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Flux and fate of small mountainous rivers derived sediments into the Taiwan Strait

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ABSTRACT

High-resolution CHIRP sonar profiles across the Taiwan Strait reveal a large silt–sand-dominated deltaic clinoform, up to 50-m thick, overlying the postglacial transgressive sea floor across the southeastern, central, and northern strait. Delta-like configuration and internal depositional sequences indicate a northwestward progradation from western Taiwan, primarily from the Choshui (Zhuoshui) River. Grain-size and mineral data confirm the sediment's Taiwanese derivation. The CHIRP profiles, together with existing radiocarbon and geomagnetic dates, suggest that the clinoform has formed over the past 10 kyr. The estimated volume of 375 km^3 of sediment (mainly sand and silt) suggests a mean annual accumulation of 60×10^6 t/yr. Presumably much of fine mud delivered by Taiwanese rivers has been washed away by the local currents, and escaped either northeastward into the Southern Okinawa Trough or southward into the South China Sea. Numerous shallow borings onshore over the central western Taiwan coastal plain reveal an additional 350 km^3 of fluvial sediment that has accumulated over the past 10 kyr. The combined onshore–offshore Holocene accumulation, together with an unknown amount of finer sediment that escapes the system, indicates that the long-term sediment flux from Western Taiwanese rivers exceeds 100×10^6 t/yr, which is not different from the present-day combined annual discharges from the Choshui, Tsengwen, Ehrjen and Wu rivers into the Taiwan Strait.

1. Introduction

Rivers are the major carriers for delivering land-derived sediment to the coastal ocean (Milliman and Meade, 1983; Milliman and Syvitski, 1992; Meybeck et al., 2006). Numerous studies have documented the fate of these river-derived sediments after delivery to the ocean, especially from large rivers such as the Amazon (e.g., Nittrouer and DeMaster, 1986,1996), Yellow (Huanghe) (Alexander et al., 1991; Liu et al., 2002a; Liu et al., 2004), Ganges-Brahmaputra (Goodbred and Kuehl, 2000; Kuehl et al., 1997), and Yangtze (Changjiang) (Chen et al., 2000; Liu et al., 2006a; 2007). Much of the large-river-derived sediment is either trapped in estuaries or deposited on adjacent continental shelves, with relatively little escaping to the deep sea (e.g., Meade, 1996).

Smaller rivers, individually and collectively, also play important roles in the transfer of terrigenous sediment to the global ocean (Milliman and Syvitski, 1992) and can have profound impacts on both the short-term and long-term characters of the coast (Syvitski and Saito, 2007) and seafloor (e.g., Milliman et al., 2007). Moreover, many smaller mountainous rivers discharge onto active narrow margins and/or deep canyon systems by which their sediment can be transported directly offshore (Milliman and Syvitski, 1992; Warrick and Milliman, 2003). Examples of such small mountainous rivers include the Choshui, Kaoping and Lanyang in Taiwan (Milliman and Kao, 2005; Liu et al., 2002b; Liu et al., 2006b; Kao, 2002; Syvitski et al., 2005), the Columbia, Eel and Santa Clara in the western USA (Sternberg, 1986; Leithold and Hope, 1999; Mullenbach et al., 2004; Ogston et al., 2004; Slater et al., 2002; Warrick and Milliman, 2003), the Sepik in Papua New Guinea (Kineke et al., 2000; Kuehl et al., 2004), and the various rivers in New Zealand (Hicks et al., 2004; Orpin et al., 2006a).

Because of their size, smaller rivers are also more likely to experience episodic events: maximum flow of the Amazon, for example, is probably only 2 times greater than average flow, whereas in smaller rivers such as the Santa Clara or Choshui maximum discharge can be orders of magnitude greater than average flow (Warrick and Milliman, 2003; Milliman et al., 2007). Not only can episodic events discharge large quantities of sediment, but concentrations in some rivers sediment can reach hyperpycnal concentrations, thereby facilitating offshore escape (Mulder and Syvitski, 1995; Warrick and Milliman, 2003; Hicks et al., 2004).

Taiwan rivers have been of particular interest since Li (1976) first pointed out their very high sediment yields, present sediment discharge estimates ranging from ~230 to 400 million tonnes (Mt) annually (Dadson et al., 2003; Kao et al., 2005;), much of it delivered at hyperpycnal concentrations (Milliman and Kao, 2005; Milliman et al., 2007). Despite the large discharge and the way in which it may be delivered to the

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coastal ocean, the fate of the sediment remains unclear (Milliman and Kao, 2006, Yu, 2006). Based on observations made before and after Typhoon Mindulle in 2004, fine mud appears to be quickly transported away from the river mouth whereas the sand may remain in coastal areas or be transported down gradient into Taiwan Strait (Milliman et al., 2007). Recent Chirp sonar surveys on Taiwan Strait, for the first time reveal the distribution and stratigraphy of Holocene sediments in Taiwan Strait, thus providing the basis by which we can estimate the long-term flux and fate of sediment discharged from western Taiwanese rivers.

2. Geological setting and oceanographic regime

2.1. The island of Taiwan and Taiwan Strait

The island of Taiwan lies along the convergence of the Luzon Arc on the Philippine Sea plate and the Asian continental margin, resulting in a convergence rate of 7.8 cm/yr and a vertical uplift of 5.7 mm/yr (Fig. 1). The 4000-m-high orogen forms a linear N–S mountain belt that links the Ryukyu and Manila subduction systems. Being in an extremely active tectonic region, Taiwan experiences a high frequency of earthquakes and has the highest rate of crustal motion in the world (Teng, 1990; Liew et al., 1993; Yu et al., 1997; Liu et al., 1997).

Taiwan Strait is a 180-km-wide, 360-km-long, and 60-m-deep channel separating Taiwan from mainland China. The narrowest part of the Strait is 130 km wide in the north. The strait connects the East China Sea (ECS) in the north with the South China Sea (SCS) to the south (Fig. 1). Previous studies show the Taiwan Strait shelf is dominated by relict sandy sediments (Niino and Emery, 1961; Boggs, 1979) and a sand ridge system (e.g., Huang and Yu, 2003; Liao and Yu, 2005; Liao et al., 2008).

2.2. Taiwan rivers and their sediment flux to the sea

Taiwan also lies along what has been called “Typhoon Alley”, on average three or four typhoons passing over the island annually. As such, Taiwan receives not only abundant precipitation due to its southern Asian monsoon climate, but periodically extremely heavy rains during typhoons. (Wu and Kuo, 1999; Lin et al., 2002b; Galewsky et al., 2006). During Typhoon Herb, 31 July and 1 August 1996, for instance, 24-hr rainfall in the Central Mountain Range approached 1800 mm, triggering landslides, debris flows, and flooding, resulting in the loss of more than 70 lives (Wu and Kuo, 1999).

Given its high relief, steep gradients, frequent tectonic activity, highly erodable rocks, heavy rainfall and the frequent typhoons, Taiwan is generally recognized as having the highest sediment production in the world, as evidenced by the fact that 7 of the 10 global rivers with the highest sediment yields are in Taiwan (Li, 1976; Milliman and Syvitski, 1992; Chen et al., 2004; Dadson et al., 2004; Lin et al., 2006). Furthermore, more than 30% of the total sediment from Taiwanese rivers is discharged at hyperpycnal concentrations (Dadson et al., 2005; Kao and Milliman, 2008). Based on historical measurements and estimates, Taiwanese rivers presently discharge >300 Mt of sediment to the surrounding ocean each year (Fig. 2). Based on 20–30 year means, the western coastal rivers, principally the Wu, Choshui, Ehrjen and Tsengwen, deliver an average of ~80 Mt of fluvial sediments annually to Taiwan Strait, half of which comes from the Choshui (Kao and Milliman, 2008). The Peinan, Hsiukuluan, Hualien, Hoping and Lanyang rivers deliver an equal amount to the narrow eastern shelf. As such, Taiwan offers an accessible site for the study of flux and fate of both sediment and particulate organic carbon (POC) from small mountainous rivers to both a shallow coastal sea (Taiwan Strait) and the deep ocean (off the east coast) (Kao and Liu, 1996; Hung and Huang, 2005; Leithold et al., 2006, Goldsmith et al., 2008).

