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事件层组合特征限定软沉积变形的地震成因——在青岛灵山岛的应用*

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摘 要：对软沉积物变形构造的形成过程解析和触发因素识别一直是国内外事件沉积学研究的重点和难点。国内外学者常将地层中保存的软沉积物变形构造的形成归因于地震作用，但缺乏足够的证据来支撑地震震动触发相应的沉积过程与变形机制。由于软沉积物变形构造可以由地震、风暴和非地震参与的液化作用、重力作用及滑坡等因素触发，且可能受瑞利—泰勒不稳定性(因密度差异沿垂向变形)或开尔文—亥姆获兹不稳定性(沿水平方向变形)机制的控制，软沉积物变形构造本身并不能作为特定触发因素的判别标志。此前，通过解析事件层组合特征来揭示与软沉积物变形构造形成相关的沉积过程和变形机制，进而限定变形构造触发因素的方法已成功应用于中东地区死海盆地(死海断裂带)的事件沉积研究中。尝试应用此方法来解析灵山岛灯塔剖面底部软沉积物变形构造的变形机制与触发因素，研究发现灯塔剖面底部的软沉积物变形构造是原位形成与保存的，并被浊流沉积层上覆，且二者之间无背景沉积物。这种独特的事件层组合指示原位变形和异地搬运两种水下沉积过程准同期发生，而能够同时激发这两类物质来源与沉积过程迥异的事件沉积响应的最可能因素是区域强震震动。结合灵山岛研究案例认为，前人所做的模式化的事件沉积成因判别标志不宜直接套用，而控制事件沉积的沉积过程与物理机制具有一定的普适性，应该是事件沉积学研究的关键。

关 键 词：软沉积变形；浊流沉积；地震震动；沉积响应

中图分类号：P512.2 **文献标志码**：A **文章编号**：1001-8166(2024)01-0096-12

1 引 言

软沉积物变形构造是松散沉积物在沉积期间或沉积后不久，受到挤压、重力或剪切应力等作用而形成的一系列不同程度的变形构造[1-6]。这些变形构造有助于我们理解沉积古环境、古斜坡方向以及盆地构造活动等[6-7]，因而受到国内外学者的重视。软沉积物变形构造的触发因素多样，如地震[2,8-11]、风暴[1,12-14]、海啸[15-16]、冰川冻融作用[17-20]和沉积物快速堆积[7,21-22]等。可靠地识别软沉积物变形构造的触发因素是恢复事件沉积历史的前提，有助于获取地震、海啸或风暴浪等重大事件的发生时

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间、强度以及复发间隔等信息，对极端地质灾害评估至关重要。例如，Lu 等[23]从死海国际大陆钻探（International Continental Scientific Drilling Program，ICDP）岩芯中识别出由地震诱发的原位软沉积物变形构造，借助流体数值模拟方法，定量获取了形成不同形态与厚度的变形构造所需的加速度（地震烈度），反演了岩芯中每个变形层位代表的地震烈度，重建了22万年连续大地震（M_W≥7.0）沉积记录。

针对软沉积物变形构造触发因素的判别，国内外学者通常采用与一套既定标准进行对比的方法[1]，最常见的就是将软沉积物变形构造与已知的由地震活动引起的变形构造进行对比。应用这种标准判别法并结合沉积环境和构造背景，灵山岛早白垩世灯塔剖面出露的70~80 cm厚的软沉积物变形构造被认为是地震作用的结果[24-28]。然而软沉积物变形构造可以由地震、风暴及其他非地震因素参与的液化作用、重力作用及滑坡等因素触发，且可能受瑞利—泰勒不稳定性机制（因密度差异沿垂向变形）或开尔文—亥姆获兹不稳定性（沿水平方向变形）机制的控制，软沉积物变形构造本身并不能作为特定触发因素的判别标志。

事实上，识别事件沉积的成因（特别是辨识地震成因）是事件沉积研究面临的最基本、最具挑战性的问题。只有解决了这一基础性问题，才能建立可靠的地震或气候事件沉积序列，进而解析其地质意义。此前，通过解析事件层组合特征来揭示与软沉积物变形构造形成相关的沉积过程和变形机制，进而限定变形构造最合理的触发因素的方法已成功应用于中东地区死海断裂带的死海盆地事件沉积研究中[29]。这为限定那些无历史地震记录[30-31]和无大范围（几十千米至几百千米）多岩芯对比资料[32-34]区域的事件沉积成因机制提供了新的方法。本文尝试应用该方法限定灵山岛灯塔剖面的上述大型事件层的沉积成因。

2　地质背景

灵山岛位于山东省青岛市以南黄海海域内[35]，属于构造掀斜成岛型海岛[36]，构造区划上位于苏鲁造山带内部的日青威盆地[37]。日青威盆地为NE-SW向展布的晚中生代裂谷盆地，向NE直到威海断隆，向SW延伸到胶南隆起，NW边界为青岛—五莲和牟平—即墨断裂带，SE边界为千里岩断裂带[38]［图1（a）］。日青威盆地在晚侏罗—早白垩世发育莱阳期被动裂谷和青山期主动裂谷（火山弧盆），二

