冲绳海槽西部陆坡碎屑沉积物的搬运方式: 滑塌和重力流*

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提要 通过对冲绳海槽 2000 多公里的实测单道地震资料(95 和 99 航次) 和沉积物柱状样(92 航次) 分析, 认为滑塌和重力流是冲绳海槽西部陆坡(东海陆坡) 碎屑沉积物向海槽搬运的重要方式; 分析结果表明, 西部陆坡这两种作用是广泛存在的。陆坡沉积物堆积速率、地形坡度和构造活动、地震、海啸等因素造成了陆坡南、北和中段之间的滑塌和重力流发育程度存在差异。海底滑塌和重力流这两种作用可以同时发生, 也可以单独发生, 但柱状样揭示重力流发生得更频繁。从空间分布上看, 海底滑塌主要分布于上陆坡的断裂带附近, 平行海槽呈带状延伸; 而重力流沉积主要分布于断裂带向下| 直到槽底的部位。重力流沉积主要有 4 种表现形式: 1) 沉积物重力蠕动; 2) 浊积平原; 3) 透镜状浊积体; 4) 沿斜坡的碎屑流沉积。上述研究表明, 滑塌和重力流不仅是陆架向海槽输送物质的重要方式, 也对陆坡沉积结构的塑造起了重要的作用。

关键词 冲绳海槽, 地震反射, 海底滑塌, 重力流
中图分类号 P736

从陆坡到深水盆地, 碎屑沉积物两个最重要的搬运- 沉积过程是滑塌和重力流。与重力驱动作用有关的高浓度沉积物流称之为重力流, 单一机制的重力流主要包括浊流、颗粒流、液体化流和泥石流(Middleton *et al*, 1976)。陆架边缘沉积结构的塑造通常与斜坡重力的驱动作用有关(Heezen *et al*, 1966; Hollister *et al*, 1972), 北大西洋和西大西洋陆架边缘(Egloff *et al*, 1975, 1978; Mountain *et al*, 1983; Tucholke *et al*, 1983; Myers *et al*, 1988; Aksu *et al*, 1989; Hesse, 1992; Locker *et al*, 1992; Stoker, 1998)、南大西洋陆架边缘(Viana *et al*, 1998) 和西南印度洋(Dingle *et al*, 1987; Ben-Avraham *et al*, 1994) 等被动陆架边缘重力流沉积和等深流沉积方面的研究已证实了这一点, 主动大陆边缘如西南太平洋也有少量的文献报道(Reed *et al*, 1987)。冲绳海槽作为一个半深水弧后盆地(Kimura, 1985; Letouley *et al*, 1985; Park *et al*, 1998), 其西槽坡与宽阔的东海陆架相邻。浊流沉积层不仅被槽底及陆坡获取的岩芯中所揭示(秦蕴珊等, 1987; 金翔龙, 1992, Ikehara, 1994; 李巍然等, 1999), 而且在现代地貌上也有表现(见封面)。有关冲绳海槽的浊流沉积前人已做了部分研究(袁迎如, 1987; 张明书, 1988; 李巍然等, 1999), 然而以往的报道缺乏对重力流声学结构、空间分布特征和对陆架塑造作用的研究。最近在冲绳海槽轴部西侧获得的单道地震调查资料表明, 西槽坡上的重力流作用是非常显著的, 不但具有多种表现形式和声学反射特征, 而且对陆坡沉积结构的塑造起了相当大的作用, 是上陆坡沉积物向海槽搬运的重要地质作用。

1 海槽西坡地形特征

冲绳海槽西部斜坡(东海陆坡) 呈 NE-SW 弧形带状展布, 地形陡而复杂, 水深从陆架坡折处的 150m 变化到槽底的 2000m 以上, 海槽长约 1200km, 宽约 140—200km, 槽底长约 800km, 宽约 36—120km; 水深 1km—2km 的区域是平面上呈弧

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形向东南方向凸出的带状斜坡地带。陆坡与槽底交接处水深北浅南深，坡度北缓南陡（图 1）。北段最大坡度为 51′33.7″，最小坡度为 24′06.5″，平均坡度为 37′50.1″，地形比较复杂，起伏较多，有台地和峡谷发育，并发育边缘沟和坎（范奉鑫等，1998）；中段平均坡度为 2°41′56.1″，地形简单，水深变化比较均匀，地震调查发现在陆坡断裂带附近可见海底滑塌现象；南段坡度平均约为 2°，地形变化复杂，有阶梯状地形和沟谷地貌发育。

