretation of the canterbury basin offshore New Zealand and potential hydrocarbon sources[D]. Master Dissertation of Ohio State University, 2018.

[31] Carter R M, Carter L. The bounty channel system: a 55-million-year-

old sediment conduit to the deep sea, Southwest Pacific Ocean[J]. Geo-Marine Letters, 1987, 7(4)：183-190.

[32] Carter L, Carter R M, McCave I N. Evolution of the sedimentary system beneath the deep Pacific inflow off eastern New Zealand[J]. Marine Geology, 2004, 205(1-4)：9-27.

[33] Kumar P C, Alves T M, Sain K. Submarine canyon systems focusing sub-surface fluid in the Canterbury Basin, South Island, New Zealand[J]. Scientific Reports, 2021, 11(1)：16990.

[34] Carter L, Mitchell J S. Late Quaternary sediment pathways through the deep ocean, east of New Zealand[J]. Paleoceanography, 1987, 2(4)：409-422.

[35] Samuel S P. Depositional history of Paleocene sediments in the offshore canterbury basin, New Zealand[D]. Master Dissertation of Victoria University of Wellington, 2010.

[36] Barrier A, Bischoff A, Nicol A, et al. Relationships between volcanism and plate tectonics: a case-study from the Canterbury Basin, New Zealand[J]. Marine Geology, 2021, 433：106397.

[37] 袭著纲, 骆宗强, 刘铁树. 新西兰坎特伯雷盆地构造-沉积演化及海域含油气远景 [J]. 海相油气地质, 2015, 20(3)：59-65. [XI Zhugang, LUO Zongqiang, LIU Tieshu. Tectonic-sedimentary evolution and offshore hydrocarbon potential in Canterbury Basin, New Zealand[J]. Marine Origin Petroleum Geology, 2015, 20(3)：59-65.]

[38] Uruski C, Baillie P. Petroleum potential of the deepwater Taranaki basin, New Zealand[M]//Fillon R H, Rosen N C, Weimer P, et al. Petroleum Systems of Deep-Water Basins–Global and Gulf of Mexico Experience. Houston: SEPM Society for Sedimentary Geology, 2001.

[39] Fulthorpe C S, Carter R M, Miller K G, et al. Marshall Paraconformity: a mid-Oligocene record of inception of the Antarctic circumpolar current and coeval glacio-eustatic lowstand?[J]. Marine and Petroleum Geology, 1996, 13(1)：61-77.

[40] Higgs K E, Browne G H, Sahoo T R. Reservoir characterisation of syn-rift and post-rift sandstones in frontier basins: an example from the Cretaceous of Canterbury and Great South basins, New Zealand[J]. Marine and Petroleum Geology, 2019, 101：1-29.

[41] Higgs K E, Funnell R H, Browne G H. A multidisciplinary study of diagenesis and pore fluid evolution in frontier basins; an example from Canterbury and Great South basins, New Zealand[J]. Marine and Petroleum Geology, 2021, 124：104817.

[42] Schiøler P, Rogers K, Sykes R, et al. Palynofacies, organic geochemistry and depositional environment of the Tartan Formation (Late Paleocene), a potential source rock in the Great South Basin, New Zealand[J]. Marine and Petroleum Geology, 2010, 27(2)：351-369.

[43] Barrier A, Browne G H, Nicol A, et al. Sedimentary architecture of a Late Cretaceous under-filled rift basin, Canterbury Basin, New Zealand[J]. Basin Research, 2022, 34(1)：342-365.

[44] Bache F, Mortimer N, Sutherland R, et al. Seismic stratigraphic record of transition from Mesozoic subduction to continental breakup in the Zealandia sector of eastern Gondwana[J]. Gondwana Research, 2014, 26(3-4)：1060-1078.

[45] Beggs J M, Ghisetti F C, Tulloch A J. Basin and petroleum systems analysis of the West Coast region, South Island, New Zealand[C]//PESA Eastern Australasian Basins Symposium III. Sydney: Petroleum Exploration Society of Australia (PESA), 2008: 14-17.

[46] Mortimer N, Campbell H J, Tulloch A J, et al. Zealandia: earth's hidden continent[J]. GSA Today, 2017, 27(3)：27-35.

[47] Mortimer N, van den Bogaard P, Hoernle K, et al. Late Cretaceous oceanic plate reorganization and the breakup of Zealandia and Gondwana[J]. Gondwana Research, 2019, 65：31-42.

[48] Strogen D P, Seebeck H, Nicol A, et al. Two-phase Cretaceous–Paleocene rifting in the Taranaki Basin region, New Zealand; implications for Gondwana break-up[J]. Journal of the Geological Society, 2017, 174(5)：929-946.

[49] Field B D, Browne G H, Davy B W. Cretaceous and Cenozoic Sedimentary Basins and Geological Evolution of the Canterbury Region, South Island, New Zealand[M]. Lower Hutt: New Zealand Geological Survey, 1989: 1-94.

[50] Hoffmann J J L, Gorman A R, Crutchley G J. Seismic evidence for repeated vertical fluid flow through polygonally faulted strata in the Canterbury Basin, New Zealand[J]. Marine and Petroleum Geology, 2019, 109：317-329.

[51] Carter L, Carter R M. Holocene evolution of the nearshore sand wedge, South Otago continental shelf, New Zealand[J]. New Zealand Journal of Geology and Geophysics, 1986, 29(4)：413-424.

[52] Browne G H, Field B D. The Lithostratigraphy of Late Cretaceous to Early Pleistocene Rocks of Northern Canterbury, New Zealand[R]. Wellington: New Zealand Department of Scientific and Industrial Research, 1985: 63.