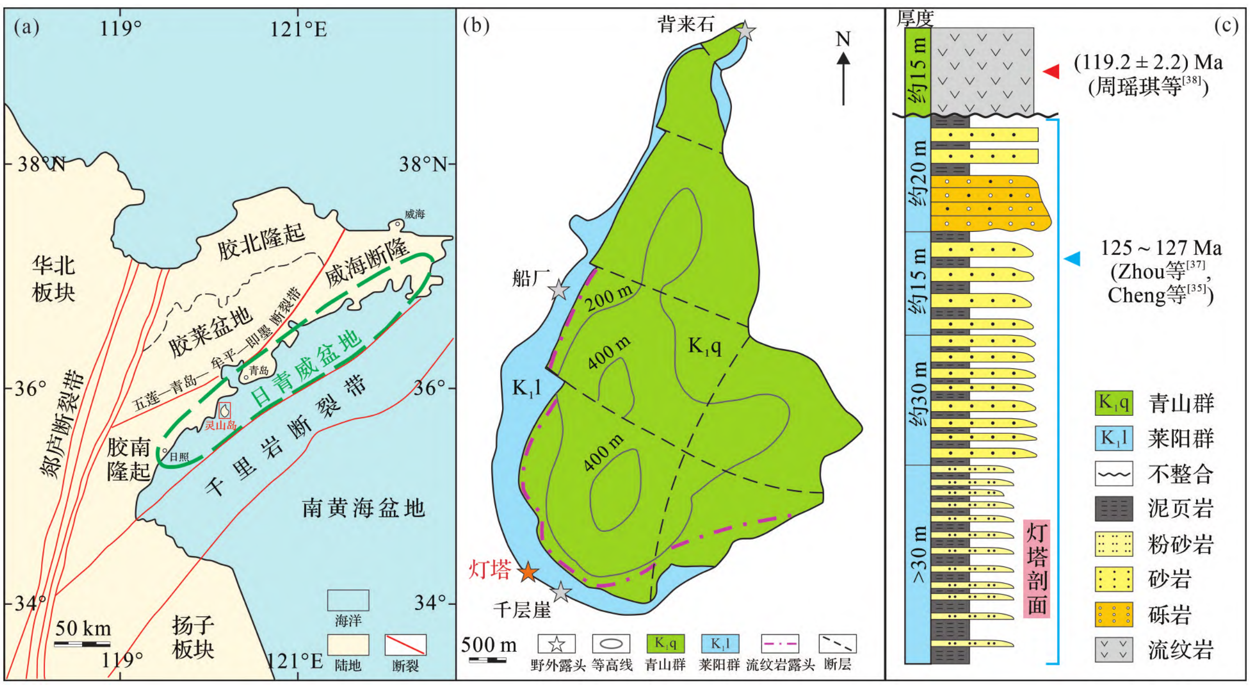

图1　灵山岛大地构造背景及地层序列

Fig. 1　Tectonic setting and stratigraphic sequence of Lingshan Island

（a）山东东部地质图（据参考文献［39-41］修改）；（b）灵山岛地质简图（据参考文献［37］修改）；（c）灵山岛莱阳群地层序列简图（据参考文献［35］修改）

（a）Geological map of eastern Shandong（modified after references［39-41］）；（b）Geological map of Lingshan Island（modified after reference［37］）；（c）Stratigraphic sequence of the Laiyang Group on Lingshan Island（modified after reference［35］）

者沉积地层之间呈不整合接触[37-38,42]。

灵山岛出露的莱阳期地层为浊积岩和泥页岩互层的深水沉积[43-44][图 1(c)],可见厚层滑塌体[45]和软沉积物变形构造[46]。其上为青山群火山溢流相流纹质火山熔岩,锆石 U-Pb 年龄为(119.2±2.2) Ma[38]。根据莱阳群地层的古地磁数据[35]与青山群底部沉凝灰岩样品的锆石定年结果[37]推断,灯塔、千层崖和船厂等野外露头记录了日青威莱阳期被动裂谷盆地萎缩阶段(125~127 Ma)的深水沉积历史[图 1(b)和图 1(c)]。其中灯塔剖面位于灵山岛的西南端[图 1(b)],剖面整体呈 NNW 方向展布,剖面长 120 m、高 15 m,地层产状 343°∠36°,地层位于岛上出露的深水沉积地层底部[图 1(c)]。

3 材料和方法

本文研究对象为灵山岛地区早白垩世莱阳群顶部的灯塔剖面深水沉积地层。通过野外露头详细勘测和镜下观察,识别了基本岩相和事件层类型。本文针对软沉积物变形构造,利用高清图片拼接技术,表征其空间分布特征。然后,获取事件层的关键细节特征,分析事件沉积过程与变形机制。

4 结果分析

灯塔剖面的上部为厚度约 5 m 的变形砂岩和泥岩,被认为是一套厚层滑塌体[45][图 2(a)]。剖面中部主要为薄层砂岩和泥岩互层。剖面底部为一套厚度为 70~80 cm 的软沉积物变形构造层,沿水平方

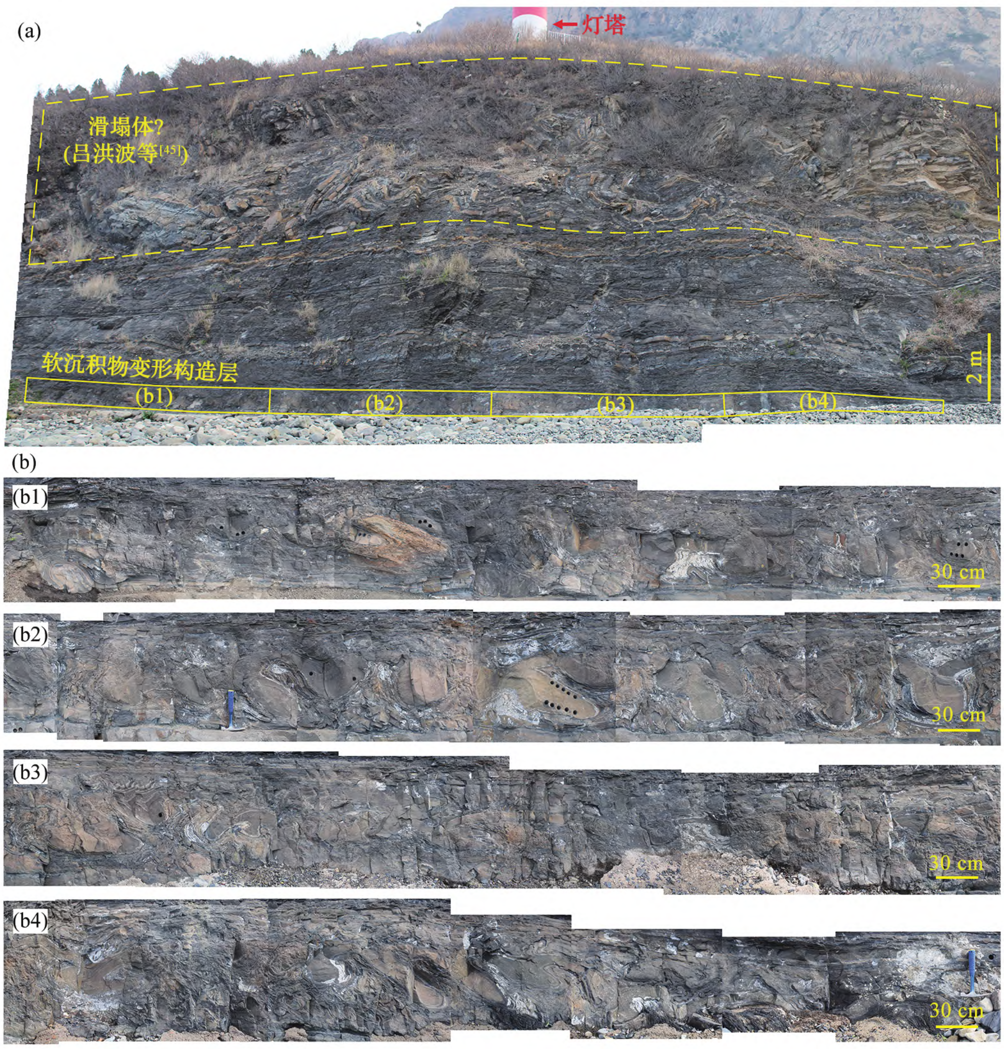

图 2 灵山岛灯塔剖面地层序列(a)及其保存的软沉积物变形构造层(b)

Fig. 2 Dengta outcrop, Lingshan Island (a) and preserved soft-sediment deformation structures (b)

(a)据参考文献[45]修改;(b)中的(b1)~(b4)对应(a)底部的软沉积物变形构造层(b1)~(b4)部分

Modified after reference [45]; The (b1)~(b4) in Fig. (b) correspond to the (b1)~(b4) parts of the soft-sediment deformation at the bottom of Fig. (a)

向延伸,可在出露的剖面中连续追踪。该变形层位夹于未变形地层之间,岩性与上下地层相同[图2(b)]。

4.1　背景沉积特征

灯塔剖面的背景沉积是深灰色泥质纹层,纹层厚度小于1 mm,界限清晰,侧向连续性好[图3(a)~图3(e)]。镜下可识别出长英质碎屑纹层、黏土纹层和有机质纹层[图3(f)]。

