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# Tectonic Control of High-Frequency Holocene Delta Switching and Fluvial Migration in Lingayen Gulf Bayhead, Northwestern Philippines

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**ABSTRACT**

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Remotely sensed images, maps, charts, and historical accounts document the evolution of the Lingayen Gulf bayhead plain in the northwestern Philippines. Beach ridges and relict channel patterns record delta progradation and switching that, together with meander belt migration, constructed the bayhead plain. The latest delta switching occurred after 1935, when the downstream portion of the Agno River, the largest river discharging into the bayhead, was artificially diverted to a more direct route. The shoreline retreated in the abandoned delta; in contrast, paired sets of beach ridges that diverge toward the new river mouth formed a cuspate delta. In the more landward portions of the coastal plain, similar but older pairs of wedge-shaped beach ridge sets occur between more continuous to parallel sets that also truncate their apical ends. The pair of wedge-shaped sets was used to map paleodelta lobes; the continuous-parallel sets record transgressive events. Within 7 kilometers of the bayhead plain, at least 15 paleodelta lobes were alternately, successively, or simultaneously built by three river systems. These paleodeltas formed during the sea level fall from 2.4 ka to the present. Before this, westward tilting because of movements along the two faults that bound the alluvial plain and switching of the main distributary channel of the Agno alluvial fan caused the lower Agno River to migrate episodically to the southwest. Continued channel avulsions in the alluvial fan changed the sediment loads of the multiple river pathways created by meander belt migration, leading to delta switching downstream. Contemporaneous 220-year recurrences of delta switching and high-magnitude Philippine Fault earthquakes indicate tectonic control of the bayhead plain evolution.

**ADDITIONAL INDEX WORDS:** *Beach ridges, strandplain, shoreline change, meander belts, alluvial fans, earthquakes, Agno River.*

## INTRODUCTION

Delta and river systems respond to processes like valley filling and channel avulsions and can be purely internal or influenced by external processes that include tectonism, changing climate and sea level, and, in recent times, human activities. An example of such a response is *delta switching,* in which a distributary channel or fluvial system adopts a new, hydraulically more efficient route. Delta switching can result naturally from delta plain aggradation, changes in sediment input, or upstream channel avulsion caused by tectonic tilting (SUTER, 1994). Modern cases of delta switching, however, have resulted from artificial alterations of deltas, such as those of the Brazos (HAMILTON and ANDERSON, 1994) and Mississippi (COLEMAN, ROBERTS, and STONE, 1998) rivers. Whether natural or induced by humans, switching of deltas and river channels leads to similar long- and short-term responses and morphologic changes. Even minor modifications can be amplified by the complex linkages between the different watershed environments and processes, leading to catastrophic adjustments that can be unexpected.

In this paper, we describe the Late Holocene geomorphic evolution of the bayhead plain of the Lingayen Gulf. We also explore how tectonic movements and climate and sea level changes might have influenced that fluviodeltaic system.

## STUDY AREA

### Physiographic and Tectonic Setting

Lingayen Gulf and its watershed (Figure 1) cover 11,330 square kilometers. It is the northern subbasin of the Central Luzon Basin, one of 13 Philippine sedimentary basins. On land, this basin is physiographically expressed as the Central Luzon Plain, which is confined to the east by the Cordillera and Caraballo mountains and to the west by the Zambales

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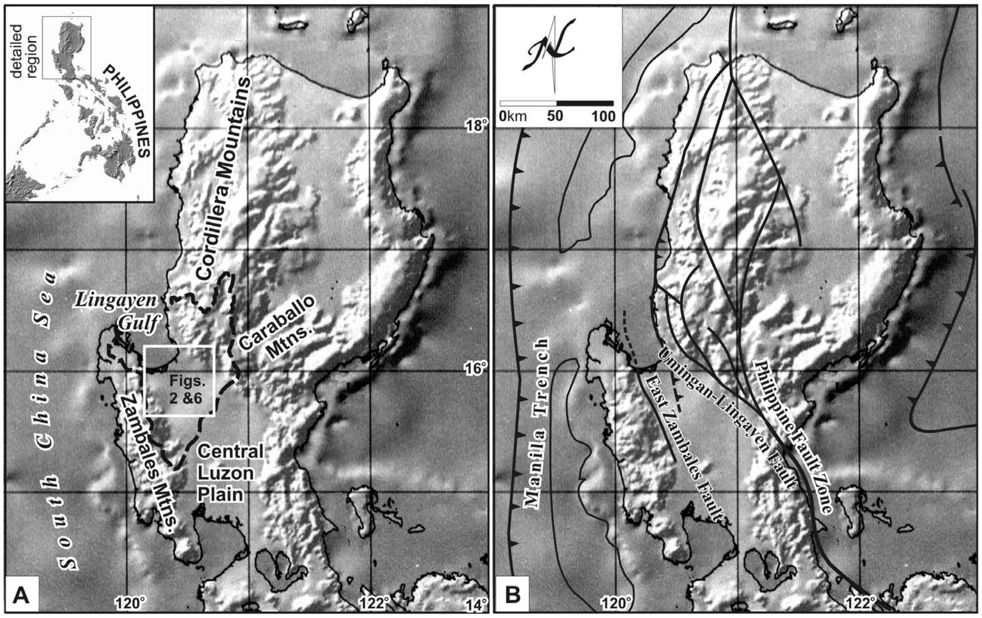


Figure 1. Relief map of Luzon, northern Philippines, showing the (A) physiographic and (B) structural features surrounding Lingayen Gulf. The watershed, delineated by the dashed line, is bounded to the east and west by mountain ranges and faults. Relief maps modified from Department of Environment and Natural Resources (1998) and http://www.ngdc.noaa.gov/seg/topo/img/philshad.gif. White box indicates location of area shown in Figures 2 and 6.

Mountains. The plain is underlain by a 14-kilometer-thick accumulation of Paleogene to Holocene sedimentary rocks intruded by Quaternary volcanic centers (BACHMAN, LEWIS, and SCHWELLER, 1983).

Active tectonic structures nearby are the east-dipping subduction zone expressed at the surface as the Manila Trench, the north–south East Zambales Fault to the west, and the northwesterly to northerly segments of the oblique Philippine Fault Zone to the east (Figure 1). LEWIS and HAYES (1983) identified the northwesterly boundary of the Caraballo and Cordillera mountains with the Central Luzon Plain as the Umingan-Lingayen Fault, which continues to the central offshore region of Lingayen Gulf. MALETERRE (1989) described this structure as an east-dipping thrust fault confined to the eastern coast of the gulf and extending southward to the center of the plain. The normal Zambales Fault to the west (BUREAU OF MINES AND GEOSCIENCES, 1981) is the boundary between the plain and the mountain range. In high-resolution seismic profiles, the fault extends northward along the western offshore margin of Lingayen Gulf (SALAS, NATIVIDAD, and ABARQUEZ, 1991).

