LATE QUATERNARY SHIFT OF MIXED SILICICLASTIC-CARBONATE ENVIRONMENTS INDUCED BY GLACIAL EUSTATIC SEA-LEVEL FLUCTUATIONS IN BELIZE

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ABSTRACT The last glacial interval (oxygen isotope stages 4 2 or 75–12 ka) is considered overall as a sea-level lowstand relative to today (Holocene, i.e., since 12 ka) and the previous interglacial highstand stage 5 (130–75 ka). During this stage 4 2 interval, an earlier lagoon and barrier-reef system—established on the edge of the southern Belize shelf margin during the previous stage 5 interglacial highstand—was completely exposed. The exposed stage 5 lagoon area became a siliciclastic fluvial plain bounded on its eastern side by a ridge of karst topography created by the exposure of the stage 5 barrier reef.

A high-resolution single-channel seismic survey in the northern part of the present Southern Shelf Lagoon off the coast of Belize was used to image two late Quaternary lowstand fluvial drainage systems consisting of a series of well-developed incised valleys, trending parallel to the strike of the exposed stage 5 barrier reef. The divide between both drainage systems, at the latitude of Dangriga (just south of 17°N), appears to be rooted on a topographic high composed of upper Tertiary deposits. South of Dangriga, the system of buried incised valleys drained the area toward the south and merged into Victoria Channel and other channels separating modem rhomboid reefs. North of Dangriga, the system of buried incised valleys drained into the single, partially filled, and deeply incised valley of the English Cay Channel. This valley cut through the exposed stage 5 barrier-reef and back-barrier-reef system and linked the fluvial drainage system north of Dangriga to the Tumeffe Basin.

The bathymetric contours at the mouth of the English Cay Channel protrude eastward across a thick, fanlike sedimentary body characterized by a series of stacked, prograding, and laterally shifting lobes. This sedimentary body is interpreted as a lowstand shelf-edge delta, similar in surface area to the modem highstand delta of the Belize River on which Belize City is located. Southerly directed currents partially reworked the lowstand shelf-edge delta and created an elongated slope fan at the toe of slope of the exposed barrier reef.

A model, tied to the established sea-level curve from 20 ka to the present, is developed to explain the lowstand geometry and morphology of the incised valleys and the sedimentary deposits in front of the modem Belize Barrier Reef. This model also describes, in a tentative time frame, the nature of the transgressive sedimentary fills in the valleys. Moreover, correlation of the single-channel high-resolution seismic grid along the western margin of the Turneffe Basin with a multichannel seismic dip line shows that the lowstand shelf-edge delta at the mouth of the English Cay Channel and the slope fan, developed on the toe of the barrier reef farther south, correspond to the latest lowstand prograding sedimentary bodies that are mostly observed underlying the modem barrier-reef and back-barrier-reef system. The establishment and growth of carbonates over siliciclastic deposits-expressed in the colonization of patch reefs over the lowstand shelf-edge delta, beach ridges, and flooded levees—appear to represent a possible mechanism by which the present barrier reef established itself. Results of our study suggest that carbonate deposition occurred during a very restricted time interval of the overall sea-level highstand and that the carbonates rest on a substratum of lowstand and transgressive siliciclastic deposits. However, the establishment of barrier reefs, stacked on top of one another during successive interglacial highstands, though exposed during intervening glacial lowstands, has influenced the orientation of the lowstand incised valleys on the exposed shelf. These valleys trend parallel to the strike of the exposed barrier reefs.

INTRODUCTION

Sequence stratigraphic models are built on a few basic principles. One of them expresses that, during sea-level lowstands, sediment in siliciclastic depositional systems is transported into the adjacent basins by rivers and deposited directly onto the upper slope, while previous highstand shelf deposits are eroded (Vail et al., 1977). This basic principle was tested in the past two decades in the context of pure-carbonate depositional systems by sequence stratigraphic studies of isolated carbonate platforms and shelves. These studies generated some controversies. On one hand, it is thought that carbonate systems respond to sea-level fluctuations as siliciclastic systems do, with only minor differences (Vail, 1987; Vail et al., 1991; Van Wagoner et al., 1992; Sarg, 1988; Jacquin et al., 1991). On the other hand, many studies have demonstrated that, in contrast to siliciclastic systems, carbonate production sites ("factories") export sediment to adjacent slopes and basins during sea-level highstands when carbonate bank tops are flooded but still situated within the photic zone (referred to as "highstand shedding"). Carbonate systems can be, therefore, completely out of phase in terms of sediment shedding relative to siliciclastic margins (Mullins, 1983; Droxler and Schlager, 1985; Schlager, 1992; Schlager et al., 1994; Handford and Loucks, 1993). In this context, some significant discrepancies are expected to arise in the construction of a eustatic sea-level curve that is based upon the seismic stratigraphic interpretation of contemporaneous siliciclastic and carbonate deposits of the shelf, slope, and rise.

Eustatic sea-level curves have been established, independently of sequence stratigraphic concepts, for the late Quaternary (Fig. 1; i.e., Lighty et al. [1982] for the past 10 k.y.; Fairbanks [1989] for the past 20 k.y.; Bard et al. [1990] for the past 140 k.y.; and Pirazzoli et al. [1993] for the past 500 k.y.). Because sea-level history is best known for the late Quaternary, sedimentary processes and primary sequence stratigraphic concepts, essentially tied to sea-level fluctuations, can be better tested in upper Quaternary sediments than in more ancient rocks. High-resolution sequence stratigraphic studies of Quaternary strata have been conducted along a number of different siliciclastic shelves and slopes (i.e., Colman and Mixon, 1988; Trincardi et al., 1994; Anderson and Thomas, 1991; Anderson et al., 1996), including studies of incised valleys (Thomas and Anderson, 1988, 1989, 1994; Carter et al., 1990; Anderson et al., 1990; Blum, 1993; Koss et al., 1994; Zaitlin et

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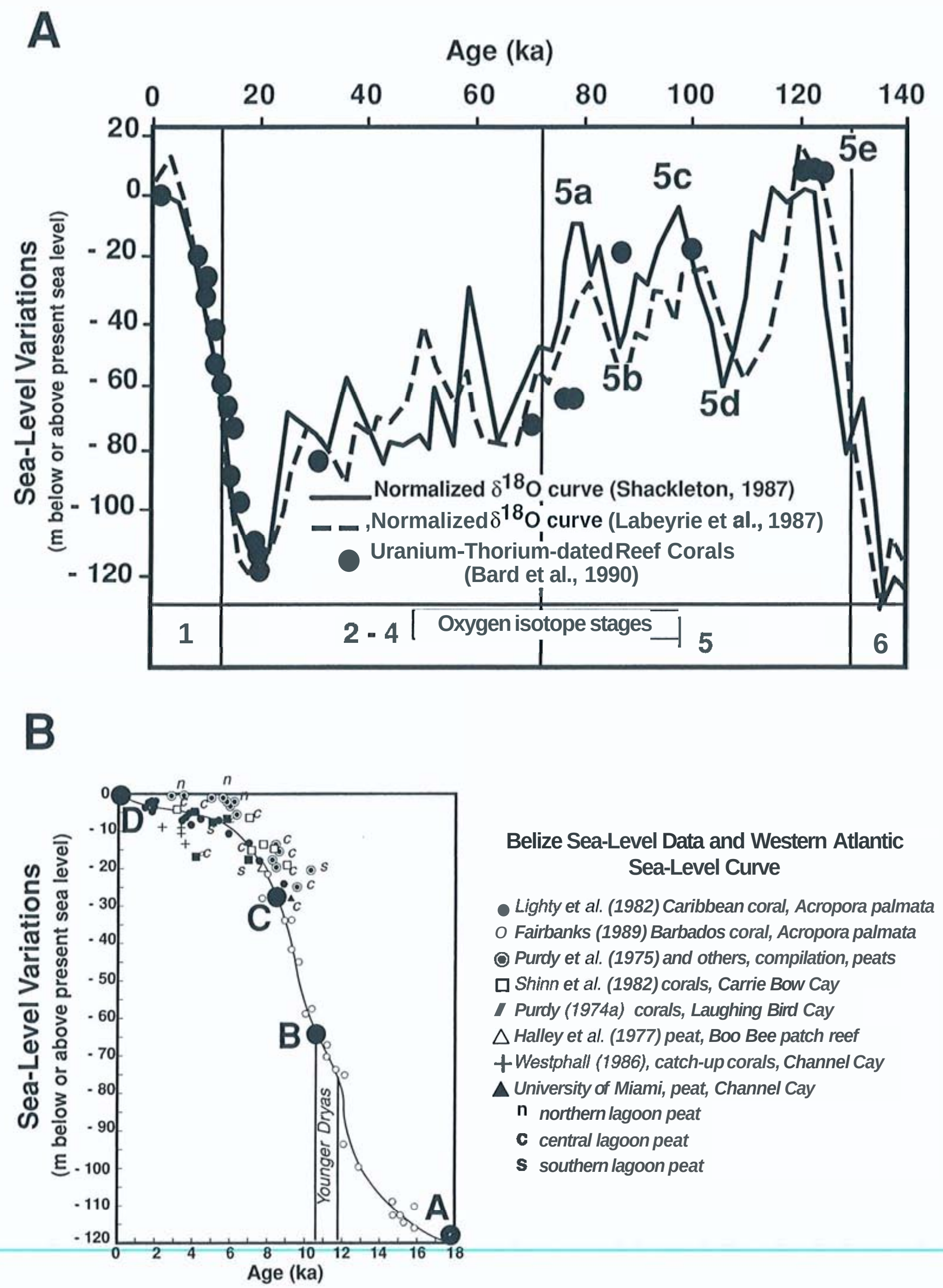

FIG. 1.—Sea-level variations for (A) the past 140 k.y. based on oxygen isotope data and dating of coral and peat samples by ^{14}C and U-Th methods and (B) the past 18 k.y. Letters A to D indicate the estimated levels of the ocean during four time intervals described in the model shown in Figure 18, which describes the evolution of the mixed siliciclastic-carbonate Belize system during the last sea-level cycle.

al., 1994; Kindinger et al., 1994; Harris, 1994; Allen and Posamentier, 1994; Nichol et al., 1994) and along carbonate-bank margins (Hine and Mullins, 1983; Droxler and Schlager, 1985; Wilber et al., 1990; Glaser and Droxler, 1991; Grammer and Ginsburg, 1992; Schlager, 1992; Schlager et al., 1994). However, studies testing sequence stratigraphic concepts either in late Quaternary or older mixed siliciclastic-carbonate sedimentary systems (i.e., Choi and Ginsburg, 1982; Belperio and Searle, 1988; Davies et al., 1989; Dolan, 1989; Peederman and Davies, 1993; Handford and Loucks, 1993; Brown and Loucks, 1993; Esker, 1998; Esker et al., 1995, Esker et al., 1998) are not as common.

Because modem siliciclastic and carbonate sediments co-exist along the Belize continental margin (Purdy, 1974b; Choi and Ginsburg, 1982; Choi and Holmes, 1982) and because this margin is reasonably accessible, the Belize margin is an excellent area in which to study the association of siliciclastic and carbonate sediments within a sequence stratigraphic framework.

In a mixed sedimentary system such as the Belize margin, the migration and export of siliciclastic sediments toward the shelf margin during sea-level regressions and lowstands are expected to overwhelm and suffocate carbonate production. A prograding wedge of siliciclastic sediments is expected to be deposited by fluvial-deltaic processes below and on the seaward side of the exposed barrier reef during sea-level lowstands. This lowstand prograding wedge may provide a surface on which the new barrier reef becomes established sometime during the following sea-level transgression. Because the extent of the carbonate production is reduced to a minimum during sea-level lowstands, little carbonate resedimentation should occur along the slope and in adjacent basins. Conversely, as observed today, the Belize carbonate sediments are expected to thrive during sea-level transgressions and highstands, while siliciclastic sediments remain contained within the coastal zone.

We are reporting here on a high-resolution seismic survey of upper Quaternary strata of the Belize margin. This study was undertaken to understand how siliciclastic and carbonate systems have interacted in constructing the continental margin during the past few sea-level cycles. Another objective of this study was to investigate lateral and vertical shifts within the siliciclastic and carbonate environments caused by these sea-level fluctuations. This was accomplished by using two grids of high-resolution seismic lines within the northern part of the Southern Shelf Lagoon and the offshore Turneffe Basin.

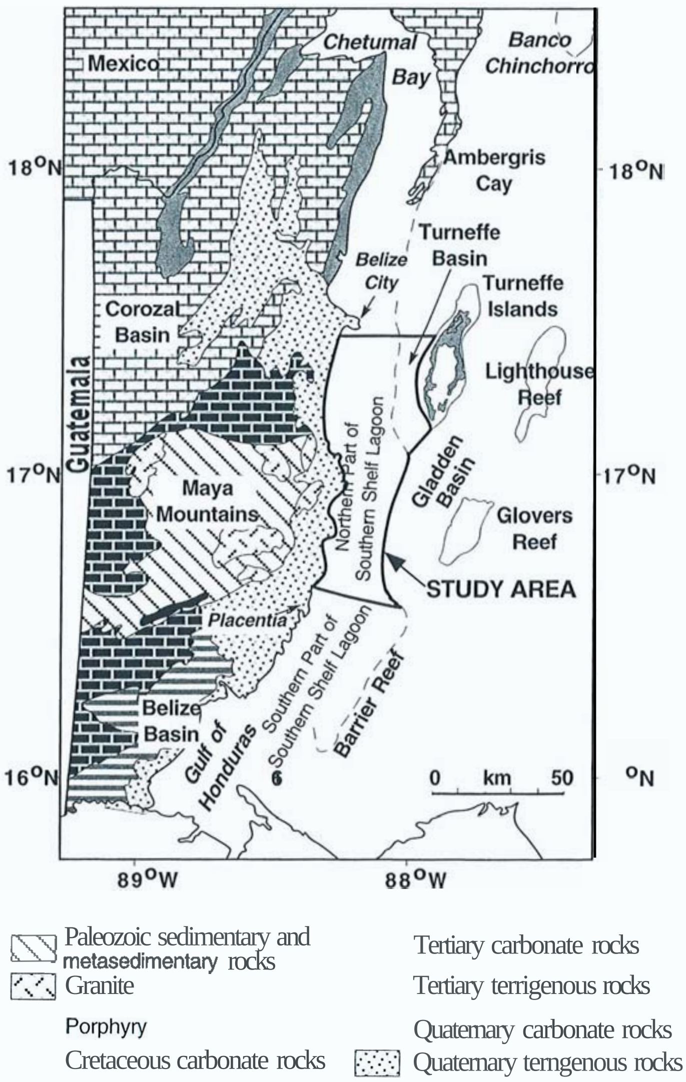

FIG. 2.—Belize geologic map modified from Wantland and Pusey (1971) and Purdy (1974a). The area where this study was conducted is also shown.

BACKGROUND

Belize exhibits two main geologic provinces linked to the Yucatan platform and the Sierras of northern Central America. Paleozoic metasedimentary rocks and granites, the oldest rock units in Belize, compose the core of the Maya Mountains. Relief in the central part of Belize reaches an elevation of more than 1,000 m at Victoria Peak (Bateson and Hall, 1977). Because of their relief and the intensity of chemical weathering, characteristic of the Belize tropical latitudes, the Maya Mountains have been a major and persistent source of siliciclastic sediments during the Cenozoic. Cretaceous carbonates, and Tertiary–Quaternary clastics and carbonates overlie the Paleozoic metasedimentarv rocks and granites on the flanks of the Maya Mountains (Fig. 2).

The Belize shelf and the offshore basins have been studied to better understand their geology and structural evolution (Dillon and Vedder, 1973; Bateson and Hall, 1977; Morrice, 1992; Lara, 1993) as well as the sedimentological and paleontological aspects of their modem and past environments (Purdy et al., 1975; Wantland, 1975; James and Ginsburg, 1979; Choi and Holrnes, 1982; Choi and Ginsburg, 1982; Shinn et al., 1982; Mazzullo et al., 1992; Precht, 1993,1994). Our study area spans the northern part of the Belize Southern Shelf Lagoon and the Turneffe Basin (Figs. 3, 4). Recently, Esker (1998) and Esker et al., 1998, conducted a study similar and in parallel to ours by focusing on the southern part of the Belize Southern Shelf Lagoon. Esker emphasized the interplay between tectonics and eustasy in the Belize mixed carbonate-siliciclastic system. In Belize, pure siliciclastic muds, silts, and sands, originating from the Maya Mountains, are currently being deposited in the fluvial plain and along the coast. The shelf is covered with a mixture of siliciclastic clays and fine carbonate muds. The carbonate content of the shelf sediments systematically increases eastward (Pusey, 1975; Scott, 1975; Purdy et al., 1975). A well-established longshore current, flowing toward the south, confined most of the siliciclastic sediment to the coastal zone. Pure-carbonate sediment, composed of coral and coralline and green algae, occurs along the Belize barrier reef and in the back-barrier environment, as well as on the offshore atolls of Glovers, Turneffe, and Lighthouse (Gischler, 1994; Figs. 2, 3, 4). Periplatform oozes are being deposited in the basins adjacent to the barrier reef and the offshore atolls (James and Ginsburg, 1979). such as the Tumeffe and Glovers Basins.