4.2　砂质浊流沉积特征

灯塔剖面发育的砂质浊积岩厚度为几厘米至十几厘米,以正粒序为典型特征(图4)。同一砂质浊积岩层通常侧向厚度稳定,底部平直,表现为无侵蚀至弱侵蚀特征,其下常见保存良好的纹层。

4.3　软沉积变形特征

软沉积物变形构造层的内部呈现各种方向的变形,包括水平方向、倾斜方向和垂直方向(图5)。水平方向变形主要表现为平卧的软沉积变形褶曲[图5(a)];倾斜方向变形主要表现为斜歪的软沉积变形褶曲[图5(c)],同时局部的块状细砂岩负载沉降[图5(e)];垂直方向变形主要表现为块状细砂岩的垂向负载沉降以及泥质纹层或薄层砂岩的向上挤入[图5(g)]。这些变形构造内部的纹层保存良好[图5(b)和图5(d)],常见纹层的卷曲变形[图5(f)和图5(h)]。

4.4　事件层组合特征

灯塔剖面底部的软沉积变形层被砂质浊流沉积上覆[图6(a)~图6(d)],且二者之间无背景沉积物[图6(e)~图6(h)]。其中砂质浊积岩层的厚度变化较大(1~12 cm),底部不规则,但顶面平直。

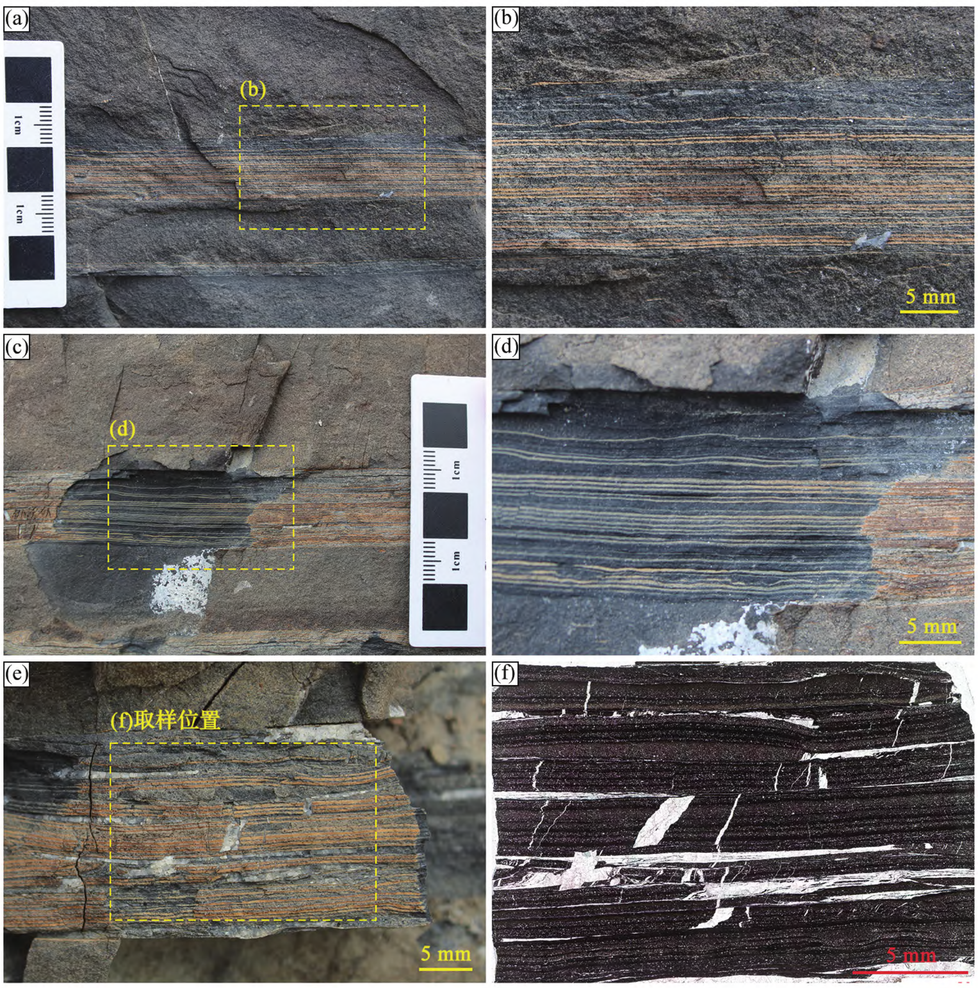

图3　灵山岛灯塔剖面保存的典型背景沉积(纹层)

Fig. 3　Typical background deposits (laminae) preserved in the Dengta outcrop, Lingshan Island

(a)~(e)纹层露头;(f)纹层的镜下特征(单偏光)

(a)~(e) Photographs showing the laminae; (f) Microscopic characteristics of the laminae (single polarized light)

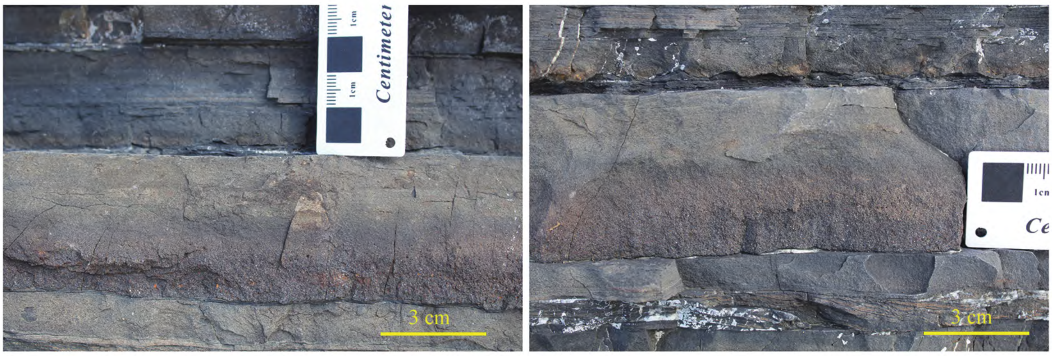

图4 灵山岛灯塔剖面保存的典型浊流沉积

Fig. 4 Typical turbidites preserved in the Dengta outcrop, Lingshan Island

5 讨 论

5.1 沉积环境

分析背景沉积形成时的沉积环境,对于正确判别事件沉积的触发因素和沉积过程非常关键。灯塔剖面广泛发育纹层(即背景沉积物,图3),指示灯塔剖面当时处于较为稳定与安静的深水/深海平原环境。只有在这种环境中才能形成层厚均一、稳定的水平纹层,并被完好地保存下来。

5.2 软沉积变形层的变形机制

有研究认为灯塔剖面底部该厚层软沉积物变形构造是滑塌导致的变形[27]。然而,大型滑塌成因的软沉积变形一般出现在滑坡体的中末端,横向延伸有限;另外,如果滑塌体内部存在软沉积变形层,则此类变形层位的顶部和底部通常会保存强烈破碎的层位作为滑塌体的一部分[47]。而本文发现该软沉积变形层侧向厚度稳定,构造类似;该层位顶部和底部既无强烈破碎的沉积物,也无明显的侵蚀基底[图7(a)、图7(c)和图7(e)]。这些沉积特征不支持滑塌过程作为灯塔剖面底部软沉积物变形构造的驱动因素。

