SEDIMENTS AND SEDIMENTARY PROCESSES IN THE YELLOW AND EAST CHINA SEAS

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Abstract. The sedimentary environment and history in the Yellow and East China seas have been influenced primarily by the broad shallow nature of this epicontinental shelf and by the large influx of fluvial sediments from the adjacent Huanghe (Yellow River) and Changjiang (Yangtze River). As a result, numerous sea-level fluctuations can be seen acoustically and sedimentologically in the Quaternary record.

During the Holocene about 90 percent of the sediment contributed to the Yellow Sea by the Huanghe has remained within the deltaic system; the other 10 percent has been eroded, primarily during winter storms, and transported southeast as far as Cheju Island. In contrast, Changjiang sediments have been transported to the south via the Changjiang Coastal Water; offshore transport has been prevented by tidal currents and by the northward movement of the Taiwan Warm Water.

While the sedimentary (and erosional) processes during the last cycle of sea level regression-low stand/transgression-high stand helped shape the morphology and sedimentary character of the present-day seafloor, much will be eroded during the next regression of sea level. A substantial portion of the eroded sediment may be transported as far seaward as the Okinawa Trough during lowered sea level.

1. Introduction

Asian seas are characterized by large influxes of sediments from rivers draining the adjacent continent and islands. Fully 70 percent of the present-day sediment reaching the ocean comes from southern Asia and adjoining Oceania (MILLIMAN and MEADE, 1983). While poor methods of soil conservation, particularly in rice agriculture, have increased river sediment loads considerably over the past 2–3 thousand years (e.g., MILLIMAN et al., 1987), the sediment entering Asian seas probably has remained relatively high throughout most of the Neogene, as the result of high topography, seasonally heavy rainfall and (in the case of islands) short, direct discharge to the sea (MILLIMAN and MEADE, 1983). Clearly this large sediment flux has had a significant, if sometimes only local, impact on the marine geology of Asia and Oceania.

Over the past five years, the first two authors have studied the marine geology and physical oceanography of the Yellow Sea as part of a cooperative research program between our two institutions (Fig. 1). Prior to that, the second author spent more than 20 years involved in various geological studies throughout the Chinese seas and coastal areas, while
Fig. 1. Area map of the Yellow and East China Seas, showing the location of seismic lines taken during 1980–1986. Also shown are the paths of the Yellow Sea Warm Water (YSWW), Taiwan Warm Water (TWW), Yellow Sea Cold Water (YSCW), Jiangsu Coastal Water (JCW), Changjiang Coastal Water (CJCW) and Korean Coastal Water (KCW). Water depths are in meters.

the third author has spent a similar period of time initiating studies off southern Korea. The senior author spent an additional three years working on the marine geology of the Changjiang and adjacent East China Sea. Collectively, we have gathered a wide suite of data and insights concerning the sedimentary environment and history in the seas off eastern China and western Korea. While we have reported on these findings in a number of papers (many of which are quoted in this paper), here we synthesize our findings into a concise description of the sedimentary character of the Yellow and East China Seas. The interested reader is referred to cited papers for further information.
2. Environment of the Yellow and Eastern China Seas

The seas between eastern China and western Korea possess two environmental characteristics that uniquely control sedimentary processes and history. First, two of the world's four largest rivers (in terms of sediment load) discharge to the ocean from eastern China—the Huanghe (Yellow River) and the Changjiang (Yangtze River), which discharge, respectively, 1.1 and $0.5 \times 10^9$ t of sediment/yr (Qian and Dai, 1980). Together these two rivers account for more than 10 percent of the fluvial sediment entering the present-day oceans (Milliman and Meade, 1983). The path of the Huanghe has meandered greatly during the last 5000 years, and our data suggest that similar meandering may have occurred throughout at least the late Quaternary. Within the past 1000 years, the Huanghe discharged into the Gulf of Bohai, then in 1128 AD its flow bifurcated to the north (Gulf of Bohai) and south (onto the Jiangsu coast). Flow was totally to the south from 1495–1855 AD, and finally, in 1855 AD, its direction of flow returned to the Gulf of Bohai. The path of the Changjiang has remained more stable, although Yang et al. (1985) have suggested that during the last glacial period the river flowed north, nearly reaching the Shandong Peninsula.

