International Field Trip

20th Caribbean Geological Conference (2015)
Port-of-Spain, Trinidad and Tobago

Geology of the Scotlands District, Barbados, and evolutionary models for the Lesser Antilles Arc and Accretionary Prism

May 22-23, 2015

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• Dr. Bob Speed and Dr. John Saunders, both supported by colleagues David Larue, Rudi Torrini, Pam Smith, James Walker, and others, who have defined a level of understanding for Bajan field geology that may never be significantly improved upon. Although this field guide offers different syntheses for the Scotland District's position and regional significance in Caribbean evolutionary models, this would not have been possible without the painstaking efforts taken by Bob and his colleagues over many years.

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Much of this guide has been excerpted from Pindell and Frampton, 2007,
Barbados Field Guide, GSTT Conference Proceedings, Port of Spain, Trinidad and Tobago.

Emergency Numbers and other Contacts:

Barbados Police: 211
Barbados Ambulance Service: 511
Barbados Fire Service: 411

Police Stations:
- Belleplain Police Station
- Oistens Police Station

Hospitals:
- The Sparman Clinic, +1 (246) 624-3278

For general assistance:
- Mr. Leslie Barker: +1 (246) 230-1525
- Mr. Mervin Gordon, Barbados National Oil Co. +1 (246) 243-4324
- Ms. Nesha Nurse, Barbados Ministry: +1 (246) 230-1014

SUMMARY OF FIELD ITINERARY: See FIGURES 3b and 3c

FRIDAY May 22

Fly POS to Barbados on BW 458, Depart Trinidad at 8:00 arrive BGI at 8:55am. People from the Butterfly Beach Hotel in Oistens will collect our baggage at the airport, letting us go straight to the field. Please wear field boots and gear on the flight, and be ready to go on arrival. If you have any particularly valuable items, keep them with you on the bus in your daypack.

9:30am Take buses from Airport to Scotlands District on NE coast of Barbados.

10:15. **STOP 1**. Barclay's Park Road stops and view of Chalky Mount, introduce Scotland Fm. structure and sedimentology.
10:30 Drive to Chalky Mount Village.
10:50. **STOP 2**. Walk the ridgeline in the Scotlands beds north of Chalky Mt village (vista overview, big folds, sandstones, mudstones, conglomerates).
11:15 Drive to Bath Cliffs, collect lunch en route from Round House Restaurant.
12:00. **STOPS 3 a and b**. Bath Cliffs Oceanic Unit and the Conset Bay Sub-Oceanic Fault Zone (low tide at 12:54). Lunch when feasible.
1:30 Return to vans, eat lunch if not already achieved.
2:00. **STOP 4**. Drive to St Mark's Church, Conset, observe Conset Marl cover sequence and discuss implications.
2:45 Drive south to Ragged Point.
3:15. **STOP 5**. Study Scotlands Fm sedimentology and structure at Ragged Point.
4:00 Drive to Butterfly Beach Hotel, Oistens, arrive 4:30-5:00pm.
Dinner at Oistens Fish Market, about 6:30pm.

SATURDAY May 23

Leave hotel at 8am.

9:00. **STOP 6**. Arrive Greenlands Shale Quarry, walk around the area, observe active oil seeps.
10:15 Drive up to Less Beholden Village, between Chalky Mt Village and Cambridge House.
10:30. **STOP 7**. Walk east/down the slope in Joe's River Mélange to the Coastal Highway.
11:45 Buses collect us on the highway, go to the Round House Restaurant for lunch.
12:00-1:30 GROUP sit down Lunch at Round House
1:30-3:15 Discuss seismic lines and models for southeastern Caribbean and Barbados Prism.
3:15 Group drives back to Butterly Beach Hotel.
4:15 Collect bags. Shower??? Trip is officially finished.
5-5:30 Go to airport in bus, eat at Airport if desired. Fly on BW 457 back to POS unless planned individually otherwise, depart BGI at 20:10 arrive in Trinidad at 21:05. Depart Airport under your own arrangements.

INTRODUCTION

1. Trip Objectives:

This field trip will endeavour to achieve three main things. First, it will visit and describe most of the major units of the Scotland District (**Figures 1a and 1b**) as well as outline other units and field relationships not easily visited, so that attendees can gain a comprehensive exposure to and understanding of the stratigraphy (tectonostratigraphy) and structure beneath the Pleistocene reef cap of the rest of Barbados.

Second, the trip will review the pre-plate tectonic paleogeographic concepts of (1) Senn (1940); (2) the plate tectonic interpretation of Bob Speed and colleagues, which holds Barbados as the product of the progressive development of a single southeast-facing accretionary prism; (3) the tectonic model of Pindell et al. (1991, 2005, 2009), which encompasses the merging of two accretionary prisms, not just one, for Caribbean-South American interaction; and (4) the model of Chaderton (200X), which

The diversity of working tectonic models shows the need for future work on the Barbados Ridge in general, particularly in geochronology (e.g., Baldwin et al., 1983), in the hope of continuing to improve our understanding of the evolution and hydrocarbon potential of Barbados Ridge and the whole of the southeast Caribbean.

2. History of primary work on the Scotland District:

Alfred Senn. In the absence of the knowledge of large-scale horizontal plate motions, Alfred Senn in the thirties attempted to develop a coherent "layer-cake" stratigraphy for the Scotland District. Senn managed to describe accurately many of the primary geological relationships which continue to guide our understanding, and it is from this great work that Barbados could be placed into a regional context for at least the next three decades. Senn's (1940) view of the Scotland District is encapsulated here:

Five levels of the Scotland Formation were laid down sequentially: Early Eocene Lower Scotlands, including the Walker's, Morgan Lewis, and Murphy's members; and Middle Eocene Upper Scotlands, including the Chalky Mount and Mount All members, with a general coarsening upward trend, although thick sands exist in all units. Sediment provenance was a metamorphic terrane, probably a Paleogene precursor to the Mérida Andes, Caribbean Mountains, and/or Araya-Northern Range trends of northern South America. Deformation of the collective Scotlands, involving SE-ward thrusting, occurred in Late? Eocene time as part of an Antillean phase of orogenesis which included the onset of volcanic activity in the Lesser Antilles arc. Subsequent to this deformation, the Joes River "Beds" were extruded through the Scotland beds by mud volcanism and locally reworked on the seafloor, primarily in ?Early Oligocene time. The deformed Scotlands/Joes River surface was then covered by the in-situ deposition of the Oceanic Beds, and this was followed by further deformation.

Poole and Barker. In 1983, E. Poole and Leslie Barker expanded upon many of Senn's descriptions and remapped much of the Scotland District into the first modern map compilation effort of the Scotland District, thereby incorporating the district into the National Geological Map of Barbados. In addition, much of the biostratigraphic work by John Saunders was underway by this time, so that the general framework for the Scotland area was finally well presented.

Robert Speed, John Saunders, David Larue, Rudi Torrini, and others. With the advent of plate tectonics, it was realised in the late sixties and seventies that the Barbados Ridge was an enormous accretionary prism of sediment moving ahead of the Caribbean Plate as it progressed eastward along northern South America (eg. Molnar and Sykes, 1969). Given the embryonic models of accretionary tectonics in the 1970's, Bob Speed and colleagues began detailed structural mapping and stratigraphic assessments in order to learn more about the processes of sediment accretion at convergent plate boundaries. One of Speed's most significant realisations was that Senn's Scotland "Formation", which Senn had described as a continuous section with members of distinctive character (i.e. Walker's, Morgan Lewis, Murphy's, Chalky Mount and Mount All), was actually a collection of packets of discrete sediment wedges that should be considered in terms of "tectonostratigraphy" (ie, the sequential structural juxtaposition of fault bounded sediment packages) rather than traditional layer cake stratigraphy in the sense of progressive vertical sediment accumulation. Speed developed a "stacking diagram" to describe the evolution of Barbadian tectonostratigraphy (**Figure 1a and 1b**). In addition, the efforts of Speed and John B. Saunders showed that there is temporal overlap in the times of deposition of the Scotland units and of the overlying Oceanic units, thus requiring a structural contact between these units of extremely different lithologic character rather than an in-situ depositional one. The oldest known Oceanic age (dated by radiolaria) is Thyrsocyrtis triacantha Zone (spanning P11/P12, or middle Middle Eocene), from a sample taken just east of Bissex Hill (Stop 12, Saunders field guide for Fourth Caribbean Conference, and the oldest foram date is Orbulinoides beckmanni Zone (P13) from Mount Hillaby. When one considers the Miocene ages of Speed's "Prism Cover" units, which also underlie the Oceanics, this structural juxtaposition is "clear".

Speed's last write up of the geology of Barbados was his field guide prepared for the Caribbean Geological Conference in Barbados (Speed, 2002). That field guide provided an update of Speed's views on the Intermediate units and on the timing of certain parts of his overall story for the evolution of Barbados. A summary of Speed's last account of Barbadian geology is outlined here (**see Figures 2, 3a and 3b**):

The Basal Complex (Scotland Fm) comprises deep sea (below CCD) radiolarite, hemipelagite, and fine to coarse and thin to thick turbidite beds set in the region between a SE-wardly advancing Caribbean arc system and the South American passive margin. Clastic source area was South America, fed onto the continental rise and abyssal plain via slope channels and canyons. Radiolarite and hemipelagic depositional zones were situated between turbidite channels and fans. On the arc's forearc, the Oceanics accumulated at somewhat less depth (above the CCD), and were bathymetrically isolated from quartzose sediments ahead of the Forearc and accretionary prism. Basal Complex sediment was progressively accreted into a growing and back-rotating accretionary prism, much of which occurred in the Late Eocene. Contraction was orientated NNW-SSE as shown by structural trends on Barbados. Prism cover *consisting of terrigenous strata, known by Barker et al. (1988) as the "Intermediate Units", were deposited on the growing prism and are as young as Early Miocene. Speed considered these as reworked material from shoaling parts of the older Basal Complex, which was thought to have been bathymetrically isolated from South America. Speed acknowledged that the contractile direction (SSE) is at odds with accepted flow lines for Caribbean-South America motion, but there is no evidence for bulk rotation of the Scotland District and he was sticking to the observed SE-NW contraction for Caribbean/South America until an alternative explanation was conceived of (pers. comm. w/ J. Pindell, 2002).*

Starting in the Middle Miocene, a second contractile accretionary event occurred. Speed argued that the forearc strata (Oceanics) were thrust EASTward over the pre-existing Basal Complex accretionary prism and at least some of its overlying Prism Cover. Thus two discrete events occurred, each with its own kinematics. Tectonic overlap between the Basal and Oceanic tectonic units was achieved by Middle Miocene, shown by the Middle Miocene Conset Marl overlap assemblage near St Mark's Church. However, deformation continued thereafter, as the overlap assemblage is quite deformed as well as the older units, and wells in the northern subsurface show imbrication of Eocene and ?Early Miocene ages on terrigenous samples to depths of 3 km. Presuming the Conset Marl deformation occurred late in the Middle Miocene as the tectonic juxtaposition of the Oceanics and Basal Complex might have waned, little more can be shown to have occurred onshore until the building of the reefs platforms in ?late Pliocene to Quaternary.

To the west, in the offshore, a significant backthrusting event took place in the Middle Miocene, in which inferred Basal Complex prism strata were backthrust onto the Tobago Trough forearc basement, and beneath a roof thrust carrying the Oceanics onto the backthrusting Basal Complex. As much as 40 km of shortening occurred in this event. This event seen in the offshore presumably was coeval with the eastward emplacement of the Oceanics onto the Scotlands in the onshore (timing and geometrical result is the same). Since that time, most accretion has been east-facing at the eastern flank of the ever-growing greater Barbados Prism, down to the present deformation toe.

Suzanne Baldwin and our own work; the age of strata and timing of events. In addition to the evolving tectonic concepts of the above workers, a discussion on the depositional chronostratigraphy and timing of structuring of the Scotland District is essential. There are three noteworthy aspects regarding age and timing.

The first aspect is Speed's (and presumably Saunders') long held view that the Scotlands are entirely Eocene. According to over 100 dated samples, the radiolarite and hemipelagic strata of Speed's "Basal Complex" range from Early to Middle Eocene, and the terrigenous (sandstone and mudstone) strata range from Middle to ?Late Eocene, although the faunal specimens for the determinations in especially the terrigenous levels are admitted to be commonly, if not totally, reworked and redeposited. Due to these ages, Speed (2002) accepted an age of latest Eocene, possibly earliest Oligocene, for the primary accretionary episode of the Basal Complex. This was then followed by an Early to Middle Miocene event wherein the Middle Eocene-Early Miocene Oceanics were thrust eastward onto already deformed Basal

Complex, whose contractile direction had been SSE. Thus, there were two discrete events with different kinematics.

The second aspect regarding age is the fission track age determinations of detrital zircons from Scotland beds (Baldwin et al., 1983). Several sample sites gave clustered ages around 30 Ma, Early Oligocene and some even younger, which would be a maximum depositional age as the grains (euhedral shapes, probably primary igneous textures) themselves must have sourced from either original ash falls or an intermediate setting from which they were eroded and transported. No samples indicated any significant post-depositional heating, a view corroborated by thermal maturation studies (very low vitrinite reflectance values). Baldwin sites 26 (Mount All beds) and 35 (Walker's Beds), in particular, gave statistically good Oligocene populations, and several other samples sites possessed Oligocene grains, too, although strong mixing with grains of older ages is common, indicating transfer from pre-existing strata as opposed to primary ash fall for these. An Oligocene depositional age is permissible in Speed's history of tectonic evolution: I suspect he wanted as much time as possible between his two discrete phases of structural kinematics, but the Oligocene depositional age would mean that his accretion of the Basal Complex would need to be Late Oligocene-Early Miocene, with thus little or no time between the two kinematic phases. Speed never accepted that the Oligocene ages were statistically valid, and maintained Eocene depositional and accretionary ages in all writings.

The third aspect concerns the various paleontological and palynological analyses made by ourselves and colleagues. We have collected clasts from the Chalky Mount conglomerate beds that we considered might give a maximum age of deposition (age of source area), given that the clasts (well rounded, subaerially eroded, up to 20 cm in size, non-glauconitic) must have been reworked from pre-existing beds in a subaerial source area. In 2004, Pindell collected a representative sampling of these and matrix. Anthony King and Maria Bolivar (BioSTRAT) examined 19 of the clasts and one matrix sample for faunal content. Three samples possessed identifiable fauna, and two species suggested a possible Oligocene age. One clast contained *Bulimina ovata*, known to range from Late Eocene to Oligocene in Barbados and from the Early Eocene in Trinidad, but it is known only from the Oligocene in Venezuela, the likely source area. The second was a finer grained conglomerate and thus it is not clear if the specimens are derived from the matrix or a clast, but a questionable *Planulina renzi* (Middle to Late Oligocene, although a related form is known back to the Late Eocene) was recovered. If the first sample age is bonafide, and if we accept the Oligocene limitation on the age range due to the likelihood that Venezuela was the source area, it requires that Oligocene beds in the sediment provenance area were first lithified (probable calcareous cement in iron-rich mudstone; hence, quick lithification at surface is possible), then eroded and rounded, and then transported to the Scotland depositional site. Whether the second sample age is from the matrix or a clast, we can consider that the re-deposition occurred in the middle Oligocene or younger. Finally, it is noteworthy that one other conglomerate clast gave a fauna indicating an open marine paleo-depositional environment of Santonian – Maastrichtian age. For reasons mentioned elsewhere, we think this is most likely to derive from central Venezuela's Mucaría Fm.

In addition, Dave Shaw (BioSTRAT) has recently conducted palynology studies from 9 random samples collected by John Frampton. Palynomorphs at Chalky Mount indicate a source area where palms, forests, and pteridophytes were common (terrestrial forest and coastal swamps), and indicate an ?Early to Middle Eocene age. The mainly terrestrial forms from the Joes River matrix indicate a source area where grasses, palms, forests, and pteridophytes were common, along with freshwater algae. The environment was judged to be a savannah with abundant freshwater supply. Age is thought to be Early to Middle Eocene age, although one form is not thought to be older than Middle Eocene. The palynomorphs recovered from the Windy Hill section suggest a source area that was coastal palm swamp with some forest, above tidal influence but with some freshwater input. The age is Early to Middle Eocene. Forms from 2 localities of the Walker's Beds were collected. One suggests a marine setting whose precise environment is uncertain, but palm pollen was present. Age is suggested to be Late Paleocene to Early Eocene. The second suggests a coastal plain setting with conifers, other forest pollen, palms and fresh water of Paleocene to Early Eocene age. The Mount All member's assemblage is comprised entirely of terrestrial pollen and freshwater algae, perhaps a palm swamp above tidal influence of Early to Middle Eocene age. The palynomorphs in all samples are well preserved and all within the immature range (spore colour 1-2) of thermal alteration in agreement with the low vitrinite reflectance referred to earlier. The assemblages show little mixing of ages, if any.

Finally, Barker et al. (1988) studied material from what these authors called the "Intermediate Unit" in outcrops and wells of Barbados. The Intermediates are, like Speed's Basal Complex, composed of terrigenous sand and shale. Shales are commonly greenish, and this is used as a distinguishing factor. The age of these beds appears to range from Late Eocene to Early Miocene, based on pollen, dinaflagellates, and other forms. Reworking of at least pollen is clear, and the older end of this age range may be suspect. At the Turner's Hall/Springvale area and wells (**Figure 4**), Basal Complex overthrusts the Intermediates at the surface, and the Intermediates are found imbricated with basal Complex to depths of at least 11,700 feet (entire depth of the wells). The structural style is one of thrust imbrication (subduction accretion?), presumably of southeast vergence, of an Early Eocene to Early Miocene stratal section. In other words, primary subduction accretion may have remained active into the Early Miocene within the zone of exposure in Barbados. Speed preferred to view this as late (Middle Miocene?) thrusting of Basal Complex with younger cover that had been deposited on the Basal Complex, presumably because in his single prism model, the trench and hence site of accretion should have migrated far away from already accreted Basal Complex by the Miocene. Judging from the intensity of imbrication as indicated in the wells, however, primary accretion seems more likely to us. Two points need to be made concerning this alternative view: (1) there may be parts of the Scotland District that have stratigraphies ranging from Early Eocene to Early Miocene, and (2) these parts may not have been accreted into an accretionary prism until the Middle Miocene.

From all of the above, we have inconsistencies in the age data for various parts of Speed's Basal Complex. Concerning the hemipelagics, radiolarites, and perhaps much of the finer grained turbidites, the Early to Middle Eocene age was established by radiolaria (Speed, 2002) and appears to be confirmed by palynology. Concerning the sandier facies of Mount All, Chalky Mount, Bissex Hill and Belle Hill, the lack of Late Eocene and younger palynomorphs also probably indicates a latest Middle to earliest Late Eocene depositional age, but the lack of younger palynomorphs is hard to reconcile with both the fission track data from sandstones as well as the maximum depositional ages from the conglomerate clasts of the Chalky Mount section. An Oligocene age might also be indirectly suggested by the presence of glaucophane in the Scotlands, because at ODP site 672 on the Tiburón Rise to the north (**Figure 5**), 5 out of six glaucophane occurrences in core reports are in the Oligocene, with only 1 (trace) in the lower Middle Eocene (Mascle et al., 1988). But unlike the Scotlands, Oligocene pelagic fauna ARE represented at Tiburón Rise. Finally, the Intermediate [terrigenous] Unit does possess Late Eocene through Early Miocene pollen and other forms, demonstrating that "Scotland-like" deposition continued for that time (Speed's Prism Cover units). An important question is whether the Intermediates were deposited ON pre-accreted Basal Complex, as Speed claimed, or if they were seafloor deposits still awaiting accretion indicating that sediment accretion continued at Barbados Island into the Early and Middle Miocene.

Is the age controversy resolvable? Not easily, and we would be the first to say that a systematic chronostratigraphic study in conjunction with structural work to determine the position of the conglomerates in relation to localities for age control, and the relationship of the Intermediates to the Basal Complex, is needed to resolve the issue.

We now pursue the probable sediment source area for the Scotlands. The requirement of ?Late Paleocene-Middle Eocene subaerial exposure in the sediment source area rules out the Serranía del Interior Oriental as a source area, because the strata of that age there are marine (Vidoño and Caratas fms), although it must be admitted that we do not know the Paleogene nature of the NE parts of the Serranía due to today's erosion level into the Cretaceous. Lack of glauconite in the redeposited Scotland conglomerate clasts also suggests a source area other than the Paleogene of the Serranía Oriental, as that mineral is ubiquitous there in Paleogene mudstones. Likewise, the Maracaibo Basin was marine through Paleocene-Middle Eocene time, so northern Maracaibo's sub-La Rosa unconformity does not seem to be the source area. Finally, the Guarico Belt of central Venezuela was marine through the Middle Eocene and possibly into the late Eocene, so uplift of the Guarico Formation strata was probably not the source area.

Another option for the Scotland source area is the unconformity below the Late Eocene marine section across much of the Bonaire Basin. The sub-crop here is metamorphic where known on the fringes (eg., La Vela Bay; Biju-Duval et al., 1983), but very little is known about the basin center. It is easily argued that this oceanic/arc area probably lacked sufficient volumes of quartz to source the Scotland, and that the Scotland was not fed by such a dominantly oceanic terrane. However, we cannot rule out that a river from western Venezuela did not cross this surface and eventually reach the Proto-Caribbean Basin to the east.

Better options for the source area lie in central onshore Venezuela. First, the Caribbean Mountains were actively thrusting and were subaerial for much of ?Late Paleocene-Eocene time, as shown by the Early Eocene Garrapata and the Middle Eocene Los Cajones flysch and other sequences. The second and perhaps more significant option is the sub-La Pascua Fm unconformity in the Guarico Basin, which spans the ?Late Maastrichtian to Late Eocene. The unconformity's sub-crop includes the entire Cretaceous (sandy here) and crystalline basement. This unconformity marks the uplift of the Caribbean forebulge prior to earliest Oligocene La Pascua foredeep onlap (Pindell et al., 1988; 1991; 1998). We suspect that it fed much of the Paleocene-Middle Eocene Guarico Formation turbidites in a shelfal "Guarico Trough" directly to the north (not to be confused with the more allochthonous syn-orogenic Los Cajones and Garrapata fms as the literature does), indicating subaerial conditions for that period and into the Late Eocene. In addition, the Upper Cretaceous Mucaría Fm is present in the sub-crop here, which is a viable candidate for many of the well-rounded clasts in the Chalky Mount conglomerates.

The dual clastic source areas in central Venezuela are essentially synchronous with the Paleocene through early Late Eocene clastic detritus in Barbados: (1) shield and autochthonous cover strata beneath the La Pascua unconformity, and (2) the rising Caribbean Mountains, much of which are comprised of the former passive margin section. By the Late Eocene/Early Oligocene, the cratonic source (1) had been submerged and onlapped by the La Pascua/Roblecito fms, perhaps causing quartz volumes to dwindle down-axis toward Barbados. However, in the Late Oligocene, a second clastic feed was established, that of the Naricual Fm, which is up to 3 km thick near Barcelona, Venezuela. If it turns out that the fission track and conglomerate clast ages are correct after further work is conducted, rather than the Paleocene-Middle Eocene palynological data noted herein, then the Scotlands would necessarily be a downdip equivalent of the Naricual. At this point, we prefer to adhere to the Late Paleocene-early Late Eocene depositional ages indicated by the palynology (and paleontology).

Another point to mention here concerns the constraints placed on Caribbean paleogeography by volcanic ash from the Caribbean arc. The Oceanic beds of the Scotland District are a rhythmic alternation of layers of fairly clean pelagic material and layers laden with volcanic ash. The ash layers occur every 1 to 4 meters or so, and provide a record of fairly constant and proximal volcanic activity. This indicates that the Oceanics have migrated with the Caribbean Arc. In contrast, the record of ash deposition at ODP site 543 at the Tiburón Rise is shown in **Figure 5**. Tiburón is situated on the Atlantic crust (autochthon with respect to the Caribbean Plate), and can be interpreted to record the progressive approach of the Caribbean arc.

Pindell's double accretionary prism model. The long-accepted model of Caribbean Plate migration along and between the passive margins of North and South America implies a single accretionary prism ahead of the Caribbean's Lesser Antilles arc, assumed to be the Barbados Subduction Accretion Complex. However, the fact remains that several hundred km of N-S convergence occurred between the North and South American plates PRIOR to and during the Caribbean's eastward migration (Pindell et al., 1988; 1991; 1998; 2007; 2009), and thus we should expect the existence of a convergent plate boundary somewhere in the Proto-Caribbean basin (east of the migrating Caribbean Plate). This Proto-Caribbean convergent boundary (accretion zone) should been encountered by the progressively migrating Lesser Antilles/Caribbean prism. But where is it, and how did the Caribbean encounter it?

In 1990, van der Hilst (thesis) prepared the first seismic tomographic cross sections of the Caribbean, which clearly show a severing of the original continent-ocean transition along northern South America, beneath the overlying allochthonous Caribbean lithosphere. Pindell et al. (1991; Trinidad Conference) employed this evidence to suggest that the pre-existing convergence zone between the Americas, or "Proto-Caribbean thrustbelt", lay along northern South America, and that the dextral oblique progressive Caribbean-South America transpressional collision was NOT of the arc-continent type, but rather a collision between two pre-existing convergent margins. This concept remained fairly dormant for several years due to the complex nature of both the southern Caribbean's actual geology and the predictions made by the concept, but Pindell et al. (2007; another Trinidad conference) considered that Cenozoic paleo-deposition and erosion history along northern South America and the southern Caribbean terranes such as Tobago were best viewed in terms of the trench-trench collision model, upon which they elaborated (**Figure 6a and 6b**).