该软沉积变形层中的泥质纹层保存良好,即便是在软沉积变形褶曲的转折端(变形程度最高)也并未破碎[图7(b)、图7(d)和图7(f)]。这表明该厚层软沉积物变形构造是原位形成与保存的,没有经历显著的搬运,否则脆弱的纹层将会被撕裂或破碎[48]。这些构造形态[图5(f)]与中东地区死海地层保存的涡旋状变形构造非常相似[23,49],以水平方向的纹层变形[图5(a)]为最显著的特征。它们的变形机制是,水饱和的层状泥质沉积物在地震触发的开尔文—亥姆获兹不稳定性(Kelvin-Helmholtz Instability)机制的驱动下,沿着地震波传输的方向以不同的速度运动,在沉积物分层的界面处产生变形[23]。

灯塔剖面软沉积物变形构造层中沿垂直方向的变形主要为负载构造[图5(g)]。它们的变形机制为瑞利—泰勒不稳定性(Rayleigh-Taylor Instability),即由反向密度驱动的重力失稳[50]。地震震动可以激发或极大地促进瑞利—泰勒不稳定性的发生。灯塔剖面软沉积物变形构造显示的沿水平与垂直方向的变形特征,指示在强震震动的状况下,开尔文—亥姆获兹不稳定性机制和瑞利—泰勒不稳定性机制共同参与了软沉积物变形构造的形成。

5.3 事件层组合限定成因

Lu等[29]在对死海ICDP长岩芯材料的事件沉积学研究中,提出通过分析事件层的组合特征来限定事件沉积的地震成因。理论上,一次强震既可以单独诱发原位发生并原位保存的沉积响应(如原位软沉积变形和同沉积微断层),也可以单独诱发流域盆地内异地搬运的沉积响应(如浊流沉积、滑塌沉积和碎屑流沉积等),还可以同时诱发原位与异地搬运的沉积响应[29]。如果一次强震同时诱发了原位与异地搬运的沉积响应,那么这2个沉积过程就是准同期发生的,相应的2个事件层之间会缺乏背景沉积物而紧密叠加。死海ICDP岩芯中存在大量的这种事件沉积组合(图8),即浊流沉积层上覆于强震触发的原位软沉积变形层[图8(d)和图8(e)]。

本文尝试应用这个方法来限定灵山岛灯塔剖面软沉积物变形构造的触发因素。作者研究发现灯塔剖面底部的软沉积物变形构造是原位形成与保存的,并被浊流沉积层上覆,且二者之间无背景沉积物[图8(a)~图8(c)]。由于原位软沉积变形层的表面存在微地形起伏,这将调节浊流沉积使其填平软沉积变形层位表面的低洼处,导致浊积岩呈现

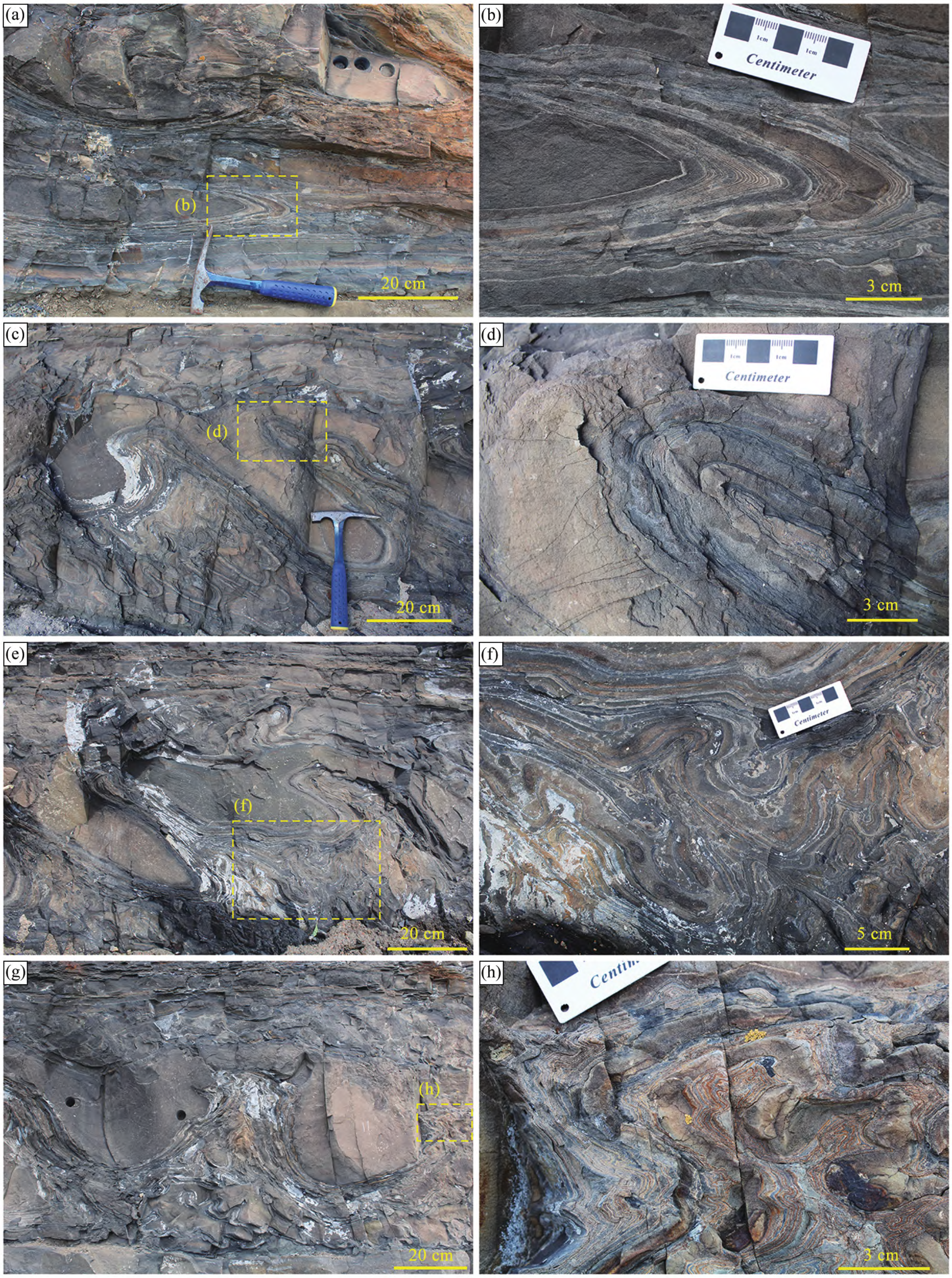

图5　灵山岛灯塔剖面软沉积物变形构造的特征

Fig. 5　Features of soft-sediment deformations in the Dengta outcrop, Lingshan Island

(a)和(b)水平方向变形及其转折端;(c)和(d)倾斜方向变形及其转折端;(e)和(f)倾斜方向变形及其内部的相互干涉的涡旋状变形构造;(g)和(h)垂直方向变形及其转折端

(a) and (b) Horizontal deformation and its hinge zone; (c) and (d) Inclined deformation and its hinge zone; (e) and (f) Inclined deformation and its internal coherent vortical deformation; (g) and (h) Vertical deformation and its hinge zone

