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The Belize margin revisited. 2. Origin of Holocene antecedent topography

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Abstract The importance of antecedent topography in dictating Holocene facies patterns has been generally recognized. There is, however, disagreement as to origin or lithology of the antecedent topography, particularly with respect to the siliciclastic or carbonate nature of the underlying topography and structural patterns. To help resolve these problems, published and unpublished information have been compiled to produce a structural fabric map of onshore and offshore Belize that includes a new geologic map of the country. The map, along with illustrated seismic lines, demonstrates the occurrence of a number of NNE-trending transpressional faults in which landward directed thrusting is consistently displayed along with tectonic inversion. Offshore wells in conjunction with the seismic lines document the inversion as post-Eocene, suggesting a similar age for transpressional fault movement. Presumably, the landward-directed thrusting reflects the opposing force of eastward-directed subduction along the western margin of Central America relative to the westward seafloor spreading of the Caribbean Cayman Ridge. The Belize faults show little current seismicity, but, nevertheless, the resulting structures have affected Quaternary carbonate deposition as evidenced on an illustrated seismic line by both seaward and landward (bi-directional) progradation of the reef margin from an underlying structural high. The structural influence on the development of Holocene antecedent topography is further suggested by the occurrence of a Bouguer gravity plateau in the same shelf area that marks

the occurrence of the Belize lagoon rhomboid shelf atolls. The youngest documented lithology of 12 illustrated offshore exploration wells is Miocene carbonate. In some wells, the carbonate is interpreted as extending into the Pliocene and Holocene although no age diagnostic criteria are in evidence. In other wells, siliciclastics of unknown age and thickness are identified as overlying Neogene carbonates. The regional distribution and age of onshore limestones suggests that unroofing of the Cretaceous carbonate cap of the Maya Mountains siliciclastic sediment source did not occur until late in Neogene time, perhaps no earlier than late Pliocene. Consequently, the Maya Mountains could not have been a major offshore source of siliciclastics until the Quaternary. Information on the lithology of the immediately underlying pre-Holocene is provided by limited penetration core data and shallow resolution seismic lines. These show that antecedent Pleistocene limestones beneath the Holocene reefs were deposited around 130,000 B.P. (isotope stage 5e). The thickness of the overlying Holocene, shelf margin, reef-capped carbonates increases along depositional strike from a few meters in the north to more than 25 m in the south. In contrast, piston cores and seismic data from the southern shelf lagoon collectively document the occurrence of antecedent siliciclastic topography. The southward dip of both carbonate and siliciclastic antecedent surfaces is presumably a reflection of increasing southerly subsidence. Increasing antecedent erosional relief in the same direction reflects the pronounced southerly increase in paleo-rainfall that presumably paralleled that of present-day rainfall.

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Introduction

Objective

The purpose of this contribution is to provide new information on the origin and lithology of the antecedent topography controlling the distribution of Holocene facies, principally reefs and carbonate shoals.

Hypotheses on underlying controls of Holocene facies patterns

Since the 1960s, the importance of antecedent topography in dictating Holocene facies patterns has been generally recognized, particularly with respect to the distribution of carbonate shoals. There is, however, disagreement as to the origin and/or lithology of the Belize antecedent topography. Purdy (1974) believed that shelf morphology was a consequence of structurally controlled karstification during glacial low stands of sea level.¹ Halley et al. (1977) suggested that Pleistocene reefs probably formed antecedent topography beneath many Holocene patch reefs, a possibility that had been previously considered by Purdy (1974) who noted that, even if this were the case, there still remained the problem of explaining the Pleistocene distribution pattern. Choi (1981), Choi and Ginsburg (1982), Choi and Holmes (1982), and Ginsburg and Choi (1983) accepted antecedent control for the distribution of carbonate shoals in the southern shelf lagoon, but speculated that the control ultimately reflected the distribution of Pleistocene siliciclastics rather than carbonates. Lara (1993) interpreted a southern shelf lagoon multichannel seismic reflection grid as indicating that parts of the bathymetry of the southern shelf lagoon reflected underlying Tertiary structural highs and lows. Purdy (1998) noted that the peculiar hook-like termination of the Belize barrier reef in the south was dictated largely by the eroded limbs of an underlying syncline. Esker et al. (1998) concluded that southern shelf lagoon shallow-penetration, high resolution seismic data demonstrated that early faulting had created preferential sites for the development of both Quaternary reefs and river valleys and that these had influenced the subsequent position of reefs and incised valleys in a feedback relationship. More recently, Ferro et al. (1999) concluded that barrier reef and barrier platform development in the central shelf lagoon area took place over Pleistocene low stand siliciclastics.

It seems clear from data presented in the foregoing references that both antecedent siliciclastic and carbonate lithologies are involved, depending on the area of investigation, but what is missing is an overall regional, rather than area-specific development link that gave rise to the Holocene antecedent surface, carbonate, or silici-

clastic. Towards that end, we begin by discussing pertinent aspects of the regional geology of Belize.

Regional geology

Prasada Rao and Ramanathan (1988) recognized three major Belize structural entities: (1) a northern Corozal Basin north of the Maya Mountains, representing an eastern continuation of the northern Guatemala Petén Basin; (2) a central Maya block of Paleozoic igneous and metamorphic rocks; and (3) a Belize Basin that borders the Maya block offshore to the east and onshore and offshore to the south, and is a continuation of the southern part of the Petén Basin. The onshore geology comprising these elements is illustrated in Fig. 1. Some of the illustrated onshore geology is taken from an unpublished map compiled by J.H. Cornec (1998). We have modified Cornec's compilation where new or seemingly better information was available (see for example the comment by Ocampo et al. 1996, p. 76). This is particularly true of northern Belize where low relief, poor exposures and extensive recrystallization have made recognition of separate limestone units difficult. Here we have relied heavily on an unpublished Chevron photogeology interpretation by Miller (1966) that includes paleontologic control.

Unfortunately, the throw or type of onshore fault is not shown on Cornec's map, even where known, and no offshore structures are illustrated. We have added both of these in an attempt to update the previously published structural fabric synthesis of onshore and offshore Belize (Purdy 1974) with the considerable amount of new data that have come to hand since then.

Stratigraphy

Stratigraphic nomenclature differs considerably between the Corozal and Belize basins, but we are concerned mainly with the offshore area, and, consequently, will be using Belize Basin nomenclature for the most part, making only occasional reference to correlative units in the Corozal Basin. Even so, the general stratigraphy of both basins is illustrated in Fig. 2 and that of all offshore exploration wells and several near-shore, southern onshore wells is illustrated in Fig. 3.

Paleozoic

The distribution of Paleozoic outcrops in the onshore central Maya block (Fig. 1) is largely the work of Dixon (1956), modified where appropriate by the later work of Bateson and Hall (1977) who identified them as variably metamorphosed Pennsylvanian to Middle Permian sedimentary and volcanic rocks of the Santa Rosa Group. The granite pluton occurrences within the Santa Rosa outcrops were originally thought to be late Triassic intrusives based

¹ The reader is referred to Purdy and Gischler (2003), this issue, DOI 10.1007/s00531-003-0324-0 for nomenclature and descriptions of the Belize offshore bathymetric framework.

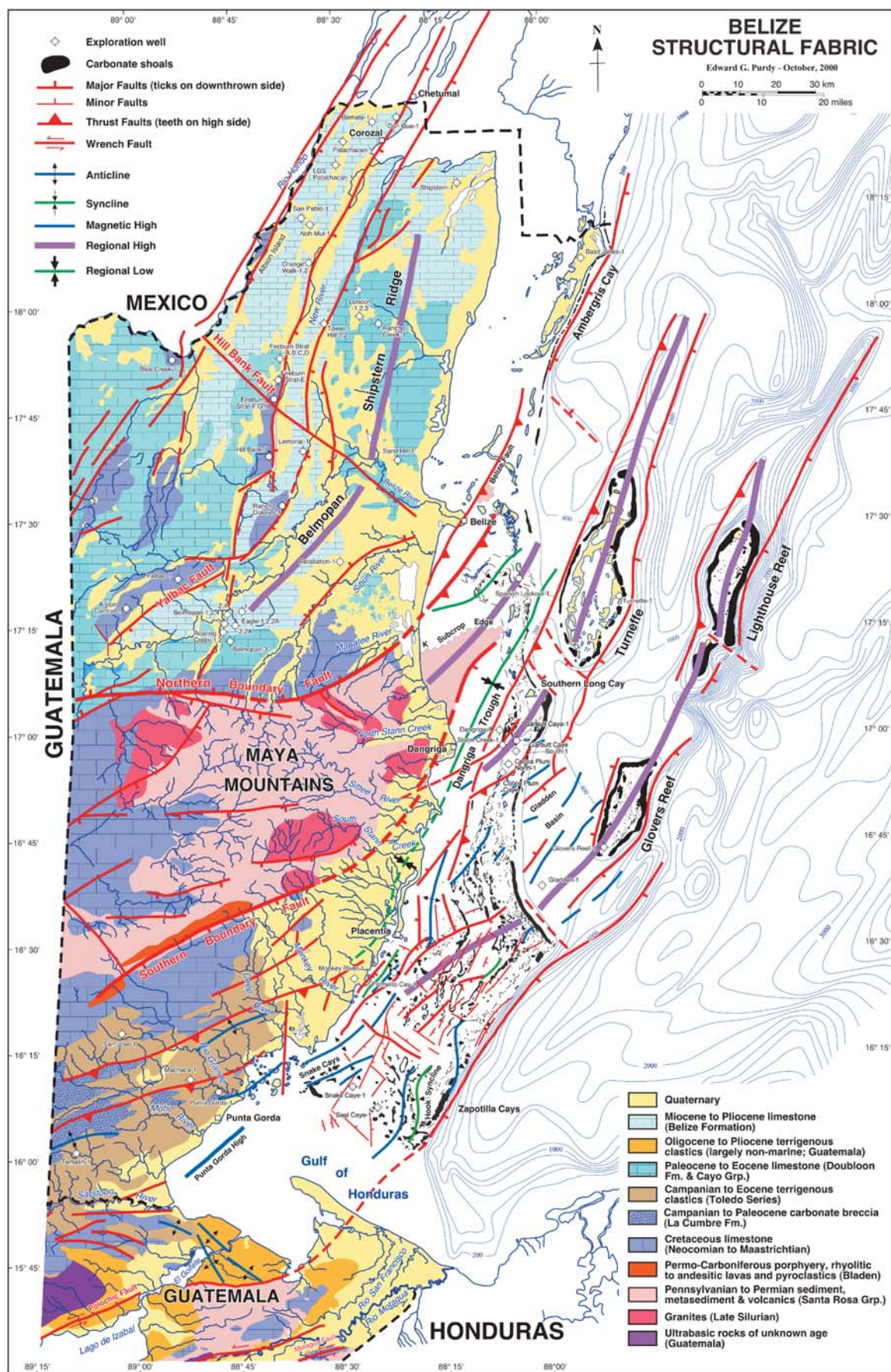
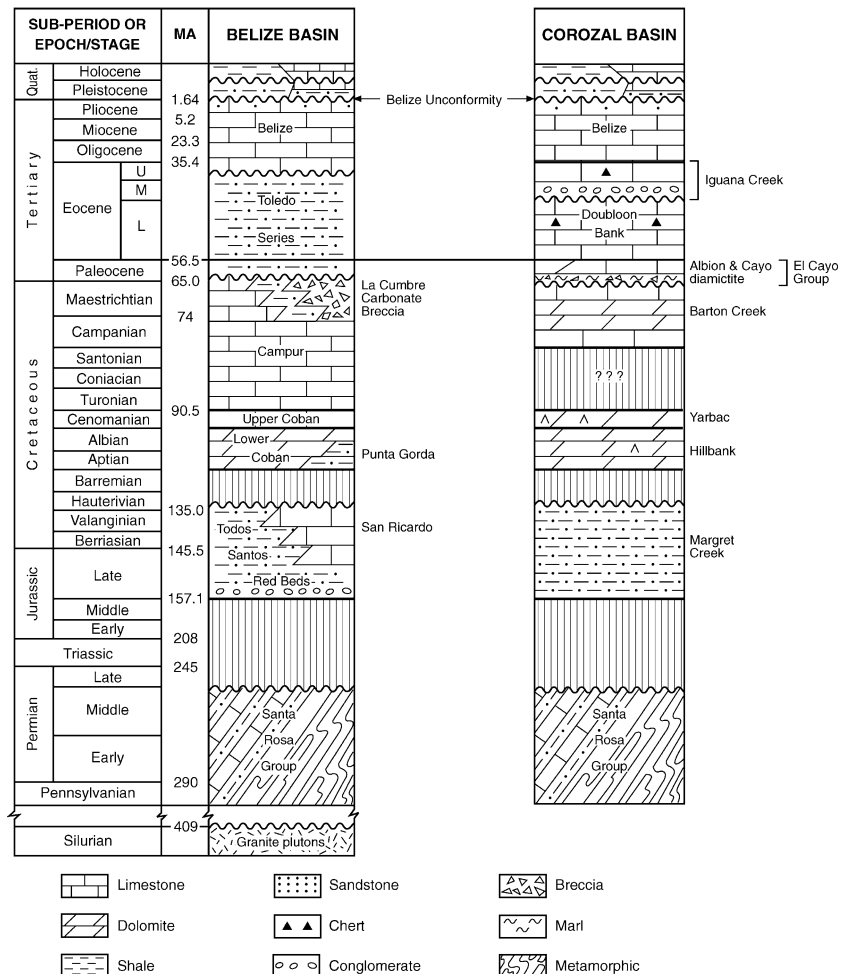