2.3. Sediment flux from mainland rivers

By far the largest single sediment source to the southwestern East China Sea (ECS) is the Yangtze River, which prior to extensive damming at the end of the last century had discharged about

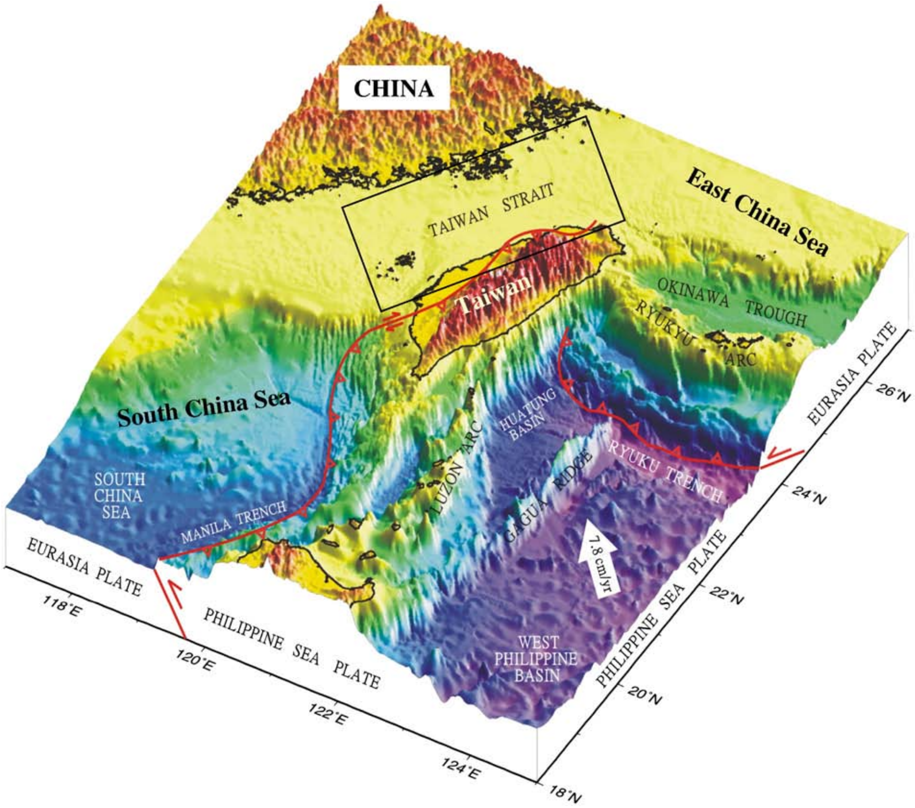

Fig. 1. Location, topography, bathymetry, and tectonic setting of the Taiwan Strait and the island of Taiwan (after Liu, 1997).

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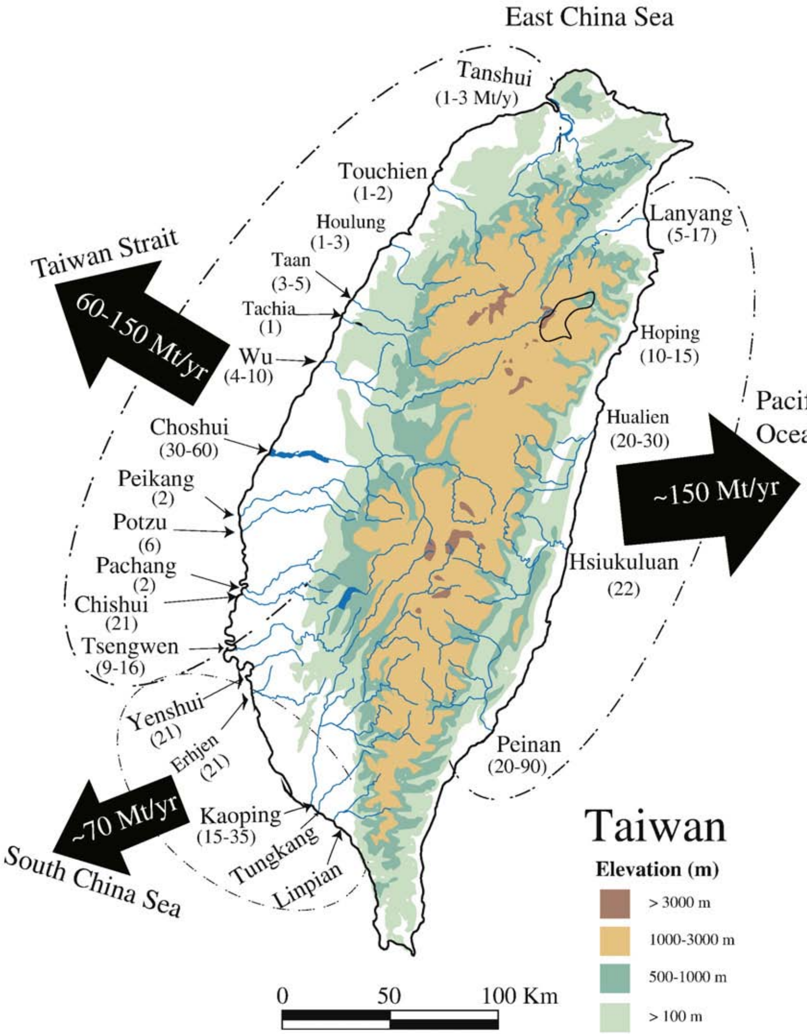

Fig. 2. Distribution of Taiwan mountainous rivers and their annual sediment loads to the surrounding seas (Data from Milliman and Meade, 1983; Milliman and Syvitski, 1992; Dadson et al., 2003; 2004; Kao et al., 2005; Milliman and Kao, 2005, and MWA).

480 Mt sediment annually (Xu et al., 2006). An estimated 30% of its sediment is resuspended and transported southward along the Zhejiang and Fujian coasts each year, primarily during winter months by the southward-flowing China (or Zhemin) Coastal Current (CCC) (Demaster et al., 1985; Milliman et al., 1985). The resulting deposit is a broad coastal mud wedge, extending ~100 km across the shelf and southward ~800 km toward Taiwan Strait, with the southernmost boundary near 24°30′N at Quanzhou Bay (Liu et al., 2006a; 2007).

Several smaller rivers south of the Yangtze drain Fujian province, the Min and Jiulong rivers, are heavily influenced by annual tropical storms. The Min discharges on average 7.5 Mt/yr of sediment, but as much as 20 Mt during peak years; like in Taiwan, peak discharge occurs in June–August. The Jiulong River's annual sediment load averages about 2.5 Mt. Most of sediment from the two rivers, however, is trapped inside or near the estuaries, and their contribution to Taiwan Strait sediments seems insignificant (Chen et al., 1998; Wang et al., 2000; Xu et al., submitted for publication).

2.4. Ocean circulation in Taiwan Strait

Southwestern ECS circulation is dominated by the Kuroshio Current, which extends from the northern Philippines to the Japanese archipelago, passing the east coast of Taiwan (Fig. 3). The Taiwan Warm Current (TWC) is a branch that separates from the Kuroshio south of Taiwan and flows through Taiwan Strait. Together with the South China Sea Warm Current (SCSWC), the TWC transports 2.7–3.1 Sv of warm oceanic water northwestward into the ECS (Fang et al., 1991; Fu et al., 1991; Wang et al., 2003), with a maximum speed of 30 cm/s (Guan, 2002). During winter months, NE winds weaken the northward-flowing warm currents (Chen, 2003; Chen and Sheu, 2006; Li et al., 2006) and strengthen the southward flow of the fresh, cold, nutrient-rich CCC (Jan et al., 2002), with a magnitude of about 0.12±0.33 Sv (Lin et al., 2005) (Fig. 3).

