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Anatomy of an evolving island arc: tectonic and eustatic control in the south Central American fore-arc area

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ABSTRACT

The southern part of the Central American isthmus is the product of an island arc. It evolved initially as a ridge of primitive island-arc tholeiites at a collision zone between the Farallón plate and proto-Caribbean crust (Albian–Santonian). During the Campanian, a major tectonic event (most probably subduction reversal) caused décollement of different units of the former plate margin. The resulting structural high was covered by a carbonate platform. From Maastrichtian to Eocene times continuous subduction produced a stable morphotectonic configuration (trench-slope–outer-arc–fore-arc–calcalkaline-arc). Fore-arc sedimentation was controlled by volcaniclastic input and tectonic activity along the outer arc's inner margin. Eustatic control is essentially recognized through lowstand signals such as extensive turbidite sand lobes. Steady accretionary uplift of the outer arc gradually closed the bypasses between fore-arc and trench slope. Eustatic control is verified by lowstand signals (sands) on the trench slope and highstand signals on the outer arc (carbonate ramps). During the Oligocene another major tectonic event affected the entire system: accretion ceased, segments decoupled, and regional compression resulted in general uplift and erosion. From latest Oligocene to Pliocene times, three episodes of tilting created a series of fault-angle depressions. Subsidence varies enormously among these basins, but sedimentation is largely shallow marine. Facies architecture reflects complex interactions between tectonic processes, changes in volcaniclastic sediment supply, and eustasy. Subsequently, very strong explosive volcanic activity resulted in excessive sediment input that overfilled most basins. The history of the island arc shows that tectonic processes largely controlled composition, distribution, and geometry of the major sedimentary units. Eustatic signals do indeed occur when they are expected, but may be considered as an overprint rather than a dominating factor.

INTRODUCTION

Island arcs are considered highly mobile tectonic belts. The aim of this paper is to evaluate whether control on island arc sedimentation is predominantly tectonic or whether other factors, such as volcanogenic sediment supply or eustatic changes, are important. The paper comprises: (1) a compilation of the present-day structural data, (2) a summary of the magmatic evolution, and (3) a step-by-step reconstruction of the evolutionary stages of the south Central American island arc to its present-day mature stage, with concomitant evaluation of data. In some cases it has proved almost impossible to present 'proper' references, as most of the data we work with are still in unpublished Costa Rican 'Licenciatura' theses and German PhD theses. In this context, it should be mentioned that this paper summarizes the results of very successful joint field work of Costa Rican and German workers, which started in 1985 with three small groups and now comprises 18 persons.

OUTLINE OF THE TECTONIC SITUATION

Fore-arc area

Central America is situated at the western margin of the Caribbean plate near the triple junction of the Cocos, Nazca, and Caribbean plates (Fig. 1). Along the Middle America Trench, the Cocos plate is currently being subducted beneath the North American and Caribbean plates. Two aseismic ridges (Tehuantepec Ridge and Cocos Ridge) intersect the Middle America Trench off southern Mexico and southern Costa Rica, respectively. The Cocos Ridge marks the southern end of the Middle America Trench.

Southern Costa Rica

In southern Costa Rica, the arrival and initial subduction of the Cocos Ridge during the Quaternary (Lonsdale & Klitgord, 1978) has affected the arc–trench system in many ways.