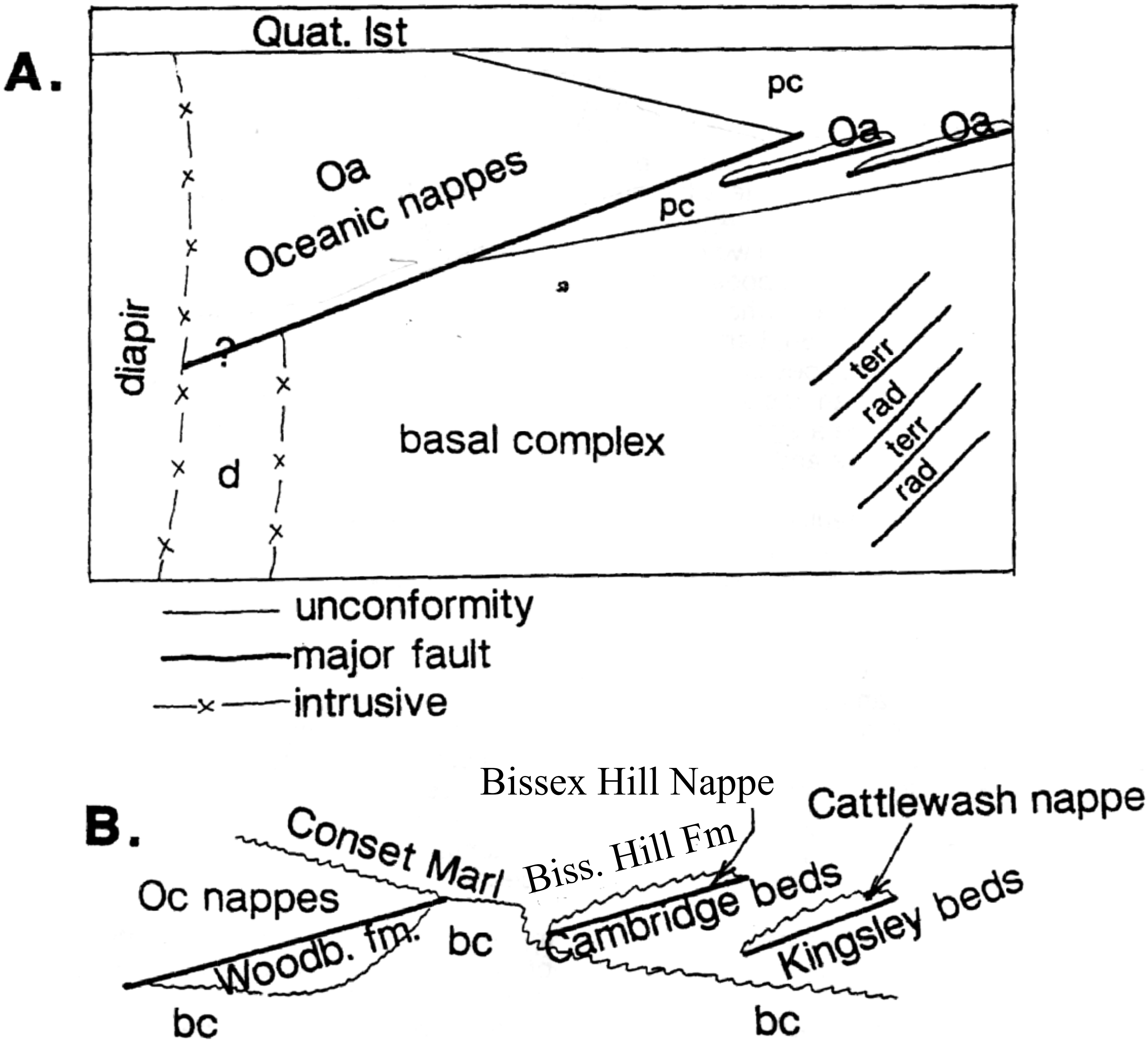
Concurrently, the seismic tomographic results of the BOLIVAR research program (Rice University) has refined the early tomographic views of van der Hilst. We now know that a swath of the Atlantic slab extends steeply beneath NE Venezuela to a depth of many hundreds of km, and that the Caribbean slab entering the NW Colombian Trench extends several hundred km into the mantle as far east as the Merida Andes (several papers by Alan Levander and colleagues). These observations confirm large allochthoneity of the Caribbean Plate, of course, but of greatest interest here is that the severing of the original Jurassic South American margin was also observed by BOLIVAR, and that the sinking Proto-Caribbean lithosphere has been forced south of its original tear line at the paleo-surface, thus recording the convergence between North and South America, which is independent of the Caribbean Plate's motions. This strongly implies the existence of shortened sedimentary section along northern South America that is unrelated to Caribbean migration, but distinguishing such terrane from Caribbean-driven shortening is not straightforward.

Pindell et al. (2007) suggested that the cooling histories of the meta-sediments of Venezuela's Caracas Group, the autochthonous parts of Araya, and the Paria-Northern Range fit a model in which progressive metamorphism in these belts was driven by Proto-Caribbean, rather than Caribbean, convergence, and that uplift and cooling of the belts were driven by Caribbean arrival. New cooling ages on some of these rocks continue to suggest this two fold-history. But more importantly, newly processed deep penetration seismic lines across the greater Barbados accretionary complex show only a relatively small amount of shortening (<200 km) ahead of the Barbados Ridge, on which Barbados Island lies. Although subduction accretion belts rarely record much of their shortening due to telescoping of the detachment surface to the paleo-seafloor at the deformation front, this low shortening value is also attributable to the two-prism model, in which we envision the Barbados Ridge as having formed by NW-vergent shortening between North and South America, and not to the migration of the Caribbean along South America. As outlined by Pindell et al. (2007; Trinidad Conference Proceedings) and Pindell et al. (2009; Geol Soc London SP328), we believe the Barbados Ridge is a Proto-Caribbean accretionary prism with a Cretaceous section beneath the Paleocene-Middle Eocene Scotland beds, that formerly continued westward from Barbados into Trinidad's Northern Range, and onward into the Araya-Paria belt, and then the Caracas Group, prior to collision with the leading edge of the Caribbean Plate. This Proto-Caribbean prism was subsequently uplifted diachronously eastward as Caribbean collision progressed (in the Early Miocene north of Trinidad), providing a northward source of largely non-volcanogenic clastic sediments to the Central Range by Early Miocene (i.e., "Northern" Nariva, Cunapo and Brasso fms; Farfan et al. 1991; Pindell et al. 2007). Farther offshore, the leading edge of the Caribbean Plate wedged into (underthrust) the west side of the Barbados Ridge prism, but overthrust the South American crustal hanging wall of the Proto-Caribbean subduction zone, such that the Ridge was accreted to the Caribbean Plate/prism and has been pushed farther eastward across the South American oceanic crust during Miocene-Recent Caribbean relative motion. All subsequent shortening east of Barbados Ridge is less than 200 km and the trace of the Proto-Caribbean Trench has been subducted beneath the southern Lesser Antilles arc system, except where it appears to exit from beneath the Caribbean Plate today along the ENE trending gravity low (Tiburón Trough) to the northeast of Barbados. In summary, the newly processed seismic dataset over Barbados further clarifies the tectonics of the SE Caribbean and hence the Pacific origin of the Caribbean Plate.

Nisha Chaderton's (2009) thesis model. Chaderton (2009) considered a viewpoint in which the Scotlands turbidite packages form a lens of strata within an enveloping and longer lived "background sedimentation" of Oceanic pelagic sediments, which were both older and younger than the Scotlands. Thus, the Scotlands-Oceanic Series boundary is not a low angle thrust plane, but a depositional contact (although potentially sheared during later deformation). Although chronostratigraphic control does not yet resolve this, we cannot rule it out. As mentioned earlier, the age overlap between Scotlands and Oceanics COULD be as little one biozone. We note, however, that if Baldwin's ages are correct and the Scotlands continue into the Oligo-Miocene, then the relationship as envisioned by Chaderton becomes very difficult.

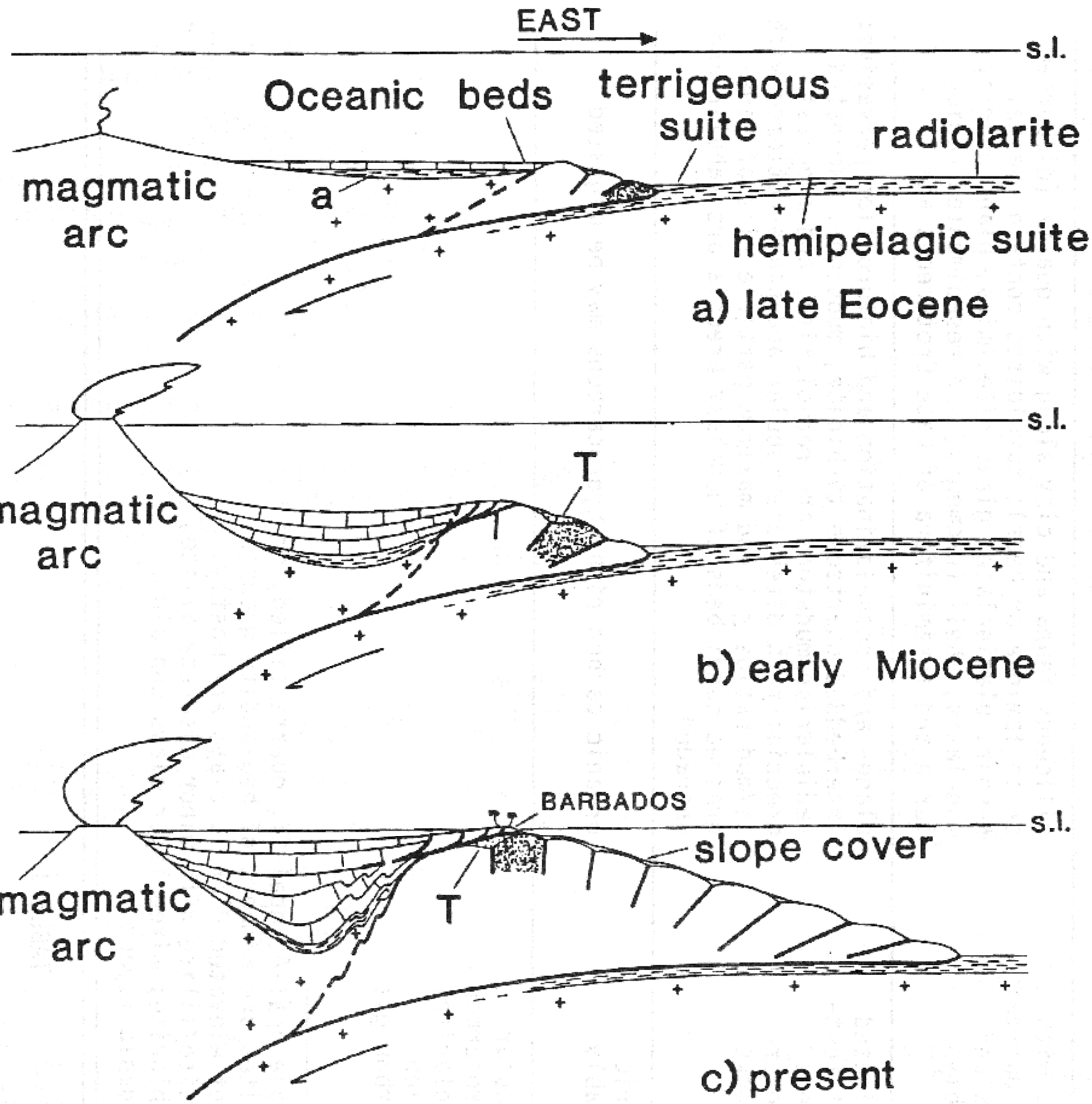
Nisha Chaderton's thesis contains an excellent analysis of the Scotlands sediments, some of which we wish to include here, with permission. First, **Figure 7** shows QFL point counts as determined by Kasper and Larue (1986), Punch (2004), and Chaderton (2009). Note the three sample sets varied by location, but if taken together as a single "composite-set", the results would indicate that the Scotlands comprise quartz arenites, sub-arkosic arenites and sub-lithic arenites; the sandstones are mineralogically very mature. Second, Chaderton showed examples of the seismic character of the three main formations beneath the limestone cap of Barbados (**Figure 8**). Third, **Figure 9** shows a mini-regional cross section of the entire Barbados Accretionary Prism, whereas **Figure 10** shows a close up of the Inner Deformation Front between the Barbados Prism and the Tobago Forearc Basin. Fourth, **Figure 11** shows the Speed concept of a thrusted relationship between the Oceanics on the Scotlands, which was based on the firm belief that the upper range of Scotlands ages was younger than the older range of Oceanic ages; this is now questioned by Chaderton. Finally, the Chaderton (2009) evolutionary model for the Tobago Basin/Barbados Ridge is shown in **Figure 12**. In short, a large, thick turbiditic sand body within an oceanic-type background depositional system is accreted with backhrusting into the Caribbean accretionary prism as convergence continues, and is subsequently carried eastward with the rest of the prism.

The above models will be the focus of some of our discussion on the field trip, and also as we look at ION seismic data in the last afternoon's session.



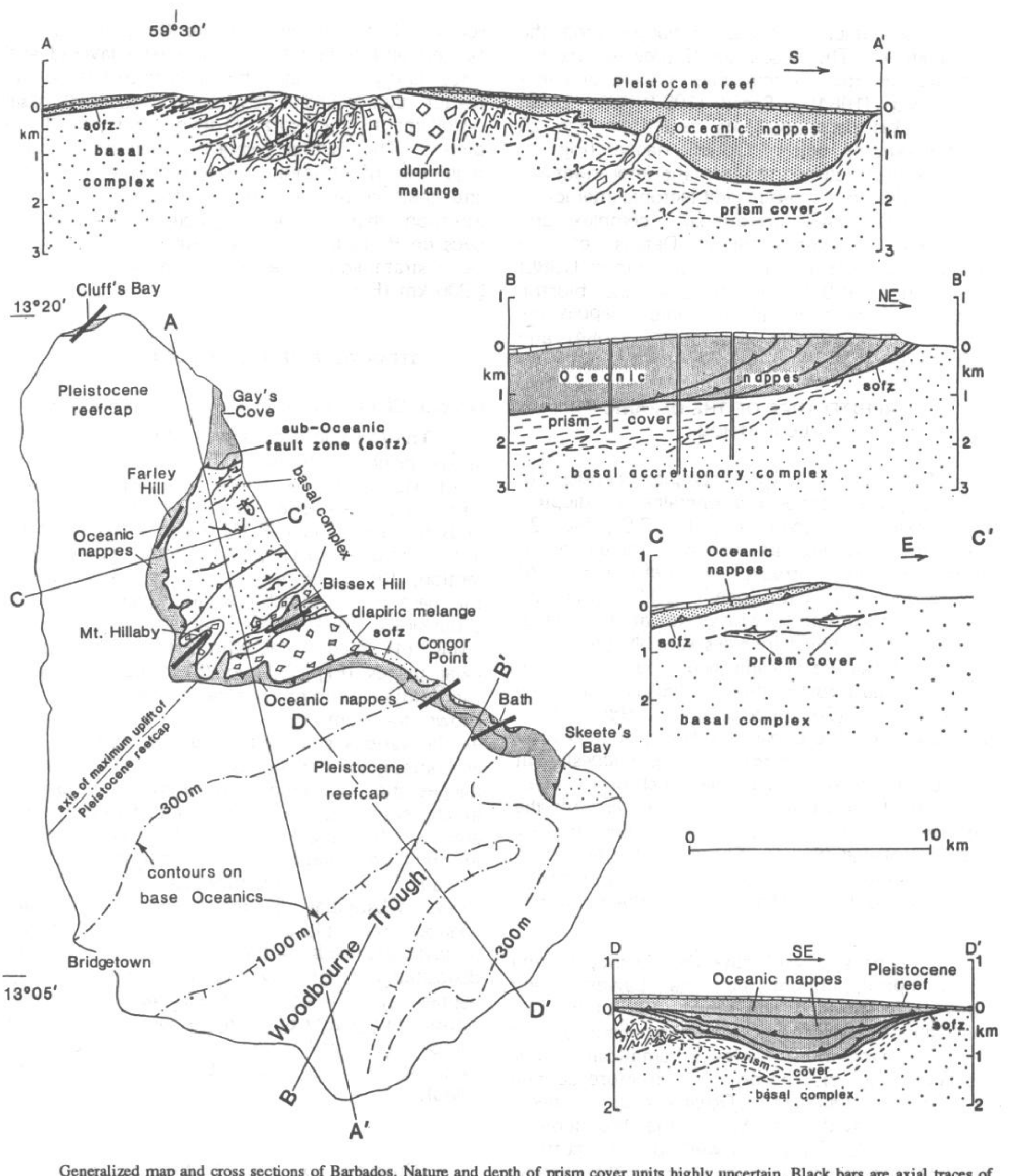
Stacking diagram for some major and minor tectonic- stratagraphic units. A: shows total stacking. B: shows detail among minor units of prism cover (pc), Oceanic allochthon (Oa), and basal complex (bc). Heavy lines are faults; wiggly lines are unconformities; dash–x are intrusive contacts.

Figure 1, after Speed (2002).



Figu: grammatic sections showing proposed depositional sites and tectonic evolution of pre-Pleistocene lithic suites of Barbados; no scale implied; s.l., sea level. a, Conceptual remnant of pre-subduction abyssal pelagite. Shaded area represents accretionary packets of the basal complex of Barbados. The hemipelagic suite may have accumulated on the proximal abyssal plain or at a trench site isolated from coarse-grained terrigenous sediment influx. T, Intermediate and T units, Oligocene(?)-Miocene slope cover. The sections do not account for the obliquity of structural trends in the basal complex with respect to the present convergence direction.

Figure 2, after Speed (1987).



Generalized map and cross sections of Barbados. Nature and depth of prism cover units highly uncertain. Black bars are axial traces of folded Oceanic nappes at different localities; axial trace of Bissex Hill nappe from Larue and speed (1984).

Figure 3a, after Torrini 1987.

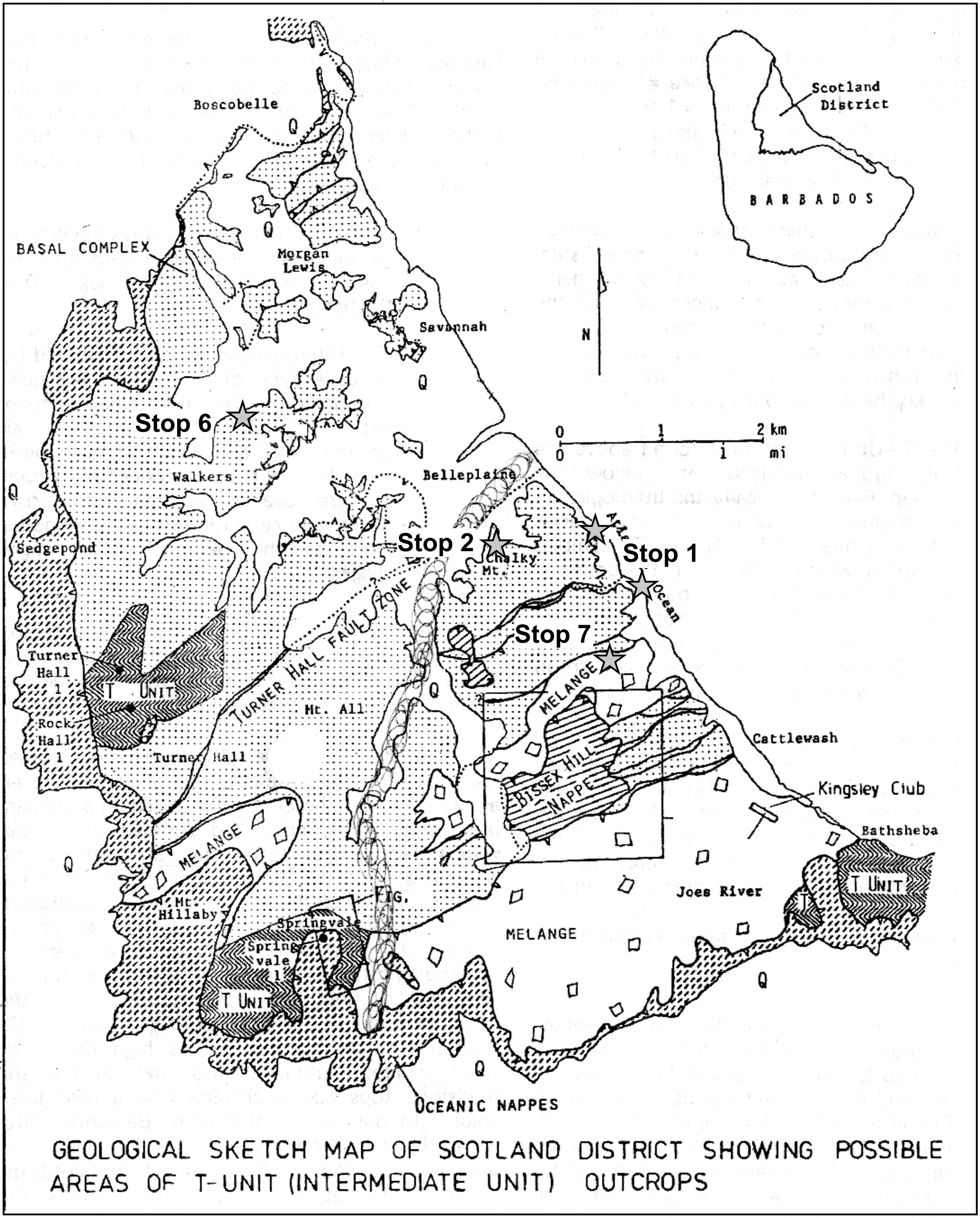


Figure 3b,NORTHERN FIELD STOPS, and general map of Scotlands, after Barker et al., 1987.

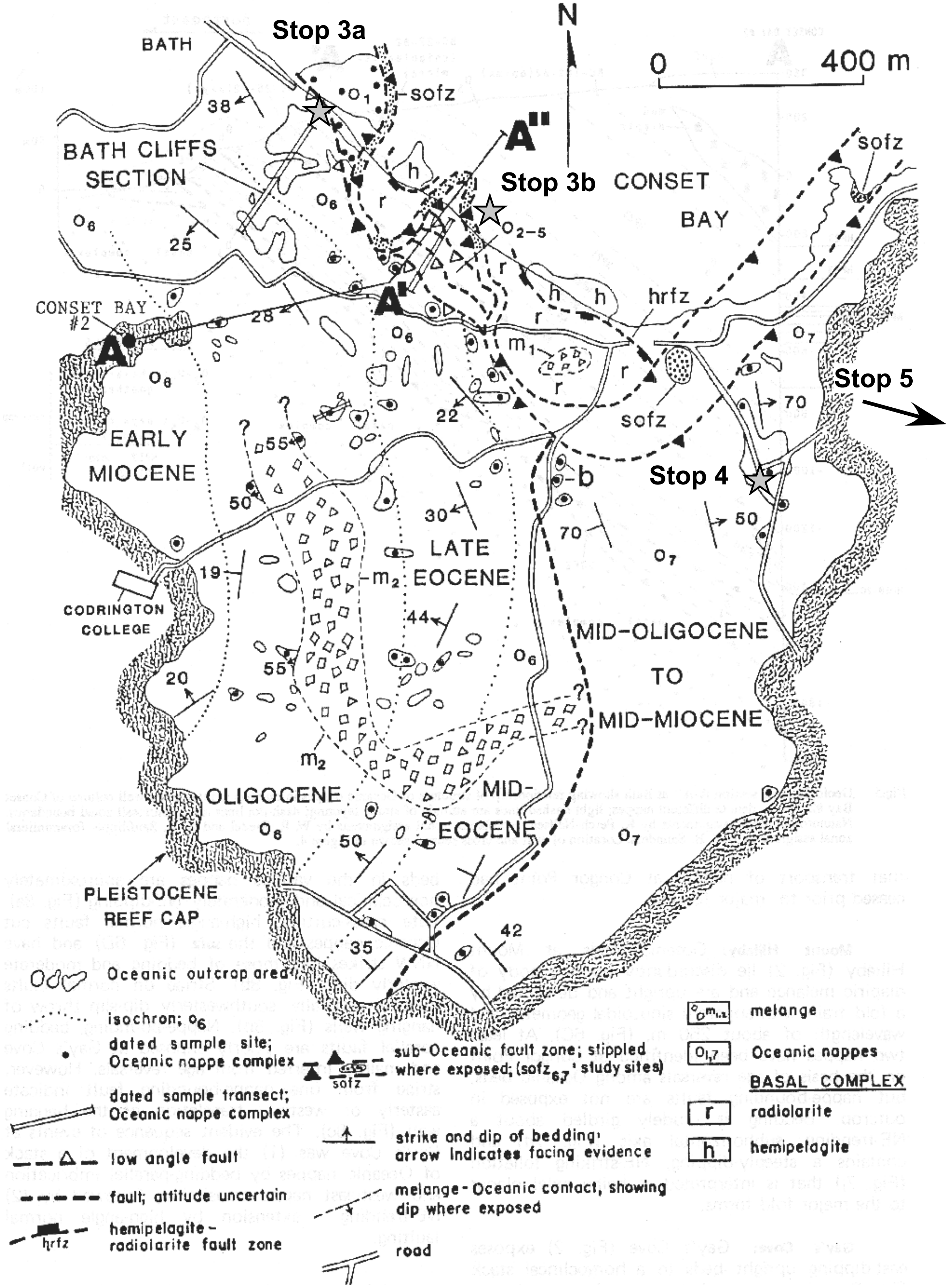


Figure 3c. SOUTHERN FIELD STOPS, and structure of the Bath Cliffs area, after Torrini, 1987.