Tides in Taiwan Strait are semidiurnal with tidal ranges up to 4 m or more. The annual mean tidal current in the strait is 46 cm/s (Wang et al., 2003), the maximum tidal current (up to 120 cm/s) occurring in Penghu Channel (Chuang, 1985). Both strong tides and seasonal circulation patterns may play important roles in controlling the seafloor sediment character and geomorphology in the Strait (Huang and Yu, 2003; Liao and Yu, 2005).

3. Methods and data

To document the distribution and thickness of Taiwanese rivers-derived sediments, three geological and geophysical cruises were conducted in June 2004, May 2006, and June 2006 (Fig. 4) using the RV Ocean Research I and II. A high-resolution EdgeTech 0512i CHIRP Sonar Sub-bottom Profiler (frequency range: 0.5–12 k) was used to obtain more than 1500-km seismic data. All sub-bottom profiles were

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post-processed using the Discover software; an acoustic velocity of 1500 ms^{-1} was assumed to calculate water depth and sediment thickness, and an isopach map of post-transgression sediment thickness was constructed. Total sediment volume was calculated using software Surfer.

The seismic data were complemented by 40 surficial sediment grab samples collected throughout the Strait (Fig. 5). Grain-size analysis was performed using the CILAS Laser Particle Size Analyzer and mineralogical data derived from these samples helped delineate the source(s) of Strait sediments. Published ^{14}C, and geomagnetic dates were used to determine the age of the fluvial sediment in the Taiwan Strait.

4. Results

4.1. Surficial sediment grain size

Grain size of surficial sediments in Taiwan Strait varies greatly, from 0% sand in the north to >95% sand in the south and near the Choshui River mouth (Fig. 5). This dramatic variability was further confirmed by CHIRP profiles (discussed further below), which show distinct strata changes from sand waves to finer sigmoidal clinoforms. In our study area, the silt fraction accounts for 50%–80% of sediment, whereas the clay fraction reaches ~10%–20% in the middle Strait, is

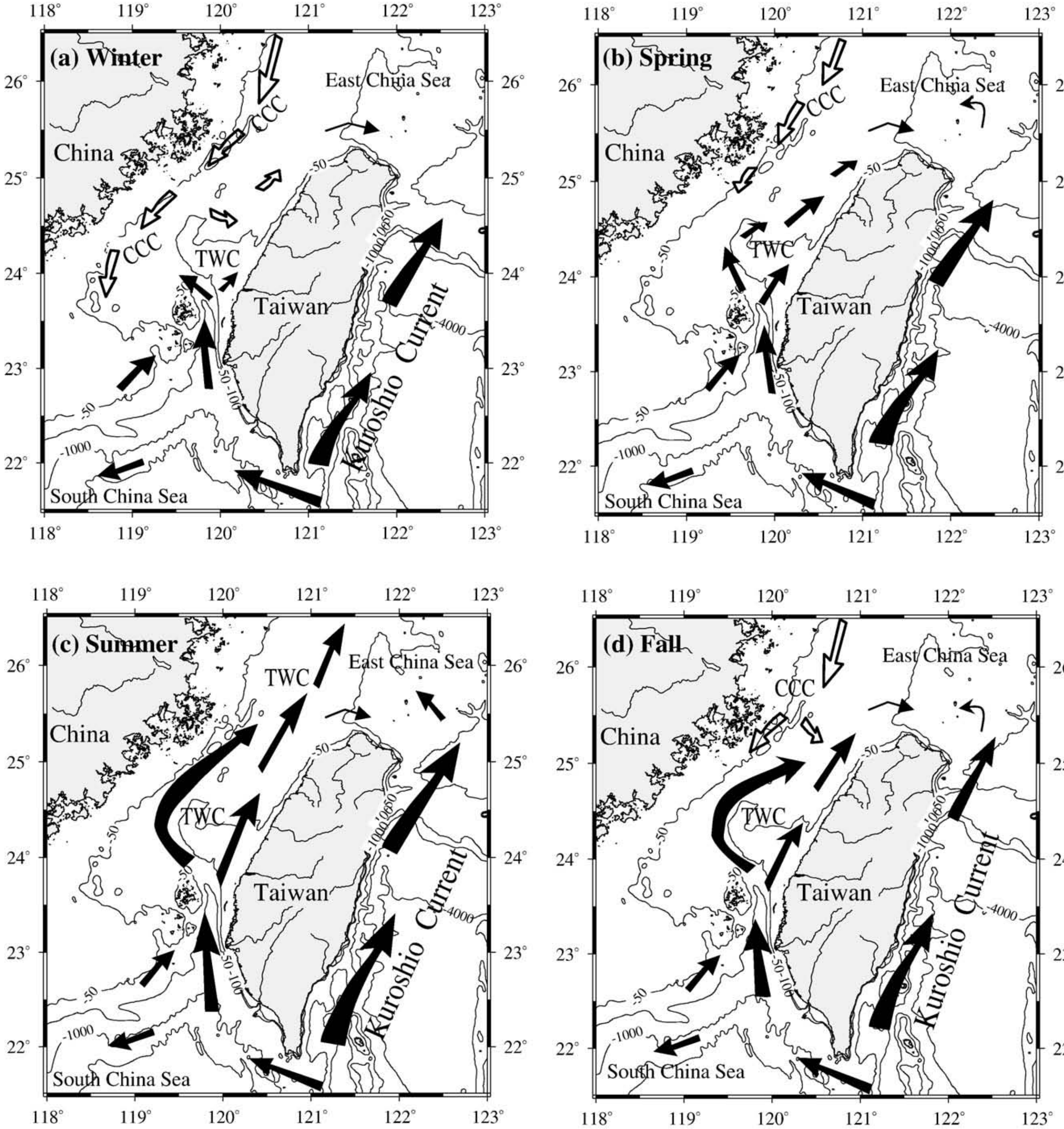

Fig. 3. Schematic map showing the seasonal variation of circulation in Taiwan Strait. In winter, the southward China Coastal Current (CCC) dominates most of the strait; the Taiwan Warm Current (TWC) only influences the southeastern part (a). In spring, the CCC weakens and retreats to the northwest; in contrast, the TWC strengthens and begins to flow trough along the eastern part of the strait (b). In summer, the CCC disappears and the TWC becomes the dominate flow in the strait (c). In autumn, with the onset of NE winter monsoon, the CCC begins to enter the strait, and, in consequence, the TWC retreats southward (d). (After Jan et al., 2002; Liang et al., 2003; Lin et al., 2005, Chen, 2003; Chen and Sheu, 2006).