Fracture zones. The plate boundary between the Nazca and Cocos plates jumped from the Coiba Fracture Zone to the Panamá Fracture Zone (which now borders the Cocos Ridge towards the east), shearing off the Coiba Ridge (van Andel *et al.*, 1971; Lonsdale & Klitgord, 1978; see Fig. 1). Recent seismic activity suggests that the plate boundary might displace again towards the west and establish in the Quepos area (Burbach *et al.*, 1984; Morales, 1985). A fracture zone along the western margin of the Cocos Ridge ('East Nicoya Fracture Zone'; Corrigan *et al.*, 1990) slightly displaces the trench towards the northeast (Burbach *et al.*, 1984; Morales, 1985; see Fig. 2). This fracture zone extends towards mainland Costa Rica, where it joins a system of braided transcurrent faults in the Valle Central area (Montero & Dewey, 1982), which has been active since at least the Oligocene (Rivier & Calvo, 1988; Astorga *et al.*, 1989). Further to the east, it merges in the Limón thrust belt, thus dissecting the isthmus into two tectonically independent parts (Astorga *et al.*, 1989; compare Figs 1, 2). In this paper, this composite structural feature is referred to as the 'Trans-Isthmic Fault System'; the area affected is called 'Dissected Zone of Central Costa Rica'.

Isostatic adjustment. Isostatic compensation produced uplift and deformation in the fore-arc (Corrigan *et al.*, 1990). In cross-section (Fig. 2), this appears as a series of arcward-tilted uplifts and fault-angle depressions (Seyfried *et al.*, 1987). According to Gardner *et al.* (1987), Wells *et al.* (1988), Corrigan *et al.* (1990) and Adamek *et al.* (1987), a major fault ('longitudinal fault', see Fig. 2), most probably with a strike-slip component, indicates tectonic decoupling between the outer and inner fore-arc areas.

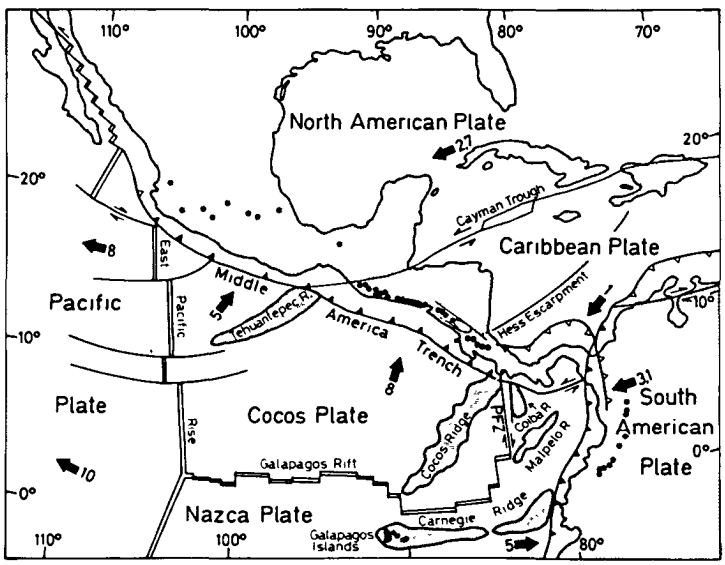

Fig. 1. Tectonic setting of Central America. Redrawn after Drummond (1981). Black arrows indicate drift directions; numbers represent absolute movements in cm/ yr; black dots are active volcanoes.