Fig. 2 Generalized stratigraphy of the Belize and Corozal basins (modified from Prasado Rao and Ramanathan 1988; Sanchez-Barreda 1990; Lara 1993; Cornec 1998). Ages shown in millions of years (MA) are from Harland et al. (1990). Belize Basin stratigraphy is based largely on the exploration well data shown in Fig. 3. Pleistocene lithologies are greatly generalized because of scale limitations and ideally should show alternations in areal extent of carbonates and siliciclastics reflecting glacially induced fluctuations of sea level. The lower stratigraphic limit of the Toledo Series is shown arbitrarily as Paleocene, but siliciclastics extend downward to the Campanian as indicated by the exploration well data of Fig. 3. Speculatively, we view this downward extension as an unnamed formation. Similarly, the offshore Belize Formation name has been used in the Corozal Basin for the unnamed Neogene units of the northern Belize mainland



on K–Ar dates and supposed contact metamorphism (Bateson and Hall 1977). U–Pb dating of two of the plutons, however, has indicated a Late Silurian age, with the K–Ar dates and supposed contact metamorphism now suggested to be a consequence of Late Triassic hydrothermal alteration (Steiner and Walker 1996). Facies relationships support the new age designations in that they suggest that the plutons were emergent during Santa Rosa deposition (Steiner and Walker 1996). Presumed Santa Rosa equivalents have been encountered in three offshore wells and one known onshore well (Fig. 3). Onshore, these Paleozoic rocks constitute the highest elevations of the Maya Mountains and are bounded on the north and south by the Northern and Southern Boundary faults, respectively (Dixon 1956; Bateson and Hall 1977).

Fig. 1 Belize structural fabric. Note the predominant northeast striking structural grain and the contrast between that grain and the convex and/or concave shelf and atoll outlines in places. Thrust fault indications are interpreted as examples of left-lateral transpressional fault movements. The Dangriga Trough is an Eocene depositional axis (Toledo Series) containing up to 4,800 m of sediment. Dashed fault lines are speculative

Late Jurassic to Middle Cretaceous

Unconformably overlying the Paleozoic succession is a Late Jurassic to Early Cretaceous red bed sequence called the Todos Santos Formation, dated from fossils occurring in the laterally equivalent marine deposits of the San Ricardo Formation of western Guatemala (Sanchez-Barreda 1990). The sequence is conglomeratic at the base, but consists dominantly of red beds and includes gray and green shales, limestones and gypsum (Donnelly et al. 1990). The red bed sequence has not been recognized in Belize outcrops, but does occur in several of the offshore wells (e.g., the Spanish Lookout and Seal Cay wells of Fig. 3). Above the red beds there is said to be a Late Jurassic transgressive sea-level cycle of fossiliferous limestones interbedded with dark limy shales dated at one southern Belize outcrop locality as Tithonian to Valanginian in age (Sanchez-Barreda 1990).

Aptian to Cenomanian carbonates unconformably overlie the Neocomian to Jurassic succession, but on the south and south-eastern flank of the Maya Mountains Cretaceous carbonates rest directly on the Paleozoic (Sanchez-Barreda 1990). In the Corozal Basin north of the Maya Mountains, the overlying carbonates are

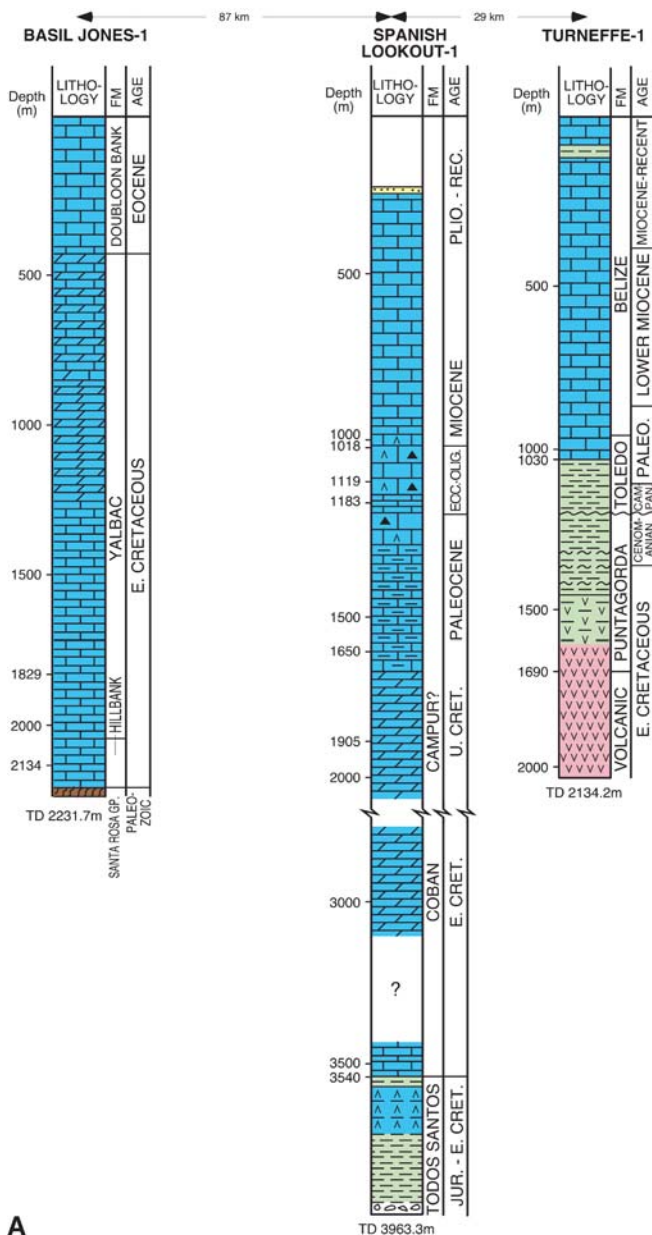


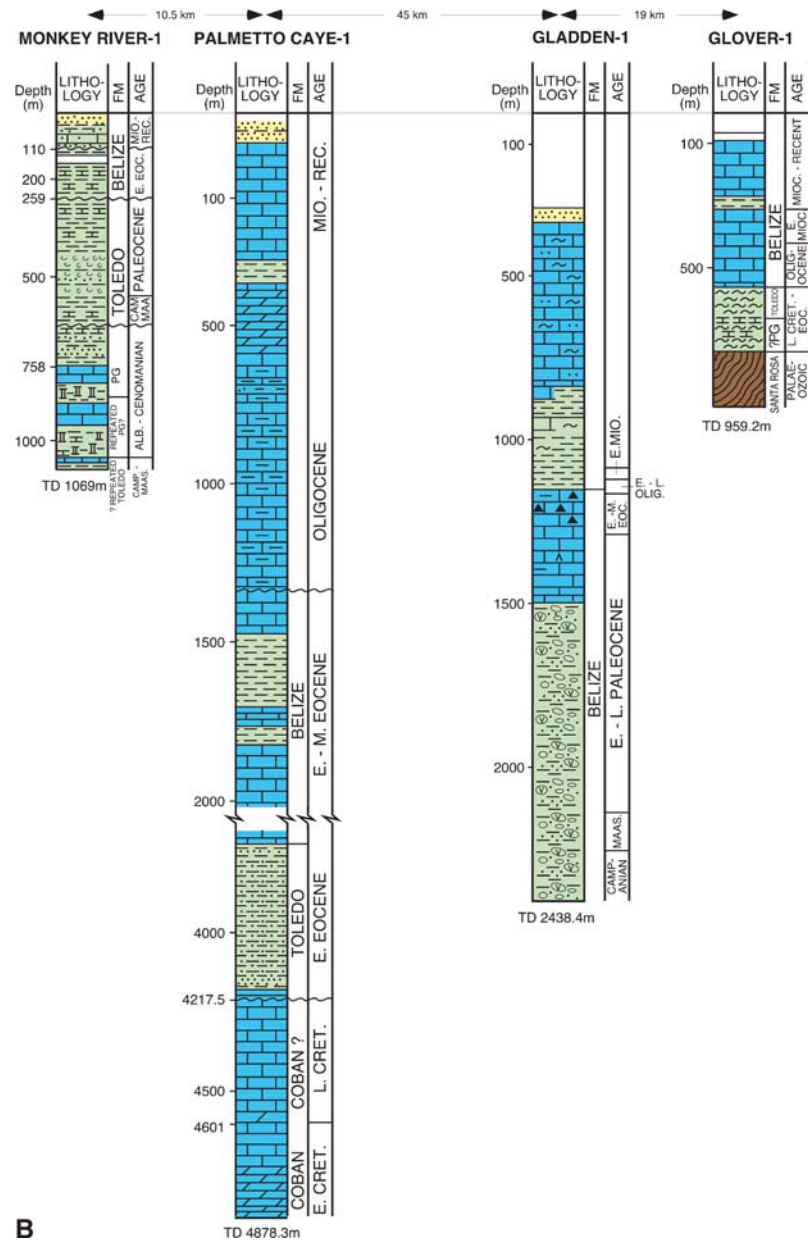
Fig. 3A–D Lithology and ages for all offshore and some onshore Belize exploration wells. Modified from information on file in the Geology and Petroleum Office of the Belize Ministry of Energy, Science, Technology and Transportation. Wells arranged from north to south in well sections A–D, respectively, and lithology legend shown in C. Distances between wells are noted but no horizontal scale is intended. There are repeated sections due to faulting in the Monkey River and Dangriga wells. The significance or age of the salt in the Punta Gorda well is unknown. The Gladden well was drilled in water depths of approximately 300 m and is the only well drilled off the shelf. The illustrated stratigraphy leaves a lot to be desired with respect to formation names. It would seem that any occurrence of a Tertiary carbonate is referred to as the Belize Formation and in some cases overlying or underlying siliciclastics are given the same Belize Formation name in spite of the obvious difference in lithology. Similarly, siliciclastics occurring between pre-Campanian and Tertiary carbonates are frequently referred to the Toledo Series. It is doubtful whether these Toledo siliciclastic occurrences are all represented by the same lithology and therefore doubtful whether they should all have the same Toledo Series name, but in the absence of more specific informa-

distinguished as the Hillbank and Yarbac formations. Elsewhere in Belize they are referred to as the Upper and Lower Coban formations (Fig. 2 and Prasada Rao and Ramanathan 1988). The main lithologic difference supporting these distinctions is the abundance of anhydrite evaporites in the Hillbank and Yarbac carbonates relative to the significantly less common occurrence of anhydrite in the Coban. An Upper and Lower Coban are said to be further distinguished by the preponderance of massive, microcrystalline dolomite in the Lower Coban and sucrosic dolomite, calcareous dolomite, and dolomitic limestone in the Upper Coban (Prasada Rao and Ramanathan 1988), the distinction apparently being an overall decrease in relative abundance of dolomite upward in the section. In the offshore wells of Fig. 3, however, the distinction between the two seems frequently to reflect Albian/Cenomanian age differences rather than any consistent lithologic contrast. The Punta Gorda Formation is a localized, presumably near-shore, siliciclastic facies of Coban carbonates (Fig. 2).