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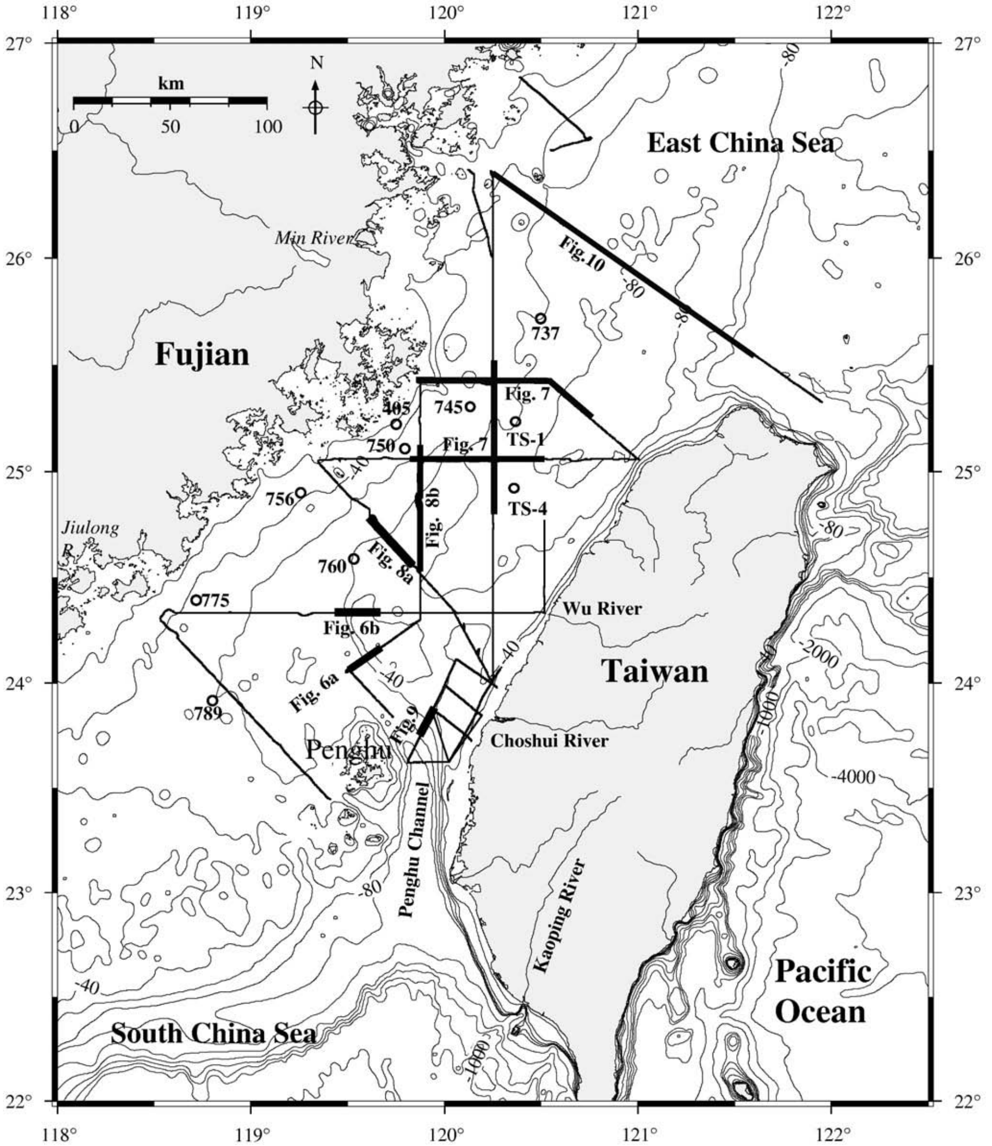

Fig. 4. Bathymetric map of the Taiwan Strait and adjacent seas. Locations of selected seismic profiles (Figs. 6–10) and cores are shown.

higher as 30–40% in the north (Fig. 5). The dominance of silt and sand is verified by sediment cores (discussed below).

4.2. Deltaic deposit in the Taiwan Strait

CHIRP profiles in the central Strait show a prominent delta-like subaqueous clinoform, up to ~50 m thick, overlying a distinct strong acoustic reflector (Figs. 6 and 7). Judging from previous geological and geophysical records from the adjacent ECS shelf (Liu et al., 2006a, 2007), this highly acoustic reflective surface appears to be the base of the post-glacial transgressive surface (TS). Below this surface, we can see incised channels and seafloor erosional features. The deltaic clinoform progrades to the southwest (Fig. 6a), west (Fig. 6b) and northwest (Fig. 8), directly overlying the postglacial TS and relict irregular seafloor, at water depths of 70–80 m (Fig. 6), indicating its derivation from Taiwan. The thickest accumulation (40–50 m) is located between 30 and 40 m isobaths, about 50 km west of Taiwan (Fig. 6). South of the Choshui River, near to the head of Penghu Channel, a CHIRP profile shows strong evidence of seafloor erosion (Figs. 4 and 9), which has been observed previously in 3.5 kHz sub-bottom profiles from this area (Huang and Yu, 2003).

4.3. Internal geometry and sediment thickness

To the southwest and west, the foreset's steep dip angle is steep (H:V=50 m:10 km) (Fig. 6) with no obvious bottomset, unlike large-river-constructed distal clinoforms (i.e. Amazon, Yangtze, etc.). At the northwestern end of the mud wedge (Fig. 8), the sediment gently progrades to water depth of 60 m with a dip angle of about 10 m/10 km.

In the northern Strait, a W–E profile (Fig. 7) shows a convex-up sedimentary body, thinning both westward and eastward at water depths of 70–80 m. As Fig. 7 shows, no modern sediment is seen in the northeastern part of the strait, i.e. inner shelf off the Touchien and Houlung rivers (Fig. 2). However, a relatively thick sediment accumulation (20–30 m) occurs in the middle shelf northwest of Taiwan (Fig. 10). Some distinct sand waves on the top of this feature infer their sandy texture and energetic environment; surficial grain size (Fig. 5) further confirms its sandy texture (88% sand).

An isopach based on the CHIRP data shows that the postglacial sediments thicken west of the Choshui River, reaching a maximum thickness at the ~40 m isobath before thinning farther to the west (Fig. 12). Pinching out near the 70–80 m isobaths (Fig. 6), the clinoform turns northward just east of the Taiwan Strait Trough. To

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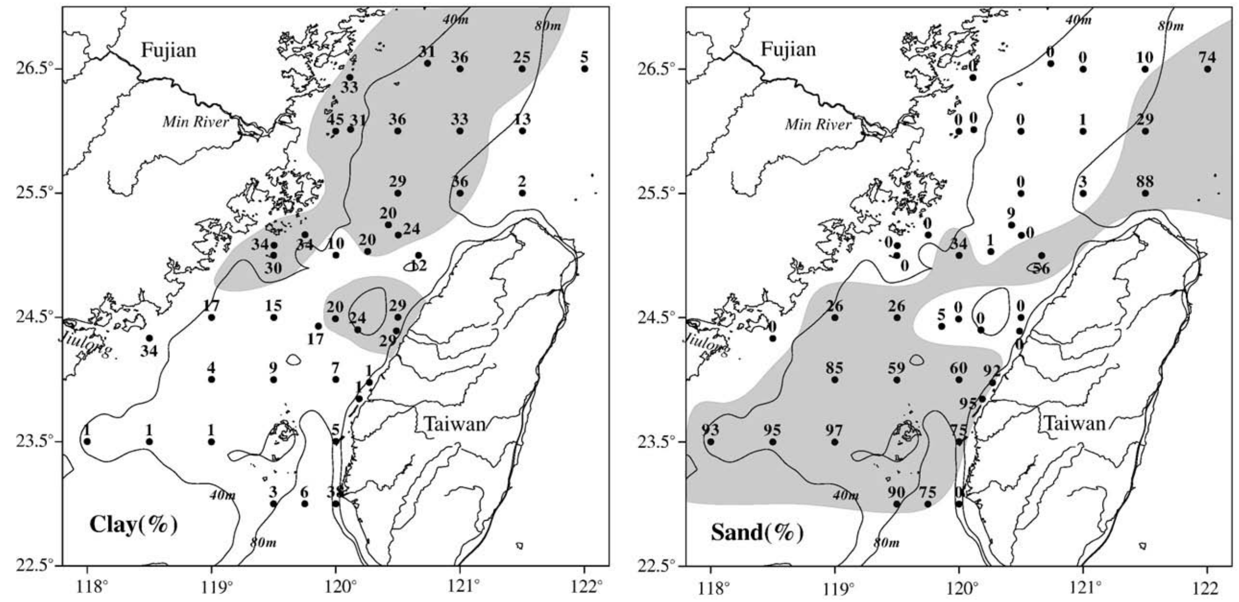

Fig. 5. Location surficial sediment grab samples in Taiwan Strait and southern East China Sea shelf, and their clay and sand contents.

