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Linkages between turbidites in the southern Okinawa Trough and submarine earthquakes

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[1] Turbidite layers in surficial (<0.4 m) sediments of the southern Okinawa Trough and its vicinity were dated by ^{210}Pb and further constrained by ^{137}Cs and inter-site correlation of downcore profiles of particle size and porosity. Here we show striking temporal and spatial correspondence of such episodic deposits to large ($M_L > 6.8$) submarine earthquakes recorded in the region since the 20th century. The repeating pattern of turbidite layers reported here on decadal to centennial time scales suggests what may be the long-term rhythm of seismic activities at this tectonically active plate boundary. *INDEX TERMS:* 0932 Exploration Geophysics: Radioactivity methods; 1035 Geochemistry: Geochronology; 3022 Marine Geology and Geophysics: Marine sediments—processes and transport; 3025 Marine Geology and Geophysics: Marine seismics (0935); 7221 Seismology: Paleoseismology. **Citation:** Huh, C.-A., C.-C. Su, W.-T. Liang, and C.-Y. Ling (2004), Linkages between turbidites in the southern Okinawa Trough and submarine earthquakes, *Geophys. Res. Lett.*, *31*, L12304, doi:10.1029/2004GL019731.

1. Introduction

[2] The southern Okinawa Trough (SOT) near the northeast of Taiwan is a tectonically active backarc basin between the subducting Philippine Sea plate in the south and the Eurasian continental plate in the north (Figure 1a). The Philippine Sea plate is advancing at a mean rate of ~7 cm yr^{-1} north-westward and plunging down the Ryukyu Trench in front of the Ryukyu Arc [*Seno et al.*, 1993; *Lallemand et al.*, 1997]. It is generally thought that the subduction of this oceanic plate is the underlying mechanism for the active seismic, rifting and hydrothermal activities in the SOT and its vicinity [*Sibuet et al.*, 1998; *Fournier et al.*, 2001].

[3] In conjunction with the collision of two major plates is crustal movement of Taiwan. It has been well documented that in response to the rapid uplift of Taiwan, the erosion rate of the island, estimated at an average rate of ~5 mm yr^{-1} over an area of 36,000 km^2, is among the highest in the world [*Dadson et al.*, 2003]. Thus, tectonic erosion of Taiwan may constitute an important source for sediments in this continental margin accretion wedge, as evidenced by high sedimentation rates in the SOT [*Lee*, 2001]. Recently, a 410-m long ODP core was drilled in the SOT (ODP Site 1202) in an attempt to unravel paleoenvironmental changes and tectonic activities in this convergent plate margin [*Salisbury et al.*, 2002]. In concert with the ODP investigation, we have collected a large number of box cores from the SOT and its vicinity, including the ODP site as a reference point, to elucidate modern sedimentation, with a view to use the present as a key to the geological past.

[4] Two fallout nuclides, ^{210}Pb and ^{137}Cs, are used as time tracers to establish sediment chronology within the past ~100 years at our coring sites. From profiles of excess ^{210}Pb ($^{210}Pb_{ex}$) in these cores [*Lee*, 2001; C.-A. Huh, unpublished data, 2004], two contrasting sediment transport processes are evident, one depicted by an exponential decrease of $^{210}Pb_{ex}$ with depth and the other characterized by a zigzag pattern superimposed on an overall decrease of $^{210}Pb_{ex}$ downcore. The former reflects steady rain of hemipelagic sediments in areas free from episodic near-bottom transport, while the latter is caused by the recurrence of turbidity flows near canyon outlets or mass failures adjacent to unstable slopes. This paper aims at studying the timing and implications of turbidites in three cores from the second type of sedimentary environment. Among various possible causes, we consider earthquakes as the most likely mechanism triggering turbidites in these cores (see the review by *Goldfinger et al.* [2003]). Because of suitable sedimentation rates and proximity to probable turbidite source areas, turbidite sequence is better shown in these cores. We therefore chose them for more comprehensive measurements to explore the connection between such deposits and seismic activities and its implications for the interpretation of longer-term records in tectonically active regions such as the SOT.