Second, the Yellow and East China seas (generally thought to be divided at the 32°N parallel; Fig. 1) collectively form a broad and shallow epicontinental sea, not unlike those whose sediments are found in ancient rocks but whose modern analogs are considered rare in modern oceans. Except for a narrow zone off southwestern Korea, depths in this epicontinental sea are less than 100 m, and the shelf break lies more than 800 km from the Shandong Peninsula.

The broad and shallow nature of this epicontinental sea has had a number of effects on the sedimentary record. During Quaternary sea-level fluctuations (to $-100$ m or more relative to present-day sea level), most (if not all) of the Yellow-East China Sea was subaerially exposed. Because of the very shallow gradient (generally less than 1 m/km), sea level retreated and advanced rapidly over the sea bed. During the most recent rise of sea level, for example, sea level transgressed horizontally as much as 80–100 m/yr (Milliman et al., 1989a). This fact, taken together with the large sediment influx and the marked shift in sedimentary environments resulting from fluctuating sea level, has meant that sedimentary features have tended to be preserved better in the Yellow and East China seas than in many marginal seas throughout the world. Finally, the shallow nature of this epicontinental shelf means that seasonal changes in circulation patterns and water character affect the entire water column, including nearbottom waters. Both tides and storm waves can erode and transport sediments through the Yellow and East China sea, and the effects of these processes are seen in both the character of the bottom sediments and the overlying waters.

3. Quaternary Record

High-resolution seismic profiles, taken primarily with an ORE Geopulse and a 3.5 kHz echo-sounder, reveal a series of repetitive cycles in the shallow seismic (Quaternary) record. The lower boundary of the most recent cycle is characterized by a prominent erosional surface, 10 to 40 m beneath the seafloor (Fig. 2A). Locally this surface is punctuated by channels that in the western Yellow Sea (south of the Shandong Peninsula) appear to be oriented along E-W drainage patterns (e.g. Fig. 2A) that merge east of 124°E with a broad meandering N-S channel system in water depths greater than 80 m (see Fig. 1). Southwest of Cheju Island the channel system is seen as several deep channels (Fig. 3). These lines of
Fig. 2. Typical high-resolution seismic profiles from the study area, showing regressive erosion surface, subaerial, transgressive and neretic facies. A) is a Geopulse record, B) is a 3.5 kHz record.

Evidence indicate that the erosion surface was formed during the last low stand of sea level and that the channels are old river channels, presumably of the Yellow River, formed during subaerial conditions. We assume that the erosion surface formed during the last regression of sea level, 70 to 80 thousand years ago.

Overlying the erosion surface, and often presenting spectacular acoustic sequences, are horizons that we consider to be channel fill; in some instances we can identify point-bar deposits (e.g., Fig. 2B) suggestive of river-deposited facies, almost certainly deposited during lowered sea level. Landward this river-channel facies grades into a deltaic facies (e.g., Fig. 4) that presumably was formed during a subsequent higher stand of sea level, perhaps during a slight warming period 25–35 thousand years ago. A prominent erosional surface within this delta (Fig. 4) also can be seen.

The late Pleistocene-early Holocene transgression of sea level is indicated (particularly in the central portions of the study area) by an acoustically dark thin layer overlying the
subaerial facies (Fig. 2). Where this dark layer has been cored, a marine peat is often noted; several C-14 dates of the peat suggest it was deposited 10 to 12 thousand years ago (ka) as sea level transgressed (e.g., Xu et al., 1982; Yang et al., 1985). In places, particularly on the outer East China Sea, there is little Holocene sediment and often the transgressive sequence is thin, such that surface sediments contain relics of former low stands of sea level (e.g., Emery et al., 1971; Wang and Wang, 1982; Yanagida and Kaizuka, 1982; Chen et al., 1985; Han and Meng, 1987).