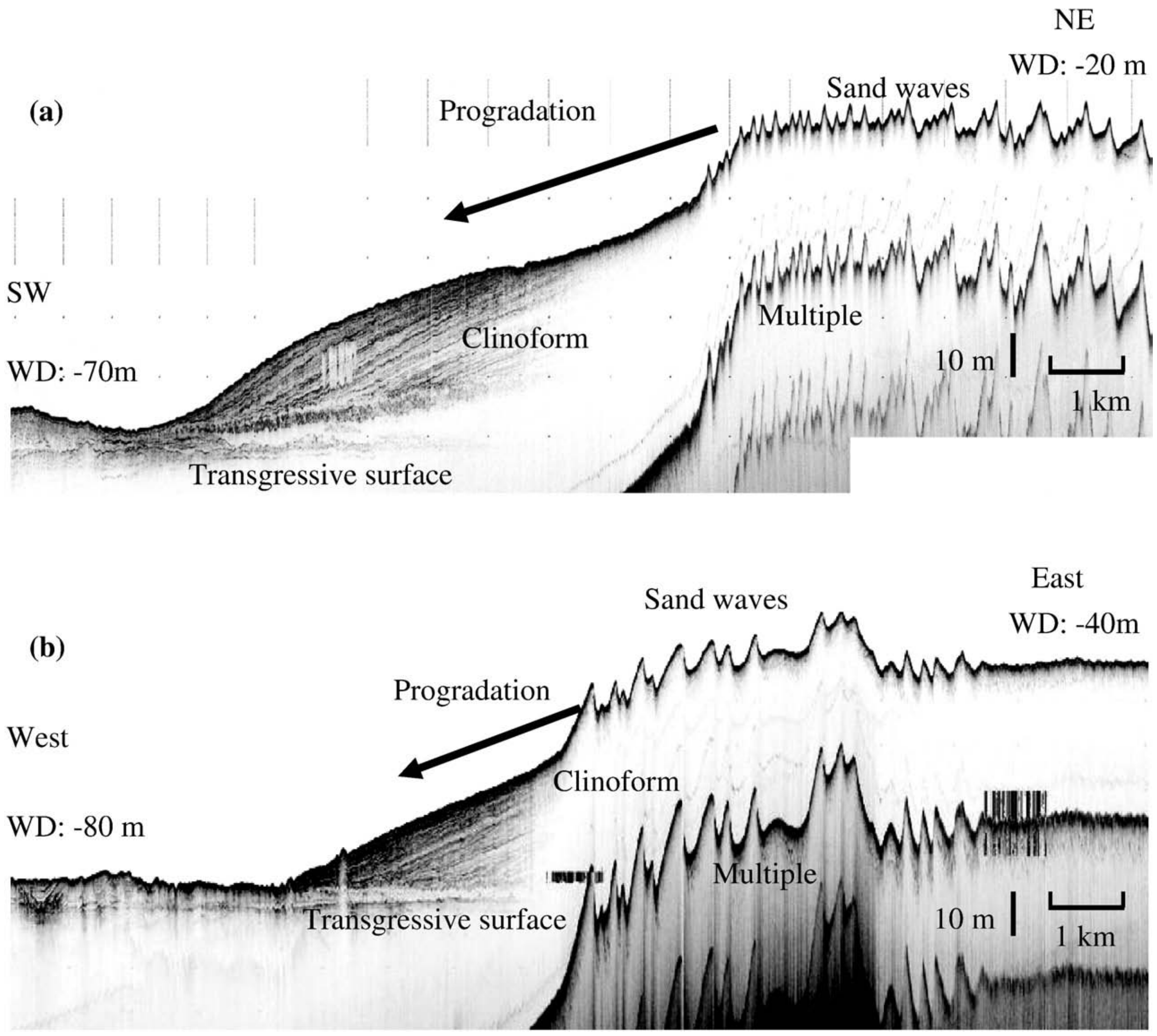

Fig. 6. Chirp sonar profiles in the central southern Taiwan Strait show a subaqueous delta progrades southwestward (a) and westward (b), and ends at water depth, −70 to −80 m off the Choshui River mouth. Topset of the clinoform is dominated by distinct sand waves, 2–5 m high.

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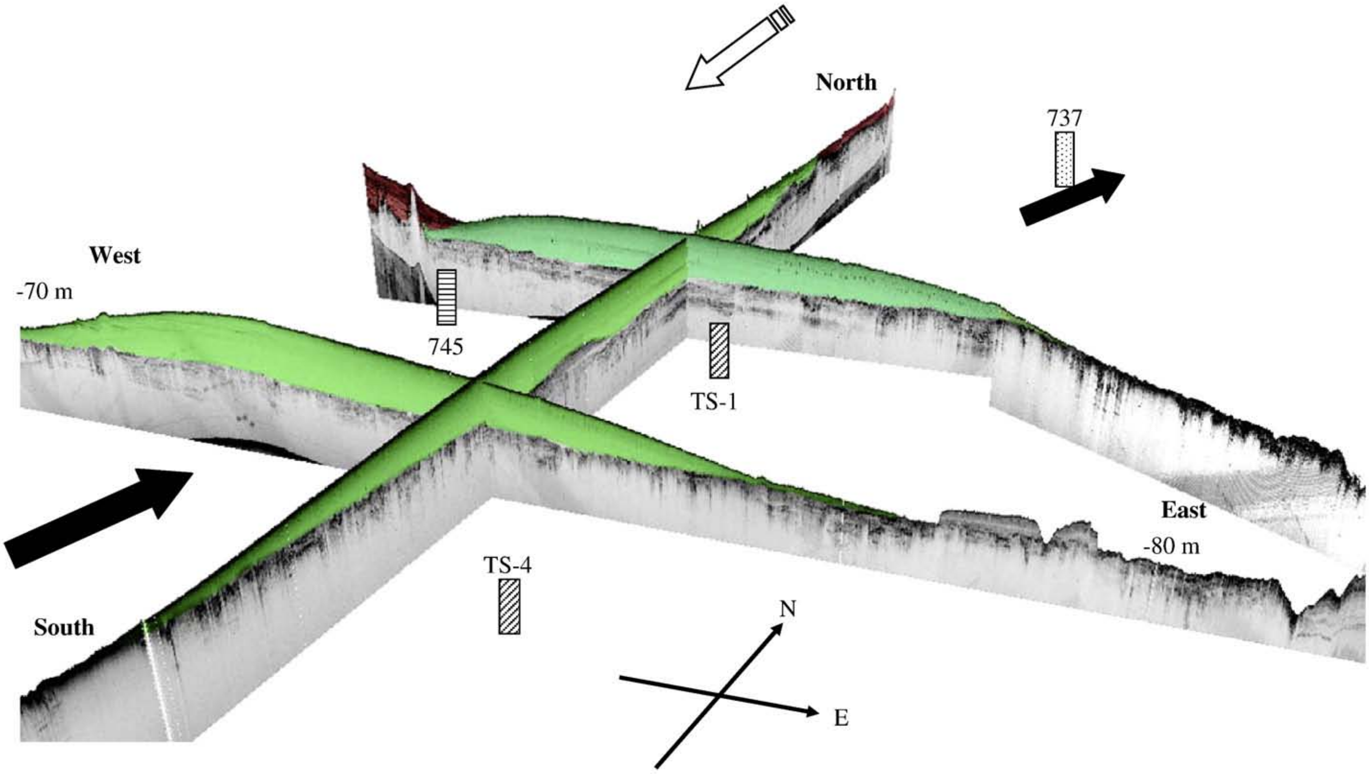

Fig. 7. 3-D crossing seismic profiles in the northwestern Taiwan Strait show the distribution of the Taiwan-derived fluvial sediment overlying the seafloor. There is no sediment accumulation in the eastern part of the northern strait. Selected cores (Fig. 11) further reveal its composition and age. The black solid arrows indicate the transport of Taiwan-derived materials, the dot and dash lines represent a possible boundary of the Taiwan fluvial sediment on the strait. The empty arrow indicates the input of the Yangtze longshore transport.

the north the clinoform lies mostly to the western part of the Strait (Fig. 12).