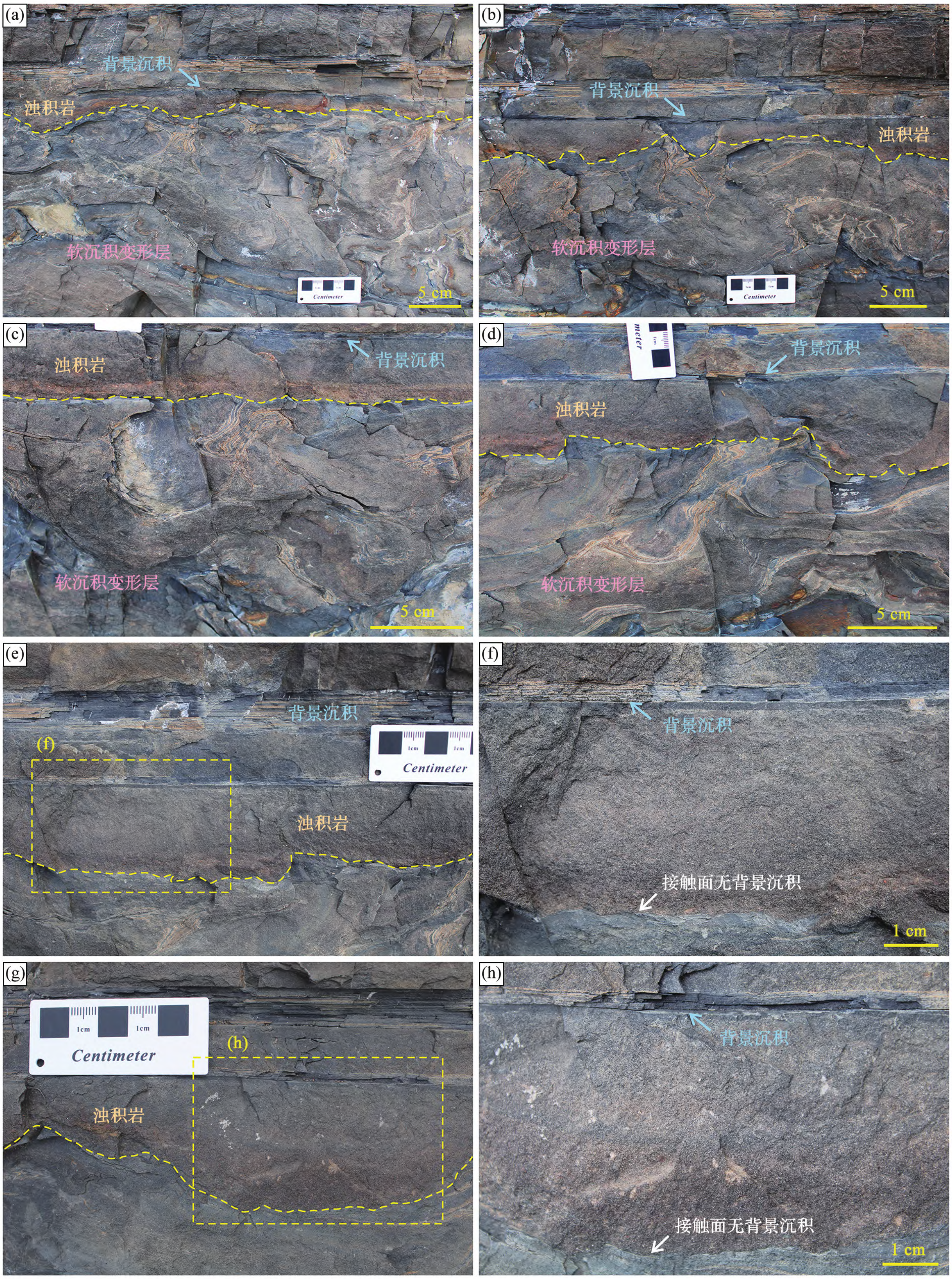

图6　灵山岛灯塔剖面事件层组合特征

Fig. 6　Feature of event bed combinations in the Dengta outcrop, Lingshan Island

(a)~(d)软沉积变形层与上覆浊积岩层的接触关系;(e)~(h)高清照片揭示软沉积变形层与上覆浊积岩层间无背景沉积物

(a)~(d) The transitions between the soft-sediment deformation and the overlying turbidite; (e)~(h) High-resolution photos reveal no background deposits between the soft-sediment deformation and the overlying turbidite

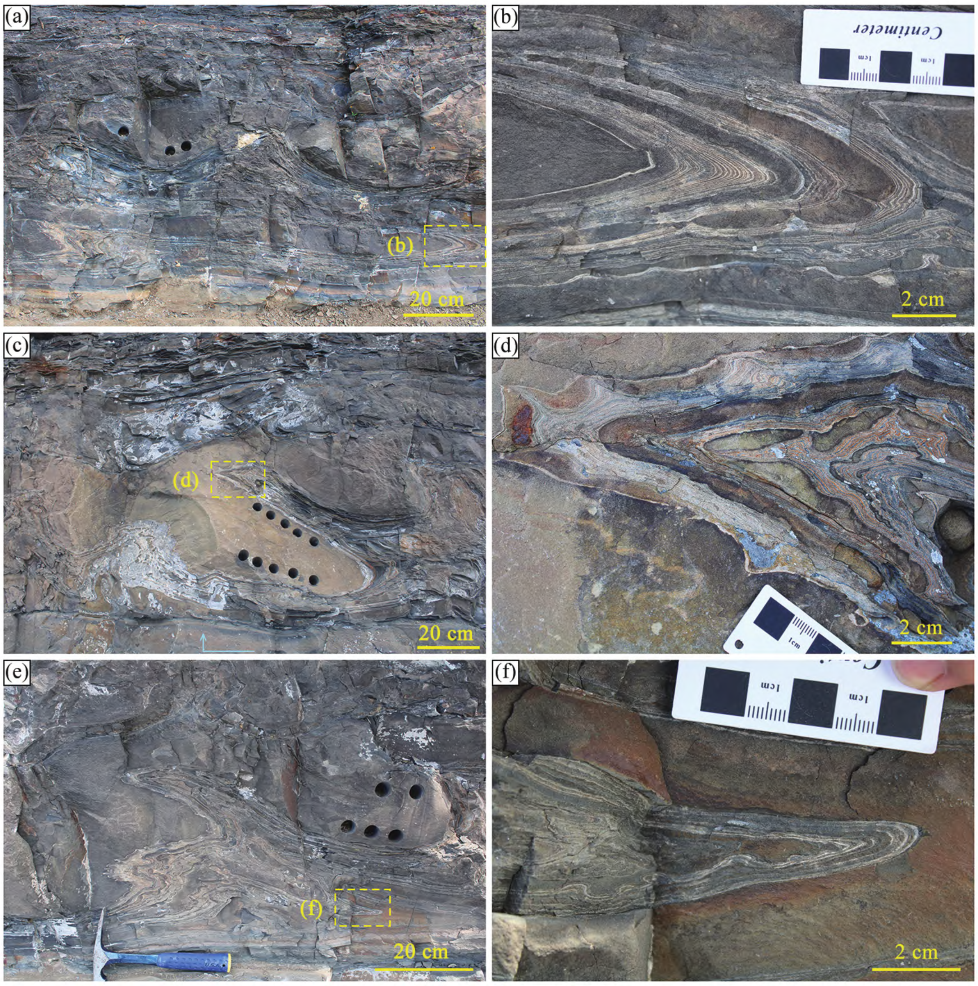

图 7　灵山岛灯塔剖面软沉积物变形构造的显著特征

Fig. 7　Significant characteristics of the soft-sediment deformation structures in the Dengta outcrop, Lingshan Island

