目錄

Abstract – a brief summary of work performed in the project period

This is a final report of the progress for a three-year project entitled "Transport processes and accumulation rates of sediments in the seas around Taiwan". In this past project period, our work was focused on the west coast of Taiwan, including Taiwan Strait and the sea off southwestern Taiwan, with the Gaoping submarine canyon located in the center of the study area. It is a sequel to a previous project entitled "Source-to-sink pathways of sediments in eastern Taiwan and the Southern Okinawa Trough". Our final objective is to elucidate the transport pathways, sinks and budgets of sediments around Taiwan. As before, fallout radionuclides ^{210}Pb, ^{137}Cs and ^{7}Be are used as tracers to elucidate the transport processes of sediments.

During this past three years, we have analyzed 210 sediment cores collected from 24 cruises. These cruises (and their timing) are:
OR3-1075 (Sept. 2004), OR1-732 (Oct. 2004), OR3-1081 (July 2005), OR2-1300 (Aug. 2005), OR1-761 (Aug. 2005), OR1-770 (Oct. 2005), OR1-779 (Dec. 2005), OR1-789 (Apr. 2006), OR1-791 (Apr. 2006), OR1-799 (June 2006), OR2-1367 (July 2006), OR1-803 (Aug. 2006), OR1-811 (Oct. 2006), OR3-1192 (November 2006), OR1-820 (Jan. 2007), OR1-825 (Mar. 2007), OR2-1442 (May 2007), OR1-841 (Sept. 2007), OR1-844 (Oct. 2007), OR1-858 (Mar. 2008), OR3-1276 (Mar. 2008), OR2-1539 (May 2008), OR2-1547 (June 2008), OR2-1559 (July 2008)。

Of the 24 cruises listed above, 11 cruises covered the Taiwan Strait from where 103 cores were collected; the other 13 (those underlined) were FATES cruises occupying an area centered around the Gaoping submarine canyon off southwestern Taiwan from where 107 cores were collected for this work. It will inevitably require substantial time and efforts in the next 2-3 years for this PI to fully digest the massive data. In this report, I shall compile the accumulated data, enumerate some major findings, and attach pdf files of papers resulting from NSC grants (either for this or the previous projects) that are published during this project period.

Keywords: Taiwan Strait, Gaoping submarine canyon, radionuclides, ^{7}Be, ^{137}Cs, ^{210}Pb, sedimentation rate, source-to-sink transport.

中文摘要 – 工作概述

本三年期(2005-2008)計畫係利用放射性落塵核種鈹七、銫一三七及鉛二一零探討台灣周圍海域沉積物之傳輸過程及沉積速率，此為第三年之期末總報告。這是接續之前的三年(2002-2005)吾人對台灣東部及南沖繩海槽之研究後，將研究區域轉移到台灣西部海域，包括台灣海峽及以高屏峽谷為主軸的台灣西南海域。最終目的是希望能對台灣周遭海域沉積物之搬運途徑、最終去處及沉積物預算作較全面的分析與了解。

過去三年中吾人分析了從 24 個航次、凡 210 個站位所採集的沉積物岩芯及表層沉積物，取得相當龐大的資料。此 24 個航次(及其時間)為:
OR3-1075 (Sept. 2004), OR1-732 (Oct. 2004), OR3-1081 (July 2005), OR2-1300 (Aug. 2005), OR1-761 (Aug. 2005), OR1-770 (Oct. 2005), OR1-779 (Dec. 2005), OR1-789 (Apr. 2006), OR1-791 (Apr. 2006), OR1-799 (June 2006), OR2-1367 (July 2006), OR1-803 (Aug. 2006), OR1-811 (Oct. 2006), OR3-1192 (November 2006), OR1-820 (Jan. 2007), OR1-825 (Mar. 2007), OR2-1442 (May 2007), OR1-841 (Sept. 2007), OR1-844 (Oct. 2007), OR1-858 (Mar. 2008), OR3-1276 (Mar. 2008), OR2-1539 (May 2008), OR2-1547 (June 2008), OR2-1559 (July 2008)。

上述 24 個航次有 11 個係於台灣海峽執行，取得 103 支岩芯；另外 13 個航次(劃底

線標示者)則是劉祖乾教授所領導的 FATES 計劃於高屏峽谷及其附近的陸棚、陸坡及深海平原作業，共採得 107 支岩芯供本計畫分析放射核種。要消化本計畫所產生龐大且不斷增加中的數據勢需於未來二、三年投入更多的時間及精力。目前此報告只擬敘述幾項重要觀測及發現，並附上截至目前為止已整理出來的數據及過去三年所發表論文。

關鍵詞：台灣海峽、高屏峽谷、放射核種、鈹七、銫一三七、鉛二一零、沉積速率、源到匯之傳輸

一、 前言─計畫之背景及目的

台灣位居西太平洋潮溼多雨的熱帶與亞熱帶，有頻繁的颱風及地震，也有陡峻的地形，致暴雨時地表逕流及河水湍急，輒使已然鬆動的土石劇烈流失。早於三十年前，李遠輝教授的研究報告(Li, 1976)即指出，中央山脈之均夷率(denudation rate；或稱剝蝕率)至少為 1,365 mg/cm^2/yr；亦即，在每平方公里之山地上，每年平均有 13650 公噸以上之土壤流失，侵蝕速率之高，無與倫比。經濟部水資會歷年(1949-1990)統計資料顯示，本島主要河川年平均總輸砂[1]量為二億六千萬噸(260 Mt)，將之除以全島面積(三萬六千平方公里)，得每年每平方公里沉積物產率(sediment yield)為 7300 公噸；亦即，全島平均侵蝕速率約為中央山脈均夷率之半。嗣後，Dadson等人根據水資會 1979-1999 年資料，將台灣河川年平均總輸砂量上修為 380 Mt (Dadson et al., 2003)，較早期估計高出 46%。近年來，高樹基博士特別於颱風引發的洪流(flash floods)發生、即河川輸砂最劇的時段，密集採樣分析，釐訂了與以往有異的河川流量與懸浮物含量對應關係的rating curve，反將台灣河川年均輸砂量大幅下修到 184 Mt (Kao et al., 2005)。因此，關於台灣全島的平均侵蝕速率究竟有多高，是否有漸增(抑減少)的趨勢，目前沒有統一的看法；但可以肯定的是，台灣的沉積物產率(sediment yield)高居世界第一，國土流失嚴重，對國家建設、永續發展及人民生命財產的安全皆構成威脅，是極為嚴峻的問題。

有源就有匯；陸地侵蝕必導致海域沉積，二者實為一體的兩面。海底的沉積記錄猶如時光隧道，透過它，吾人或可回溯過去陸地侵蝕的歷史。沉積物由陸地河川攜帶入海後，其中一部分可能暫時堆積在河口鄰近的海域，嗣後如受擾動，其中細泥特別容易經再懸浮(resuspension)被海潮流搬運到距其來源更遠處沉積。這種再懸浮、再沉積(redeposition)的過程可能輾轉發生多次，直至沉積物被“永久”埋藏為止。選擇適當的親顆粒性(particle-reactive)落塵放射核種(fallout radionuclides)作示蹤劑，吾人可望解析沉積物由源到匯(source-to-sink)的傳輸途徑、過程、沉積速率及沉積歷史；這正是美國NSF Margins計畫下，四個核心計畫之一的S2S (Source-to-Sink) Initiative所勾勒的研究目標(http://www.nsf-margins.org/S2S/S2S.html)，也是筆者多年來執行國科會計畫所聚焦的議題。

關於陸地侵蝕及與之有因果關係的山(岩)脈崛起(exhumation)、河床切割(incision)、沉積物輸出等議題，台灣是絕佳的天然實驗室，多年來備受國內外學者關注，有相當豐碩的、經典的研究成果。相形之下，海域沉積(尤其是現代沉積)方面的探索，明顯見拙。有鑒於此，筆者回台時，即將此議題列為主要工作之一，希望能在個人有限的研究生涯中，盡綿薄之能，建立台灣周遭海域現代(<100 年)沉積物沉積速率的基本資料，作為探討沉積物傳輸途徑及計算沉積物預算的基礎。

本於地質學「古今同一說」(Uniformitarianism；或稱「均一說」)的信條，觀察、

[1] 本報告所謂河川輸「砂」泛指所有顆粒；一般是泥多於砂。

了解地球上當下發生的現象，是洞達過去之鑰(The present is the key to the past)。是以，往者雖已矣，百年內猶可追尋的沉積記錄或可擬為探索古沉積環境的現代啟示錄。

以下略述筆者十二年來研究此議題的歷程，依時序回顧(1)東海陸棚 (1996-2002)，(2)南沖繩海槽(2002-2005)，(3)台灣西南外海高屏棚坡峽谷體系(2005-2008)，及(4)臺灣海峽(2005-2008)。該四個研究區域的相對位置、範圍、及附近海底地形概如圖一所示。本節（前言）之敘述將止於南沖繩海槽；西南外海及臺灣海峽的部份將述於下一節，係本報告之重心。

1. 由東海到南沖繩海槽

筆者於 1996 年六月回國，進入中研院地球所任職，立即接受劉康克教授的徵召，投入當時值第二階段的「東海與黑潮邊緣交換過程」(Kuroshio Edge Exchange Processes) 整合研究計畫(即 KEEP-II)，利用天然(^{7}Be、^{210}Pb)及人工(^{137}Cs、^{239,240}Pu)放射性落塵核種為示蹤劑，探討東海陸棚沉積物的來源、傳輸途徑及沉積通量等。該計畫研究範圍西從大陸沿岸橫跨東海陸棚至大陸斜坡，東與黑潮流徑相接；南由台灣北部(~26°N)向北抵長江口(~32°N)，北與黃海互鄰。因探測幅員遼闊，需時較長，由 KEEP-II 延續至 KEEP-III，到 2002 年甫告一段落。

於參加 KEEP 計畫的六年期間，筆者共規劃海研一號出海作業五個航次，取得沉積物岩心(包括箱式及重力岩心)凡八十三支，進行放射核種分析。除了探討沉積動力(Huh and Su, 1999; Su and Huh, 2002b)，所得結果亦引申至其他相關議題，如陸棚水之循環(Chen and Huh, 1999)、長江輸出污染物之傳輸及污染歷史等(Huh and Chen, 1999; Chen et al., 2000)，增添了原計畫之附加價值。之後，轉到其他區域研究，依然循此模式，不放棄「節外生枝」、開花結果的機會，以提升研究計畫的投資報酬率。

從 KEEP 沉積物岩心中 ^{137}Cs 及 ^{239,240}Pu 垂直剖面，吾人計算各採樣點近四十年來的沉積速率，其分佈如圖二所示。根據沉積速率之分佈，研究區域內沉積物之年平均埋藏量約為 13 億噸(Su and Huh, 2002b)，超過文獻上所記載長江輸出 (每年平均約 2 至 5 億噸; Milliman and Meade, 1983; Yang et al., 2003) 和台灣河流輸出 (每年平均 1.8 至 3.8 億噸;經濟部水利署歷年年報; Dadson et al., 2003; Kao et al., 2005) 的總和。因此，關於東海陸棚沉積物的收支是否平衡，吾人只能暫時提出若干可能的解釋(Su, 2000; Su and Huh, 2002b)，包括十年至百年尺度過渡期(transient)的物質不平衡狀態(mass imbalance on decadal to centennial timescales)。

KEEP 於 2002 年結束時，筆者接下來將探測目標轉向南沖繩海槽；那裡在西太平洋的海洋科學上極為重要，也是台灣附近沉積速率頗高的一個海域。KEEP 計畫下的假說之一(即「旋轉門假說」)有云：南沖繩海槽是東海陸棚沉積物的一個歸宿(Wong et al., 2000; Liu et al., 2003)。就此觀點而言，南沖繩海槽的研究可視為 KEEP 計畫的自然延伸。

南沖繩海槽夾在東海陸架及琉球島弧間，在地體構造上，是一個弧後擴張海盆(back-arc spreading basin)，地殼運動活躍，地震頻繁，是海洋地質及地球物理研究的一個熱門地帶。在海洋物理上，精彩的程度亦不遑相讓：黑潮沿臺灣東海岸北流，進入南沖繩海槽後撞上陸架，導致其主流向東偏，並於北棉花峽谷形成分支，該支流沿峽谷仰衝上來後，沿逆時針方向旋轉，形成渦流，黑潮次表層水於渦流中心湧升，與東海水混合及交換。一般咸認為那裡是東海陸棚與外洋進行物質交換的重要孔道，即所謂的「旋轉門」，居樞紐地位，重要性不言而喻。

2. 南沖繩海槽沉積物的來源與預算

於研究南沖繩海槽計畫的三年期間(2002-2005)，筆者共規劃海研一號出海作業六個航次，採得沉積物岩心近百支，進行放射核種及其他相關分析。這些岩心的分析結果顯示海槽中有個沉積速率超過 1 cm/yr 的沉積中心(圖三 a)。表面沉積物顆粒分佈(圖三 b)及$\delta^{13}C$ 分佈(圖三 c)皆透露臨近的蘭陽溪為海槽中沉積物的主要來源。根據圖三 a 所顯示的沉積速率分佈，該區域內年沉積量約為一千八百萬噸(Lee et al., 2004)，與 Dadson et al (2003)根據經濟部水利署歷年水文資料所推算之蘭陽溪年輸砂量(17 Mt/y)若合符節，但較高樹基等人所估算之蘭陽溪年輸砂量(6.5 Mt/y; Kao et al., 2005)高出有 2-3 倍之多。

John Milliman (私下討論)認為 Dadson 等人對臺灣(尤其是東部)河川的輸砂量估算可能高估。根據水利署 1949 年至 1990 年、凡四十二年的水文資料所統計，蘭陽溪年輸砂量接近八百萬噸，只能供應南沖繩海槽部份的沉積。如仔細觀視圖三 a，東海陸棚(可能包括台灣北海岸)隱然為一次要供應源。Chung and Hung (2000)沉積物收集器之研究指出，南沖繩海槽北坡存在一股反流(黑潮反流？莊氏反流？)，將沉積物往西南傳送。若然，則由蘭陽溪方向進入南沖繩海槽之沉積物可能就挾帶了從陸棚下來的沉積物。
除了蘭陽溪及東海陸棚外，台灣東部的其他河流所輸出之懸浮沉積物，也可能會有部份被黑潮挾帶至南沖繩海槽，但鑒於黑潮的高流速及低懸浮物含量，此來源的懸浮物在該範圍內沉積下來的份量可能不重。在河川輸出量有不同估計的情況下，南沖繩海槽沉積物各個可能來源的貢獻有待進一步釐清。

3. 南沖繩海槽的濁流層—成因與時空分佈

於南沖繩海槽周邊之陸坡底部(base of continental slope)所採箱式岩心沉積物一般構造單純、粒度均勻，落塵核種剖面揭示近百年內沉積速率幾乎固定不變，且由不同核種(^{137}Cs, ^{210}Pb, $^{239,240}Pu$)所測得沉積速率相當吻合，為穩定的半遠洋(hemipelagic)沉積環境。在此以下的沉積物就開始顯現不同的沉積環境；結構上出現粗細相間的互層，^{210}Pb、粒度及含水量剖面顯示數個濁流層(turbidite)間夾於規律的 hemipelagic 背景沉積物中。值得注意的是，這些含濁流層的岩心位址集中在一個凹陷的海床，其範圍與前述的沉積中心有相當程度的重疊。無疑的，濁流層來自周圍不穩定的邊坡。更重要的是，根據定年結果，各濁流層沉積年代與二十世紀以來臺灣東部海底大地震發生的時間吻合，證明這些濁流層是地震引發造成的，其特性與河川濁流有所不同(請見下一節)。在此項發現的初步結果發表後(Huh et al., 2004)，吾人對濁流層分佈及特徵進行了更進一步的探究(Huh et al., 2006b)，發現濁流沉積帶可根據 ^{210}Pb 剖面特徵劃分成北、中、南三區；北區之濁流層沉積年代由上而下分別與 2002 AD、1986 AD、1959 AD、1947 AD、1922 AD 等歷史大地震對應；中區之濁流層年代由上而下為 2002 AD、1986 AD、1966 AD、1959 AD；南區由於崩塌量甚大，半米長的箱式岩心中只觀察到 2002 AD 及 1986 AD 兩個濁流層，其間夾了一層 5-10 公分厚的半遠洋背景沉積層(hemipelagite)。