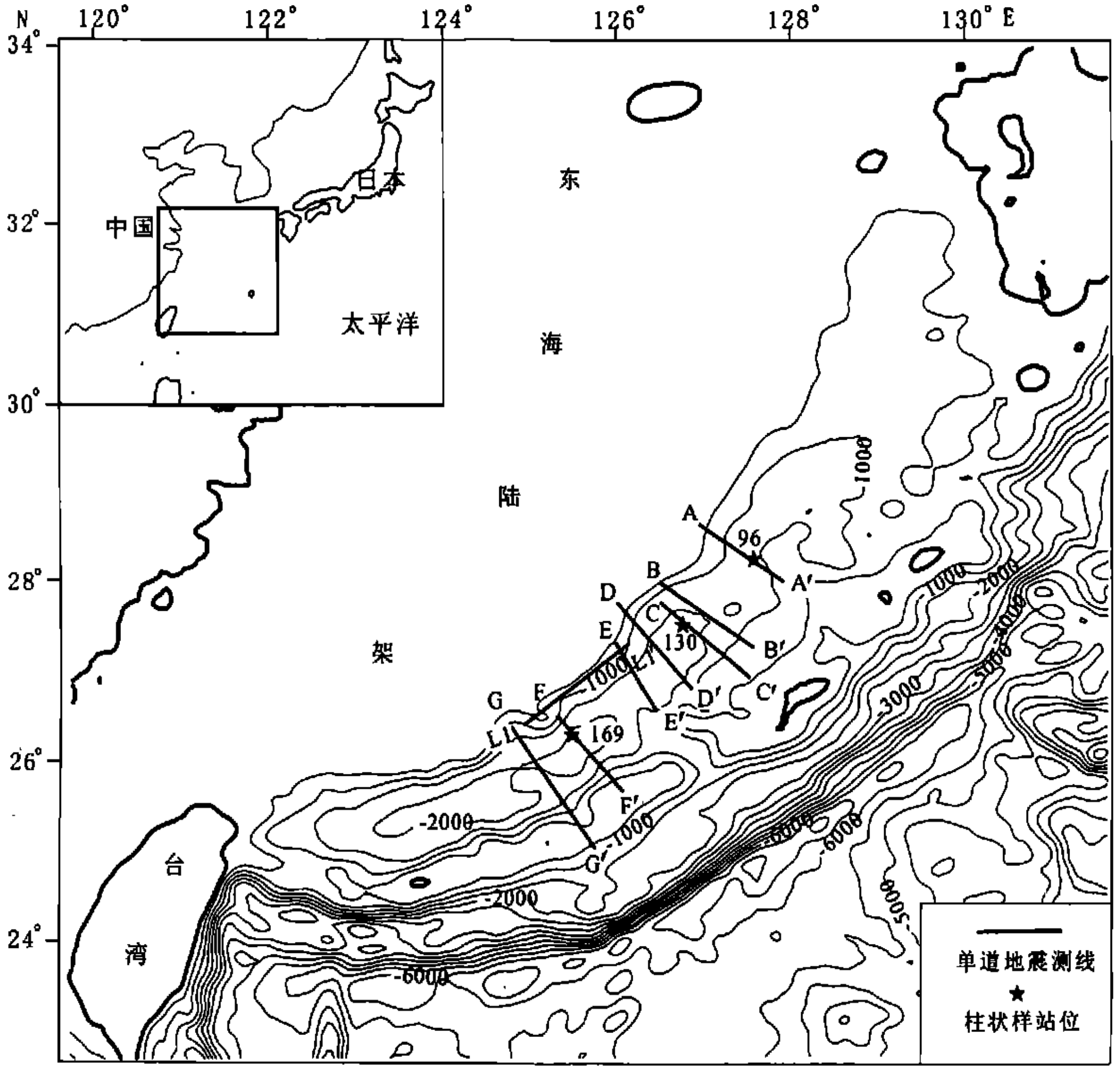

图 1 研究区位置及冲绳海槽海底地形图

Fig 1 Study area and submarine topographical map of the Okinawa Trough

2 资料来源

研究所使用的资料为沉积物柱状样和单道地震剖面。柱状样来自“向阳红 16 号”92 航次在冲绳海槽中段和南段进行的地质调查；单道地震资料来自“向阳红 9 号”95 航次和“东方红 2 号”99 航次在冲绳海槽进行的地球物理调查。地震测线覆盖部分外陆架、陆坡及部分槽底。地震采集系统为DELPH 系统，震源为G.I.枪。柱状样选取了与地震测线靠近的 3 个样品：96、130 和 169 号站取得的岩芯，其长度分别为 579、272 和 347cm，分布于冲绳海槽陆坡和槽底。