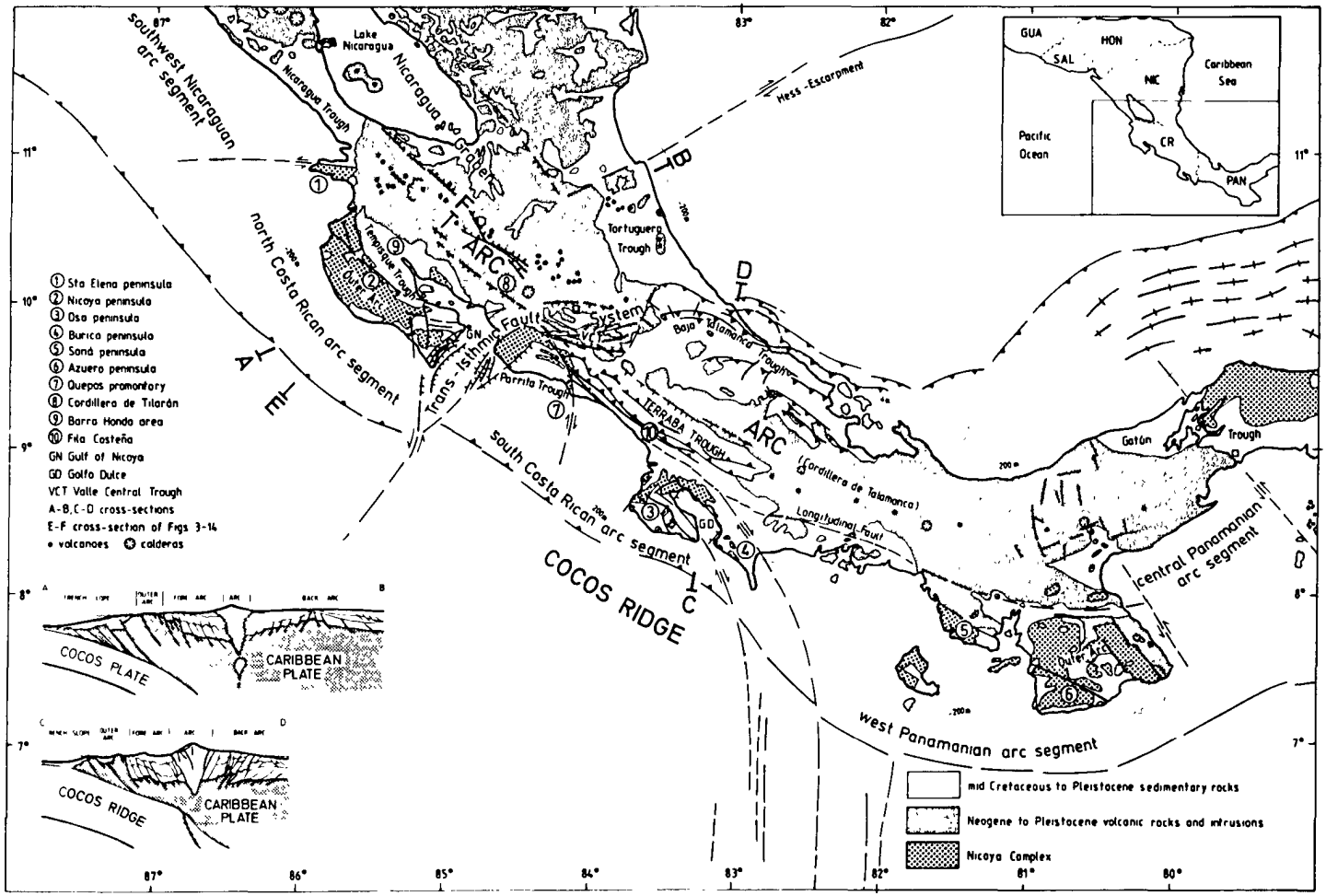

Fig. 2. Structural map of southern Central America, showing major tectonic elements, main tectonostratigraphic units, large sedimentary basins, and localities mentioned in text. Synthesized after Case & Holcombe (1980), Dengo (1962), Campos (1987), Fernandez (1987), Gardner *et al.* (1987), Berrangé & Thorpe (1988), de Boer *et al.* (1988), Denyer & Montero (1989), Astorga *et al.* (1989), Berrangé *et al.* (1989), and unpublished mapping by the authors.