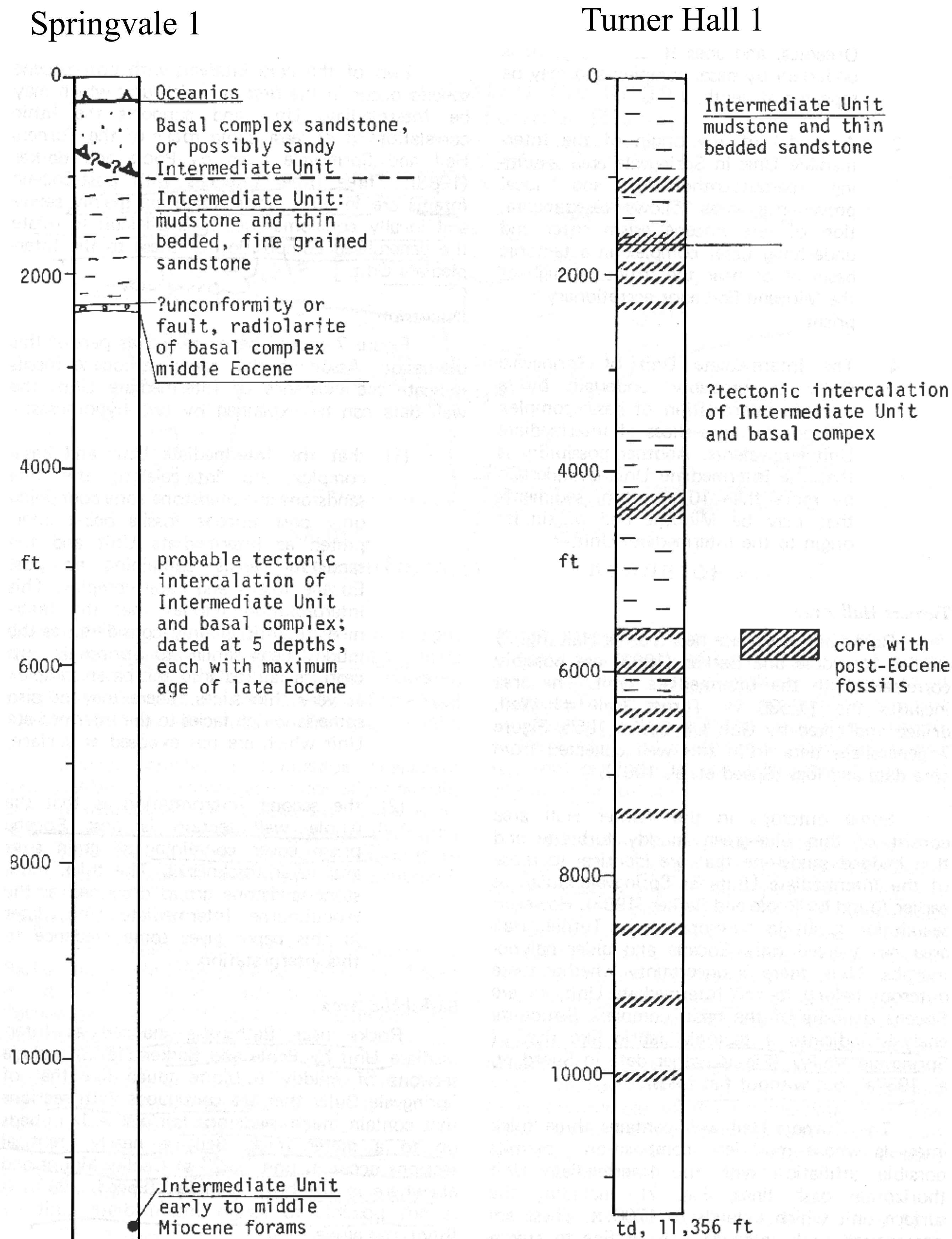
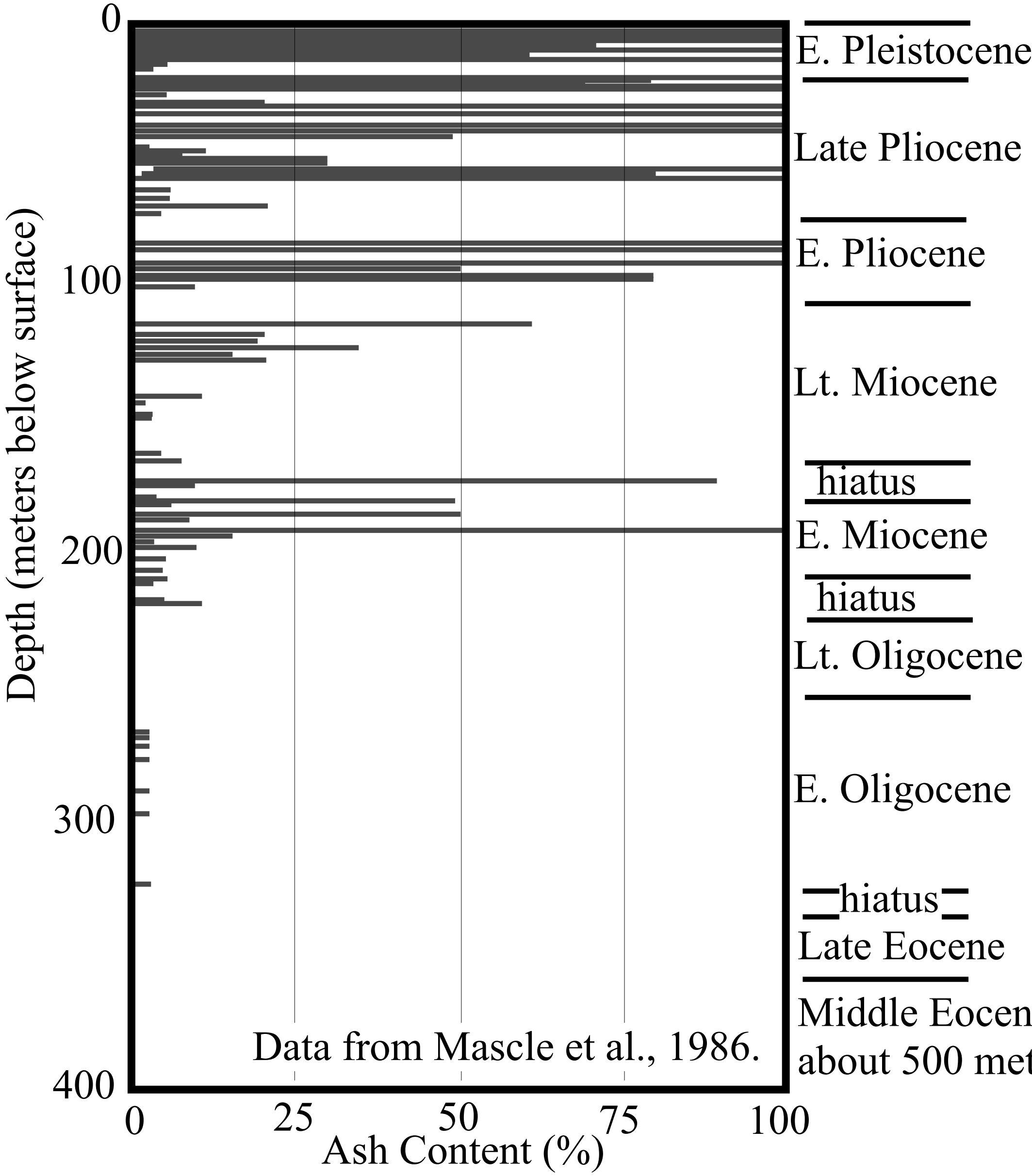


Figure 4, after Barker et al., 1987.



ODP Site 672A, Tiburon Rise, east of prism deformation front adjacent to northern Lesser Antilles.

Option 1: Lesser Antilles Arc began activity in Early Miocene and volcanism progressively increased.

Option 2: Lesser Antilles Arc was active prior to Early Miocene and the Arc and Tiburon converged progressively.

Observation: A complete Eocene to Recent volcanic record is present in the northern Lesser Antilles.

Correct answer: Option 2.

Corollary: Absence of Cretaceous tuff in Proto-Caribbean passive margins requires allochthoneity of Caribbean Arcs.

Figure 5, ODP site 537, Tiburón Rise.

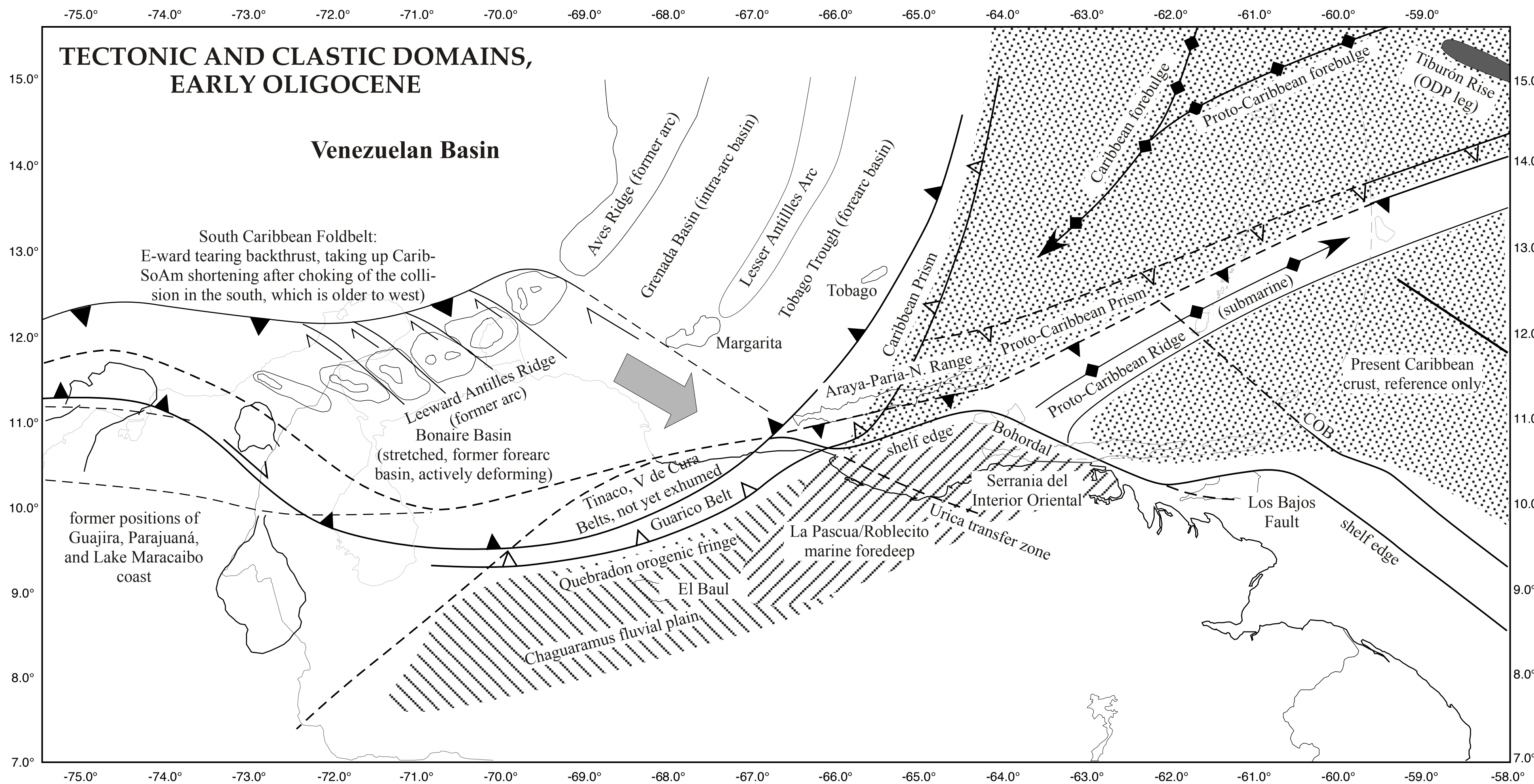


Figure 6a. Mid-Teritary tectonic elements of the Tertiary Caribbean-Proto-Caribbean trench-trench collision, compiled from features identified and defined in Pindell et al., (1998; 2006). South American passive margin geometry is palinspastically restored. Speckle pattern, deep sea turbidite domains. Right slant pattern, marine shelf. Left slant pattern, non-marine fluvial plains. The Proto-Caribbean and Alaskan subduction zones are analogues, although directions (N and S) are reversed. From Guajira to the Serrania Oriental, the trench hanging wall was continental, as is the southern Alaskan segment, and from Trinidad eastwards the trench was intra-oceanic, like the Aleutian segment. It is not clear whether a narrow oceanic or a thinned continental forearc existed north of the Serrania, and thus whether the Urica or the Bohordal faults, which flank the Serrania Oriental, marked the exact transition from a continental to oceanic hanging wall.

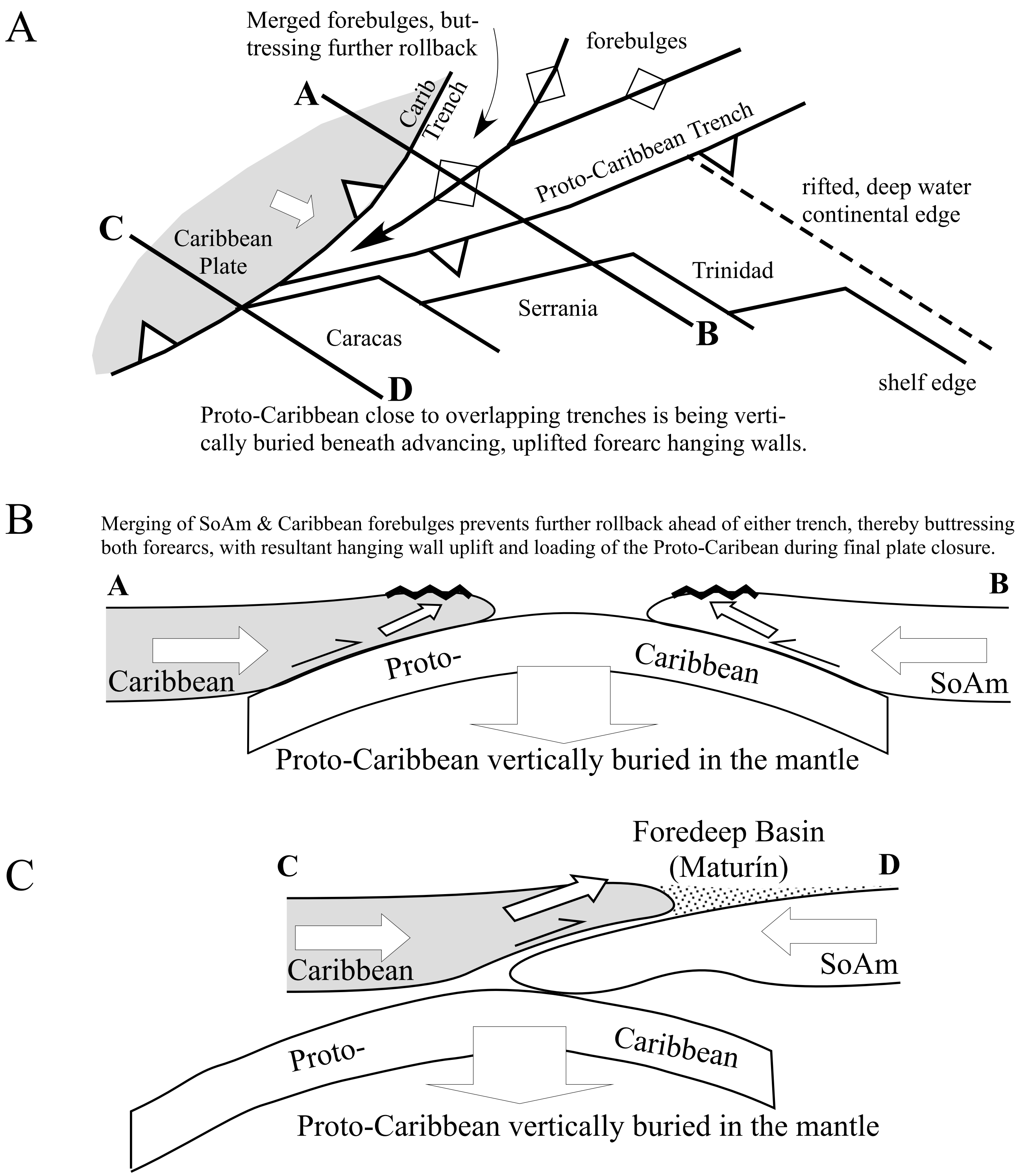


Figure 6b, after Pindell et al., 2006; 2009.

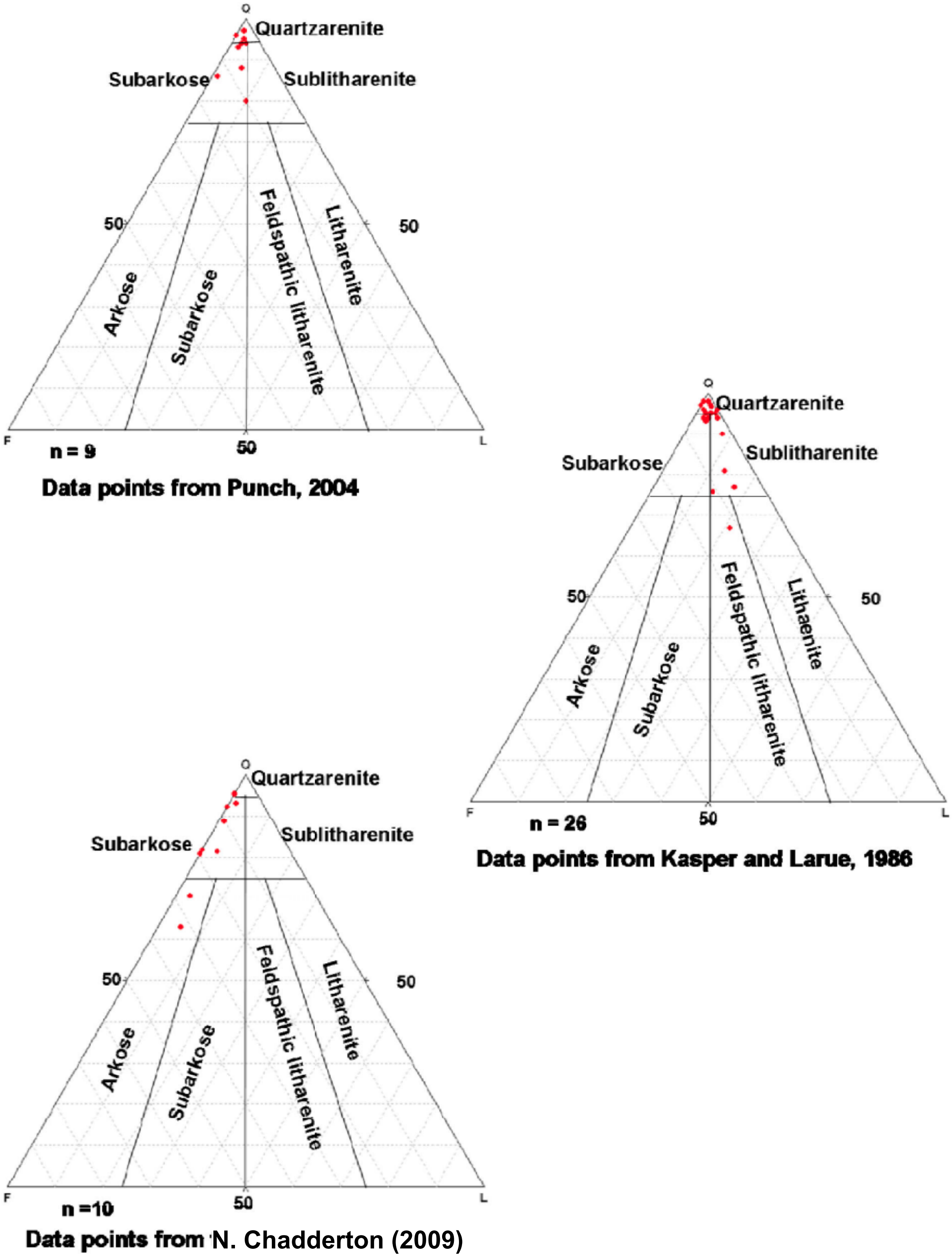


Figure 7. Composition of Scotland Fm samples by author, all from Chadderton 2009).

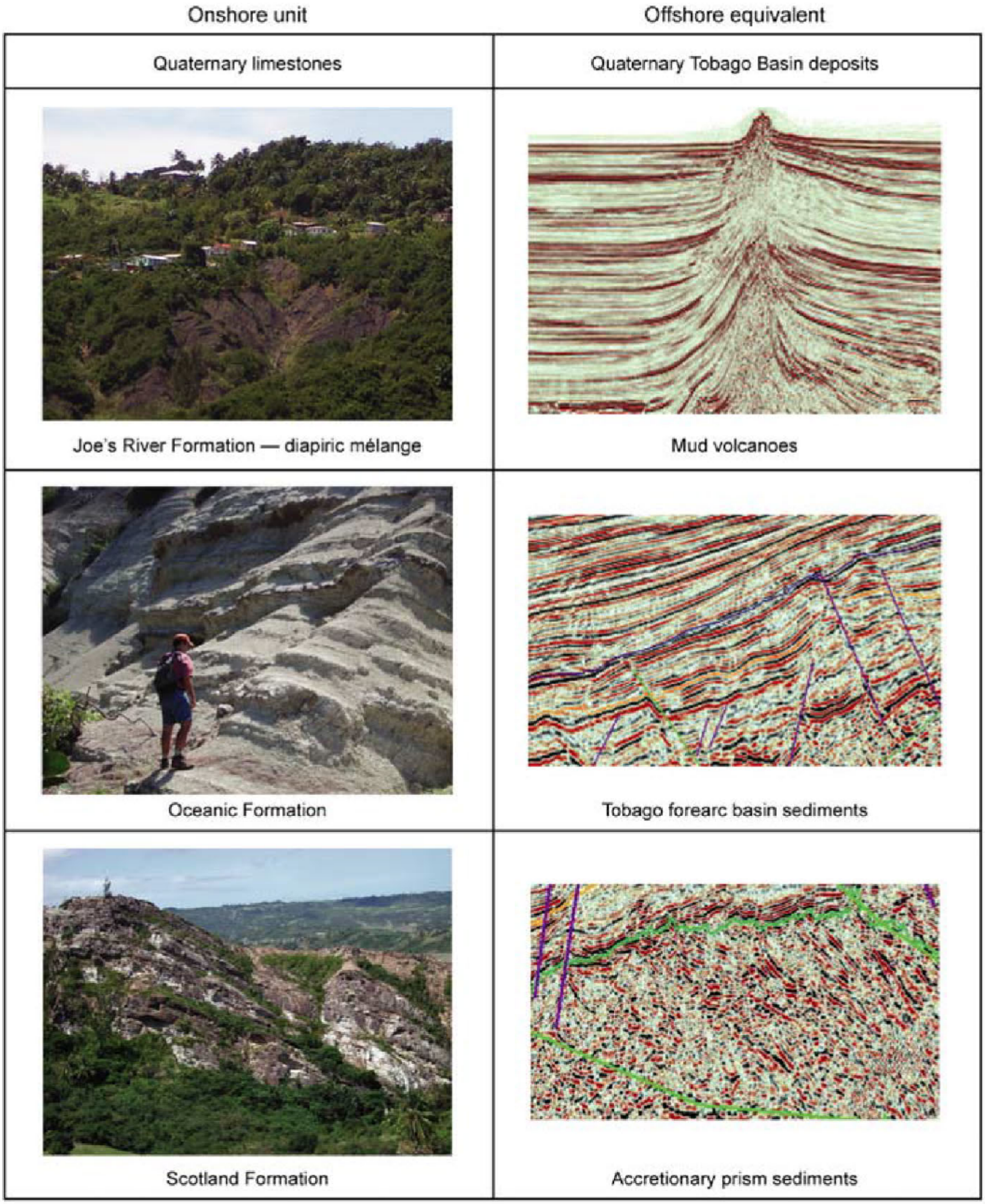


Figure 8. Main Bajan sedimentary units in outcrop and their offshore seismic expressions, after Chadderton (2009).

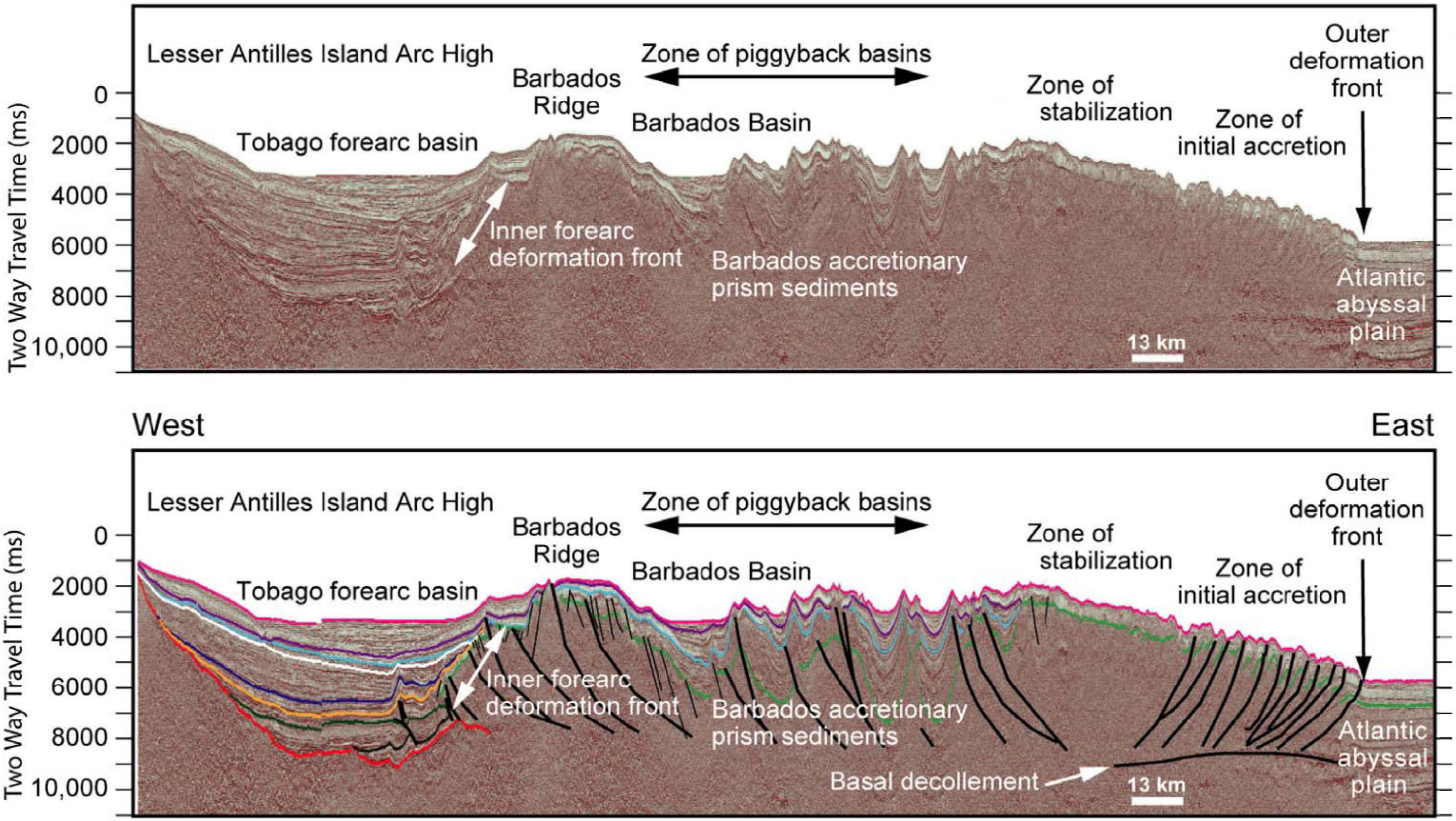


Figure 9

East-west seismic reflection profile showing the structural provinces within the Greater Barbados Accretionary Prism. The Lesser Antilles Island Arc High bounds the western margin of the Tobago Forearc Basin (TFB) that has up to 12 km of sediment fill in its deepest part. The Inner Forearc Deformation Front marks the boundary between the highly deformed Barbados Accretionary Prism sediments and the less deformed TFB sediments. The Barbados Ridge is the highest part of the accretionary prism and is characterized by extensive crestal normal faulting. The Barbados Basin is the largest of several piggyback basins that have formed on the eastern slopes of west-facing thrusts. The Zone of Stabilization is a region of less intensely deformed sediment that is a transition zone between the Zone of Initial Accretion and the Zone of Piggyback Basins. The Zone of Initial Accretion is made up of an imbricate fan of east-facing thrust faults (shown as dark blue lines) and marks the youngest phase of deformation in the prism, thus it is the zone where previously undeformed sediments of the Atlantic Abyssal Plain are offscraped and accreted to the prism. The Outer deformation Front marks the boundary between the imbricate fan and the undeformed sediments of the Atlantic Abyssal Plain. (after Chadderton, 2009, with permission)

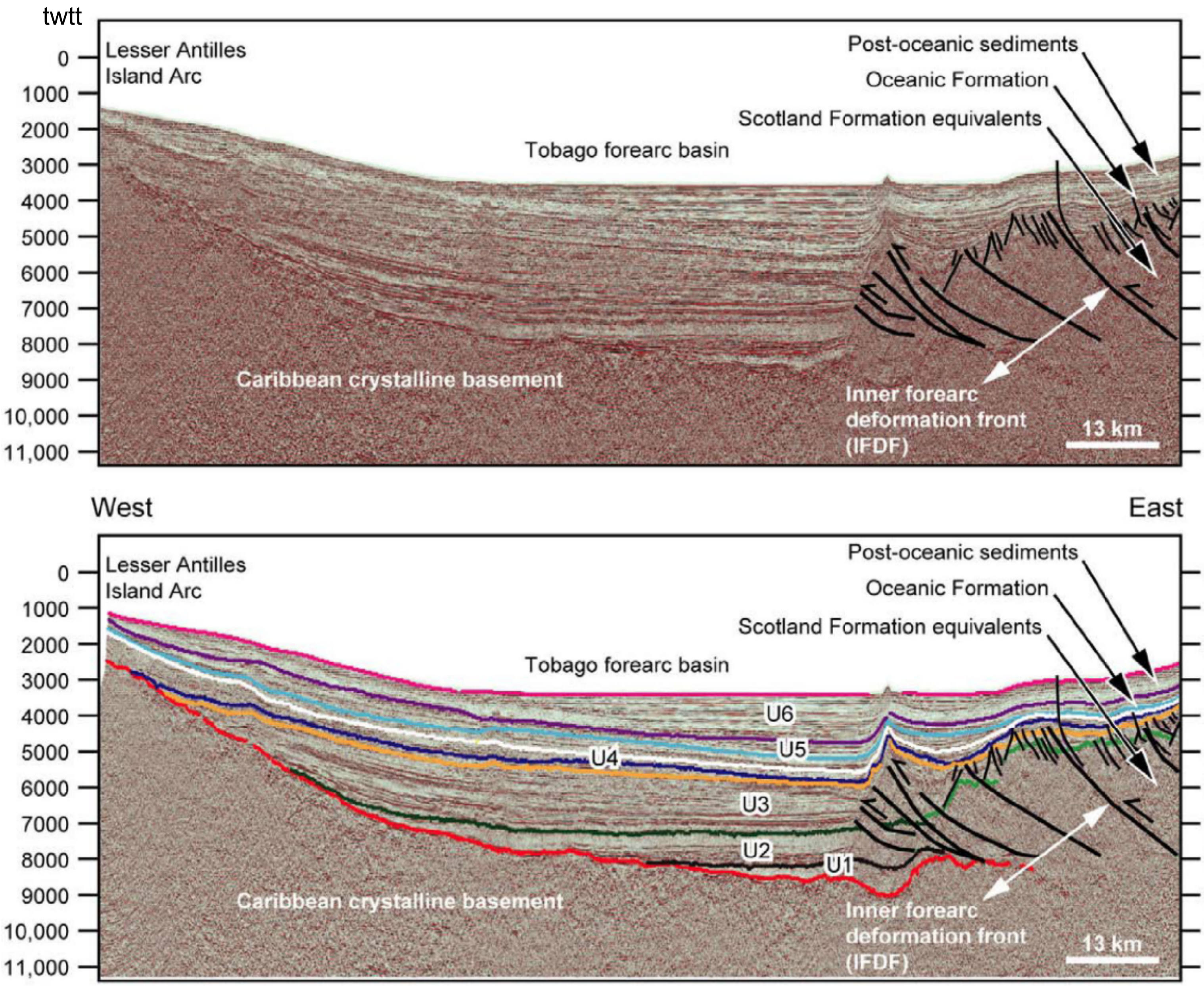


Figure 10. East-west reflection seismic profile, shown as line 3 in Figure 4.1, showing 9 horizons mapped across the study area. The Tobago Basin fill is bounded by the crystalline Caribbean Basement and the sea floor. Surfaces shown in the figure are as follows: Bright red- top of the crystalline Caribbean basement; Black- top of Unit One/ Pre-Eocene (no definitive age data exists on this surface but it is thought to be Cretaceous) Dark green, top of Unit Two/ Lower Eocene-Lower Oligocene; Gold - top of Unit Three/ Lower Oligocene to Lower Miocene; Dark blue, top of sub-unit A; White-top of sub-unit B. Light blue- top of sub-unit C/Unit Four/ Lower-Middle Miocene; Purple-top of Unit Five/ Upper Miocene unit; Pink top of Unit Six/seafloor/ Pliocene-Pleistocene ; Bright Green- top of sediments. Oversized Plate (11x17) requires plotter or printer with tabloid printing. (after Chadderton 2009).