Late Cretaceous

The Turonian to Campanian Campur Formation carbonates overlie the Coban Formation and are, in turn,

tion, the formation names and limits are shown as they appear on file in the Belize Geology and Petroleum Office. Regardless of this nomenclature problem, note that the predominantly carbonate sections are punctuated by significant thicknesses of terrigenous clastics that range in age from Campanian to Late Eocene, though usually the upper age limit is given as Middle Eocene. Typically the exploration well paleo-water depth of these terrigenous clastics is given as bathyal and the sands that occur within it are considered deep water sands. The source of these sands was not the Maya Mountains but neighboring Guatemala (Donnelly et al. 1990). Additional evidence pointing to the same conclusion is the apparent facies change from Toledo Series siliciclastics in the south (B–D) to age equivalent shaly limestone in the Spanish Lookout well and to limestone farther north in the Basil Jones well (A). Interestingly, the bathyal paleo-water depths recorded for the Toledo siliciclastics of the Turneffe well (Belize Geology and Petroleum Office) are succeeded upward by Lower Miocene shallow water Belize Formation limestone (Shell log) indicating significant post-Paleogene structural movement. There is some discrepancy in the ages shown for the Palmetto Cay well in that Lara (1993) reports a Pleistocene to Holocene age for the 311–314-m interval and a Pliocene age for the 772–775-m interval. The limited amount of information, however, makes changes in the vertical extent of the ages illustrated inappropriate. We would place the upper limit of the Belize Formation below the sands that occur at or near the top of the Belize Formation in several of the wells as this would seem to reflect the combined event of extensive exposure of the Maya Mountains siliciclastic provenance and the first glacial lowstand of sea level. The position of that boundary in the Turneffe well would be below the shales, but in the Snake Cayes well its position is debatable. Following this line of reasoning the overlying siliciclastics would be largely Quaternary in age, as they are on the mainland. The sands could only extend to the shelf edge if they preceded barrier platform development, as once formed, the positive relief would constitute an impediment to seaward traction or saltation transport. Seaward passage then could only be accommodated via channels through the barrier platform such as English Cay Channel



B

Fig. 3B

overlain in places by a Campanian to early Paleocene carbonate breccia known as the La Cumbre Formation. Sanchez-Barreda (1990) regarded the breccia as a collapse feature of the Campanian carbonate margin. The limited extent of the La Cumbre breccia on the geologic map of Fig. 1 is taken from Cornec's 1998 map, but is misleading in that extensive areas of the breccia are also known to occur in the Cretaceous Cave Branch limestones just north of the Northern Boundary Fault and in the Cretaceous limestones of the Vaca Plateau of western Belize (Miller 1996; Reeder et al. 1996; Ford 2000). Its distribution in both those areas, however, has not been mapped. Consequently, the generalized Cretaceous limestone distribution of Fig. 1 shows only the relatively small

area of La Cumbre breccia in the south. The breccia seems similar to that of western Guatemala depositional breccias described by Blount and Moore (1969) from what would appear to be a Campanian time equivalent unit (upper part of the Ixcuy limestone). We have some difficulty in treating all of these occurrences as expressions of proximal collapsed carbonate bank margins because their widespread distribution would necessitate either a multiplicity of carbonate banks or one large bank with an extremely irregular outline. Nonetheless, a seemingly similar occurrence on the west side of the Yucatan Peninsula in Mexico has been interpreted by Grajales-Nishimura et al. (2000) as reflecting K-T Chicxulub impact collapse of the Campeche carbonate

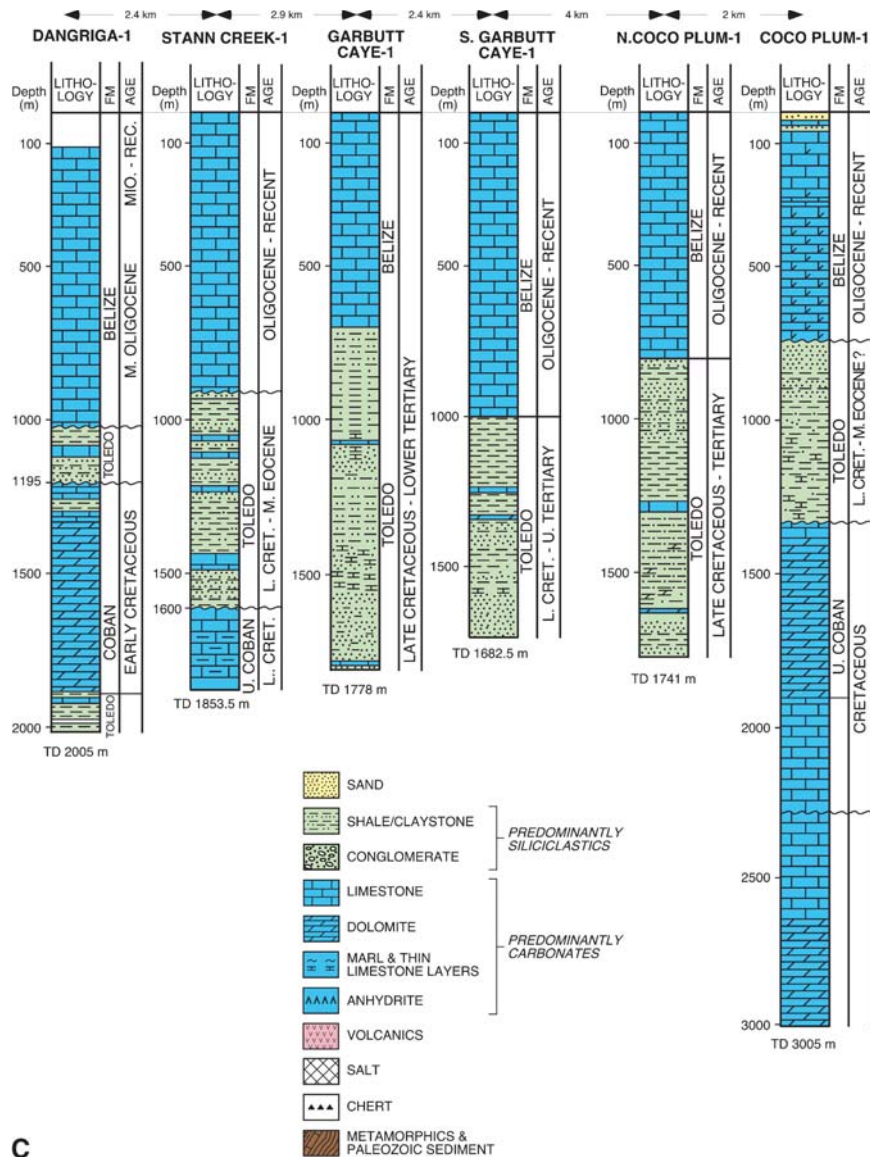
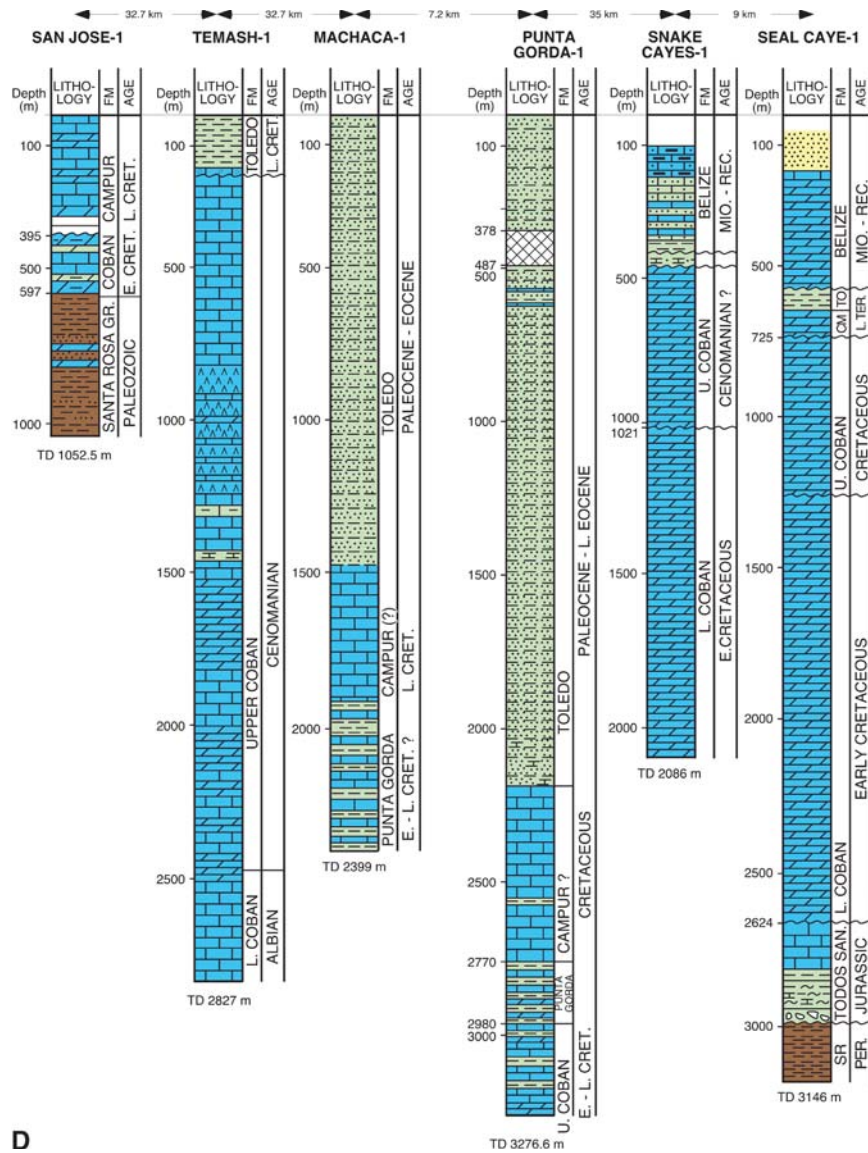


Fig. 3C

platform. There is also substantial sedimentologic and petrographic evidence of Chicxulub proximal impact ejecta from a quarry on Albion Island (Fig. 1) in the Rio Hondo separation of Mexico from northern Belize (Ocampo et al. 1996; Pope et al. 1999). Miller (personal communication cited in Ford 2000) has suggested a possible ejecta derivation for the Belize breccias as well, and Ford (2000) has noted that a Chicxulub impact firestorm conceivably could have been the depositing mechanism. Whatever the cause, it seems strange that none of the offshore Belize wells (Fig. 3) encountered this breccia, although conglomerates are recorded in the Gladden-1 and Monkey River-1 wells. The problem of the origin of these breccias certainly warrants considerably more study, but further speculation is unwarranted by the data in hand.

Late Cretaceous to Early Tertiary

Unconformably overlying the Campur or older formations (Figs. 2 and 3) are deep-water shales and sands of the Toledo Series. The lower age limit of the Toledo Series appears to be problematical. Prasada Rao and Ramanathan (1988) regard it as a deep sea facies equivalent of the Campur Formation and no younger than Maestrichtian in age. Sanchez-Barreda (1990) regards the lower part of the Toledo Series as Campanian and extends its age upward to include the Paleocene and possibly the Eocene. A Campanian age is also indicated by the Belize offshore Turneffe-1 and Gladden-1 exploration wells; however, in general the offshore wells document a Paleocene to Middle Eocene age with some limited indications of extension into the Campanian and Late Eocene, respectively (Fig. 3). We



D

Fig. 3D

have arbitrarily shown the lower limit of the Toledo Series as Paleocene in age (Fig. 2), but recognize that siliciclastics also extend downward into the Campanian as a facies equivalent of both the La Cumbre carbonate breccia and the Campur Formation. These relationships have a bearing on the regional extent and/or timing of the Chicxulub Yucatan impact, but the unknown nature of the stratigraphic relationships preclude further speculation.