METHODS

Two grids of high-resolution single-channel seismic profiles were acquired in 1992–1993 onboard the R/V *Lone Star*

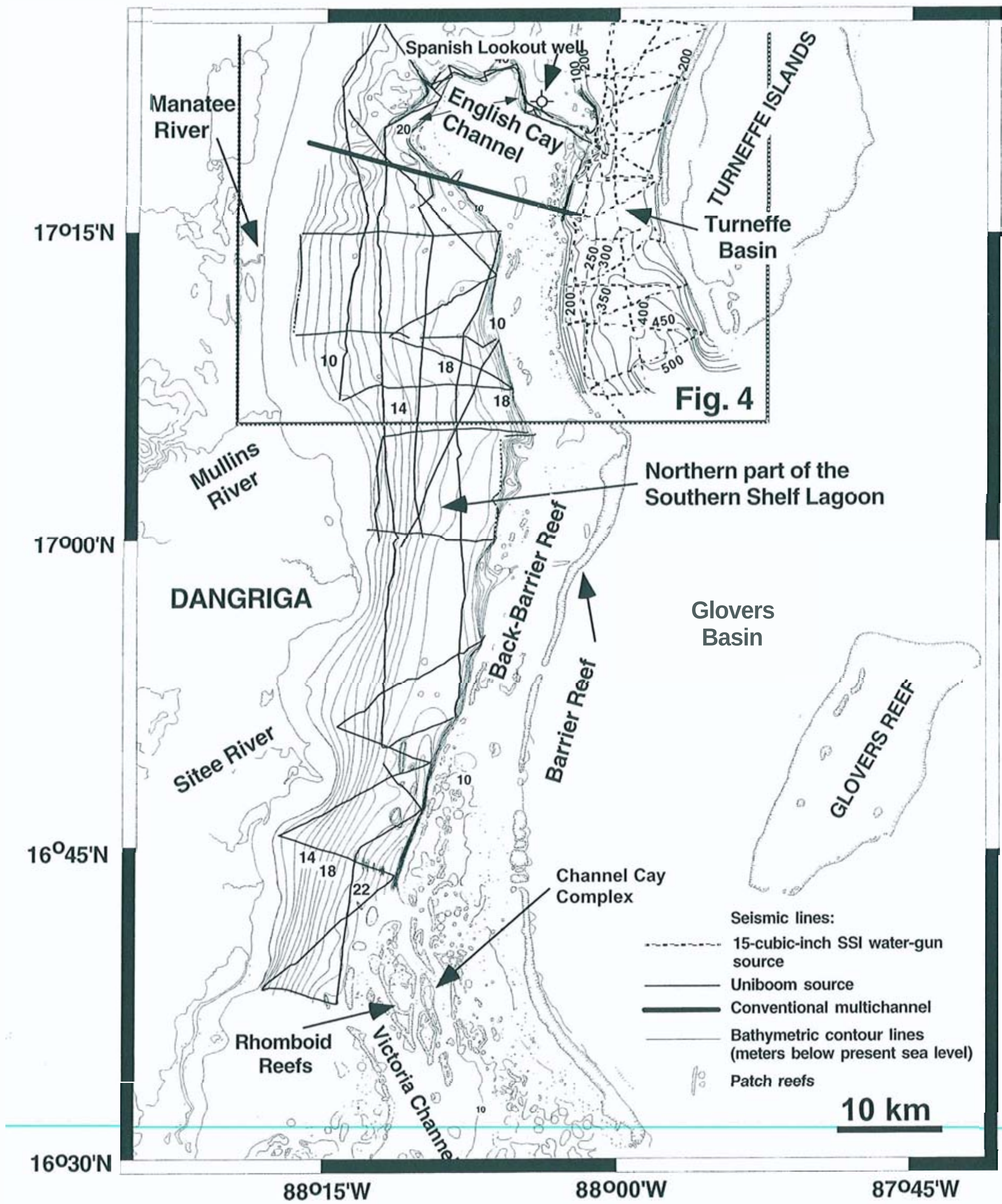

FIG. 3.—Modem bathymetry of the northern part of the Southern Shelf Lagoon and the Turneffe Basin modified on the basis of data sets newly collected during this study. These new data sets consist of two high-resolution single-channel seismic grids (data collected with the use of a Uniboom and a 15-in.^{3} SSI [Seismic Systems Incorporated] water gun), one conventional multichannel seismic line, and some lithologic and biostratigraphic information from the Spanish Lookout well. Note the overall southward dip of the modem sea floor from the entrance of the English Cay Channel (at the –20 m contour near the north edge of the map) to the southern part of the Southern Shelf Lagoon (just north of the Victoria Channel). Detailed modern bathymetry of the Turneffe Basin, the English Cay Channel, and the northern part of the Southern Shelf Lagoon at the western entrance of the English Cay Channel is shown in Figure 4.

(Fig. 3). The data sets were collected in the northern part of the Belize Southern Shelf Lagoon, the English Cay Channel, and in the basin—referred to here as the Tumeffe Basin—located between the modem barrier reef and the atolls and islands of the Tumeffe Islands (Fig. 3). A Uniboom (high-frequency seismic energy source) was used as the energy source to acquire about 500 km of data in the relatively shallow (<100 m) waters of the Southern Shelf Lagoon and the English Cay Channel, and a

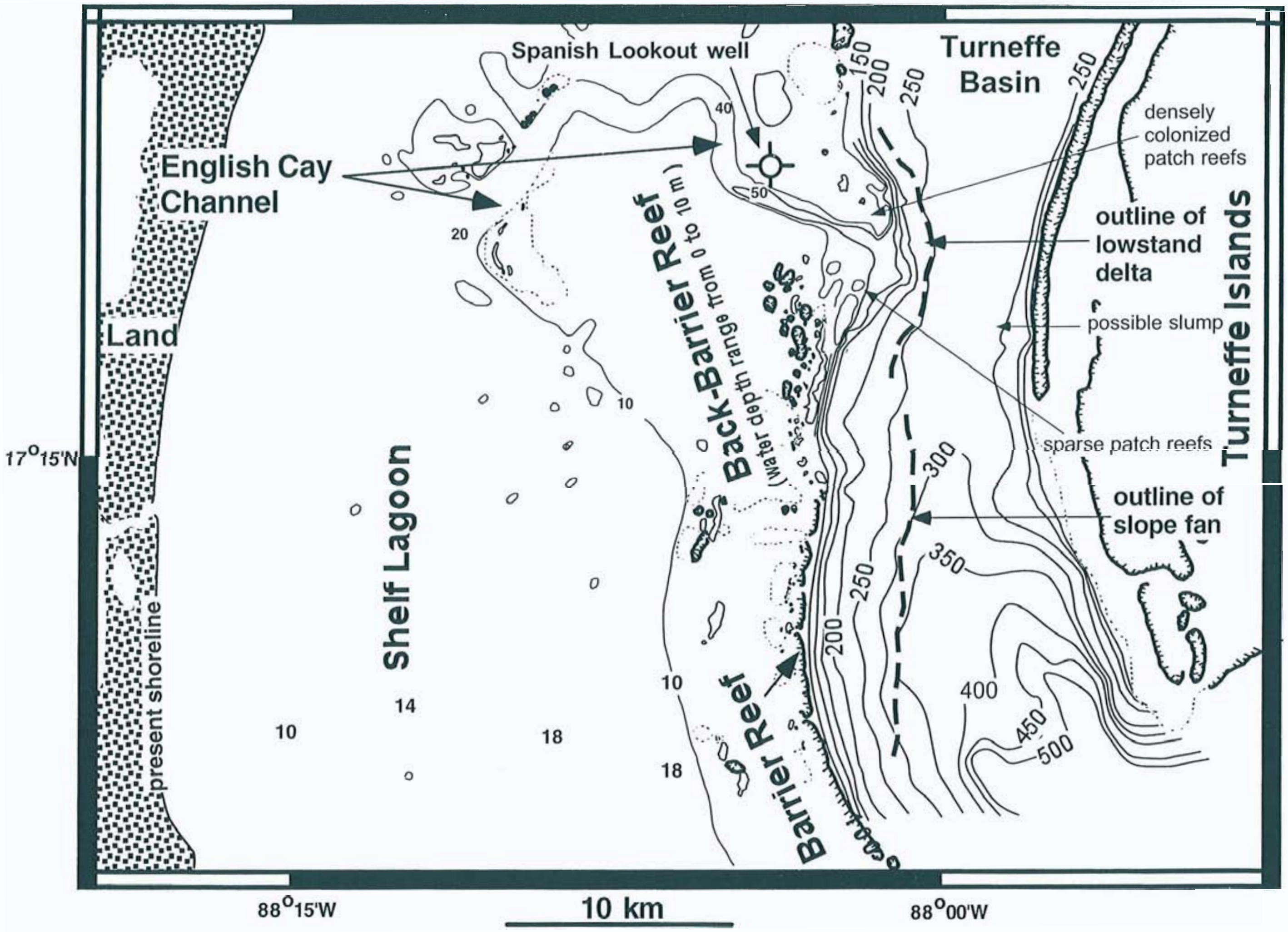

FIG. 4.—Detailed bathymetry of Turneffe Basin, the English Cay Channel, and the northern part of the Southern Shelf Lagoon at the western entrance of the English Cay Channel. Contour intervals are 10 m in Tumeffe Basin and the English Cay Channel and 1 m in the Southern Shelf Lagoon. The overall southward-sloping floor of the Southern Shelf Lagoon is shown in Figure 3. From its entrance to its mouth, the English Cay Channel exhibits an eastward-sloping bathymetry. This map also shows a lowstand shelf-edge delta and a lowstand slope fan. Note also that the shallowest part of the Turneffe Basin sea floor is located in front (i.e., east) of the mouth of the English Cay Channel.

246-cm^3 (15-in.^{3}) water gun was used to acquire 800 km of data in the deep basins, including the Turneffe Basin. The seismic lines were digitally recorded in a pseudo SEG-Y format by using an Elics Delph2 system.

The seismic data were later processed at Rice University with PROMAX seismic processing software. Uniboom data were processed with the following sequence: single-filter Ormsby bandpass from 70 to 3200 Hz, time-offset variant gain, spiking-predictive deconvolution, automatic gain control (AGC), and trace muting. Water-gun data sets were processed twice with a single-filter Ormsby bandpass (from 80 to 900 Hz), AGC and trace muting. Seismic velocities of 1.5 km/s for the water and 1.7 km/s for the sediment were used to estimate the depth of sea floor and subsurface reflectors (Choi and Holmes, 1982). A 25-km-long multichannel seismic line (84–01) and well-log information and lithologic description of cuttings from the Spanish Lookout well were correlated with the high-resolution seismic grid (locations in Fig. 3).

RESULTS

Modern Bathymetry in the Northern Part of the Belize Southern Shelf Lagoon

The seismic data were used to map the bathymetry of the Belize Southern Shelf Lagoon. The lagoon floor slopes toward the south, from –11 m just north of the English Cay Channel to about –25 m near the northern boundary of Victoria Channel (Figs. 3, 4). The west-east bathymetric profile of the lagoon is asymmetric; the western floor slopes gradually toward the east, but the eastern floor of the lagoon is steep as it approaches the adjacent back-barrier-reef environment (Figs. 3, 4). Relatively flat areas along the axis of the shelf lagoon are located immediately south of the entrance to the English Cay Channel (Fig. 4) and in front of Dangriga (Fig. 3).

The overall southward slope of the lagoon contrasts with the English Cay Channel bathymetry, which slopes to the east. Water depths in the English Cay Channel range from about –20 m at the western head of the channel to about –60 m near its mouth (Fig. 4). The channel mouth expands onto a relatively flat surface that reaches a depth of about –90 m. The surface forms an eastward bulge in the bathymetric contours. Farther east, the floor slopes more steeply to about –250 m in Tumeffe Basin. The northern part of the channel mouth is densely colonized by patch reefs, whereas the southern part has only sparse patch reefs (Fig. 4).

The shallowest depths (about 260 m) of the Turneffe Basin floor are found seaward of the English Cay Channel, where there are a few small, elongated, bathymetric ridges, interpreted as possible slumps (Pig. 4). The areas to the north and south of English Cay Channel reach maximum depths of about –280 m and –500 m, respectively. The western slope of Tumeffe Basin is much gentler than its eastern slope. Comparisons of the maps shown in Figures 3 and 4 with previously published maps (Purdy et al., 1975; Defense Mapping Agency Hydrographic-Topographic Center, 1984; Morris, 1989) yield broadly similar features in the shelf lagoon, except that the areal extent of patch reefs is generally smaller in our maps (Fig. 3). Our Tumeffe Basin bathymetric map (Figs. 3, 4) provides much greater detail than previously published maps.

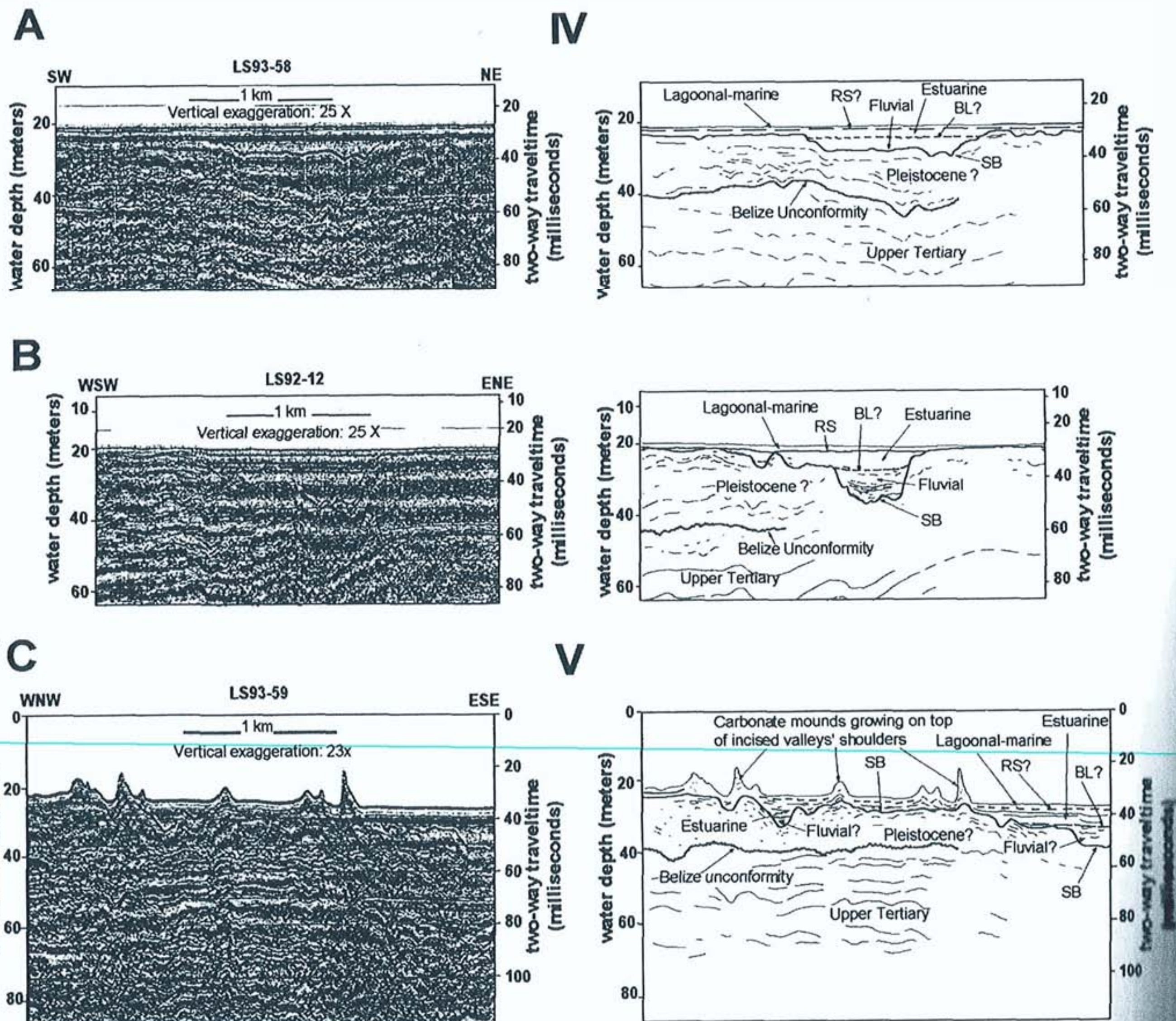

FIG. 5.—High-resolution single-channel seismic profiles (A–C), interpreted in adjacent line drawings, of the buried incised-valley system in the area [illegible] Southern Shelf Lagoon south of Dangriga. These particular lines cross the complex drainage system of the lowstand fluvial plain between stations IV and V ([illegible] in Figs. 8, 10). In this area of the Southern Shelf Lagoon, the incised valleys are filled predominantly by seismically homogeneous deposits, which makes the [illegible] ration of fluvial, estuarine, and lagoonal-marine seismic facies difficult. Patch reefs have developed over the levees of the incised valleys, as observed in C. [illegible] ravinement surface, SB = last glacial maximum sequence boundary, BL = bayline.