除了上述的沉積中心外，吾人發現於 122°50’E 以東，地震活動較頻繁的的弧後張裂谷兩側，及南沖繩海槽外的和平海盆(屬弧前海盆)北坡，亦有濁流層。除了箱式岩心，吾人於和平海盆採得兩米半的活塞岩心，岩心的 X-ray radiograph 影像顯示記錄完整、時間尺度幾近千年的濁流層序列，這將是研究古地震及地震再現性(recurrence)的極佳素材。濁流層的發現及追查是筆者所始料未及的，但頗引人入勝，使研究成果更豐富且多元化。

二、 過去三年研究台灣西南海域及台灣海峽的過程與一些結果

1. 台灣西南海域高屏溪高屏峽谷河海傳輸體系

如前所述，建立台灣周遭海域現代沉積的基礎資料為筆者研究生涯若干職志之一。當南沖繩海槽的研究計畫於 2005 年告一段落後，我們轉移陣地到台灣西海岸，進行台灣海峽及台灣西南海域的調查研究。其中，台灣西南海域的工作是以劉祖乾教授所領導的FATES-KP (The **Fa**te of **Te**rrestrial **S**ubstances in **K**ao-**P**ing Submarine Canyon)整合型計畫為平台，以非破壞性的加瑪計測法分析FATES計畫所採得的大量沉積物岩心樣本。過去三年餘我們分析了取自 13 個航次的岩心共 107 支，得到了豐富的數據(請見 http://dmc.earth.sinica.edu.tw/Contributor/Huh/Huh_et_al2007a)，部份結果已為文，即將發表於*Journal of Marine Systems*的 FATES專刊（Huh et al., in press；附件一）。

FATES-KP 的研究區域以高屏峽谷為主軸，峽谷始於高屏溪河口附近，穿過狹窄的陸棚，經陸坡通往馬尼拉海溝。此區域沉積物主要來源為高屏溪流域，流域面積(3257 km^2)屬臺灣最大的。高屏溪水系源頭在臺灣(與東北亞)第一高峰—玉山；由源之高(3952 m)到匯之深(~3600 m)途經陡峻的地形及脆弱的地表，沉積物很可能藉由濁流(turbidity flow)、甚或超密流(hyperpycnal flow)的發生而快速的、大量的從高山被搬運到深海。

從研究臺灣東北的南沖繩海槽到台灣西南的高屏河海傳輸體系，我們發現這兩個研究區域有幾項特徵迥異，很值得作沉積作用的比較研究。在地體構造上，前者為臨主動邊緣(active margin)的弧後盆地(back-arc basin)，後者為界主動邊緣及被動邊緣(passive margin)的陸前盆地(foreland basin)；在流體力學上，前者被強勁的西方邊界流（即黑潮）所籠罩，而後者受潮汐及河川流所主宰(tidal and flood dominated)；在沉積物從源到匯(source-to-sink)的傳輸上，前者的弧後擴張海槽地形為沉積物的匯集處(receptacle)，而後者的峽谷地形則構成很好的沉積物輸送孔道(conduit)。鑒於這種頗為尖銳、典型的對比，以及台灣海峽又是另外一種很具有代表性的傳輸體系(敘述於後)，筆者覺得台灣「麻雀雖小，五藏俱全」，周遭有不同的沉積環境，真是研究沉積物傳輸及現代沉積的天然寶地!

根據落塵核種在台灣西南海域沉積物之分佈，吾人推斷此區域河川輸出沉積物有兩種主要的傳輸及堆積(或侵蝕)模式：沿峽谷的沉積物堆積或沖蝕(scouring)主要受重力所驅動的濁流(gravity-driven turbidity flow)所主宰，而峽谷外的開放棚坡及坡底處的沉積物堆積則主要由表層及次表層擴散舌(surface and subsurface plumes)中懸浮顆粒在水柱(water column)的沉降所控制。

從沉積速率的分佈，吾人估計此研究涵蓋區域(面積約 3,000 km^2)之平均沉積速率為 0.22 g cm^{-2} yr^{-1}，得沉積物年埋藏量 6.6 Mt/yr，僅佔高屏溪年輸出泥砂量(21.2 Mt/yr，Kao et al., accepted; 36 Mt/yr, WRA, 1998；49 Mt/yr，Dadson et al., 2003)的 13-31%。此估算結果意味大部份(69-87%)的陸源沉積物可能經高屏峽谷被快速搬運到遠處的深海。超密流在這種搬運上扮演了一定的角色，與海底峽谷的切割、形成有密切關聯(Mulder et al., 2003）。

吾人在高屏峽谷外亦發現濁流沉積物，最值得注意的是一片面積約 1200 km^2 的濁流層，分佈於高屏峽谷兩側的上部陸坡(upper slope)，厚度可達 12 公分，為 2005 年七月 18-20 日超級颱風「海棠」過境台灣時所引發的洪水造成的。這種洪水濁流層沉積物與南沖繩海槽的地震濁流層沉積物(seismoturbidite)結構有別；前者粒度一般較其周圍沉積物(ambient sediment)細，有機質多，後者則一般較粗，有機質少。

以上僅擇要略述此區域所觀測之若干結果，有關細節已載於附件一，不需贅述。

2. 台灣海峽沉積物的來龍去脈

臺灣海峽夾在中國大陸和台灣間，北鄰東海、南接南海，東西平均寬約 180 公里，南北長約 380 公里。台灣西部河川所攜帶之沉積物出河口後，有多少埋藏(或停留)在台灣海峽？多少往西南輸送，進入南海？多少往北傳送，進入東海，抑或繞經台灣北部沿岸進入南沖繩海槽？這真是個大哉問！要回答此問題，吾人必須以設定時間尺度為前題。不幸的是，此海域現代(<100 年)沉積物之定年及沉積速率基本資料極為不足，有待建立— 正如過去十年吾人於廣袤的東海、南沖繩海槽及高屏外海之所為。

根據吾人目前的了解，除了澎湖水道以南的台灣西南部河川(如高屏溪、東港溪)之沉積物，主要受海底地形控制，朝西南往南海輸送外，台灣西部河川之沉積物皆朝台灣海峽輸送，入海後受波浪及潮流控制其搬運及沉積。鑒於臺灣海峽是臺灣周遭最淺、地形相對狹隘，而河川泥砂輸入量最大的海域，且有大陸沿岸流、黑潮支流、台灣暖流、潮汐及東亞季風的影響，這裡沉積動力之錯綜複雜是可以想像的。臺灣海峽有夠大的沉積物容納空間(accommodation space)、能長期(>10^{3-4} years)的積蓄來自臺灣西部河川之沉積物嗎？若無，則沉積物的短期(<10^{1-2} years)預算及搬運途徑為何？最終歸宿在哪？這是我們亟思探索的問題。

自 2005 年迄今，筆者實驗室已處理、分析臺灣海峽的沉積物岩心 103 支；這些樣本蒐集自筆者及台大林曉武教授、蘇志杰教授所分別領導的海研一號及海研二號共 11 個航次，採樣點空間分佈如圖四所示。為了觀察隨時間(尤其是颱風前後)的變化，其中部份站位係重複造訪。在此必需強調: 這些岩心多取自海峽東半部，將來需加強西半部的調查、採樣。

落塵放射核種分析結果一如預期，顯示臺灣海峽沉積動力遠比前述台灣東北及台灣西南海域複雜。整體言之，臺灣海峽的沉積速率較高、變化大，擾動較頻繁，不符 steady-state 的條件，使得由 $^{210}Pb_{ex}$ 及 ^{137}Cs 所訂出沉積速率鮮有完全符合者，尤其是在海峽的中軸線及中間地帶。圖五所示為較罕見的幾個例子，該等採樣點靠近台灣西岸或大陸沿岸，不但沉積物供給充足，且沉積環境於過去數十年相對上較為穩定。靠近台灣沿岸地帶，^{137}Cs 的次表層最高值所在深度(代表 1963 AD 落塵量最高時)與由 $^{210}Pb_{ex}$ 定出之年代吻合，而 $^{210}Pb_{ex}$ 剖面透露最近二、三十年的沉積速率(OR1-790 BC7 為 0.84 cm/yr; OR2-1442 GC24 為 1.3 cm/yr)為近百年內最高者，可能反映台灣的土壤流失因土地利用或八零年代以來降雨強度的增加而加劇。這一點對解析台灣周遭海域的現代沉積動力非常重要，必需加強求證。另一方面，閩浙沿岸之沉積速率於過去數十年有降低之趨勢，可能反映近半世紀以來長江之輸砂之銳減。

其他已有分析結果顯示，大部份採樣點受頻繁的河川濁流影響，$^{210}Pb_{ex}$ 剖面呈不規則狀，難以用指數曲線數值模擬(exponential curve fitting)來估算沉積速率。在此情形下，吾人可設定 ^{137}Cs 穿透深度(penetration depth)等同 1950 AD(大氣核爆落塵開始散佈)的前提來估計近五十多年來的平均沉積速率。雖有其他研究(e.g., Crockett and Nittrouer, 2004）將海洋沉積物中初現(initial appearance) ^{137}Cs 的時間訂為 1954 AD，但筆者認為有可議之處。由於敝實驗室加瑪能譜儀計測效率高（容後述），藉其靈敏度我們可將量測極限(detection limit)往前推到更早期樣本中更低的核爆落塵核種活度，故將 ^{137}Cs 之初現時間設為 1950 AD。如此計算出來的初步結果(如圖六)彰顯濁水溪是海峽北部沉積物最大的來源。

如果單是根據圖六的既有數據點所描繪出來的輪廓，該區域平均沉積速率約為 0.5 cm/yr。筆者研判圖六所顯示的應是台灣海峽沉積速率較高的區域；海峽西部因距臺灣

(最重要的沉積物來源)較遠，沉積速率應會較低。目前既有樣本的分析仍在進行，沉積物採樣工作也將繼續下去，日後將根據分析結果逐步規劃後續的採樣，加密空間分佈，祛除盲點，期能增進估算沉積物搬運及埋藏通量的精確度。

3. 台灣海峽表層沉積物的快速堆積、搬運及短期變化

2004 年七月初「敏督利」颱風過境臺灣時帶來七二水災，重創中臺灣，濁水溪於四天內排放約 72 Mt 沉積物到台灣海峽，河水濁度最高時懸浮物濃度超過 200 g/L，遠超過造成超密流(hyperpycnal flow)所需的臨界濃度 (~40 g/L)，致出海時於河口附近堆積大量以細泥為主的洪積物。之後，此堆積物中細泥受潮汐及台灣暖流之擾動而再懸浮(resuspension)，漸漸地往北移動，一個月後杳然無蹤。

以上所述是國內數位同仁與美國的 John Milliman 教授合作，利用 Chirp sonar 調查海床淺層結構，輔以濁水溪水文、沉積物 C/N、$\delta^{13}C$ 及粒徑分析等資料，歸納所得(Milliman et al., 2007)。

本計畫提供另一個研究表層沉積物傳輸的利器—^{7}Be，即敝實驗室以加瑪能譜分析，例行量測的落塵核種之一。^{7}Be 在土壤中的分佈集中於表土(topsoils) (Huh and Su, 2004)，很容易受到表面侵蝕(sheet erosion)的影響而大舉遷移，是近海地區近期(約半年內)堆積的河氾沉積物(river flood sedimentation)極佳的示蹤劑(Sommerfield et al., 1999; Mullenbach et al., 2004; Moralles et al., 2006)，可以用來追蹤河川細泥進入台灣海峽後之行蹤。由於 ^{7}Be 半衰期短(53.4-54.2 天，隨化學形態而稍異；Huh, 1999)，樣本採取後需儘快分析，否則稍縱即逝。吾人於過去三年的航次所採表層沉積物樣本常可測得 ^{7}Be；其時空變化如圖七所示。以從 OR1-799 航次 (2006 年 4 月 6-8 日)到 OR2-1367 航次(7 月 27-29 日)的變化為例，其間相隔 112 天(約為 ^{7}Be 半衰期的二倍)，^{7}Be 於表層(<2 cm)沉積物的分佈情形截然不同。2006 年 4 月初時，有一層最近輸出的河川細泥出現於濁水溪口以北及烏溪口以西的離岸(中心位置: ~24°20'N, 120°17'E)，到七月底時該片細泥就從調查範圍消失，而大甲溪河口(~24°24'N, 120°30'E)出現另一堆新沉積的河川細泥，應是 4 月初以後、七月底以前(可能是七月中的碧利斯颱風發生時)自濁水溪、烏溪或大甲溪輸出，沿海岸往北搬運至該處暫時停留。我們相信這種搬運過程於台灣海峽時時刻刻進行著，從未間斷，只是不很清楚河水攜帶入海的細泥最終的歸宿為何。

沉積物的快速堆積也可從落塵核種於岩心中的垂直剖面得知。例如，今(2007)年 9 月中旬的 OR1-841 航次，在大甲溪河口三個測站所採岩心的初步分析結果(圖八)顯示，在距表面十公分以下的沉積物仍可量測到 ^{7}Be 的存在， ^{137}Cs 之穿透深度當然就更深了(恐非一般約半米長的箱型岩心可完全涵蓋)，至於 $^{210}Pb_{ex}$ 的剖面則不規律，不能用指數遞減的函數關係來模擬。這樣的資料目前只能以短期(<60 d)內快速堆積數公分(譬如在 OR1-841 BC8 及 BC10 處)至十數公分(譬如在 OR1-841 BC9 處)來判讀。

其實，河口的沉積動力極其複雜，沉積物與時推移，有時沉積，有時侵蝕。譬如，當超密流發生時，它往往排開或沖刷河床及河口附近沉積物。所以在計算年際 (>10^{0} 年)的沉積物預算時，河口地區不能納為匯(sink)的範圍，只能視為沉積物的傳輸通道(pathway)；如將時間尺度拉長(例如，>10^{1-2})，則近岸地區究係沉積物的源、匯抑或傳輸通道，亦須謹慎評估。

台灣海峽因水淺，沉積物通量高、變化大，沉積物所含 $^{210}Pb_{ex}$ 活度低(未有超過 10 dpm/g 者)且較無規律性，不適宜單獨作為定年劑使用，必需另以 ^{137}Cs 制約，以估計過

去五、六十年來之總沉積量及平均沉積速率。在這種情況下，^{7}Be 的重要性也相對大為增加，為探討短期內沉積物傳輸不可或缺的示蹤劑。

以加瑪能譜法分析近海沉積物，除了 ^{210}Pb (46.52 keV)、^{137}Cs (661.62 keV)、^{7}Be (477.56 keV)這三個落塵核種外，我們可同時測得 ^{40}K (1460.75 keV)、^{212}Pb (238.63 keV)、^{214}Pb (351.99 keV)、^{228}Ac (911.09 keV)等核種的活度，可能可利用多變數分析(multiple variable analysis)進行 provenance study，分析沉積物的流域來源。另外，沉積物在搬運過程中，與海水接觸，會吸附海水中由 ^{238}U 衰變產生的親顆粒性(particle-reactive)子核種 ^{234}Th (63.29 keV)，構成沉積物中超量(excess) ^{234}Th （$^{234}Th_{ex}$）。當沉積物遭掩埋、失去與海水的接觸後，$^{234}Th_{ex}$ 以 24.1 天的半衰期衰退，所以 $^{234}Th_{ex}$ 會是另一個探討短時間尺度沉積動力極佳的示蹤劑，可與 ^{7}Be 搭配，相得益彰。未來三年我們的研究仍然以台灣海峽為焦點，將加列 $^{234}Th_{ex}$ 於分析核種名單中。

總之，根據過去三年的調查研究，我們發覺台灣海峽的沉積動力比東海、南沖繩海槽、西南外海更為複雜、有趣，需要在空間上更綿密、時間上更頻繁的進行調查，利用多示蹤劑法(multi-tracer approach)來解析沉積過程與速率。

4. 面臨的若干問題及解決之道

(1) <u>船時不足</u>

本計畫遭遇的最大困難為船期的取得不易。過去三年我們原申請海研一號及海研二號航次每年各二週，並規劃於每年夏季颱風發生前後皆至少有一個航次，俾觀察颱風發生時的沉積物傳輸及其與臺灣西部河川水文(hydrograph)及臺灣海峽海象的對應關係。但，實際上我們連一半的船時都得不到，大大的降低了出海作業的天時能如願的機率。前年度甚至完全未獲得海研一號船期，未能取得箱式岩心，對本計畫之執行極為不利。筆者曾忝為學門召集人，深悉研究船(尤其是海研一號)船時遠不敷所需，且在國際油價飆漲的情勢下，研究船之運作費用節節升高。因此對分配到的船時珍惜有加，歷次出海作業無不處心積慮，親身經歷，並邀請其他研究相同海域的學界同仁同行，共用如此昂貴的平台，期能提高研究船的使用效益。目前國研院雖然正在主導二千七百噸新研究船的籌建，但一時緩不濟急，最早要俟 2010 年以後，新船才可能服役。未來三年，船時將持續吃緊。祈望學界同仁能拋棄本位主義，互相伸出援手，提供「搭便船」的機會給研究社群，作到「同舟共濟」。這樣的話，對紓解當前船時不足的窘困，應該會有非常大的助益。