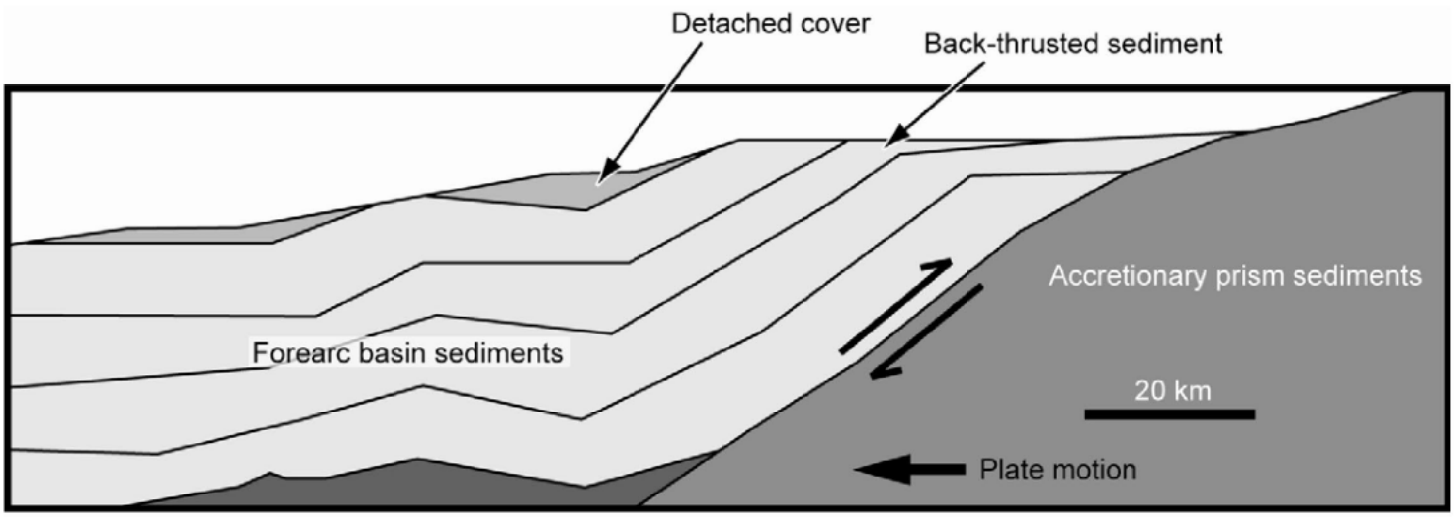


Figure 11. Depiction of the Speed model for tectonic emplacement of the Oceanic Series (Tobago forearc basin sediments) onto the Scotland accretionary prism sediments, from Chadderton (2009).

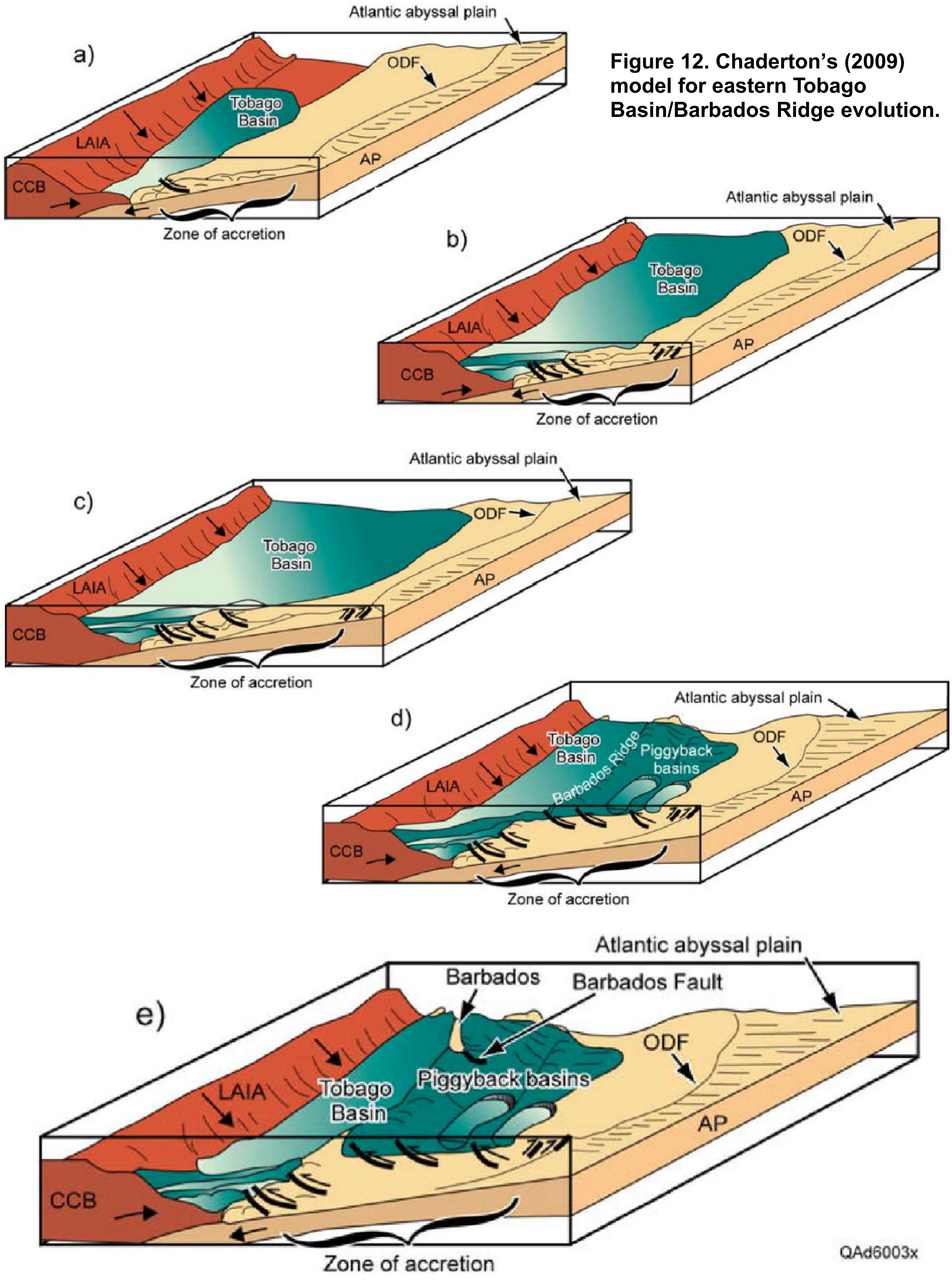


Figure 12. Chaderton's (2009) model for eastern Tobago Basin/Barbados Ridge evolution.

FIELD ITINERARY: FRIDAY DAY 1 STOPS:

STOP 1.

Be wary of cars and trucks.

10:15. Introduction to the Scotlands beds, or Scotland Formation. Barclay's Park road cuts and view of Chalky Mount Ridge.

After a brief overview and introduction, we will look at several outcrops along the road and beach which comprise massif, thick turbiditic sandstone beds, conglomerate beds, and mudstone. In addition, we will get a good view of Chalky Mount Ridge, where we can see bedding character and the typical structure of the Scotlands. **Figure 13** shows the section in the ridge view.

Concerning the conglomerate beds, several 1-2 m thick conglomerate beds are exposed in the road cut and on the beach in the surf about 1 km north of Barclay's Park). These occur within the Chalky Mount succession and they carry well-rounded (i.e., of fluvial or coastal origin) clasts of mudstone, fine sandstone, reddish to brown iron-rich siltstone, and at least one apparently foliated cobble that may be from a deeply buried source, requiring significant erosion or unroofing prior to transportation. The clasts reach 20 cm in diameter. The clasts themselves do NOT carry glauconite. Because glauconite is ubiquitous in the Serranía Oriental for the latest Maastrichtian through Oligocene (ie, Vidoño, Caratas, Areo fms), we believe that the conglomerates more likely derive from central Venezuela (west of Urica Fault). These conglomerate beds are probably channel fill (Bouma facies A). By comparing the thicknesses of the conglomeratic sections on the road and in the surf, it is apparent that the conglomerates thin by at least 50% within 100 m, supporting the channel interpretation.

Collectively, the main points to gather from this stop are:

- structural vergence is primarily to the north, in contrast to the southeastward vergence seen north of the Turner Hall Fault.
- fold axes average about 80°, giving a bulk contractile trend of NNW-SSE.
- many bed sets are broken, and many others appear to be slumped, both suggesting high water content, and possibly non-lithification during deformation.
- dewatering of the sandstone beds is a common feature of the deformation.
- turbidites of nearly all Bouma facies can be found, but sand beds are often very thick, and grain size is often very coarse. This section has been deposited more rapidly, on average, than were the Walker's, Morgan Lewis, and Murphy's sections.
- conglomerates carry rounded clasts of up to 20 cm diameter, and appear to derive from central Venezuela (section of the correct age is missing there, glaucophane is there, lack of glauconite is there, and paleogeographic models point to there, too. One conglomerate clast has given a possible age of Oligocene.
- the Chalky Mount section is generally coarser and more proximal (inner fan facies) than the Windy Hill sections.

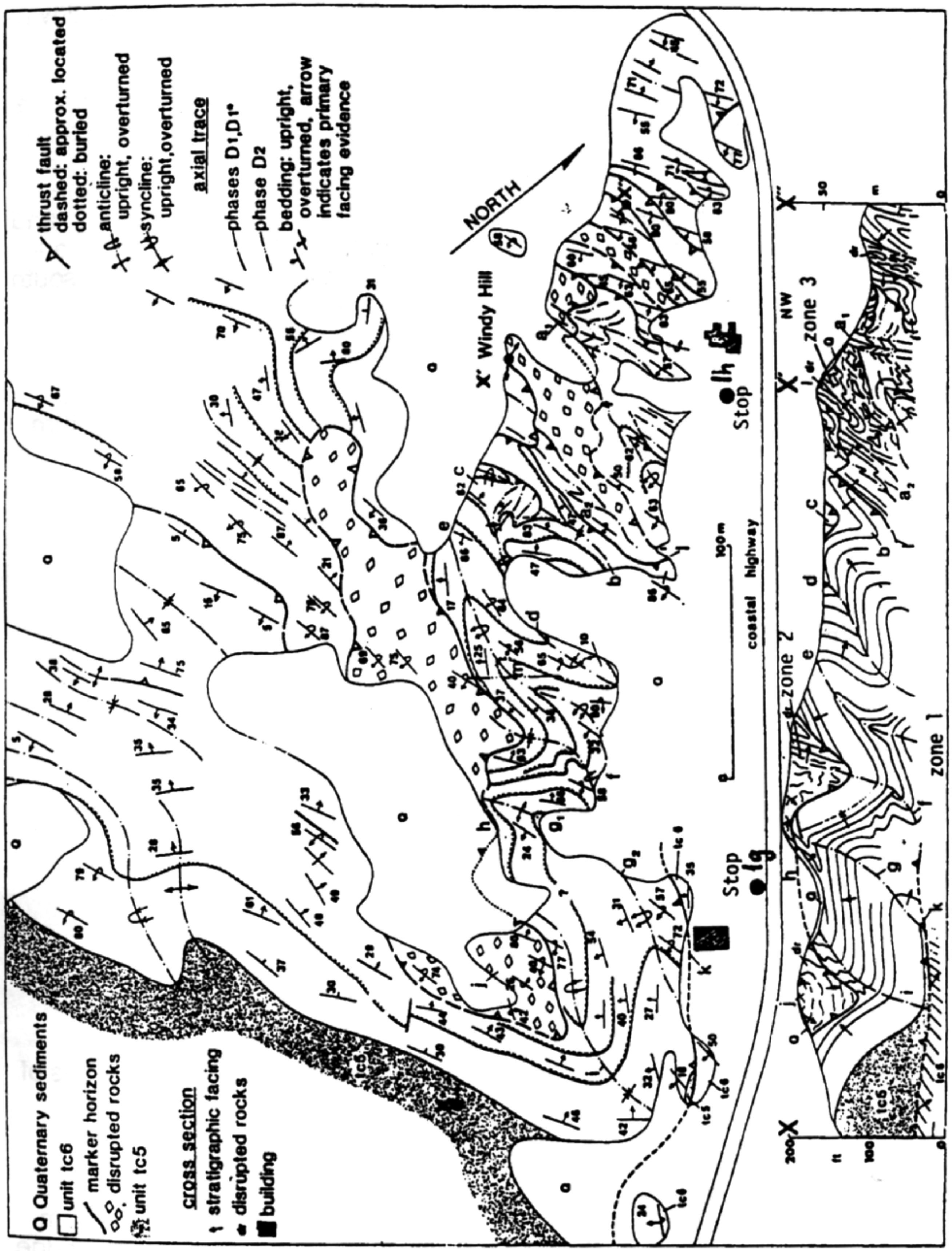


Figure 25: Geologic map and section of Windy Hill, at northern margin of Chalky Mt. area;

Figure 13, after Speed 2002.

• although we will not see it, Speed reports a zone of "broken formation" along the crest of the ridge line, which he infers may relate to the basal tectonic contact of the Oceanic nappes that once passed over this area in a presumably eastward direction.

In addition, things to keep in mind and try to sort out include:

• do you think the rocks were well lithified during deformation?
• do you think the deformation might relate to "toe-folding" at a gravitational slump province as opposed to tectonic accretion at a trench?
• do you see anything in the sandstones or conglomerates that reminds you of a certain position along northern South America from which these clastic may have been derived?

STOP 2.

10:50. **"Regional" overview of Scotland District, and walk the ridgeline in the Scotlands beds north of Chalky Mount Village (vista overview, big folds, sandstones, mudstones, conglomerates).**

The local geology here is shown in **Figure 14**, but we will also wish to begin discussing regional matters at this stop, with reference to **Figures 15 and 16**. Some features that might be seen from here are: the areas of the Walker's beds, the Morgan Lewis beds, the Chalky Mount-Windy Hill beds, the Mount All-Belle Hill beds, some of the Joes River diapiric mélange beds, and the trace of the Oceanic beds between the Scotlands and the Quaternary reef cap that rims the Scotland District. Also: the Medical Officer Fault, the Turner's Hall thrust, the coastal Quaternary sand dune and quarry pits, Mount Hillaby, Bissex Hill, Fruitful Hill, the Chalky Mount Potteries, Conset Bay, and Ragged Point Lighthouse.

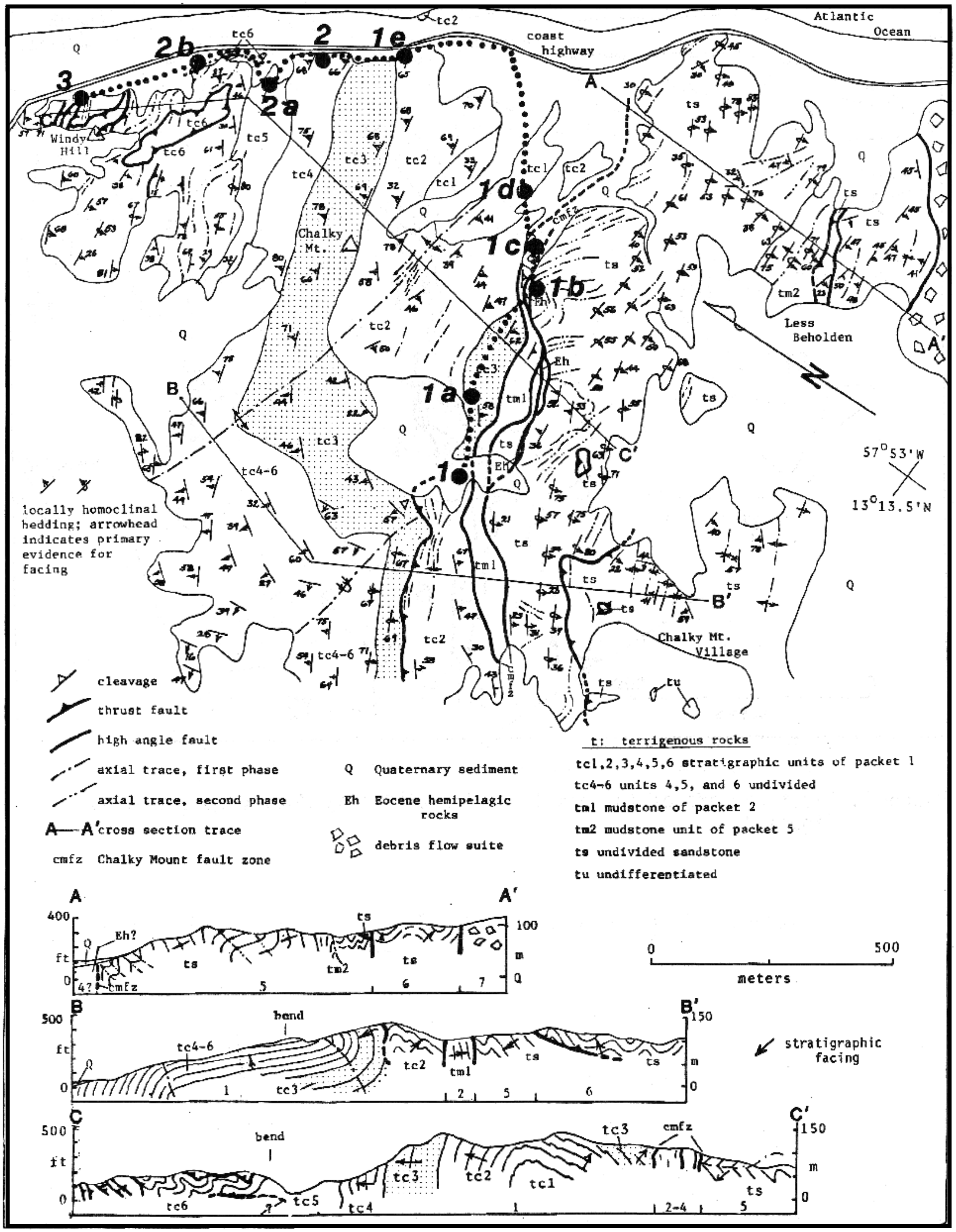
The purpose of the walk along the ridge is to:

(1) see more of the Chalky Mount section for sandstone development,
(2) consider the scale and integrity of folds within the section.

Excellent quality reservoir sandstones are developed here, along with some interbedded shales, as seen in the pathways along the crest of the Mount. The fact that the locals make pottery here suggests a certain level of clay development too, which I suspect is either the product of feldspar break up or a primary Shield derived detrital component of the clastic fairway. Where visible the clay horizons are light in colour, perhaps kaolinite to illite.

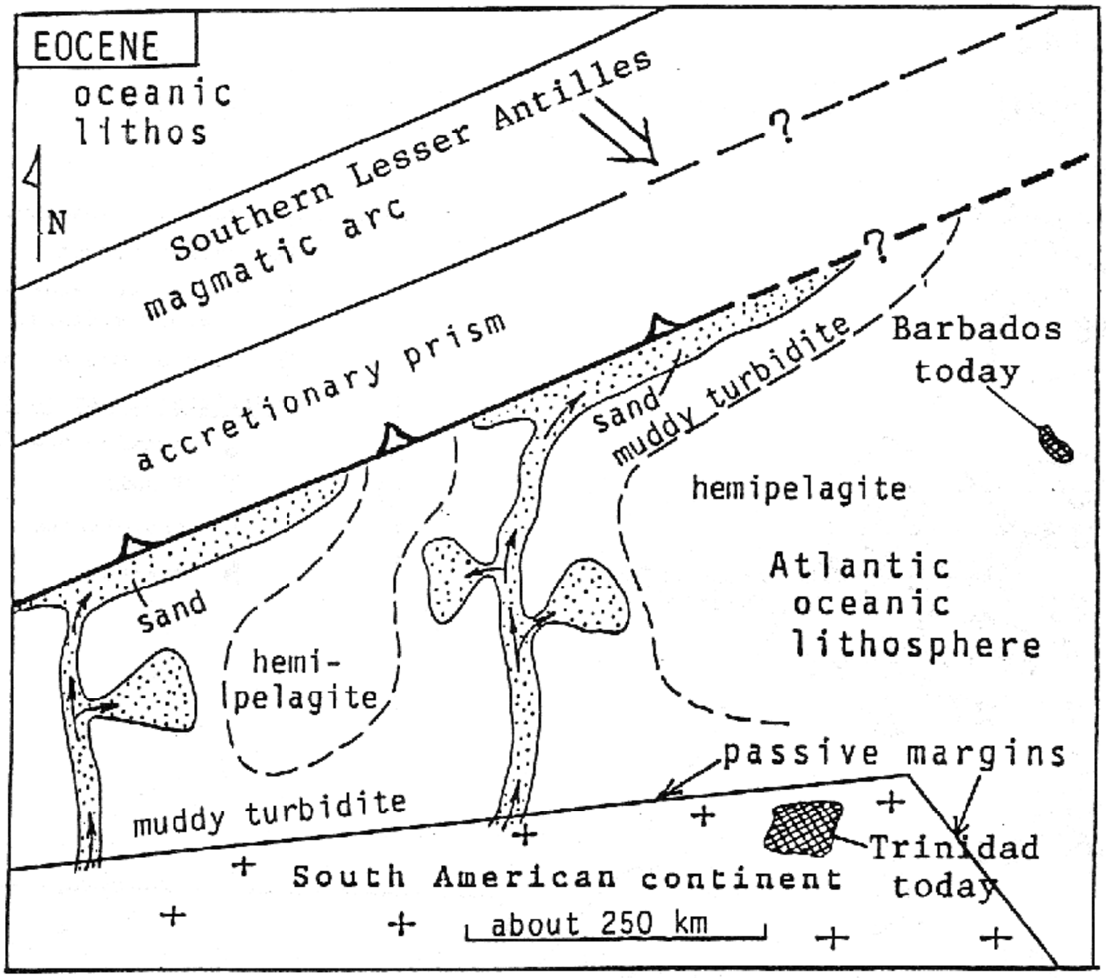
At the gap through to the north, at the end of the road, one can see the scale of the anticlinal fold (core is breached) in the Chalky Mount section. This is the largest fold seen in the Scotlands to our knowledge.

STOP 3.



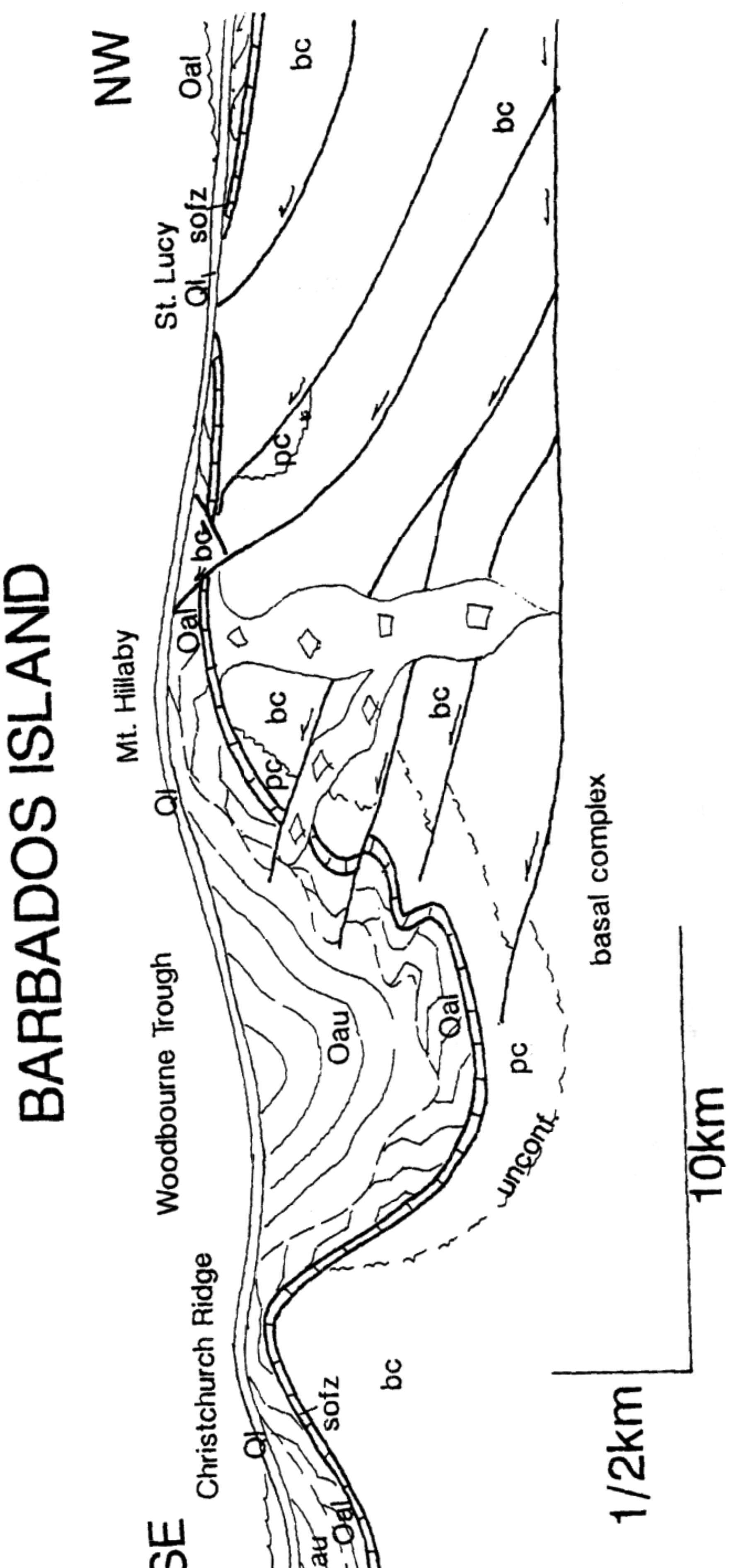
Geological map and section of Chalky Mount.