3 结果与讨论

3.1 地震相特征

3.1.1 海底滑塌 在陆坡断裂带位置，单道地震资料揭示了许多海底滑塌的存在。走向剖面上海底滑塌现象通常表现为海底的强相位突然变得不规则或断开，具有丘状或透镜状外形的块体下部有一条比较清晰的强反射界面。块体的内部可

以是比较杂乱的反射, 也可以保持原来的层理。滑塌体中的变形构造随沉积物岩性、固结程度、滑塌块体的厚度或搬运距离等因素的变化而变化。图 2 展示了陆坡上一处明显的滑塌, 滑塌体位于三角洲沉积的头部和水深突然变深处, 该处地震剖面上的反射强相位突然中断, 滑塌体内部反射连续性较好, 强振幅; 滑体的厚度在 60—70m, 滑体顺陆坡方向上的长度为 6km 左右, 按滑体的长短轴之比为 2∶1 来计算的话, 估计滑体的体积为 $9\times10^8 m^3$。

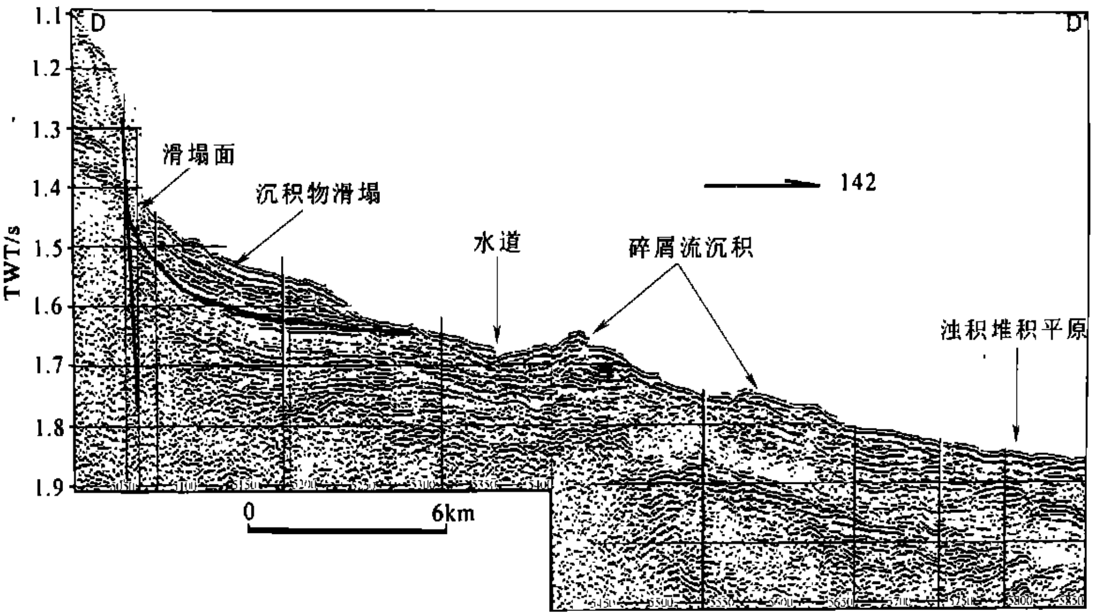

图 2　陆坡海底滑塌与重力流沉积典型剖面

Fig. 2　Slump and gravity flow deposits on the Okinawa Trough slope revealed by single channel seismic profile

3. 1. 2　重力流　　单道地震资料揭示了冲绳海槽西部陆坡上重力流沉积具有多种表现形式, 这些形式主要包括: 沉积物重力蠕动、浊积平原、透镜状浊积体和沿斜坡的碎屑流沉积。它们在地震反射结构上各具不同的特征, 并且声学反射沿陆坡向下逐渐变得有规律。沉积物重力蠕动表现为海底表层沉积物反射为波状(图 3) 或不规则中断, 反射振幅强, 这种反射特征是由于斜坡上沉积