2. The Sampling and Analytical Methods

[5] Box cores used for this study were collected onboard R/V *Ocean Researcher-I*. The core tops were well preserved upon collection as evidenced by transparent water above the sediment-water interface in the box corer. BC3 (25°00.18′N, 122°30.31′E, water depth = 1,457 m) and BC22 (24°55.02′N, 122°25.11′E, water depth = 1,445 m) were taken during the OR-642 cruise (April 24–30, 2002) from the western edge of SOT; BC18 (24°18.01′N, 122°5.99′E, water depth = 3,025 m) was taken during the OR-687 cruise (June 29–July 1, 2003) from the Ho-Ping Basin; and BC7 (24°48.18′N, 122°31.04′E, water depth = 1,284 m) was taken during the OR-679 cruise (April 17–24, 2003) at ODP Site 1202. Note that BC7 does not contain turbidites; it is shown here as a reference site with only background sedimentation. The coring sites are shown in Figure 1b.

[6] Upon collection of the box cores, subcores were taken and sectioned for radionuclide and particle size analyses and slabs were taken for X-ray radiograph. Pb-210 was determined via ^{210}Po by α spectrometry, with ^{209}Po added as the

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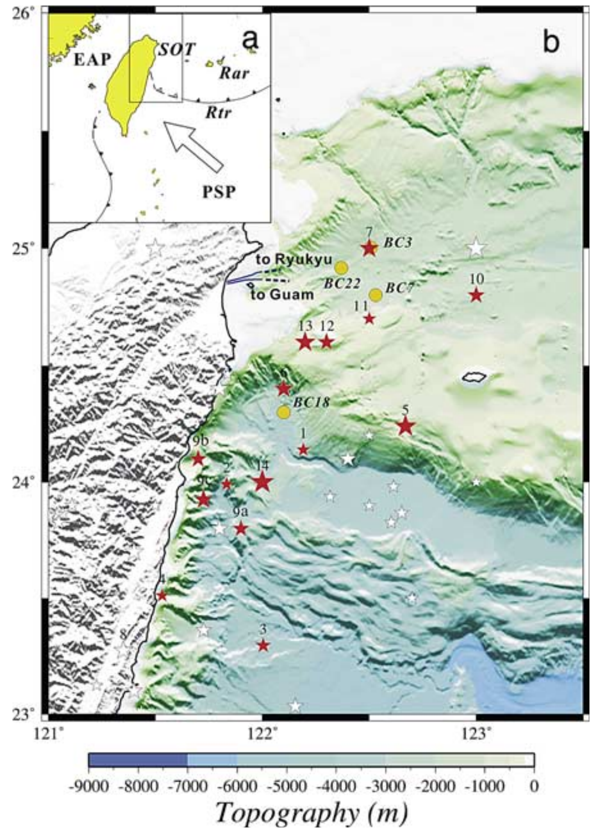

Figure 1. (a) The upper left inset is a schematic representation of lithospheric plates and geotectonic framework around Taiwan. SOT, southern Okinawa Trough; Rar, Ryukyu arc; Rtr, Ryukyu trench; EAP; Eurasian plate; PSP; Philippine Sea plate. (b) Enlarged map showing localities of the sediment cores (yellow circles), epicenters of major earthquakes with magnitude (M_L) greater than 6.5 (stars), and the position (solid lines) and direction (dashed lines) of submarine cables. Red stars represent most probable earthquakes causing turbidites in the studied cores. The numbers follow the order listed in Table 1. (Source of bathymetry data: *Liu et al.* [1998].)

yield determinant prior to sample dissolution. Pb-214 (an index of supported ^{210}Pb) and ^{137}Cs were measured by γ-spectrometry. Particle size was analyzed using a Laser Coulter counter and X-ray images were taken using an X-ray scanner. More details of the sampling and analytical procedures can be found elsewhere [*Bouma*, 1969; *Huh and Su*, 1999; *Su and Huh*, 2002].

3. Results and Discussion

[7] Shown in Figure 2 are X-ray images (in positives) of the core slabs and downcore profiles of water content, grain size, ^{210}Pb$_{ex}$ and ^{137}Cs. Turbidite layers are in general characterized by darker color, coarser particle size, lower water content, and lower ^{210}Pb$_{ex}$ relative to fine-grained ambient sediments. Chronologies of the turbidite layers, also indicated on Figure 2, were established based on the decay of ^{210}Pb$_{ex}$ in the non-turbidite, hemipelagic sediments and were further constrained by the ^{137}Cs stratigraphy (in particular, the subsurface ^{137}Cs maximum as the time marker of global fallout maximum from atmospheric nuclear tests circa 1963 A.D.) and by correlation of profiles between cores. The results show strong correspondence in timing between the turbidites and the history of major submarine earthquakes in the region, as summarized in Table 1 and discussed below.