(a)~(f)高清照片揭示灵山岛灯塔剖面软沉积变形构造中的纹层强烈变形但未破碎

(a)~(f) High-resolution photos reveal well-preserved strongly deformed laminae in the soft-sediment deformation structures of the Dengta outcrop, Lingshan Island

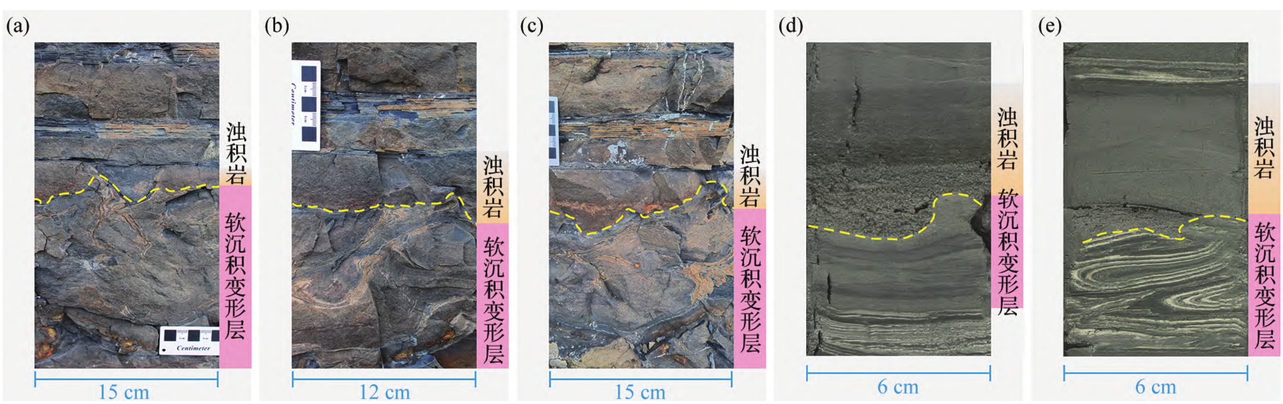

图 8　灵山岛事件层组合特征与全球已知典型事件层组合特征的对比

Fig. 8　Comparison of event bed combination features between Lingshan Island and global known typical cases

(a)~(c)灵山岛灯塔剖面浊流沉积层与原位软沉积变形层的组合特征;(d)和(e)中东地区死海断裂带的浊流沉积层与原位软沉积变形层的组合特征(据参考文献[29]修改)

(a)~(c) Combination features of turbidite and *in situ* soft-sediment deformation in the Dengta outcrop, Lingshan Island; (d) and (e) Combination features of turbidite and *in situ* soft-sediment deformation in the Dead Sea Fault, Middle East (modified after reference [29])

出不规则的底界形态，而非浊流沉积层软负载的结果。这种独特的事件层组合指示原位软沉积变形与异地搬运（浊流沉积）2种水下沉积过程准同期发生。而能够同时激发这2类物质来源与沉积过程迥异的事件沉积响应的最可能因素是盆地尺度的区域强震震动。

综上所述，本文通过识别灯塔剖面底部独特的事件层组合特征，解析了事件层相关的沉积过程与变形机制。结合灵山岛活跃的地质构造背景[24,37,42]和灯塔剖面地层沉积所处的深水平原环境，我们将灯塔剖面底部软沉积物变形构造的成因限定为地震震动。而变形层位上覆的浊积岩则为典型的震浊积岩[51]。

6 结论与启示

灯塔剖面底部的厚层软沉积物变形构造是原位形成与保存的，地震驱动的开尔文—亥姆霍兹不稳定性是其主要的变形机制。这个变形层位被浊流沉积层上覆，且二者之间无背景沉积物。这种独特的事件层组合指示原位变形与异地搬运2种水下沉积过程准同期发生，它们最可能的触发因素是区域强震震动。结合灵山岛研究案例，本文认为前人所做的模式化的事件沉积成因判别标志不宜直接套用，而控制事件沉积的沉积过程与物理机制具有一定的普适性，应是事件沉积学研究关注的重点。

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参考文献（References）：

[1] OWEN G, MORETTI M, ALFARO P. Recognising triggers for soft-sediment deformation: current understanding and future directions[J]. *Sedimentary Geology*, 2011, 235(3/4): 133-140.

[2] DU Yuansheng. Discussion about studies of earthquake event deposit in China[J]. *Journal of Palaeogeography*, 2011, 13(6): 581-586. [杜远生. 中国地震事件沉积研究的若干问题探讨[J]. 古地理学报, 2011, 13(6): 581-586.]

[3] ARNAUD E. The paleoclimatic significance of deformation structures in Neoproterozoic successions[J]. *Sedimentary Geology*, 2012, 243: 33-56.

[4] LI Yong, ZHONG Jianhua, SHAO Zhufu, *et al*. An overview on the classification and genesis of soft-sediment deformation structure[J]. *Geological Review*, 2012, 58(5): 829-838. [李勇, 钟建华, 邵珠福, 等. 软沉积变形构造的分类和形成机制研究[J]. 地质论评, 2012, 58(5): 829-838.]

[5] TOPAL S, OZKUL M. Soft-sediment deformation structures interpreted as seismites in the Kolankaya Formation, Denizli Basin (SW Turkey)[J]. *Scientific World Journal*, 2014. DOI: 10.1155/2014/352654.

[6] CHEN Jitao. Research progress of soft-sediment deformation structures[J]. *Journal of Stratigraphy*, 2020, 44(1): 64-75. [陈吉涛. 软沉积物变形构造研究进展[J]. 地层学杂志, 2020, 44(1): 64-75.]

[7] LIANG Zhao, YUN Yupan, WEI Hao. Soft-sediment deformation structures induced by rapid sedimentation in Lower Cretaceous turbidites, Lingshan Island[J]. *Acta Sedimentologica Sinica*, 2023, 41(2): 450-458. [梁钊, 云玉攀, 魏浩. 快速沉积引发的软沉积物变形构造特征——以灵山岛下白垩统浊积岩为例[J]. 沉积学报, 2023, 41(2): 450-458.]

[8] MONTENAT C, BARRIER P, D'ESTEVU P O, *et al*. Seismites: an attempt at critical analysis and classification[J]. *Sedimentary Geology*, 2007, 196(1/2/3/4): 5-30.

[9] QIAO Xiufu, LI Haibing. Effect of earthquake and ancient earthquake on sediments[J]. *Journal of Palaeogeography*, 2009, 11(6): 593-610. [乔秀夫, 李海兵. 沉积物的地震及古地震效应[J]. 古地理学报, 2009, 11(6): 593-610.]

[10] MORETTI M, RONCHI A. Liquefaction features interpreted as seismites in the Pleistocene fluvio-lacustrine deposits of the Neuquen Basin (Northern Patagonia)[J]. *Sedimentary Geology*, 2011, 235(3/4): 200-209.