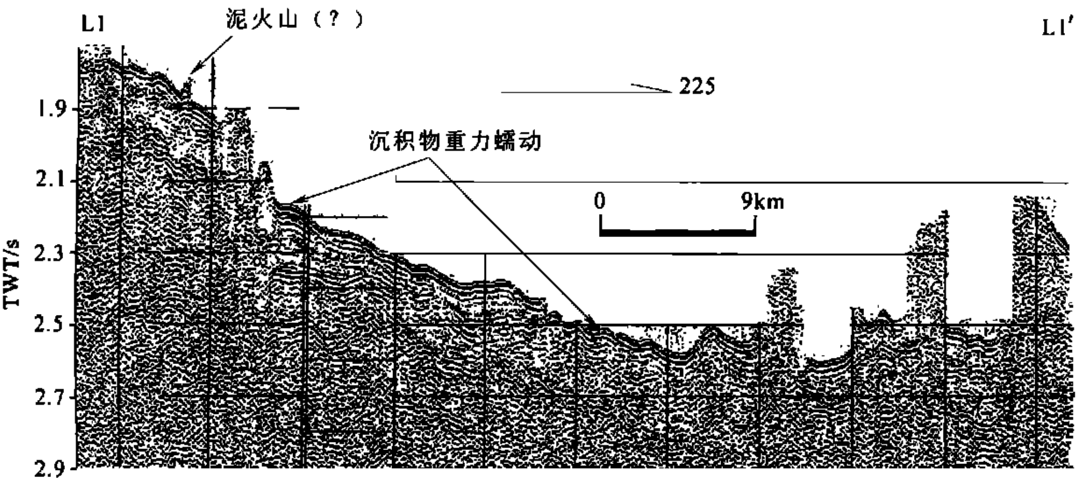

图 3　海底沉积物重力蠕动

Fig. 3　Sediments creeping under the gravity on the sea floor

物在重力作用下发生变形,且速度过于缓慢而未形成沉积物流;浊积平原内部反射振幅较弱,连续性好,层理稍有倾斜(图4),与等深流形成的沉积地震相特征十分相似;透镜状浊积体在纵剖面上表现为透镜状的反射外形,内部为近杂乱的中等强度反射,上下均为强反射界面(图5)。沿斜坡的碎屑流表现为沿斜坡的一系列丘状沉积体,其内部为连续性较差的强反射(图6)。