[8] Two cores, BC3 and BC22, are located in the SOT at the base of a submarine canyon directing from Lanyang River's mouth toward the northeast. A very recent event was registered at the core tops of these two cores. There is no doubt that this turbidity flow is due to the 2002 magnitude (M_L) 6.8 Hualien earthquake, which happened on March 31, less than one month prior to our sample collection. This turbidite layer is most likely caused by a submarine mass failure, rather than flood generated, because the spring of 2002 was an unusually dry season, with extremely low water flow and suspended sediment load from the nearby Lanyang River, as documented in the database of Taiwan's Water Resources Agency (http://gweb.wra.gov.tw/wrweb). Although the epicenter of the 2002 event was ~90 km away, this shallow (13.8 km) earthquake had a profound impact to the Ilan and Taipei Basins in the north, with its intensity kept largely above 5 within a radius of ~100 km (http://scman.cwb.gov.tw/eqv3/eq_report/special/20020331/0331pgalist.asp). Based on Taiwan Central Weather Bureau's report, the horizontal peak ground acceleration (PGA) generated by this earthquake could reach 200 gals (~0.2 g) within 80 km and larger than 100 gals within 150 km, which were adequate to trigger mass failures in this region [*Chen et al.*, 1991]. On the other hand, it is

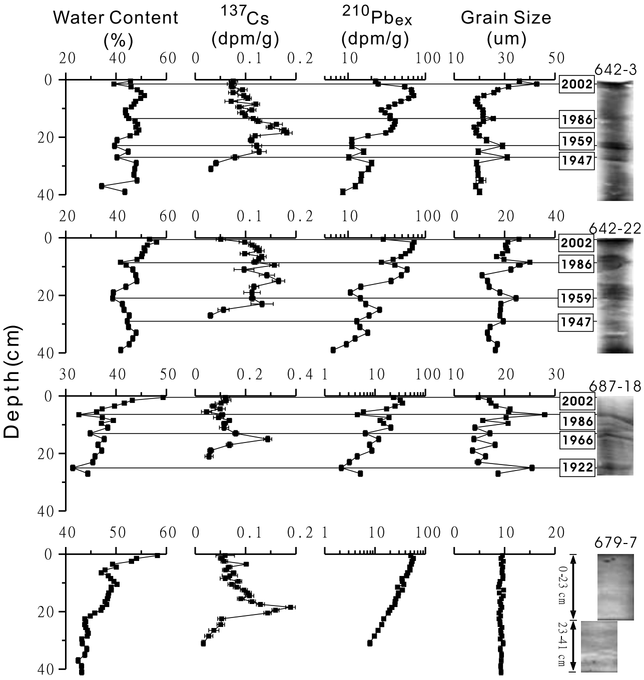

Figure 2. X-ray images and profiles of water content, grain size, ^{210}Pb$_{ex}$ and ^{137}Cs for three cores containing turbidites (BC3, 22 and 18) and one core without turbidites (BC7). Chronologies of the turbidites are indicated. Error bars on the ^{137}Cs data represent ±1σ around the means based on counting statistics. Where error bars are not shown, they are smaller than the size of the data points.

Table 1. Submarine Earthquakes Responsible for Triggering Turbidites in the Studied Cores[a]

Event No.	Time (y/m/d)	Epicenter Latitude, Longitude; Depth (km)	M_L
1	2002/03/31	24.1398°N, 122.1915°E; 13.8	6.8
2	1986/11/14	23.992°N, 121.833°E; 15.0	6.8
3	1978/12/23	23.297°N, 122.0047°E; 4.1	7.0
4	1972/04/24	23.5118°N, 121.5325°E; 15.4	6.7
5	1966/03/12	24.24°N, 122.67°E; 42	7.8
6	1963/02/13	24.4°N, 122.1°E; 47	7.4
7	1959/04/26	25.0°N, 122.5°E; 150	7.5
8	1951/11/24	23.275°N, 121.35°E; 36	7.3
9a	1951/10/22	23.8°N, 121.9°E; 20	7.1
9b	1951/10/22	24.1°N, 121.7°E; 30	7.2
9c	1951/10/22	23.925°N, 121.725°E; 9	7.4
10	1947/09/26	24.8°N, 123.0°E; 110	7.2
11	1946/12/19	24.70°N, 122.5°E; 100	6.5
12	1922/09/14	24.6°N, 122.3°E; 20	7.2
13	1922/09/01	24.6°N, 122.2°E; 20	7.6
14	1920/06/05	24.0°N, 122.0°E; 20	8.0

[a]Data source: *Cheng and Yeh* [1989] and Central Weather Bureau's earthquake catalog (in Chinese) at: http://scman.cwb.gov.tw/eqv3/eq_report/seismisity.html.

important to note that there is no turbidites in these cores corresponding to the 1999 M_L 7.3 Chi-Chi earthquake, a catastrophic inland event in the south. Ground shaking in the Taipei basin caused by the 2002 M_L 6.8 earthquake was even stronger than that by the 1999 M_L 7.3 Chi-Chi earthquake, also suggesting bigger impact of submarine earthquakes off eastern Taiwan to basins in the north.