[53] Browne G H, Field B D. A review of Cretaceous-Cenozoic sedimentation and tectonics, East Coast, South Island, New Zealand[C]//Sequences, stratigraphy, sedimentology: surface and subsurface. Calgary: Canadian Society of Petroleum Geologists (CSPG), 1988: 37-48.

[54] Marsaglia K M, Browne G H, George S C, et al. The transformation of sediment into rock: insights from IODP Site U1352, Canterbury Basin, New Zealand[J]. Journal of Sedimentary Research, 2017, 87(3)：272-287.

[55] Carter R M, Landis C A. Correlative Oligocene unconformities in southern Australasia[J]. Nature Physical Science, 1972, 237(70)：12-13.

[56] Lewis D W, Belliss S E. Mid tertiary unconformities in the Waitaki subdivision, North Otago[J]. Journal of the Royal Society of New Zealand, 1984, 14(3)：251-276.

[57] King P R. Tectonic reconstructions of New Zealand: 40 Ma to the Present[J]. New Zealand Journal of Geology and Geophysics, 2000, 43(4)：611-638.

[58] Lu H, Fulthorpe C S. Controls on sequence stratigraphy of a middle Miocene-Holocene, current-swept, passive margin: offshore Canterbury Basin, New Zealand[J]. GSA Bulletin, 2004, 116(11-12)：1345-1366.

[59] Mitchum R M, Vail P R, Sangree J B. Seismic stratigraphy and global changes of sea level: Part 6. Stratigraphic interpretation of seismic reflection patterns in depositional sequences: Section 2. Application of seismic reflection configuration to stratigraphic interpretation[M]// Payton C E. Seismic Stratigraphy: Applications to Hydrocarbon Ex-

ploration. Tulsa: AAPG, 1977.

[60] Posamentier H W, Kolla V. Seismic geomorphology and stratigraphy of depositional elements in deep-water settings[J]. Journal of Sedimentary Research, 2003, 73(3)：367-388.

[61] Catuneanu O. Principles of Sequence Stratigraphy[M]. 2nd ed. Amsterdam: Elsevier, 2022.

[62] Chima S, Reece J C, Milley K, et al. Decision support tools to improve cancer diagnostic decision making in primary care: a systematic review[J]. British Journal of General Practice, 2019, 69(689)：e809-e818.

[63] Brown A R. Interpretation of three-dimensional seismic data[M]. Tulsa: American Association of Petroleum Geologists (AAPG) & Society of Exploration Geophysicists (SEG), 2004.

[64] Chenin J, Silver C, Bedle H. Seismic geomorphology anomalies within a Pliocene deepwater channel complex in the Taranaki Basin, offshore New Zealand[J]. Interpretation, 2021, 9(1)：C1-C10.

[65] Back S, Van Gent H, Reuning L, et al. 3D seismic geomorphology and sedimentology of the Chalk Group, southern Danish North Sea[J]. Journal of the Geological Society, 2011, 168(2)：393-406.

[66] Zeng H L, Backus M M, Barrow K T, et al. Stratal slicing, Part 1: realistic 3-D seismic model[J]. Geophysics, 1998, 63(2)：502-513.

[67] Strogen D P, King P R. A New Zealandia-Wide Seismic Horizon Naming Scheme[M]. Lower Hutt, New Zealand: GNS Science, 2014.

[68] Slootman A, Cartigny M J B. Cyclic steps: review and aggradation-based classification[J]. Earth-Science Reviews, 2020, 201：102949.

[69] Cartigny M J B, Postma G, van den Berg J H, et al. A comparative study of sediment waves and cyclic steps based on geometries, internal structures and numerical modeling[J]. Marine Geology, 2011, 280(1-4)：40-56.

[70] Covault J A, Kostic S, Paull C K, et al. Cyclic steps and related supercritical bedforms: building blocks of deep-water depositional systems, western North America[J]. Marine Geology, 2017, 393：4-20.

[71] Mayall M, Jones E, Casey M. Turbidite channel reservoirs: key elements in facies prediction and effective development[J]. Marine and Petroleum Geology, 2006, 23(8)：821-841.

[72] Posamentier H W, Davies R J, Cartwright J A, et al. Seismic geomorphology: An overview[M]//Davies R J, Posamentier H W, Wood L J, et al. Seismic geomorphology: Applications to hydrocarbon exploration and production. London: Geological Society of London, 2007: 1-14.

[73] Moscardelli L, Wood L. New classification system for mass transport complexes in offshore Trinidad[J]. Basin Research, 2008, 20(1)：73-98.

[74] Urlaub M, Talling P J, Masson D G. Timing and frequency of large submarine landslides: implications for understanding triggers and future geohazard[J]. Quaternary Science Reviews, 2013, 72：63-82.

[75] Talling P J, Masson D G, Sumner E J, et al. Subaqueous sediment density flows: depositional processes and deposit types[J]. Sedimentology, 2012, 59(7)：1937-2003.

[76] Miller K G, Kominz M A, Browning J V, et al. The phanerozoic record of global sea-level change[J]. Science, 2005, 310(5752)：1293-1298.

[77] Shanmugam G, Moiola R J. Eustatic control of turbidites and winnowed turbidites[J]. Geology, 1982, 10(5)：231-235.

[78] Peakall J, Amos K J, Keevil G M, et al. Flow processes and sedimentation in submarine channel bends[J]. Marine and Petroleum Geology, 2007, 24(6-9)：470-486.

[79] Sylvester Z, Deptuck M, Prather B, et al. Seismic stratigraphy of a shelf-edge delta and linked submarine channels in the northeastern Gulf of Mexico[M]//SEPM Special Publication, No. 99. Tulsa: Society for Sedimentary Geology (SEPM), 2012: 31-59.