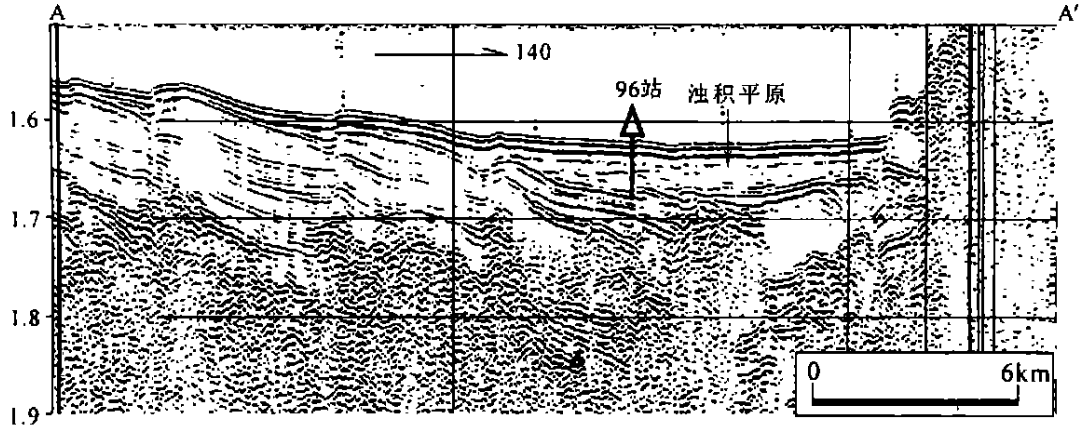

图4 单道地震揭示的浊积平原

Fig. 4 Turbidity plain revealed by single channel seismic profile

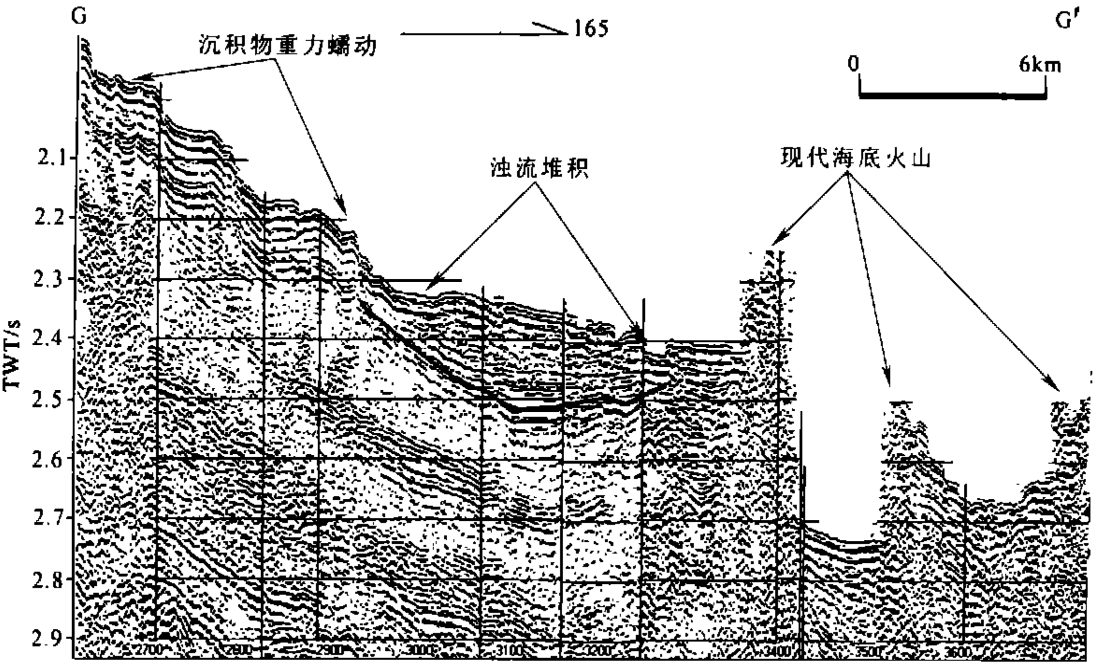

图5 透镜状浊积体

Fig. 5 Lentoid turbidities body revealed by single channel seismic profile

3.2 柱状样揭示的重力流沉积特征

在陆坡和槽底所取到的柱状样中,主要存在3种类型的沉积:火山碎屑层、半远洋沉积层和浊积层,个别柱状样中浊流沉积甚至占到50%—80%。由此可见,西槽坡浊流是非常发育的。样品中单个浊积层厚度最厚可达1m以上,最薄仅有1cm,沉积层有明显的递变层理。根据粒度的差异,可将浊积层分成泥质和砂质两种类型[1)]。3

1) 国家海洋局第一海洋研究所, 1995. 冲绳海槽中段沉积物特征及物质来源. 1—10, 270—291

个样品中 96 号站位于 A-A′线上, 浊积沉积以泥质为主, 样品中可明显识别出两层浊积层; 130 号站位于 G-G′线上, 浊流沉积以砂质为主, 埋深 40—61cm、174cm 至底层段为浊流沉积; 169 号站位于 F-F′线上, 样品以泥质碎屑流沉积为主。