(2) <u>採樣設備欠缺</u>

我們之所以對海研一號的需求最般，無非是因為她的規格及配備。海研一號船尾的甲板面積、A 架高度及它往內外伸縮的彈性空間較適合箱式岩心的操作。海研二號船身小，沒有配備重型的箱式岩心，只適合操作輕便的重力岩心及以抓泥器取表面沉積物。我們雖曾嘗試克服困難，向海科中心借調較輕型的箱式岩心到海研二號使用，但並不成功。另外，海研二號的重力岩心於取得樣本後，必需平躺在後甲板上，以便抽取岩心。這樣的操作方式常會擾動上層沉積物，影響分析結果的詮釋。我們曾向林曉武教授商借二米長的重力岩心採樣器在海研一號使用，可以吊於適當高度，在垂直位置，卸下岩心，避免擾動表層沉積物。但借用器材非長久之計，筆者已經自籌經費，訂製一米半的重力

岩心採樣器，希望將來在海研一號或海研二號上皆可使用。

(3) 人員更迭頻仍

本計畫需採取、處理、分析大量的沉積物樣本，敝實驗室七台加瑪能譜儀全年無休，工作繁重。近兩年來，敝實驗室專任研究助理平均任職期間僅約一年，俟工作日漸熟悉，即差不多為準備離職，出國深造或另有高就的時候。吾輩藉執行國科會計畫為年輕人提供跳板，對國家社會而言，雖稱得上是善用資源，但頻仍的遴選、訓練新進人員，就個別實驗室來看，投資報酬率實在欠佳，是一項很大的負擔。如何在現行制度下，提供誘因，留住優秀的研究助理，一直是道複雜、難解的習題。也許一個權宜之計為與學界同仁合作，共同指導勤奮、有潛力的研究生，來暫時紓解研究人力不足或不穩定的困境。

(4) 文獻資料眾說紛紜

如前所述，吾人對東海與南沖繩海槽沉積物的預算，迄未能以收支平衡的立論來解釋。判斷是在本研究所牽涉的時間尺度上，此兩體系沉積物之收支係呈動態不平衡，也可能是文獻資料有所偏差，或吾人對沉積物的供應、來龍去脈與傳輸途徑還不夠了解。根據近年來相關研究所透漏的訊息，這些可能皆呼之欲出，謹略述於下。

關於長江泥砂的年輸出，吾人(包括“它人”)過去常習慣性的採納 Milliman and Meade (1983)的報導，以五億噸為準。然而，Yang et al (2003) 綜合整理長江水下三角洲地形演變，及大通水文測站自 1958 年以來的資料，作了一個回顧與前瞻，指出長江泥砂年輸出量在過去四十多年來有顯著減少的趨勢，從五億噸左右降至二億噸上下。他們預測此趨勢將持續下去，到 2009 年三峽大壩工程竣工後，將降到一億五千萬噸，然後大致持平至本世紀中葉(圖九；如下)。這很可能會對未來長江口以南的海岸線及東海生態環境造成重大的衝擊，是學門中其他計畫探討的議題。必需一提的是：Yang et al (2003) 所回顧的時間與吾人以落塵核種研究沉積物岩心所牽涉的時間尺度吻合 — 根據 ^{137}Cs 所估計之沉積速率亦係自 1950 年代以來的平均值。因此，對本研究而言，長江輸砂量應與時下修，不宜一律以每年五億噸來計算，才能比較正確的評估長江沿岸流對東海及台灣海峽北部沉積物預算的可能貢獻。

同樣的，臺灣河流泥砂的輸出量，也需要重新評估。臺灣面積雖然只有長江流域的百分之二，但侵蝕速率之高，舉世矚目，河川總輸砂量似已超越長江。前面提到：從水利署 1949 年至 1990 年，凡四十二年的水文資料所推算出來的全島年均輸砂量為二億六千萬噸。近來，Dadson et al (2003) 根據水利署從 1979 年至 1999 年的水文資料，推算該二十一年間的全島年均輸砂量為三億八千餘萬噸，較水利署先前的估算多了將近一半。雖然有學者(如 Milliman)對 Dadson 等人的估算存疑，但鑒於台灣近二、三十年來土地開發的加速及水土保持的因應措施相對不足，土地侵蝕及河川輸砂量增加是很可能的，尤其是考量近年來氣候變化劇烈，降雨強度屢創新高，加上地震、颱風的推波助瀾，土石流失甚為嚴重。據 Milliman et al. (2007)之估計，濁水溪在過去四十年(自 1965 起) 輸出泥砂約 15-20 億噸，其中的四分之一到三分之一(約 5 億噸) 是在 1996-2001 短短的六年間輸出，相當於目前的長江向東海連續輸出 2-3 年(每年約兩億噸；Yang et al., 2003) 所累積的量。如考量流域面積(長江流域為濁水溪流域的 570 倍)，濁水溪流域近年來沉積物的產率($\sim 2.6\times 10^4$ ton km^{-2} yr^{-1})為長江流域(~ 110 ton km^{-2} yr^{-1})的兩百倍以上！

由於臺灣地形陡峻，河流短促，絕大部份的沉積物是在颱風或短暫的豪雨、暴雨發生時，被洪水攜帶入海。因此，洪水時的樣本極為重要。然而，於惡劣天氣下採樣，其困難與危險是可想而知的，取樣如有偏差，會影響樣本的代表性及分析結果的可信度。

近來，根據新的分析數據，高樹基博士在建立台灣河川水流量與輸砂量的關係(即 rating curve)上有異於以往的結果(Kao et al., 2005)，是否會顛覆水資會歷年來的報告及 Dadson 等人的研究? 值得拭目以待。

5. 未來尚需進行的工作

過去的三年 (2005 年 8 月起)敝實驗室於從事台灣海峽北半部的調查之際，同時參與 FATES-KP 整合型計畫(儘管筆者並無 FATES-KP 之子計畫)，分析該計畫所有沉積物岩心，提供沉積速率的基本資料。由於前者(即筆者之個別型計畫)所獲得的船時遠不敷需求，致時間多投入後者(FATES)，使後者進度反而居上。衡量台灣海峽目前既有樣本的分佈情形(如圖四)，吾人必需於目前新的計畫期間加強海峽中線以西的調查，希望於未來三年內完成台灣西部海域的調查。

三、 本計畫之研究方法

1. 採樣

沉積物岩心以泥質較易採，分析結果一般也較精彩、有趣。但粉砂質及砂質沉積物樣本也須酌情採集、分析，不宜偏廢。泥質區以取箱式岩心為主，但堆積厚、高沉積速率之處加採重力岩心。如沉積物多砂，不利箱式岩心施作，則以重力岩心、甚或活塞岩心取代之。岩心品質攸關分析結果的解釋至鉅，需極謹慎。敝實驗室過去採岩心的作業流程概如圖十所標示。

2. 儀器設備及核種分析

本研究將以加瑪能譜儀分析各落塵核種活度。敝實驗室具備 ORTEC 最高端、具不同功能的高純鍺(HPGe)偵檢器七台 (請見圖十一，如下)；其中一台為效率高達 150% (相對於 3x3 NaI)的 GEM 型，三台為相對效率 100%至 130%的 GMX 型，兩台為相對效率 120%的 GWL 型，一台為高解析度的 Lo-AX 型偵檢器。所有偵檢器分別聯結到七台串聯起來的 ORTEC DSPec Plus® 數位能譜儀，訊號輸入 PC，以 Gamma Vision-32 軟体分析能譜。各偵檢器均以國際標準參考品(Standard Reference Materials，如 NBS-4353、IAEA-133A, 327, 375 等)進行能量、效率及質量(或體積)校正。敝實驗室亦備有 ^{152}Eu, ^{137}Cs、Congo pitchblende (鈾系核種)及混合人工核種之標準溶液，可用標準添加法 (standard addition)自製各種基質的校正標準。藉這些儀器的搭配、選擇，我們能快速、精確的分析樣本中多種核種。由於此方法是非破壞性的，量測過的樣本可由 FATES 或其他計畫同仁接收，作破壞性的化學分析。

本計畫主要藉五台 HPGe 偵檢器來執行：一台 GEM、一台 Lo-AX 及三台 GMX。偵測重點是沉積物中 ^{7}Be (477.56 keV)、^{137}Cs (661.62 keV)、^{210}Pb (46.52 keV)、^{214}Pb (351.99 keV)、^{234}Th (63.29 keV)，但亦能同時測得其他許多核種，供輔助 provenance study 之用(如十二、(二)、1 (6)節所述)。這些 HPGe 偵檢器的解析度及效率俱佳，敝實驗室有恆溫、恆濕控制，穩壓及不斷電系統維持乾淨、穩定的電源，上述核種的能峰不會受到

干擾。下表列出各偵檢器量測上述核種的解析度(resolution)及絕對效率(absolute efficiency)。表列數據除 GWL 型偵檢器外，係假設沉積物樣本質量為 20 公克 (置於內徑 8.5 公分、高 7.5 公分之塑膠圓盒中)。

nuclide	^{7}Be (477.56 keV)		^{137}Cs (661.62 keV)		^{210}Pb (46.52 keV)	
	FWHM (keV)	% efficiency	FWHM (keV)	% efficiency	FWHM (keV)	% efficiency
GEM	1.35	7.9	1.49	6.4	-	-
GMX	1.37	7.5	1.64	5.8	0.78	17.6
Lo-AX	0.90	4.3	1.10	2.2	0.50	12.9
GWL*	1.52	17.0	1.80	11.4	1.39	65.8

* 3 公克以內樣本置於 2-dram polyvial 中。

圖十二所示為計測效率對核種能量(在幾個不同樣本質量下)的校正曲線(以 GMX 偵檢器之一為例)。

敝實驗室曾參加 2002、2006 及 2007 年國際原子能總署(IAEA)的“Proficiency Test for Determination of γ-emitting Radionuclides” ，近年來亦屢次應邀參加原能會台灣輻射偵測中心所主辦的我國實驗室間核種分析比對計畫，對放射核種定量之分析工作熟稔。敝實驗室加瑪能譜儀計測容量(counting capacity)大，具備大量、快速分析樣本的優勢條件。

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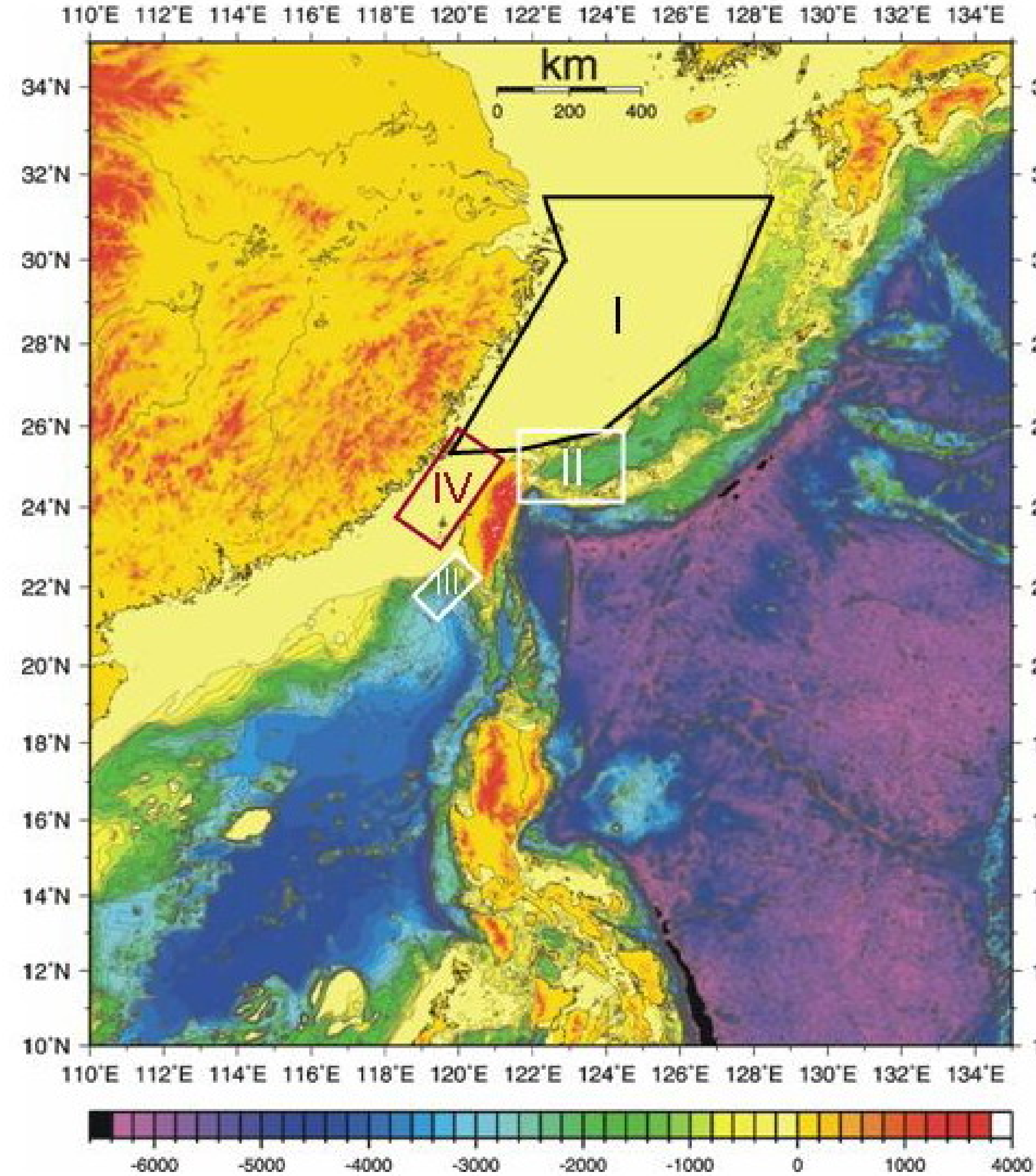
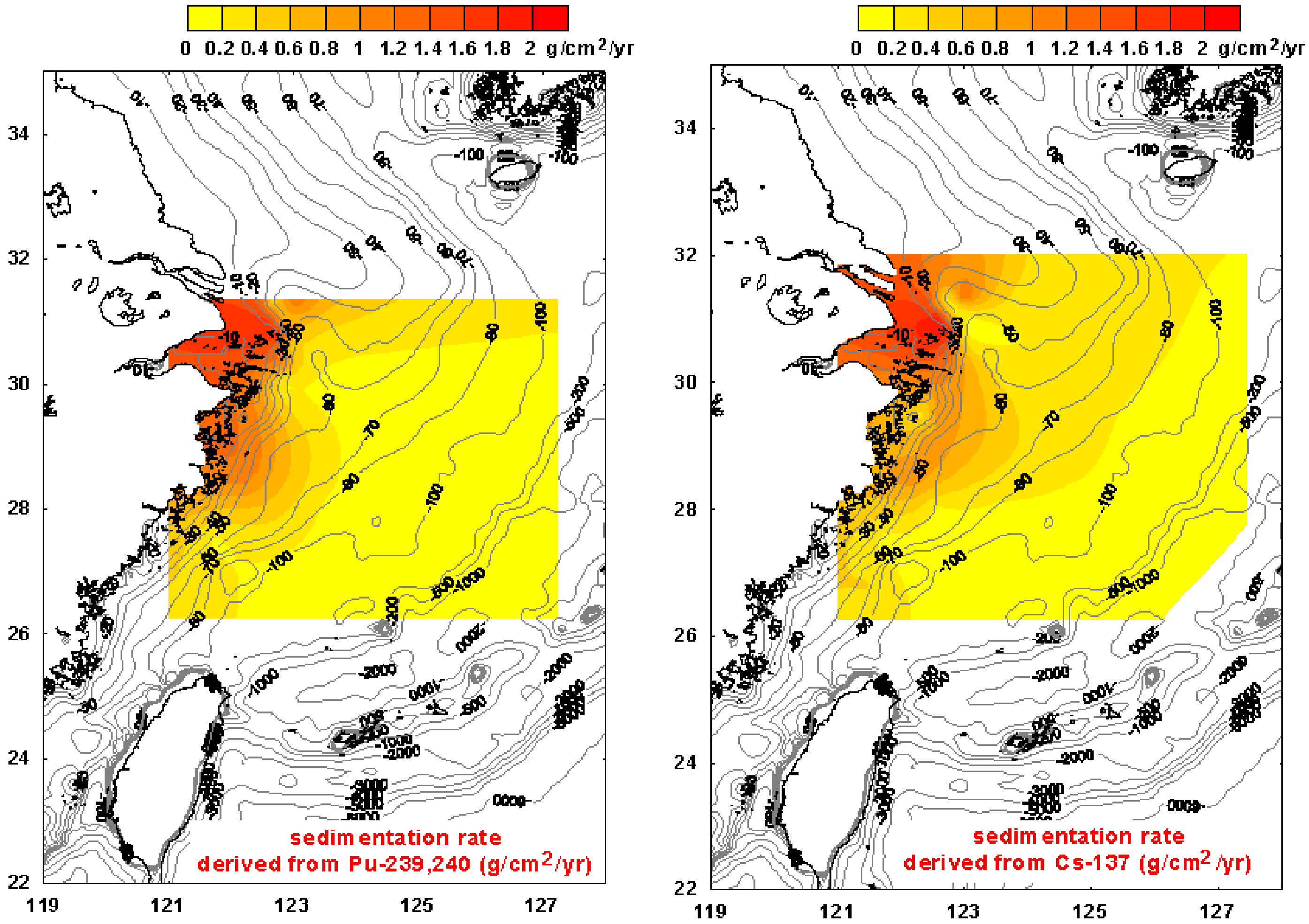
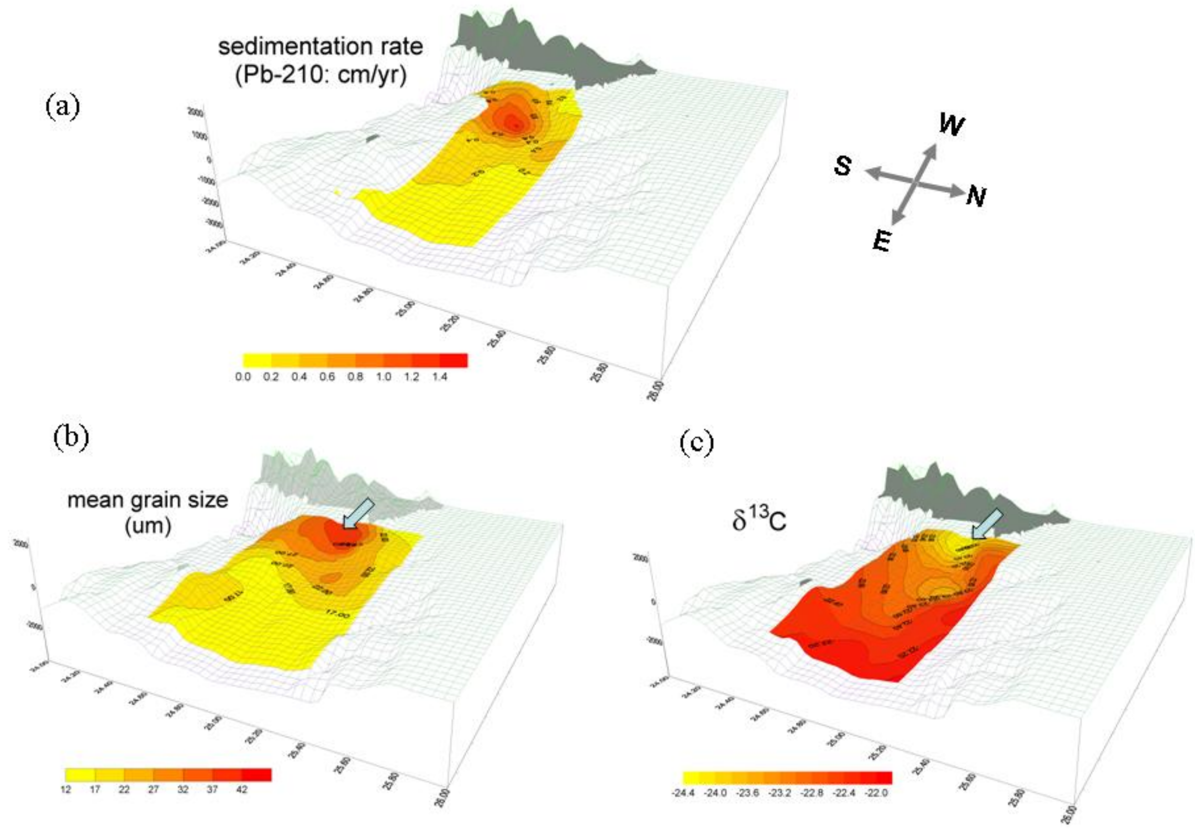
經濟部水利署編印 臺灣歷年水文年報