Incised Valleys

High-resolution seismic profiles from the shelf lagoon show a series of incised valleys (Figs. 5–7) that, when mapped, clearly delineate two paleodrainage systems separated by a drainage divide offshore Dangriga (Figs. 8, 9). South of Dangriga, individual valleys have U-shaped cross-sectional profiles (Figs. 5, 10A). Seismic lines display a complete cross-sectional profile of the main incised valley only in the northernmost part of the area. Farther to the south, it was not possible to acquire profiles across the valley because of shallow water depth. Hence, the deepest part of the incision was not always imaged. The maximum depth of the main channel ranges from –27 m in the northern part of the study area to –39 m in its southernmost part (Fig. 10B). A local gradient of 0.06° was calculated for the shallowest incision in the north to the deepest incision in the south (Fig. 10B). However, connection of the main incised valley in the north to the one reported by Choi and Holmes (1982) in the south yields an average gradient of 0.04° (Fig. 10B). The average subbottom depth of the highest interfluve areas near the back-barrier reef is –20 m. Patch reefs have commonly established themselves on top of the interfluves. In the south, the lowstand drainage configuration may have been influenced by local preexisting (substages 5e, 5c, and 5a?) topography consisting of exposed, elongate carbonate mounds. The occurrence of these older mounds resulted in the anastomosing character of the drainage pattern.

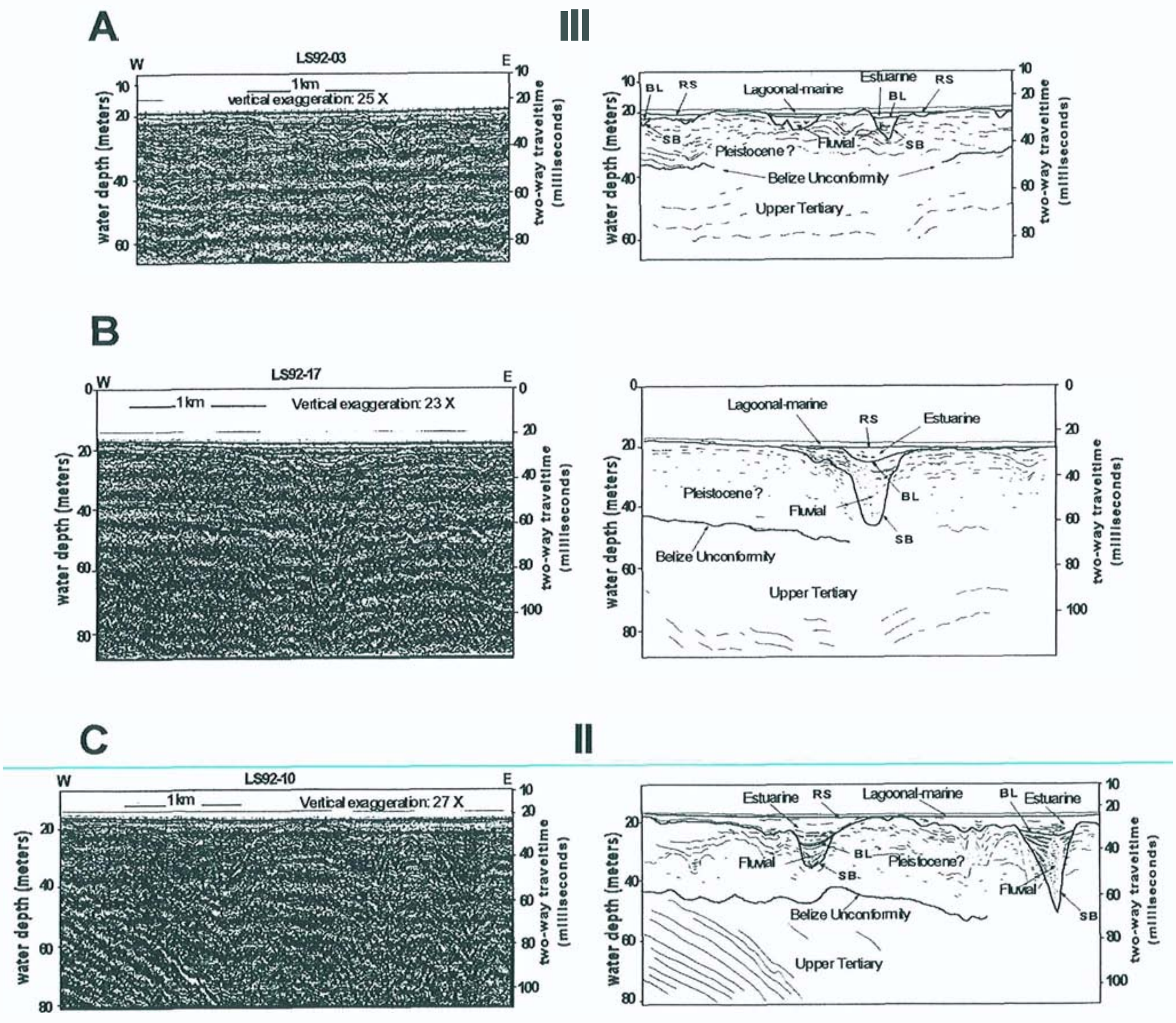

FIG. 6.—High-resolution single-channel seismic profiles (A–C), interpreted in adjacent line drawings, of the buried incised-valley system in the area of the Southern Shelf Lagoon north of Dangriga. These particular lines are located within the complex drainage system of the lowstand fluvial plain between stations II and III (located in Figs. 8, 10). In this area of the Southern Shelf Lagoon, incised valleys exhibit V-shaped cross-sectional profiles, and their fill is characterized by higher-amplitude seismic reflectors and more distinguishable seismic character than in the incised valleys south of Dangriga, allowing for better distinction between fluvial, estuarine, and lagoonal-marine seismic facies. The average depth of the incised valleys' shoulders is –18 m (Fig. 7A), increasing to about –23 m toward the entrance of the English Cay Channel (Fig. 7C). RS = ravinement surface, SB = sequence boundary formed at the last glacial maximum, BL = bayline.

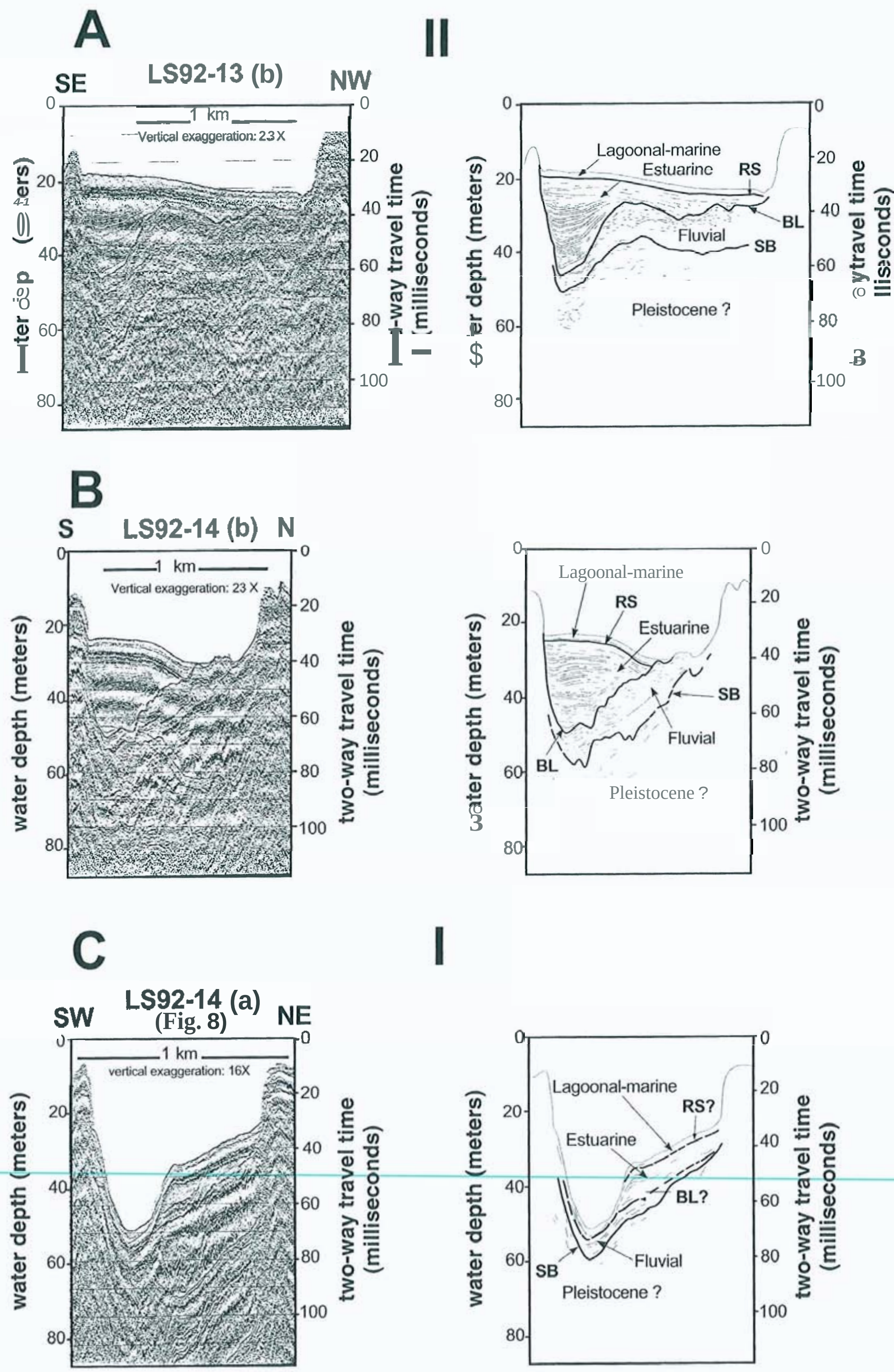

FIG. 7.—High-resolution single-channel seismic profiles (A–C), interpreted in adjacent line drawings, of the English Cay Channel incised valley. These particular lines are located within the complex drainage system of the lowstand fluvial plain between stations I and II (located in Figs. 8, 10). Sediment thickness of the valley fill increases dramatically upstream (from C to A). Note the difference in seismic character between the fluvial (chaotic) and the estuarine (laminar) seismic facies. As in the Southern Shelf Lagoon, the lagoonal-marine facies is very thin in the English Cay Channel. RS = ravinement surface, SB = sequence boundary formed at the last glacial maximum, BL = Bayline. Note the opposite asymmetries in the cross sections shown in A and B between the LGM deepest incision and the modem sea floor. This observation demonstrates that the modem sea-floor morphology of the English Cay Channel is mostly influenced by the westward flow of the incoming tide, whereas the LGM incision was cut by a river flowing from west to east.

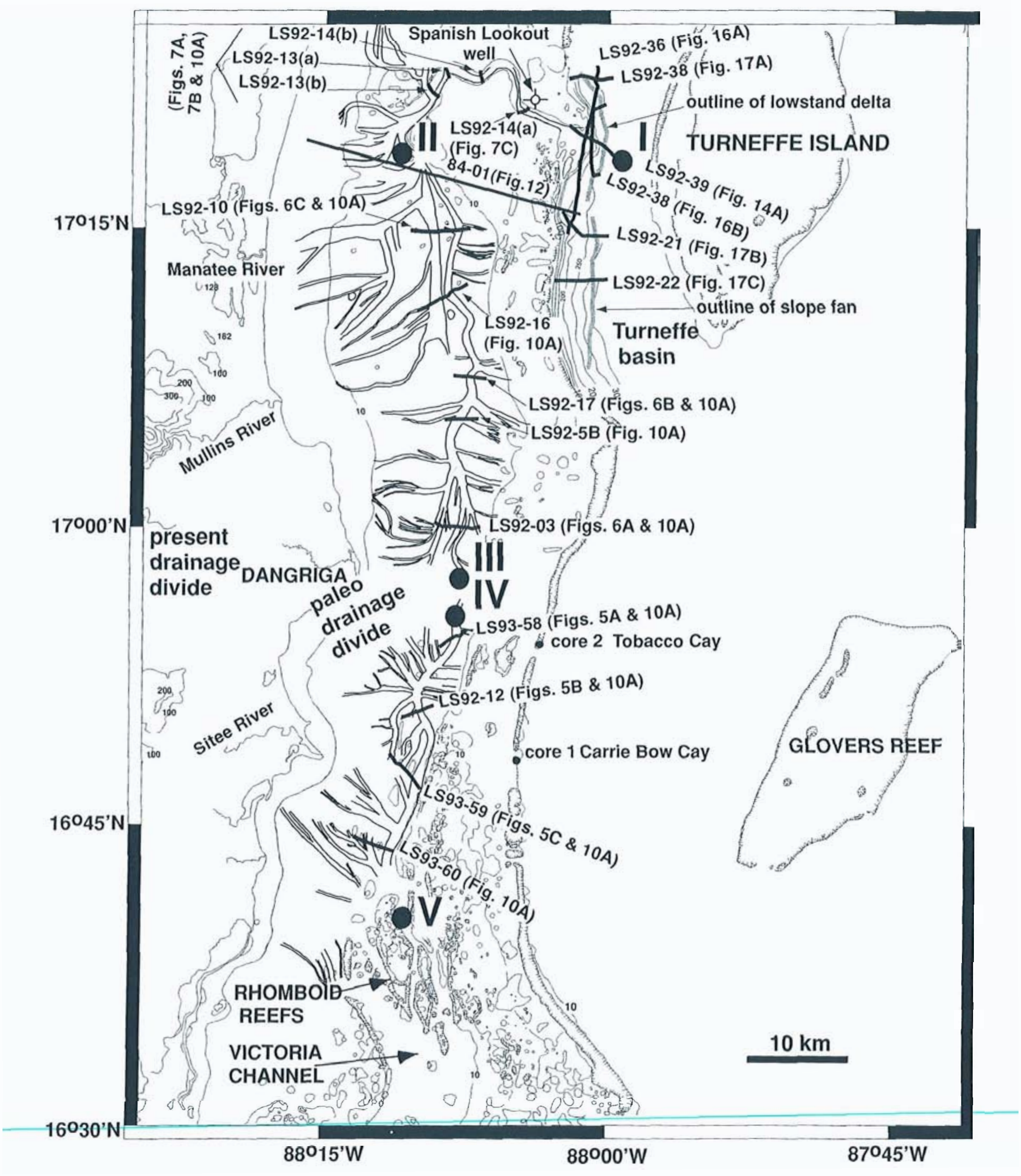

FIG. 8.—Paleodrainage during the last glacial maximum, 18–20 ka. Locations I to V are the positions of stations along the maximum incision of the main valley systems. Successive values of maximum incision were used to calculate the valley systems' gradient along the segment south of Dangriga (IV to V), the segment north of Dangriga (III to II), and the segment of English Cay Channel (II to I), shown in Figure 10B. Note how the complex drainage system north of Dangriga merges into the English Cay Channel and that the system south of Dangriga drains into the modem Victoria Channel complex. Compare the position of the paleo-drainage divide offshore Dangriga with the position of the dip divides of the upper Tertiary strata and the Belize unconformity (see Fig. 13).

A striking difference between the drainage system south and north of Dangriga is the occurrence of carbonate mounds in the southern area overlapping the shoulders of the incised valleys (Fig. 5). Although these features are local, they appear to be the northernmost expression of the well-developed, larger, rhomboid reefs in the south (Figs. 8, 9). These reefs are mainly growing on lowstand levee deposits (Choi and Ginsburg, 1982; Choi and Holmes, 1982) or on top of exposed stage 5(?) reefal limestone (Westphall, 1986).

North of Dangriga, the average subsea depth of the highest interfluve areas near the back-barrier reef is –19 m. The incised valleys show V-shaped cross-sectional profiles (Figs. 6, 10A).