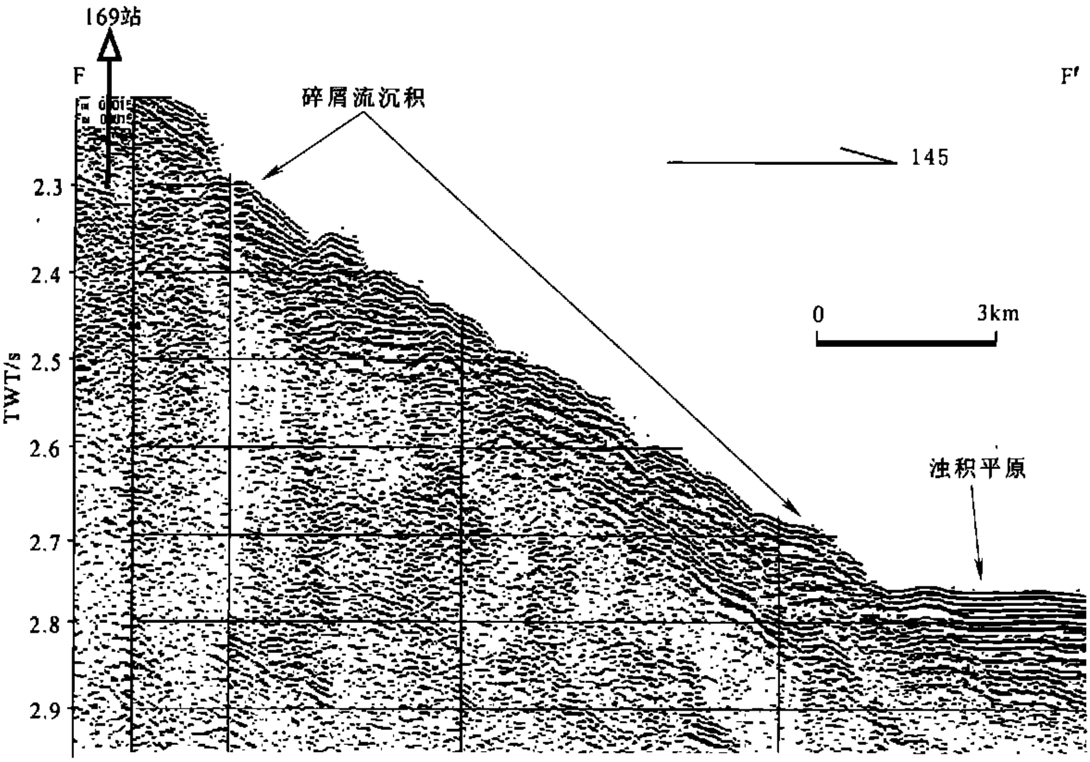

图 6 沿陆坡的陆源碎屑流

Fig. 6 Continental source debris flow deposit along the slope

3.3 滑塌、重力流发育条件

根据力学分析, 滑塌和重力流只有在重力沿斜坡的分量超过沉积物的剪切强度的情况下才发生, 所反映出的地质条件是快速的沉积物堆积和合适的地形。另外, 地震、火山活动和海啸也是促进海底滑塌和重力流产生的外部触发因素, 陆坡上一些峡谷型沟槽也促进了重力流的产生。冲绳海槽中段和南段地震活动、火山活动要比北段更频繁、更强烈, 因而更容易产生重力流。在无外部因素条件下, 引发浊流的最合适的坡度为 1—2°(王琦等, 1989), 碎屑流产生的坡度稍大, 滑塌则要求的坡度更大。冲绳海槽南、中、北三段中, 南段和中段陆坡坡度平均在 2°以上, 北段平均坡度为 37′50.1″, 因而从地形条件上来说中段和南段比北段更适合滑塌、重力流的产生。

从李凤业等(1992) 和李培英等(1999) 通过岩芯计算的冲绳海槽沉积速率来看, 其中段沉积速率最高(全新世为 10—40cm/ka, 晚更新世在 10cm/ka 以上), 北段次之(全新世在 10cm/ka 以下, 晚更新世在 10cm/ka 以上), 南段最小(全新世在 5cm/ka 以下, 晚更新世在 10cm/ka 以下), 因而从沉积物堆积条件上来说, 中段优于北段和南段。现有的岩芯资料和地震剖面资料揭示冲绳海槽的中段重力流最为发育, 南段次之, 北段最弱。其中, 在北段获取的所有岩芯中几乎都没有发现浊流沉积。

3.4 滑塌、重力流发育的空间特征及对陆架结构的塑造过程

西部陆坡的滑塌和重力流沉积除了沿海槽方向具有的带状分布特征外, 更具有探讨意义的是滑塌和重力流沉积在沿斜坡- 槽底方向上的分布特征。整个陆坡可以划分出 3 个部分: 上陆坡、中陆坡和陆坡坡麓(图 7)。陆坡断裂带处地形坡度突然变陡, 加之陆架大量沉积物质积聚在上陆坡,