The significance of the Toledo Series is that their occurrence marks the first major occurrence of siliciclastics in the previously dominant carbonate succession. The source of the terrigenous clastics is from the south in neighboring Guatemala where Rosenfeld (cited in Donnelly et al. 1990) is said to have demonstrated a southerly derivation for sedimentary debris in the Sepur Group, which includes the Toledo Series. Moreover, in

Belize, as in the Petén District of Guatemala, there is a facies change from terrigenous clastics in the south to carbonates in the north, again suggesting that the flysch-like siliciclastics had a southern origin. These facies relationships indicate that the Paleozoic Maya Mountain non-carbonates could not have been a significant source of terrigenous clastics during Lower Tertiary time because, if this had been the case, the dominant coeval lithology north of the Northern Boundary Fault would have been siliciclastics rather than the carbonates that occur there.

Early Tertiary to Quaternary

The onshore carbonate lithology of the overlying Upper Eocene to Pliocene Belize Formation is indicative of the

same conclusion, although one would like more paleontologic confirmation of this age range as offshore well data (Fig. 3) expand the age range from Paleocene (Turneffe-1 and Gladden-1 wells) to Recent (several wells). The Recent designation is obviously in error as Holocene carbonate deposits are generally unconsolidated and, consequently, mark an important lithologic distinction with underlying lithified carbonates. Notwithstanding the continuation of several of the well column lithologies to the sea bottom (Fig. 3), the upper age limit of the Belize Formation is also suspect because it is usual to have no sample returns for the first several hundred feet of well penetration. In these instances lithology is either not recorded or is based solely on electric logs. This seems to be the case for some of the illustrated wells (Fig. 3) in which lithologic information begins some distance below rather than at the sea floor. It is not known to what extent electric logs were used, if at all, in interpreting the lithology of the Fig. 3 well columns that continue either to the sea bottom or land surface.

Similarly, the extension of the Belize Formation downward in time to include the Paleocene is suspect as the well column data suggest that any penetrated Tertiary limestone was regarded as an expression of the Belize Formation. Without having access to lithologic descriptions and paleontologic data, it is impossible to verify or refute this suspicion. In addition, the possibility of unrecognized repeated sections due to faulting is very real considering both the frequency and age of the faulting and the poor resolution of the early seismic lines used to locate drilling sites.

Especially important is the age at which the terrigenous clastics begin to appear in the Upper Tertiary section of the well columns because this identifies the time of general subaerial exposure of the Paleozoic Maya Mountains provenance for siliciclastic sediment. Presumably these rocks were covered by Cretaceous carbonates before then. As it stands now, the largely non-carbonate lithology of Quaternary age sediment on the Belize mainland strongly suggests that extensive unroofing of the Paleozoic provenance did not occur until Pleistocene time, although perhaps beginning earlier. The origin of the Maya Mountains as a structural entity would, of course, pre-date unroofing and does not of itself preclude the earlier fault movements advocated by others (e.g., Bateson and Hall 1977).

Structural fabric

The structures illustrated in Fig. 1 have been compiled from a number of sources. In the Maya Mountains, the indicated faults are from Dixon (1956) and Bateson and Hall (1977). The extension of the Maya Mountains northern and southern boundary faults into the offshore is based on a 1975 Chevron seismic interpretation that included recognition of an offshore Paleozoic subcrop. The Southern Boundary Fault extension into the offshore

was additionally guided by unpublished aeromagnetic data. The onshore thrust faults in southern Belize are taken from unpublished Phillips Petroleum Company fieldwork previously illustrated by Purdy (1974). In onshore northern Belize, the illustrated Belmopan–Shipstern Ridge and Hill Bank Fault have been taken from Prasada Rao and Ramanathan (1988), the latter feature having the strong aeromagnetic expression illustrated in the same article. The remaining onshore faults north of the Maya Mountains are redrawn from an unpublished 1972 Chevron Overseas Petroleum Company Belize Tectonic Map.

In the southern offshore, the Punta Gorda High is taken from Prasada Rao and Ramanathan (1988). Folds and faults in this same area are from Purdy (1974, 1998), Lara (1993), and Esker et al. (1998). The regional high traversing the shelf in the southern shelf lagoon is based on the occurrence of a positive Bouguer gravity plateau, illustrated by Prasada Rao and Ramanathan (1988, their Fig. 7) in the same area. Unpublished gravity and seismic interpretations by Belize Natural Resources Ltd. (1995) indicate a continuation of that regional shelf high into Glovers Reef atoll and the same source provided the basis for the distribution of offshore magnetic highs. The continuation of the regional shelf high into Lighthouse Reef atoll is based on the interpretations of Dillon and Vedder (1973), Purdy (1974), and Lomando et al. (1995), but modified by the bathymetric contour patterns of Dillon and Vedder (1973). The landward thrust direction of all but three offshore faults is from Prasada Rao and Ramanathan (1988). The evidence for landward-directed thrusting for two of these shelf faults is presented subsequently, but the thrust fault direction of the Belize Fault has been reversed from that illustrated by them on the basis of an unauthored 1975 Chevron Overseas Petroleum Company Belize Tectonic Map that shows the same fault as being down-thrown toward the west. The location of the Dangriga Eocene depositional trough (Fig. 1) is from the same Chevron map and was previously interpreted as a major low by the Phillips Petroleum Company (illustrated in Purdy 1974).

As will be apparent to anyone who has compiled geologic information from different sources, interpretations, particularly from adjoining areas, are not always compatible. We have tried to reconcile these differences wherever possible with regard to the limitations imposed by the areal distribution of the data used for the interpretation. Thus, interpretations of structures that occur on data margins are more suspect than those that are more centrally located (e.g., the seismic coverage for Lara's 1993 interpretation), and we have biased our compilation accordingly. Nonetheless, it would be misleading to believe that we have reconciled all differences accurately. Rather the resulting map (Fig. 1) should be regarded as a synthesis step that is hopefully in the right direction.

One of the unanticipated attributes of Belize faulting is the frequent occurrence of landward-directed thrusting.

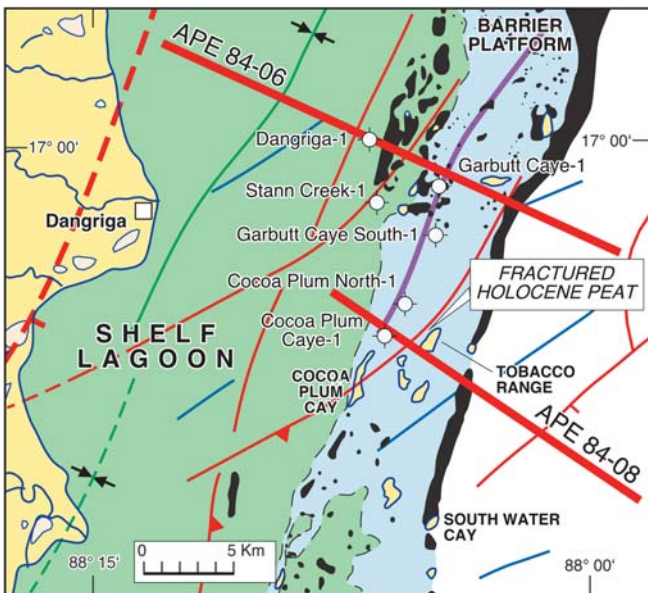


Fig. 4 Location of Shell Pecten seismic lines shown in Figs. 5 and 6. Structural symbols and colors as in Fig. 1. Carbonate shoals indicated in black and offshore exploration wells identified. Note the fractured peat occurrence on the west side of the northernmost Tobacco Cay Range island. Thrust fault connection between the two seismic lines is problematical as the illustrated fault strike on line APE 84-06 does not parallel that of the adjacent magnetic lineation. If they are not connected, two approximately parallel transpressional faults must be present. In either case, the strike of the faults does not explain the trend of the barrier reef, but differential seaward progradation and/or shelf edge gravitational slumping would

The reality of this phenomenon is illustrated in Figs. 4, 5, and 6. The Fig. 5 seismic line leaves little doubt that a prominent landward-directed thrust fault lies beneath the Tobacco Cay Range of islands, illustrated in plan view in Fig. 4. Less obvious is a similar feature located near the edge of the shelf in Fig. 6. Speculatively, we have connected the two, but are not convinced that this is necessarily the case because of the illustrated high angle relationship between a shelf edge magnetic high and the connected faults (Fig. 4). Consequently, these fault occurrences may represent two separate thrust faults rather than the one shown. Figure 5 also demonstrates inversion of a Toledo Formation lens as the structurally high position of a Toledo "thick" can hardly be construed as a depositional relationship. These attributes along with the ones listed by Lara (1993) for southern shelf lagoon faults suggest the occurrence of transpressional strike-slip faults.

A possible explanation for the landward-directed thrusting is the eastward opposition to westward Cayman expansion of Caribbean oceanic crust by simultaneous eastward-directed subduction along the west coast of Central America (Fig. 7). Conceivably the compressional aspect of these two opposing forces is resolved in Belize by transpressional landward-directed thrusting.

There is some evidence to suggest that the compressional faulting continues northward of Belize. Rosen-

crantz (1990) illustrates a NNE–SSW-striking series of troughs and ridges extending from Belize northward into the deepwater borderland of the Yucatan Peninsula (Fig. 7). Just south of the Mexican island of Cozumel, a multichannel seismic line is illustrated and interpreted by Rosencrantz (1990, his Fig. 6) as having a reverse fault near the shelf margin of the line. The morphology of that fault block looks suspiciously like that of the Belize thrusts, suggesting that the Belize transpressional event extends at least this far north.

Tectonic timing

The age of faulting illustrated in Fig. 5 is clearly post-Belize Formation. As noted previously, however, the upper age limit of that formation is questionable, but seems likely from the indicated onshore range to extend into the Pliocene. Farther south in the southern shelf lagoon, Lara (1993) recognized a Pliocene or younger tectonic event that she related to transtensional faulting based on the absence of pure wrench type en echelon folds. The conspicuous thrust fault in Fig. 5, however, clearly indicates the transpressional nature of the faulting as does the repeated thrusting identified on Fig. 1. The absence of thrusts in the area studied by Lara (1993) may well reflect the poorer resolution of her seismic data (see her Fig. 4) compared with that illustrated in Fig. 4. It seems reasonable to assume that all this thrusting was contemporaneous and, hence, Pliocene or younger in age. The folds identified by Lara (1993) and others (Purdy 1974, 1998; Esker et al. 1998) in the southern shelf lagoon may well be similar evidence of the same compression rather than an exclusive product of the sidestepping fault geometry relationship advocated by Lara (1993). What is puzzling, however, is the decrease in frequency of occurrence of folds northward into the central shelf lagoon area (Fig. 1). Perhaps this decrease simply reflects northward development of higher amplitude thrust folds rather than a lessening of regional compression.

Lara (1993) also recognized an older Tertiary transtensional tectonic event that occurred between the end of the Cretaceous and the early Eocene and created a major series of northeast–southwest-trending en echelon horsts and grabens. Among other things, the Eocene Dangriga Trough (Figs. 1 and 6) was formed and filled with more than 4,800 m of sediment. The older event broadly coincides with the age range of the La Cumbre breccia and the change from Upper Cretaceous carbonates to Lower Tertiary siliciclastics. Some of the older Tertiary faults were reactivated during the younger tectonic episode (Lara 1993).