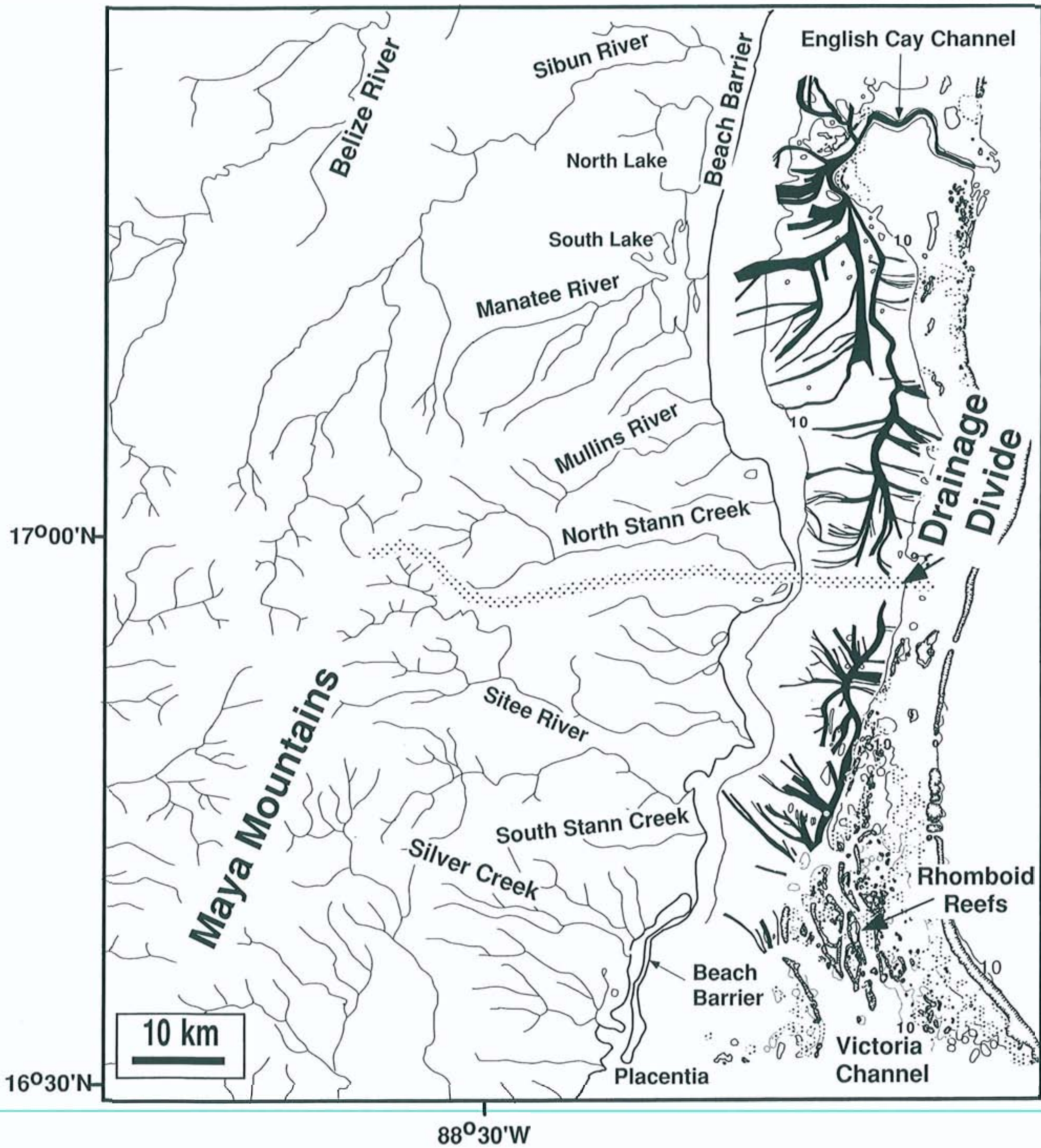

FIG. 9.—Comparison of the present onshore drainage with the paleodrainage during the last glacial maximum. The divides for both drainage systems at about lat 17°N appear to be connected.

In contrast with the area south of Dangriga, carbonate mounds are rare and small and appear to have a random distribution. The gradient of the main incised valley averages 0.032° (Fig. 10B), although gradients can be as steep as 0.22° (an order of magnitude steeper) in some segments of the main valley. In these segments, seismic facies of the valley fill are characterized by high-amplitude, chaotic reflectors, interpreted to correspond to coarse-grained sediment. A sharp increase in gradient occurs along an enclosed depression situated at approximately latitude 17°07'N (Fig. 10B). This depression has a depth of about 9 m below the local sea floor.

The English Cay Channel displays V-shaped, asymmetric cross sections, gradually deeper incisions toward the east, and a progressive decrease in thickness in its valley fill (Figs. 7, 10). In curved segments of the channel, the deepest fluvial incision is usually located at the inside bend of the channel (Fig. 7). This pattern contrasts with the overall asymmetric morphology of the modem sea floor that systematically displays the deepest part of

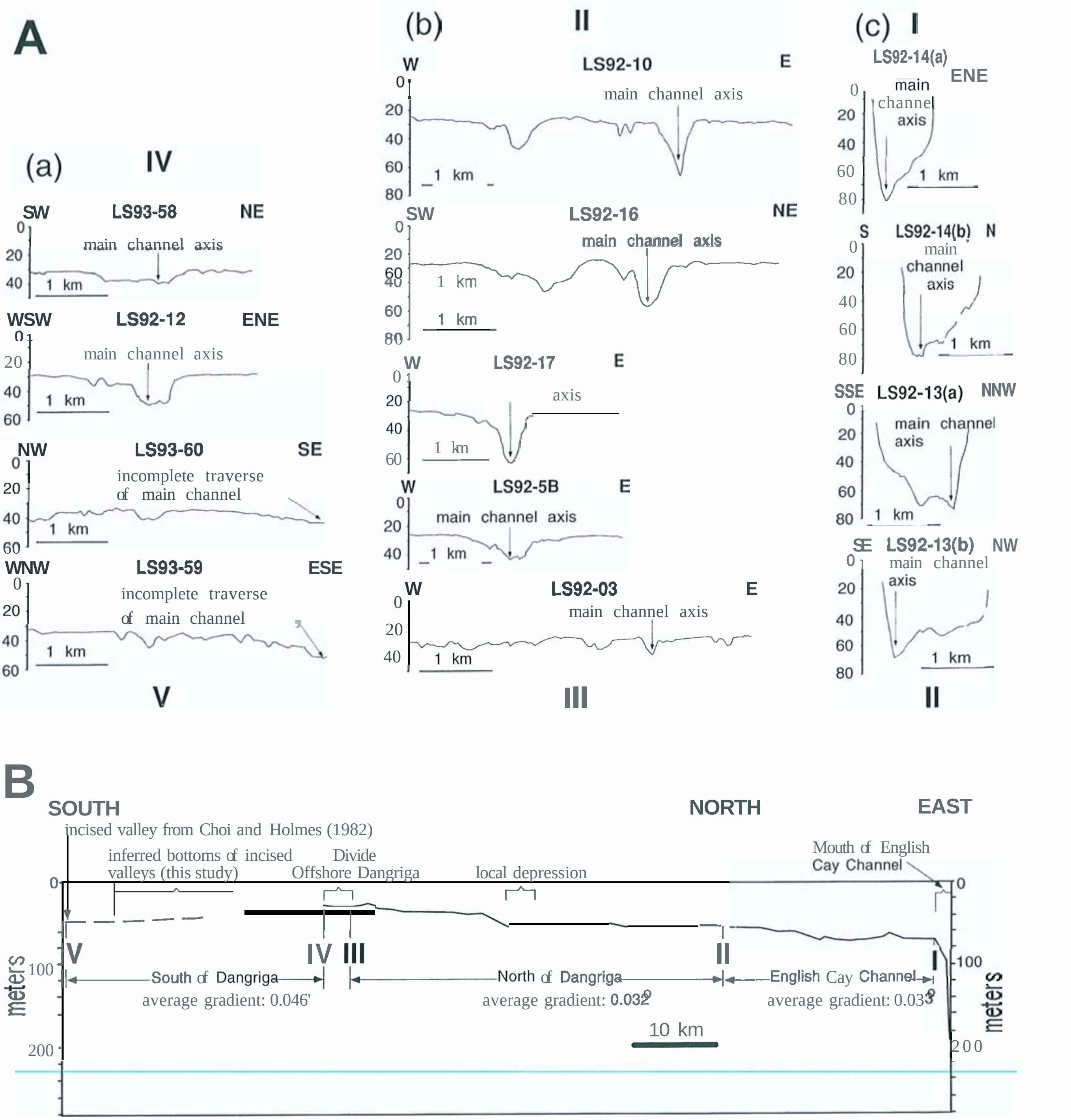

FIG. 10.—Cross sections of the valleys incised in the northern part of the Southern Shelf Lagoon and the English Cay Channel during the LGM, based on high-resolution seismic lines and the overall estimated sea-floor gradients. (A) Cross sections of incised valleys in three segments of the paleo–drainage system (located in Figs. 8, 9). (a) South of Dangriga, segment from N to V. (b) North of Dangriga, segment from II to III. (c) English Cay Channel, segment from I to II. Vertical scale is two-way traveltime in milliseconds. (B) The longitudinal profiles of the main LGM incision, north and south of Dangriga, and along the English Cay Channel.

the channel floor on the opposite channel bank when compared with the last glacial maximum (LGM) incision (Fig. 7). This observation demonstrates that the modem sea-floor morphology of the English Cay Channel is mostly influenced by the westward flow of the incoming tide.

In summary, interpretation of the high-resolution seismic profiles from the Belize Southern Shelf Lagoon clearly shows two paleodrainage systems of incised valleys (Figs. 5–7), separated by a drainage divide offshore Dangriga (Figs. 8, 9). The valleys achieved maximum incision during the LGM (18–20 ka). During the last glacial interval, the fluvial plain north of Dangriga drained toward the north. When active, these valleys converged into the English Cay Channel, which drained across an exposed and karst-modified stage 5 barrier reef and into

Turneffe Basin (Figs. 8, 9). South of Dangriga, rivers flowed toward the south. The system of incised valleys, now buried in the shelf area between Dangriga and lat 16°40′N, merged into the modem channels that separate the rhomboid reefs (Figs. 8, 9).

Comparison Between Offshore Paleodrainage and Onshore Modern Drainage Systems

Two large dendritic rivers, the Belize and Sibun Rivers, and numerous streams (e.g., Mullins and Sitee Rivers, North Stann Creek, etc.) currently drain the eastern and northern flank of the Maya Mountains (Fig. 9). The Belize and Sitee Rivers carry relatively high sediment loads and form lobate deltas. Most of the streams carry less sediment and form small cuspate deltas (e.g., South Stann Creek). Southerly longshore currents partially rework these deltas and form a series of beach barriers composed of accreted beach ridges. Behind these barriers are small isolated lagoons such as North Lake and South Lake (Fig. 9). North of Dangriga, the modem river drainage is toward the east-northeast, whereas south of Dangriga, the drainage is toward the east-southeast. This modem drainage system between Belize City and Placentia contrasts with the overall north-south channel orientation of the paleodrainage system. The older north-south orientation appears to have been influenced by the overall north trends of the previous late Pleistocene interglacial stage 5 barrier reef.

The separation between the two different paleodrainage systems offshore Dangriga (Figs. 8, 9) appears to be structurally rooted on an upthrown block along a tectonic wrench zone in the central part of the Belize margin (Morrice, 1992). Although the structural high seems to have remained in the same location during most of the Quaternary, it is noteworthy that the paleodrainage system is in the opposite direction of the slope of the lagoon floor in the area between Dangriga and English Cay Channel (Figs. 3, 8, 9).

The paleodrainage system consists of numerous east-west tributaries feeding into the main north-south paleochannels. It is not possible to directly connect the paleodrainage system of the Southern Shelf Lagoon with the modem river system because the seismic profiles did not extend far enough landward. However, larger streams, like the Mullins River, North Stann Creek, and Sitee River, do not seem to be linked to any of the paleovalleys of the Southern Shelf Lagoon. The only exception is the Manatee River, which appears to be linked to an incised valley (Fig. 8). This apparent poor correspondence between modem and paleodrainage systems is in agreement with results of laboratory experiments that have demonstrated that, following an overall transgression, new drainage systems are usually established independently from paleodrainage systems (Koss et al., 1994).

The Belize Unconformity and Upper Tertiary Reflectors

Interpretation of the high-resolution seismic grids reveals that the paleodrainage was controlled by a topographic high in the upper Tertiary strata of the Southern Shelf Lagoon (Figs. 11–13). The dips of upper Tertiary main seismic reflectors define two sectors within the northern part of the Southern Shelf Lagoon (Figs. 11, 13). At the latitude of Dangriga, the reflectors are generally subhorizontal and extend farther south into smooth, concave, southward-dipping planes (Fig. 13). North of Dangriga, upper Tertiary strata dip toward the northeast. whereas farther to the north, they dip to the east. Closer to the coast, the upper Tertiary reflectors have dips ranging from 7° to 12° (Figs. 11–13). Farther offshore, these reflectors are characterized by gentler dips that range from 4° to 7° (Fig. 12). The variations of the upper Tertiary stratal geometries in the northern part of the Southern Lagoon define a topographic high, interpreted to have subsequently influenced the location of the late Quaternary drainage divide (Fig. 13A). A well-developed regional unconformity, observed within the entire Belize Southern Lagoon and referred to here as the "Belize unconformity," clearly truncates the upper Tertiary dipping reflectors (Figs. 6C, 11, 12). This unconformity appears to follow the physiography of the topographic high located offshore Dangriga (Fig. 13B).

Upper Quaternary Sedimentary Deposits

The incised valleys south of Dangriga seem to merge into the Victoria Channel system, whereas the incised valleys north of Dangriga are connected to the open sea through the English Cay Channel (Fig. 8). A lowstand shelf-edge delta and an overlying smaller delta, interpreted as a landward-stepped delta, occur at the mouth of the English Cay Channel. In Turneffe Basin, a slope fan occurs south of the shelf-edge delta and in front of the modern barrier reef. The two systems of incised valleys south and north of Dangriga show characteristic valley fill seismic facies (Figs. 5–7). These seismic facies, which are better imaged in the incised valley north of Dangriga, are described here by area.

Incised valleys in the Belize Southern Shelf Lagoon, south of Dangriga.—
On the basis of studies of Quaternary incised valleys (e.g., Abdulah and Anderson, 1991; Thomas and Anderson, 1994; Kindinger et al., 1994; Nichol et al., 1994), parallel and laminar seismic reflectors are characteristic of estuarine and marine muds, whereas chaotic reflectors represent sandy fluvial sediment of the valley-fill succession. The incised valleys south of Dangriga are filled with low-amplitude, generally laminar reflectors (Fig. 5). Because of the subtle variations of seismic facies of the valley fill, it is difficult to divide it into fluvial, estuarine, and lagoonal-marine deposits. Faintly aligned reflectors, visible only locally, were selected as boundaries between the different seismic facies, although commonly they could only be inferred. On the basis of observations of sediment provenance, discussed later in this paper, the lower transparent seismic facies of these valley fills is inferred to represent fluvial facies consisting of fine-grained sands. This section is overlain by slightly more laminar reflectors interpreted to correspond to estuarine and marine muds.