Uplift history. According to Morales (1985) and McGeary *et al.* (1985), spatial gaps in arc volcanism indicate collision with oceanic plateaux. In southern Costa Rica, the width of the Cocos Ridge corresponds almost exactly to the breadth of the summit level of the Cordillera de Talamanca, which is the volcanically inactive segment of the arc. In the Chirripó area (with a present maximum altitude of 3820 m), mid-Miocene shallow-water volcaniclastics, pyroclastic flows, lahars, and intrusive granodiorites (G. Calvo, 1987; Wunsch, 1988), as well as late Pleistocene moraines (Weyl, 1956), indicate the maximum timespan for the uplift. Detrital quartz appears for the first time in upper Miocene shallow-water deposits of the back-arc basin (Campos, 1987); granodioritic boulders follow in lower Pliocene fan-delta deposits (Bottazzi, personal communication, 1989; F. Alvarado, 1984). Thus, the uplift of the Cordillera de Talamanca must have started as early as the late Miocene. This early uplift may have been a side-effect of the collision between the Panamá block and northwest South America (Wadge & Burke, 1983; Mann & Burke, 1984; Pindell *et al.*, 1988). According to S. Mora (1979), Rivier (1985), and Rivier & Seyfried (1985), the imbrication of the Fila Costeña and Limón thrust belts along the flanks of the Cordillera de Talamanca (see Fig. 2) also can be placed into the late Miocene timespan. Subsequent arcward tilting of both thrust belts also affected late Pliocene to early Pleistocene alluvial fans (Campos *et al.*, 1984) and thus can be dated as late Pleistocene. It is considered to be an effect of the compression exerted by the approaching Cocos Ridge (Heywood, 1984; Corrigan *et al.*, 1990).

Northern Costa Rica

North of the Trans-Isthmic Fault System, the neotectonic situation is less complicated than in southern Costa Rica. In a cross-section from SW to NE (Fig. 2), it appears that tilting is also arcward. There are only minor trenchward thrusts in the inner fore-arc region prior to tilting ('Barra Honda' area; see Fig. 14); imbrication occurred more or less simultaneously with the Fila Costeña and Limón thrusts (C. Calvo, 1987). The trench slope is rather uniform and reaches the Middle America Trench without any indications of an approaching aseismic ridge (Mora, 1985; Crowe & Buffler, 1985). The present volcanic arc has been very active since at least Pliocene times (Tournon, 1984; G. Alvarado, 1985).

The present-day neotectonic features of the fore-arc area in southern Central America are the result of a rather complex structural history. The present arc is divided into the following segments (Fig. 2): southwest Nicaraguan arc segment, north Costa Rican arc segment, south Costa Rican arc segment, west Panamanian arc segment, and central Panamanian arc segment. Each segment has an individual structural, magmatic, and sedimentary history. This study deals mainly with the north and south Costa Rican arc segments and the dissected zone in between.

Back-arc area

From a structural point of view, the back-arc area is far less complicated than the fore-arc area. Since the Late Cretaceous, a thick (almost 8 km) shallowing upward sedimentary sequence has been laid down more or less continuously (Fig. 3). The final transition from marine to terrestrial deposits started in the mid-Miocene (Obando, 1986; Calvo & Bolz, 1987); in places, marine ingressions are recorded until the early Pliocene (Astorga *et al.*, 1989). Seismic data reveal that an 'outer' structural high was emergent during the late Eocene.

The Trans-Isthmic Fault System divides the back-arc area into two structurally different regions: the Baja Talamanca Trough in the south and the Tortuguero Trough and Nicaragua graben in the north (Fig. 2). In the Baja Talamanca Trough (Rivier & Seyfried, 1985), late Miocene thrusting has been related to the initial uplift of the Cordillera de Talamanca and to the collision of the Panamá block with northwest South America, respectively. The Limoń Thrust Belt merges in the 'Panamá Deformed Belt' (Heywood, 1984; Vitali, 1985; see Fig. 2). Huge, extremely coarse Pliocene to lower Pleistocene clastic wedges were trapped between the imbricated sheets of the Limón Thrust Belt. Late Pleistocene arcward tilting was caused by the collision with the Cocos Ridge.