## Coastal Morphology

Lingayen Gulf is a north-trending U-shaped embayment and trough that opens to the South China Sea (Figures 1 and 2). Averaging 40 kilometers in width and 63 kilometers long, the gulf has an area of approximately 2520 square kilometers. The 49-kilometer-long curvilinear bayhead coast stretches eastward from Sual to San Fabian. Along this shoreline are the four distributaries of the Bued-Patalan, Dagupan, and Agno rivers. Two of these distributaries belong to the Agno River: the Agno-Lingayen and Agno-Labrador channels. Of the four river mouths, only the Bued-Patalan and Agno-Lingayen have deltas. Cuspate in plan, they indicate the dominance of wave processes (COLEMAN and WRIGHT, 1975), which have also built beach ridges that form a 16-kilometer-wide strandplain. In aerial photographs and satellite images, well-preserved beach ridges oriented parallel or slightly oblique to the shore occur within 5 to 7 kilometers of the present shoreline. Similar ridges 5 to 16 kilometers from the shoreline have been dissected, partially eroded, or covered by river channels and floodplain deposits.

## River and Alluvial Fan Systems

The Central Luzon Plain comprises broad, fertile fluvial and deltaic plains dissected by numerous active and relict river channels that indicate frequent channel avulsion. The latest avulsion occurred near Urbiztondo, from a channel that previously flowed east of San Carlos and through Binmaley (PUNONGBAYAN *et al.,* 1990). At present, five major river systems supply most of the fresh water and sediment received by Lingayen Gulf (Table 1). Three of these, the Bued-Patalan, Dagupan, and Agno rivers, traverse the bayhead plain (Figure 2).

The Bued-Patalan River system at the northeastern side of the bayhead coast drains 630 square kilometers of the southern Cordillera Mountains and empties $388 \times 10^6$ $m^3$ $y^{-1}$ of water into the gulf near San Fabian. The Bued River descends across two levels of alluvial fans (Figure 2), and tributaries of the Patalan River also emanate from another alluvial fan to the east.

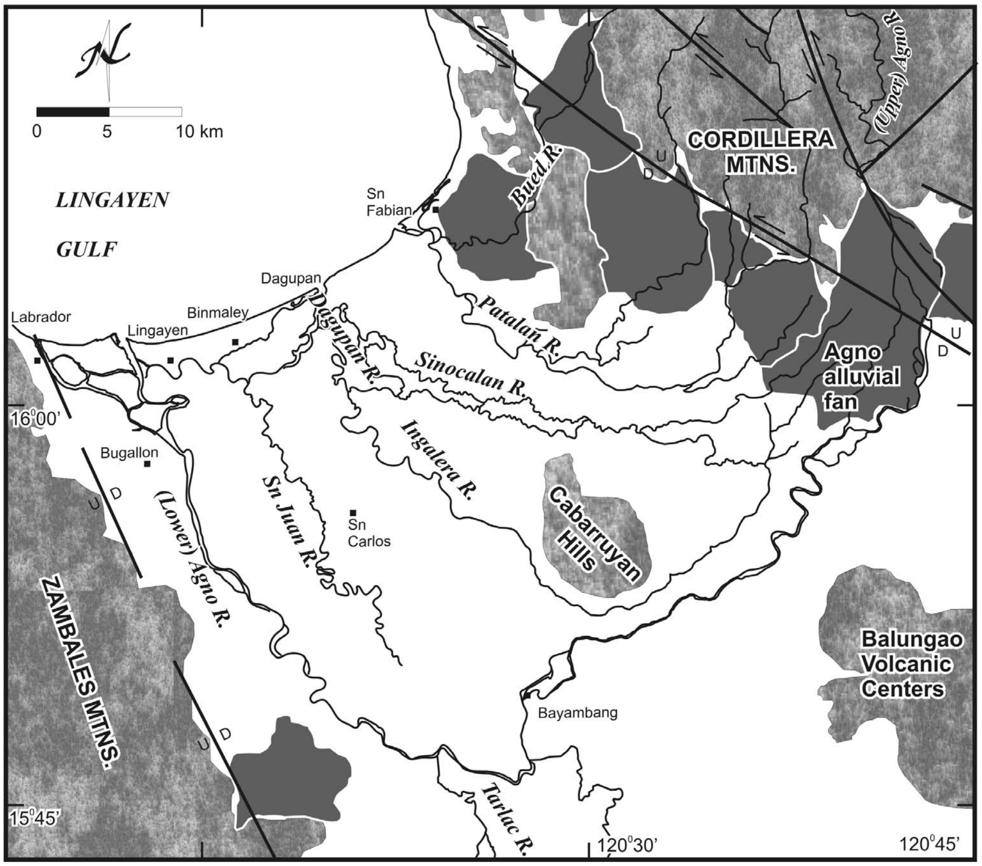


Figure 2. Drainage map showing the three major river systems—Agno, Dagupan, and Bued-Patalan—emptying to the Lingayen Gulf through four deltas. Tributaries of the Dagupan River extend to the western section of the Agno alluvial fan. These alluvial fans along the eastern foothills are controlled by the Lingayen-Umingan Fault, a splay of the Philippine Fault Zone. Gray-shaded areas are higher than 100 m.

Near the center of the bayhead coast, the Dagupan River system drains 1115 square kilometers of the northern region of the Central Luzon Plain through three major tributaries that converge near Dagupan City. The easternmost major tributary is the Sinocalan River, and occupying the midsection of the plain is the Ingalera River. Both rivers have tributaries that emanate from the Agno alluvial fan (Figure 2).

Table 1. *Major river systems draining into Lingayen Gulf. Only Agno, Dagupan, and Bued-Patalan enter along the bayhead coast. (Compiled from National Water Resources Council [1976, 1983] and Japan International Cooperation Agency—Department of Public Works and Highways [1991].)*

| River System | Drainage Area ($km^2$) | Length (km) | Discharge ($10^6$ $m^3$ $y^{-1}$) |
|---|---|---|---|
| Agno | 5952 | 275 | 6664 |
| Dagupan | 1115 | 75 | 1002 |
| Bued-Patalan | 630 | 61 | 388 |
| Aringay | 397 | 75 | 929 |
| Bauang | 516 | 92 | 674 |
| Total | 8610 | 578 | 9657 |

The third major tributary of Dagupan River is the San Juan River, which drains the region west of San Carlos.

The Agno River is the longest at 275 kilometers and is largest of the river systems, delivering $6664 \times 10^6$ $m^3$ $y^{-1}$ or 70% of the annual freshwater and sediment budget of Lingayen Gulf from 5952 square kilometers or 68% of the watershed area. It originates within the Cordillera at an elevation of 2090 meters, flowing southward along an incised channel (Figure 1). Where it emerges from the Cordillera Mountains, the river has built a south-facing alluvial fan and, at present, follows its easternmost distributary channel (Figure 2). Emerging from its canyon on the Luzon Central Plain, the Agno River meanders southwestward to its confluence with the Tarlac River coming from the south. From this junction, the Agno River veers north toward Lingayen Gulf and drains the northeastern flank of the Zambales Mountains. Finally, the Agno River enters the gulf through the Agno-Labrador and the Agno-Lingayen or Limahong distributary channels.

Alluvial fans all occur along the southwestern foot of the Cordillera Mountains, a topographic boundary defined by several segments of the Philippine Fault Zone. Movements along these faults are major influences on the evolution of these alluvial fans (SAITO, 1996).