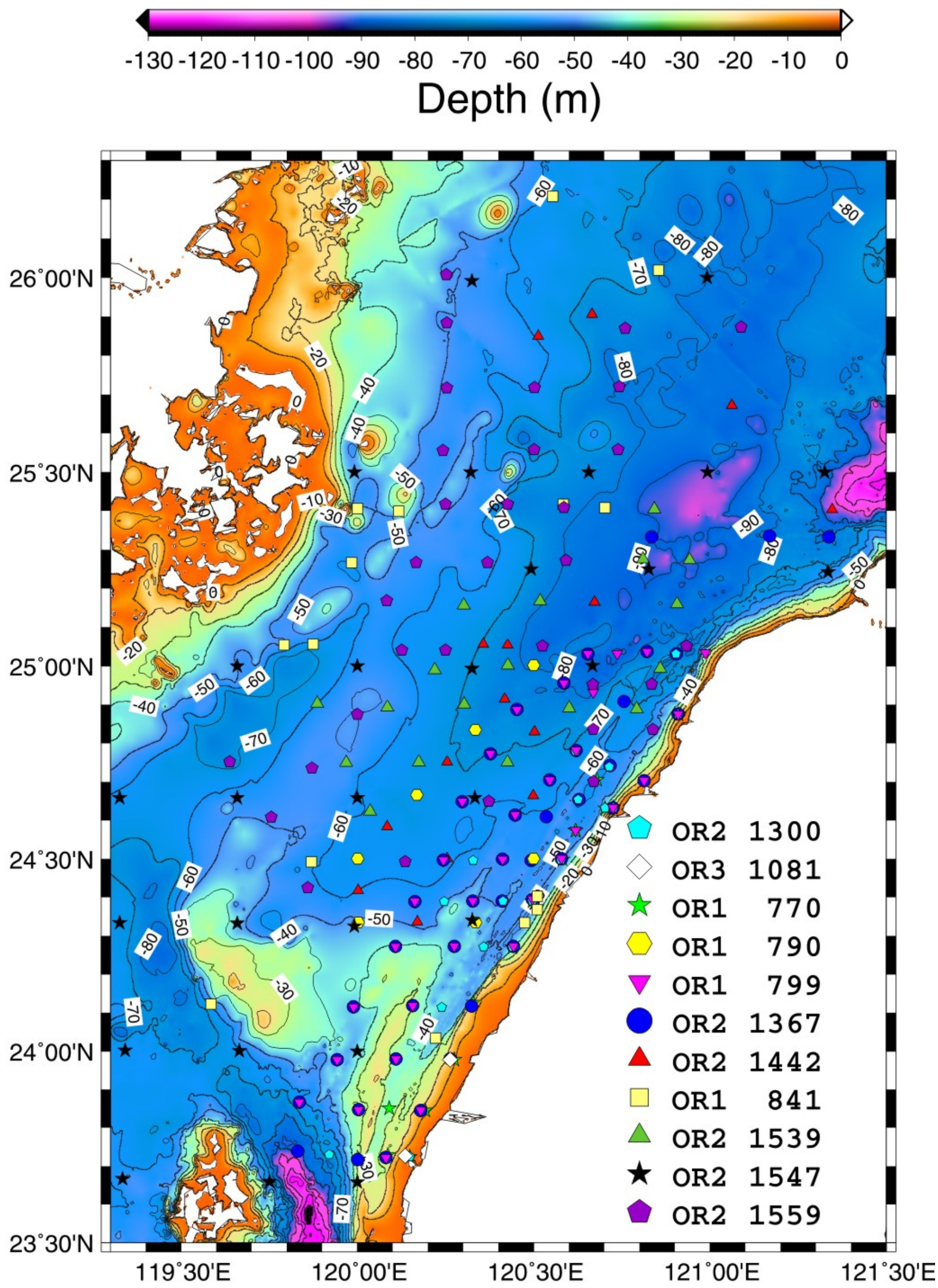
圖一、筆者十一年來依序(由 I 至 IV)調查研究的海域範圍



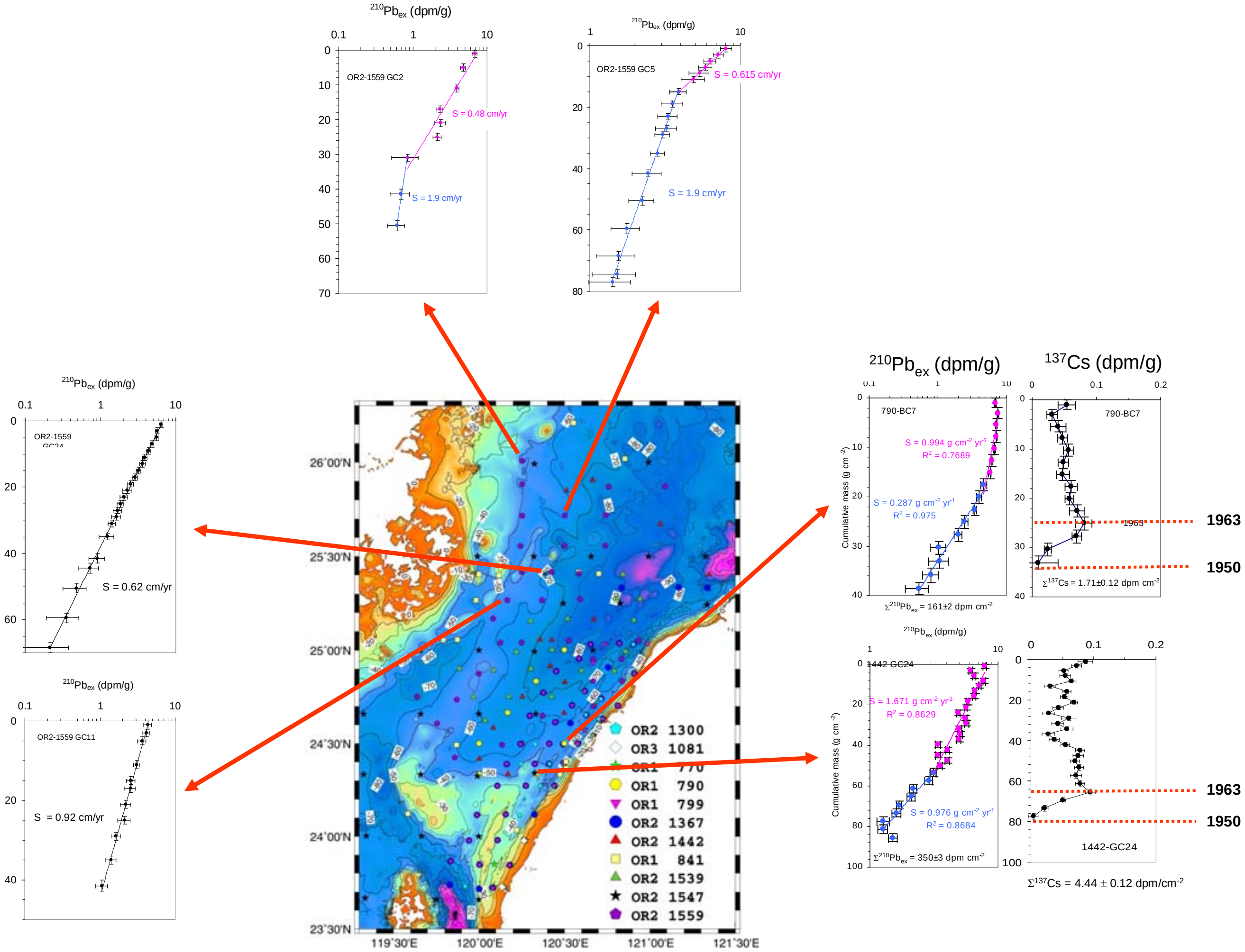
圖二、根據岩心 ^{137}Cs 及 ^{239,240}Pu 垂直剖面所估得東海陸架沉積速率分佈圖



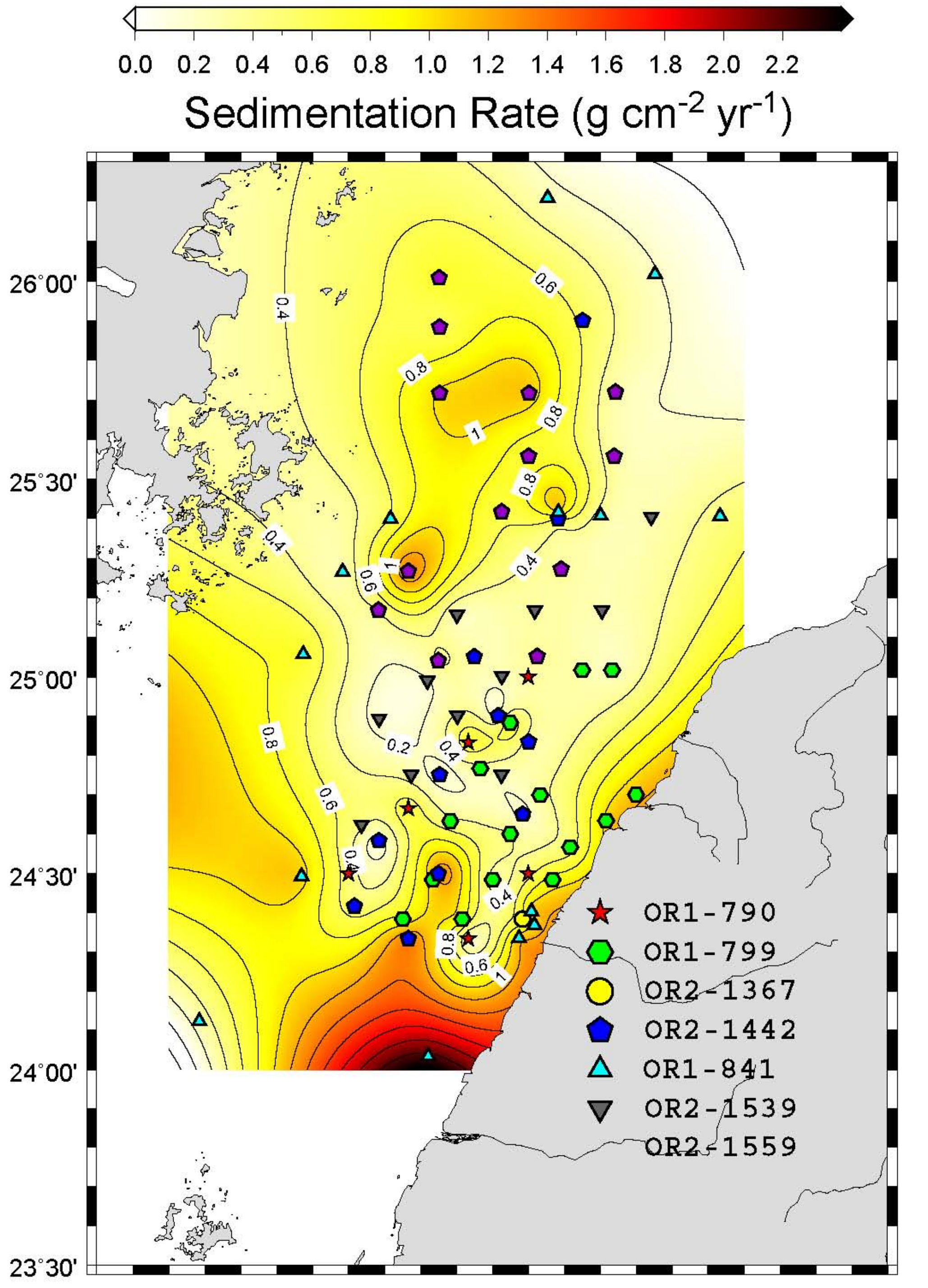
圖三、南沖繩海槽(a)沉積速率分佈，(b)表面沉積物顆粒分佈及 (c) 表面沉積物δ^{13}C 分佈