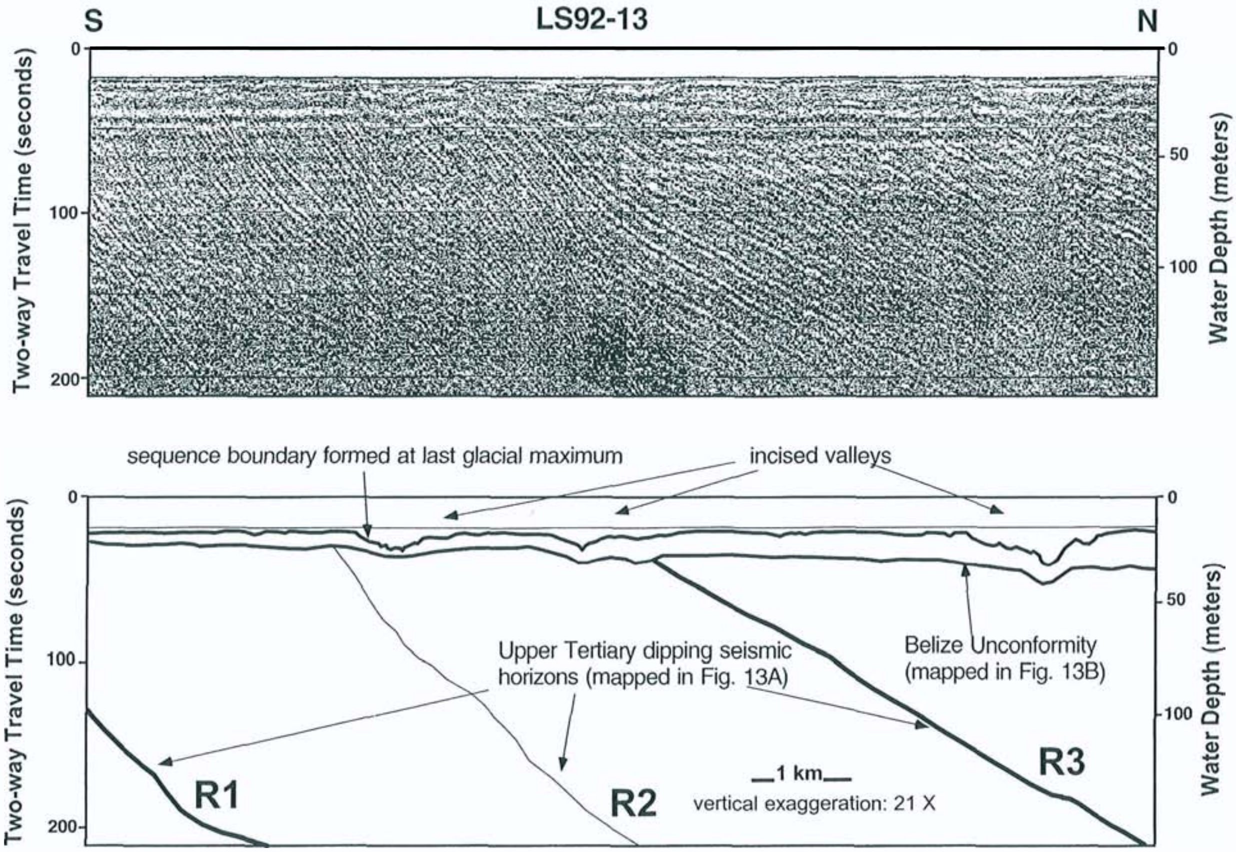

FIG. 11.—Segment of a south-to-north high-resolution single-channel seismic line located in the Southern Shelf Lagoon between Dangriga and the western entrance of the English Cay Channel located in Figure 13. Interpretation of the seismic line segment is shown in accompanying line drawing. Also shown are details of the relationship between the upper Tertiary dipping seismic reflectors, the Belize unconformity, and the incised valleys. The upper Tertiary seismic horizons R1, R2, and R3 as well as the surface representing the Belize unconformity are mapped in Figure 13.

Incised valleys in the Belize Southern Shelf Lagoon, north of Dangriga.—

In contrast to the seismic character of the valley fill south of Dangriga, the seismic character of the incised valley fill north of Dangriga can be more easily differentiated into three different seismic facies—(1) fluvial, (2) estuarine, and (3) lagoonal-marine sediments (Fig. 6)— presented below from bottom to top:

1. The fluvial facies is represented by high-amplitude and discontinuous reflectors, probably corresponding to coarse sediment. The fluvial sediments overly the surface of maximum incision, interpreted to be a sequence boundary cut during the LGM at 18–20 ka. The depth of maximum incision in the main channel ranges from –27 m offshore Dangriga to –53 m near the entrance to the English Cay Channel (Figs. 6–10).
2. The estuarine facies is characterized by laminar seismic reflectors representing alternating fine and coarse sediment (e.g., shale, silt, and fine sand). The estuarine sediment is separated from the underlying fluvial sediment by the bayline, a surface that formed as the sea transgressed within the incised valleys. The maximum depths of the bayline in the main channel range from –23 m offshore Dangriga to –35 m near the entrance of the English Cay Channel.
3. The lagoonal-marine facies is characterized by weak seismic reflectors, in some cases almost transparent, corresponding to fine homogeneous sediment, possibly a mixture of terrigenous and carbonate muds (Fig. 6). This seismic facies covers the entire shelf lagoon and overlies a widespread flat reflector, interpreted as a marine ravinement surface.

English Cay incised valle

Along the English Cay Channel, the vertical stacking of seismic facies is similar to that observed in the other incised valleys on the shelf, except that the estuarine deposits are thin in the eastern part of the channel and thicken abruptly toward its western part (Fig. 7). Estuarine sediment thickness ranges from about 4 m close to the mouth of the channel to 27 m in the western part of the channel. The maximum depth of the bayline surface is calculated to reach -61 m close to the mouth of the English Cay Channel and –47 m in the western part of the channel. The depth of the oldest fluvial facies, also corresponding to the level of maximum incision, ranges from –68 m in the eastern part of English Cay Channel to –53 m in the western part of the channel.

Elongated, commonly wedge-shaped sedimentary bodies

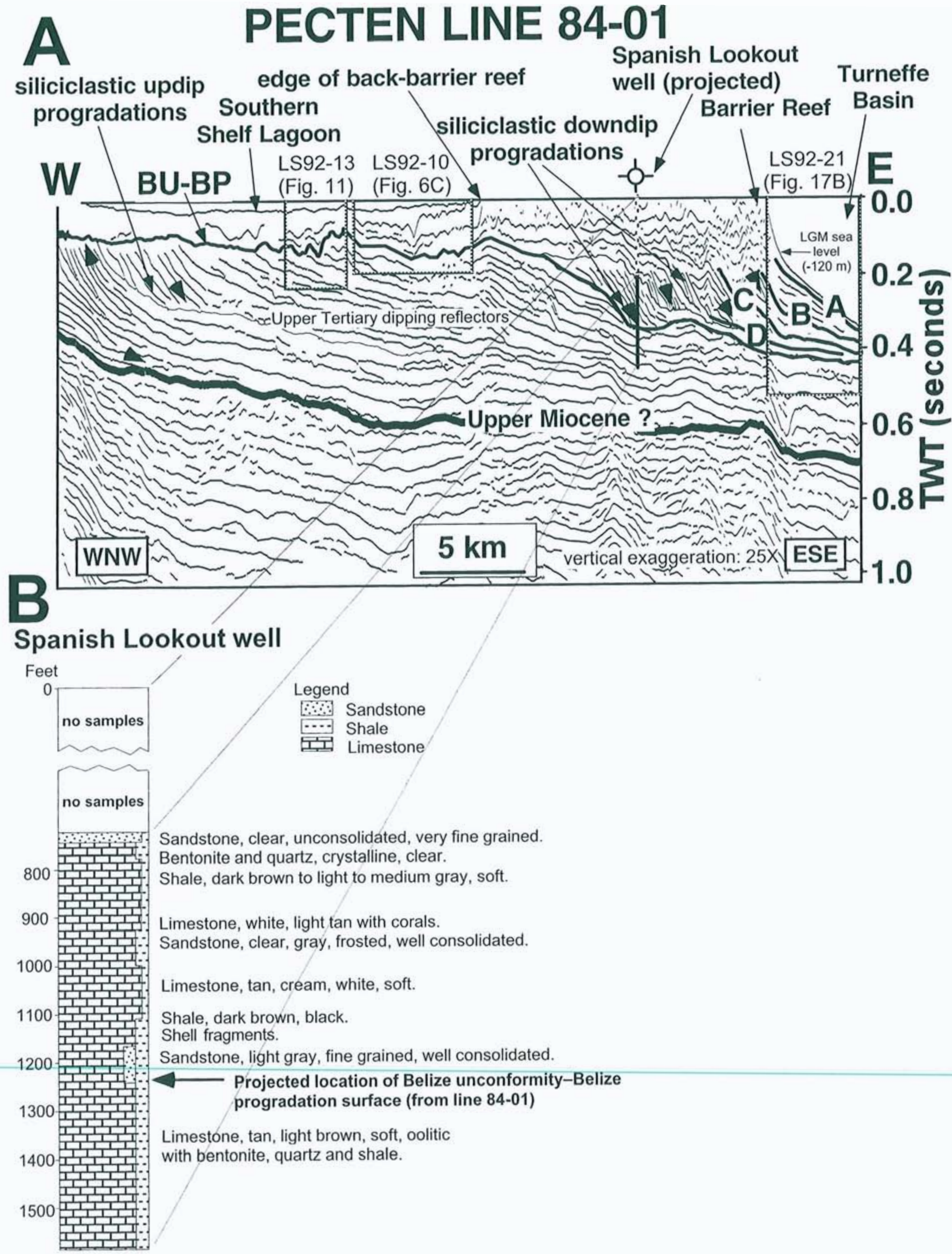

FIG. 12.—(A) Interpretation of multichannel seismic line 84-01 (located in Figs. 8, 13) and its correlation with the projected Spanish Lookout well. Tile outlined boxes indicate the projection of the high-resolution seismic lines shown in Figures 6C, 11, and 17B. The Belize unconformity truncates the top of the siliciclastic updip progradation complex in the west part of the seismic line and becomes a downlap surface for the siliciclastic downdip progradation complex observed beneath the barrier and back-barrier reef system in the east part of the seismic line. These progradations appear to be connected to wedges of sediment (LS92-21, Fig. 17B) associated with the lowstand shelf-edge delta and slope fan (LS92-39, Fig. 14A; LS92-22, Fig. 17C). Reflectors A to D can be correlated from this multichannel line to the high-resolution lines in Turneffe Basin (see Figs. 14A, 16A, 17B). The modem reef overlies wedges of downdip progradations. In Figure 12B. a schematic representation of the lithology at the Spanish Lookout well shows intercalations of siliciclastic and carbonate sediment in the interval corresponding to the downdip progradations. TWT = two-way traveltime.

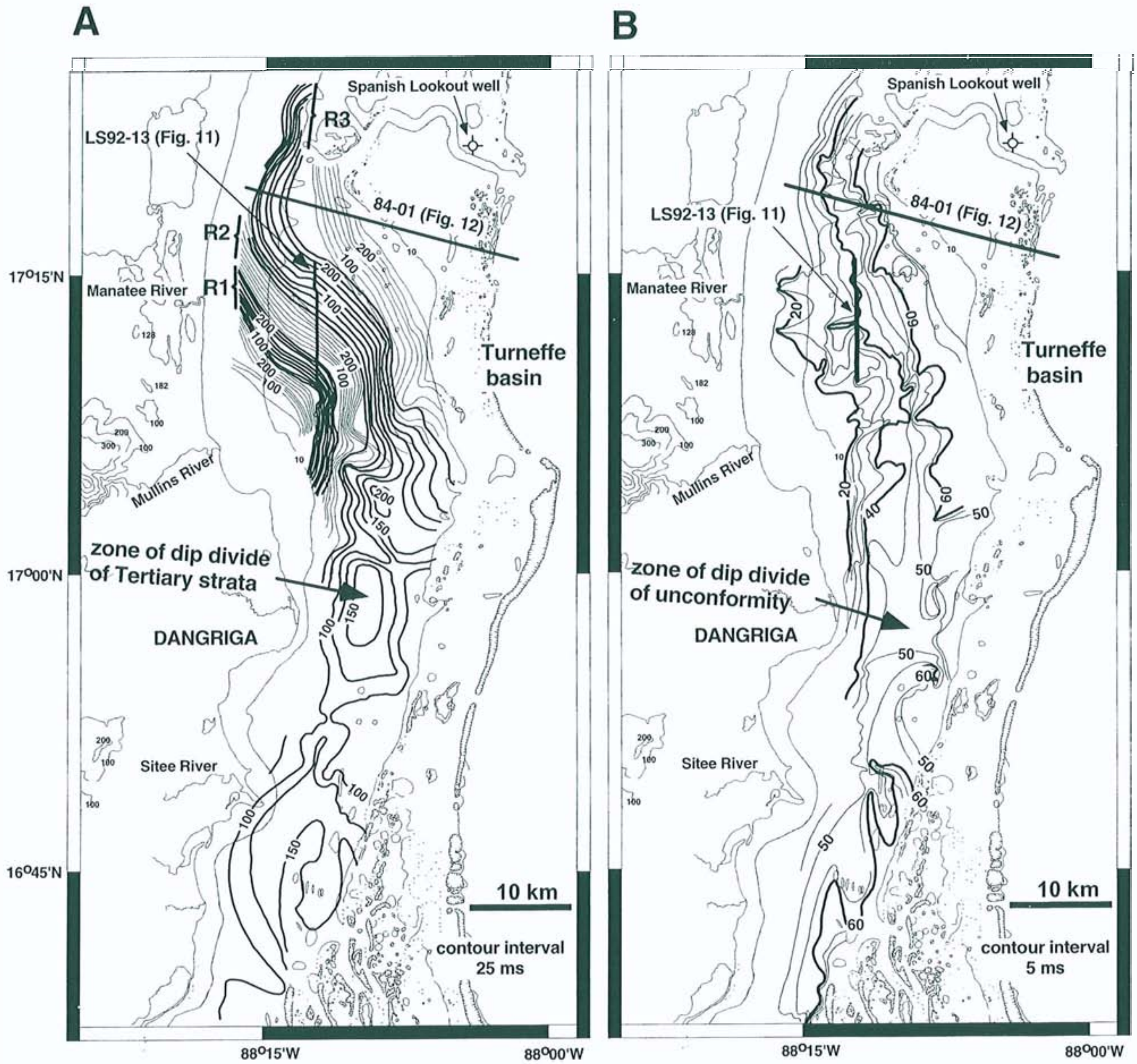

FIG. 13.—(A) Contour map of three upper Tertiary seismic horizons R1, R2, and R3 identified below the sea floor of the Southern Shelf Lagoon (Fig. 11). The R3 horizon displays a high. plateaulike area offshore Dangriga where the lowstand drainage system of valleys incised during the last glacial maximum shows a clear divide (see Figs. 8, 9). In the area north of the elevated plateau, the R1, R2, and R3 horizons dip toward the northeast, whereas in the area south of the plateau, the R3 horizon dips toward the south. (B) Contour map of the Belize unconformity identified below the sea floor of the Southern Shelf Lagoon (Figs. 5, 6, 11). The Belize unconformity displays a high, plateaulike elevated area offshore Dangriga where the lowstand drainage system of valleys incised during the last glacial maximum shows a clear divide (see Figs. 8, 9).

occur within the estuarine facies along English Cay Channel. These deposits generally show a laminar reflection character, and are locally chaotic. They are separated from the estuarine facies by an erosional surface and are interpreted to represent tidal creek bars.

Lowstand shelf-edge delta.—

A thick, eastward-bulging sedimentary deposit occurs at the mouth of the English Cay Channel (Figs. 3, 4). This sedimentary body is characterized in dip lines by a series of steep sigmoidal prograding reflectors with angles of about 10° (Figs. 14A, 15). This feature is interpreted as a lowstand shelf-edge delta. A strike section shows stacked delta lobes that display a clear shift of the depocenter toward the south (Fig. 16B). A high-amplitude seismic reflector cuts the upper part of the delta, clearly truncating the underlying dipping reflectors (Figs. 14A, 15). This particular reflector occupies the entire mouth of the English Cay Channel. The surface representation of this reflector reaches its