[11] HE B, QIA X. Advances and overview of the study on paleo-earthquake events: a review of seismites[J]. *Acta Geologica Sinica-English Edition*, 2015, 89(5): 1 702-1 746.

[12] MOLINA J M, ALFARO P, MORETTI M, *et al*. Soft-sediment deformation structures induced by cyclic stress of storm waves in tempestites (Miocene, Guadalquivir Basin, Spain)[J]. *Terra Nova*, 1998, 10(3): 145-150.

[13] ALFARO P, DELGADO J, ESTEVEZ A, *et al*. Liquefaction and fluidization structures in Messinian storm deposits (Bajo Segura Basin, Betic Cordillera, southern Spain)[J]. *International Journal of Earth Sciences*, 2002, 91(3): 505-513.

[14] CHEN J, CHOUGH S K, CHUN S S, *et al*. Limestone pseudoconglomerates in the Late Cambrian Gushan and Chaomidian Formations (Shandong Province, China): soft-sediment deformation induced by storm-wave loading[J]. *Sedimentology*, 2009, 56(4): 1 174-1 195.

[15] MATSUMOTO D, NARUSE H, FUJINO S, *et al*. Truncated flame structures within a deposit of the Indian Ocean Tsunami: evidence of syn-sedimentary deformation[J]. *Sedimentology*, 2008, 55(6): 1 559-1 570.

[16] MESHRAM D C, SANGODE S J, GUJAR A R, *et al*. Occurrence of soft sediment deformation at Dive Agar beach, west coast of India: possible record of the Indian Ocean tsunami (2004)[J]. *Natural Hazards*, 2011, 57(2): 385-393.

[17] HARRIS C, MURTON J, DAVIES M C R. Soft-sediment de-

formation during thawing of ice-rich frozen soils: results of scaled centrifuge modelling experiments [J]. *Sedimentology*, 2000, 47(3): 687-700.

[18] WEAVER L, ARNAUD E. Polyphase glacigenic deformation in the Waterloo Moraine, Kitchener, Ontario, Canada[J]. *Sedimentary Geology*, 2011, 235(3/4): 292-303.

[19] GRUSZKA B, van LOON A J. Genesis of a giant gravity-induced depression (gravifossum) in the Enkoping esker, S. Sweden[J]. *Sedimentary Geology*, 2011, 235(3/4): 304-313.

[20] PISARSKA-JAMROZY M, WECKWERTH P. Soft-sediment deformation structures in a Pleistocene glaciolacustrine delta and their implications for the recognition of subenvironments in delta deposits[J]. *Sedimentology*, 2013, 60(3): 637-665.

[21] MORETTI M, SORIA J M, ALFARO P, *et al*. Asymmetrical soft-sediment deformation structures triggered by rapid sedimentation in turbiditic deposits (Late Miocene, Guadix Basin, southern Spain)[J]. *Facies*, 2001, 44: 283-294.

[22] MORETTI M, SABATO L. Recognition of trigger mechanisms for soft-sediment deformation in the Pleistocene lacustrine deposits of the Sant'Arcangelo Basin (Southern Italy): seismic shock vs. overloading[J]. *Sedimentary Geology*, 2007, 196(1/2/3/4): 31-45.

[23] LU Y, WETZLER N, WALDMANN N, *et al*. A 220, 000-year-long continuous large earthquake record on a slow-slipping plate boundary[J]. *Science Advances*, 2020, 6(48). DOI: 10.1126/sciadv.aba4170.

[24] ZHOU Yaoqi, ZHANG Zhenkai, XU Hong, *et al*. Soft-sediment deformation structures in the sediments at Lingshan Island [J]. *Marine Geology Frontiers*, 2015, 31(4): 42-54. [周瑶琪,张振凯,许红,等. 灵山岛沉积物软变形构造特征[J]. 海洋地质前沿,2015, 31(4): 42-54.]

[25] ZHANG Fengxiao, ZHUO Yaoqi, WANG Andong, *et al*. Load structures and ball-and-pillow structures on the Lingshan Island, Shandong[J]. *Sedimentary Geology and Tethyan Geology*, 2015, 35(3): 42-50. [张风霄,周瑶琪,王安东,等. 山东省灵山岛负载构造和球—枕构造研究[J]. 沉积与特提斯地质, 2015, 35(3): 42-50.]

[26] GE Yuzhu, ZHONG Jianhua. Discussion about triggers of Early Cretaceous soft-sediment deformation structures on the Lingshan Island and the implications for palaeo-environment [J]. *Geological Review*, 2017, 63(4): 927-940. [葛毓柱,钟建华. 灵山岛早白垩世软沉积物变形构造触发机制及其古环境意义探讨[J]. 地质论评,2017, 63(4): 927-940.]

[27] LIANG Zhao, ZHOU Yaoqi. Soft-sediment deformation structures related to slumping in Lower Cretaceous turbidite in Lingshan Island, Shandong Province [J]. *Earth Science*, 2017, 42(10): 1 715-1 724. [梁钊,周瑶琪. 山东省灵山岛下白垩统浊积岩中与滑塌作用相关的软沉积物变形构造[J]. 地球科学, 2017, 42(10): 1 715-1 724.]

[28] SUN Funing, YANG Renchao, FAN Aiping, *et al*. Classification and geological significance of soft-sediment deformation structures of Lower Cretaceous in Lingshan Island [J]. *Acta Sedimentologica Sinica*, 2018, 36(6): 1 105-1 118. [孙福宁,杨仁超,樊爱萍,等. 灵山岛下白垩统软沉积物变形构造类型划分及其地质意义[J]. 沉积学报, 2018, 36(6): 1 105-1 118.]

[29] LU Y, MOERNAUT J, BOOKMAN R, *et al*. A new approach to constrain the seismic origin for prehistoric turbidites as applied to the Dead Sea Basin[J]. *Geophysical Research Letters*, 2021, 48(3). DOI:10.1029/2020GL090947.

[30] MOERNAUT J, VAN DAELE M, HEIRMAN K, *et al*. Lacustrine turbidites as a tool for quantitative earthquake reconstruction: new evidence for a variable rupture mode in south central Chile[J]. *Journal of Geophysical Research-Solid Earth*, 2014, 119(3): 1 607-1 633.

[31] WILHELM B, NOMADE J, CROUZET C, *et al*. Quantified sensitivity of small lake sediments to record historic earthquakes: implications for paleoseismology[J]. *Journal of Geophysical Research-Earth Surface*, 2016, 121(1): 2-16.

[32] GOLDFINGER C, MOREY A E, NELSON C H, *et al*. Rupture lengths and temporal history of significant earthquakes on the offshore and north coast segments of the Northern San Andreas Fault based on turbidite stratigraphy[J]. *Earth and Planetary Science Letters*, 2007, 254(1/2): 9-27.

[33] GOLDFINGER C, IKEDA Y, YEATS R S, *et al*. Superquakes and supercycles[J]. *Seismological Research Letters*, 2013, 84(1): 24-32.

[34] HOWARTH J D, BARTH N C, FITZSIMONS S J, *et al*. Spatiotemporal clustering of great earthquakes on a transform fault controlled by geometry[J]. *Nature Geoscience*, 2021, 14(5): 314-320.