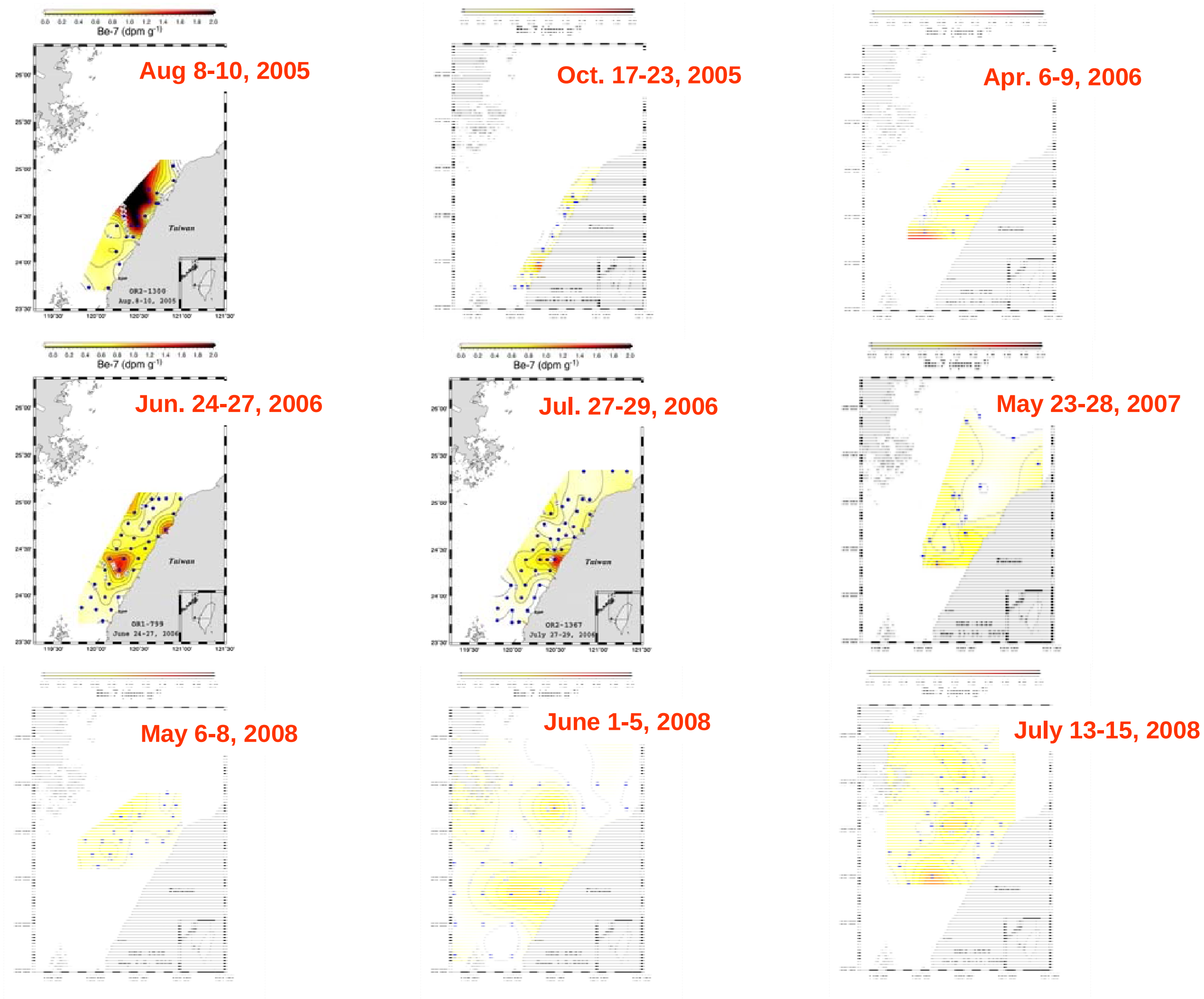
圖四、於台灣海峽 11 個航次所採表面沉積物及沉積物岩心地點分佈



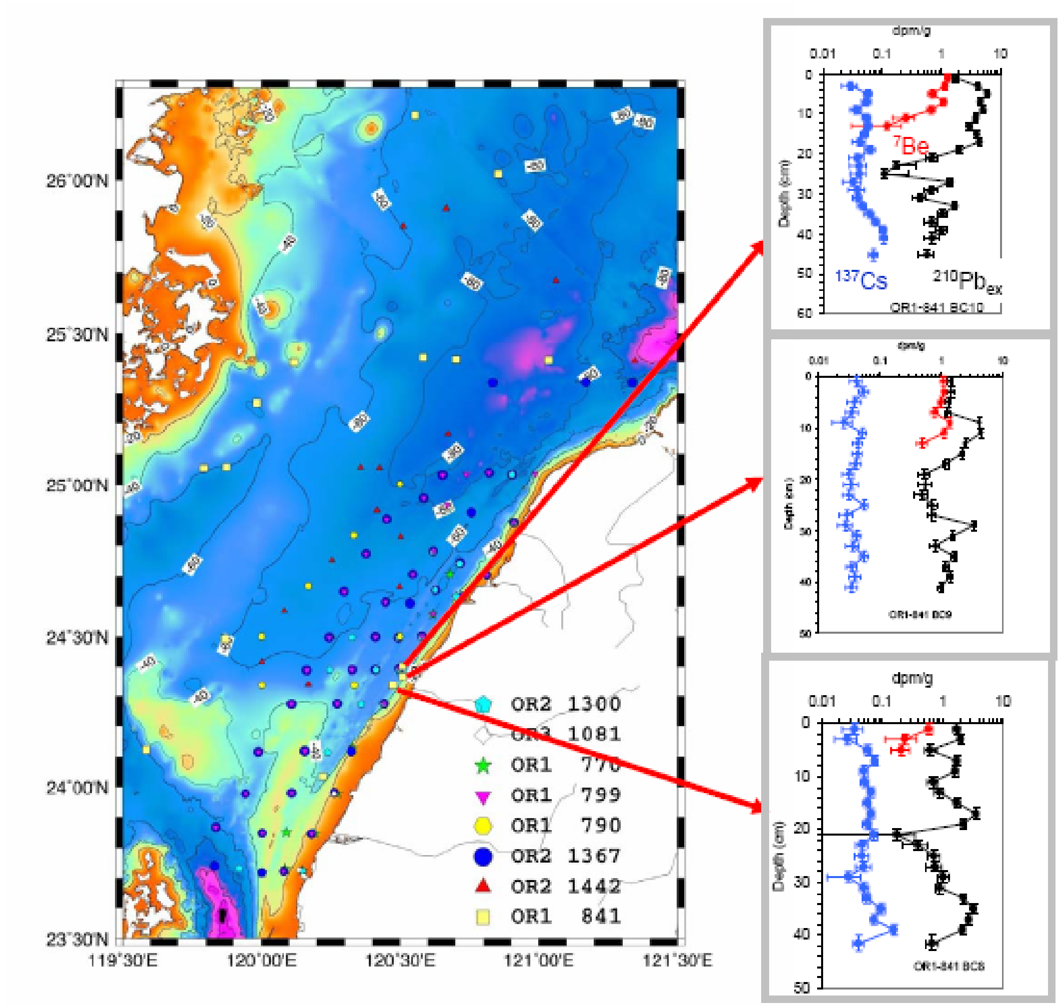
圖五、台灣海峽沉積物岩心 $^{210}Pb_{ex}$ 及 ^{137}Cs 垂直分佈的幾個例子（請參考內文說明）



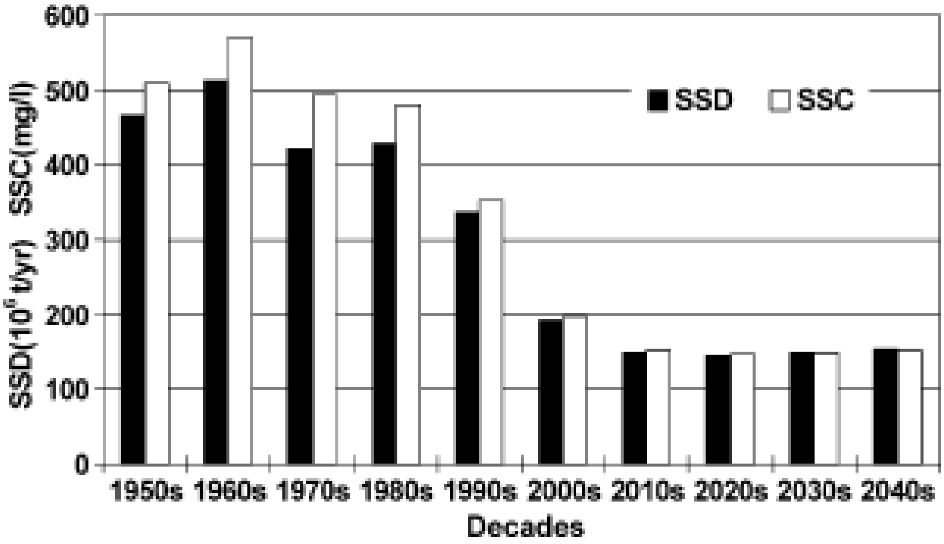
圖六、台灣海峽部份區域現代(<100 年)沉積速率分佈(初步結果)



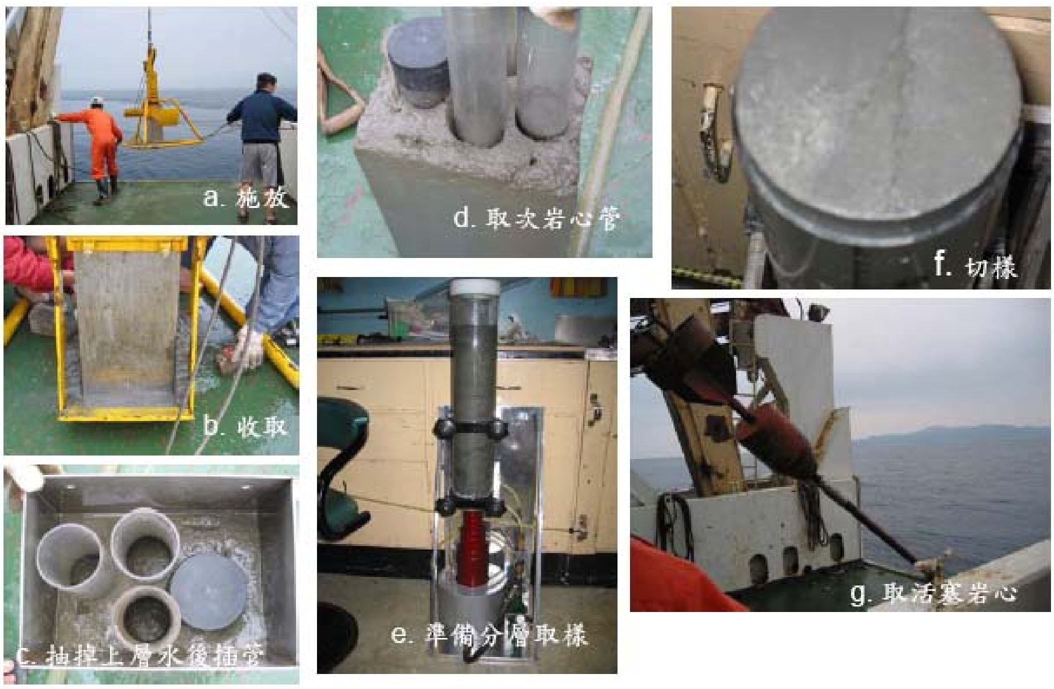
圖七、 台灣西海岸表層(<2 cm)沉積物 ^{7}Be 分佈之時空變化情形



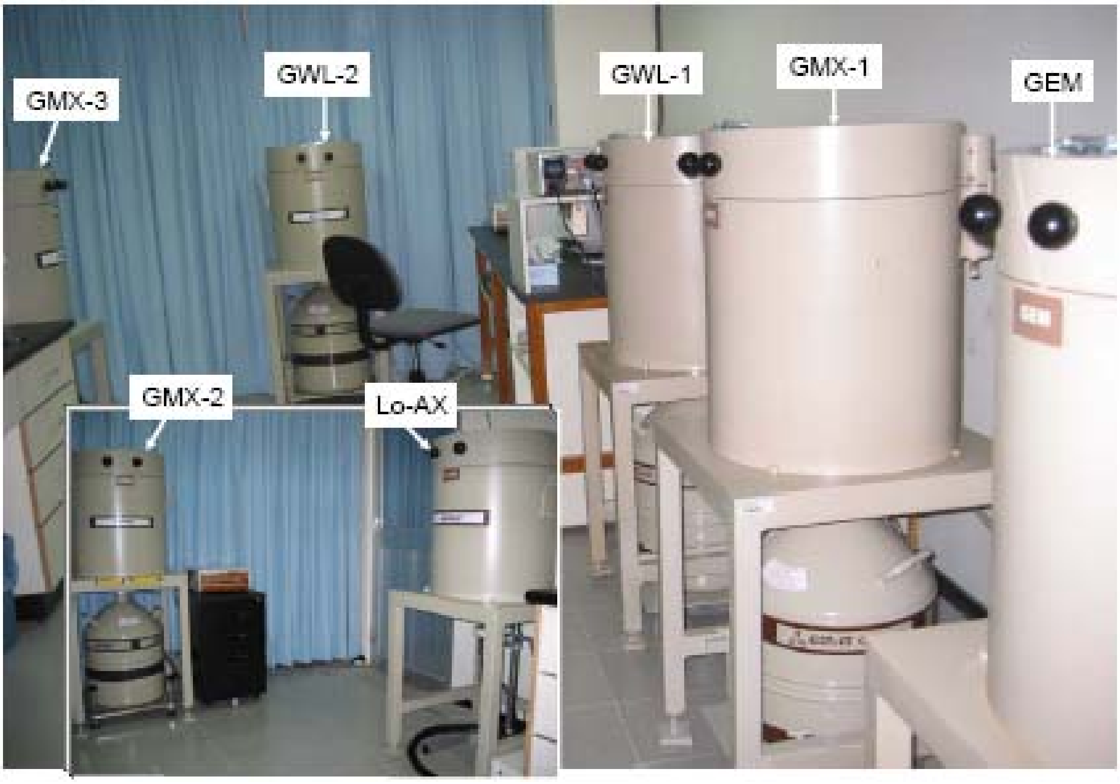
圖八、 2007 年 9 月中旬大甲溪河口三個測站沉積物岩心中 ^{7}Be、^{137}Cs、^{210}Pb$_{ex}$ 垂直剖面(台灣海峽岩心分析仍在進行中)



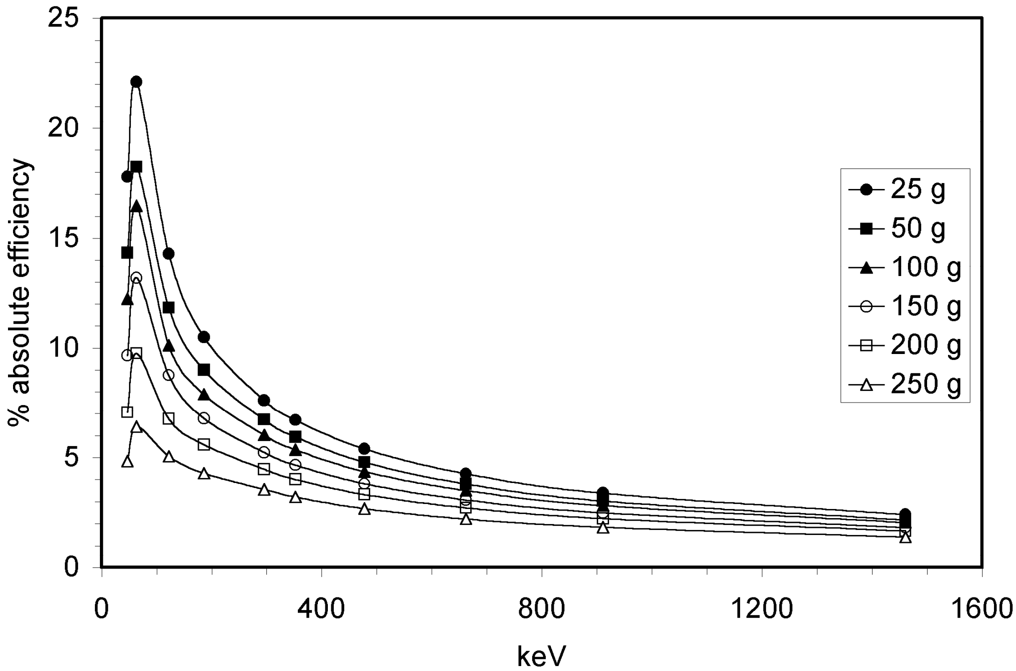
圖九、二十世紀中葉以來長江(大通測站)懸浮沉積物排放量(SSD)及濃度(SSC)變化趨勢



圖十、箱式岩心採取、處理過程(a 至 f)及活塞岩心施放作業(g)



圖十一、中研院地球所放射計數室(兩間)有四種類型純鍺偵檢器之加瑪能譜儀系統共七台：一台 GEM 型，三台 GMX 型，二台 GWL 型，一台 Lo-AX 型。其中僅有一台(GWL-1)係十一年前經國科會支助所購置。



圖十二、敝實驗室 GMX 型偵檢器之計測效率對核種能量及(沉積物)樣本質量的關係

附件一

Huh, C.-A., et al., Modern accumulation rates and a budget of sediment off the Kaoping River, SW Taiwan: a tidal and flood dominated depositional environment around a submarine canyon. *Journal of Marine Systems* (2008), doi: 10.1016/j.jmarsys.2007.07.009.