## Database and Methods

This study investigates the evolution of the Lingayen Gulf bayhead plain on two time scales: modern (the last century) and prehistory (the last 10,000 YBP). Modern spatiotemporal changes in the position of the bayhead shoreline were determined from topographic maps, nautical charts, aerial photographs, and a synthetic-aperture radar (SAR) image. The positions of the bayhead shoreline were digitized and, after appropriate scale and projection corrections, were transferred to a 1 : 50,000 topographic base map (National Mapping and Resource Information Agency, 1977) for graphical and numerical data comparisons.

Documentation of older events also required the analysis of relict geomorphic features such as beach ridges and swales and river channels. Beach ridges were traced from a mosaic of unrectified 1 : 40,000 aerial photographs and grouped into sets and systems on the basis of relative positions, spatial relationships, patterns, orientations, and continuity.

Paleodrainages were reconstructed by tracing active and relict channels from SAR images of the bayhead plain. Morphologic analysis of the active and relict channels was based on channel continuity and proximity, meander orientations, and the density of surrounding vegetation. The traces were then grouped to define major meander belts, and their relative ages were determined from cross-cutting relationships. Such information, coupled with the identified patterns of meander loop preservation (ALEXANDER *et al.,* 1994; WELLS and DORR, 1987), was used to determine the general direction of fluvial migration. Later channel-switching events were confirmed in historical documents and by interviewing long-time local residents.

# RESULTS

## Modern Channel and Delta Switching

When Spanish friars prepared a detailed map of the Lingayen Gulf bayhead plain in 1858 and in the late 19th century (CORTES, 1974; MANILA OBSERVATORIO, 1900; Figure 3A), the Agno River was already the largest river draining the region, but it differed significantly from its present route. It used to bifurcate near Bugallon, formerly called Salasa; the shorter, more efficient route to Lingayen Gulf was through a western distributary that still exists: the Agno-Labrador Channel from Bugallon northwestward to Labrador. A second distributary channel used to run eastward from Bugallon, paralleling the coast south of Binmaley and north of San Carlos City before veering north to empty into the gulf at Dagupan City. At that time, the only well-defined promontory along the bayhead coast was situated off Dagupan. In the 1901–1903 USCGS Chart 4209, however, the Dagupan promontory no longer existed, and a delta lobe had formed off the Agno-Labrador Channel (ALLIED GEOGRAPHICAL SECTION, 1944; Figure 3B).

The 1858 map shows a short, north-flowing channel originating at Bugallon and intersecting Basing River, a tidal creek paralleling the coast from Binmaley to San Isidro. After a large flood in 1935, the Agno-Lingayen cutoff channel (Figure 3C) was constructed to improve flushing of the Agno River. Long-time residents say that the cutoff was initially only a meter deep and about 50 meters wide, but continuous dredging has deepened it to around 4 meters and widened it to approximately 500 meters. Channel shortening of about 7 kilometers increased the channel gradient, enhancing the delivery of bed load to the Agno-Lingayen coast. This reduced the flow of freshwater and sediment through the Agno-Labrador Channel, starving the former deltaic shoreline and exposing it to wave attack. In contrast, the Agno-Lingayen River mouth prograded rapidly, transforming the previously linear shoreline into a distinct deltaic promontory.

## Modern Beach Ridges of the Agno Deltas

Beach ridges are well defined in 1992 aerial photographs and 1991 SAR images of the newly prograded Agno-Lingayen Delta (Figure 4). As demonstrated elsewhere (TANNER, 1987; TAYLOR and STONE, 1996), the individual shapes and orientations of these ridges indicate both littoral and fluvial sediment sources. On the western flank they are curvilinear, but those on the eastern flank are recurved where they form a spit. Two genetically distinct groups compose these beach ridges. Covering the inner 500 meter-wide zone of the delta plain, the first set of ridges are spaced about 100 meters apart and gradually become shorter and more recurved toward the river mouth, especially on the western flank. This bidirectional tapering indicates the primary role of longshore drift in the development of ridges. Beach ridges of the outer, second group are more closely spaced at 15–30 meters. They diverge toward the river mouth to form the triangular western delta plain, consistent with the positive relationship between sediment supply and their spacing.

Ages of the beach ridges were approximated by superimposing the historical shoreline positions. The first group was formed from the early 1950s to late 1970s, while the nearby Agno-Labrador Delta was being rapidly eroded. Morphological indicators such as easterly river mouth bar closure suggest that the eroded materials were transported alongshore toward the Agno-Lingayen Delta (Figure 3C). However, discharge from Agno-Lingayen Channel acted as a jetty that trapped the drifting sediments on the western delta flank—hence, the alongshore and rapidly prograded character of this set of ridges. The second group of ridges began to form when the eroded materials derived from the Agno-Labrador River diminished and the sediment delivery of Agno-Lingayen Channel increased. At the same time, the growth of the Agno-Lingayen Delta promontory reversed the longshore drift westward, as indicated by the direction of the Agno-Labrador mouth bars.

The Agno-Lingayen Delta beach ridges onlap a similar set farther inland that outline the former Agno-Labrador subaerial delta lobe (set 13 in Figure 4). However, the Agno-Labrador Channel runs along the foot of the Zambales Mountains, and so these beach ridges define only the eastern delta flank, converging toward Lingayen, away from the fluvial point source. The outermost ridge approximates the 1954 shoreline position and defines the boundary with the younger Agno-Lingayen beach ridges. Aside from being constructed just before the shift of the active outlet channel, it also rep-