5. Discussion

5.1. Provenance of Taiwan Strait sediments

X-ray Diffraction (XRD) mineralogical analyses show that the medium silts and very-fine sands in Taiwan Strait are characterized by low feldspar/quartz and low K-feldspar/plagioclase ratios, indicating derivation from Taiwanese rivers (Xu et al., in review). Illite-dominated clays, however, suggest derivation from the Yangtze River in the north. As the deltaic clinoform identified in this study appears to be silt- and sand-dominated, a supposition supported the down-core texture of five cores taken in the area (see below), and since the internal geometry of the delta indicates westward and northwestard transport from Taiwan, it seems clear that the Taiwan Strait clinoform is predominantly derived from Taiwanese rivers, mostly particularly the Choshui River (Fig. 12).

5.2. Age and sediment volume of the Taiwan Strait deltaic deposit

Five cores in the study area (Figs. 4 and 11) provide ^{14}C and paleomagnetic dates (Fig. 11) suggest that the transgression surface over which the delta prograded is post-LGM (Last Glacial Maximum) in age. Based on sea-level curves derived for the East China and Yellow seas (Liu et al., 2004), we infer that most of the sediment in the Taiwan Strait delta accumulated within the past 10 thousand years (kyr). Yet, how much has escaped the clinoform and been transported northward or southward is not known (Kao et al., 2003). The total volume of the postglacial sediment over the transgressive surface offshore in the Taiwan Strait is calculated to be ~375 km^3.

5.3. Transport and deposition pattern of Taiwan river-derived sediment in the Strait

The sediment distribution pattern strongly reflects the local circulation in Taiwan Strait (Figs. 3 and 12). In summer, when most sediment is discharged from Taiwanese rivers, the strong TWC plays a major role in carrying the Taiwan-derived fluvial sediment into the middle and northern Taiwan Strait, possibly transporting eastward into the Southern Okinawa Trough bypassing northern Taiwan (e.g., Tseng and Shen, 2003). In winter, the CCC carries Yangtze-derived sediment southward to mix with Taiwan-derived materials (Lin et al., 2002a, Liu et al., 2007), and some mixed fine particles are likely carried down to the northern slope of the South China Sea (Fig. 12), as has been verified by recent clay mineral analysis from ODP1146 (Liu et al., 2003). The ubiquitous sand waves on the topset and the sand body configuration indicate the local tidal currents play major roles in trapping and forming the subaqueous sediment body in the Taiwan Strait (Liao et al., 2008).

5.4. Holocene delivery of sediment from western Taiwan rivers

Assuming a dry bulk density of 1.6 t/m^3, the Taiwan Strait clinoform volume of 375 km^3 equates to a sediment mass of ~600 × 10^9 t, which over the 10,000-yr period represented by the clinoform, gives a mean annual sediment delivery of 60 Mt/yr, not very different from the 80 Mt presently collectively discharged by the Tsengwen, Choshui and Wu rivers (Fig. 2). But another sink for western river sediment is the broad western coastal plain stretching from the Tsengwen northward to the Tanshui River (Fig. 12), which numerous shallow borings and ^{14}C dates

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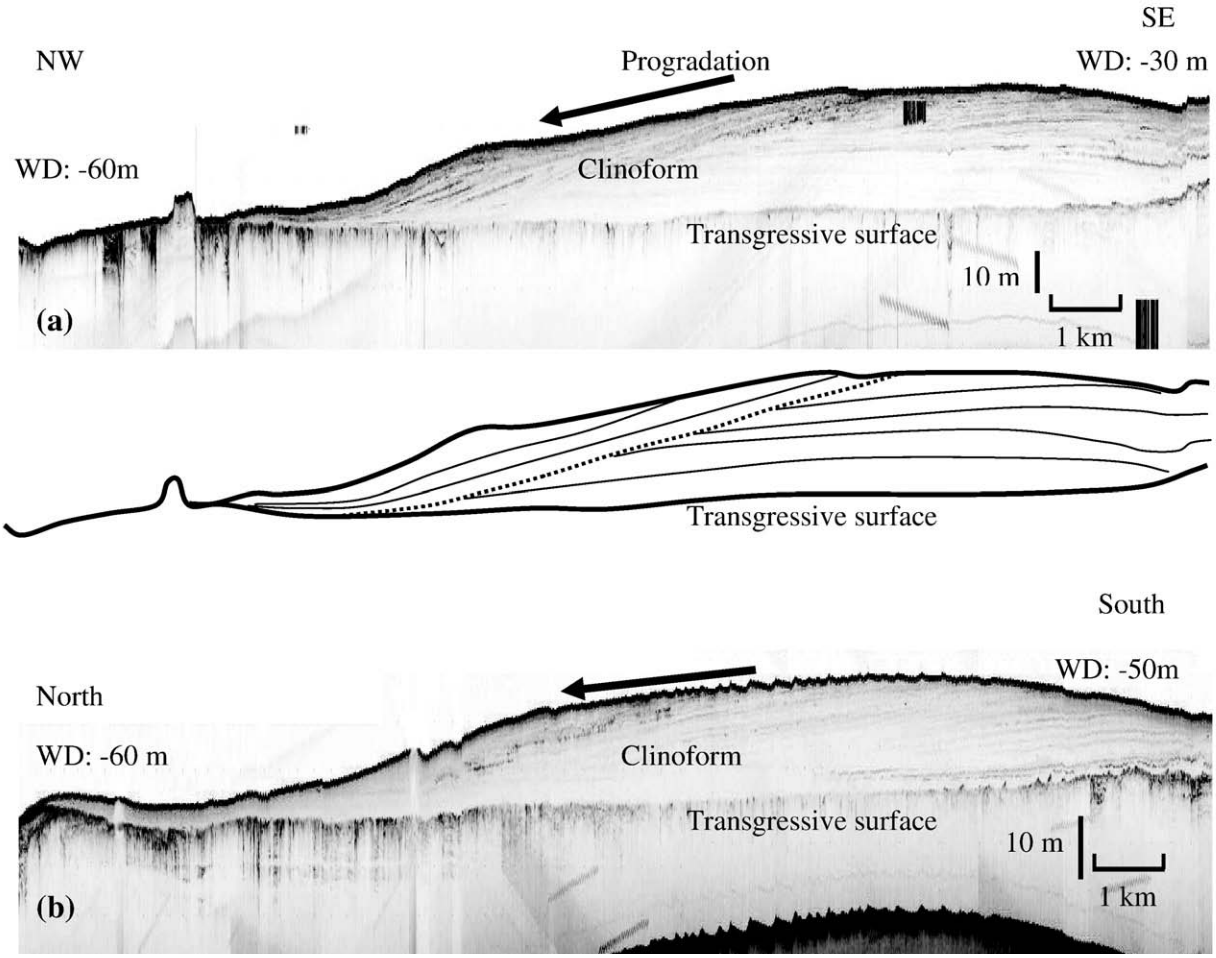

Fig. 8. Chirp sonar profiles in the central Taiwan Strait, offshore the Choshui River mouth, show the subaqueous delta progrades northwestward (a) and northward (b), and ends at water depth, −60 m, the middle of Taiwan Strait Trough. The progradation direction further indicate the source of this subaqueous delta is from southeast, not northwest.