Figure 14, after Speed 2002.



Paleogeographic model of sites of deposition of strata in the basal complex; based on paleotectonic model of Speed (1985).

Figure 15.



Schematic cross section through Barbados showing major tectonic-stratigraphic units. Oceanic allochthon nappes subunit divided into lower (Oal) and upper (Oau) tiers. SOFZ is sub-Oceanic fault zone. Diapir identified by block pattern.

Figure 16, after Speed 2002.

12:00. **Bath Cliffs Oceanics Unit and Conset Bay Sub-Oceanic Fault Zone** (low tide at 12:54). Lunch when feasible.

Stop 3a. Bath Cliffs, the Oceanics Allochthon, 2:50-3:15. Figures 17, 18 and 19.

The rocks are principally of biogenic origin with some clay and volcanogenic fragments, with interspersed beds of volcanic ash, and range in age from late Middle Eocene to Early Oligocene. The pelagic rocks vary from totally non-calcareous to highly calcareous, with the end members being radiolarian indurated oozes and nannofossil marly chalks. This variation suggests that the section was deposited close to the CCD. Benthonic foraminifera present indicate water depths greater than 2000m.

R.C. Speed and J.B. Saunders extensively sampled the outcrop, including trenching in covered sections, and the results of detailed paleontological work and stable isotope analysis on these samples are given in Saunders et al (1984). Important results included:

i) The replacement of the *Theocyrtis bromia* radiolarian Zone of the Late Eocene with three new zones.
ii) The determination of a linear sedimentation rate of the Late Eocene interval of 27.1m/m.y uncorrected for compaction. This is 18 times faster than the rate at DSDP site 543 and 11 times faster than site 149, suggesting accumulation in an area of greater than usual siliceous biogenic activity (upwelling?).
iii) In the section immediately above the Eocene/Oligocene boundary there is a sharp drop in paleo-bottom water temperature of 5-6° C and 3-4°C for intermediate water; but with no measurable change for surface water.

Because of (1) an overlap in the ages of the Basal Complex and the Oceanics (ie, oldest Oceanics are older than youngest Basal Complex), (2) structural differences in the Basal Complex and the Oceanics, and (3) the interpretation that their mutual boundary, where seen, is a fault, and that the lower parts of the Oceanics are imbricated internally, Speed and colleagues proposed that the Oceanics form an internally deformed nappe package that was thrust onto already-deformed Basal Complex. Speed maintained this throughout his work, even though the provable age overlap was small (one or two biozones). Because we suspect that the age of much of the Basal Complex is Oligocene, the degree of overlap in the ages increases dramatically, and the structural juxtaposition, rather than deposition on an unconformity, is, in agreement with Speed, a required part of our viewpoint.

One concern with the Speed “single prism” model is that to date, no primary volcanic ash material has been found within the Basal Complex. Here in the Oceanics we can see 5 to 30 cm thick ash beds every meter or so. If the timing of accretion in the Basal Complex was Late Eocene, as Speed claimed, then accretion matched the time of ash deposition in the Oceanics, and much of the Basal Complex strata would have been exposed to ash fall prior to accretion. However, no one has ever found any ash layers in the Basal Complex. We suspect that the geographic separation between the Oceanics and the Scotlands was larger in the Eocene-Oligocene than envisioned by Speed. The Oceanics were obviously near to the arc (normal forearc width?), but the Scotlands may have not have been.

Stop 3b. 12:30. **Conset Bay coastal section, the Sub-Oceanic Fault Zone, Figures 17, 18 and 19.**

We now will walk south along the coast (best at low tide) to see the contact between the Oceanics (above) and rocks that Torrini et al. (1985) considered were Basal Complex (below). This is the sub-Oceanic Fault Zone (SOFZ). The SOFZ is sub-horizontal over large areas, but here the fault zone itself is folded to form a SE-vergent antiform.

CAUTION: Note and avoid the old rusted VERTICAL SPIKES of the railway ironwork.

As we head south, the Oceanic beds dip north and then turn up steeply (still dipping north) at the contact with the underlying "radstone" of the Basal Complex. This is the beginning of the anticlinal fold in the fault's surface. Here we can assess the nature of the fault, and consider the unusual facies in the Basal Complex (no sand here).

A little farther south, we come to some highly deformed hemipelagics in the surf, as well as to some material that looks to us like Joes River mélange at the foot of the highly erosional cliff along the beach. Although Torrini did not map this section as mélange, it may be that mélange has become exposed in the 30+ years since Torrini's work was done. Torrini did map mélange within a few hundred meters inland of here, so the local occurrence should not be surprising. Now we are on the south limb, which is nearly vertical, of the anticlinal fold in the fault zone. I suspect that this vertical limb of the fold has been transposed to the point of faulting), allowing extrusion of mélange into the fault zone.

Nearby, where the little cliff juts out toward the ocean, the Oceanics are vertical. As we continue, the Oceanics will begin to dip south (southward facing) and eventually they will flatten out as we cross the core of the synform. Beyond the synclinal nose, they dip to the north again. Several tens of metres on we return to the SOFZ and can see better more of the fault textures and fabrics that have formed along this tectonic boundary. Speed (2002) says that any carbonate within the zone is inorganic, formed by deposition from fluids.

As at the Bath Cliffs, the Oceanics are riddled with ash layers in this section. This is also true of the Oceans in the northern Scotland area, at Gay's Cove. It seems to be a ubiquitous feature of the Oceanics.

In nearly all locations where the SOFZ can be seen, the underlying rocks are saturated with oil. This is a function of the excellent sealing character of the Oceanic pelagic beds.

As we now return to the north, we can take in one more feature of the section. This is the hemi-pelagics near the vertical limb of the folded thrust. Torrini et al. (1985) claimed that this as a fault within the Basal Complex, separating hemi-pelagic and radiolarite. According to Torrini et al., this hemipelagite-radiolarite fault zone (HRFZ) is also fold anticlinally in this position. As far as we can tell, laboratory analysis is required to ascertain the difference in these two units. Because this boundary seems to be of little significance, we shall not consider it further.

To summarise the deformation history according to Torrini et al. (1985), then, the rocks of the Basal Complex were deformed and the style of faulting, imported from elsewhere, is presumed to be of a high angle brittle nature. As for the Oceanics, some or much of their internal imbrication is believed by Torrini et al. (1985) to pre-date the tectonic juxtaposition with the Basal Complex. Both deformations could range in age from Late Eocene or Oligocene to Early Miocene. Also, both sections likely had cover assemblages deposited on them during that interval (not seen here).

In the late Early Miocene or the early Middle Miocene, the already-deformed sections were juxtaposed by low angle nappe emplacement of the Oceanics onto the Basal Complex. Thrust direction of the Oceanics was assessed by Speed to be eastward, some 50 to 80 degrees different to the average contractile direction of the Basal Complex folding. This difference in contraction direction was never well explained by Speed. Tomorrow we will see the Middle Miocene overlap assemblage (Conset Marl) that covers BOTH the Basal and Oceanic complexes in this area, and which presumably dates the tectonic juxtaposition of the two.

This section presents some interesting questions to the authors. The main one is, "why is there no sand in the Basal Complex here?" The radstones and hemipelagics were considered as Basal Complex because similar rocks occur at fault zones between packets in the Chalky Mount and Bissex Hill areas. However, as far as we can judge, such rocks were rarely seen by Speed and colleagues as actual components of the stratal successions themselves. Thus we are suspicious that such rocks have found their way into the packet fault zones, possibly from below, and are not actually part of the sandy Basal Complex as presented at Chalky Mount and the other coarse units (eg., Mount All, Belle Hill). Bedded hemipelagics definitely were seen as part of the Walker's section at the large excavation stop. Is it possible that those hemipelagics correlate to the ones along Conset Bay below the SOFZ, and that both pre-date the coarse sands of Chalky Mount, Bissex Hill, Mount All, and Belle Hill?

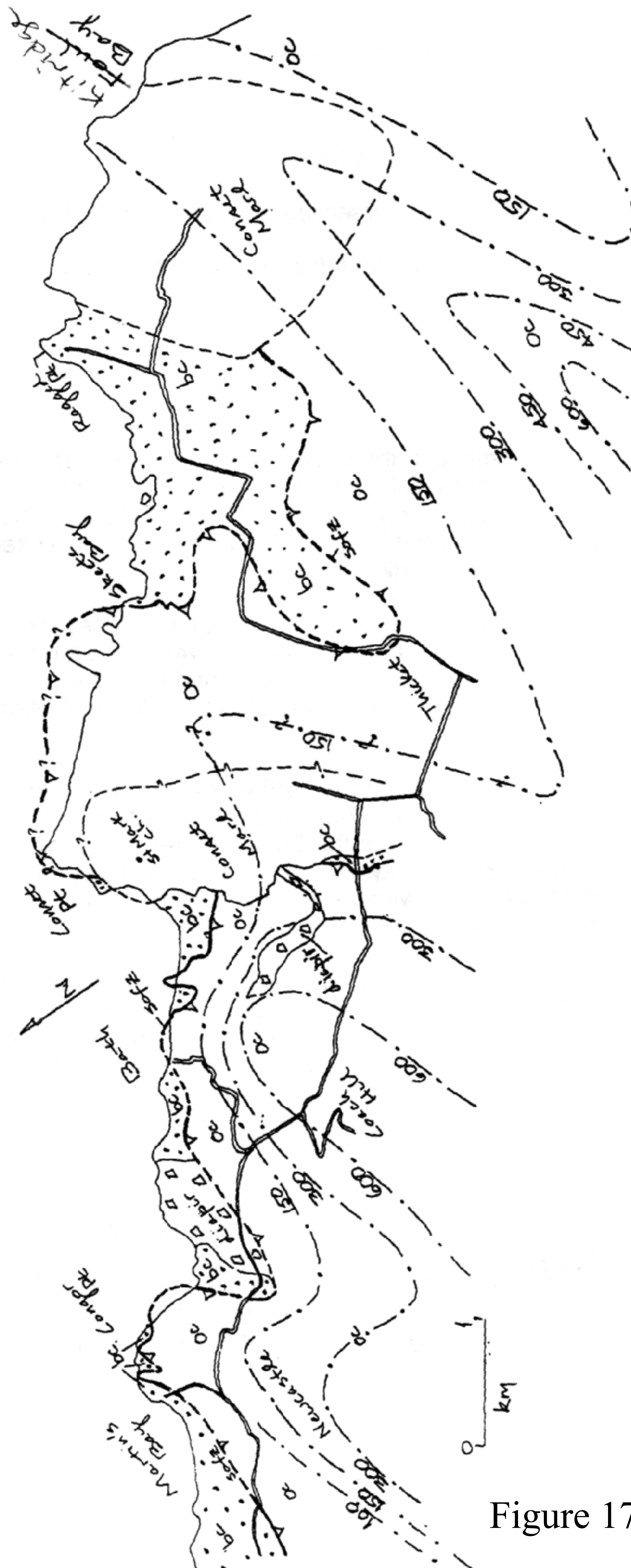
STOP 4.

2:15. **Conset Marl (Middle Miocene) cover sequence at St Mark's Church, Conset. Discuss implications. Figures 1 and 2.**

This 15m section is an easily accessed outcrop of the Conset Marl. Senn (1948) considered the unit to be 900 m thick. Beckmann (1956) gives an age range, including the subsurface sections, from the *Globigerinatella insueta* (N7) Zone, Early Miocene to *Globorotalia fohsi* s.l. (N9 – N12) Zone, Middle Miocene. Saunders (1979) notes that, to date, all his surface samples, including those from this stop, are *Globorotalia fohsi peripheroronda* (N9) Zone age.

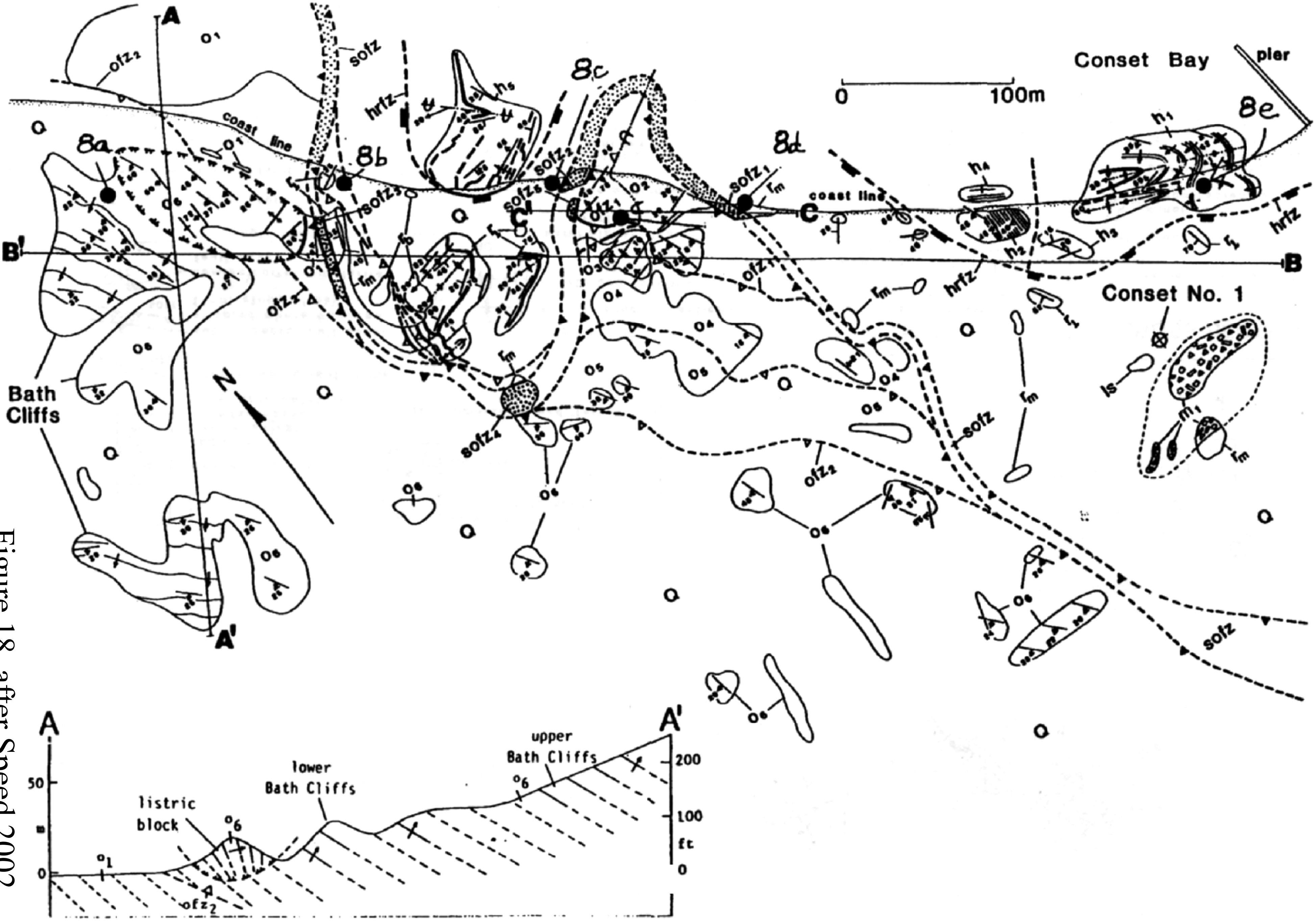
An analysis of the benthonic foraminiferal component by Steineck and Murtha (1985) gives a depth of deposition of 1000m – 1500m.

Sanfilippo and Riedel (1974) found well-preserved radiolaria that placed the section in the *Dorcadospyris alata* Zone of the Middle Miocene.



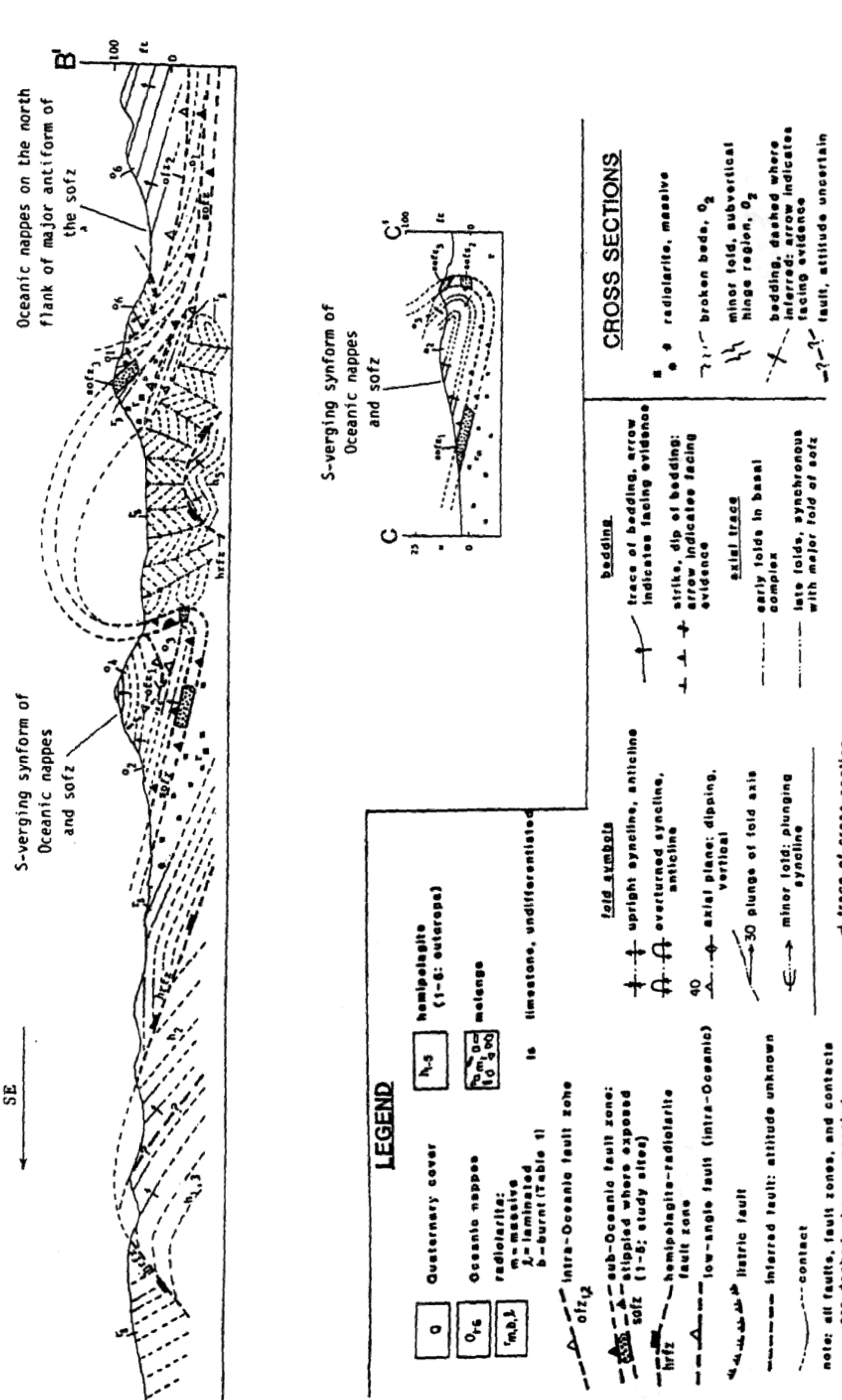
Regional map between Martin's Bay and Foul Bay of sub-Quaternary outcrop and subcrop. Nearly continuous fault trace is SOFZ — Sub-Oceanic Fault Zone, between Oceanic allochthon (Oc) and basal complex (bc). Contours are isopachs of Oceanic allochthon in meters.

Figure 17, after Speed 2002.



Geological Map and section of Bath Cliffs.

Figure 18, after Speed 2002.



Geological Map and section of Bath Cliffs.

Figure 19, after Speed 2002.

Speed (2002) notes that there are three lithologies i) pelagic marl and ash, ii) arenitic carbonate turbidites and iii) debris flows. He describes the marl as an important prism cover unit, with its deposition following the emplacement of the Oceanic allochthon. The Conset Marl apparently forms an overlap assemblage on both the Basal and the Oceanic complexes (**Figure 1**). However, it is strongly deformed (ie., dips are often well over 30°), and thus significant deformation has continued since the time of juxtaposition. If the unit is truly 900 m thick, then deposition itself contributed significantly to the shallowing of the depositional surface.

STOP 5.

3:15. **Study Scotlands Fm (southernmost exposure) sedimentology and structure at Ragged Point. Figure 20.**

Ragged Point is the southernmost exposure of the Basal Complex on Barbados, although Basal Complex occurs farther south in the subsurface in the southern part of the island. Very coarse and very thick sand beds occur here, and one is struck by the probable rapid depositional rate in geologic terms. The section is mainly overturned with some minor folds. Vergence is likely southwards, and Speed suggests that this is probably the overturned limb of an anticline whose axial plane dips northward. However, Speed's cross section (**Figure 18**) has the parasitic folds in the wrong sense, casting some doubt on the structure here: it should be examined again.

The section here is "harder" than most. This could be due to its exposure to the sea, with constant removal of weathered surface layer, but it also may be due to a difference in cementation. We have not looked at any thin sections to see if there is any sign of a difference in maximum depth of burial, etc. It is noteworthy that this section is more or less on trend with the productive Woodbourne Trough, which must plunge WSW-ward from here.

Although we have not seen them, Oceanic beds are meant to occur on the south side of the bay here, attesting to the regionality of the overthrust nappes. The Oceanics also cover the entire Woodbourne area.

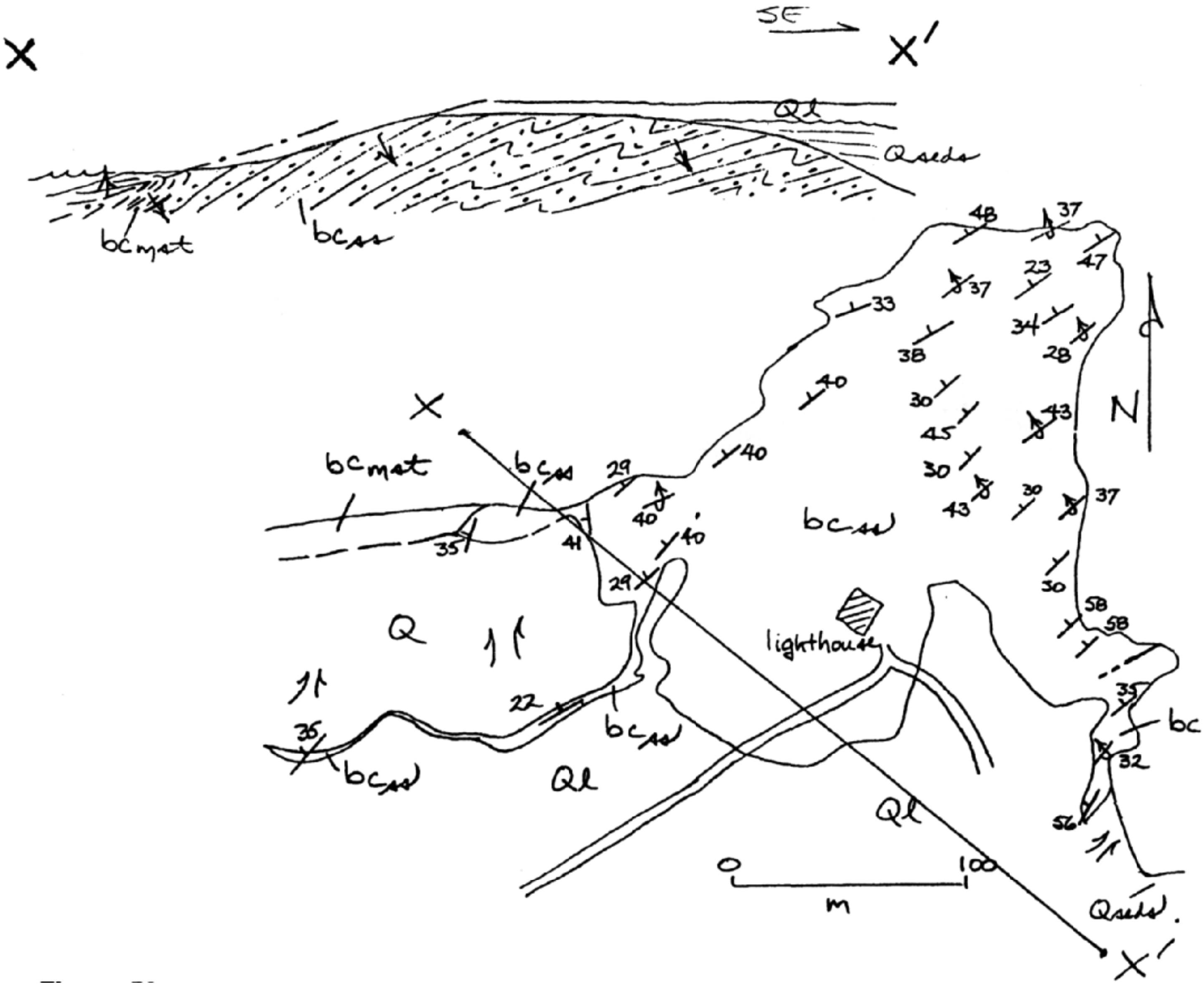
4:00 Drive to Butterfly Beach Hotel, Oistens, arrive 4:30-5:00pm.

DAY 2. SATURDAY MAY 23

STOP 6.

9:00. **Greenlands Shale Quarry (originally Walker's Beds). Walk around the area, observe active oil seeps.**

Take care when walking to mind the possible excavated gullies and steep embankments, and erosional incisions.



Geological Map and Section of Ragged Point. Arrows in section show facing.

Figure 20, after Speed 1987.

The point of this stop is to see the types of lithologies comprising the Walker's beds of Senn. The unit is predominantly shaly, although some very thick sand beds (several meters) occur, along with numerous levels of thin, rhythmically bedded (<5cm) hemipelagite. Oil impregnation is ubiquitous, to the point of visibly flowing at some spots. Faulting in the area of excavation is common, although exposures do not afford an understanding of actual structure. However, the Walker's area lies within an area of pronounced SSE-vergence, as we are situated north of the Turner's Hall Fault, which seems to be a boundary between the south-vergent structure of the Morgan Lewis, Walker's and Belle Hill areas, and the N-vergent structure of Chalky Mount and Windy Hill.