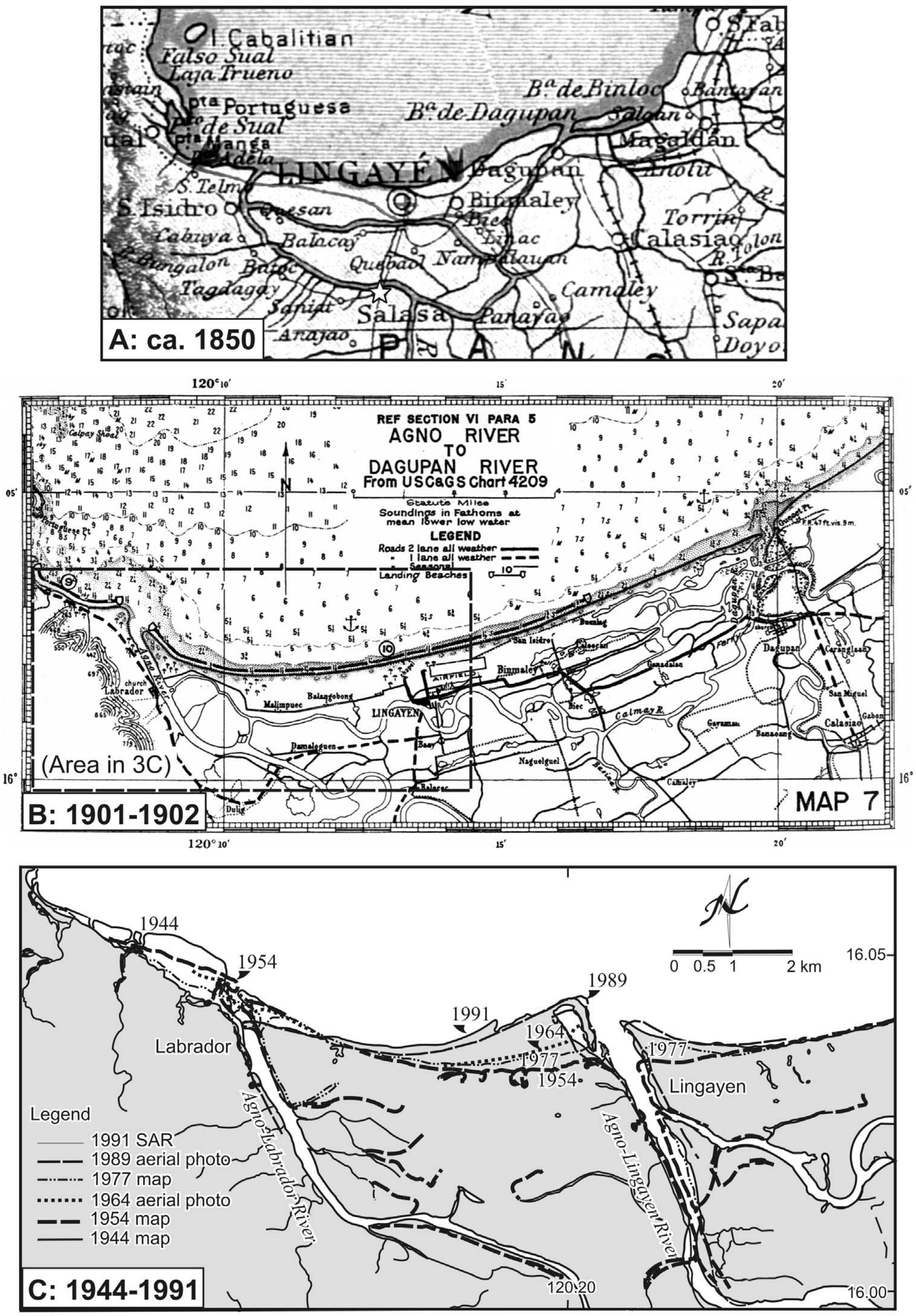


Figure 3. Time series of maps and chart showing changes in the position of the active delta. From the (A) mid-19th to the (B) early 20th centuries, the active delta switched from the Dagupan River to the Agno-Labrador channel. (C) The switch to the Agno-Lingayen cutoff is documented by the progradation of a deltaic shoreline and retreat of the former. Note that Salasa, marked by a star in panel A, is presently called Bugallon.

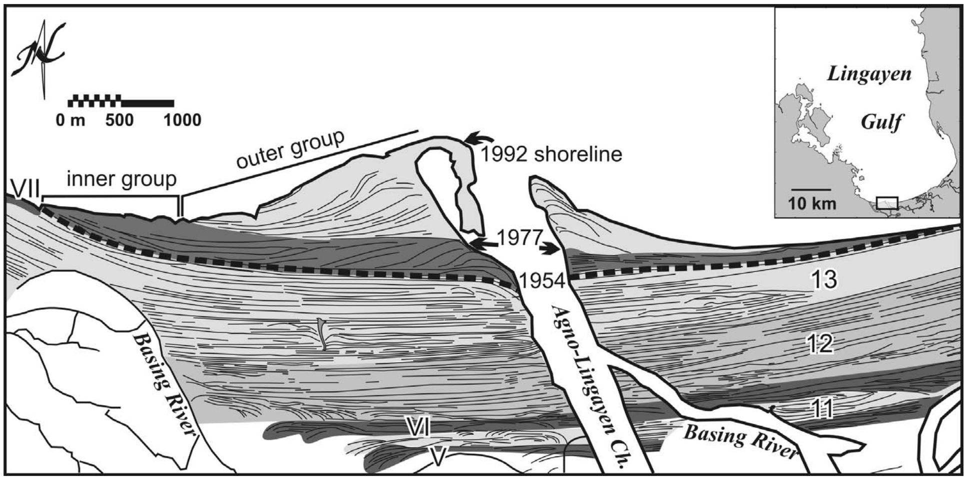


Figure 4. The newly formed Agno-Lingayen Delta, seaward of bold-dashed line, shown with two morphologically and genetically distinct beach ridge sets that characterize a prograding delta. The closely spaced and longer inner group of ridges formed between the 1950s to 1980s, mostly from longshore transport of eroded sediments of the Agno-Labrador Delta to the west. The high-angle and shorter ridges of the outer group reflect dominance of sediment supply from the Agno-Lingayen channel. Similarity of older and more inland sets, such as 11, 12, and 13, indicate that these are remnants of paleodelta lobes.

resents the farthest progradational extent of the Agno-Labrador Delta. This ridge set was truncated by delta abandonment and retreat and lies at an angle to the new shoreline. Nonetheless, the outermost of these ridges projects 800 meters seaward of the present Agno-Labrador River mouth, defining the former delta plain.

## Prehistoric Delta Switching

Applying the principles just discussed, similar paleoenvironments and landforms were identified from older beach ridges as far inland as 16 kilometers (Figure 5A). Aside from indicating paleoshorelines, beach ridge plains that are triangular in plan centered across a channel are identified as paleodelta lobes (CENCINI, 1998; CIABATTI, 1967; DOMINGUEZ, MARTIN, and BITTENCOURT, 1987; INNOCENTI and PRANZINI, 1993; MASON, 1993; PSUTY, 1967; SIRINGAN and RINGOR, 1997). Discordant beach ridge sets therefore reflect a shifting river mouth (CIABATTI, 1967; PSUTY, 1967; SIRINGAN and RINGOR, 1997). Beach ridges are present as far inland as 16 kilometers but are discontinuous, so we interpret only the more continuous ridges within 7 kilometers from the present shoreline. These occur in sets of two morphologically and genetically contrasting types: wedge-shaped and continuous-parallel ridge sets, respectively numbered in Roman and Arabic numerals (Figure 5A).

## Wedge-Shaped Beach Ridge Sets and Paleodelta Lobes

Two to three wedge-shaped to lensoidal sets of beach ridges, chronologically designated 1–16 in Figure 5A, are situated between the continuous-parallel sets. These are low-lying and are generally spaced 20–45 meters, but as much as 100 meters apart. In plan, individual ridges are convex, occur as crude mirror images on both sides of a river, and widen toward an axis that represents an existing or relict channel. Thus, each is oriented oblique to the continuous-parallel ridge sets seaward and landward of it. The landward limit of a wedge-shaped set is tangential with the adjacent continuous-parallel set but forms a more angular relationship of about 5° to 20° with the seaward-bounding continuous-parallel beach ridge set, indicating shoreline truncation. In some places, however, ridges are more parallel and have bifurcating or landward-recurved distal segments, such as those west of the Agno River. Within 7 kilometers of the bayhead shoreline, 17 sets of wedge-shaped beach ridge sets are distributed among the three bayhead rivers. Sets 1, 3, 4b, 7, 9b, and 13 all diverge toward the Agno River. Sets 5, 8, 10, and 12 have more distinct patterns and occur on both sides of the Dagupan River; farther upstream, sets 2 and 4a were identified only in the west. Diverging less regularly, sets 6, 7, 9a, 14, 15, and 16 are associated with the Bued-Patalan River.