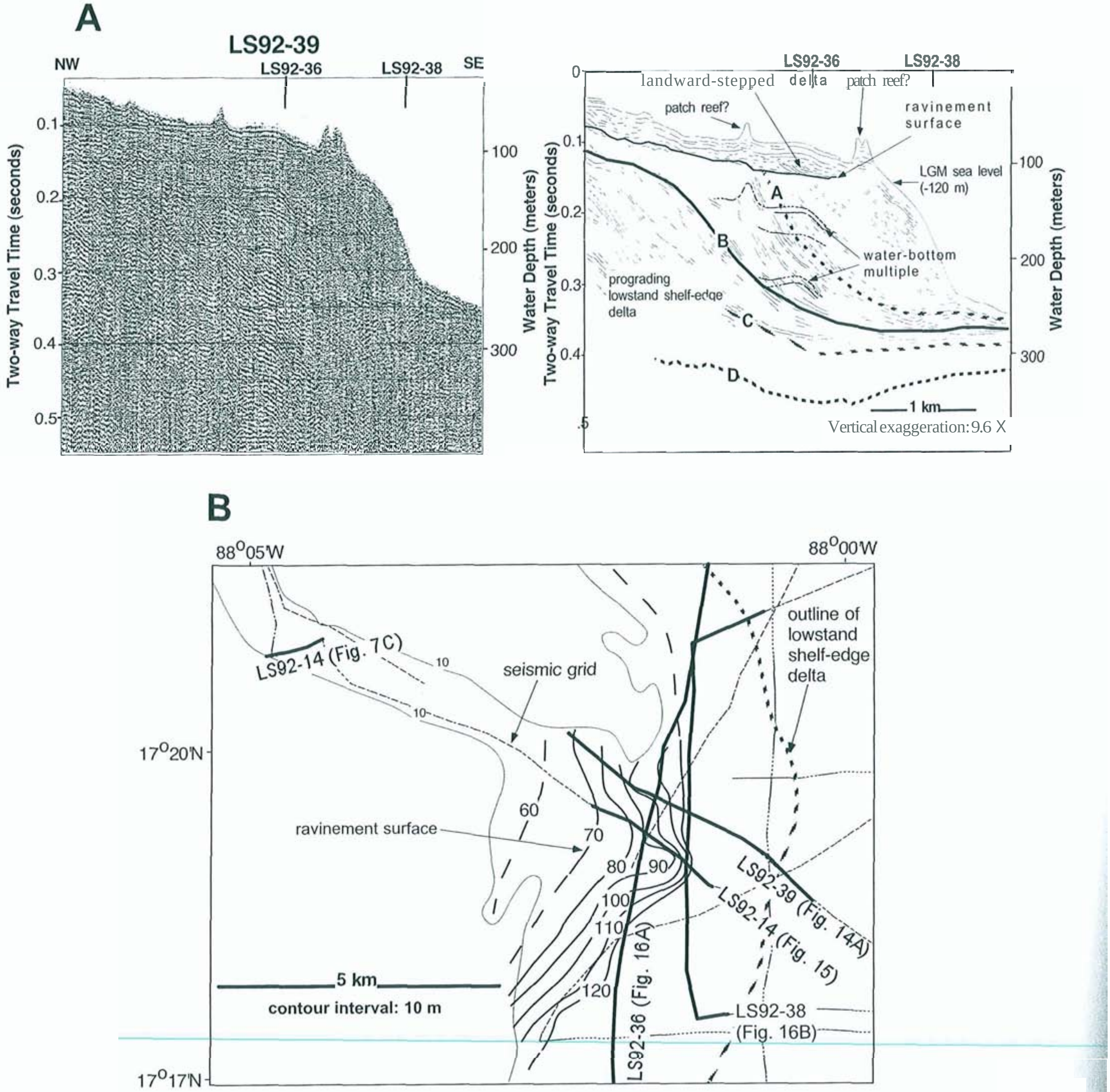

FIG. 14.—(A) High-resolution, single-channel, dip-oriented seismic profile, interpreted in the adjacent line drawing, showing a lowstand shelf-edge delta deposited at the mouth of the English Cay Channel (see location of line in B). A ravinement surface truncates the top of the prograding lowstand delta. A landward-stepped delta, deposited during the Younger Dryas, overlies the ravinement surface. Drowned patch reefs appear to have been established on top of the landward-stepped delta. Four seismic horizons (A to D) have been identified in the prograding lowstand shelf-edge delta. These horizons are correlated along dip and strike in single-channel and multichannel seismic lines in the Turneffe Basin (see Figs. 12, 16, 17). (B) Contour map of the ravinement surface on top of the lowstand shelf-edge delta. The ravinement surface reaches its lowest point at about 110 m below sea level in the most distal area of the channel mouth, which corresponds well to the LGM sea level (see Fig. 1).

lowest point at about –110 m in the most distal area of the channel mouth, rising upstream in a westerly direction to approximately –65 to –70 m (Figs. 14, 15). This reflector is interpreted to represent the ravinement surface generated during the initial and rapid sea-level transgression subsequent to the LGM lowstand.

A thin, delta-shaped sedimentary deposit overlies the ravinement surface (Fig. 14A). This body is characterized by lower-angle clinoforms relative to those in the underlying shelf-edge delta and extends up the English Cay Channel to -65 m (Figs. 14, 15). This sedimentary body is interpreted as a landward-stepped delta, resulting from fluviodeltaic sedimentation at the mouth of the English Cay Channel as sea level paused at ca. 11 ka during the Younger Dryas (Fig. 1; Fairbanks, 1989; Ruddiman and McIntire, 1981).

Slope fan.—
A strike line (Fig. 16A) that extends along the front of the barrier reef and across the mouth of the English Cay Channel shows that the lowstand shelf-edge delta ends abruptly to the north whereas it tapers more gradually to the south. About 15 km south of the lowstand delta, a morphologically distinctive, eastward-bulging sedimentary body is observed that is interpreted to correspond to a slope fan (Fig. 17C). This slope fan is connected to the lowstand delta by wedge-shaped slope deposits (Fig. 17B). The wedge-shaped deposits located north of the lowstand delta are much thinner than the ones south of the lowstand delta. This observation is illustrated in line LS92-38 (Fig. 17A), which exhibits a much thinner sediment wedge in the north than in the area south of the lowstand shelf-edge delta (Figs. 17B, 17C). The thickness of the sedimentary subunits defined by reflectors A, B, C, and D varies within the slope fan (i.e., interval between reflectors B and C, Fig. 17).

The slope-fan surface area is comparable to the surface area of the lowstand shelf-edge delta, about 8 km long and 4 km wide. A very steep slope connects the barrier reef to the top of the slope fan at about –200 m. From this depth to about –340 m, the slope is much gentler, forming an eastward-bulging surface, though the bathymetric expression of this bulge is not as accentuated as the bulge formed by the lowstand shelf-edge delta (Figs. 17C, 14A). In each subunit of the slope fan, laminar seismic reflectors downlap onto major reflectors A, B, C, and D, which define the top of a series of laminar concordant reflectors.

Correlation of Slope Deposits with Prograding Units Beneath the Barrier and Back-Barrier Reefs

Seismic line LS92-21, located south of English Cay Channel, shows wedgelike slope deposits in the basin (Fig. 17B). In strike lines, these deposits are shown to connect the lowstand shelf-edge delta at the mouth of English Cay Channel with the deposits in the slope fan (Fig. 16A). They are interpreted to result from the reworking of the lowstand shelf-edge delta by southward-directed currents.

Correlation of multichannel seismic dip line 84-01 (Fig. 12), acquired across the barrier reef, with line LS92-21 shows that the foreslope deposits in front of the barrier reef within Tumeffe Basin represent the last depositional phase of a series of prograding clinoforrns observed beneath the barrier reef itself (Figs. 12, 17B). The reef appears, therefore, to be resting on top of these prograding sedimentary bodies. The sediment underlying the back-barrier reef, partly recovered in Spanish Lookout well located 9 km to the north, consists of sandstones, shales, and limestone with corals and shell fragments (Fig. 12). These prograding units are overlain by high-amplitude discontinuous reflectors, interpreted to partially result from a series of collapse structures related to karst dissolution within the reefal cover. The base of this zone occurs at a mean depth of –110 m, calculated from a seismic velocity of 2.133 km/s (obtained from stacking velocities of nearby seismic lines and well information). The base of this zone is in good agreement with the lowest sea-level lowstands that occurred during several maximum glacial stages in the past 500 k.y. (Bard et al., 1990; Pirazzoli et al., 1993). This zone may, therefore, correspond to a succession of karst-modified surfaces included within the several generations of barrier reefs that grew during late Pleistocene highstands of sea level.

INTERPRETATION AND DISCUSSION

The pre-Holocene bathymetry of the Belize margin was characterized by a complex suite of incised valleys, organized in two distinct sea-level lowstand drainage systems. A high plateaulike area offshore Dangriga acted as a drainage divide. The main incised valleys within the lowstand fluvial plain did not run perpendicular to the basin axis, as is usually shown in the models for carbonate-siliciclastic margin evolution, Rather they trended parallel to the shoreline and the exposed, karst-modified paleo–barrier reef. The drainage system south of Dangriga merged farther south into different channels that currently separate the rhomboid reefs, whereas the drainage system north of Dangriga was linked to the English Cay Channel, currently a detached, single, large incised valley only partly in-filled with sediment. A well-developed lowstand shelf-edge siliciclastic delta formed at the mouth of the English Cay Channel in the Tumeffe Basin and was partially reworked into a slope fan farther south along and in front of the modem barrier reef. This lowstand delta-slope fan system appears to be the last phase of a series of siliciclastic(?) progradations that are observed beneath the modem barrier and back-barrier reef system.

On the basis of these new findings, the following questions are posed. What controlled the distribution of the two paleodrainage systems and the observed differences between both systems in terms of (1) their general morphology and sedimentary infill and (2) the preferential occurrence of reefal mounds on top of channel levees developed along the drainage system south of Dangriga? How can the lowstand morphology of the Southern Shelf Lagoon be so different from its modem bathymetry? If, as postulated, the lowstand delta-slope fan system at the mouth of the English Cay Channel consists of the latest depositional phase in a series of lowstand coastal progradations, as observed beneath the barrier and back-barrier reef system, is it reasonable to think that the modem and late Pleistocene interglacial barrier and back-barrier reef systems were established on top of siliciclastic deposits? In this interpretation, did the carbonate sediment preferentially grow on top of, and subsequently cover, a series of lowstand siliciclastic paleocoastlines during successive late Quaternary sea-level highstands? In the following paragraphs, we will attempt to answer those questions.

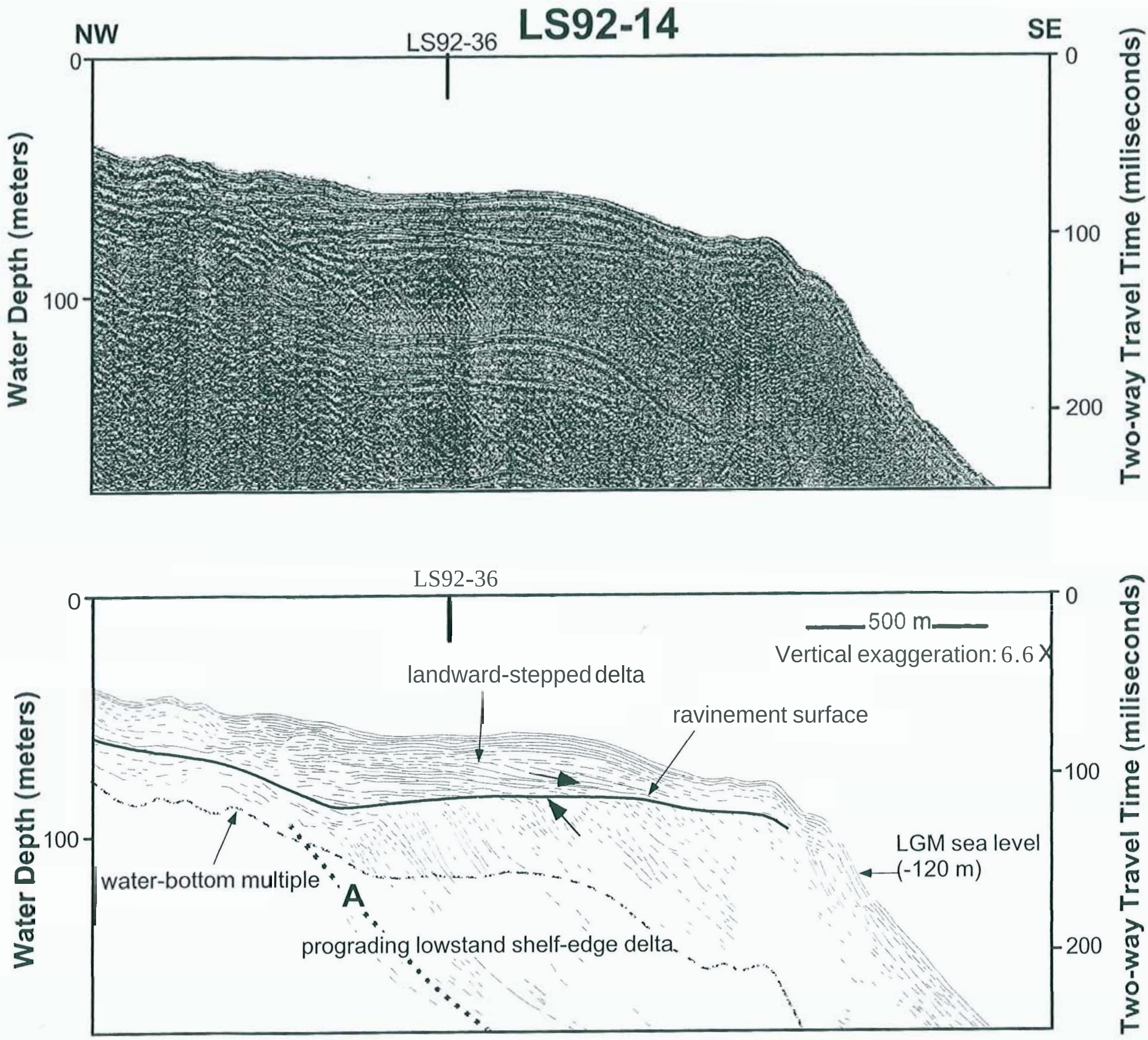

FIG. 15.—Interpreted high-resolution, single-channel. dip-oriented seismic profile (location in Fig. 14B; energy source was Uniboom). showing the upper part of a lowstand shelf-edge delta located at the mouth of the English Cay Channel. When compared with the water-gun seismic line (Fig. 14A), this Uniboom seismic line displays in greater detail the geometry of reflectors and relationship between the landward-stepped delta and the prograding lowstand shelf-edge delta.

1. Tectonic Control on the Organization of the Paleodrainage System

The organization of the incised valleys into two distinct drainage systems in the lowstand fluvial plain appears to have been dictated by a paleo–structural high at the latitude of Dangriga and by the karst-modified barrier reef running parallel to the paleocoastline. The two drainage systems of incised valleys follow a general trend already observed in the upper Tertiary reflectors and the upper Pliocene Belize unconformity (cf. Figs. 9, 13). Deposition of the upper Tertiary strata was probably influenced by a paleo–topographic high related to a narrow, upthrown, wrench-faulted zone reported by Morrice (1992). It appears, therefore, that tectonic elements have exerted an important control on sedimentary distribution patterns in the study area. Karst modification of limestones is also reported to have influenced fluvial drainage (Purdy, 1974a, 1974b). However, this study clearly demonstrates that the karst-modified barrier reef, established during the previous sea-level highstand(s), controlled the paleodrainage, mainly by causing the fluvial systems to run behind and parallel to the exposed barrier reef.

2. Differences Between Paleodrainage Systems

The sediment fill of the incised valleys north of Dangriga is characterized by high-amplitude, continuous to discontinuous, and chaotic reflectors (Fig. 6). This seismic character is inter-

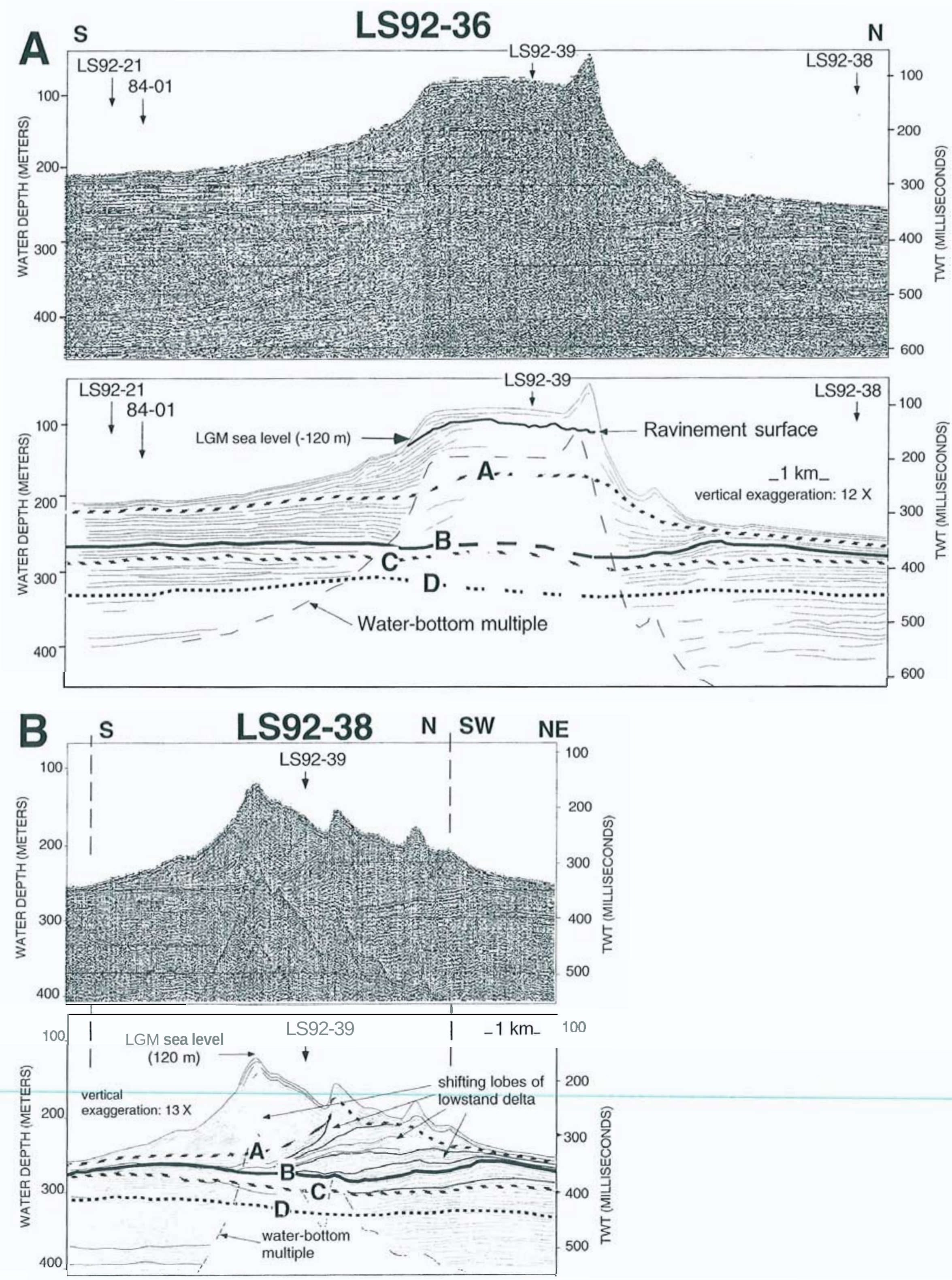

FIG. 16.—Interpreted high-resolution, single-channel, strike-oriented seismic profiles (location of lines in Fig. 14B; energy source was an SSI [Seismic System Inc.] 15-in.^{3} water gun), showing a lowstand shelf-edge delta located at the mouth of the English Cay Channel. Reflectors A to D were used for correlation between the different data sets and the multichannel seismic line (84-01) in the Turneffe Basin and beneath the barrier- and back-barrier-reef system (see Figs. 12, 14. 17). (A) Proximal, strike-oriented, seismic profile across the lowstand shelf-edge delta and along the slope of the barrier reef. Sediment thickness decreases gradually toward the south of the delta and abruptly toward the north, which reflects reworking of deltaic sediments by southward-flowing longshore currents during the last glacial maximum. Note that the reflectors A to D, directly connected to the lowstand delta, can be tied to the downdip progradations observed beneath the barrier and back-barrier reef system along the line 84-01 (Fig. 12). (B) Distal, strike-oriented, seismic profile across the lowstand shelf-edge delta. Note the southward shift of the delta lobes, also explained by southward-flowing longshore currents during the last glacial maximum. TWT = two-way traveltime.