The present-day seafloor is covered mostly by Holocene sediments, up to 30 meters thick. The thickest deposits are deltaic sediments off the Changjiang and Huanghe in the west (e.g., Fig. 5) and a wedge of sediment just east of the Shandong Peninsula (Fig. 6). We are not sure whether the Shandong mud wedge was deposited during sea level rise, but at least some appears to be presently accumulating as sediment escapes the Gulf of Bohai and northern Yellow Sea. Distal facies of the Huanghe sediments occur throughout the Yellow Sea and northern East China Sea, the results of oceanic processes discussed in the following section.

Two zones with little or no Holocene sediment cover are seen (Fig. 7). A rather small zone just south of Qingdao, in the western Yellow Sea, has relict deltaic sediments exposed at or near the seafloor (e.g., Fig. 4). The second, and much larger, relict sediment zone occurs at the leading edge of the Holocene mud wedge that extends south of Cheju Island (Fig. 8); to the south, east and west, Holocene sediment cover is nil (Fig. 7).

The correlation between Holocene sediment thickness (Fig. 7) and surface sediment texture (Fig. 9) is not as simple as one might imagine; sandy sediments do not necessarily infer relict sediment, and muds do not necessarily indicate rapid accumulation. For instance, the sands in the western Yellow Sea south of Qingdao are relict, but the sands off Jiangsu are deltaic sands deposited (and winnowed) within the past 500 years. Similarly, Holocene clays in the central Yellow Sea range in thickness from 1 to 20 m. The texture and thickness of the seafloor sediment therefore reflect both the modern oceanic environment and recent sedimentary history.

4. Effect of Modern Oceanographic Environment on Sediments

Throughout the past eight years, we have continually increased the regional scope of our hydrographic and suspended matter studies until, in 1986, we completed two quas-
Fig. 4. Interpreted W-E Geopulse profile across the Yellow Sea (profile located between the words “Yellow” and “Sea” in Fig. 1). In the west a relict delta is exposed at the sea floor, thus explaining the relict sands seen in the seafloor sediments (e.g., Fig. 7). Note the erosional surface within the deltaic sequence, suggestive of a period of sealevel transgression and subsequent regression. In the central part of the profile, the Shandong wedge of Holocene neritic sediments is seen, thinning considerably to the east. The erosion surface, associated with the last major regression of sea level, is more or less horizontal; seafloor relief is defined by the accumulation of sediments overlying this reflector. From Milliman et al. (1989a).
Fig. 5. Interpreted SSW-NNE Geopulse profile across the Holocene Huanghe delta in the western Yellow Sea. Line is located off the protruding 20 m isobath off Jiangsu Province in Fig. 1. Note the erosion surface, showing more than 60 msec thickness of post-regressional sediment. From Milliman et al. (1989a).

Fig. 6. E-W 3.5 kHz profile across the Shandong mud wedge. The prominent reflector underlying the entire sequence is thought to represent the regression erosion surface. Figure courtesy of Clark Alexander, North Carolina State University.

Synoptic studies of the entire Yellow Sea and northern East China Sea, one cruise in January (winter) and one in July (summer). Nearbottom conditions during both seasons showed similar water masses and net movements, although the relative intensities of currents and transports varied considerably with season.