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Modern accumulation rates and a budget of sediment off the Gaoping (Kaoping) River, SW Taiwan: A tidal and flood dominated depositional environment around a submarine canyon

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ABSTRACT

Ninety-two box cores collected during 2004–2006 from an area of ~3000 km^2 off the Gaoping (formerly spelled Kaoping) River, SW Taiwan, were analyzed for fallout radionuclides (^{210}Pb, ^{137}Cs and ^{7}Be) to elucidate sedimentation rates and processes, and for the calculation of a sediment budget. The study area is located at an active collision margin with a narrow shelf and a submarine canyon extending essentially into the river's mouth. The results indicate fairly constant hemipelagic sedimentation in much of the open margin and for most of the time except in the inner shelf and along the axis of the canyon where sediment transport is more dynamic and is controlled by tidal current and wave activities constantly, and by fluvial floods or gravity-driven flows episodically. Sedimentation rates in the study area derived from ^{210}Pb and constrained by ^{137}Cs vary from 0.04 to 1.5 cm/yr, with the highest rates (>1 cm/yr) flanking the Gaoping canyon over the upper slope (200–600 m) and the lowest rates (<0.1 cm/yr) in the distal basin beyond the continental slope. The depocenter delineated from ^{210}Pb-based sedimentation rates overlaps with the area covered by a flood layer resulting from super-typhoon Haitang in July 2005. Such correspondence supports the notion that the processes operating on event timescale have bearing on the formation of the sediment strata over centennial or longer timescales.

From the distribution of sedimentation rates, sediment deposited in the study area annually is estimated to be 6.6 Mton/yr, accounting for less than 20% of Gaoping River's sediment load. The calculated budget, coupled with the presence of the short-lived ^{7}Be and non-steady-state distribution of low levels of ^{210}Pb in sediments along the canyon floor, suggests rapid transport of sediment from Gaoping River's mountainous watershed (the source) via the Gaoping (Kaoping) Submarine Canyon and adjacent channels (as the conduit and temporary sink) to the abyssal plain and the Manila Trench in the South China Sea (the ultimate sink).

1. Introduction

The Gaoping (formerly spelled Kaoping) River (KPR) is the second longest river in Taiwan whose main stem meanders 171 km through a highly rugged terrain in the Central Mountain Range, from the Jade Mountain (Yushan) at an elevation over 3000 m toward the southwest, creating the largest drainage basin (3257 km^2) in Taiwan (Fig. 1). Climate in the KPR drainage basin is tropical to sub-tropical and influenced by typhoons and the annual monsoon cycle. Mean annual rainfall in the KPR drainage basin is 3046 mm, which sustains an annual river discharge of 8.5×10^9 m^3. More than 70% of the basin's annual rainfall and river discharge occurs during May–September, and is closely linked with the occurrence of typhoons. Highly

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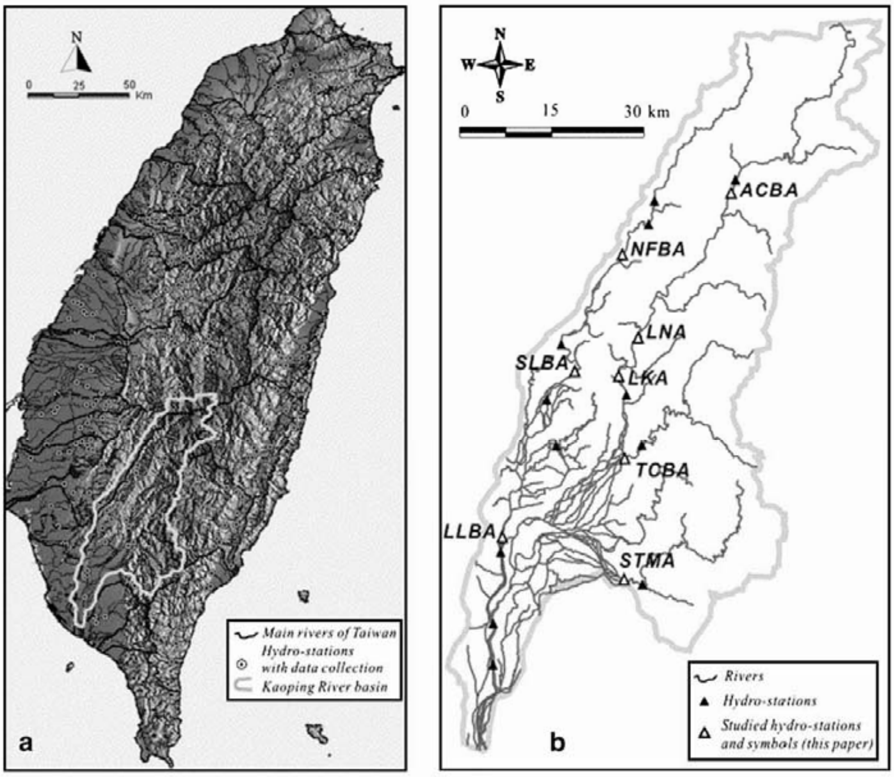

Fig. 1. (a) Gaoping River's drainage basin in southwestern Taiwan. (b) Tributaries and hydrological gauging stations in the basin (after Li et al., 2005, with permission from Elsevier).

erodible sedimentary and metamorphic rocks in the drainage basin, coupled with a steep landscape, humid climate, frequent typhoons and earthquakes, provide favorable conditions for bedrock weathering and soil erosion in the KPR drainage basin. Consequently, during periods of high flow, the river water is rather turbid.

Sediment load of the KPR is reported to range from 36 Mton/yr (Water Resources Bureau, 1998; Milliman and Kao, 2005) to 49 Mton/yr (Dadson et al., 2003), which is among the top three of Taiwan's rivers and gives rise to a sediment yield of 1.5×10^4 ton km^{-2} yr^{-1} in the KPR basin. Although this sediment yield ranks only fourth among Taiwan's major watersheds, it is still about an order of magnitude higher than similar high-yield rivers such as the Eel River in Northern California (1.7×10^3 ton km^{-2} yr^{-1}; highest in the conterminous United States; Brown and Ritter, 1971) and the Sepik River in New Guinea (1.1–1.3×10^3 ton km^{-2} yr^{-1}, Chappell, 1993; Syvitski and Morehead, 1999; Walsh and Nittrouer, 2003).

Like the Eel and Sepik rivers, the KPR is a mountainous river located at an active margin with a submarine canyon near its mouth traversing a narrow shelf. It has been increasingly recognized that such rivers play an important role in transporting terrigenous materials from land to sea and are likely representative of conditions during the Pleistocene. Lowered sea level at that time exposed many of the world's shelves, and rivers delivered their sediment load directly to the continental slope and beyond (Milliman, 1995; Woolfe et al., 1998). Although the KPR is much smaller (in length and drainage basin area) compared with the Eel and Sepik rivers, its exceptionally high sediment yield and tidal-dominated dispersal system presents a unique case for comparative study.

During the FATES-KP program, the shelf and slope areas around the Gaoping Submarine Canyon (KPSC) off the KPR were extensively surveyed and sampled. As a component of FATES-KP, we have analyzed almost all sediment cores collected for the program since 2004 for ^{210}Pb, ^{137}Cs and ^{7}Be. Using these fallout radionuclides as time and process tracers, our objective is to elucidate rates, budget and dispersal pathways of sediment in the study area.

2. Materials and methods

2.1. The study area

To facilitate this study, we delimited a rectangle-shaped domain of ~3000 km^2 centered offshore of the KPR mouth that

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encompasses the upper KPSC (<2000 m depth) and its adjacent shelf and slope (Fig. 2). The KPR is inferred to be the dominant source of terrigenous sediment delivered to the area, given the river's high discharge (the second largest in Taiwan), the proximity (~1 km) of its river mouth to the head of KPSC (Liu et al., 2002), and local seafloor morphology. Smaller discharges from other rivers draining southwestern Taiwan and littoral drift are probably intercepted by and trapped in the neighboring canyons and channels (Lewis and Barnes, 1999), hence insignificant in the study area. Thus, the study area represents a fairly well defined system around the KPSC for assessing source-to-sink sediment dispersal and the calculation of sediment budgets. For more details about the seafloor morphology and its implications on geotectonics and sediment dispersal, please refer to Yu et al. (2008-this issue).

2.2. Sampling

A total of 92 box cores were collected onboard R/V *Ocean Researcher-I* (OR1) and R/V *Ocean Researcher-III* (OR3) from eight cruises during 2004–2006, including OR3-1075 (September 30, 2004), OR1-732 (September 30–October 4, 2004), OR1-761 (August 2–3, 2005), OR1-779 (December 18–21, 2005), OR1-789 (March 29–April 2, 2006), OR1-791 (April 11–15, 2006), OR1-803 (August 5–9, 2006) and OR1-811 (October 11–15, 2006). Fig. 3 shows the location of sampling sites. Some reference stations were occupied on two or more cruises to follow the evolution of a flood layer as it was gradually buried during the two-year study period.

After the overlying water was siphoned from the box corer, core barrels were used to collect subcores for lab analyses. Sediments in the subcores were immediately extruded and sectioned at 2-cm intervals from the top. The sectioned sediment slices were sealed in plastic bags and kept frozen until being freeze-dried in the laboratory. Based on weight loss after freeze-drying, water content (hence, porosity) of the wet sediments was determined. Dried samples were then transferred to plastic jars (i.d., 8.5 cm; height, 7.5 cm) for non-destructive gamma spectrometric assay of radionuclides of interest followed by destructive chemical analyses for other studies performed by the FATES-KP team. The data reported in this paper are calculated on a salt-free dry-weight basis.

2.3. Gamma spectrometry

Four radionuclides (^{210}Pb, ^{137}Cs, ^{7}Be and ^{214}Pb) were analyzed, all by the non-destructive gamma spectrometry. ^{210}Pb and ^{137}Cs are used as sediment chronometers while ^{7}Be is used to trace flood sedimentation. ^{214}Pb, a precursor of ^{210}Pb, is used as an index of supported ^{210}Pb. It is necessary to subtract supported ^{210}Pb from the measured ^{210}Pb in order to obtain unsupported ^{210}Pb (also called excess ^{210}Pb).

Five HPGe detectors were used in this study: one 150% efficiency (relative to 3×3 NaI) detector (EG&G ORTEC GEM-150230), three 100% efficiency detectors (EG&G ORTEC GMX-100230) and one Lo-AX detector (EG&G ORTEC Lo-AX-100230), each interfaced to a digital gamma-ray spectrometer (DSPec Plus®). All detectors were calibrated using IAEA standards 133A,

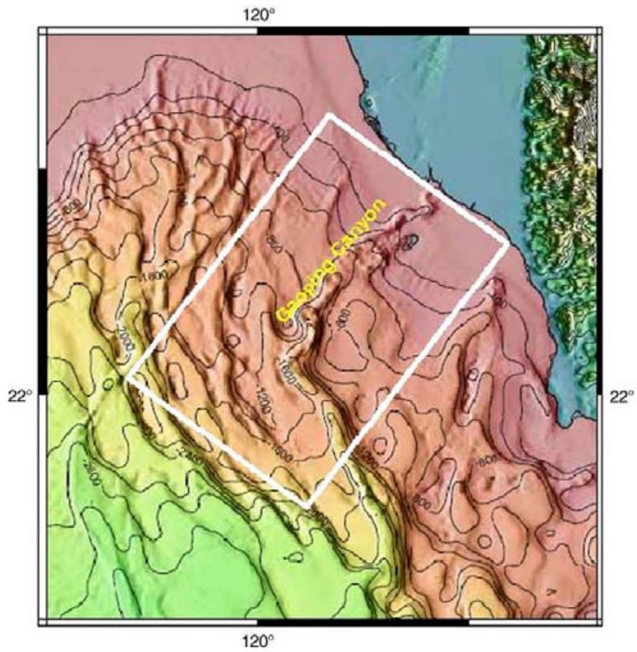

Fig. 2. Map showing the bathymetry off the Gaoping River's mouth around the Gaoping Canyon. The rectangle marks the area covered in this study.

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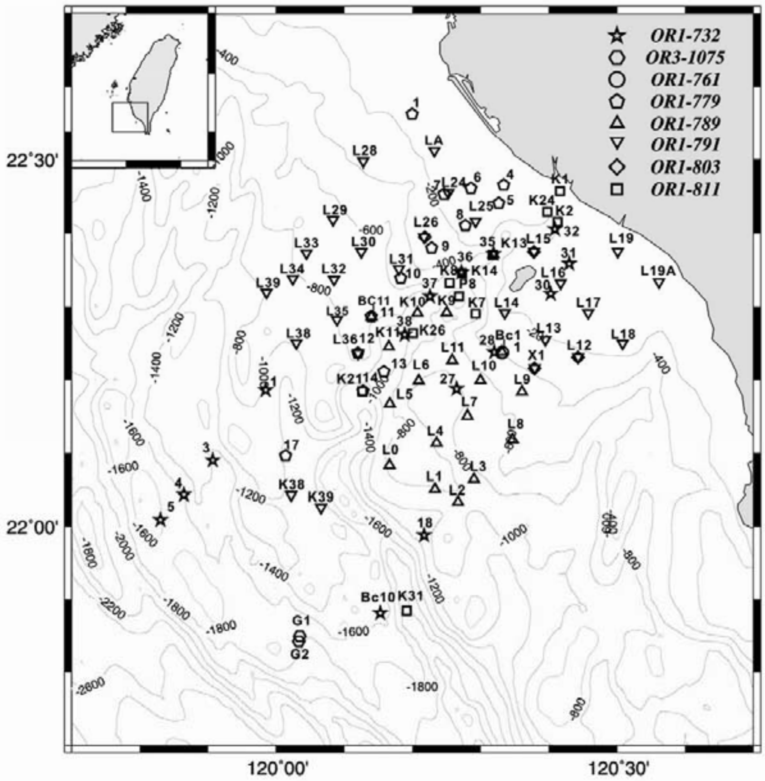

Fig. 3. Map showing sampling sites. Coring sites in different cruises are denoted by different symbols. The numbers marked by the coring sites represent box core numbers. The data for all studied cores are archived at: http://dmc.earth.sinica.edu.tw/Contributor/Huh/Huh_et_al2007a/.

327 and 375 for sample weight at 100 g as a reference, coupled with an in-house working standard for various masses from 10 g to 250 g.

Among the three types of HPGe detectors, the GEM detector has higher efficiencies for counting high-energy gammas, including those of ^{214}Pb (351.99 keV), ^{7}Be (477.56 keV) and ^{137}Cs (661.62 keV), whereas the Lo-AX detector has the best resolution and efficiency for counting low-energy gammas such as that of ^{210}Pb (46.52 keV). As for the GMX detectors, they are capable of counting both high and low-energy gammas, although they are less effective than the Lo-AX detector for counting ^{210}Pb and less efficient than the GEM detector for counting ^{214}Pb, ^{7}Be and ^{137}Cs. When the measurements of ^{7}Be and ^{137}Cs are critical, the GEM is the detector of choice. In that case, it is necessary to engage a combined use of the GEM and Lo-AX detectors to yield the best dataset.