The Tortuguero Trough (see Fig. 2) is the undeformed northern complement of the Talamanca Trough; extensive coastal swamps indicate that the basin is still subsiding. According to Astorga *et al.* (1989), the Nicaragua graben started to subside in the late Miocene; there is sedimentological evidence that the graben was still active at the beginning of the late Pliocene (Kolb, 1990). It extends from the Honduran Pacific coastal borderlands through Nicaragua (Lake Managua and Lake Nicaragua) to northern Costa Rica, where the southeastern termin-

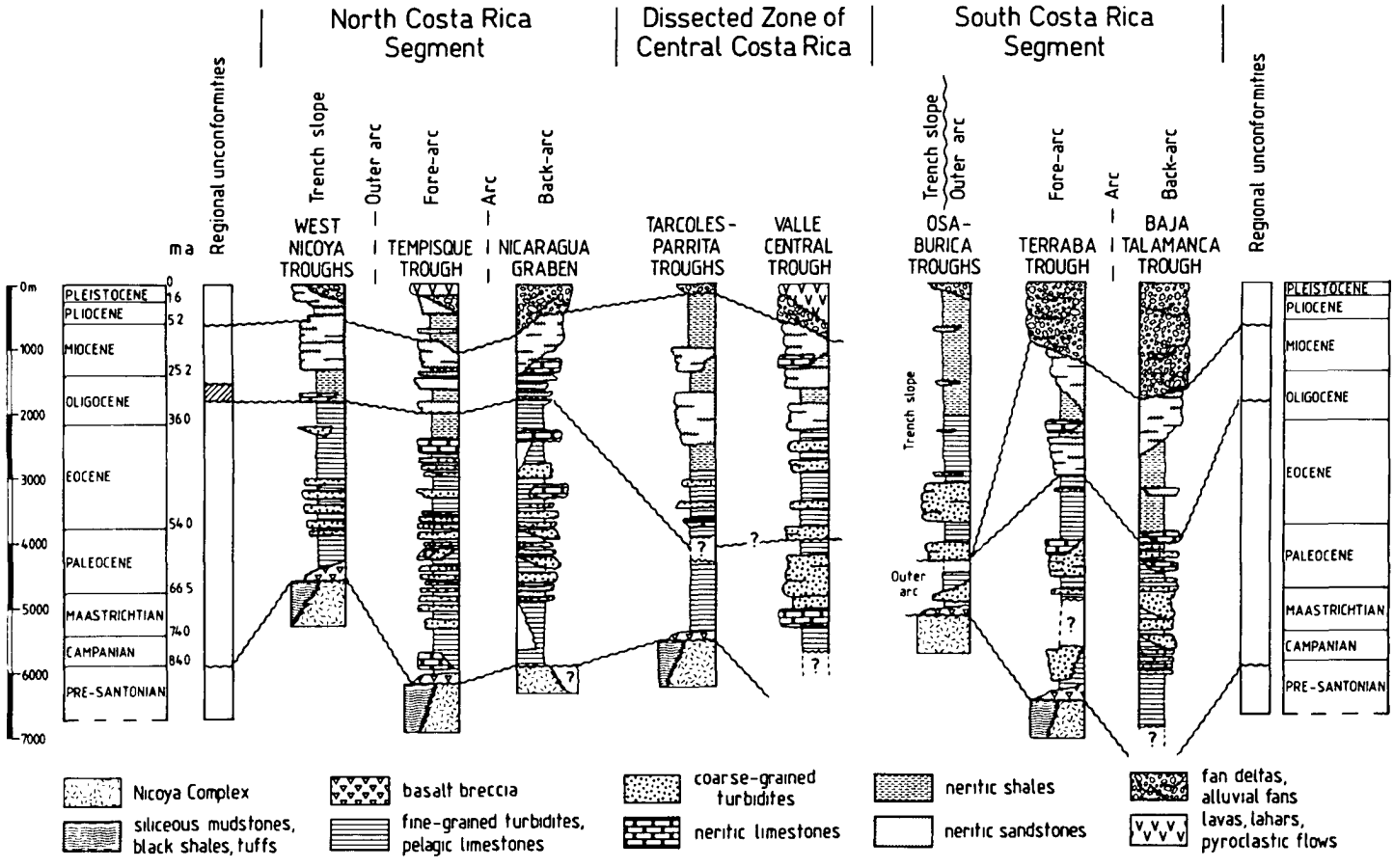

Fig. 3. Generalized stratigraphic sections along and across the Costa Rican part of the south Central American isthmus. For location, compare with Fig. 2. Compiled after Astorga *et al.* (1989), Rivier & Calvo (1988), Corrigan (1986), and unpublished data from the authors.