[9] Below the core tops and within the length of BC3 and BC22 are three more turbidites dated circa 1986, 1959 and 1947 A.D. The chronology leads us to believe, once again, that they are most likely seismoturbidites linked to the 1986 M_L 6.8, the 1959 M_L 7.5, and the 1947 M_L 7.2 earthquakes, respectively. The 1986 earthquake is analogous to the 2002 earthquake mentioned above. Although the epicenter was fairly distant in the south, the amplification effect of long-period ground motion caused severe damages in heavily populated Taipei and Ilan basins in the north [*Cheng et al.*, 1999]. It is informative to point out that, the breakage on Nov. 15, 1986 of two submarine cables near the Kueishan islet, one between Ilan and the Guam Island and the other between Ilan and the Ryukyu Island (see Figure 1b), can only be ascribed to submarine landslides triggered by the 1986 M_L 6.8 earthquake.

[10] The third turbidite from the top is located a few centimetres below the 1963 A.D. ^{137}Cs fallout maximum. Based on this and the trend of ^{210}Pb$_{ex}$ decay in the ambient hemipelagic sediments, we believe this turbidite layer was triggered by the 1959 M_L 7.5 event, a nearby earthquake related to the subduction of the Philippine Sea plate. Further downcore is the fourth and lowest turbidite, deposited about 12 years prior to the third turbidite above. We consider the 1947 M_L 7.2 earthquake in the Okinawa Trough as the most probable event causing this turbidite. The 1946 M_L 6.5 earthquake, although smaller in magnitude, is so close in space and time that it cannot be dismissed, either.

[11] BC18 (24°18.01′N, 122°5.99′E, water depth = 3,025 m) was taken from the northern slope of the Ho-Ping Basin, a forearc basin on the subducting Philippine Sea plate, where the bathymetry precludes the possibility of any flood-generated turbidites. From ^{210}Pb$_{ex}$ profile of the core at least four turbidite layers can be identified and they are dated circa 2002, 1986, 1966 and 1922 A.D, respectively. Considering that BC18 is much closer than BC 3 and 22 are to the epicenters of the 2002 and the 1986 earthquakes, the occurrence of the top two turbidites in BC18 corresponding to these two events is quite conceivable. However, the uppermost turbidite in BC18 is not as "sharp" as the coeval turbidite seen in BC3 and BC22. This is because BC18 was collected 16 months subsequent to the 2002 earthquake; therefore, the turbidite layer has been obliterated to some extent by mixing with freshly deposited hemipelagic sediments at the core top. In contrast, the 1986 turbidite in BC18 is more pronounced than the corresponding turbidite layers in BC3 and 22, attesting to the proximity of BC18 to the epicentre. As for the lower two turbidites in the Ho-Ping Basin core, they are probably generated by the 1966 M_L 7.8 event and those during 1920–1922 (M_L 7.2 to 8.0) related to subduction of the Philippine Sea plate. We have as yet not found turbidites synchronous to these events in the SOT. In addition to the above, there may exist two less pronounced events in BC18, one sandwiched between 1986–1966 and the other between 1922–1966. The former may be related to the 1972 and/or the 1978 event(s), both of M_L 7.2, while the latter, found below the ^{137}Cs peak, may be related to a swarm of 1951 events (M_L 7.1 to 7.4) in the south or the 1959 event (M_L 7.5) in the Okinawa Trough.

[12] Finally, it is of interest to compare modern sedimentation revealed in BC7 with long-term sedimentation recorded at the same site in the ODP core. Since the study of the 410-m long ODP core is still underway, detailed data are not yet available. However, the absence of pink *G. ruber* throughout the ODP core suggests that the age at 410 m depth is <127 ka and thus average sedimentation rate at the site is at least 0.3 cm yr^{-1} [*Salisbury et al.*, 2002]. Considering compaction of sediments at depth, this minimum rate for the ODP core compares favourably with ^{210}Pb-drived sedimentation rate of 0.48 cm yr^{-1} for modern sediments at the same site. The top $\sim$100 m of the ODP core is fairly homogeneous, Just like BC7 (see Figure 2), but turbidite layers scattered throughout the lower section of the ODP core, suggesting that when sea level was $\sim$100 m lower during the last glacial time, ODP Site 1202 was closer to terrigenous input, like BC3 and BC22 at the present time.