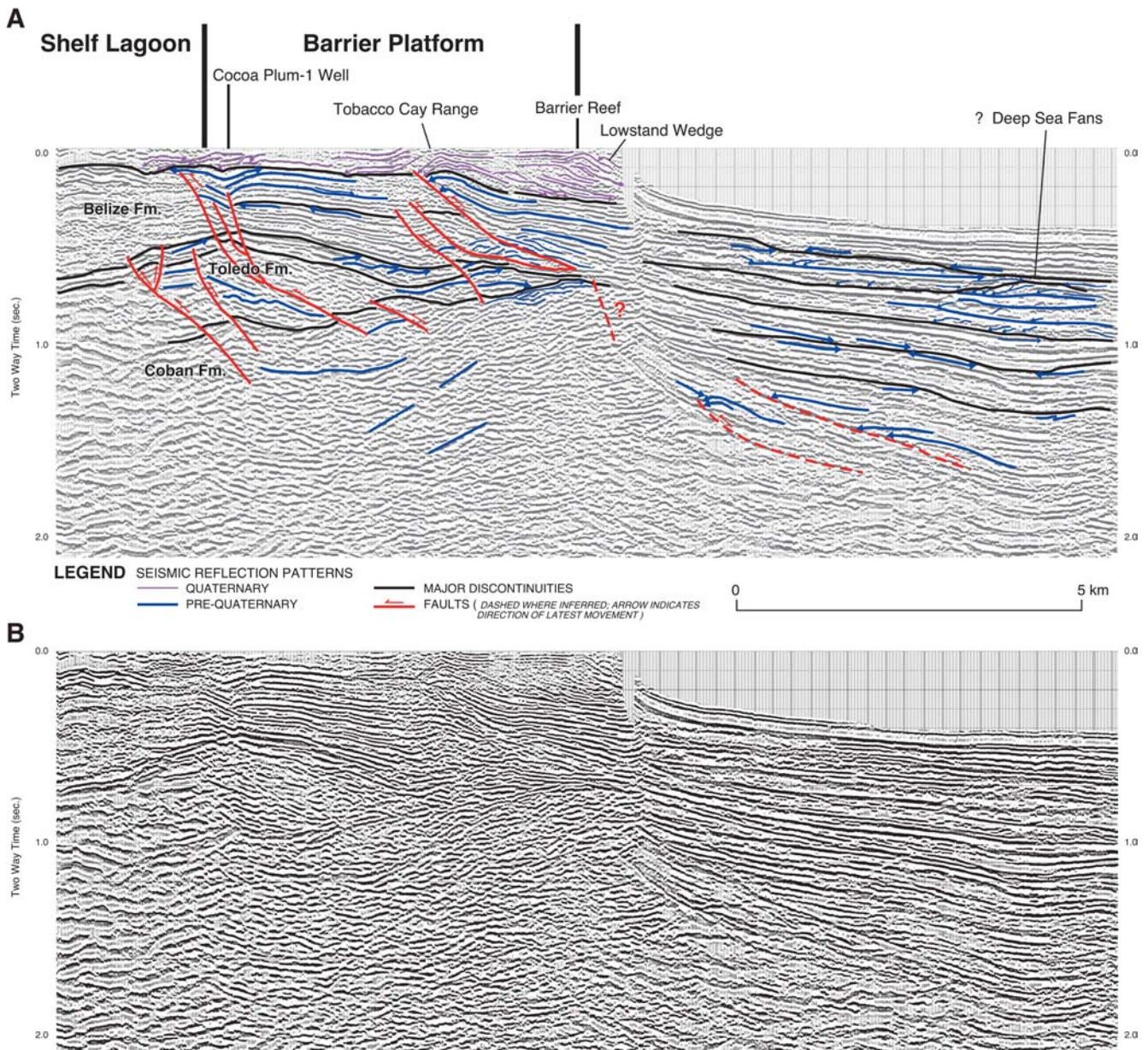


Fig. 5A, B Seismic line APE 84-08 located in Fig. 4. **A** Interpreted line. **B** Uninterpreted line. Note the near-surface expression of the prominent landward-directed thrust fault located beneath the Tobacco Cay Range and the high position of the inverted Toledo Series thick, both of which indicate transpressional fault movements when taken with the evidence for strike-slip movement reported by Lara (1993). The prominent thrust beneath the Tobacco Cay Range seems to sole out at shallow depths, but the faults farther toward the shelf lagoon seem to be more deep rooted. Notwithstanding the Oligocene to Recent designation for the Belize Formation in the Cocoa Plum-1 well (Fig. 3), the tectonic episode resulting in these fault movements would seem to be Pliocene in age (Lara 1993; Esker et al. 1998). With this in mind, as well as the doubtful upper age limit of the Belize Formation, the overlying section has been interpreted as Quaternary. Bilateral progradation is apparent within this section beginning at the position of the thrust fault high. It is much more apparent in the seaward as opposed to the lagoonward direction, probably because of the infilling of deeper seaward water. There is some slight suggestion of a slightly thicker interval between two reflections within the Quaternary reflections directly above the thrust fault high that very speculatively could be considered a reefal interval. Otherwise, there is no indication of possible reefing in the prograding section until the indicated position of the present barrier reef, suggesting that the barrier reef is very young in inception.

Seaward of that position there is a possible indication of a glacial sea-level lowstand wedge. Still farther seaward, the gap in the upper surface of the seismic record is an artefact of the navigational impasse created by the barrier reef that necessitated shooting the seismic line in two parts with no common depth point between them. The result is a lack of reflection continuity between the shelf and adjoining deep water and the misleading appearance of a fault separating the two areas. The reflection continuity gap also makes correlation between the shallow and deep-water parts of the line difficult with any degree of confidence. The evident bilateral progradation not only indicates a lagoon prograding origin for the barrier platform, but also identifies the prograding section as carbonates rather than siliciclastics as the point source origin for the progradation is clearly not compatible with a siliciclastic origin. Erosional attenuation of the lagoonward extent of the progradation must have occurred during glacial lowstands of sea level, but it is not apparent on the seismic line, possibly because of scale limitations. The down-bending of reflections within the Belize Formation beneath the Cocoa Plum-1 well and above an underlying fault may signify the existence of a carbonate solution collapse feature developed beneath the overlying Belize Unconformity. We have no information on the velocities of the prograding sequences, but the thickness of the westward prograding sequence approximates 150 m using an arbitrary velocity of 2,500 m/s

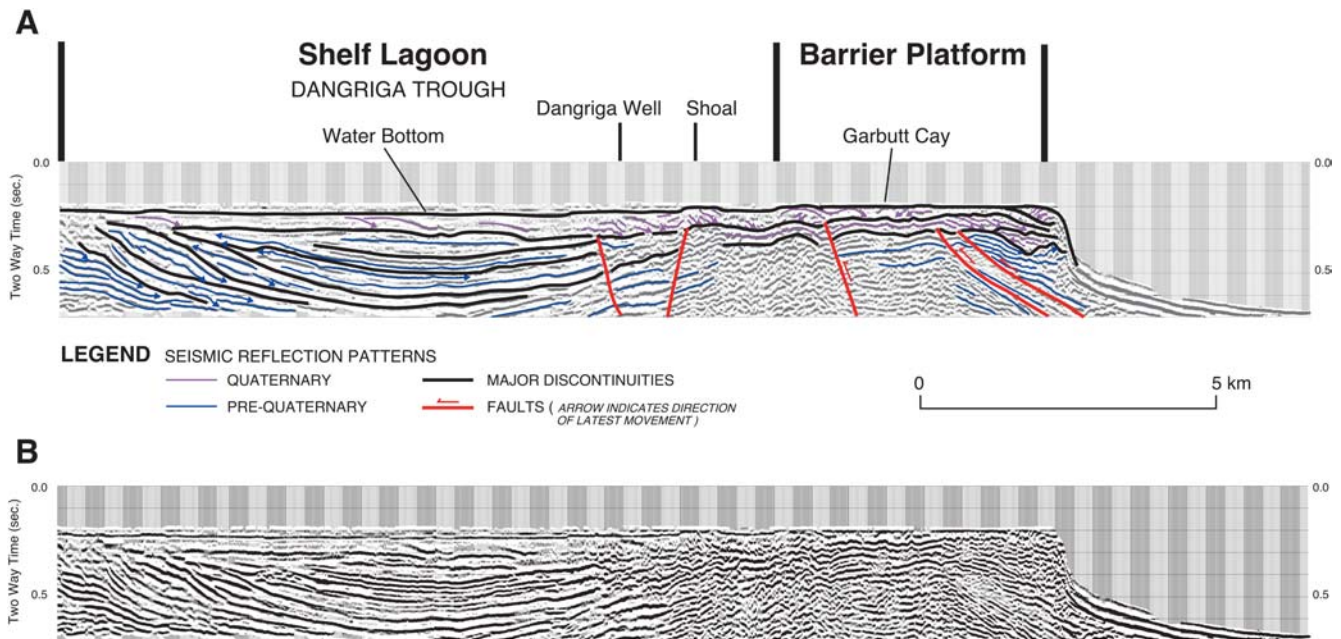


Fig. 6A, B Seismic line APE 84-06 located in Fig. 4. Water bottom from digitized echo-sounding records. **A** Interpreted line; **B** uninterpreted line. Unfortunately, the bottom of the line has been cut off, presumably in the interests of confidentiality, making interpretations difficult. Nonetheless, it seems clear that a landward-directed thrust fault is present near the shelf edge end of the line and this feature has been correlated speculatively with the better-expressed thrust of Fig. 5; however, it may be a different structural entity. The repeated Toledo Series section of the Dangriga well documents the presence of another fault (Fig. 3). The Dangriga Trough is well evidenced beneath the shelf lagoon and the landward down-lapping wedge within it probably represents siliciclastics rather than carbonates. The uppermost seaward-

directed down-lapping events are also interpreted as siliciclastics. Seaward progradation is also evident within the lower Quaternary section of the barrier platform and debatable weak indications of lagoonward progradation overlie it unconformably. The carbonate shoals lagoonward of the barrier platform are associated with an underlying fault and show very weak evidence of a Quaternary build-up down lapping in both directions. The lowermost unconformity within the barrier platform is interpreted as the Belize Unconformity but its position in the Dangriga Trough is unclear due to the appearance of a younger unconformity within the barrier platform above the prograding section that is interpreted as Quaternary in age

Antecedent topography

Structural Influence

The bilateral progradation apparent in the presumably Quaternary seismic sequence above the thrust fault high of Fig. 5 is certainly indicative of near-surface structural influence on antecedent topography. The location of the mid-platform Tobacco Range of islands directly above the thrust fault high suggests further that that influence extends to the Holocene. Even more compelling is the occurrence of Holocene-fractured peat along the western shoreline of the northernmost Tobacco Cay Range island (Littler et al. 1995). The peat is up to 10 m thick with the oldest part radiocarbon dated at $6,920 \pm 80$ years B.P. (Macintyre et al. 1995). The distinctive feature of the peat, however, is not its considerable thickness, but the fact that it is fractured with most of the fractures oriented at right angles to the shoreline (Littler et al. 1995). The origin of the fractures is not known, although several possibilities, including peat collapse, have been suggested (Littler et al. 1995), but whatever the precise origin, it seems clear that the unusual occurrence of fractures is

somehow related to the occurrence of the underlying thrust fault.

A further near-surface expression of structure is provided by Fig. 8 in which a sparker profile across Ships Bogue demonstrates that the western flank of the modern-day channel is located on the dip slope of an underlying thrust fault high. Further indications of structural control on Holocene facies occur in Lighthouse Reef and Turneffe lagoons where vibracore data in conjunction with the linear trends of reef shoals and islands collectively suggest underlying fault control (Gischler and Lomando 1999; Gischler 2003). The peculiar hook-like termination of the Belize Barrier Reef in the Gulf of Honduras is also indicative of near-surface structural control; this time by folds rather than faults although, more speculatively, faults may also be involved (Purdy 1998). Similarly, the carbonate shoals of the East Snake Cays are located above a fold on siliciclastics (Purdy 1974 and Fig. 1).