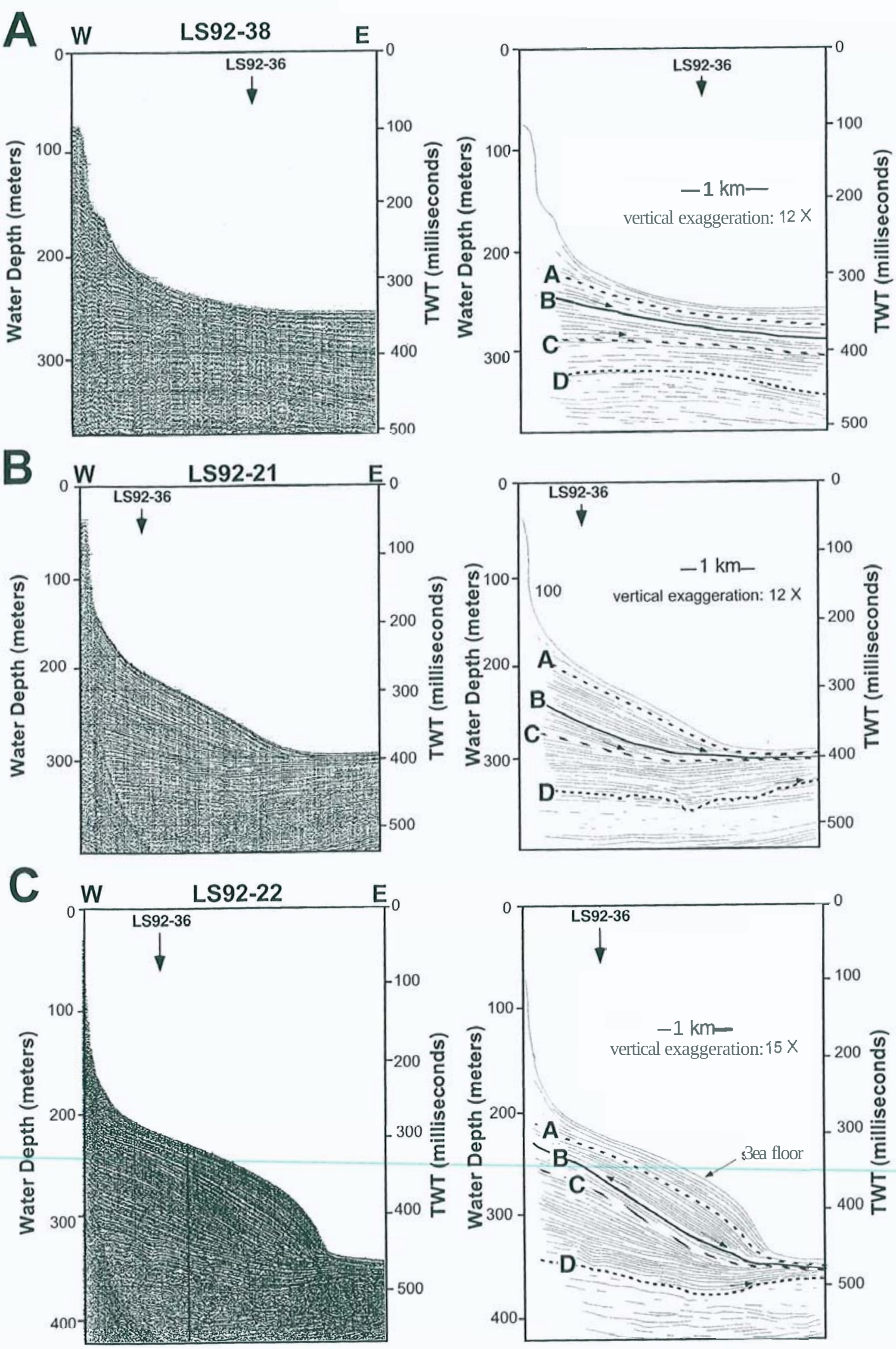

FIG. 17.—Interpreted high-resolution, single-channel, dip-oriented seismic profiles (location of lines in Fig. 8; energy source was an SSI [Seismic System Inc.] 15-in.^{3} water gun), showing the variable thickness of sediment along the slope of the western margin of the Turneffe Basin. The seismic lines are displayed from north (A) to south (C). Reflectors A to D have been identified and used for correlation in the seismic lines throughout the Tumeffe Basin (see Figs. 12, 14, 16). (A) Dip-oriented seismic line north of the lowstand shelf-edge delta. The wedgelike slope deposit is very thin. (B) Dip-oriented seismic line between the lowstand shelf-edge delta and the slope fan. The slope sedimentary wedge displays a slight bulge. Reflectors B, C, and D identified in this wedge of slope sediment correlate with reflectors B, C, and D identified in the progradations that are observed beneath the barrier and back-barrier reef in the multichannel line (Fig. 12). (C) Dip-oriented seismic line across the lowstand slope fan. Note the slight bulge. mainly formed by reflectors that do not appear to connect with the barrier reef to the west. These reflectors are thought to represent an accumulation of reworked deltaic sediment by southward-flowing longshore currents transported from the lowstand shelf-edge delta. TWT = two-way traveltime.

preted to represent coarse sediment. In contrast, the equivalent fluvial seismic facies in the incised valleys south of Dangriga consists of low-amplitude and mostly transparent reflectors, interpreted to correspond to fine sediment (Fig. 5).

The Paleozoic Santa Rosa Group, which forms the bulk of the Maya Mountains, consists of coarse-grained arenaceous-rudaceous and fine-grained argillaceous rocks (Bateson and Hall, 1977). The contact between these arenaceous-rudaceous and argillaceous rocks strikes irregularly eastward at about lat 17°N. A close examination of the present Maya Mountains drainage systems shows that most of the area containing the coarse-grained Paleozoic rocks and granites is drained by rivers flowing to the north of Dangriga. Conversely, rivers reaching the modern shoreline south of Dangriga drain most of the terrane with fine-grained argillaceous rocks (Fig. 9). During sea-level lowstands, the drainage system north of Dangriga may have received even larger volumes of coarse sediment than the drainage system to the south. The coarse sediment carried through the lowstand incised valleys north of Dangriga, possibly bed-load–dominated streams, may also explain the formation of the characteristic V-shaped profiles of these valleys. The fine-sediment load of the lowstand rivers flowing south of Dangriga suggests that these were suspended-load–dominated rivers and streams and accounts for their U-shaped profiles (Fig. 10A).

The gradient in the paleodrainage system that extends north of Dangriga is similar to the gradient in the system that extends southward (Fig. 10B). This fact rules out gradient as a possible contributor to the morphological differences observed in the incised valley profiles and valley fill of the paleodrainage systems.

3. Mode and Timing of Shelf-Lagoon Flooding During the Last Glacial to Interglacial Transition

The occurrence of patch reefs on top of the incised valley shoulders south of Dangriga, their absence along the drainage system north of Dangriga, and the different depths of the interfluvial areas between both systems help us to understand the mode and timing of the most recent flooding of the Southern Shelf Lagoon. The current depths of the shallowest shoulders along the incised valleys offshore Dangriga and near the barrier reef average –18 m below sea level. Farther to the north, near the entrance of the English Cay Channel, the shoulders occur at about –23 m (Fig. 6). This increase in depth implies that, during the development of the fluvial system, the barrier reef was modified by karst processes and its top was at a depth shallower than –18 m. During the last transgression, long and narrow estuaries were formed by flooding the lowstand incised valleys. When sea level rose above –18 m, the karst-modified barrier reef still formed a protective barrier between the lagoon and the sea. The English Cay Channel was probably the only break within this barrier. The incised valley shoulders in the lagoonal area north of Dangriga were submerged by restricted, poorly ventilated, and brackish waters. These conditions, which are inimical to carbonate-mound establishment, would explain the absence of patch reefs in the shelf lagoon north of Dangriga.

The –18-m sea-level position corresponds to ca. 8 ka in the Fairbanks (1989) eustatic sea-level curve (Fig. 1). Existing data show that the reestablishment of corals over the karst-modified surface of the previous highstand barrier reef occurred more recently than 8 ka. By drilling on Carrie Bow Cay, Shinn et al. (1982) recovered, at a depth of –16.2 m, Pleistocene limestone with leaching and caliche staining, indicating subaerial exposure. This exposure surface is covered by corals in growth position, radiocarbon dated at ca. 7 ka (core 1 in Fig. 8). In an earlier study, Purdy (1974b) encountered, in a bore hole on Tobacco Cay (core 2 in Fig. 8), a leached and recrystallized coralline limestone surface at a subbottom depth of –14 to –16.5 m. On the basis of these two studies, the top of the karst-modified barrier reef in this central segment of the barrier is situated at about –16 m and was submerged at ca. 7 ka.

Sea-water circulation appears to have exerted an important influence on reef development in the shelf lagoon. In the lagoon south of Dangriga, patch reefs occur on channel levees (Fig. 5C). The same mode of growth has been found by Choi and Ginsburg (1982) and Choi and Holmes (1982) in the lagoon farther to the south. Choi and Holmes (1982) suggested that rhomboid and long sinuous reefs were established and grew on old river levees during successive late Pleistocene transgressions and highstands. Shinn et al. (1979) recovered coral-bearing Pleistocene (stage 5?) limestone beneath the outer rim at the Channel Cay Reef complex and nearby beneath the Boo Bee Patch Reef. On the basis of these findings, Shinn et al. (1979) and Westphall (1986) suggested that the substratum of the rhomboid reefs consists of a multistoried reef complex upon which the Holocene reefs became established. This interpretation has been strengthened by drilling (Robert Ginsburg, pers. commun., 1992) in the area of the rhomboid reefs, which recovered a 30-m-thick coral-bearing upper Pleistocene limestone. In several borings, the uppermost upper Pleistocene limestones overlie stiff clays, interpreted as Pleistocene levee and floodplain deposits that served as the substratum for the rhomboid reefs (Choi and Ginsburg, 1982; Choi and Holmes, 1982). Moreover, nonmarine quartz silts, underlying a peat layer radiocarbon dated at 9,200 yr B.P., were sampled in the enclosed lagoon of the Channel Cay Complex at –32 m (Westphall, 1986). By plotting radiocarbon ages of unaltered corals found in living position from the Channel Cay Complex and the barrier reef (Shinn et al., 1982) against a Belize sea-level curve, Westphall (1986) demonstrated that the Belize Barrier Reef was topographically higher, by as much as 13 m, than the Holocene reef at Channel Cay. According to their growth curve, the reefs at Channel Cay first grew in waters as deep as 15–12 m and subsequently grew to sea level ("catch-up" reefs). Westphall (1986) attributed this catch-up mode of Channel Cay reef growth to the semirestricted water circulation behind the barrier reef. Although the area of the rhomboid reefs remained restricted to the east by the barrier reef itself; it was open to normal-marine conditions from the south. In contrast, the shelf lagoon north of Dangriga, where the English Cay Channel was the only connection with the open sea during the initial flooding, a highly restricted marine environment remained. Conditions inimical to reef growth within this restricted-marine environment can explain the absence of patch reefs in this part of the shelf lagoon.

4. Paleobathymetry and Modern Bathymetry of the Southern Shelf Lagoon

It has long been thought that the modem bathymetry of the Southern Shelf Lagoon, characteristically sloping toward the south (Fig. 3), was inherited from the pre-Holocene bathymetry (Purdy, 1974a, 1974b; Purdy et al., 1975). In this context, the last marine transgression progressed from south to north across the shelf lagoon. The timing of Holocene reef establishment and growth behind the barrier reef was directly influenced by this south to north transgression across the Southern Shelf Lagoon (i.e., Precht, 1993, 1994). However, results of the present study demonstrate that the pre-Holocene bathymetry was characterized by two fluvial drainage systems separated by a drainage divide offshore Dangriga. In the area of the shelf lagoon north of Dangriga, the fluvial paleodrainage dips to the north whereas the modem lagoon floor slopes to the south (Figs. 3, 8). The gradient change from north during the LGM to south today may have its origin in the unusually large volume of lagoonal-marine sediment deposited during the early Holocene in the shelf lagoon north of Dangriga. During the last transgression, a large volume of sediment, comparable in size to the sediment volume that was funneled through the English Cay Channel into Turneffe Basin during the last sea-level lowstand, filled in, at least partially, the area adjacent to the western entrance of the English Cay Channel. Moreover, during the early highstand, sediment from the Belize City delta probably contributed to the sediment fill in the northern part of the lagoon and ultimately to the reversal in gradient.

5. Lowstand Delta and Slope-Fan Development in Front of the Exposed Reef: Ready-Made Substratum for Reef Development During the Following Transgression

Large rivers, such as the Belize River, North Stann Creek, and Sitee River, deliver large volumes of sediment to the modem Belize shoreline. At the mouth of these rivers, deltas are formed and then partially reworked by southward-flowing longshore currents. Reworked deltaic sediment is ultimately deposited along a series of well-developed prograding beach ridges on the south side of the main river mouths. The late Pleistocene lowstand shelf-edge delta at the mouth of the English Cay Channel appears to have been also influenced by southward-flowing longshore currents. Seismic profiles show that individual delta lobes shifted through time toward the south, and the overall deltaic package of strata thickens toward the south (Fig. 16). These observations indicate that the morphology of the lowstand shelf-edge delta was strongly influenced by longshore currents. The slope fan, located 10 to 15 km south of the English Cay Channel lowstand shelf-edge delta, was most likely formed as reworked deltaic sediment by southward-flowing longshore currents. Seismic lines in the lagoon show no incised valleys breaching the barrier reef at the location of the slope fan. Thus, the slope fan does not appear to have been built by sediment coming directly from the shelf lagoon, as was the lowstand shelf-edge delta. Dip sections across the slope fan show that some of the youngest sediment (represented by some reflectors overlying A and B in Figure 17 does not extend beneath the barrier reef. Instead, these younger strata appear to have been derived from the north and transported along strike by southward-flowing longshore currents that are acting today (Wüst, 1964).

In contrast, older slope deposits (sedimentary units between reflectors B, C, and D in seismic line LS92-21, Fig. 17) appear to be associated with prograding wedges, well developed beneath the modern barrier- and back-barrier-reef system (Fig. 12). Strike lines also show that the sedimentary units of the slope deposits (defined by reflectors B, C, and D in Fig. 17) are the condensed continuation of much thicker sedimentary units that form the lowstand shelf-edge delta, defined by reflectors B, C, and D (Figs. 14A, 16), and that the seismic facies between these reflectors do not change along strike (Fig. 16A). These correlations suggest that the progradation observed beneath the barrier reef was produced during a series of sea-level lowstands. The shelf-edge delta and slope fan observed at the mouth of the English Cay Channel, therefore, consist of the latest phase of a series of lowstand siliciclastic prograding wedges, which have served as a substratum for reef establishment during successive transgressions and highstands.