reveal to have Holocene fluvial deposits locally thicker than 100 m (Cheng et al., 1999; Chen and Liu, 2003; Hsieh et al., 2006). A preliminary isopach map of the Holocene sediment in coastal plain (Fig. 12) is ~350 km^3, or an additional~560 × 10^9 t of sediment. Collectively, then, the western coastal plain together with the Taiwan Strait clinoform have a total of ~1160 × 10^9 t of Holocene sediment. If one includes the finer grained sediments that probably has been transported northward and out of the Strait, the total volume is almost certainly greater. Even ignoring the escaped sediment, the mean annual discharge of western Taiwan rivers must have reached or exceeded 110 Mt/yr over the last 10,000 years. There is no reason, of course, to assume that sediment influx has been constant; in fact there is some evidence in the coastal plain cores of higher sediment fluxes during the early Holocene (Hsieh et al., in review, Diekmann et al., 2008; Hsieh and Knuepfer, 2001). Thus

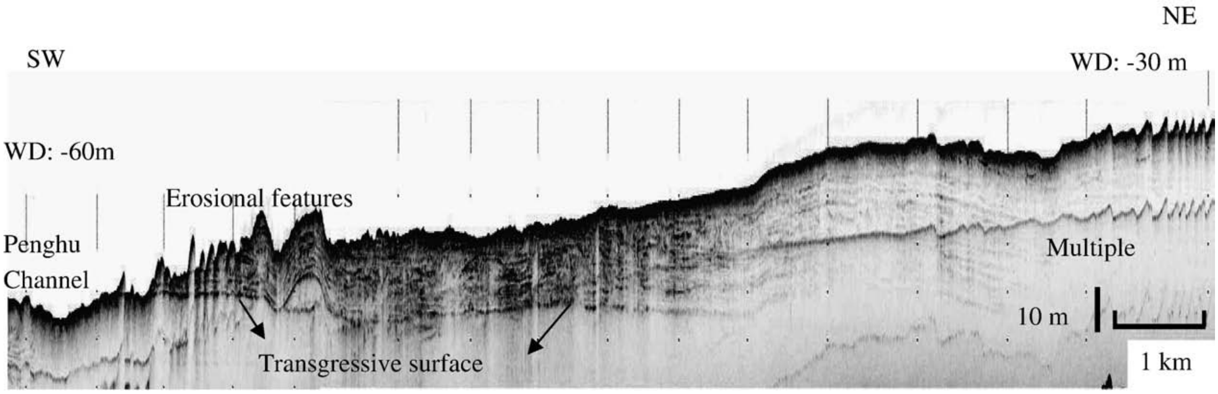

Fig. 9. Chirp sonar profile in the central southeastern Taiwan Strait, offshore the Choshui River mouth, shows a eroded subaqueous delta progrades southwestward, and ends at water depth, −60 m, the head of Penghu Channel. Topset of the clinoform is dominated by distinct sand waves, 2–5 m high.

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Fig. 10. Chirp sonar profile in the north Taiwan Strait, southern ECS, shows the Yangtze long-shore transported mud in the northwest, and possible Taiwan derived sediment in the middle shelf, north of the Taiwan island. See Fig. 4 for profile.

late Holocene fluxes may have been somewhat less than 100 Mt/yr, but perhaps not too different from the present-day combined loads of the western rivers.

The possibility that present-day sediment loads may be representative of much longer-term sediment fluxes from western Taiwan appears contrary to other evidence noted both in other Taiwanese rivers and throughout southern Asia. (Kao and Liu, 2000) for instance have shown that road construction, urbanization and increased agricultural activities in NE Taiwan have increased the sediment load of the Lanyang River by roughly 5–6 fold since 1960, and a similar increase in sediment discharge has been noted for the Peinan River due to increased agriculture (Kao and Milliman, 2008). Over the longer term, the sediment load of the Yellow River is thought to have increased by 5–10 fold ~2000 years ago in response to deforestation and farming of the loess plateau in northern China (Milliman et al., 1987; Saito et al., 2001). Our observation that sediment delivery from western Taiwan rivers has not noticeably increased throughout the Holocene, in contrast, suggests that the impacts of recent human activities (e.g. deforestation, farming, and road constructions, etc.) have been relatively minor, buffered in part, perhaps by the construction of dams and reservoirs.

5.5. Comparison with sediments derived from other small mountainous rivers

Many of the world's large river systems produce prominent shoreline-attached clinoform mud deposits, which have already been greatly attenuated in the alongshore direction of dominant sediment transport (e.g., Amazon, Yangtze, Yellow, and Mississippi) (Nittrouer and DeMaster, 1986,1996; Alexander et al., 1991; Liu et al., 2002a; 2004; Liu et al., 2006a; 2007; Wright and Nittrouer, 1995, Neill and Allison, 2005). In contrast, smaller mountainous rivers less commonly produce delta plains and underwater clinoforms, and appear in many cases to have a more direct connection with the deep sea (e.g., Eel, Sepik, Kaoping) (Mullenbach et al., 2004; Ogston et al., 2004; Kineke et al., 2000; Kuehl et al., 2004; 2006c; Liu et al., 2002b; 2006b), with significant occurrence of event-driven gravity or hyperpycnal sediment transport. Recent studies off the Waiapu and Waipaoa rivers, which drain the tectonically active East Coast North Island of New Zealand, reveal the efficiency of such systems in allowing sediment escape from the shelf, and highlight some of the sediment dispersal modes characteristic of small mountainous rivers (Hicks et al., 2004; Orpin et al., 2006b;Ma et al., 2008).

The Choshui River is one of the catchments having the highest sediment yields in the world, and routinely produces river suspended sediment concentrations at hyperpycnal levels (Milliman and Kao, 2005; Milliman et al., 2007). Observations of recent typhoon-derived sediment deposits off the Choshui reveal strong evidence of hyperpcnal input, rapid deposition, strong current sorting, and quick recovering of the pre-typhoon seafloor character (Milliman et al., 2007). The high-resolution Chirp sonar profiles in this study reveal an offshore accumulated silt–sandy subaqueous deltaic deposit linking to a high-yield, episodic small mountainous river. More interestingly, the topset of this deltaic deposit body is usually dominated by well-developed sand waves (Figs. 6, 9 and 10) (Yu and Chang, 2002; Yu and Chou, 2001; Liao et al., 2008), which indicate the influence of strong tidal and oceanic currents in this dynamic

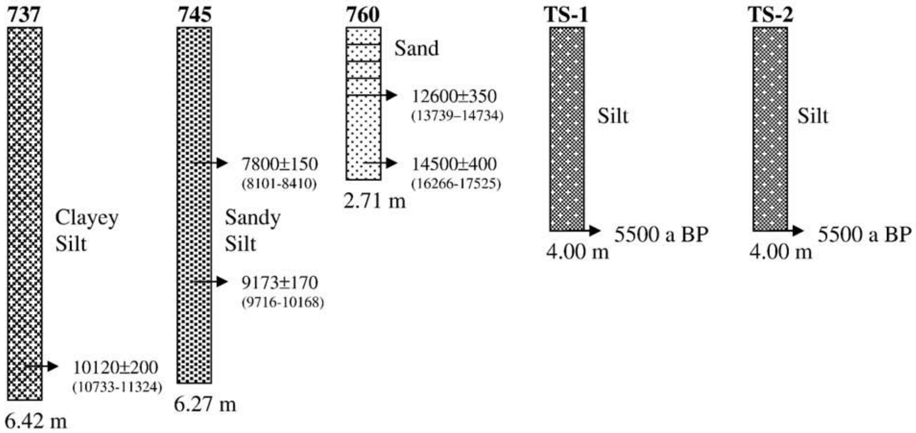

Fig. 11. Selected sediment cores and dates. Data of core 737, 745 and 760 is from Lan et al., 1993; All ^{14}C ages have been calibrated using the Calib5.0 (http://calib.qub.ac.uk/). TS-1 and TS-2 are from Chien and Leu, 1984.