On a larger scale, Lara (1993) concluded that southern shelf lagoon multichannel seismic data demonstrated a close but imperfect match between the main seismically determined structural features in the southern shelf lagoon and the distribution of Holocene reef shoals. More

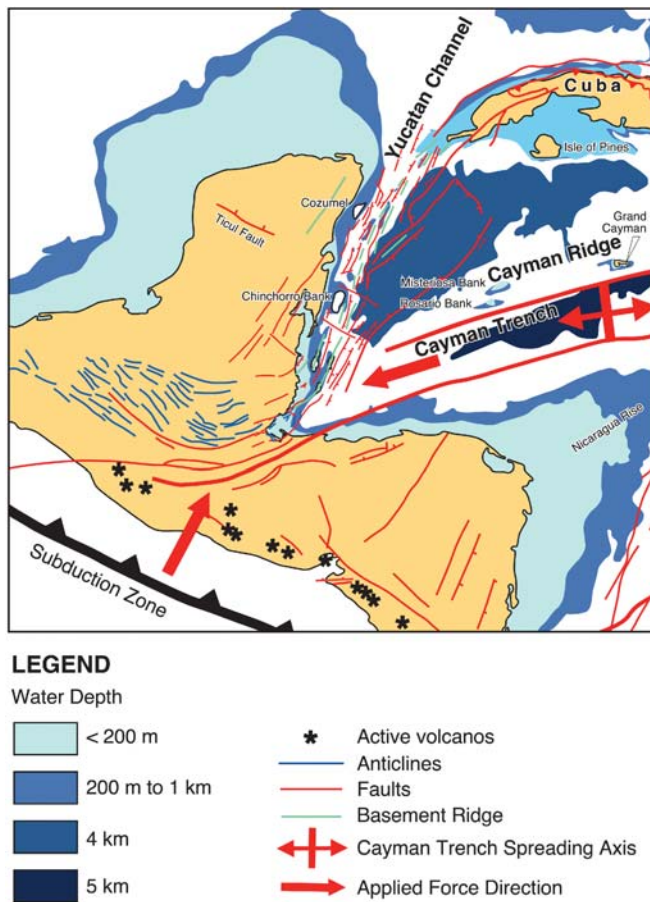


Fig. 7 Regional structural fabric showing relationship of Belize structures to surrounding area. Offshore Caribbean structures surrounding Belize are largely from Rosencrantz (1990), the principal difference being that his basement scarps are shown here as faults. Within the 4-km-deep area the indicated strike slip faults are identified by Rosencrantz (1990) as transform faults bounding Eocene oceanic crust. The Eocene fabric is too old to be related to the Belize Neogene transpressional thrusts, unless, of course, some of the older faults were rejuvenated during the late Neogene. Seemingly more significant is the contrast in regional push direction between the Cayman Trench spreading center and the Central America subduction zone. The resulting impediment to westward Cayman Trench spreading is presumably the reason for consistent landward directed thrusting on Belize transpressional faults. Puzzling, however, is the apparent occurrence of a reverse fault on a seismic line just south of Cozumel (illustrated by Rosencrantz 1990, his Fig. 6), because this location is far removed from the Cayman Trench spreading center. Moreover, one would like more conclusive information on the left lateral nature of the north-northeast-striking transpressive fault movements as the west-northwest-striking faults that continue from the mainland offshore appear to be antithetic to right lateral rather than left lateral faults, notwithstanding Rosencrantz's mention of a slight dextral en echelon distribution pattern for the west-northwest-striking set

specifically, structural highs were observed underlying Laughing Bird shelf atoll, an unnamed shelf atoll to the south and the barrier platform while underlying fault controlled troughs acted as the template for Victoria Channel and the channel connecting it to the south (Lara 1993). These structural features were suggested to be long-lived Tertiary features dating back to the Paleocene

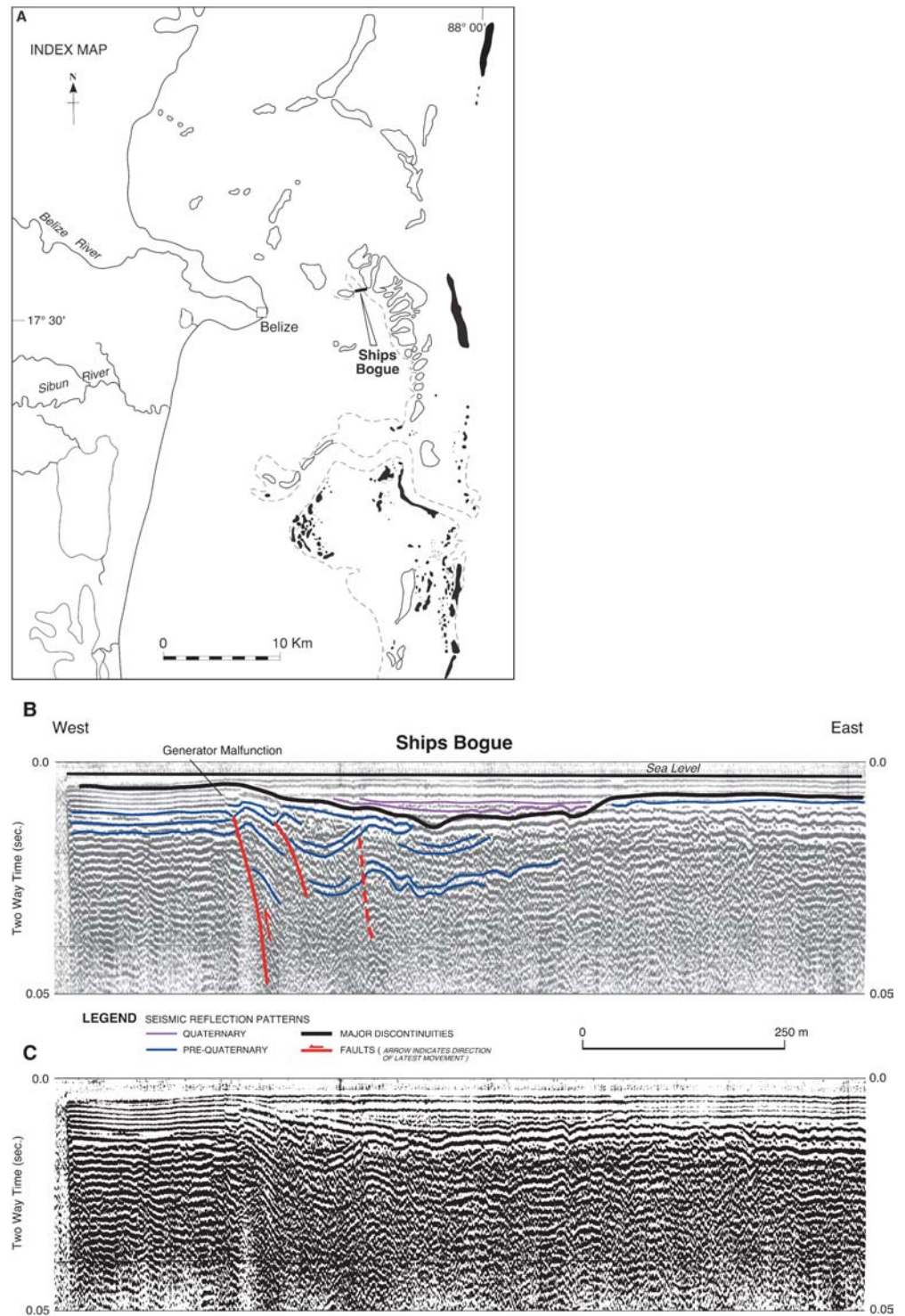
and, although Pliocene or younger faults were noted, their upward extent could not be determined because the upper 150–200-ms two-way travel time of the seismic data had been muted (Lara 1993). Consequently, a more precise comparison between the distribution of carbonate shoals and underlying structural entities was not possible. Nonetheless, a rose diagram showing the orientation of 48 shoals in the present Victoria Channel area is highly suggestive of near surface structural control (Purdy 1974, his Fig. 19) and the extension of faulting to the surface has been reported for off-shelf sediments by Dillon and Vedder (1973).

The suggestion that the rhomboidal shape of the reefs was due to early Pleistocene river morphology (Choi 1981; Choi and Ginsburg 1982; Choi and Holmes 1982) should now be abandoned as there is no evidence to support it. Certainly Pleistocene river channels occur between the rhomboid shoals, but they are generally much narrower in width than the bathymetric channels in which they occur. For example, two Pleistocene river channels are visible in Fig. 9J of Purdy (1974), but the collective width of these is insufficient to account for the width of Victoria Channel in which they occur. In addition, no modern Belize onshore river valleys remotely approximate the width of the larger offshore bathymetric channels, indicating a further anomaly. There is, however, evidence of the indirect influence of faulting on the location of Pleistocene river valleys. Esker et al. (1998) concluded from a study of high-resolution southern shelf lagoon single channel seismic data that early faulting had created preferential sites for both Quaternary reefs and river valleys. They identified a Miocene–Pliocene stage of en echelon faulting and folding followed by the development of a regional unconformity (the Belizean Unconformity) above which faulting decreased upward in a section that on-lapped the unconformity to the north and west and contained as many as 11 subhorizontal Pleistocene sequences (Esker et al. 1998). The early influence of faulting on reef development was perpetuated upward in the section in broadly influencing the location of lowstand incised valleys between the paleo-highs and subsequent highstand development of reefs on the highs (Esker et al. 1998). Unfortunately, seismic acquisition was limited to the relatively deeper water areas of the southern shelf lagoon by the draft of the seismic vessel so that no seismic coverage of the barrier platform and the shallower lagoon shoals was possible. Interestingly, a somewhat similar rhomboidal pattern of carbonate shoal development is illustrated by Roberts and Murray (1988, their Fig. 20) for the Gulf of Suez, Strait of Jubal. There too, evidence indicates that the distribution is controlled fundamentally by faulting (Roberts and Murray 1988).

The barrier platform

The seismic interval above the Belize Formation in Fig. 5 shows bilateral progradation from the high created by the underlying thrust fault. Additional evidence for lagoon-

Fig. 8 A Location of Ships Bogue Profile with **B** and **C** showing interpreted and uninterpreted sparker sections, respectively. A near-surface reverse fault is in evidence on the western side of the channel. Pre-1972 conventional seismic also showed a down to the west fault in this location. Data resolution is too poor to trace the faults to the bottom of the section. Compare with the better reverse fault geometry examples of Figs. 5 and 6



ward barrier platform progradation is provided by a seismic line between the Stann Creek-1 and S. Garbutt Cay-1 wells (Fig. 4) illustrated by Prasada Rao and Ramanathan (1988, their Fig. 14, necessary to view with a magnifying glass). The same phenomenon is apparent on an unpublished sparker line north of English Cay Channel.

The point source of the prograding sequence from below the present day Tobacco Cay range of islands leaves little doubt that a carbonate lithology forms the foundation of the present-day barrier platform. Instances of seaward progradation of a carbonate sequence are commonplace, but lagoonward progradation is rarely mentioned. Notable exceptions are the Indonesian Kalimantan descriptions of Oligocene platform development

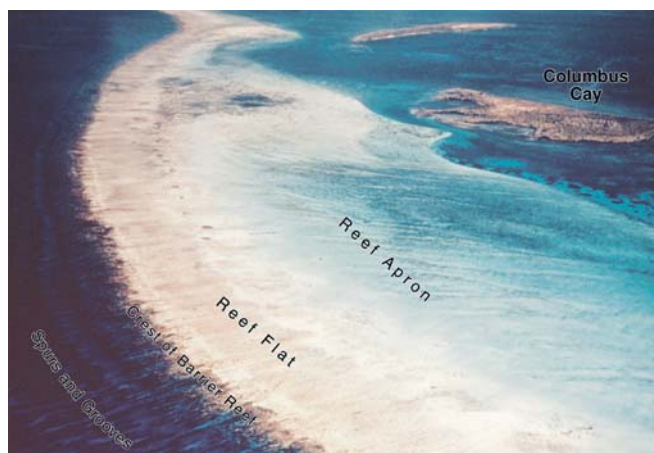


Fig. 9 Oblique aerial view of Columbus Cay barrier reef looking south. A complete reef facies spectrum is shown from spur and groove fore-reef to the brown *Acropora palmata* crest of the barrier reef to lagoonward successive zones of reef flat, reef apron, and lagoonal barrier platform sediment (modified from Purdy et al. 1975). The reef flat is dominated by coarse reef-derived rubble and submarine cement. The reef-derived debris constituting the apron can be seen to be clearly transgressing over the adjacent barrier platform sediment. Farther south in the Tobacco Cay area, the sediment composition of apron sediment has been described by Macintyre et al. (1987). Dark colored areas adjacent to Columbus Cay reflect shallow water *Thalassia* grass meadows. Where the barrier reef is discontinuous, the lagoonward extent of the reef apron is attenuated, suggesting largely seaward transportation of reef-derived material by currents created by the hydraulic head of reef-breaking waves rather than the predominant lagoonward dissipation of the head where the barrier reef is laterally continuous

by Saller et al. (1993) and the South China Sea Miocene Liuhua platform stratigraphy illustrated by Erlich et al. (1990). In contrast to these few paleo-examples, there are numerous instances in reefs throughout the world of modern sand aprons occurring directly behind atolls and barrier reefs that would seem to reflect sediment transport occasioned by lagoonward dissipation of the hydraulic head resulting from waves breaking on the seaward front of the reef. For example Holocene lagoonward progradation by reef-derived sediment has been mentioned in the Maldives (Purdy and Bertram 1993, particularly their Fig. 33) in the Cocos (Keeling) Islands (Woodroffe et al. 1994), and in the Japanese Ryukyu Islands where both seaward and lagoonward (bilateral) progradation of a Holocene fringing reef have been reported (Yamano et al. 2001).