Circulation is dominated by the northward flow of two loops of the Kuroshio Current, the Taiwan Warm Water (TWW) in the west and the Yellow Sea Warm Water (YSWW) in the east (Fig. 1); both water masses are characterized by high salinities and warm water temperatures. In contrast, southward flow in nearbottom waters occurs by flow of the Changjiang and Jiangsu coastal waters (CJCW and JCW, respectively) along the Chinese coast, the Korean Coastal Water (KCW) in the east, and the Yellow Sea Cold Water (YSCW) in the north. The coastal currents in particular appear as seasonally cold and brackish water masses (e.g., Figs. 10 and 11).
Superimposed on, and related to, this regional circulation is the distribution of suspended sediments within the Yellow and East China seas (Figs. 10 and 11). Surface concentrations generally range from 1 to 100 mg/l in winter and 0.5 to 5 mg/l in the summer (e.g., Fig. 12). Nearbottom concentrations tend to be more equal throughout the year, although in winter nearbottom values still can be considerably higher than surface values. High wintertime concentrations reflect the resuspension of bottom sediments during storms, particularly from the Jiangsu coastal area, and redistribution into the well-mixed water column (Fig. 11). Winter storms often are related to outbreaks of arctic air from the northwest; associated wind-driven currents particularly enhance southeastern flow of the JCW. As a result, a turbid plume of nearbottom water (and often surface water) can be seen extending from Jiangsu to the southeast, often as far as Cheju Island and beyond (Fig. 10).

High TSM concentrations also occur off the eastern tip of the Shandong Peninsula, particularly in winter (e.g., Fig. 10). At present, however, we do not know whether these
plumes of suspended sediment represent southward transport of Yellow River sediment, from the Gulf of Bohai and northern Yellow Sea, via the YSCW, or simply local resuspension of muds within the Shandong mud wedge.

Summer winds tend to come from the south. Except during major storms (typhoons), resuspension is infrequent. Moreover, except in very shallow waters, the water column is stratified, and therefore resuspended sediment tends to remain confined to nearbottom waters below the pycnocline (Fig. 13). Nevertheless, although concentrations are somewhat lower and currents tend to be slower, similar transport paths are seen during the summer (Fig. 11). Suspended particulates above the pycnocline, however, tend to be dominated by biogenic components, such as diatom frustules and organic debris (e.g., HONJO et al., 1974; MILLIMAN et al., 1986).

While our data indicate that resuspension of sediment is largely the result of storm activity and the subsequent transport of this sediment by regional currents, tides can also locally affect surface sediment distribution. Tides are particularly dominant in the East China Sea off the mouth of the Changjiang and off southwestern Korea (Fig. 14). In both instances tidal currents are sufficiently strong (1 to 2 knots; CHOI, 1983; LARSEN et al., 1985) to erode and transport sediments. The combination of the high tidal currents and intrusion of the TWW between the CJCW and the JCW results in a seaward transition from turbid (CJCW) to clear (TWW) to turbid (JCW) waters east of the Changjiang estuary (e.g., Figs. 10–13). As a result, Changjiang sediment tends to remain in the coastal waters and be transported to the south by the CJCW, while the sediments to the east of the TWW are predominantly Huanghe sediments (YANG and MILLIMAN, 1983) transported south by the JCW. The seafloor underlying the clear TWW is covered by relict sands (Figs. 7 and 9).

Off southwestern Korea, a prominent nearbottom sediment plume extends to the west (Figs. 10 and 11). The prominent turbidity front along the southern edge of the plume and analysis of satellite images led WELLS (1988) to conclude that this sediment moves eastward with the Korean Coastal Current, primarily during winter storms. However, both our and Wells’ data indicate that the sediment plume coincides almost exactly with the westward direction of maximum tidal stress. The southern turbidity front shown by Wells, therefore,
appears to represent the abrupt transition from maximum tidal stress from west (north of the front) to east (south of the front) (Fig. 14). We conclude that the net movement of the sediment plume is to the west, facilitated perhaps by the W-NW-flowing YSWW (Fig. 1). Erosion and transport of sediment in this area has resulted in a narrow zone, about 50 km wide, in which little Holocene sediment has accumulated (Fig. 7). Eroded sediment has apparently been deposited on either side of the erosional band in localized mud lenses, 5 to 10 m thick (Milliman et al., 1989c).