3. Results and discussion

The full dataset generated from the 92 cores are too massive to be fully presented in this paper, and thus the following figures prepared from the dataset are used to illustrate salient features and highlight the major points. The dataset is archived in its entirety at the website: http://dmc.earth.sinica.edu.tw/Contributor/Huh/Huh_et_al2007a/.

3.1. Sedimentation rates

Owing to its constant production, ubiquitous distribution and ease of measurement, ^{210}Pb is the most commonly used chronometer for the determination of modern sedimentation rates in continental margin environments. In most of cores from the study area, except those from the inner shelf and canyon floor, profiles of excess ^{210}Pb ($^{210}Pb_{ex} = {}^{210}Pb - {}^{214}Pb$) show exponential or quasi-exponential decreases with depth. Such profiles are customarily interpreted by a steady-state advection-decay model assuming that fluxes of sediment and ^{210}Pb at a given site are constant, with the influx of $^{210}Pb_{ex}$ by precipitation at the sediment–water interface balanced by radioactive decay following burial. The distribution of excess ^{210}Pb downcore is thus invariable with time and can be described by: $^{210}Pb_{ex})_z = {}^{210}Pb_{ex})_0 \exp(-\lambda/S)$, where $^{210}Pb_{ex})_0$ and $^{210}Pb_{ex})_z$ are excess ^{210}Pb at the sediment–water interface and depth Z, respectively, λ is the decay constant of ^{210}Pb and S is the sedimentation rate. From the slope of the regression line ($-\lambda/S$) fitting the depth trend of $^{210}Pb_{ex}$ on a semi-log plot

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(i.e., ln $^{210}Pb_{ex}$ *versus* apparent depth in cm or cumulative mass in g cm^{-2}), S (linear sedimentation rate in cm yr^{-1} or mass accumulation rate in g cm^{-2} yr^{-1}) can be derived. Some representative profiles of $^{210}Pb_{ex}$ and sedimentation rates thus estimated are shown in Fig. 4.

Although ^{137}Cs can be measured along with ^{210}Pb by gamma spectrometry, it is time-consuming to obtain ^{137}Cs data owing to its much lower activities. Thus, this anthropogenic nuclide is analyzed only for selected cores to help constrain ^{210}Pb chronology. ^{137}Cs commonly displays a subsurface activity maximum, from which activity usually decreases gradually upward but sharply downward, reflecting the history of production, cycling and removal of this anthropogenic nuclide in the Earth's surface environments. In this study, ^{210}Pb-based sedimentation rates agree reasonably well with those estimated from the depth of the subsurface ^{137}Cs peak (marking 1963A.D.) or the penetration depth of ^{137}Cs (circa ~1950A.D.). This suggests that, in this study, sediment profiles of particle-reactive nuclides such as ^{210}Pb and ^{137}Cs are controlled primarily by syndepositional sedimentation and that the impact of post-depositional processes on calculated sedimentation rates is less important.

Integrating radionuclide results over the study area reveals the spatial distribution of sedimentation rates (Fig. 5). The most striking feature revealed is a pair of depositional lobes with sedimentation rates >1 cm/yr that flank the KPSC along the upper slope (200–600 m). This depocenter may be caused by sedimentation from turbidity flows overflowing the canyon. It is noteworthy that the depositional lobe is centered along the canyon axis at a locale where the channel turns and widens abruptly, with some topographic highs protruding the channel floor. We suspect that such a topographic setting may dissipate the energy of fluvial plumes or turbidity flows, thus facilitating over-bank levee sedimentation.

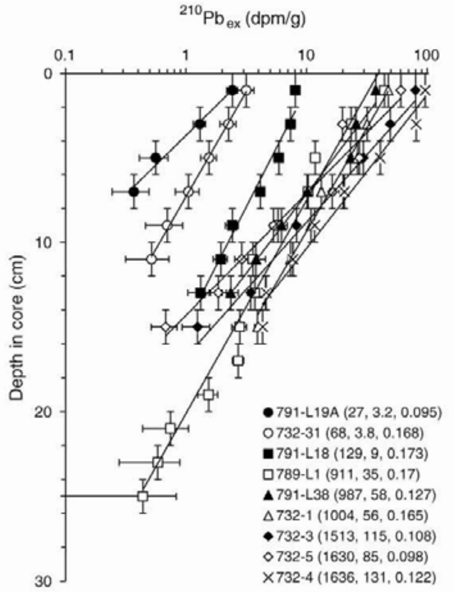

Fig. 4. Profiles of $^{210}Pb_{ex}$ in the open margin away from the Gaoping canyon and the flood-affected area depicted in Fig. 7 commonly show good fit (with R^2>0.95) to a steady-state sedimentation-decay model, with core-top $^{210}Pb_{ex}$ activity (C_o) generally increasing with water depth (Z) (please also refer to Fig. 6). Following the cruise/core numbers in the legend are Z (m) and best-fit values of C_o (dpm/g) and S (cm/yr) corresponding to each profile.

From the aforementioned depocenter, sedimentation rates generally decrease toward the base of the slope and basin floor where pelagic or hemipelagic sedimentation of fine-grained (silty and clayey) sediment results in the area's lowest sedimentation rates (<0.1 cm/yr). Low sedimentation rates (or no net accumulation of sediments) were also observed on the inner shelf covered primarily by reworked sands. Although the muddy component of fluvial sediment can accumulate ephemerally nearshore during or shortly following floods, over longer timescales it cannot withstand strong shear generated by tidal currents and wave activity and is preferentially transported down the canyon and offshore (Liu et al., 2002; Crockett and Nittrouer, 2004).

3.2. A differentiation of sedimentation regimes by core-top $^{210}Pb_{ex}$ versus water depth

In theory, specific activities of excess ^{210}Pb in sediment particles are controlled primarily by particle size, residence time of particles in the water column, atmospheric flux and water-column production rate of ^{210}Pb. In general, sizes of sediment particles decrease, while their residence times in seawater increase, with distance offshore and resulting greater water depths. Thus, it is reasonable to expect higher excess ^{210}Pb activities in fine sediments freshly deposited in deep waters under steady-state conditions. Any deviations from this general rule may be largely ascribed to non-steady-state conditions.

By plotting $^{210}Pb_{ex}$ activity at core top *versus* water depth (Fig. 6) and from the spatial distribution of core-top $^{210}Pb_{ex}$ (Fig. 7), we can differentiate two sedimentation regimes. In Fig. 6, data points from the open shelf and slope area outside the canyon (open circles) follow a linear increase with depth, reflecting continuous scavenging of ^{210}Pb from seawater as particles work their way down the water column slowly. In contrast most samples from the canyon floor or its vicinity with steep topography (closed circles) show anomalously low $^{210}Pb_{ex}$ activities (Fig. 7), which may be explained by post-depositional disturbances such as slumping, scouring, or rapid down-canyon transport and deposition of fresh fluvial or old reworked shelf sediments low in excess ^{210}Pb. The data imply that, on ^{210}Pb timescale (~100 years), the KPSC is not a steady setting for ^{210}Pb scavenging and sediment accumulation; rather, it is mainly at a transient state, with intermittent sediment transportation.

3.3. A flood layer deposited during typhoon Haitang in July 2005 — its spatial distribution and implications

During July 11–12, 2005, typhoon Haitang developed in the western Pacific, about 3500 km to the east of Taiwan. As Haitang proceeded toward the west, it intensified, reaching the highest category on July 16 and making landfall at eastern Taiwan on July 18. In the ensuing days, the typhoon caused unprecedented

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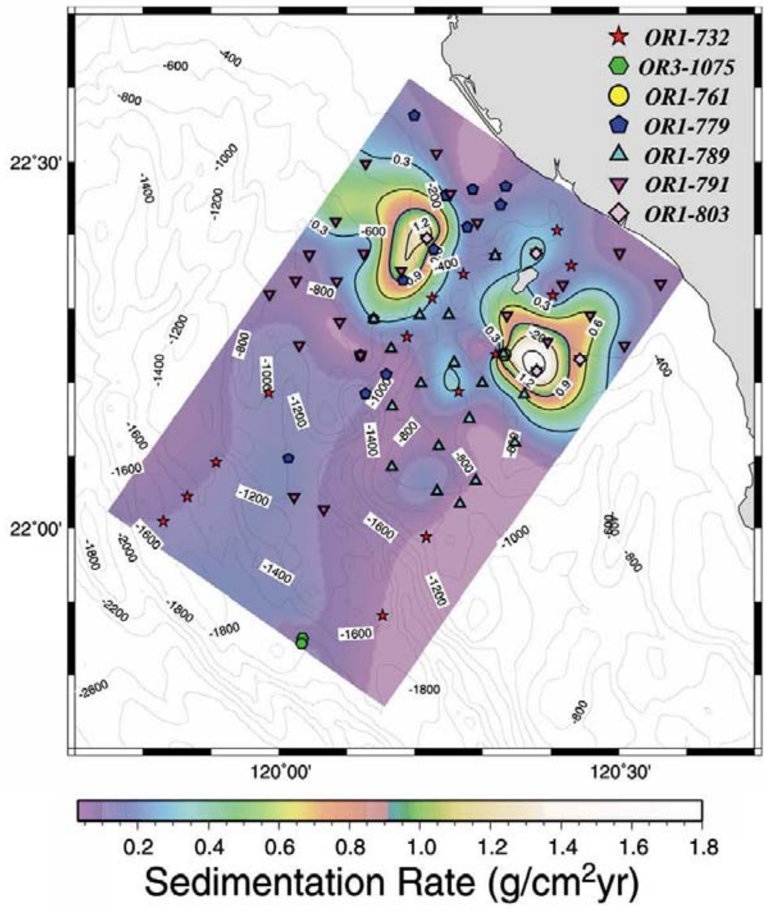

Fig. 5. Contour map showing spatial distribution of ^{210}Pb-based sedimentation rates.

rainfall in KPR's drainage basin. Near the river's headwater at Alishan, for example, daily rainfall reached 663 mm on July 19, 2005, with a 3-day cumulative rainfall of 1226 mm during July 18–20, 2005. Rainfall so intense would conceivably bring about high river discharge and high sediment load. On August 2, 2005, two weeks following Haitang, a box core was collected on the OR1-761 cruise (OR1-761 BC1) from a depth of 389 m on the upper slope. A freshly deposited flood layer about 4 cm thick was identified at the core top. This layer is characterized by anomalously low ^{210}Pb and appreciable ^{7}Be (~1 dpm/g). Below this layer, $^{210}Pb_{ex}$ decreases exponentially with depth from a rather high activity while the deposition record of ^{137}Cs reflects the history of nuclear fallout very well, with a subsurface maximum located at 34–36 cm (see Fig. 9a). Both $^{210}Pb_{ex}$ and ^{137}Cs profiles point to an average sedimentation rate of 0.77 cm yr^{-1} at least in the past four decades prior to the deposition of the flood layer induced by typhoon Haitang.

The flood deposit, first discovered on the OR1-761 cruise, was observed in all subsequent cruises and its distribution mapped (Fig. 8). It is important to note that the area covered by this event layer corresponds closely to the depositional lobe delineated from ^{210}Pb. In fact, similar correspondence was documented previously for a flood dominated continental shelf off Eel River's mouth in Northern California, suggesting that the processes creating event layers may be relevant to the formation of the sediment strata over time scales of 100 years or longer (Sommerfield and Nittrouer, 1999; Bentley and Nittrouer, 2003).

Besides the data for OR1-761 BC1, Fig. 9 shows two more sets of $^{210}Pb_{ex}$ and ^{137}Cs profiles in the flood-affected area. From the depletion of ^{210}Pb near core top, the thickness of the flood layer is estimated to vary between 2 and 12 cm. Where the flood layer is thicker (e.g., in OR1-789 BC11; see Fig. 9b), it appears that this event contained two separate episodes which can be correlated

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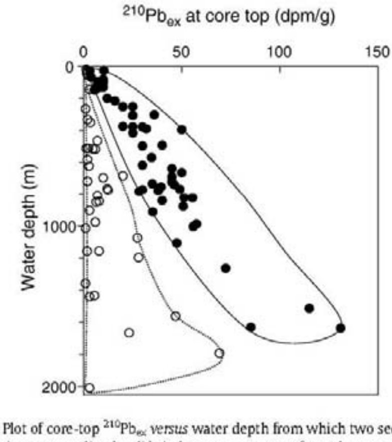

Fig. 6. Plot of core-top $^{210}Pb_{ex}$ *versus* water depth from which two sedimentation regimes are outlined, solid circles represent cores from the open shelf and slope showing fairly steady sedimentation whereas open circles represent cores from the canyon floor or walls showing non-steady-state $^{210}Pb_{ex}$ profiles. See text for explanation.

among some adjacent cores. By comparing downcore distribution of ^{210}Pb observed at different times, it can be noted that the flood material, represented by a ^{210}Pb minimum near core top (Fig. 9a), was gradually buried by and mixed with hemipelagic sediment deposited following the flood (Fig. 9c). In summary, this flood deposit is manifested in the $^{210}Pb_{ex}$ profiles as a dramatic event of perhaps 100-year recurrence. Given the deposit's thickness and high sedimentation rates in the depocenter, the flood layer is unlikely to be completely eroded by post-depositional processes. In fact, in addition to the most recent flood deposit found at core top, there appears to be some indication of buried flood layers or mixed layers in some cores (e.g., 779-9, 791-L31, 791-L24, 791-L17, 791-L13) around the depocenter.

3.4. Recent down-canyon transport of fluvial sediments elucidated from ^7Be and ^{210}Pb

To understand sediment transport pathways along the KPSC, the last two cruises for this study (OR1-803 and 811) focused on surveying the thalweg of the canyon. In the hope of finding a flood deposit and following its evolution, the

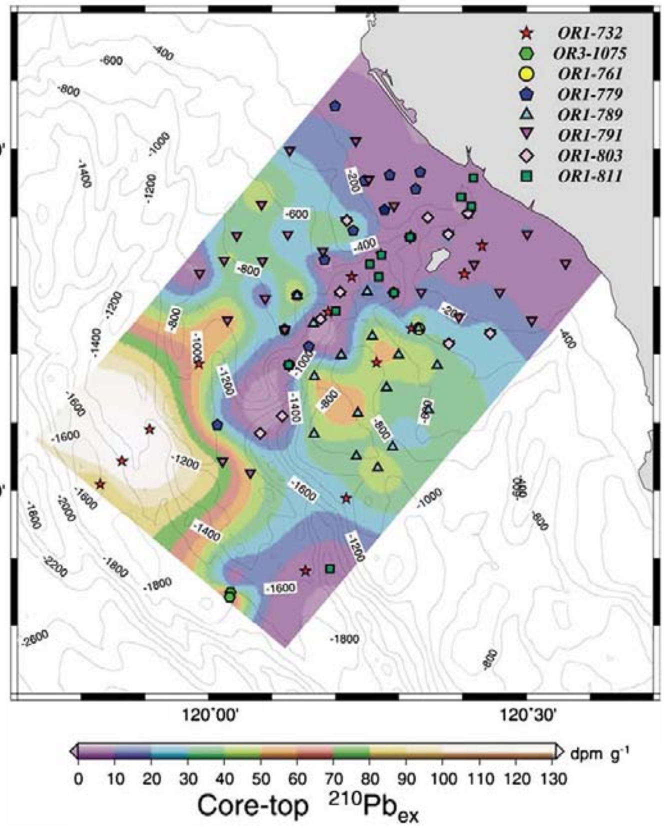

Fig. 7. Spatial distribution of core-top $^{210}Pb_{ex}$ shows low values along the axis of Gaoping canyon.