A Belize barrier reef example is shown in Fig. 9 where one gains the clear impression that the reef apron is transgressing over the adjacent barrier platform sediment. The phenomenon is also apparent on the windward sides of Glovers and Lighthouse Reefs, and the northernmost windward reef margin of Turneffe (Gischler and Lomando 1999). The lagoonward extent of these modern sand aprons is minimal (up to 2 km in northern Turneffe) simply because sea level only reached its present level some 3 to 5 K years ago. Before then, the rapid rise in post-glacial sea level would have encouraged vertical

accretion over lateral progradation. However, the longer duration of prior inter-glacial still stands compared with that of the still-evolving Holocene would have insured a greater lagoonward progradation of sediment than is now apparent. Moreover, if lateral progradation had gone unchecked, lagoons ultimately would have been filled by reef-derived sediment. But the glacial low stands of sea level aborted the filling process, leaving in its wake a partially filled lagoon that constitutes the abrupt increase in water depth occurring some distance from many modern reef margins. In the case of Belize, as presumably elsewhere in the world, this abrupt increase in depth approximates the former edge of high stand lagoonward prograding sediment, modified by subaerial erosion during subsequent glacial low stands. The lateral extent of lagoonward progradation will vary dependent upon reef barrier continuity. Where reef barriers are markedly discontinuous, much of the hydraulic head created by the breaking waves will be dissipated in a seaward direction through reef passes with a consequent transport of reef-derived sediment through the passes and deposition in adjoining deep water (Fig. 10). Depth relations in the Belize central lagoon also suggest the reality of this phenomenon as they increase progressively toward the barrier platform before being terminated by the abrupt shoaling that marks the lagoonward edge of that entity. This suggests that prior to reef development the shelf simply increased in depth toward the shelf edge, as is the case with the great majority of continental shelves. Reef development on or near the shelf edge, including the contribution of isolated reef buildups, reversed this depth relationship by reversing the underlying morphology with carbonate deposition that prograded in a lagoonward as well as a seaward direction.

It is tempting to attribute barrier platform development here and elsewhere in the world to the last interglacial high stand of sea level 125,000–130,000 years B.P. (isotope stage 5e). Certainly that event must have been a major contributory factor in the lagoonward advancement of the barrier platform, but each of the prior interglacial high stands would have contributed to the aggradation and lagoonward advance of the platform and each of the following glacial low stands of sea level would have subjected the barrier platform to subaerial exposure and resulting erosion, largely through solution. Viewed in this context, today's barrier platform is an eclectic product of all previous glacial fluctuations of sea level.

The case for karst

Purdy (1974) interpreted the relief of the Belize shelf as largely reflecting drowned, structurally directed karst topography. The three dish-shaped depressions in the Holocene limestone antecedent surface of the northern shelf (Pusey 1975, his Fig. 29) still seems to be an extension of the shallow doline mainland karst and the partly drowned parallel ridges of Ambergris Cay continue

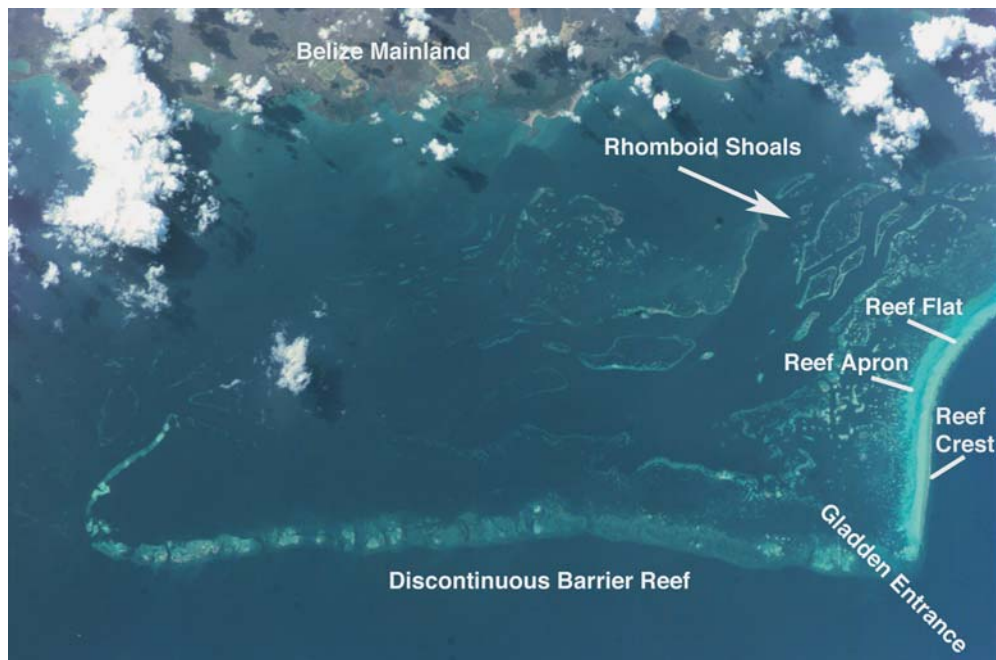


Fig. 10 Modified astronaut photograph of the southern Belize shelf (Image ISS003-ESC-7757 Courtesy of Earth Sciences and Image Analysis Laboratory NASA Johnson Space Center). South of Gladden Entrance the barrier reef is discontinuous and there is little or no development of a reef apron. North of Gladden Entrance the barrier reef is continuous and the reef flat and reef apron

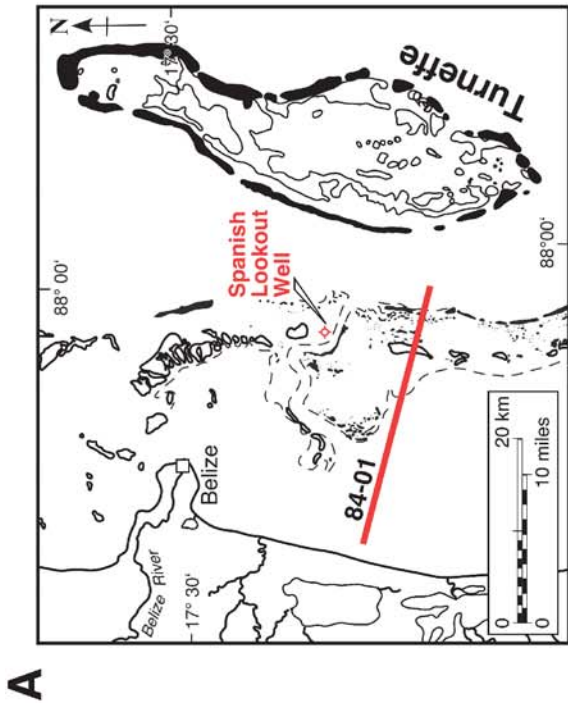
collectively comprise the light colored area immediately lagoonward of the barrier reef. The *light coloration* reflects substrate mobility that inhibits colonization by marine algae to some extent, but, more importantly, acts as a deterrent to colonization by marine grasses. The identified rhomboid shoals area includes the occurrence of several shelf atolls

to be suggestive of structural control (Purdy 1974, his Figs. 12 and 13). Some of the solution seems to have been quite extensive, as for example the 30-m-deep drowned cave containing speleothems on the east side of Cay Corker that is as much as 600 m in diameter and over 3 km long (Miller 1996). Purdy's (1974) interpretation of the central and southern shelf lagoon as a drowned karst marginal plain with tower karst occurrences in the form of isolated carbonate shoals and the irregular bathymetry of the barrier platform as drowned conical karst, however, requires major revision. In the case of the karst marginal plain, the apparent prograding origin of the barrier platform renders this interpretation untenable as it would appear to be lagoonward progradation from the barrier reef that has created the depth disparity between the barrier platform and the shelf lagoon. The edge of this progradation has undoubtedly been modified and in places attenuated by glacial lowstand subaerial exposure, but the resulting bathymetric contrast between the two cannot be logically attributed to the exclusive development of a karst marginal plain. Isolated shoals within the central shelf lagoon may represent erosional outliers attesting to the former lagoonward extent of barrier platform progradation, especially when in close proximity to the present edge of the barrier platform. However, these are best considered as antecedent erosional examples of immature tower karst. The irregular bathymetry of the barrier platform still seems to represent an expression of solution morphology, but the magnitude of the relief

expressed seems insufficient for a conical karst designation, although there may well be isolated examples that conform (e.g., see Purdy and Waltham 1999 for a discussion of the attributes of modern tower and conical karst). In this regard they are probably similar in expression to the nascent cone karst developed on the last interglacial limestones (125,000–149,000 years B.P.) of Santo Island, Vanuatu (Strecker et al. 1986).