The paired sets of wedge-shaped ridges define a triangular geometry by diverging on an active or relict channel. Agreeing with the reasoning of CIABATTI (1967), DOMINGUEZ, MARTIN, and BITTENCOURT (1987), PSUTY (1967), and SUTER (1994), we interpret these as paleodelta lobes that represent a regressive phase in the shoreline development. A modern example is the pattern of the newly prograded Agno-Lingayen delta plain. At least 15 paleodelta lobes are identified on the bayhead plain (Figure 5B).

## Continuous–Parallel Beach Ridge Sets

Each continuous-parallel beach ridge set comprises three to 10 fairly continuous ridges oriented parallel to the present shoreline and standing higher than flanking ridges and swales (Figure 5A). These sets are designated I–VII in order of their age and distance from the coast. The average widths of the sets range from 0.4 to <0.1 kilometers and decrease toward the coast (Figure 5A, inset graph). The highest ele-

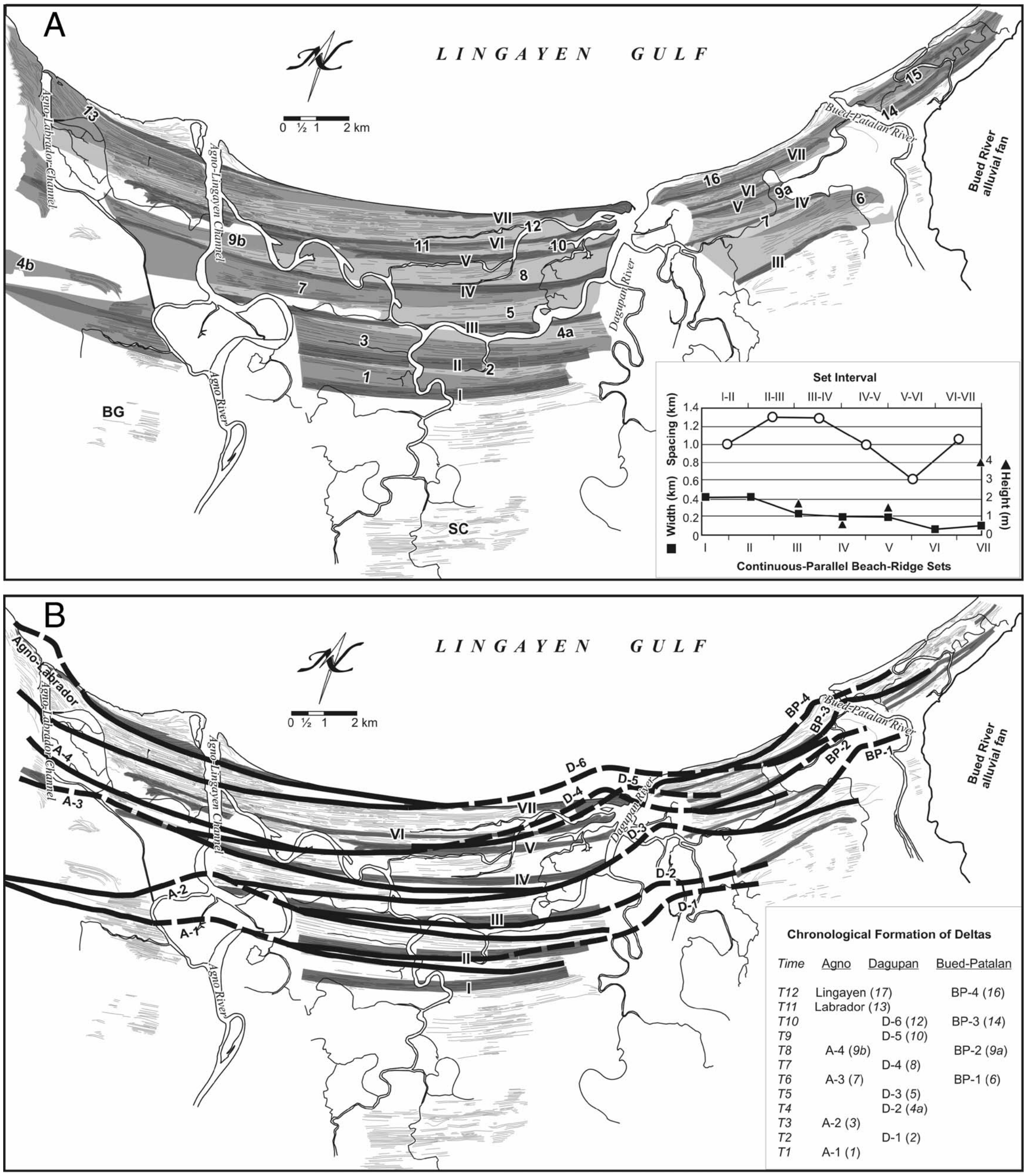


Figure 5. (A) Wedge-shaped (1–16, BG, SC) and continuous-parallel (I–VII) sets of beach ridges formed during delta progradation and erosion, respectively. Insert is a graph of the morphologic parameters of the continuous-parallel beach ridge sets showing a gradual decrease in set width and a regular change in set intervals. (B) Positions and reconstructed extents of paleodelta lobes that formed the bayhead plain. Dashed lines delineate delta sections reworked to form a segment of a continuous-parallel ridge set. Within 5–7 kilometers of the shoreline, 16 deltas formed. (Insert) A table showing the relative temporal succession of the different deltas, and the corresponding wedge-shaped set in parentheses.

vation, at 4 meters, is in the youngest set. Spacing between the sets range from 0.6 to 1.3 kilometers.

The oldest set I lies 6250 meters inland between the Agno and Dagupan rivers. Set VII, the youngest and northernmost, has a steep landward flank and follows the present shoreline from northern Binmaley to western Dagupan City. A 31.5-meter-long core, drilled at an elevation of 4.3 meters, consists of 18.5 meters of medium-dense, grayish, fine to medium sand underlain by 9.5 meters of gray fine sand and a basal 3.5 meters of dark-gray, clayey silt (Japan International Cooperation Agency—Department of Public Works and Highways, 1991). East of Dagupan River, set VII continues west of the Bued-Patalan River mouth. Unlike the segment west of the Dagupan River, this eastern segment is 500 to 750 meters landward of the shoreline; seaward of this are the paired wedge-shaped beach ridge sets built by the Agno River.

The continuous-parallel beach ridge sets correspond to the transgressive beach ridges of PSUTY (1967) and TAYLOR and STONE (1996). Following delta construction, headland erosion truncates the delta lobes (PSUTY, 1967; TAYLOR and STONE, 1996), and the reworked materials are deposited alongshore and landward, forming transgressive ridges. The Agno-Labrador Delta is the modern equivalent of the eroded deltas.

### Meander Belts

At least 10 meander belts are associated with seven present-day river systems (Figure 6). Their cross-cutting relationships and patterns of meander loop preservation (ALEXANDER *et al.,* 1994; WELLS and DORR, 1987) document the relative ages and general direction of migrations. The first and northernmost meander belt is R1, originating from the Agno alluvial fan and emptying through the Dagupan Delta. Another avulsion forced the active channel to flow farther south around the Cabaruyan Hills, creating meander belt R2.