At the bottom of the "quarry", where two dirt roads intersect (SE corner), lies a small occurrence of a sand-rich and foliated mélange, probably equivalent to the Joes River mélange. We will see much better exposures of the Joes River later, but it is useful to note that it exists in isolated areas and in different stratal packets such as this. Joes River is not a stratigraphic unit per se, but rather diapiric and intrusive at a variety of levels and associated with various formations.

STOP 7.

10:30. **Joe's River Mélange. Stop at Less Beholden hamlet, and walk east/down the slope in the mélange to the Coastal Highway.**

Starting at the bus turn-around point toward the north end of the village of Less Beholden, walk east about 200 meters, downhill, to the first large outcrop of Basal Complex beds (GPS: 21224084E, 1464144N).

The Basal Complex beds here strike 140 and dip 50S, and are upright as shown by grading, scour and fill, and flame (dewatering) structures. Some beds are very coarse, carrying flakes of either chalk or bleached hemipelagite, and occasional well rounded white limestone cobbles (possibly concretions, but I think not) up to 8 cm, whereas other beds are very fine and dominated by grey clay which presumably could be used for the local pottery operations. The flakes, some clay, and a limestone cobble from this site were sampled for faunal dating, results of which are pending. 1 to 6 cm chunks of selenitic gypsum are also common in small dislocations in the beds here, attesting to flow of sulfate-rich fluids. Cementation in the sand beds appears to be calcite, not silica; again, there is no indication that these beds were ever buried very deeply. This section appears to be continuous with the rest of the Chalky Mount succession to the north; however, the Joes River diapiric mélange dominates the ravine to the south of here.

At this point, attendees have the choice of walking down difficult terrane to see several aspects of the Joes River mélange, or to walk down a gentle path and rejoin the group later. The terrane is difficult due to fissures which have opened up during ground failures of the mélange muds, although not strenuous as it is downhill. When the grass covers the fissures they are easily stepped into leading to falls. As long as one STEPS FIRST and THEN applies weight, the walk is not too bad.

An overview of the Joes River from the above described Scotland outcrop shows: (1) numerous crevasses and ravines where slope failure has occurred; (2) a large section of Basal Complex beds which is surrounded by mélange, and which dip very differently to the above outcrop section, and which may be a raft within or on the mélange; (3) some steep <5m high "cliffs" or joint surfaces where material has been mass wasted from the outcrop altogether.

We start by walking toward the possible raft of Scotland beds within the mélange. Immediately, you might smell the scent of oil from the mélange underfoot. Many oil seeps occur in the ravine. When the raft is reached, you will notice a much finer grained and well laminated, more distal turbidite facies, not very similar to the adjacent section seen earlier. And it is saturated in bitumen, appearing on weathered surfaces as "flakes" that might be taken as lignite. At the "raft" edges, shearing is evident, and layers of sandy lithology that look like beds but must be some kind of boundary to the raft, formed perhaps by concentric cementation in sandy material around the raft, or by flow of sandy material in fluids around the raft edges prior to exposure. The uppermost such border is black with bitumen. The raft strikes 100 and dips 45N. Way up is difficult to determine.

The block of Scotland formation is most likely a chunk of Basal Complex that was broken away from its mother beds to move freely with the mobile mélange. This may have occurred uphill at the surface so that all movement is gravitational, or it could have occurred at depth such that it subsequently was carried to the surface within the mélange diapir. It is very laden with oil, more so than the beds seen earlier, perhaps favouring the latter option.

Next we move down the ravine. The first aspect to note is the oil covered surface of a joint face which forms a 4 meter cliff. This same face shows some small folds in beds which are overlain by beds of a finer grained facies that are flat-lying. The folds are either soft-sediment slumps that were planed flat before renewed deposition (preferred interpretation), or they are possibly overlain by a roof thrust.

Next, several oil seeps might be seen, depending on their persistence through the season. Volumes may be great enough for samples to be taken.

Finally, we come to a collapsed wall of Joes River material. Here, many large fresh chunks of mélange are displayed in various cross sections. We see floating sub-rounded (sheared) to angular (broken) lithic clasts within the mud matrix ranging in size from grains to boulders up to a meter in diameter. The clasts include the constituents of the Basal Complex, such as oil-stained sandstones; grey poorly sorted mica-bearing sandstones; mudstones; purple-weathering radstone and hemipelagic fragments; and manjack fragments. There are also some limestones and pelagic-looking material that is believed to be Upper Cretaceous calcareous shale with fair kerogen content (Eric Deville, IFP, pers. comm., 2006). In addition, several "fault" or joint planes cut the mélange, leaving slickensides on the mud and broken clast walls. When the mud matrix is broken open, shear stria are seen to occur on every face, in every orientation. This is common in structurally-formed mélanges (mud diapirs) in general. The entire area smells strongly of oil. The prevalent depositional mica flakes in the sandstone blocks is reminiscent of the Guarico (central Venezuela) or the Lecheria (Early Oligocene) of the NW Serranía Oriental.

Considering the boundary between the mélange and the Scotlands beds, it seems to be a high angle fault striking at about 110 degrees for perhaps 100 m or so, with presumably upward movement of the mélange on the south side of the fault initially, and then gravitational flow downward once the surface is breached and mass wasting begins. In any case, the diapiric mélange seems to escape to the surface through gaps or faults within the Scotlands. This occurrence is active now. Others elsewhere have been considered as having been active in Middle Miocene, as they appear to underlie the Oceanics or Intermediate Unit (Barker et al., 1988). Proposed contact relations for the Joes River include: (1) sill like injection between the Basal Complex and the Oceanics (Mid Miocene or younger); (2) intrusive into Basal Complex along pre-existing faults (mid-Miocene or younger); (3) extrusive onto Basal Complex, Oceanics, and prism cover strata (post-Middle Miocene); (4) onlapping/downlapping onto all units (modern gravitational creep).

A final word about the Joes River mélange unit concerns its historical perception. Senn (1940) suggested an origin by mud volcanism, while Baadsgaard (1960) suggested the origin was related to mobilisation of material in a shear zone (tectonic mélange). Davies is cited in Barker et al. (1988) as having proposed an olistostromal origin, while Speed (1981) considered it as a debris flow early on, but later (2002) argued strongly for diapiric mélange. Poole and Barker (1983) thought it was the result of intrusive sedimentary activity, linked to mud diapirism seen in other parts of the Barbados Accretionary Prism. Kugler et al. (1984) interpreted the unit as mobilised, overpressured beds within the accretionary prism, which diapirically broke through the paleo-sea floor, with accompanying mud volcanic manifestations. All of these except for the debris flow/olistostrome mechanism are genetically related, and we strongly side with the diapiric mélange interpretation, having worked such "rocks" in Dominican Republic (Pindell and Draper, 1991), Trinidad (Tectonic Analysis, unpublished), observed the textures within the mud matrix, and seen diapirs feeding blocks to the surface in many places in Trinidad and in video of the seafloor of the Barbados Prism. We consider a tangible difference exists between "mud volcanism" and "mud diapirism". Mud volcanoes comprise highly fluid slurries and the material involved cannot transfer a shear stress very effectively, and likely cannot carry large chunks of exotic rock. However, mud (or shale) diapirs carry much less fluid and do have significant shear strength, they do transmit shear stress, and they obviously can carry enormous chunks and rafts of exotic rock to the surface, as is clearly visible on Trinidad's south coast. Mud diapirs are commonly extruded along transpressive faults, such as at the Williamsville building site in the western Central Range of Trinidad. They behave most plastically.

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12:00-1:30 GROUP SIT DOWN LUNCH AT ROUND HOUSE, BATHSHEBA.

1:30-3:15 DISCUSSION OF ION GEOPHYSICAL SEISMIC LINES

APPENDIX 1

CENOZOIC CARIBBEAN-SOUTH AMERICA TECTONIC INTERACTION: A CASE FOR PRISM-PRISM COLLISION IN VENEZUELA, TRINIDAD, AND BARBADOS RIDGE

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From:
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The Following figures are from Pindell et al. 2009 (GSL SP 328).

The subsequent text is from Pindell and Frampton, Barbados Field Guide, 4th GSTT Conference, Port of Spain, June 17-24, 2007, and is a discussion of points concerning the prism-prism collision model.

Clastic domains of sandstones in central/eastern Venezuela, Trinidad, and Barbados: heavy mineral and tectonic constraints on provenance and palaeogeography

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Abstract: Current models for the tectonic evolution of northeastern South America invoke a Palaeogene phase of inter-American convergence, followed by diachronous dextral oblique collision with the Caribbean Plate, becoming strongly transcurrent in the Late Miocene. Heavy mineral analysis of Cretaceous to Pleistocene rocks from eastern Venezuela, Barbados and Trinidad allow us to define six primary clastic domains, refine our palaeogeographic maps, and relate them to distinct stages of tectonic development: (1) Cretaceous passive margin of northern South America; (2) Palaeogene clastics related to the dynamics of the Proto-Caribbean Inversion Zone before collision with the Caribbean Plate; (3) Late Eocene–Oligocene southward-transgressive clastic sediments fringing the Caribbean foredeep during initial collision; (4) Oligocene–Middle Miocene axial fill of the Caribbean foredeep; (5) Late Eocene–Middle Miocene northern proximal sedimentary fringe of the Caribbean thrustfront; and (6) Late Miocene–Recent deltaic sediments flowing parallel to the orogen during its post-collisional, mainly transcurrent stage. Domain 1–3 sediments are highly mature, comprising primary Guayana Shield-derived sediment or recycled sediment of shield origin eroded from regional Palaeogene unconformities. In Trinidad, palinspastic restoration of Neogene deformation indicates that facies changes once interpreted as north to south are in fact west to east, reflecting progradation from the Maturín Basin into central Trinidad across the NW–SE trending Bohordal marginal offset, distorted by about 70 km of dextral shear through Trinidad. There is no mineralogical indication of a northern or northwestern erosional sediment source until Oligocene onset of Domain 4 sedimentation. Paleocene–Middle Eocene rocks of the Scotland Formation sandstones in Barbados do show an immature orogenic signature, in contrast to Venezuela–Trinidad Domain 2 sediments, this requires: (1) at least a bathymetric difference, if not a tectonic barrier, between them; and (2) that the Barbados deep-water depocentre was within turbidite transport distance of the Early Palaeogene orogenic source areas of western Venezuela and/or Colombia. Domains 4–6 (from Late Oligocene) show a strong direct or recycled influence of Caribbean Orogen igneous and metamorphic terranes in addition to substantial input from the shield areas to the south. The delay in the appearance of common Caribbean detritus in the east, relative to the Paleocene and Eocene appearance of Caribbean-influenced sands in the west, reflects the diachronous, eastward migration of Caribbean foredeep subsidence and sedimentation as a response to eastward-younging collision of the Caribbean Plate and the South American margin.

Supplementary material: Location maps and detailed heavy mineral data tables are available at http://www.geolsoc.org.uk/SUP18365.

Current kinematically rigorous Cenozoic models for the evolution of northeastern South America invoke a Palaeogene tectonic phase due to inter-American convergence followed by diachronous dextral oblique collision with the Caribbean Plate (Pindell *et al.* 1991, 2006; Perez de Armas 2005), which became strongly transcurrent in the Late Miocene (Pindell *et al.* 1998, 2005). In eastern Venezuela and Trinidad, the collision and subsequent shear between the Caribbean Plate and South America (Fig. 1) juxtaposed, imbricated and offset former palaeogeographic elements, hindering reconstruction of former depositional systems. Correct reconstruction of these is important because certain palaeogeographic aspects pertain directly to petroleum exploration. For example, fluvial–depositional

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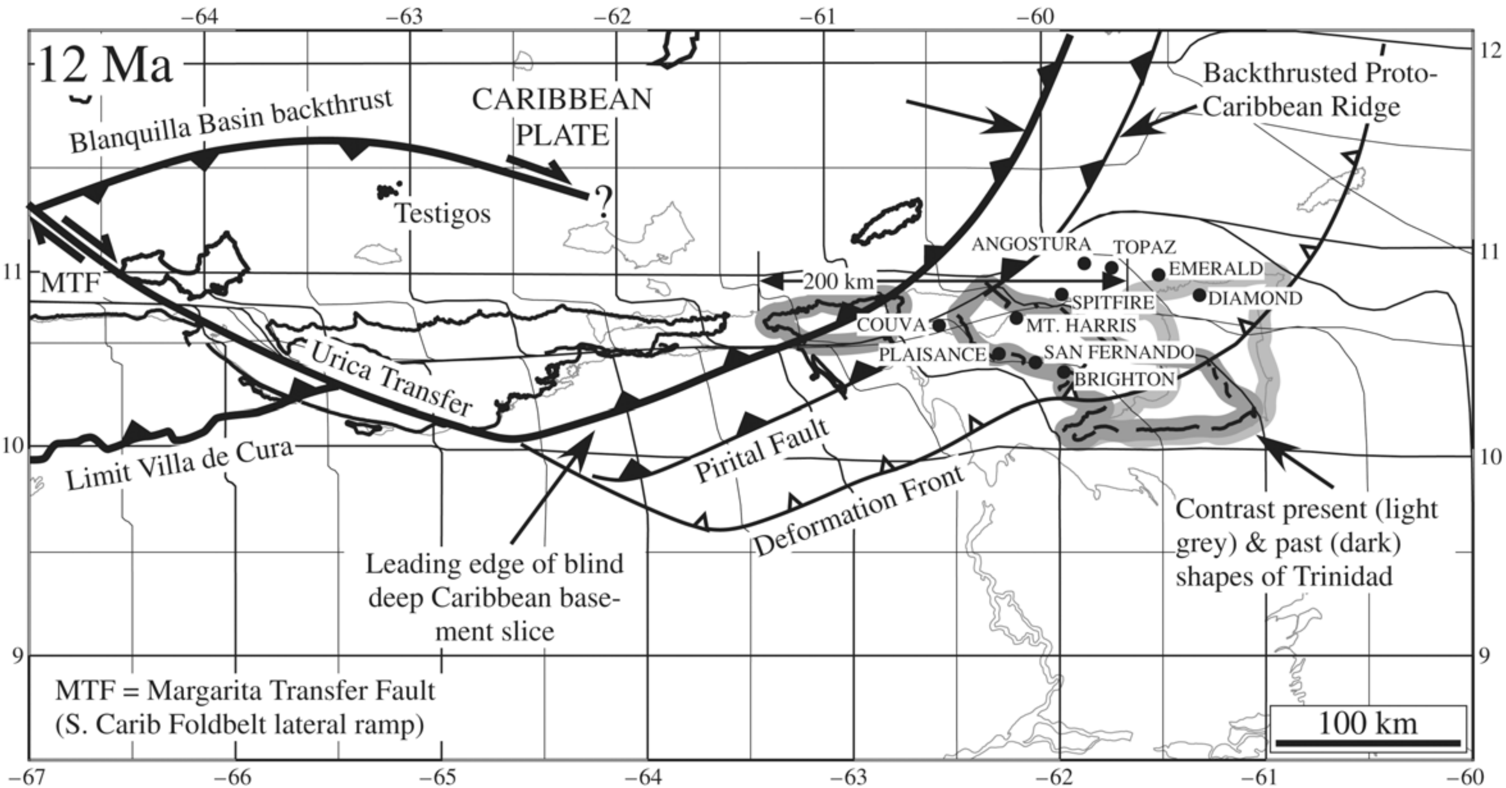

Fig. 10. Palinspastic reconstruction for 12 Ma, close to the end of Middle Miocene orogeny showing the geometry of the orogen before Late Miocene and younger deformation? Distorted latitude–longitude grids account for cumulative deformation and the resulting map is analogous to a restoration of a balanced structural cross-section. Restoring even Late Miocene and younger deformation dramatically distorts the shape of Trinidad (palaeoshape shown with bold lines). To make this map we used relatively conservative shortening and shear estimates south of El Pilar, Caroni Fault. The position of the Northern Range is harder to constrain because of uncertainties in the amount and age of internal strain. The map provides a geographic framework for plotting and reconstructing Middle Miocene deformation.

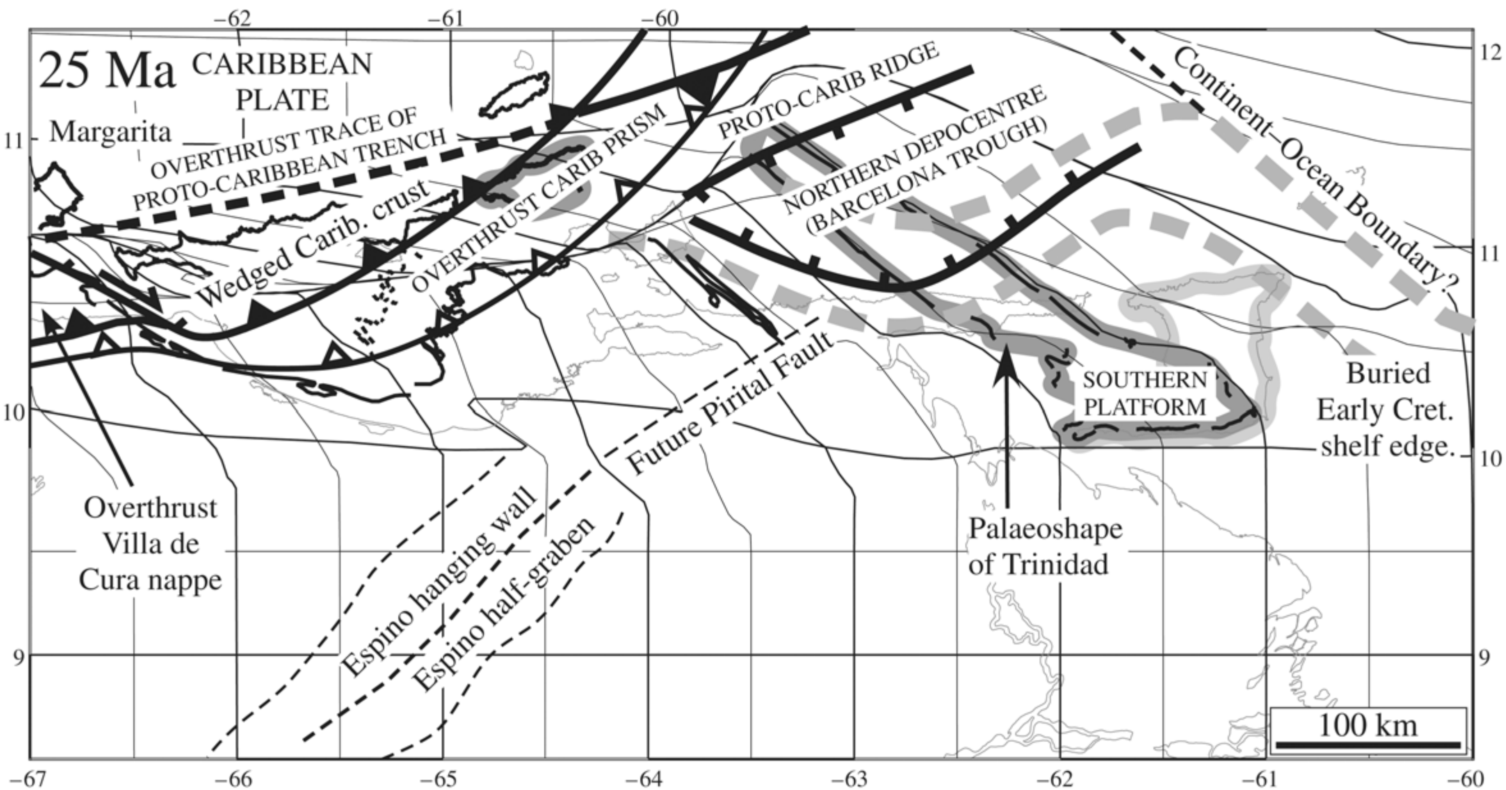

Fig. 11. A 25 Ma palinspastic reconstruction, showing the geometry of the orogen before Early and Middle Miocene deformation. Note that the distortion in the shape of Trinidad indicates that apparent north–south facies changes between the Central Range and Southern Basin in present-day geographic coordinates are in fact NW–SE facies changes parallel to the Bohordal Escarpment. One important effect of the retro-deformation is to place the northern depocentre or Barcelona Trough adjacent to the Serranía Oriental, such that Palaeogene sands can be derived from the west or SW without crossing the southern Trinidad Platform pelagic shelf, where carbonates prevailed. Large Early Cretaceous clasts (such as in the Plaisance conglomerate) can derive from either/both the NE facing Bohordal slope or the north-facing Central Range slope through incision of bypass surfaces with little Late Cretaceous or Palaeogene cover. The map supports the hypothesis of a point source for sediment from what we refer to as the 'Espino–Maturín River'. The proposed 'Espino–Maturín River' was almost certainly the source of the San Juan Sand Lobe of Maastrichtian age (see Fig. 15 below).

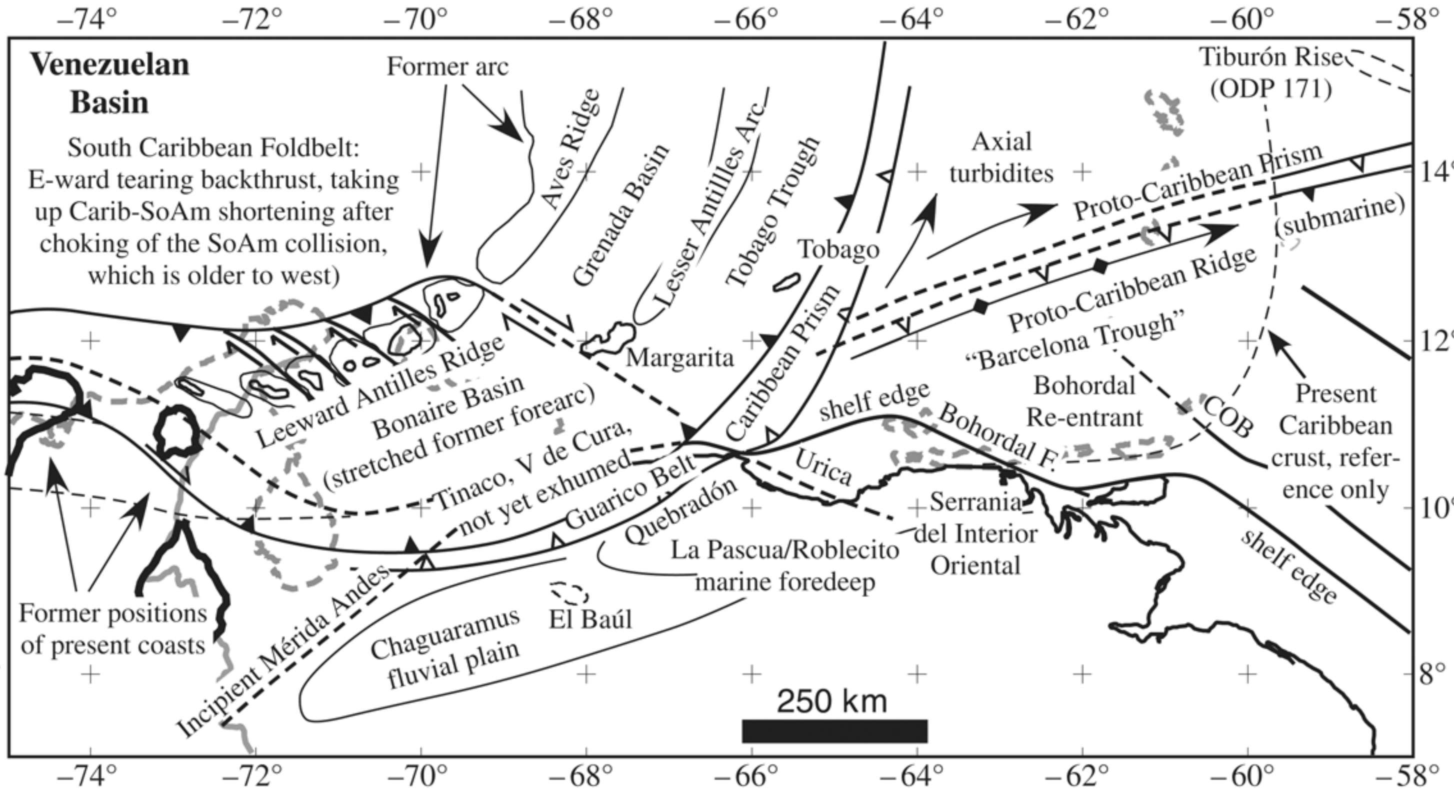

Fig. 12. Mid-Cenozoic tectonic elements of the Cenozoic Caribbean–Proto-Caribbean trench–trench collision, compiled from features identified and defined in Pindell *et al.* (1998, 2006). This reconstruction shows a v-shaped remnant of the Proto-Caribbean Seaway in the NE, bounded by the Caribbean and Proto-Caribbean accretionary prisms. The Proto-Caribbean Ridge is thought to have developed as the South American Plate ramped up over underthrust Proto-Caribbean crust and initiated prism formation. It acted as a bathymetric barrier to sediment flow between the Barcelona and Proto-Caribbean basins, still visible on basement structure maps to the east of the present day Caribbean Prism and south of the Tiburón Rise. From Guajíra to the Serranía Oriental (overridden by the Caribbean by the time of this reconstruction), the hanging wall of the trench was continental, and from Serranía Oriental eastwards the trench was intra-oceanic. It is not clear whether a narrow oceanic or a thinned continental forearc existed north of the Serranía or in the Bohordal re-entrant. Caribbean collision with the Proto-Caribbean Inversion Zone was diachronous from west to east, reaching the Guajíra area in the Maastrichtian–Paleocene, Maracaibo in the Eocene, Central Venezuela in the Oligocene, and Eastern Venezuela in the Miocene.