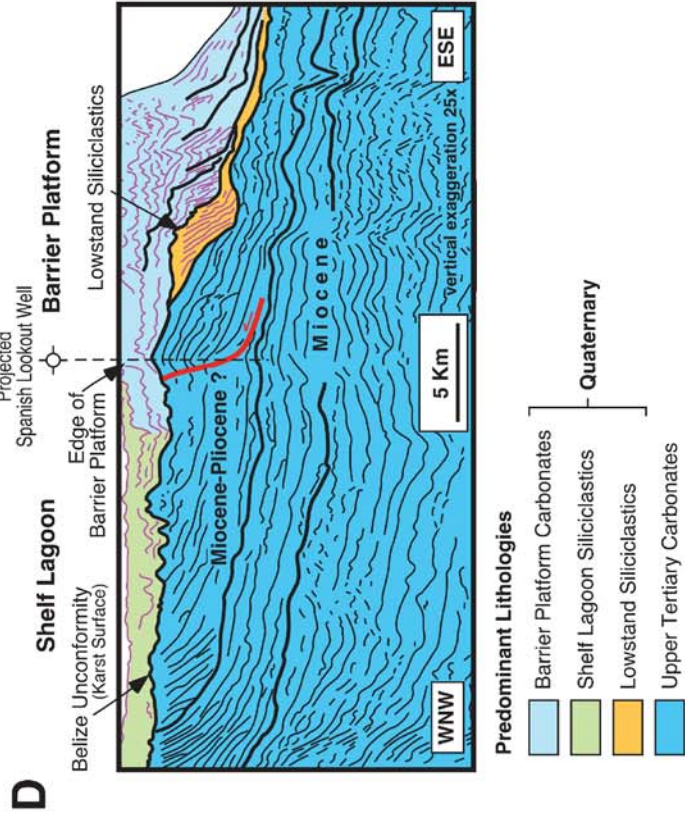
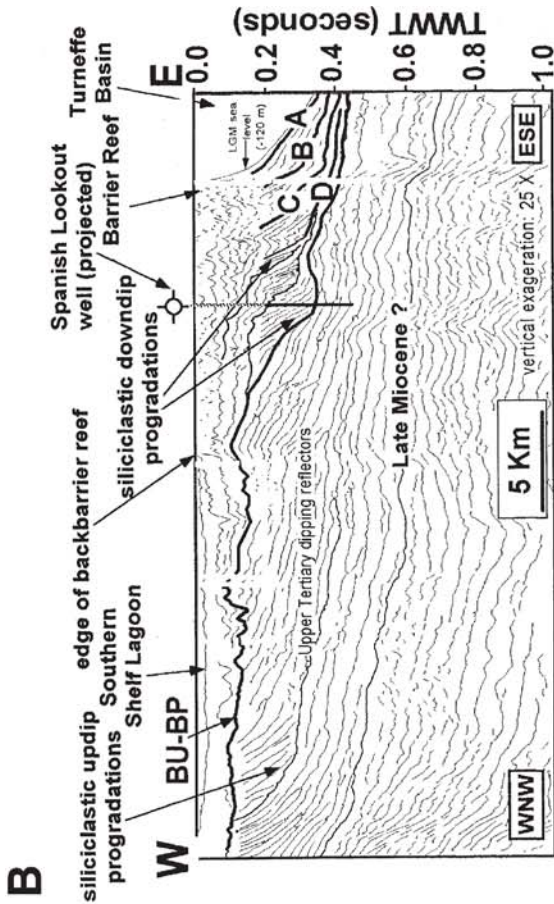
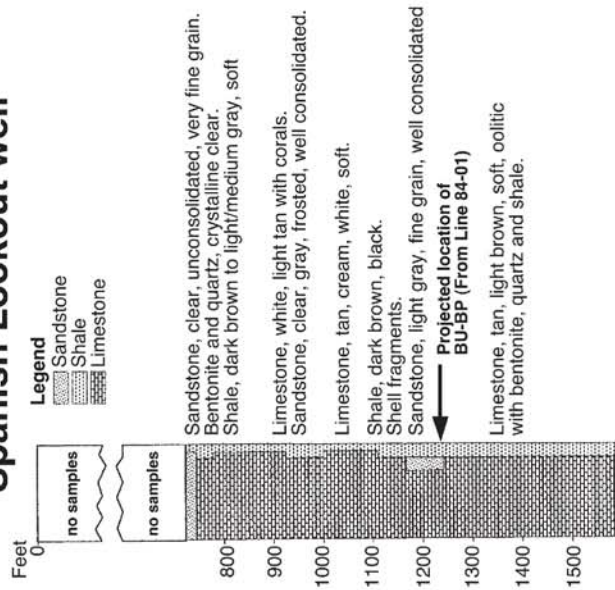
In addition, there are many barrier platform examples of what appear to be drowned karst dolines that are not deep enough to have the distinctive dark blue color of blue holes that, for example, characterizes the 120-m-depth of the 300-m-diameter Lighthouse Reef blue hole (Dill 1977). There are also shoal patterns suggestive of karst topography such as the honeycomb pattern identified by Macintyre et al. (2000) in the southern lagoon Pelican Cays and interpreted by them as drowned karst topography. The interpretation of increasing karst relief in a southerly direction still appears acceptable as an explanation for antecedent barrier platform and carbonate shoal relief that increases in expression in the same direction as the significant increase in mainland rainfall. The previously cited evidence for near-surface structures would necessarily impose a structural influence on karst development.

Tectonics have also been suggested as a causal agent in contributing to general present-day bathymetric relief. Choi and Ginsburg (1982), for example, mentioned the possibility of increased subsidence toward the south. The



C

Spanish Lookout well



progressive increase in depth of the Holocene antecedent surface from approximately 6 m in the northern shelf lagoon to more than 40 m in the southern shelf lagoon (Purdy 1974, his Fig. 10) supports that conclusion, but well data (Fig. 3) do not, probably because the wells have been drilled on structural highs that experienced differential uplift. The general westward shift of the coastline south of Placentia (Fig. 1) also supports the concept of southerly-directed subsidence.

On the off-shelf atolls, Dill (1977) and Dill et al. (1998) believed that the Lighthouse Reef blue hole inclinations of Pleistocene stalactites indicated a sub-recent southward tilt of the Lighthouse platform. In contrast, Miller (1996) noted that such features are common in large inland cave entrances where they apparently reflect differential carbonate precipitation rather than structural movement. Additionally, borehole data show no indication of a southward tilt of the Lighthouse Pleistocene surface (Gischler and Hudson 1998; Gischler and Lomando 2000; Gischler 2003). Nonetheless, the general Holocene antecedent depth increase of similar age shallow water Pleistocene limestone between Turneffe and Lighthouse Reef, on the one hand, and Glovers Reef, on the other, is suggestive of southerly subsidence whereas the accentuation of relief on that surface is consistent with increasing karstification in the same direction (Gischler and Hudson 1998; Gischler et al. 2000).

Barrier reef substrate

Ferro et al. (1999) concluded that the modern barrier reef only established itself along the Belize margin in the past 7,000 years B.P. and that prior to that siliciclastic sedimentation had dominated the Belize margin for most of the last 30,000 years and perhaps even the last 75,000 years. They further concluded that the seismic progradations observed by them, and reproduced here in Fig. 11, were examples of prograding siliciclastics. We

have some major disagreements with these conclusions. First, the well lithologies on which the Ferro et al. (1999) interpretation of prograding siliciclastics is based indicate a marked predominance of carbonates over siliciclastics, not the reverse (Fig. 11C). Consequently, a siliciclastic interpretation for their prograding sequences is untenable, notwithstanding the occurrence of some siliciclastics within the penetrated section. Second, we are provided with no information as to how well depths were converted to two-way time on the seismic section (i.e., no velocity information or synthetic seismogram) and, therefore, the seismic position of the well lithologies can only be accepted on faith. Finally, the projected position of the Spanish Lookout well onto their seismic section seems to be grossly in error. Their essentially north to south projection (Fig. 11A) conflicts with the regional north-east-trending structural grain (Fig. 1). Moreover, the structural high on which the Spanish Lookout well was drilled (indicated in close proximity to the projected location of the Spanish Lookout well by Prasada Rao and Ramanathan, 1988, their Fig. 3) would seem to be a continuation of the high indicated beneath the barrier platform on the seismic section. The high itself seems to be an expression of an underlying landward-directed thrust fault (Fig. 11D). Certainly, its morphology is similar to that of the seismic thrust faults identified in Figs. 5 and 6. Even so, extrapolation of well stratigraphy to the position of the structural high is still misleading as we know neither the plunge of the structure between the two data points, nor the velocity information that is necessary to convert well depths to two-way seismic time. Nevertheless, the position of the well on this high (Fig. 11D) is apt to be more accurate than the projected position of Ferro et al. (1999).

It is difficult to see how terrigenous sands could have been deposited at the shelf edge once the barrier platform had been initiated as this would have involved transportation over a topographic high during glacial low stands of sea level and over a bathymetric high during intervening high stands. With this in mind, the sand

Fig. 11 A Location of seismic line and Spanish Lookout well illustrated in B and C (after Ferro et al. 1999). B Ferro et al. (1999) illustration of a seismic section over the central shelf lagoon and barrier platform with projected Spanish Lookout well lithologies. The well projection onto the seismic section appears to be essentially straight line from north to south. Their original illustration has been modified only to the extent of eliminating non-essential information relative to their prograding siliciclastic interpretation. As illustrated by Ferro et al. (1999), the Spanish Lookout lithologies in C are predominantly carbonates, not siliciclastics, and on this basis alone contradicts their siliciclastic progradation interpretation. D Alternative interpretation of B. The well location has been shifted to the crest of the adjoining structural high in keeping with structural trends in the area. The well projection now identifies a predominantly carbonate lithology beneath the Belize Unconformity that is interpreted as a karst erosion surface. The precise position of the well lithologies within the seismic sequence is unknown both because of the lack of well velocity information and the unknown plunge of the structure between the seismic high and the position of the well. The structural high is interpreted as a landward-directed thrust fault

similar in geometry to the thrusts illustrated in Figs. 5 and 6 and like them probably soles out at shallow depth. A fault is also indicated near the Spanish Lookout well by Prasada Rao and Ramanathan (1988, their Fig. 3). More speculatively, a lowstand siliciclastic wedge is shown as occurring in a downdip position above the Belize Unconformity seaward of the thrust. The underlying Belize Unconformity may not have been subaerially exposed in this downdip position. The barrier platform makes its appearance above this interval and, consequently, restricts deposition of siliciclastic sands to the shelf lagoon. Note that the lagoon position of the barrier platform seems to have migrated lagoonward at first from its position above the thrust fault high and then seaward to its present position, suggesting possible lowstand erosional attenuation of its former lagoonward extent. Shale intervals probably occur in the barrier platform carbonate sequence as a product of clays settling out of suspension during initial interglacial platform flooding prior to the main highstand phase of carbonate deposition. There is also the possibility of siliciclastics in the coeval barrier platform deep-water sequences because of lowstand siliciclastic deposition at the mouth of the English Cay Channel break in the barrier reef (Ferro et al. 1999)

recorded at the top of the prograding interval of the barrier platform, Spanish Lookout well, should pre-date the origin of the barrier platform. The projected position of the well either in the original interpretation (Fig. 11B), or in the position proposed here (Fig. 11D), indicates that this is the case. Conceivably, the lowermost downdip progradation (Fig. 11D) is a lowstand siliciclastic wedge developed as a consequence of the drop in sea level that produced the Belize Unconformity. The siliciclastic interpretation is identical to that of Ferro et al. (1999), but for far different reasons. Overlying units would presumably have a carbonate lithology because of the traction transport impediment imposed by development of the barrier platform (Fig. 11D). Once the barrier platform had developed, subsequent lowstand siliciclastic sand deposition would have been confined to the shelf lagoon (Fig. 11D). The lowstand terrigenous delta recognized by Ferro et al. (1999) in front of the barrier reef trend poses no problem as transportation was effected through the major English Cay Channel break in the barrier platform. Shale occurrences within the barrier platform sequence would not be anomalous as the constituent clays could have settled out of suspension during the initial stages of flooding before carbonate deposition began in earnest.

Barrier platform relationships indicated by the bilateral progradation of Fig. 5 also support the near-surface occurrence of carbonates. The point source of the sediment comprising the bilateral progradation strongly argues for an overall carbonate lithology. The same illustration suggests that reefal development at the shelf margin may be relatively late in occurrence, supporting that part of the Ferro et al. (1999) interpretation.

Confirmation of the carbonate composition of the underlying Holocene lithology is provided by recent drilling on the barrier reef crest at nine locations, evenly spaced between the northern Gallows Point Reef off Belize City and the Zapotilla Cays near the southern limit of the barrier reef. These drilling results consistently encountered coral limestone as the antecedent lithology underlying the Holocene barrier reef. Radiometric dates are not yet available, but the common occurrence of *Acropora palmata* indicates that these limestones are probably Pleistocene in age. No siliciclastics were encountered (Gischler, unpublished data).

Conclusions

The distribution of Belize Holocene facies, particularly reefs and carbonate shoals, has been strongly influenced by the position of near-surface folds and faults developed in both carbonates and siliciclastics. The youngest age of extensive near-surface faulting appears to be Pliocene and was followed by the development of a regional unconformity (the Belize Unconformity) on which the modern barrier platform began its prograding development. From limited data, the present-day barrier reef would seem to be a late Quaternary development on the edge of an underlying clinoforming carbonate shelf edge. The pro-

grading nature of the carbonates may not always be in evidence as gravitational slumping into deep water may have removed some or all of that evidence from the shelf. Indeed, seismic evidence for slumping in deeper water has been noted by Dillon and Vedder (1973). Where the plan view outline of the barrier reef is relatively straight (e.g., south of Gladden Entrance and offshore of Ambergris Cay) a faulting limit is probable. Elsewhere, its concave or convex seaward outline (e.g., between Gladden Entrance and Southern Long Cay, or the irregular outlines of Turneffe or Lighthouse Reef) probably signifies differential progradation or gravitational slumping or both. Where the underlying lithology is carbonate, karst solution has contributed to antecedent relief that increases in a general southerly direction.

Additional Belize margin problems meriting research attention include the overall timing of barrier reef development and the importance of controlling factors on reef margin anatomy. Closer to shore, the effect of clastic input on coral communities needs to be examined. Most important is the documentation of the carbonate response to the rate of Holocene sea-level rise as it progressively inundated antecedent topography along depositional strike from south to north.

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