To the southwest, a meander belt and minor cutoff record R3, the second oldest river system. It is more sinuous than R2 and consists of five almost symmetrical meanders with an average wavelength of 7 kilometers. R2 and R3 merge midway toward the Dagupan Delta. An avulsion created a shorter route through the second meander (Figure 6, point a). There, a similar avulsion subsequently formed R4, which flowed sinuously westward, southward, and northward to join the first two river systems (Figure 6, point b). Meander belt R5, delineated by several surviving oxbow lakes, was formed by three subsequent avulsions. After flowing 7.5 kilometers westward, R5 veered northwestward and merged with R3. Meander belts R1–R5 entered Lingayen Gulf through the Dagupan area. A penultimate avulsion (Figure 6, point c) created R6, which meandered more tortuously (Figures 2 and 6). It branched to the west to merge with R7, represented by the present Tarlac–Lower Agno River, which was probably coeval with R1. To summarize, at least seven midstream avulsions have caused meander belts to migrate southwestward across the bayhead plain. The abandoned channels still funnel the runoff from local rain, as evidenced by old cutoffs that connect successive major meander belts.

## DISCUSSION

### Age of the Beach Ridges

Tidal notches and uplifted coral reef terraces in the Philippine archipelago define at least two higher-than-present Holocene stillstands (MAEDA *et al.,* 2004). The older one, which occurred around 7.2–5.5 ka, was less than 1 meter higher than present sea level. After an abrupt rise, sea level then stood more than 1 meter above the present level from around 5.5 to 2.4 ka. We infer that the oldest beach ridge 16 kilometers inland formed between 7.2 and 5.5 ka and that the well-preserved beach ridges situated from the coast to 7 kilometers inland formed while sea level fell from 2.4 ka to the present. This age estimate yields an average progradation rate of 3 m $y^{-1}$, which, when applied to the innermost ridge 16 kilometers from the shoreline, indicates an age of around 5.3 ka, close to the time when the second stillstand was initiated. The age should be greater, however, to account for the several hiatuses associated with delta switching.

### Timing and Causes of Meander Belt Migration

Meander belts were migrating long before the beach ridges situated from the coast to 7 kilometers inland formed, as evidenced by the cross-cutting relationships. The well-preserved meander belts indicate episodic shifts.

Meander belt migration created multiple pathways for the upper Agno River as it entered the alluvial plain. Tectonic tilting, lateral valley filling, or both could have caused the meander belts to migrate southwestward. This will be expounded in a subsequent section, together with their relationship to the origin of the sets of beach ridges.

### Beach Ridge Formation and the Delta Cycle

Each couplet of continuous-parallel and wedge-shaped sets is produced by one complete deltaic cycle (Figure 7). The regressive phase is fairly straightforward: wedge-shaped ridges mark successive shoreline positions that record the advance of the delta plain (Figure 7A). Internal or external factors slow and eventually end the progradation, succeeded by the transgressive phase, which is more complicated. The headland of a wave-dominated cuspate delta is eroded first (PRANZINI, 1989). Some of the reworked material is distributed alongshore, and the delta flanks prograde as new beach ridges are formed, similar to those created earlier (INNOCENTI and PRANZINI, 1993; ÖTVOS, 2000; PILKEY and THIELER, 1992; see Figure 7B). The rest is transported onshore along the eroding delta coast, forming relatively high ridges with steep leeward sides in angular contact with the truncated wedge-shaped set. Longshore transport can also form spits. Nearby, a new deltaic cycle creates a new pair of wedge-shaped ridge sets, discordant to the first, and a set of continuous-parallel ridges that eventually coalesces laterally with that of the first delta (Figure 7C and 7D).

Formed in this cyclical fashion, the Lingayen bayhead paleodelta lobes record frequent switching. The oldest pair of wedge-shaped beach ridges (A-1, Figure 5B) is associated with the Agno River, which at that time already had the Tarlac River as a tributary (Figure 6). Truncation of this lobe formed continuous-parallel beach ridge set II. Simultaneously, a new delta lobe, D1, was built to the east, centered at the present Dagupan River. Following a second switch, D1 also eroded and formed a lateral extension of a preexisting transgressive beach ridge. A third delta lobe then formed along the Agno River, and another cycle of delta switching started beyond the first transgressive ridge set. At least 15 deltas were established as the bayhead shoreline prograded to its present position.

Given the 11 Agno and Dagupan deltas, delta switching occurred at an average interval of approximately 220 years. A less regular periodicity is suggested, however, by the varying widths of paleodeltas and spacing between the transgressive sets (Figure 5A, inset graph).

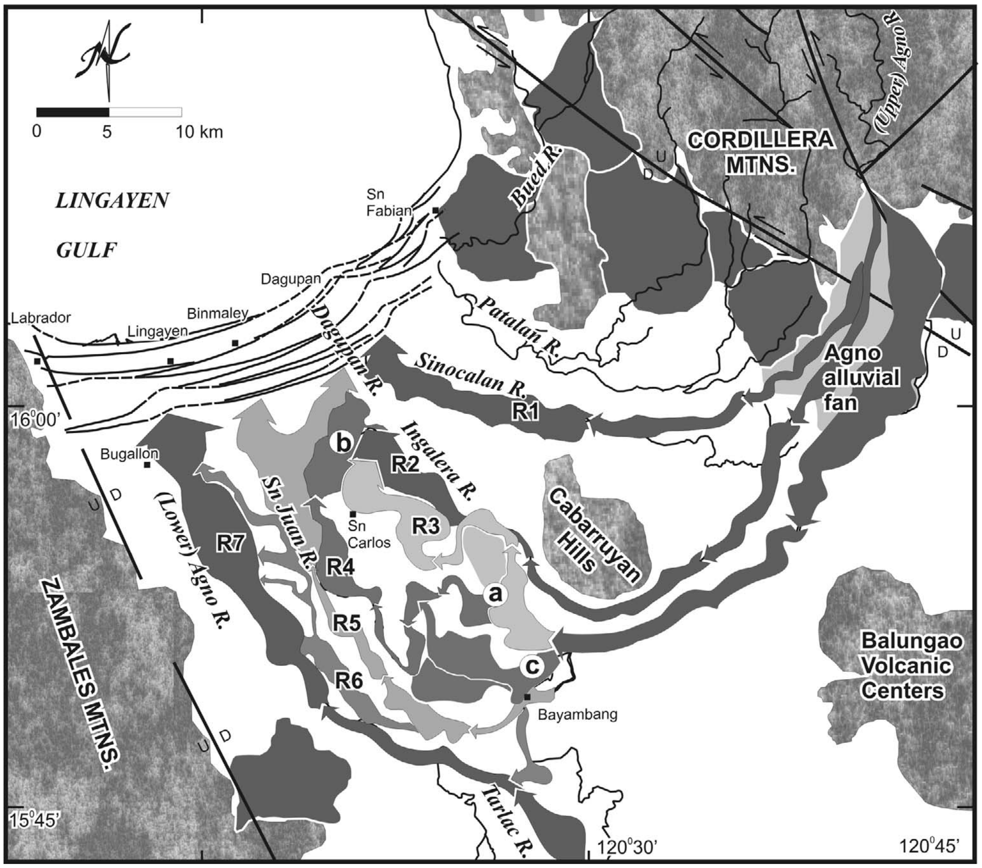


Figure 6. Meander belts established within the bayhead plain through the southwestward migration of the Sinocalan River (R1) toward the ancient Tarlac–Lower Agno River (R7). Points a and c are sites of avulsions, and point b is an area of confluence. Meander belts R1–R5 all entered the gulf through Dagupan River. The lower and upper segments of the present Agno River was established following R6 by an avulsion near point c. Also indicated in the figure are the traces of the paleodeltas.