The Spanish Lookout well, located about 10 km to the north of this area, sampled a mixture of siliciclastic and carbonate sediment, which appears to correspond to the progradational section in line 84-01. The distance between the Spanish Lookout well and line 84-01 is too large for reliable correlation. Line 84-01 shows subhorizontal reflectors beneath the prograding complex (Fig. 12). Given these observations, it is feasible that the prograding unit imaged in line 84-01 consists, at least in part, of siliciclastic sediment. The correlation of lines 84-01, LS92-21 and LS92-36 (Figs. 12, 17B, and 16A, respectively) suggests that the prograding wedges beneath the barrier and back-barrier reef complex and the shelf-edge delta-slope fan complex in front of the modem barrier reef were deposited during lowstands and are composed mostly of siliciclastic sediment. It is significant that the top of the prograding wedges beneath the barrier and back-barrier reef, in addition to the edge of the delta at the mouth of the English Cay Channel, range from about –100 and –120 m below sea level (Figs. 12, 14A, 15) and, therefore, correspond well to late Pleistocene lowstands (Fig. 1; Fairbanks, 1989; Bard et al., 1990; Pirazzoli et al., 1993).

6. Model for the Evolution of the Belize Siliciclastic-Carbonate System Tied to the Last Sea-Level Cycle

Despite the limited paleontologic age control for this study, we are confident that the high-resolution seismic data have imaged the youngest phase of the evolution of the Belize margin. The lowstand and transgressive deposits correlate with the well-established eustatic curves for the past 20 k.y. (Fig. 1) (Fairbanks, 1989; Bard et al., 1990).

During the LGM (18–20 ka), the shoreline was situated at what is now approximately –120-m depth (i.e., Fairbanks, 1989; Bard et al., 1990). In Belize, the shoreline shifted to the front of the previous interglacial stage 5 barrier reef, at about the location where the modem barrier reef exists today (Fig. 18A). A lowstand shelf-edge delta was deposited at the mouth of the English Cay Channel (Figs. 14, 15, 16, 18A). Longshore currents removed some sediment from this delta and redeposited it 15 km to the south into a slope fan. During the LGM, the Southern Shelf Lagoon was divided in two fluvial paleodrainage systems with a divide at the latitude of Dangriga (Figs. 9, 18A).

Following the LGM, the sea transgressed quickly across the top of the previously deposited shelf-edge delta and formed a clear ravinement surface (Figs. 14–15). The ravinement of the shelf-edge delta top reached its lowest level at about (110 m (relative to current sea level), corresponding well with the estimated LGM sea-level lowstand (Figs. 1, 14B). In the middle of this transgression, there was a pause or at least a significant decrease in the rate of sea-level rise for 1 k.y., at ca. 11 ka (Fig. 1B). This event is known as the Younger Dryas (Fig. 1B) and represents a time when the climate returned to almost full glacial (Fairbanks, 1989). During this pause, when sea level is estimated to have been at approximately -65 m, a new fluvio-deltaic system evolved, producing a landward-stepped delta on top of the ravinement surface (Figs. 14, 15, 18B).

After the Younger Dryas, sea level rose quickly and flooded the lower part of the English Cay Channel. The depth of the bayline in the lower part of the English Cay Channel is at about –61 m and marks the initial transgression along this segment of the valley. During this flooding episode, the river deposition was not able to keep up with the rapid sea-level rise and, as a result, only a thin (approximately 4 m) transgressive sedimentary section was deposited in the eastern segment of the English Cay Channel (Fig. 7C). As the rate of sea-level rise slowed, thicker transgressive sediment was deposited (Figs. 7A and 7B) within the upper reaches of the channel. In this part of the channel, the bayline was at a depth of -47 m and 27 m of estuarine sediment was deposited in the valley.

As the ocean flooded the incised valleys farther upstream, in the area of the lowstand fluvial plain that is today the Southern Shelf Lagoon, the river rapidly filled the valleys with estuarine deposits. Rates of sea-level rise had slowed during this time (Fig. 18C). Because the English Cay Channel was the only connection to the sea for the entire drainage area north of Dangriga, strong tidal currents swept along the English Cay Channel depositing tidal-creek bars, and the more brackish waters on the shelf prevented the growth of carbonate mounds. In contrast, South of Dangriga, the estuaries were connected to the open sea, promoting the growth of abundant patch reefs in that area of the Southern Shelf Lagoon.

At ca. 7 ka, the karst-modified surface of the previous (stage 5) barrier reef was finally submerged, and the modem barrier reef became established. Siliciclastic sediment became confined to the coastal area by the establishment of southward-flowing longshore currents. Thus, after a long interval (stages 4–2, or perhaps as long as 60 k.y.; Fig. 1) during which siliciclastic sediment was dominant along the Belize margin, carbonate production began again (Fig. 18D). The establishment of a pure carbonate barrier and back-barrier reef environment marks the beginning of the modem mixed siliciclastic-carbonate sedimentary system along the Belize margin.

7. Reservoir Implications

Understanding the origin of incised valleys and studying the sedimentary processes that are responsible for their development enhances oil exploration and production from these important reservoirs (Bowen et al., 1993). Models for mixed carbonate-siliciclastic margin evolution (i.e., Handford and Loucks, 1993) usually show the main incised valley system within a lowstand fluvial plain running perpendicular to the shoreline and a series of lowstand shelf-edge deltas consisting of several sedimentary bodies with point sources. In contrast to these models, the present study has demonstrated that the main lowstand fluvial-drainage systems of incised valleys on the Belize margin extended parallel to the shore and to the exposed barrier reef.

These results, among others of this study, could have some significant implications for hydrocarbon reservoir exploration and production along ancient mixed siliciclastic-carbonate margins. During sea-level lowstands, when the barrier and back-barrier reefs, deposited along the shelf edge during the previous highstand(s), became exposed, any rivers would tend to flow parallel to the reef. Thus the main reservoirs will trend parallel to the reef, not perpendicular. If sea level fell below the carbonate shelf edge, the fluvial system would dissect the shelf break. Massive coarse-grained lowstand sediment would subsequently be deposited in the basin at the mouth of the channel and along the trend of the exposed reef. Longshore currents would partially redistribute the sediments in front of the exposed barrier reef, forming a suite of subparallel beach ridges in the shallowest part of the lowstand coastline and a lowstand slope fan in deeper waters. However, if the subsequent sea-level rise was rapid, ravines would be cut into the upper parts of the lowstand delta, including the delta front, thus diminishing the quality of the reservoir.

CONCLUSIONS

1. Two lowstand fluvial drainage systems, consisting of a series of incised valleys, were observed in high-resolution seismic grids in the northern part of the Belize Southern Shelf Lagoon. These drainage systems, most likely developed during the LGM, are separated by a divide at the latitude of Dangriga. The drainage divide apvears to be rooted on a topographic high in the upper Tertiary deposits of the Southern Shelf Lagoon offshore Dangriga.
2. South of Dangriga, a system of incised valleys drained the LGM fluvial plain toward the south and merged into Victoria Channel and other channels separating modem rhomboid reefs. North of Dangriga, a second system of incised valleys drained the area of the LGM fluvial plain toward the north into the incised English Cay Channel. These paleodrainage systems exhibit differences in the morphology of the incised valleys and the seismic character of their valley fill. The coarse-grained sediment carried through the incised valleys north of Dangriga may have contributed to the characteristic V-shaped profiles, whereas the fine-grained sediment load of the lowstand rivers flowing south of Dangriga could explain their characteristic U-shaped profiles.

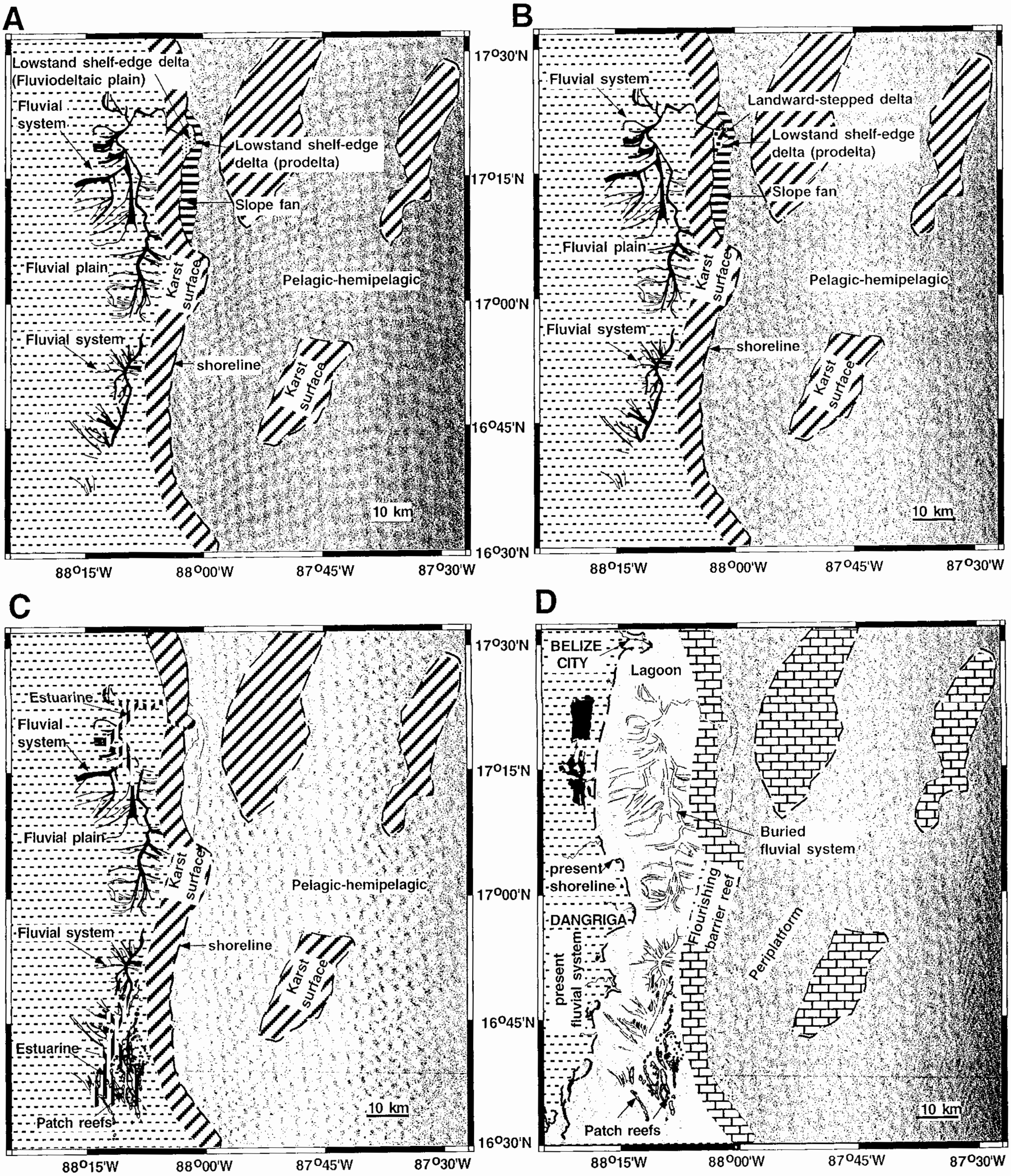

FIG. 18.—Model for the evolution of the mixed siliciclastic-carbonate system along the Belize margin during the last sea-level cycle. Letters A to D in Figure 1[illegible] indicate the estimated sea level at each of four time intervals described in the model. (A) During the last glacial maximum, 18–20 ka, the lowstand shoreline was located in front of (i.e., east of) the position of the modern barrier reef. A complex drainage system of incised valleys was developed in the lowstand fluvial plain parallel to and west of the exposed oxygen isotope stage 5 barrier reef. The drainage system south of Dangriga merged into the modern rhomboid reefs, whereas the drainage system north of Dangriga merged into a single incised valley of the English Cay Channel. A lowstand shelf-edge delta and associated slope fan were deposited at the mouth of the English Cay Channel along the western margin of the Turneffe Basin, located where the coastline was during the lowstand. (B) During the Younger Dryas, 11.8–10.6 ka, the rates of sea-level rise decreased, and sea level may have remained constant for about 1 k.y. As a result, a landward-stepped delta formed on top of the lowstand shelf-edge delta. (C) About 8.5 ka, the sea started to transgress across some parts of the lowstand fluvial plain, today the Southern Shelf Lagoon. Estuaries formed in the areas north and south of Dangriga. In the north, the estuaries were still funneled through the English Cay Channel. These environments therefore remained restricted. In the south, however, the estuaries were directly connected to the open sea, which probably favored the growth of patch reefs on river levees. Note that the dominant depositional environment in the shelf area was still siliciclastic. (D) During the past 7 ka, the sea flooded the top of the karst-modified barrier reef to establish the mixed siliciclastic-carbonate system that exists today.

3. A thick, fanlike sedimentary body, characterized by a series of stacked, prograding, and laterally shifting lobes, occurs at the mouth of the English Cay Channel. This sedimentary body is interpreted as a lowstand shelf-edge delta, similar in surface area to the modem highstand delta of the Belize River on which Belize City is located. Southerly longshore currents partially reworked the lowstand shelf-edge delta and created an elongated slope fan at the toe of the exposed barrier reef. The shelf-edge delta and slope fan, observed at the mouth of the English Cay Channel and in front of the barrier reef, served as a substratum for establishment of reefs during the last glacial to interglacial transgression.
4. The well-established sea-level fluctuations during the past 20 k.y. can explain the most recent sedimentary deposits observed in the high-resolution seismic grids across the Belize margin. The shelf-edge delta and slope-fan complex was deposited at the mouth of the English Cay Channel and in front of the barrier reef during the LGM –120 m sea-level lowstand. Subsequent rapid rise cut ravines into the top of the shelf-edge delta. A landward-stepped delta was deposited on top of the ravinement surface. This landward-stepped delta was probably deposited during the Younger Dryas in a 1-k.y.-long interval when rates of sea-level rise greatly diminished. Maximum rates of sea-level rise followed the Younger Dryas, resulting in a thin estuarine deposit in the lower part of the English Cay Channel. As the rate of sea-level rise slowed again, thicker estuarine sediment was deposited in the upstream segment of the English Cay Channel. Finally, as sea level reached the modem shelf lagoon (lowstand fluvial plain), sediment completely filled the incised valleys. During the last phase of the LGM to Holocene sea-level transgression, the entire area of the Southern Shelf Lagoon was covered by a thin blanket of lagoonal sediment.
5. Seawater circulation appears to have played a key role in reef development in the shelf lagoon and influenced the distribution of patch reefs. These reefs occur along the flanks of incised valleys south of Dangriga. Patch reefs are absent north of Dangriga,
6. For most of the past 30 k.y., and perhaps even the past 75 k.y., siliciclastic processes dominated sedimentation along the Belize margin. Carbonate environments were reestablished along the Belize margin only in the past 7 k.y. once the sea submerged the karst-modified barrier reef and flooded the LGM fluvial plain, creating the modem mixed siliciclastic-carbonate system.
7. The slope deposits in front of the modem barrier reef appear to be the continuation of well-developed prograding sedimentary units observed beneath the barrier and back-barrier reef complex. These findings suggest that the prograding strata beneath the barrier reef were produced during a series of sea-level lowstands. In this context, the shelf-edge delta and slope fan at the mouth of the English Cay Channel consist of the latest phase in a series of lowstand siliciclastic prograding wedges, which have served as a substratum for reef establishment during successive sea-level transgressions and highstands.
8. The mixed siliciclastic-carbonate system of the late Quatemary Belize margin is quite different from that of pure carbonate or siliciclastic systems. In the mixed system, the migration and export of siliciclastic sediments toward the shelf margin during sea-level regressions and lowstands overwhelms and suffocates carbonates. Prograding wedges of siliciclastic sediment are deposited below and on the seaward side of the exposed barrier reef by fluvial-deltaic processes during lowstands. These prograding wedges created a surface on top of which a new barrier reef was established during the following transgression. Because the extent of carbonate production is reduced to a minimum during lowstands, little carbonate resedimentation occurs along the slopes and in the adjacent basins. Belize carbonate sediment production was abundant during the succession of late Quatemary sea-level transgressions and highstands, whereas siliciclastic sediments were contained within the coastal zone and/or were transported along the shoreline by longshore currents. In Belize, both siliciclastic and carbonate systems have played an important role in building the continental margin, though at a different time of the sea-level cycle.
9. Results of this study could have significant implications for hydrocarbon reservoir exploration and production along ancient margins, where a siliciclastic shoreline coexisted with an offshore shelf-edge barrier and back-barrier reef system. Unlike most published models, where the lowstand incised valleys extend perpendicular to the reef, here the incised valleys run parallel to the strike of the reef and breach the exposed reef at only a few locations, where lowstand shelf-edge deltas are deposited. These deltas are partially reworked into slope fans in front of and in an orientation parallel to the exposed barrier reef.

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