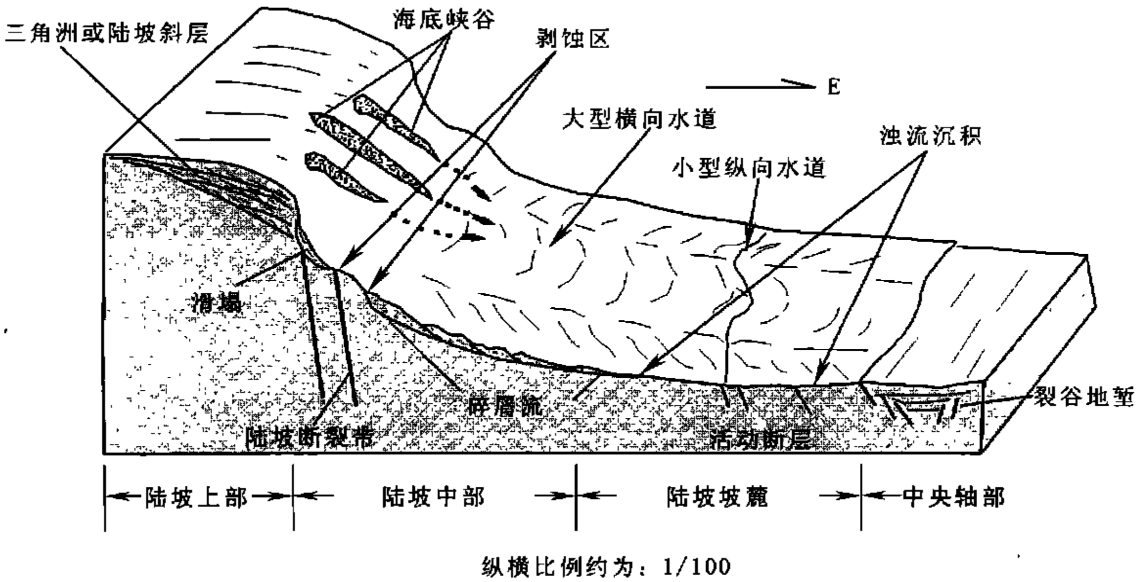

图 7 重力作用对陆坡沉积结构的塑造示意图

Fig. 7 Sketch map of shaping depositional architecture on the slope by gravity

因而沿陆坡断裂带走向滑塌现象呈带状分布。大部分块状和碎屑状沉积物质很快堆积下来, 其余的碎屑物质在自身重力作用下沿斜坡继续向下流动, 造成陆坡断裂带下方不远处受到强烈的侵蚀作用(图 8)。当重力流动能减弱时便开始发生堆积, 常形成丘状沉积体。如果规模足够大, 碎屑物质可以继续流动, 一直到陆坡坡麓(靠近中央海槽) , 这样便形成滑塌- 重力流沉积的一个完整的过程。很显然, 上述作用在任何一次搬运事件中都有可能同时发生, 有时一次事件中可能只发生某个作用。岩芯中存在多个薄层碎屑流或浊积层, 这可能说明了重力流搬运作用的频率较大。