[13] In summary, based on two cores from a backarc basin and one core from a forearc basin, we have found remarkably strong spatial and temporal correlations between turbidite layers in surface sediments (<0.4 m) and major submarine earthquakes recorded in the past century. The combined datasets are consistent with a decadal time scale for the recurrence of $M_L > 7$ submarine earthquakes in this tectonically active convergent plate margin. Such a time scale for the recurrence of earthquake-triggered turbidites is the shortest ever reported. Obviously, it would require more work to describe the source, pathway, spatial extent, and kinetics of each individual turbidite bed. Nevertheless, we believe what is shown here has important implications for the interpretation of long-term sedimentary records in seismically active regions. We propose that the study of seismoturbidites by sediment coring and ocean drilling is an invaluable supplement to the ongoing investigation of paleoseismicity in the Taiwan region by land drilling into seismogenic faults.

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References

Bouma, A. H. (1969), *Methods for the Study of Sedimentary Structures*, John Wiley, Hoboken, N. J.

Chen, M.-P., C.-T. Shyu, G.-S. Song et al. (1991), Seabed survey off Ho-Ping (in Chinese), report, Taiwan Power Co., Taipei.

Cheng, S.-N., and Y.-T. Yeh (1989), *Catalog of the Earthquakes in Taiwan From 1604 to 1988*, *Rep. IES-R 661*, Inst. Earth Sci. Acad. Sinica, Taipei.

Cheng, S.-N., Y.-T. Yeh, M.-T. Hsu, and T.-C. Shin (1999), Photo album of ten disastrous earthquakes in Taiwan, *Rep. CWB-9-1999-002-9*, Cent. Weather Bur., Taipei.

Dadson, S. J., et al. (2003), Links between erosion, runoff variability and seismicity in the Taiwan orogen, *Nature*, *426*, 648–651.

Fournier, M., O. Fabbri, J. Angelier, and J. P. Cadet (2001), Regional seismicity and on-land deformation in the Ryukyu arc: Implications for the kinematics of opening of the Okinawa Trough, *J. Geophys. Res.*, *106*, 13,751–13,768.

Goldfinger, C., C. H. Nelson, and J. E. Johnson (2003), Holocene earthquake records from the Cascadia subduction zone and northern San Andreas Fault based on precise dating of offshore turbidites, *Annu. Rev. Earth Planet. Sci.*, *31*, 555–577.

Huh, C.-A., and C.-C. Su (1999), Sedimentation dynamics in the East China Sea elucidated from ^{210}Pb, ^{137}Cs and ^{239,240}Pu, *Mar. Geol.*, *160*, 183–196.

Lallemand, S., C.-S. Liu, and Y. Font (1997), A tear fault boundary between the Taiwan orogen and the Ryukyu subduction zone, *Tectonophysics*, *274*, 171–190.

Lee, S.-Y. (2001), Sedimentation dynamics off northeastern Taiwan elucidated from fallout nuclides, M.S. thesis, 63 pp., Natl. Taiwan Univ., Taipei.

Liu, C.-S., S.-Y. Liu, S. E. Lallemand et al. (1998), Digital elevation model offshore Taiwan and its tectonic implications, *Terr. Atmos. Oceanic Sci.*, *9*(4), 705–738.

Salisbury, M. H., et al. (2002), Leg 195 summary, *Proc. Ocean Drill. Program Initial Rep.*, 22–32.

Seno, T., S. Stein, and A. E. Gripp (1993), A model for the motion of the Philippine Sea plate consistent with NUVEL-1 and geologic data, *J. Geophys. Res.*, *98*, 17,941–17,948.

Sibuet, J. C., et al. (1998), Okinawa Trough backarc basin: Early tectonic and magmatic evolution, *J. Geophys. Res.*, *103*, 20,245–20,267.

Su, C.-C., and C.-A. Huh (2002), ^{210}Pb, ^{137}Cs and ^{239,240}Pu in East China Sea sediments: Sources, pathways and budgets of sediments and radionuclides, *Mar. Geol.*, *183*, 163–178.

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