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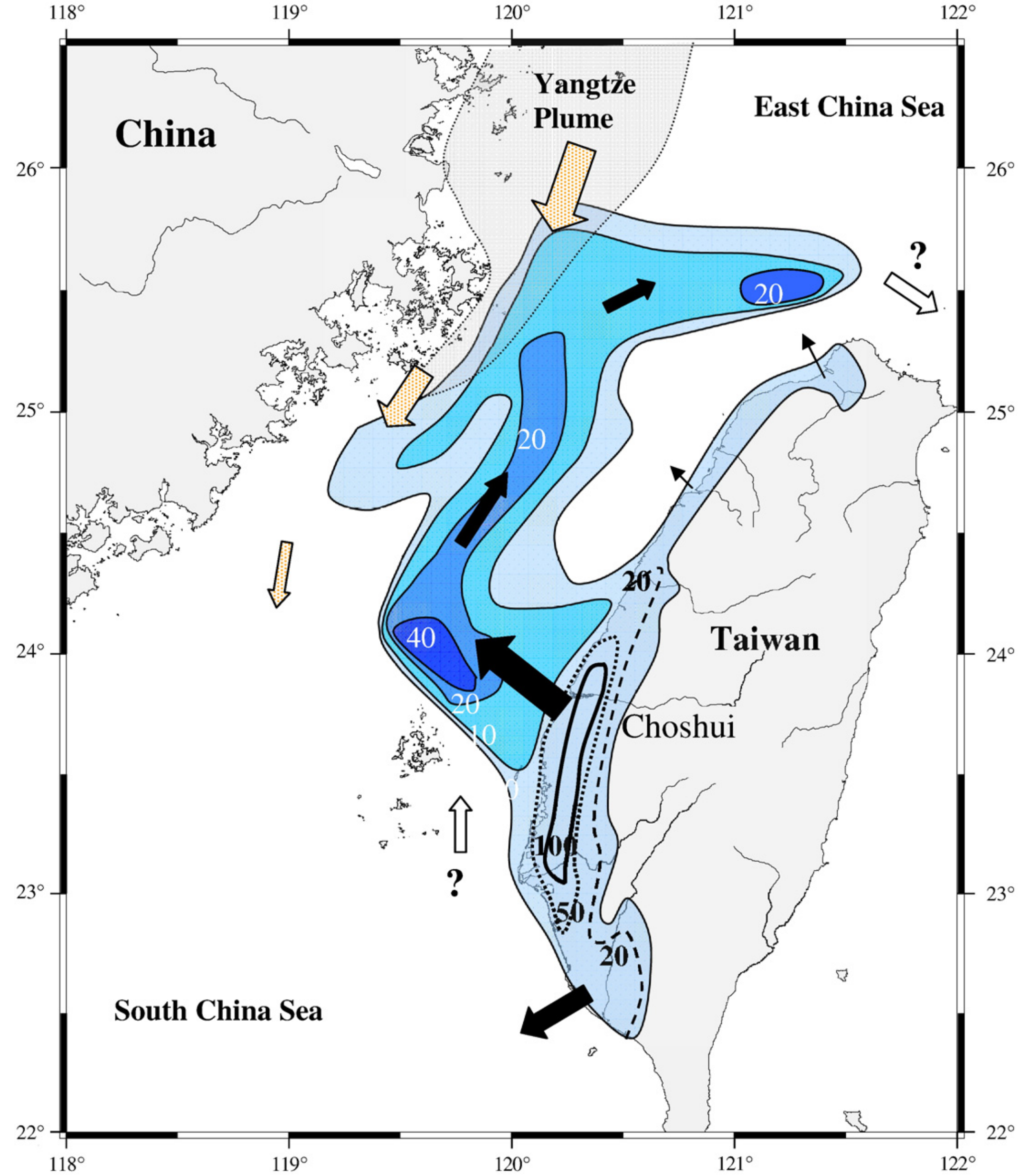

Fig. 12. Isopach of the post-glacial fluvial sediment distribution in the Taiwan Strait. The onshore part are made based on data from Cheng et al., 1999; Chen and Liu, 2003; Hsieh et al., 2006. The black arrows represent the inputs and transport of the Taiwanese rivers derived sediment to the strait. The open arrows with question mark (?) represent unknown transport. The shallow arrows represent the inputs from Yangtze and other mainland rivers.

depositional environment. Box cores study off the Choshui (Milliman et al., 2007) and grain-size analysis in the middle and northern strait indicate that most of the clay and silt derived from Taiwanese rivers is washed away within weeks of initial deposition, apparently transported northwards, although its ultimate fate is not yet clear.

Another striking feature in the seismic observation off Choshui is the general lack of gas (Figs. 6–10), unlike some offshore records from other small mountainous river systems, such as the Waipaoa (Orpin et al., 2006b) and Eel rivers (Orphan et al., 2004; Yun et al., 1999). We also note the lack of biogenic gas in the Chirp sonar profiles off the Lanyan River, northeastern Taiwan, although Holocene accumulation has locally exceeded 200 m (unpublished data). Limited published chirp profiles off the Waiapu River, a river that yearly reaches hyperpycnal concentrations, also indicate there is no strong gas effect (Addington et al., 2007). This may suggest the episodic hyperpycnal deposit derived from a high-sediment-yield watershed contains less labile organic carbon, since a larger part of the POC is contributed directly from bedrock erosion (Leithold et al., 2006). Although, a large POC flux among suspended sediment (0.5 Mt vs. 61.4 Mt, or 0.8%) has been reported at Choshui River mouth during the a typhoon-magnitude storm event (Goldsmith et al., 2008), the episodic hyperpycnal flow and rapid accumulation may also confine or restrain biogeochecmical reduction of land-derived particulate carbon, thus limiting the production of methane, further studies are needed.

6. Conclusions

High-yield small mountainous rivers represent a major pathway by which terrestrial sediment is discharged to the global ocean. Taiwan is not only an ideal area to study the flux and fate from small mountainous rivers, but offers a good study site to document the influence of episodic storms on sediment discharge. Collectively Taiwan rivers discharge more than 300 Mt of sediment annually to the surrounding ocean. The

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western coastal rivers alone, which include Choshui, Wu, Pazhang, and Tsengwen rivers, deliver 60–150 Mt/yr of sediment to Taiwan Strait.

Recent high-resolution CHIRP sonar profiles across the Taiwan Strait reveal a large silt–sand-dominated deltaic deposit, up to 50-m thick, overlying the postglacial transgressive sea floor in the south-eastern, central, and northern strait. The distribution and internal depositional sequences indicate that this sedimentary deposit progrades northwestward from the Taiwan western coast-specifically, from the Choshui River. Radiocarbon and geomagnetic dating from previously collected cores suggest this subaqueous deltaic clinoform has formed over the past 10 kyr. Geochemical and clay mineral data confirmed its Taiwanese origin. Based on a Holocene sediment isopach map, we estimate there is ~600×10^9 t of Taiwan-originated fluvial sediment has accumulated in the strait; an unknown amount – but presumably large – of finer sediment has escaped either southward into the South China Sea or northeastward into the Okinawa Trough. Combined with a roughly equal amount of Holocene sediment that has accumulated on the central western coastal plain, western Taiwanese rivers on average have discharged at least 100 Mt/yr throughout the Holocene, a figure not too different from the mean observed load in present-day rivers. Contrary to elsewhere in southeastern Asia, these data imply that, comparing to the long-term geological records, the modern human activities have had relatively little impact in affecting sediment discharge from western Taiwanese rivers to the sea.

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