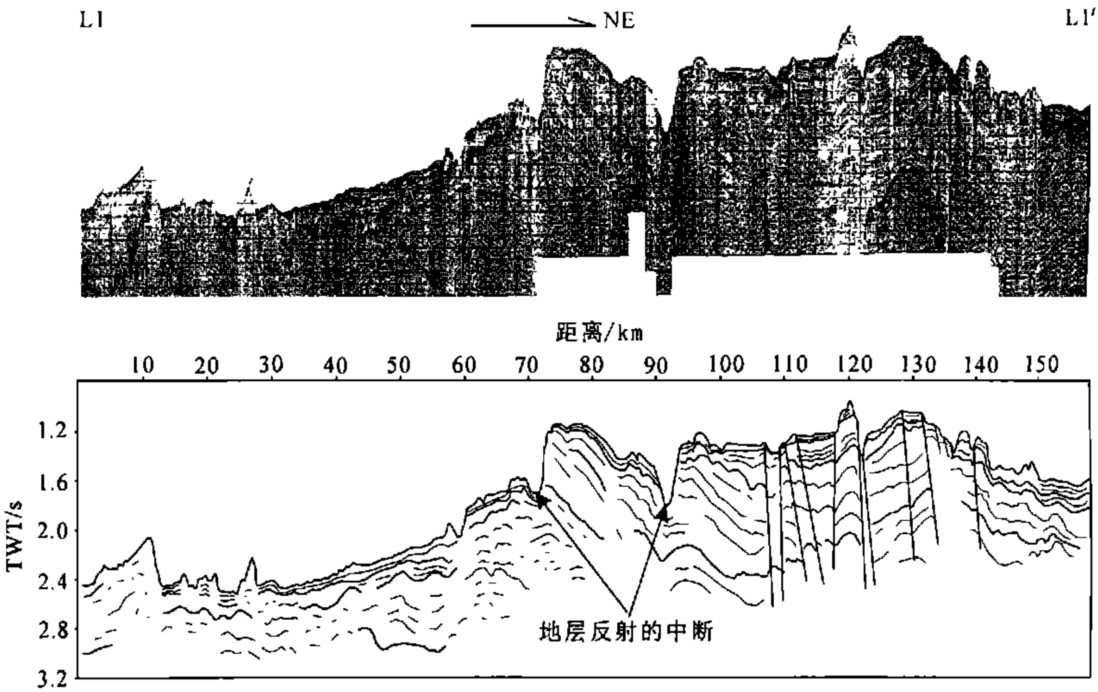

图 8 上陆坡位置受到重力流的强烈侵蚀作用

Fig. 8 The upper slope eroded strongly by gravity flow

4 结语

单道地震资料和沉积物柱状样分析表明,滑塌和重力流是冲绳海槽西部陆坡碎屑沉积物向槽底搬运的重要方式。滑塌常出现于上陆坡的断裂带处,而重力流多位于滑塌的下方,但这并不反映二者存在着必然的联系,滑塌和重力流可以同时发生,也可以单独发生。重力流沉积表现为4种形式:碎屑流、沉积物蠕动、浊积平原和透镜状浊积体。陆坡上部地层受到现代碎屑流的侵蚀作用,而下部则主要发生碎屑物质的堆积。地形、沉积物供应量和地震活动、海啸等因素决定了海槽中段和南段的滑塌、重力流比北段更发育;陆坡的构造特征决定了滑塌和重力流沿海槽延伸方向上的带状分布。在沿陆坡—槽底的方向上分布形式为:滑塌- 碎屑流(浊流沉积),声学反射结构由杂乱向规则反射(平行或前积)变化。

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DEBRIS TRANSPORT ON THE WESTERN CONTINENTAL SLOPE OF THE OKINAWA TROUGH: SLUMPING AND GRAVITY FLOWING

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Abstract　Slumping and gravity flowing are the most important ways of transporting sediments from upper slope to basin and their implication to slope structure in passive or active continental margins has been discussed in many papers. Okinawa Trough (OT) is a tectonically active back-arc basin. Turbidity deposits have been revealed by piston core samples. However, few papers discussed acoustic characteristics on the slumping and gravity flowing and their deposition impact on the west slope of the OT. About 2000 km of high-resolution single channel seismic profiles were collected in 1995 and 1999 and 3 gravity cores were collected in 1992 in the area. Analyses of these data have shown characteristics of slumping and gravity flowing and the deposition impact on the slope. The gradient of slope and sediment supply indicates that slumping and gravity flowing deposits are extensive on the west slope. But asymmetric development in the north, south and middle part of the western slope was affected by different factors, such as depositional rates, tectonic movements, earthquakes, tsunami and so on. Lithological analysis on core samples showed that the main lithological components of gravity flowing deposits are sand and mud. The layers of the event deposits are very thin with high frequency of occurrences vertically. Slumps distribute mainly in a belt along the through near the fault zone on the upper slope. Gravity flowing deposits distribute mainly from the lower of the fault zone to the OT bottom Four types of occurrence were recognized in seismic reflection patterns: a) undulation reflection configuration indicating sediments creeping, b) flat sheet reflection demonstrating turbidities plain, c) irregular reflection denoting lentoid turbidities body and d) hummock clinoform reflection showing debris flow deposits. Single channel seismic profiles showed that the upper slope had been eroded heavily. The location of slumps and type of gravity flowing deposits followed certain rules. Slumping often appears the top of slope and downward the slope is the sediments creeping or debris flowing deposits. Lentoid turbidities bodies are often on the foot area of the slope, and turbidity plain appears on the bottom of the trough. In general case, slumping and gravity flowing often happen simultaneously, but in this area, they did not. Gravity flowing took place more frequently. In overall, the structure of the slope was the result of serial erosion-deposition.

Key words　Okinawa Through, Seismic reflection, Slump, Gravity flowing