5. Synthesis

Sea-level fluctuations over a shallow gradient epicontinental shelf, when combined with large fluxes of river-derived sediment as well as the periodically high energy conditions of the overlying water column, have produced a unique Quaternary sedimentary record in
the Yellow and East China seas. Regressions of sea level are marked by prominent erosional surfaces. Low stands and subsequent transgressions of the sea have produced a series of subaerial and intertidal facies, overlain by a series of neretic to intertidal facies formed during high stands of the sea.

At present, of course, the Yellow-East China Sea is the site of proximal sedimentation from the Huanghe, when it flows south of the Shandong Peninsula, and the Changjiang
Fig. 11. Distribution of temperature (A), salinity (B), density (C) and total suspended matter (D) in nearbottom waters, July 1986. From MILLIMAN et al. (1989b).

(although only in coastal areas). About 90 percent of the Huanghe sediment remains in the proximal environment (BORNHOLD et al., 1986; MILLIMAN et al., 1987); dispersal of the remaining 10 percent occurs primarily during winter storms and, to a lesser extent, by tidal currents, with subsequent transport by regional currents.

If sea level were to remain high for a sufficiently long time, the thick deltaic facies in the west would gradually transgress over the relatively thin neretic sediments and topographic
Fig. 12. W-E profile of temperature, salinity, density and TSM across the southern Yellow Sea in January 1986 (profile located between north shore of Changjiang and west coast of Cheju Island).

relief would be accentuated. Our seismic data, however, show that erosional surfaces in the Yellow-East China Sea are more or less horizontal and show none of the topographic relief seen in the present-day seafloor. This indicates that the regressing sea is capable of eroding much of the sediment deposited during high stands of sea level. For example, while late Pleistocene and Holocene (younger than 18 ka) sediments account for as much as the upper 50 m of sediment directly off the Changjiang, only an additional 40 m of sediment, much of it lag gravels, lies above a horizon dated at 233 ka (Qin, 1987). Clearly, periods of considerable erosion or non-deposition have occurred during the late Quaternary, presumably during sea level regression and/or low stands.
Fig. 13. W-E profile of temperature, salinity, density and TSM across the southern Yellow Sea in July 1986 (profile located between north shore of Changjiang and west coast of Cheju Island).

Much, if not most, of the sediment eroded by the regressing sea was probably transported seaward. Some of it was spread over the shelf, but at least some reached the Okinawa Trough, as indicated by sediment progradations along the northern slope of the Trough (Fig. 15). The lack of a prominent delta (for example, a Mississippi bird's foot) alongside the Okinawa Trough may simply mean that the meandering Huanghe did not occupy a single channel long enough (perhaps no more than a year or two, judging from the history of the modern Huanghe) to permit accumulation of a thick deltaic sequence. Moreover, the tectonic activity of the Okinawa Trough, plus the strong erosional potential of the Kuroshio Current, also may have transported a substantial amount of sediment
Fig. 14. Vectors of maximum nearbottom tidal stress in the Yellow and East China seas. Note high levels of bottom stress east of the Changjiang and off southwestern Korea. After Choi (1983).

downslope or downstream, thus blurring any deltaic morphology. We hope that future work in this area will allow us to define in greater detail the history of sediment flux to the Trough, particularly during low stands of sea level.
Fig. 15. Interpreted multichannel seismic profile across the northern edge of the Okinawa Trough, near the probable mouth of the Huanghe during lowered sea level. The marked progradation of sediment across the Trough, plus the low acoustic velocity of this sediment (generally 1.9 to 2.3 km/sec; e.g., LEYDEN et al., 1973; LUDWIG et al., 1973), suggest this sediment to be Neogene in age, thus supporting the Huanghe origin. Profile courtesy of Chevron Oil Company.

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