ation is obscured by Quaternary volcanics (see Figs 1, 2). Existing geological maps suggest (but provide no definite evidence) that the master faults cut across an older, ENE–WSW-striking structure, which is considered to represent the onshore prolongation of the Hess Escarpment (Burke *et al.*, 1984; Astorga *et al.*, 1989; compare Figs 1, 2). Most probably, it is this same fault that reappears underneath Quaternary volcanics at the Pacific side of Costa Rica in the area of the Santa Elena Peninsula (Tournon & Azéma, 1980; Burke *et al.*, 1984; see Fig. 2). Calvo (1987), Astorga (1988), and Winsemann & Seyfried (in their chapter) demonstrate that this fault (or one of its predecessors) has been active at least from Late Cretaceous to early Eocene times; in contrast, the geological situation at the Caribbean side (see Fig. 2) suggests that it may have been active even until the Pliocene.

THE MAGMATIC SUITE

Outer arc

Northern Costa Rica

In northern Costa Rica, the basement of the outer arc is formed by harzburgites and lherzolites (and their serpentinized equivalents), dunites, gabbros, plagiogranites, normal and transitional 'mid-ocean ridge' basalts (N-MORB, T-MORB), within-plate alkalibasalts and within-plate tholeiites (WPA, WPT), and 'island-arc' tholeiites (IAT) (Jager, 1977; Kuypers, 1980; Tournon & Azéma, 1980; Tournon, 1984; Wildberg, 1984,1987; Bourgois *et al.*, 1984; Azéma *et al.*, 1985; Desmet & Rocci, 1988; Meschede *et al.*, 1988; Sick, 1989; Appel, 1990). Discontinuous units of radiolarites found among the basalts have been assigned ages ranging from early Liassic until Santonian (de Wever *et al.*, 1985; Schmidt-Effing, 1979,1980; H.J. Gursky & Schmidt-Effing, 1983; Baumgartner, 1984,1987; Baumgartner *et al.*, 1984; Azéma *et al.*, 1985; H.-J. Gursky, 1988). Dengo (1962) named this ensemble the 'Nicoya Complex'. Schmidt-Effing (1979), Wildberg (1984), M.M. Gursky (1986), and H.-J. Gursky (1988,1989) made a further subdivision into 'Lower Nicoya Complex' (LNC), which comprises the oceanic suite, and 'Upper Nicoya Complex', which contains island-arc tholeiites and their associated sediments as well as within-plate basalts, which Wildberg (1984) related to the Santonian 'Caribbean flood basalt event' *sensu* Donnelly (1975,1985).

No radiometric age determinations older than 85 Ma (late Santonian) have been obtained so far from the Nicoya Complex. According to G. Alvarado (written communication), most determinations concentrate between 65 and 55 Ma (Paleocene). Recently, Appel (1990) also obtained K–Ar ages between 65 and 54 Ma, with samples coming from both the Lower and Upper Nicoya Complexes. He draws the conclusion that these ages, which are not in agreement with biostratigraphic and sedimentological data, represent alteration ages due to a thermal event. Kussmaul (1987) inferred that widespread crustal heating is needed to create the extensive granitic batholiths that penetrated the Cordillera de Talamanca during the Miocene. Because of the location (calc-alkaline arc) and age of these intrusions, this possibility should be discarded as a source of Paleocene heating in the outer arc. Marshak & Karig (1977), Hill *et al.* (1981), and Forsythe *et al.* (1986) argued that short-lived pulses of thermal and magmatic activity in the fore-arc area might be related to the subduction of an oceanic spreading centre. The WPT, which have recently been recognized throughout the outer arc area, are mostly attributed a Paleocene age, but their geochemistry does not correlate with an MOR derived magma. In addition, it is still not clear whether their emplacement was hot (intrusion) or cold (obduction).