## Possible Causes of Delta Switching

Alternate progradation and retreat of Agno and Dagupan paleodeltas cannot be explained simply by switching of distributary channels within the bayhead or delta plain because there is no deltaic distributary channel through which this could have occurred. The most reasonable explanation involves shifting of the main distributary channel of the Agno alluvial fan to connect at various times with the lower Agno, Ingalera, or Sinocalan rivers, the multiple pathways formed through meander belt migration at an earlier time (Figure 8).

Switching of the main distributary channel of the Agno alluvial fan would have changed the sediment loads of the multiple pathways, thereby determining whether a delta lobe was to prograde or transgress. However, with the Tarlac River feeding R7, and with more than one active distributary channel in the Agno alluvial fan, multiple delta lobes could have been active at any time. At present, the most active distributary channel, along the eastern flank of the alluvial fan, delivers most of the Upper Agno sediments to the lower Agno River. Shoreline progradation therefore dominates the western side of the bayhead coast. Previously, the active distributary channel was directed to either the Sinocalan or Ingalera rivers, both of which would cause the Dagupan Delta to prograde. Successive distributary shifting to these two river systems produced the successive delta lobes D2–D3 and D5–D6.

The switching of an alluvial fan distributary channel can be controlled by a number of internal or external factors. Such changes generally are controlled by sediment supply, which is closely linked to the external processes of sea level and climatic changes, or tectonism (*e.g.,* Schumm, 1993). In India, aggradation and switching caused by earthquakes or floods have caused the distributary channels of the Kosi River fan to shift unidirectionally (Wells and Dorr, 1987).

### Sea Level and Climate Changes

The rise and fall of sea level alters the gradients of distributary channels, forcing deltas to adopt more efficient courses (Dominguez, Martin, and Bittencourt, 1987). Moreover, the very low elevation of bayhead plains allows even minor sea level changes to propagate their effects far upstream. Minor sea level changes often cause stream patterns to transform, and slower fluctuations permit considerable lateral mi-

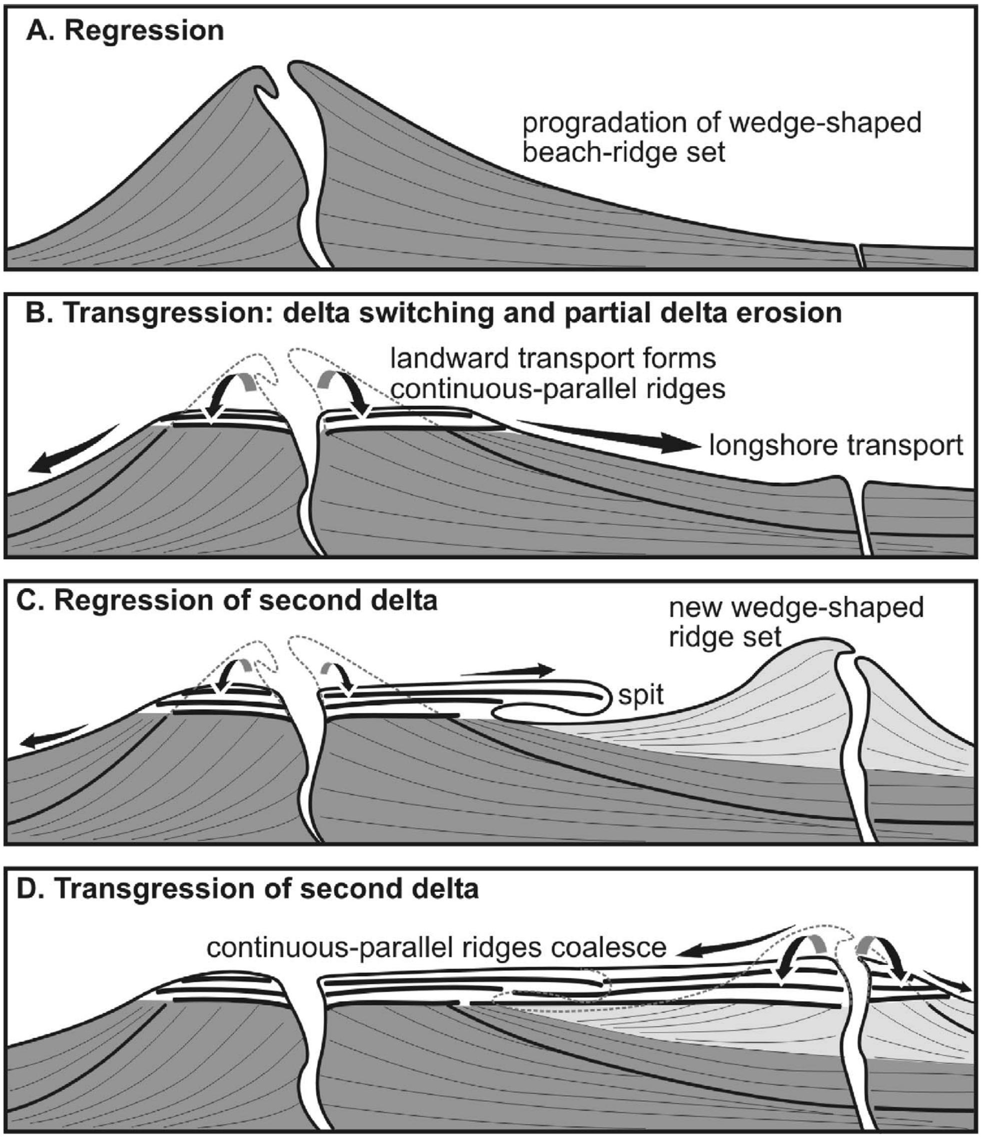


Figure 7. Formation of regressive and transgressive beach ridge sets during a delta switching cycle.

gration (SCHUMM, 1993). The primary control of channel and delta migrations by sea level changes has been well documented in the northwestern Gulf of Mexico (ANDERSON *et al.,* 1991; SUTER, 1994). Similar shifts in response to changes in lakeshore position have also been identified in southwestern Montana (ALEXANDER *et al.,* 1994).

In the mid-Holocene of the Baltic Sea, YU (2003) extracted sea level oscillations of 150–450-year cycles; dominating the signal is the 220-year cycle associated with the solar Suess Period. TANNER (1995), on the basis of the morphology and sedimentology of late Holocene sandy beach ridges and swales from several locations worldwide, inferred higher frequency sea level changes with 30–60-year periodicity and 5–30 cm of amplitude. This cannot be applied to the Lingayen coastal plain because detailed studies of sea level change have yet to be conducted there.