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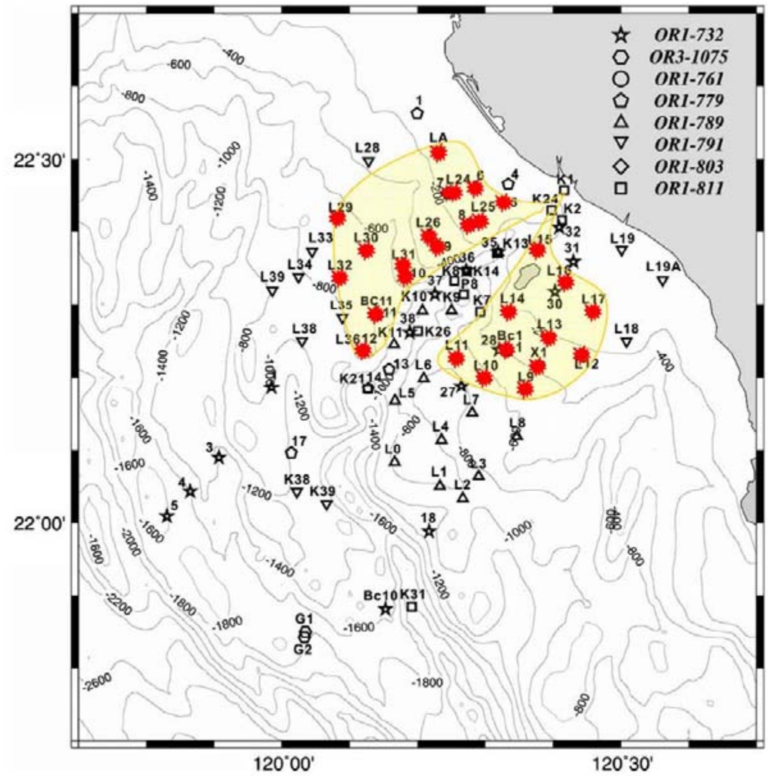

Fig. 8. Distribution of the flood layer deposited following typhoon Haitang (July 18–20, 2005). The red explosion sign indicates sighting of this event deposit in cores collected since August 2005.

cruises were conducted during the typhoon season of 2006 following typhoons Bilis (July 11–17, 2006) and Kaemi (July 24–27, 2006) which had affected the study area. Special attention was made to measure the short-lived ^{7}Be, a useful tracer for flood sedimentation in coastal zones (Sommerfield et al., 1999; Mullenbach et al., 2004; Moralles et al., 2006). ^{7}Be was found widely in surficial sediments from the upper reaches of the canyon, with generally higher activities in samples from the OR1-811 cruise (October 11–15, 2006) compared with those from OR1-803 (August 5–9, 2006). Since there were no floods between these two cruises, the temporal variation could be attributed to sufficiently long water-column residence times (of one to several months) for suspended fluvial particles. Indeed, during the OR1-803 cruise SPM concentrations along the canyon were substantially higher than those measured during the OR1-811 cruise, suggesting that much of the suspended fluvial sediments discharged in July were deposited after August 2006.

In addition to temporal variability, spatial patterns in ^{7}Be activity also reveal higher levels near the river mouth, with the highest ^{7}Be activity of ~1 dpm/g observed near the canyon head (site K1) during the OR1-811 cruise. In addition to the high activity measured at the sediment surface, ^{7}Be was measured to a depth of 12 cm in core OR1-811 K1, with a large inventory of 7.8 ± 0.4 dpm cm^{-2} (Fig. 10 inset). At sites further offshore of the river mouth, ^{7}Be was detectable only in the top layer (0–2 cm). As discussed earlier, it is highly likely that the ^{7}Be-enriched sediment layer was formed by gradual removal (in 2–3 months) of fluvial SPM introduced by typhoons Bilis and Kaemi in July 2006.

Fig. 9. Examples of $^{210}Pb_{ex}$ and ^{137}Cs profiles in cores collected at different time and location from the flood area outlined in Fig. 6. Shown here are (a) in the top row: a sharp depletion of ^{210}Pb in the flood layer deposited at the site of OR1-761 BC1 two weeks following Haitang, (b) in the middle row: a thick (>10 cm) flood layer in core OR1-789 BC11 suggesting two episodes in the event, and (c) in the bottom row: gradual burial of the flood layer in core OR1-791 L29 by hemipelagic sediment deposited following the event.

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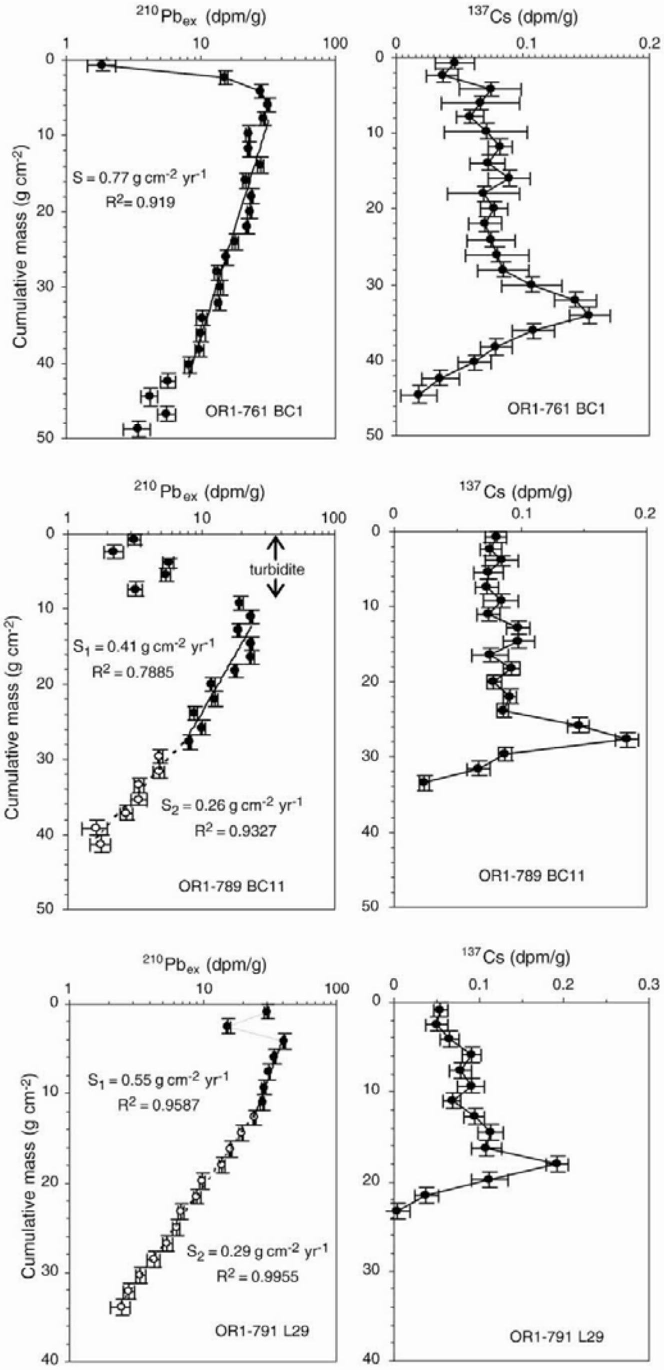

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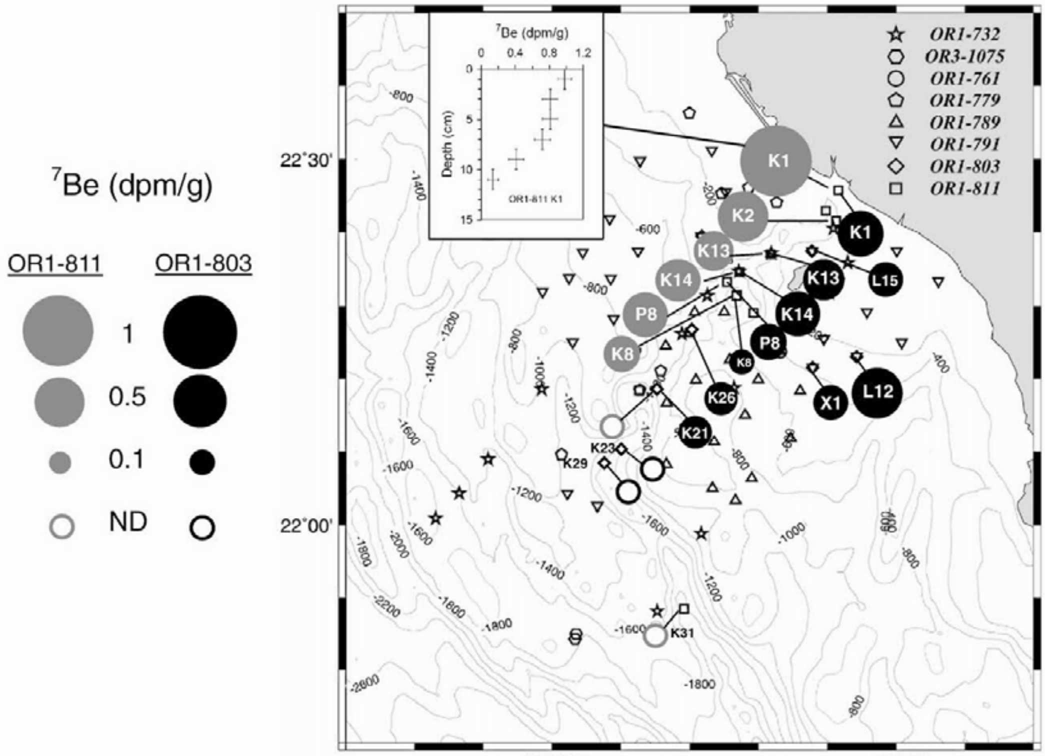

Fig. 10. Activities of ^{7}Be in surficial sediments along the thalweg of the KPSC during the OR1-803 cruise (August 5–9, 2006; black circles) and the OR1-811 cruise (October 11–15, 2006; gray circles). Empty circles indicate ^{7}Be not detectable (N.D.). The plot in the upper inset shows that ^{7}Be can be detected down to 12 cm in core OR1-811 K1 near the head of the Gaoping Canyon.

Besides sampling along the canyon during the OR1-803 cruise, three previously (on OR1-791) occupied sites outside the canyon (L12, L15 and L26) were re-occupied with a view to trace the dispersal of flood sediment. Indeed, ^{7}Be was detected at the sediment surface of sites L12 and L15 (Fig. 10). This, in conjunction with ^{210}Pb profiles in these cores, indicates the presence of a freshly deposited flood layer above the flood layer caused by typhoon Haitang one year ago (see the supplemental material archived at the website: http://dmc.earth.sinica.edu.tw/Contributor/Huh/Huh_et_al2007a/). As with the studies off the Eel Shelf (Sommerfield et al., 1999) and the Sepik River (Kineke et al., 2000), our observations suggest divergent pathways for the transport of flood sediments off the KPR: the dominance of gravity-driven flows through the canyon *versus* surface and subsurface plumes on the adjacent open shelf and slope.

3.5. A sediment budget in the study area

An important goal of this study is to calculate a sediment budget with respect to the sediment supplied to the margin from the KPR's drainage basin. The study area includes both conduits (mainly the KPSC) for the transport of sediments toward their ultimate sinks and accommodation space for the local storage of sediments across various timescales. Based on ^{210}Pb-derived sedimentation rates and a finite-element approach, the accumulation flux of sediment was calculated using a framework of 105 triangular grids and covering an area of 3045 km^2 (Fig. 11). A mean sedimentation rate is calculated for each grid block by averaging sedimentation rates at the apices of each triangle. Multiplying the area of each triangle by the mean sedimentation rate within it yields the flux of sediment within each grid block. The total flux of sediment from all 105 triangular elements thus calculated is approximately 6.6×10^6 ton/yr (Table 1). Of this annual depositional flux, 17% is distributed on the shelf (<200 m), 64% over the slope (200–1000 m) and 19% in the basin (>1000 m). So, much of the narrow (<20 km) shelf is probably above the level of wave-tide remobilization and unfavorable for sediment accumulation. In comparison, the slope region appears to be a more stable setting for the accommodation of sediments dispersed off the KPR's mouth.

The calculated budget for the shelf–slope–canyon system can only account for 13–18% of the KPR's annual sediment

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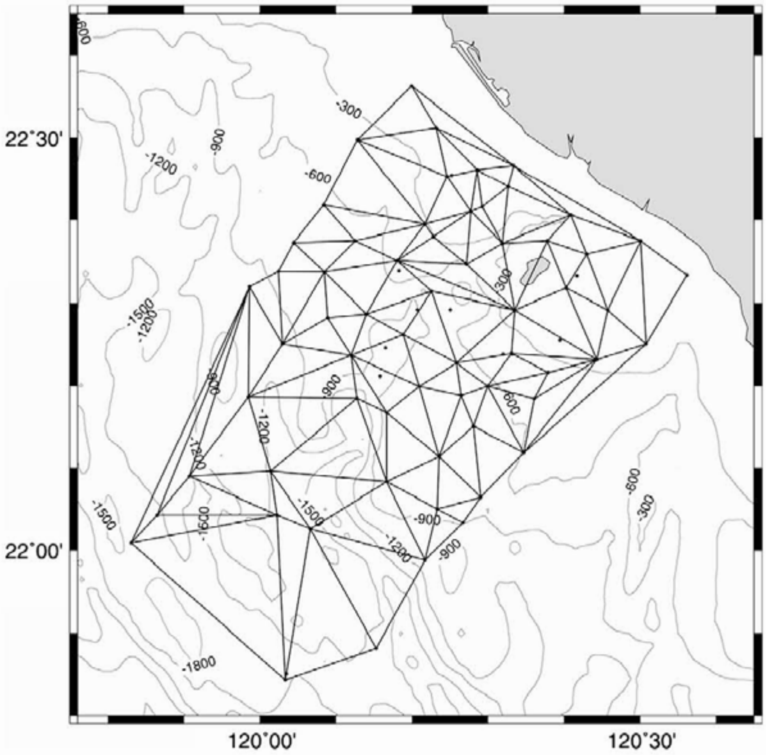

Fig. 11. A framework configured to calculate a sediment budget in the study area. The annual sediment load in the covered area is 6.6 Mton. See text for details.

load, which is reported to be from 36 Mton/yr (Water Resources Bureau, 1998; Milliman and Kao, 2005) to 49 Mton/yr (Dadson et al., 2003). The remaining majority (82–87%) of the river's sediment load may be exported out of the study area by gravity flows through the KPSC. This hypothesis is consistent with efficient sediment dispersal from a small mountainous river off an active collision margin with a narrow shelf and a submarine canyon extending almost into the river's mouth (Milliman and Syvitski, 1992).

Table 1
Sediment budget divided into four bathymetric units in the study area

Depth region	Area (km^2)	Areal-weighted mass accumulation rate ($g\ cm^{-2}\ yr^{-1}$)	Annual accumulation of sediment ($Mton\ yr^{-1}$)
Shelf (<200 m)	488	0.23	1.11
Upper slope (200–600 m)	567	0.44	2.49
Lower slope (600–1000 m)	780	0.22	1.72
Basin (>1000 m)	1210	0.10	1.26
Total	3045	0.22	6.58

4. Conclusions

Based on the distribution of fallout radionuclides in ninety-two box cores collected during 2004–2006 from an area of ~3000 km^2 off the Gaoping River's mouth in SW Taiwan, sedimentation rates and processes are studied. A sediment budget is calculated and compared with the river's annual discharge to elucidate pathways and processes of sediment dispersal and deposition. Detailed analyses of the profiles and the calculated budget lead us to the following conclusions:

(1) Except along the Gaoping Submarine Canyon and the inner shelf region, sedimentation in much of the study area is controlled mainly by steady settling of suspended particles down the water column. Sedimentation rates derived from downcore distribution of ^{210}Pb using a steady-state model and constrained by ^{137}Cs vary from <0.1 cm/yr in the deep basin to >1 cm/yr in a depositional lobe flanking the canyon at the upper slope region.

(2) From the distribution of sedimentation rates in the study area, we calculate a spatially weighted mean mass accumulation rate of 0.22 g cm^{-2} yr^{-1}, and thus a sediment burial flux of 6.6 Mton/yr in an area of

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~3000 km^2. This budget can account for no more than 20% of Gaoping River's annual load, suggesting that the remaining majority of the sediment is most likely exported out of the system via the Gaoping Submarine Canyon.

(3) The extremely intense rainfall in the KPR's drainage basin induced by super-typhoon Haitang during July 18–20, 2005 resulted in an extensive flood layer in the study area. The distribution of this flood layer coincides with the depocenter deduced from ^{210}Pb chronology. The correspondence suggests that the processes creating event layers may be relevant to the formation of the sediment strata over time scales of 100 years or longer.

(4) The presence of ^{7}Be coupled with low levels and non-steady-state distribution of ^{210}Pb in sediments along the canyon floor point to rapid transport of fluvial sediments through the canyon, probably by gravity-driven turbidity flows.

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