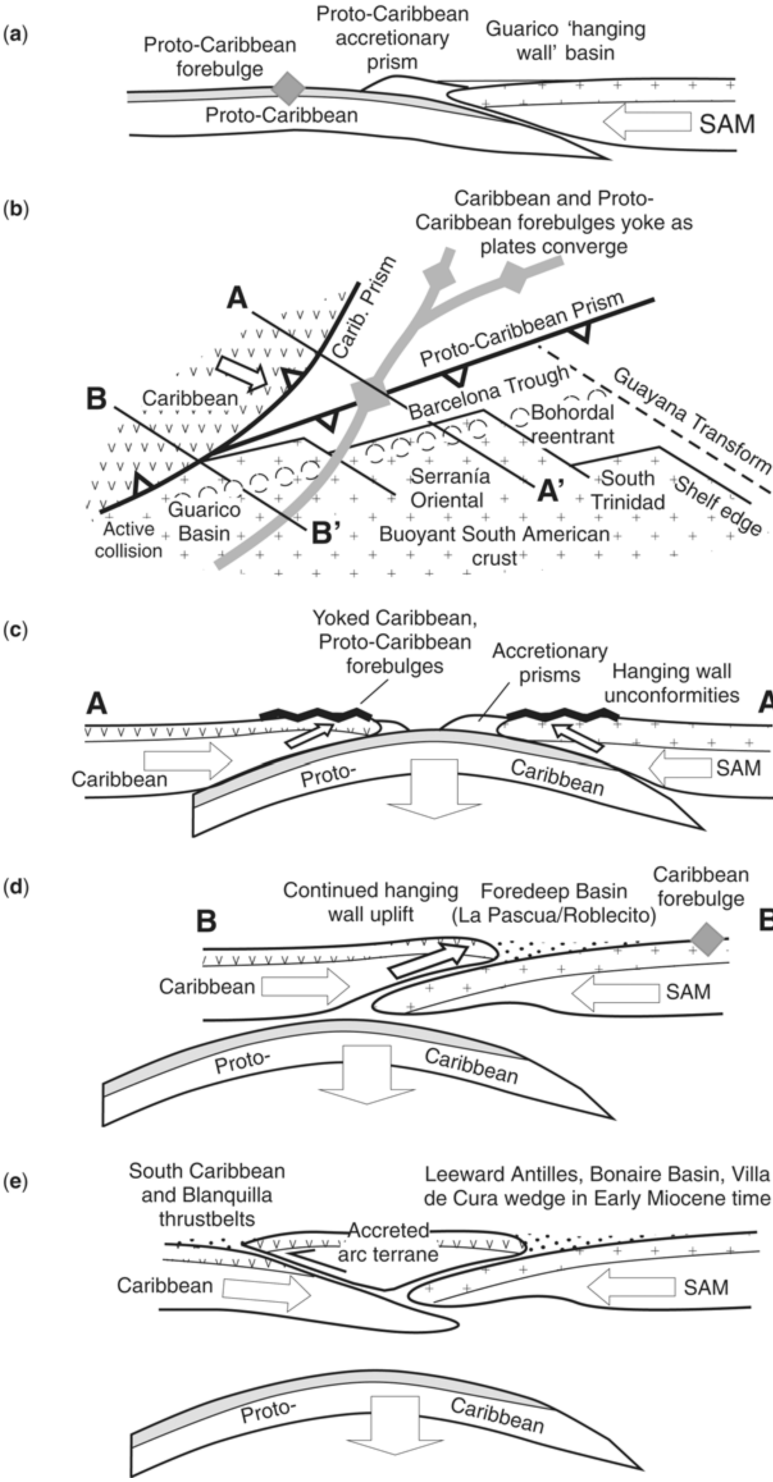

Fig. 13. Schematic history of Caribbean–South American interactions. (**a**) Onset of Proto-Caribbean underthrusting prior to Caribbean arrival, producing Proto-Caribbean accretionary prism. Guárico Basin lies in hanging wall of South

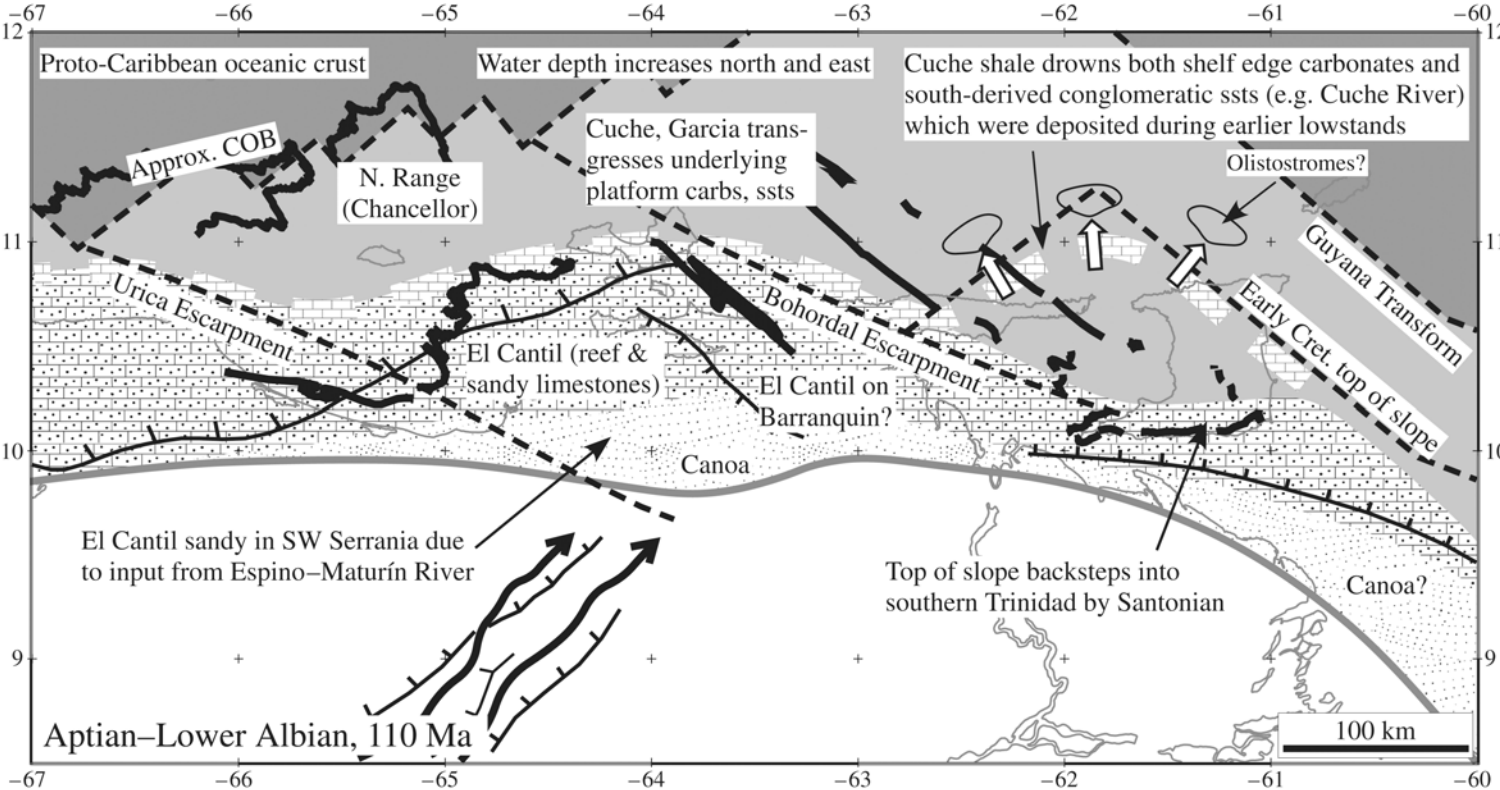

Fig. 14. Palaeogeographic reconstruction for Aptian to Early Albian time. Northern Venezuela and Trinidad were part of the Domain 1 passive margin at this time, facing the Proto-Caribbean Seaway, with continent–ocean boundary (COB) probably located near the palinspastically restored position of the Araya–Paria Peninsulas and the Northern Range. A former shelf (represented by the Barranquín and Morro Blanco Formations in Venezuela) was drowned by the Garcia Shale transgression and only in Venezuela did a widespread carbonate shelf re-establish itself (El Cantil Formation). In Trinidad, Early Cuche sandstones, limestones and conglomerates were buried by the Cuche Shale and succeeding Gautier Shale in the Central Range, also near a drowned shelf edge. We interpret the outcrops in the Cuche River as south-derived, part of a pre-transgression reef or reef-fringing trend, analogous to similar south-derived facies of Cenomanian–Santonian age in southern Trinidad. They are overlain conformably by the Late Aptian Maridale Marl (Garcia equivalent). Strata older than the Maridale Marl have not been drilled in southern Trinidad, but to the south in Venezuela there is a thick sand and conglomerate clastic fringe of Early Aptian and older age overlying the Guayana Shield.

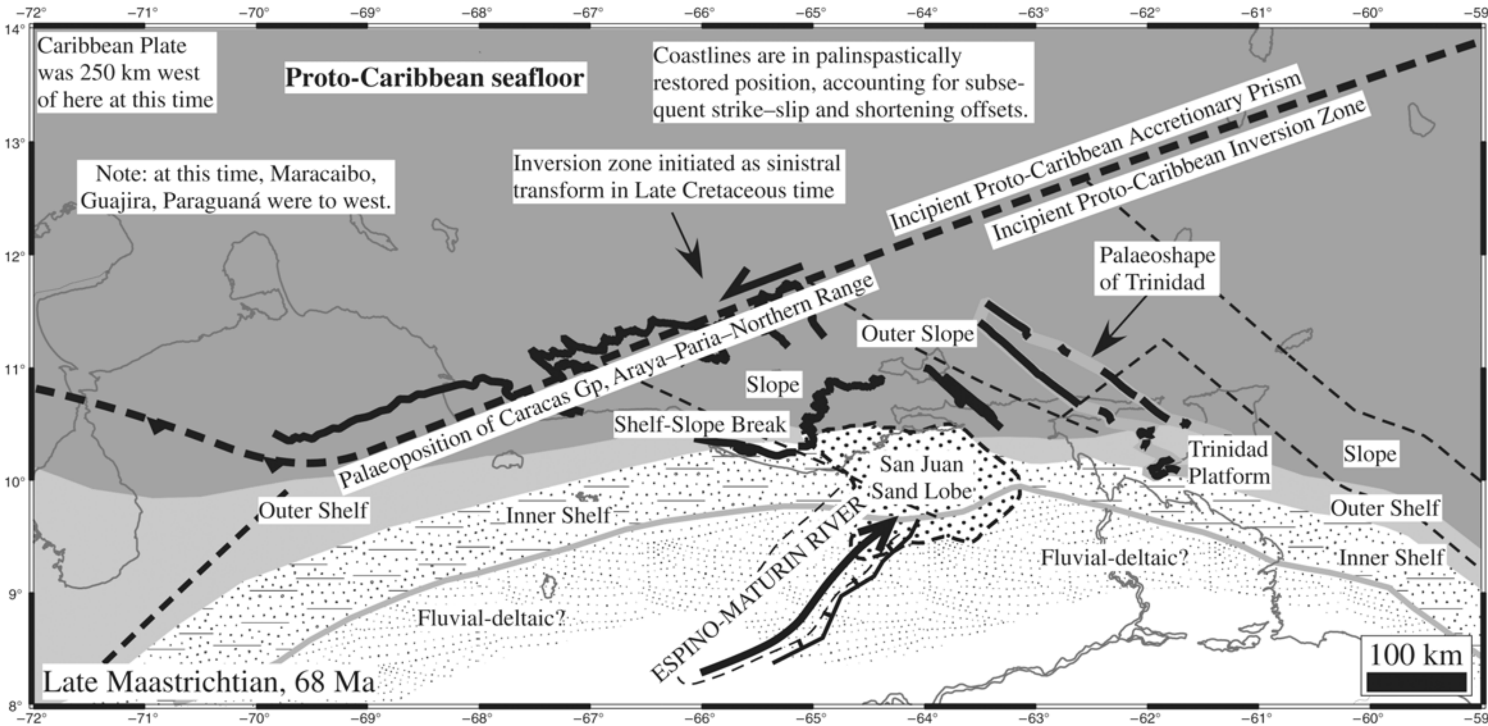

Fig. 15. Palaeogeographic reconstruction for the Maastrichtian (68 Ma) of northeastern South American continental passive margin (Domain 1). Present day coastlines are shown with fine grey lines and restored positions of coastlines are shown with heavy black lines. The palaeogeographic map is drawn for the period immediately prior to the onset of underthrusting on our proposed 'Proto-Caribbean Inversion Zone'. The map shows the buried positions of the Early Cretaceous shelf-slope break beneath the Central Range of Trinidad, which continued to support a relatively shallow 'Trinidad Platform'. Sedimentary facies indicate the existence an inner slope close to the south coast, but the ultimate drop to abyssal depths lay north of the buried older shelf edge. The buried 'Bohordal Fault' is inferred to bound the Serranía Platform on the east, and the ancestral Urica Fault is thought to separate the Serranía from Central Venezuela. Both were active as sinistral transfer faults during Early Cretaceous and older rifting. The continent–ocean boundary to the east of Trinidad is well constrained from present-day Columbus Channel to Suriname. Prior to Jurassic opening of the Proto-Caribbean Seaway, the deep basement of Cuba and the Bahamas Platform lay NE of this line. Sedimentary facies are shown as fluvial fringe, shallow marine inner shelf, outer shelf or upper slope (light grey) and mid-slope and deeper (dark grey). The interpretation is based on well data and our own field work. The southern fluvial fringe is mostly eroded and onlapped by La Pascua and younger formations (Domain 3, southern onlap edge of Caribbean foredeep, see Fig. 17). Of particular note is the San Juan Sand Lobe (isopachs based on Di Croce 1989), which appears to originate from the axis of the Jurassic Espino Graben. The southern boundary faults of this graben (inactive by this time) may have controlled topography and the course of an 'Espino–Maturín River'. The faults were subsequently inverted during the Late Cenozoic (as the Anaco Thrust).

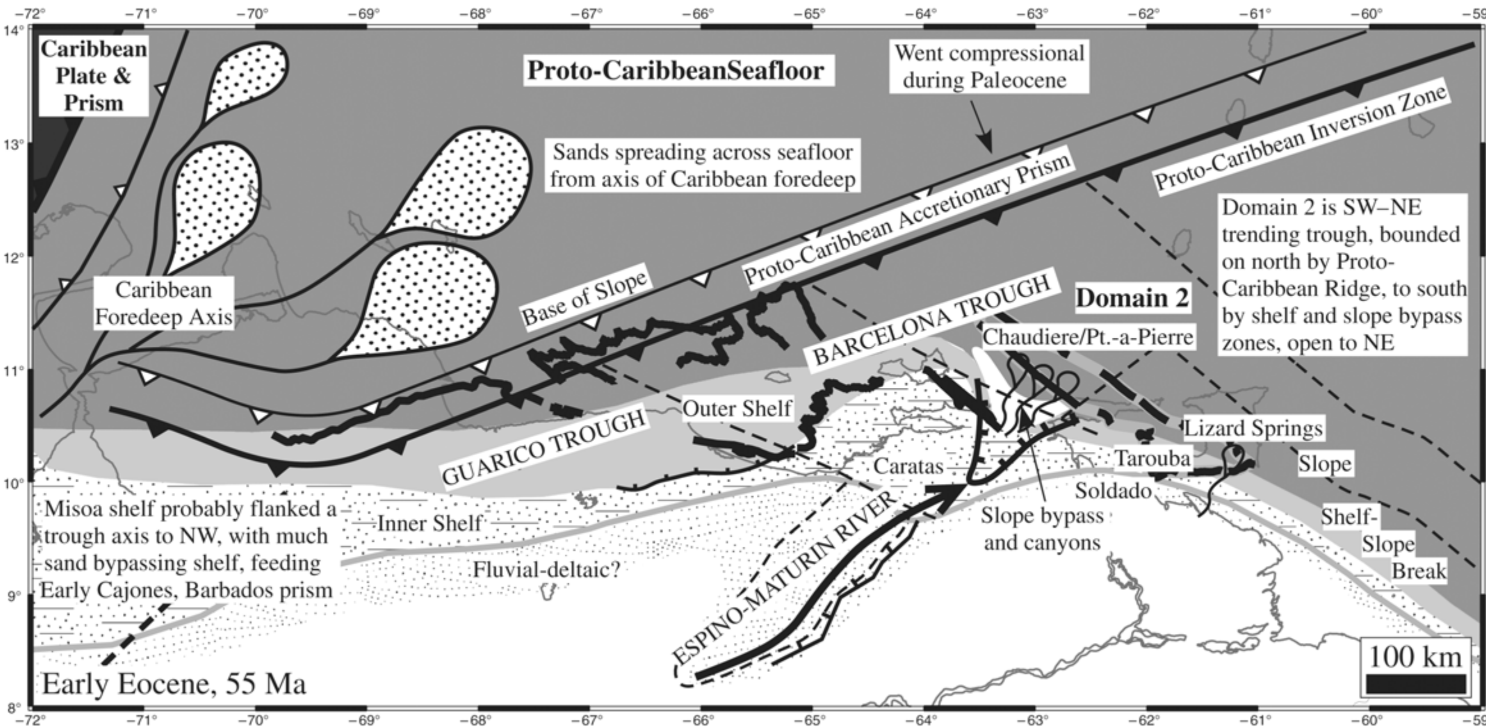

Fig. 16. A reconstruction for Earliest Eocene time (*c.* 55 Ma) shows the effect of the initiation of Proto-Caribbean underthrusting on the north side of the former passive margin. Clastic Domain 2 developed to the south of the uplifted Proto-Caribbean Ridge and associated accretionary prism, to the north of the former Cretaceous slope in the Central Range, and east of the Bohordal Fault, with sedimentary facies and thickness indicating substantially greater waters within the Barcelona Trough than in the Serranía to the SW. At this time, the Caribbean Plate lay about 800 km to the west and was not influencing subsidence and sedimentation in eastern Venezuela and Trinidad. There is no indication of a northern source for any of the sediment in the Barcelona Trough. Instead, reconstructions indicate a point source in the embayment between the Bohordal Fault and Central Range slopes, which may have been fed by the 'Espino–Maturín River' (which previously sourced the San Juan Sand Lobe). The area of the future northeast Serranía unconformity is shown dashed. At this time basement was probably uplifted immediately south of the Proto-Caribbean Inversion Zone, resulting in deposition of a thin and shallow Caratas section, with exposure and erosion only occurring during the latest Eocene to earliest Oligocene.

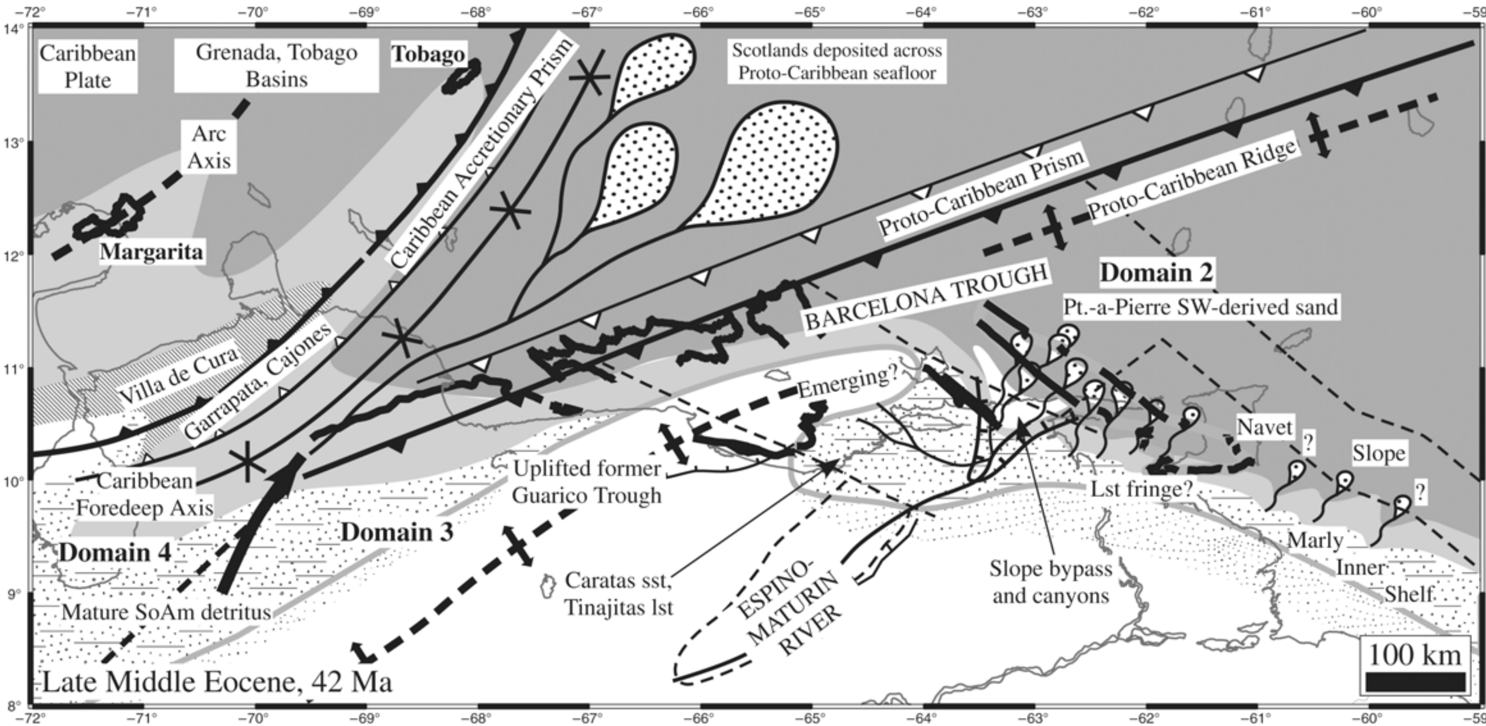

Fig. 17. A late Middle Eocene (*c.* 42 Ma) reconstruction shows a possible interpretation of the depositional context for the Scotlands of Barbados, if we accept Middle Eocene foraminfera and pollen in the Scotlands as non-reworked and honour the apparent absence of any Late Eocene fauna. The majority if not all of the Scotland sands were probably deposited about 600–700 km downstream of the onshore end of the Caribbean foredeep axis ahead of the leading edge of the Caribbean Plate. It is also possible that some of the Scotland strata were deposited to the north of the Proto-Caribbean Inversion Zone, particularly if the Proto-Caribbean Inversion Zone axis was overfilled, such that accommodation space was only available to the east along the Proto-Caribbean Trench. The presence of trace glaucophane as far as Tiburón Rise to the east of the present-day Barbados Prism shows that Caribbean derived debris may have been spreading over the entire Proto-Caribbean seafloor. A trench associated with a Proto-Caribbean Inversion Zone seems a logical place to expect accumulation of Caribbean-derived turbidites. In the southern Scotlands there is a coarser fraction (conglomerates containing what appear to be Rio Chavez shales and carbonates) that is clearly of South American provenance, and there is also abundant mature quartz sand together with Caribbean immature orogenic heavy minerals. Some of this South American component could come from the proposed northeastern Serranía unconformity. Alternatively, south-derived sediment from the western Guayana Shield may have been transported onto Proto-Caribbean Seafloor along the foredeep axis of the Caribbean. Carbonate and shale clasts may be derived in this case from South American margin rocks already incorporated into the leading edge of the Caribbean orogen in western Venezuela. The map also shows the Caribbean forebulge rolling from west to east. Associated uplift drives a diachronous tectonic lowstand, in this case uplifting the former Guárico Trough. Detritus uplifted off the forebulge may have been deposited to the NW, in the northeastern Barcelona Trough, or to the south and transported to the Trinidad region by the proposed Espino–Maturín River.

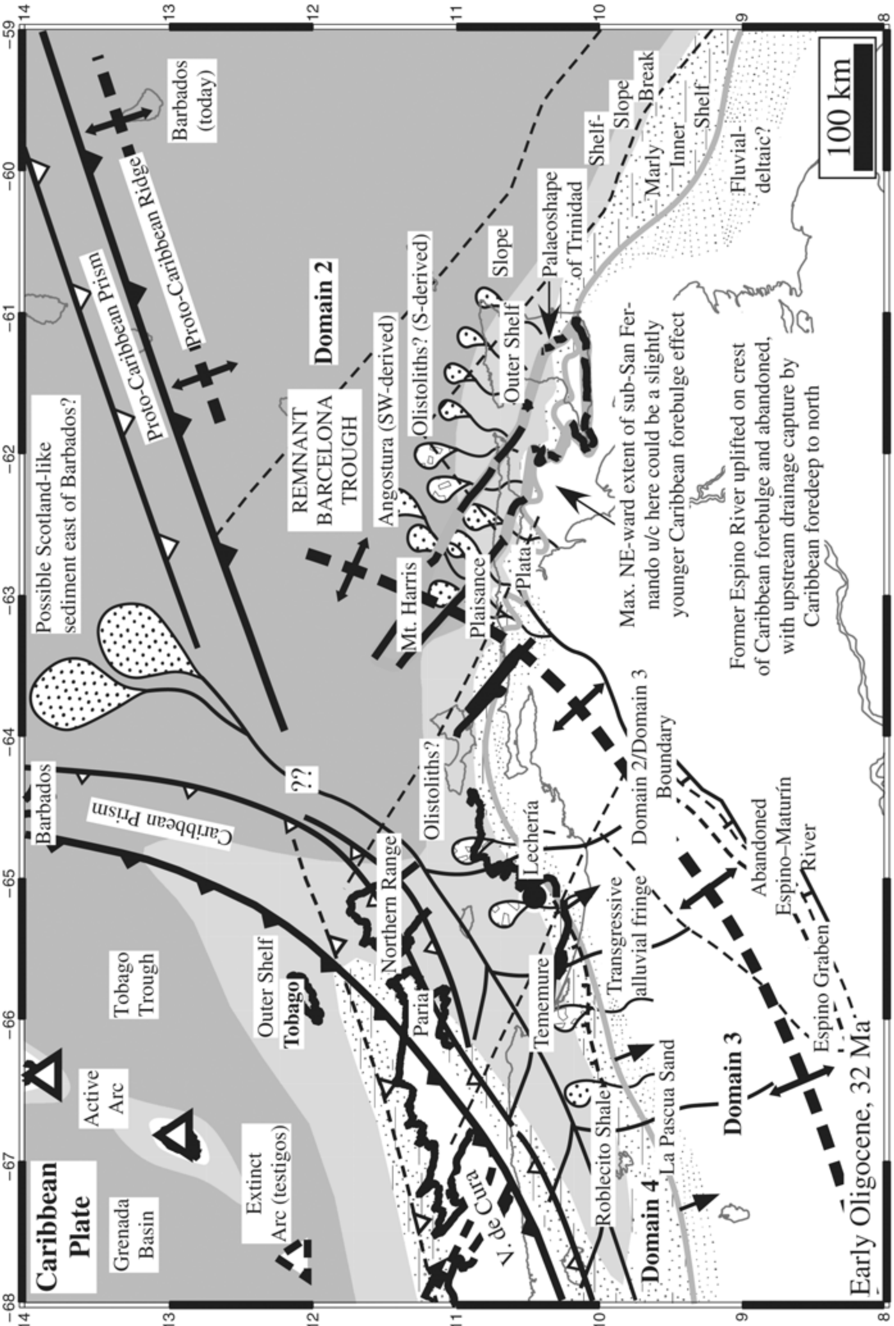

Fig. 18. *Continued.*

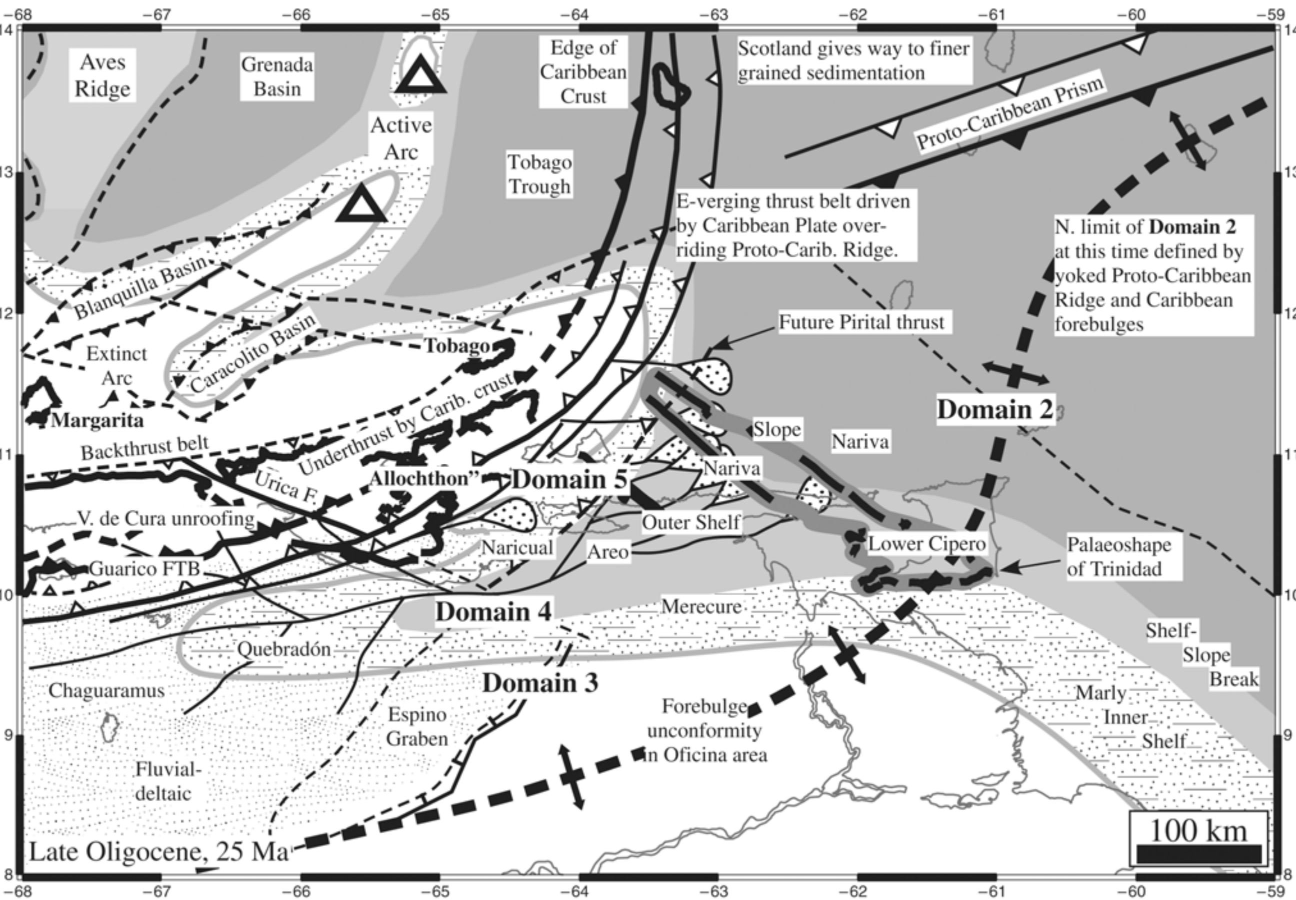

Fig. 19. Reconstruction for Late Oligocene time (*c.* 25 Ma). The leading edge of the Caribbean crust had migrated sufficiently far to the SE to interact strongly with eastern Venezuela. East of the Urica Fault, rather than overthrusting the margin, the leading edge of Caribbean crust seems to have wedged between crystalline basement (below) and passive margin sediment (above) and started to drive shortening to the SE in the passive margin section. The onset of shortening in the Serranía pushed the foredeep axis to the south far enough that the downstream end of the foredeep now drained into the former Domain 2 Barcelona Trough. This in turn led to the abandonment of coarse-grained sedimentation in the Scotland of Barbados shortly before the accretion of the former Proto-Caribbean and advancing Caribbean prisms. We see important along-strike and across-strike facies variations in the Caribbean foredeep. Domain 3 south-derived mature sandstones are initially buried by axial foredeep (Domain 4) shale-dominated sections, with minor sandstone content. The section becomes sandier approaching the active thrust front (Domain 5). To the west, in shallower marine to alluvial settings foredeep axis sediment tends to be sandier, and the transition from coarse to fine facies in the foredeep axis migrates from west to east as the trough fills in. In Trinidad, sandstone facies in the Nariva formation become more abundant in northern or western outcrops, and younger in the formation, relative to shale and marly facies developed towards the east end of the foredeep axis. These sandstones carry a distinctive heavy mineral signature indicating input from high-pressure metamorphic terranes that is absent from Domain 2 and Domain 3 sediments.