[35] CHENG Y, WU Z, LIU X, *et al*. Late Jurassic to early Cretaceous magnetostratigraphy of scientific drilling core LK-1 in the Lingshan Island of Riqingwei Basin, eastern China[J]. *Science China-Earth Sciences*, 2022, 65(4): 742-758.

[36] LUAN Guangzhong, LI Anlong, WANG Jian, *et al*. The geological origin division of the main sea island in Qingdao area and environment analysis[J]. *Periodical of Ocean University of China*, 2010, 40(8): 111-116. [栾光忠,李安龙,王建,等. 青岛主要海岛成因分类及其地质环境分析[J]. 中国海洋大学学报(自然科学版), 2010, 40(8): 111-116.]

[37] ZHOU T, ZHOU Y, SOAGER N, *et al*. Late Mesozoic rifting and its deep dynamic mechanisms in the central Sulu orogenic belt: records from Lingshan Island [J]. *Science China-Earth Sciences*, 2022, 65(9): 1 751-1 771.

[38] ZHOU Yaoqi, ZHANG Zhenkai, LIANG Wendong, *et al*. Late Mesozoic tectono-magmatic activities and prototype basin restoration in Eastern Shandong Province, China[J]. *Earth Science Frontiers*, 2015, 22(1): 137-156. [周瑶琪,张振凯,梁文栋,等. 山东东部晚中生代构造—岩浆活动及原型盆地恢复[J]. 地学前缘, 2015, 22(1): 137-156.]

[39] YANG T, CAO Y, FRIIS H, *et al*. Origin and evolution processes of hybrid event beds in the Lower Cretaceous of the Lingshan Island, Eastern China [J]. *Australian Journal of*

Earth Sciences, 2018, 65(4): 517-534.

[40] ZHANG Z, ZHOU Y, ZHOU T, *et al*. Geochemistry of siltstones of the Early Cretaceous Laiyang Group in Taolin area, Shandong Province, Eastern China: implications for provenance, source weathering, palaeo-environment, and tectonic setting[J]. *Geological Journal*, 2018, 55(1): 133-146.

[41] CHEN Y, ZHOU Y, ZHOU T, *et al*. Geochemical characteristics and evaluation criteria of overmature source rock of the Laiyang Formation in Well LK-1, Riqingwei Basin, Eastern China [J]. *Energies*,2023,16(8). DOI:10.3390/en16083482.

[42] ZHOU Yaoqi, ZHANG Yue, ZHOU Tengfei, *et al*. The tectonic transition of the Late-Mesozoic Yellow Sea and adjacent region and its tectonic framework of the proto-basin[J]. *Earth Science*, 2023, 48(4): 1 461-1 480. [周瑶琪,张悦,周腾飞,等.黄海及邻区晚中生代构造转换与原型盆地构造格局[J].地球科学,2023, 48(4): 1 461-1 480.]

[43] WANG J, CHANG S C, LU H B, *et al*. Detrital zircon U-Pb age constraints on Cretaceous sedimentary rocks of Lingshan Island and implications for tectonic evolution of Eastern Shandong, North China[J]. *Journal of Asian Earth Sciences*,2014, 96:27-45.

[44] YANG T, CAO Y, LIU K, *et al*. Depositional elements and evolution of gravity-flow deposits on Lingshan Island (Eastern China): an integrated outcrop-subsurface study[J]. *Marine and Petroleum Geology*,2022,138(1). DOI:10.1016/j.marpetgeo.2022.105566.

[45] LÜ Hongbo, WANG Jun, ZHANG Haichun. Discovery of the Late Mesozoic slump beds in Lingshan Island, Shandong, and a pilot research on the regional tectonics[J]. *Acta Geologica Sinica*, 85(6): 938-946. [吕洪波,王俊,张海春.山东灵山岛晚中生代滑塌沉积层的发现及区域构造意义初探[J].地质学报,2011, 85(6): 938-946.]

[46] YANG R, van LOON A J. Early Cretaceous slumps and turbidites with peculiar soft-sediment deformation structures on Lingshan Island (Qingdao, China) indicating a tensional tectonic regime[J]. *Journal of Asian Earth Sciences*,2016,129: 206-219.

[47] BULL S, CARTWRIGHT J, HUUSE M. A review of kinematic indicators from mass-transport complexes using 3D seismic data[J]. *Marine and Petroleum Geology*,2009,26(7): 1 132-1 151.

[48] LU Y, WALDMANN N, ALSOP G I, *et al*. Interpreting soft sediment deformation and mass transport deposits as seismites in the Dead Sea depocenter[J]. *Journal of Geophysical Research-Solid Earth*, 2017, 122(10): 8 305-8 325.

[49] WETZLER N, MARCO S, HEIFETZ E. Quantitative analysis of seismogenic shear-induced turbulence in lake sediments[J]. *Geology*, 2010, 38(4): 303-306.

[50] LU Yin, WETZLER N, MARCO S, *et al*. Subaqueous event deposits response to regional neotectonics: case studies of the Dead Sea Basin and the Qaidam Basin[J]. *Quaternary Sciences*,2022,42(3):617-636. [卢银,WETZLER N,MARCO S,等.区域新构造活动的水下事件沉积响应:以死海盆地和柴达木盆地为例[J].第四纪研究,2022, 42(3): 617-636.]

[51] DU Yuansheng, HAN Xin. Seismo-deposition and seismites [J]. *Advances in Earth Science*,2000,15(4):389-394. [杜远生,韩欣.论震积作用和震积岩[J].地球科学进展,2000,15(4):389-394.]

Feature of Event Bed Combinations Constrains the Seismic Origin for Soft-sediment Deformation as Applied to the Lingshan Island, Qingdao, East China*

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Abstract: Identification of trigger(s) and understanding of formation mechanism(s) and process(es) are the primary focus of event sedimentology studies. The triggering of soft-sediment deformation is usually attributed to earthquake shaking, despite the lack of solid evidence to support seismic-forced deformation mechanisms and sedimentary processes, *e.g.*, previous study cases from the Dengta outcrop, Linshan Island, Qingdao, and East China. However, soft-sediment deformation can be triggered by either earthquakes, storms, non-earthquake events involving liquefaction, gravitational loading, or slumping. In addition, the deformation can be controlled by either the Rayleigh-Taylor instability or the Kelvin-Helmholtz instability. Therefore, features of the deformation structure alone cannot be used as indicators for trigger identification. A new approach for trigger identification that involves analyzing the combined features of two event layers has been successfully applied in the Dead Sea Basin (Dead Sea Fault) in the Middle East. In this study, we apply this novel approach to analyze the deformation mechanism and trigger of a large-scale soft-deformed layer in the Dengta outcrop, Lingshan Island, Qingdao. We observe that ① large-scale soft-sediment deformation is *in situ* formed and preserved; ② a turbidite layer overlies the *in situ* deformed layer; and ③ no background sediments have accumulated between the two event layers. These features indicate that *in situ* and *ex situ* sedimentary responses occurred simultaneously. Strong regional seismic shaking is the most plausible trigger for the contemporaneous occurrence of *in situ* and *ex situ* sedimentary responses when considering regional geological settings.

Key words: Soft-sediment deformation; Turbidite; Seismic shaking; Sedimentary response.

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