Changes in precipitation, especially intensity, could also lead to changes in sediment delivery to the alluvial fan, resulting in channel aggradation or erosion and eventual avulsion. Geochemical proxies document that the Indian monsoon and wet periods in northeastern China vary with changes in total solar irradiance, with one of the periodicities at 200 ± 20 years (AGNIHOTRI *et al.,* 2002; HONG *et al.,* 2001). In the central Philippines, a coral $\delta^{18}O$ record for temperature and rainfall from 1859 to 1980 indicate a shift from cooler and drier to warmer and wetter conditions about 1940 (GAGAN *et al.*, 2000; PÄTZOLD, 1986). The driest period occurred from 1870 to 1885 and coincides with the switch from D-6 to the Agno-Labrador Delta. However, a longer climate record is needed to resolve the nature of climate oscillations in the Philippines for the last 2.4 ka when the deltas were constructed.

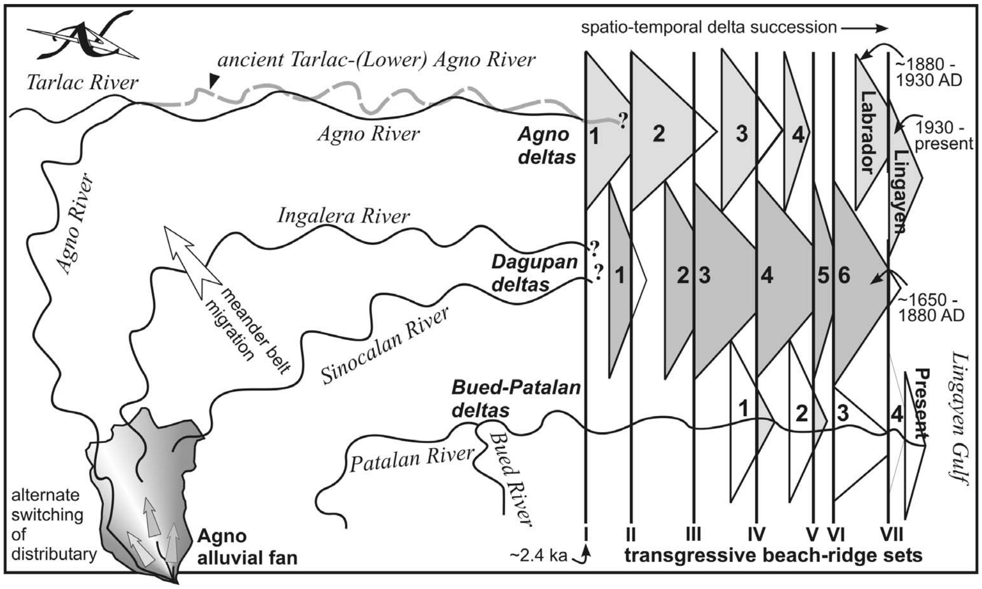


Figure 8. Spatiotemporal succession of deltas and migration of river systems. Earlier southwestward migration of the main distributary of the Agno alluvial fan, from tectonic tilting, valley filling, or both, created multiple pathways for the upper Agno River as it enters the alluvial plain. Continued tectonism and switching of the main distributary channel changes the sediment loads of the multiple pathways, leading to episodes of delta switching and transgression. The oldest beach ridge is tied to the last highstand around 2.4 ka (Maeda *et al.,* 2004), and the approximate age of Dagupan Delta-6, Ango-Labrador and Agno-Lingayen deltas are based on historical documents and correlation to major earthquake events (Bautista and Oike, 2000).

### Tectonism

Fault movements can modify local base level and sediment yield (Schumm, 1993; Schumm and Rea, 1995). Accommodation space also changes, allowing the alluvial fan to steepen or flatten. Such changes are often accompanied by switching of active fan distributaries. The evolution of a series of the Agno and other alluvial fans along the southwestern margin of the Cordillera Mountains can be associated with active splays of the Philippine Fault Zone (Figure 2).

Experimental (Schumm and Rea, 1995) and empirical data (Dadson *et al.*, 2004) have also demonstrated that coseismic uplifts almost instantaneously induce very rapid increases in fluvial sediment yield and delivery that can result in delta progradation. Through time, a waning stage marked by a decrease in sediment yield would cause a deficit in the sediment needed to maintain a delta, thereby causing retreat.

Regional tectonic tilting best explains the episodic and unidirectional meander belt shifting across the Lingayen bayhead plain. This implies that vertical displacements of the East Zambales Fault are less than those of the Umingan-Lingayen Fault to the east. Episodes of tectonic tilting likely coincided with shifts of the main distributary of the Agno alluvial fan, which would have ensured meander belt migration. Similarly, Chen and Stanley (1995) attributed the unidirectional migration of the Yangtze River primarily to tectonism. Tectonic tilting has changed the courses of the Ganges-Brahmaputra River system (Morgan and McIntyre, 1959) as well as the Madison and South Fork rivers in southwest Montana (Alexander *et al.*, 1994; Leeder and Alexander, 1987). For the Lingayen coastal plain, further westward migration of the meander belt is constrained by the foothills of the Zambales range.

The Philippine Fault Zone generated six earthquakes with surface wave magnitude (Ms) of $\geq$7.5 from 1608 to 1895 (Bautista and Oike, 2000). The epicenter of those in 1645 and 1880 (Ms 7.9 and 7.6, respectively) were no farther than 120 kilometers south of the Agno alluvial fan. The 235-year interval between them is close to the approximated period of 220 years for delta switching. Hence, the youngest Dagupan Delta, D6, is reasonably associated with the 1645 event, and historical maps document that the inception of the Agno-Labrador Delta was contemporaneous with the 1880 event.

## SUMMARY AND CONCLUSIONS

The Lingayen Gulf bayhead plain was formed and is continually being built by prograding and switching deltas. The latest switch, the result of an artificial rerouting of the active Agno River distributary, led to the partial erosion of the former Agno-Labrador Delta and the progradation of the Agno-Lingayen Delta through beach ridge accretion.

Beach ridge patterns indicate alternate and occasionally simultaneous delta progradation and retreat of the Agno, Dagupan, and Bued-Patalan rivers. The 15 deltas within 7 kilometers of the coast have formed since 2.4 ka on the basis of Holocene sea level change for the region. The progradation rate of 3 m $y^{-1}$ for these younger beach ridges, when applied to those within 7 to 16 kilometers inland, suggest that they started forming around 5.5 ka. This is when the second highstand commenced.

The beach ridges formed during the first highstand might have been partially eroded during the rise to the second. This is a worthy subject of further research.

How climate and sea level changes might have influenced the delta switching still cannot be evaluated because we lack age control and applicable paleoclimate and paleosea level reconstructions for the Philippines. Until these data become available, tectonism is the favored driving mechanism because it explains both fluvial migration and delta switching. Regional tectonic tilting and shifts of the main distributary channel of the Agno alluvial fan caused episodic meander belt migration southwestward across the alluvial plain. Continued tectonism caused the distributary of the Agno alluvial fan to switch frequently between the Agno and Dagupan rivers, leading to delta switching along the coast.

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