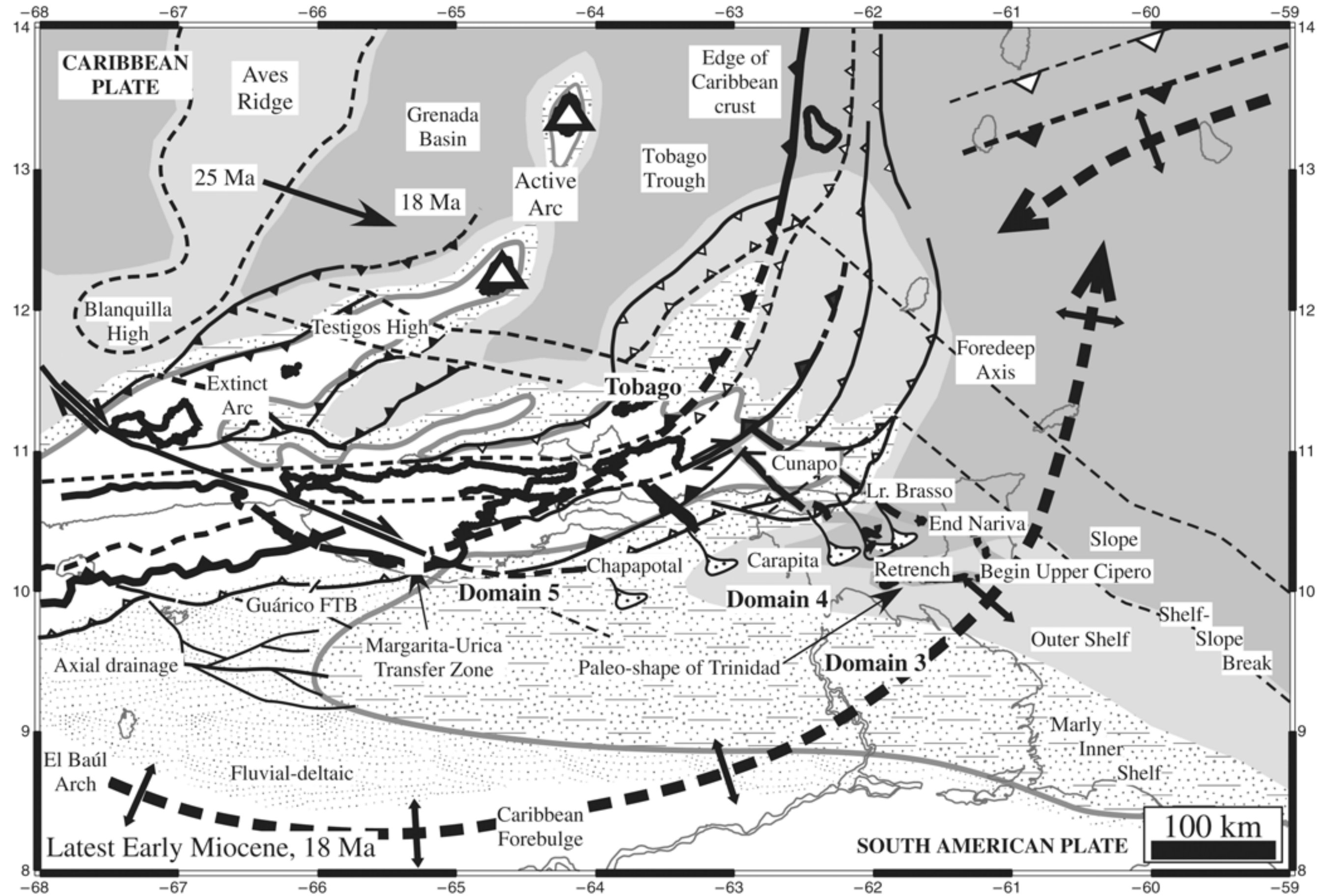

Fig. 20. Reconstruction for earliest Middle Miocene time (*c.* 18 Ma) shows the Caribbean Prism as having over-ridden the Proto-Caribbean prism north of Tobago. This was followed by wedging of the crystalline Caribbean basement under the merged prisms, forming the characteristic 'oceanics' blind roofthrust over backthrusted structural style seen from Tobago to Barbados. To the south, the Caribbean crust had accreted parts of the Proto-Caribbean Ridge in front of Tobago and was probably driving thin-skinned basement thrust sheets within the Serranía and Gulf of Paria resulting in a dramatic shoaling of the Serranía and Trinidad thrust belts, where unconformities developed in the north and former deep marine thrust belts (Nariva) were uplifted above imbricated thrust sheets of Cretaceous strata. The shallow marine Brasso Formation was deposited above the thrust belt, and was dominantly carbonate on structural highs and conglomeratic in structural lows, defined by transtensional lateral ramps. By this time, the Caribbean forebulge had swept through Trinidad sediments of Late Nariva age were deposited in central and southern Trinidad, while Brasso facies were deposited north of the thrust front in what is now the Central Range.

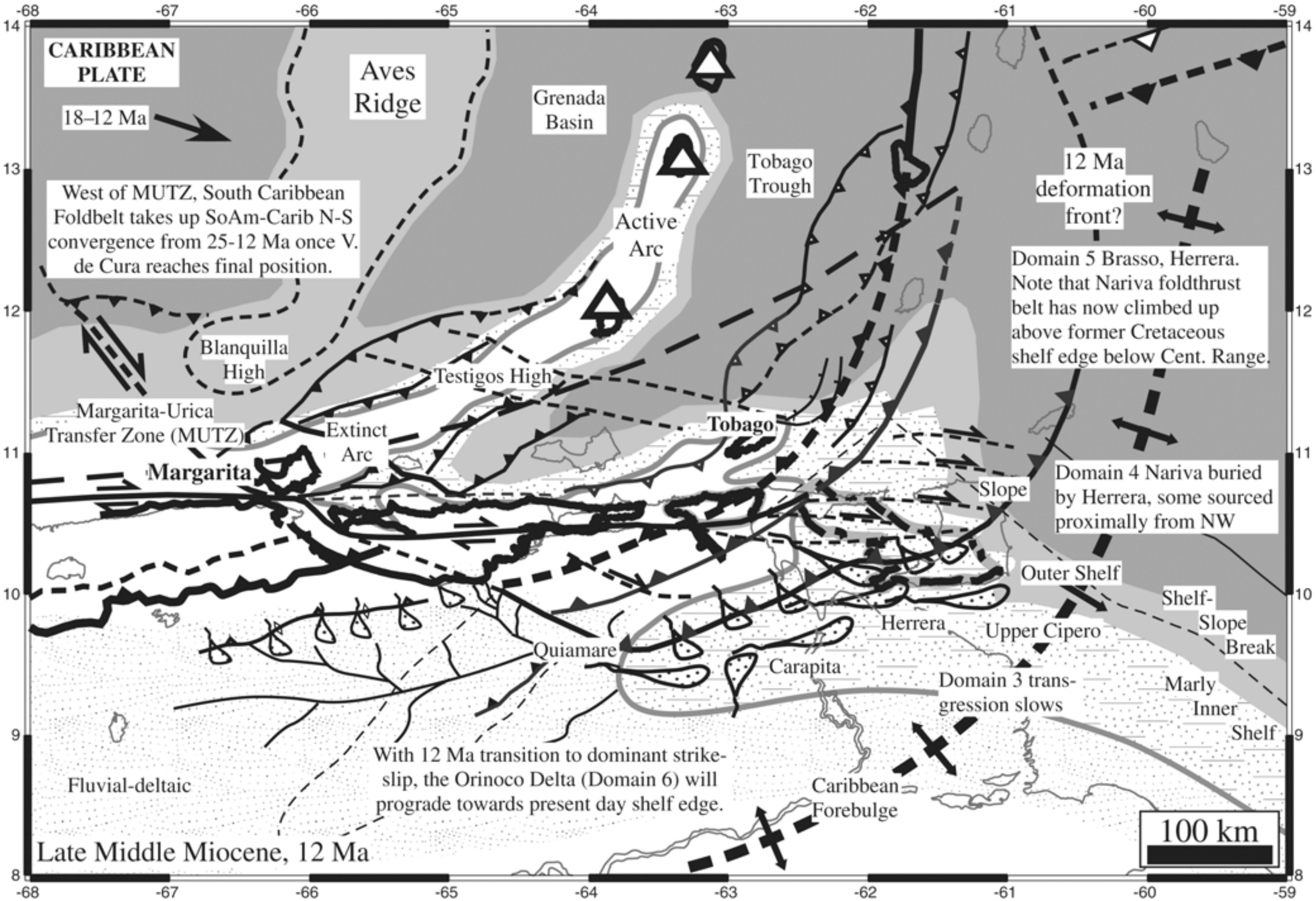

Fig. 21. Reconstruction at the culmination of Middle Miocene orogeny in Venezuela and Trinidad at about 10–12 Ma shows substantial areas of the former foreland basin incorporated into the orogen. Proximal fine through coarse-grained clastic and carbonate facies accumulated on the north side of the foreland basin, deposited in shallower water conditions than in the axial trough to the south. Sands in Domain 5 were sourced from nearby pre-Miocene outcrops, including reworked foreland basin sediment. Significant east–west extension in the orogen is indicated by thick carbonate and clastic sediments deposited in waterdepths far less than the sediment thickness. True basement subsidence is indicated by continued foredeep subsidence beyond the deformation front, and additional accommodation space resulted from thinning of the allochthons. With the end of SE-directed relative plate motion we see continued subsidence driven by distant loads of the Caribbean Plate but not in most areas by active continued foreland shortening. As a result, Domain 6 Orinoco sediments, although of the same origin as older foredeep axis sediments, are able to overstep and bury the thrust front active during deposition of Domain 5 sediments.

FURTHER DISCUSSION OF THE PRISM-PRISM COLLISION MODEL

Enormous effort by the collective geological community has been devoted to the description and characterisation of the Caribbean-South American plate boundary zone. Less but still considerable effort has gone into understanding the history of the Caribbean-South American plate collision, and still less effort has gone into trying to understand the nature of the South American margin prior to Caribbean collision. Was it a passive margin as the Caribbean progressively collided with it from the west, as many have come to believe, or was it already active during the Caribbean collision? If active, how so? Understanding the answer to this question is important for understanding the history of the collision itself and the structure of today's plate boundary zone, as well as for better understanding the paleo-environments and distribution of source and reservoir rocks in various petroleum systems along the margin.

Prior to the advent of plate tectonic theory, workers envisioned an end-Cretaceous-Eocene northern marginal high that provided detritus with an orogenic signature to various clastic depocenters such as the Scotland Formation in Barbados (eg., Senn, 1940). With the advent of plate tectonics, but prior to accurate plate kinematic control, came the idea that arc-continent collision caused tectonism and metamorphism in the Caribbean Mountains and Margarita of Late Cretaceous age, followed by some thin-skinned thrusting or gravity sliding in the Guarico foreland basin in the Paleogene (eg., Maresch, 1974). With (1) the definition of accurate circum-Caribbean plate kinematics as allowed by early SEASAT and GEOSAT data, and (2) the realisation that northern South America's foreland basin subsidence history youngs diachronously eastward (Pindell, 1985), came the realisation that the predominantly Cretaceous metamorphic and igneous rocks must be Pacific-derived allochthons that were not emplaced onto the margin until the Paleogene, and that the northern South American shelf was passive at least until the Maastrichtian and possibly to the time of Caribbean collision, facing onto the Proto-Caribbean Seaway, an arm of the Atlantic (Pindell, 1985; Dewey and Pindell, 1986; Pindell et al. 1988). But the arc-passive margin collision model was always hostage to one major problem: N-S convergence between North and South America since the Maastrichtian was significant (ie, hundreds of km) and convergence began before the arrival of the Caribbean allochthons in Venezuela and Trinidad.

Thus, suspicion of a "pre-Caribbean-arrival" convergent boundary between the North and South American plates, somewhere in the Proto-Caribbean Seaway, clouded our confidence in the margin remaining passive until the time of Caribbean collision (ie, during the Paleogene). It was not until the first seismic tomographic work in the Caribbean (Van der Hilst, 1990) that the geological community had good evidence that South American continental lithosphere had been severed from the Proto-Caribbean lithosphere which had been subducted beneath the Lesser Antilles. Driven by the suspicion of convergence since the Maastrichtian, Pindell et al (1991) honoured the Cenozoic inter-American relative motion history by proposing that the northern South American Cretaceous passive margin was converted in the Late Maastrichtian-Paleocene to a south-dipping "Proto-Caribbean" thrustbelt or inversion zone along the toe of the margin. Further, it was suggested that this structure drove N-vergent accretion of South American continental slope and rise strata to South America's northern edge (eg, Caracas Group, Paria, and Northern Range strata), PRIOR to the eastwardly diachronous collision of the Caribbean Plate, and associated emplacement of the Cretaceous allochthons, with Venezuela and Trinidad. In such a model, the term "trench-trench collision" is a more accurate description of Caribbean-South American interaction during Cenozoic time than is "arc-passive margin collision", although convergence at the Proto-Caribbean thrustbelt or subduction zone has been too small for a magmatic arc to develop.

Evidence for this Proto-Caribbean subduction zone is geologically subtle in the onshore, but defining the Paleogene existence of the plate boundary (Pindell and Kennan, 2001; Pindell et al., 2006) is critical for understanding the origin and distribution of Paleogene reservoir clastics and burial/unroofing histories of Cretaceous source rocks, and thus deserves our full attention. Evidence for the Proto-Caribbean subduction zone/thrustbelt now includes the following items.

(1) Atlantic plate kinematic history requires about 150±50 km of North America-South America convergence to have already occurred at the longitude of Late Eocene Caribbean collision in western Venezuela, and at the longitude of Early Miocene Caribbean collision in Eastern Venezuela (Pindell et al., 1988; Muller et al., 1999), which must have had a pre-Caribbean-arrival geological expression within or at the margins of the Proto-Caribbean Seaway.

(2) Mantle seismic tomography beneath the Caribbean and northern South America (Van der Hilst, 1990) shows a subducted Proto-Caribbean slab beneath the Caribbean Plate, and this subducted slab is both severed from, and overthrust by, the northern edge of South American continental lithosphere. The Caribbean slab also underthrusts northern South America, through the severed tear between the Proto-Caribbean and South American lithospheres. However, because the Proto-Caribbean slab continues some 150 km south of the southern limit of subducted Caribbean lithosphere, overthrusting of the Proto-Caribbean by South America must have started earlier; ie, there was a S-dipping Proto-Caribbean trench or thrust zone along northern South America *before* the arrival of the Caribbean Plate along northern South America.

(3) ENE of Barbados on the Atlantic floor, a paired basement ridge/trough (south side/north side, respectively) projects ENE into the Atlantic from beneath the Barbados accretionary ridge, which we interpret as the eastward continuation of the N-facing Proto-Caribbean subduction zone's hanging wall (ridge) and trench (trough), not yet overthrust in this area by Caribbean lithosphere or Barbados Prism (Pindell et al., 2006). This ridge/trough pair extends out to about magnetic anomaly 31 (Late Maastrichtian), which is the age when convergence between the Americas began, hence the Proto-Caribbean subduction zone may have initiated simply as a third arm extending from a triple junction between it and the Maastrichtian mid-Atlantic spreading center. Assuming rigid plates, the 150 km of shortening which had already occurred at a given longitude of Caribbean collision theoretically should have diminished eastward from that longitude to zero at the effective pole of rotation for the convergence. However, the observable geological manifestation of this shortening may appear to have propagated eastward through Paleogene time.

(4) Paleogene uplift and erosion of section along the South American shelf was once interpreted as being due to the passage of the Caribbean forebulge (Dewey and Pindell, 1986; Pindell et al., 1988), but our field studies in Eastern Venezuela and Trinidad now show that subaerial erosion reached at least Turonian levels (note: prime source rock interval), and possibly Albian levels locally, and thus often exceeds that predictable by forebulge uplift alone. Further, seismic records in Central Venezuela (eg., PDVSA 1995 bid round samples) show normal fault offsets at the basal foredeep unconformity that are often larger than those predicted by lithospheric forebulge flexure alone. This erosion and faulting may better be related to slow but progressive hanging wall uplift as the Cretaceous passive margin was converted into the "Proto-Caribbean" subduction zone (Pindell and Kennan, 2001). Local occurrences of extensional faulting in the basement and/or the passive margin section (northward slumping) may owe their origin to gravitational relaxation of hanging wall elements toward the free face of the new trench.

(5) Fission track cooling ages in apatite grains from the Barranquín Fm of the Serranía Oriental are mostly Miocene and Oligocene, but some are as old as Eocene. (Perez et al., 2005; Locke and Garver, 2005). These authors speculate an Eocene onset of uplift in the Serranía Oriental, which pre-dates the Late Oligocene onset of Caribbean collision first suggested by Dewey and Pindell (1986) in that area, and may relate, if not due to partial annealing, to the hanging wall uplift noted above.

(6) Post-orogenic cooling of the "Caribbean Series" metasediments through 350°C, as shown by Ar-Ar dating of first foliation micas, was underway in the Caracas Group by 42 Ma (Middle Eocene), and in the Paria Peninsula and Northern Range by about 26 Ma (Oligocene) (Sisson et al., 2005; Foland and Speed, 1992). A zircon fission track age of 29 Ma from Paria Peninsula (Cruz et al., 2004; in press) suggests that uplift and cooling locally may have begun even earlier. These ages predate the time of Caribbean collision at these places as judged from adjacent initial foredeep development (Oligocene in Guarico Basin; mainly Miocene in Maturín Basin), suggesting that the primary metamorphism in these ranges pertains not to the collision of the Caribbean, but to an earlier event or process which may be the accretion of these strata at the Proto-Caribbean trench/foldbelt prior to the arrival of the Caribbean. If anything, the arrival of the Caribbean forearc at the margin triggered the cooling, not the heating, of these rocks.

(7) Speed (2002 and many earlier references) built a comprehensive model for the depositional and deformational history of the Scotland District, Barbados, employing a single trench model in which Eocene-earliest Miocene forearc pelagic strata overthrust, in the Miocene, Eocene-?Oligocene fine to coarse grained clastic accretionary prism strata that originally lay trenchward of the forearc basin. However, there are several apparent inadequacies in this model, some of which are: 1) fold and thrusts trend ca. 070°, not 010°-030° as expected in a single, ESE-migrating prism model; 2) much of the Scotland District deformation is NW-vergent, as opposed to

the expected ESE-vergence (trenchward), thereby requiring special structural dynamics or backthrusting during initial accretion to explain; and 3) there is no gradation in lithology or composition between the Oceanics (pelagic forearc) and Basal Complex (clastic prism) strata, except for some radiolarites in the lower Basal Complex that could, but do not appear to, relate to the Oceanics; this raises doubt over whether the two units were ever adjacent enough to form parts of the same forearc-subduction complex. In contrast, a prism-prism collision model appears to explain the geology of the Barbados Ridge better, although such a model is the subject of ongoing work by us. Much of the Basal Complex may pertain to the Proto-Caribbean Prism, rather than the Caribbean Prism, whereas the Oceanics may correspond to the Caribbean Prism. If so, N-vergence with fold-thrust trend 070° in the Basal Complex is precisely that predicted for the Proto-Caribbean prism along northern South America. Furthermore, in this model, tectonic juxtaposition between the Oceanics of the Caribbean Forearc (?Prism) and the Basal Complex of the Proto-Caribbean Prism should not have happened along Barbados' migration path until the Middle Miocene, which is the age proposed by Speed for the thrusting of the Oceanics onto the Basal Complex. Speed also concluded that the juxtaposition of the Oceanic and the Basal complexes was E-directed, in keeping with collision of two pre-existing prisms driven by Caribbean migration. The first overlap sequence lying on both is the Conset Marl of Middle Miocene age, marking the completion of this process. Finally, the backthrusting of Prism material into the Tobago Trough forearc strata (Torrini et al., 1989) would be seen in this model as the Caribbean crystalline forearc wedging into the pre-existing Proto-Caribbean Prism. Since this Middle Miocene tectonic juxtaposition and accretion of Proto-Caribbean Prism to the leading edge of the Caribbean, the two prisms have moved eastwards, only 20° different to the Basal Complex's original 070° fold trend (ie, 70° change in bulk shortening direction), by some 200-300 km relative to South America as a composite accretionary prism terrane.

The Paleogene development of the Proto-Caribbean subduction zone/thrustbelt caused progressive shallowing of the South American hanging wall margin as it was telescoped [homoclinally?] northwards onto the Proto-Caribbean lithosphere. Uplift of this hanging wall was then reversed to foredeep subsidence as the Caribbean arrived from the WNW diachronously, due to the loading effect of the Caribbean lithosphere on first the Proto-Caribbean lithosphere immediately ahead of the Proto-Caribbean trench and then the South American lithosphere itself once the trench had been crossed by Caribbean lithosphere. Thus the culmination of uplift and onset of Caribbean load-induced subsidence on South America is predicted to, and does (Pindell et al., 1991), young eastward with the migration of the Caribbean Plate. In the eastern Serranía Oriental, the hanging wall uplift culminated in the Late Eocene and/or earliest Oligocene, producing such redeposited slope facies as the Plaisance Conglomerate of Trinidad. But the uplift was homoclinal over the whole of the Serranía, and the resulting angular discordance of only 2 or 3 degrees is not observable in the field. In addition, South American hanging wall uplift produced a Cenozoic paleobathymetric ridge projecting and plunging ENE from the northern flank of the Serranía del Interior out to about lat/long 15N/53W in the Atlantic, passing under the present position of Barbados. This submarine ridge probably was not buried by abyssal plain sedimentation until the Middle or Late Miocene, and thus separated the Paleogene clastic dispersal pattern from South America into 2 realms: (1) a deep water Proto-Caribbean realm whose complex heavy mineral signature reflects Eocene-Oligocene orogenesis in western and Central Venezuela (eg., Barbados, Tiburon ODP cores), and (2) a Guyana-Trinidadian realm on the backside (south) of this ridge that remained entirely cratonic and mineralogically mature until the Upper Oligocene onset of Nariva Formation deposition, marking the closure of the Proto-Caribbean Trough at the longitude of the Serranía/Trinidad, such that orogenic minerals could finally reach Trinidad. This underlying Atlantic basement ridge, with about 3 km of relief at the basement level, is also responsible for Barbados' present, unique subaerial exposure on the E-wardly migrating Barbados Ridge.

Establishment of the Proto-Caribbean subduction zone likely provided additional first order controls on deposition in western Venezuela, but these will be harder to identify because the effects of Caribbean-South America collision there are more coeval with those of Proto-Caribbean hanging wall uplift, and the two may interfere. But the issue is large enough for us to question past suggestions of the down-dip continuation of the Misoa depositional system. From central Venezuela to Trinidad and possibly to Barbados, the Proto-Caribbean subduction zone produced a N-vergent fold-thrust belt at the foot of the South American Plate's Paleogene hanging wall margin. We have found no evidence whatsoever that any of this accreted continental slope and rise material was thrust tectonically or shed depositionally southward onto the South American shelf margin until after it was first incorporated into the migrating Caribbean accretionary belt, and thus obducted diachronously from west to east with Caribbean elements. This occurred at about 15 to 20 km/my back to the Paleocene: Paleocene in Guajira, Late

Eocene in Falcon, Oligocene in Guarico Basin, and Middle Miocene in the Maturín-Southern Basin, as shown by cooling ages on obducted terranes and foredeep subsidence history ahead of the allochthons (Pindell et al, 1991).

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