Southern Costa Rica

Osa and Burica Peninsulas. This area shows basement rocks similar to the outer arc of northern Costa Rica (mainly T-MORB, N-MORB, IAT, and radiolarites; Lew, 1983; Tournon, 1984; Obando, 1986; Berrangé & Thorpe, 1988; Berrangé *et al.*, 1989; Sick, 1989; Appel, 1990). Biostratigraphically and radiometrically obtained ages range from Early Cretaceous to mid-Eocene (Azéma *et al.*, 1981; Lew, 1983; Tournon, 1984; Baumgartner, 1987; Berrangé *et al.*, 1989). Recently, WPA and WPT have also been identified in the Osa–Burica area (Berrangé & Thorpe, 1988; Sick, 1989; Appel, 1990). The spatial and genetic relations of these intra-plate basalts with the MORB and IAT units are still unclear. They might correspond to the younger magmatic events (Paleocene, mid-Eocene) that have been identified by Azéma *et al.* (1981), Tournon (1984), and Berrangé *et al.* (1989).

Quepos promontory and Parrita Basin. Wildberg (1984), Sick (1989), and Appel (1990) reported extensive outcrops of WPB (which commonly display high contents of vesicles) and IAT (with almost no vesicles). According to Azéma *et al.* (1979a) and Baumgartner *et al.* (1984), interpillow sediments assign these basalts an early Paleocene age. In contrast, Appel (1990) obtained K–Ar ages that spread around 46 Ma (mid-Eocene). Azéma *et al.* (1979a) and Sick (1989) describe both cold and hot contacts with overlying sediments. The presence of IAT and the occurrence of boulders of radiolarite and pebbles of Late Cretaceous limestones (Henningsen, 1966) among lower Paleocene conglomerates, which overlie the basalts in places, point to the existence of an older, Nicoya Complex type, basement in this area. These data allow two explanations: (1) cold emplacement – the intra-plate basalts are sheared-off remnants of a subducted seamount that obducted on to the trench slope and subsequently became uplifted (Sick, 1989; Appel, 1990); (2) hot emplacement – as in the Osa–Burica area, a two-phase magmatic evolution might explain the superposition of WPB over IAT. The intrusion of an alkaline magma into an island arc, however, requires a back-arc setting. This in turn means a temporary reversal of subduction polarity in the south Costa Rica arc segment. A back-arc origin has already been seriously discussed by Berrangé & Thorpe (1988) for the basalts of the Osa–Burica area. However, apart from the Paleocene heating event there are no further unambiguous facts that would point to subduction reversal. In the following, we shall adapt the obduction hypothesis as a working base. The question of the Paleocene thermal event must remain open for the time being.

Palaeomagnetic data

Sick (1989) reports counter-clockwise rotations for the different units of the Nicoya Complex ranging from 90° to 37°. The different amounts of rotation are explained as a result of Campanian shear tectonics. The Nicoya Complex must have originated at near-equatorial latitudes. The tracks of relative motion of the Nicoya Complex and South America are almost exactly parallel from Late Jurassic until Oligocene times. This implies that an origin at a suture within the Pacific plate (as proposed by Burke *et al.* (1984) and Ross & Scotese (1988)) must be discarded. Post-Campanian rocks of the north Costa Rican arc segment do not show rotations, whereas their equivalents from the southern sector register slight differential rotations.

The calc-alkaline arc

Palaeogene volcanics

In northern Costa Rica, the first appearance of calc-alkaline volcanic detritus in the fore-arc sedimentary record dates back to the Maastrichtian (Tournon, 1984; Astorga, 1988; see chapter by Winsemann & Seyfried). Measured transport directions and proximality estimations throughout the Palaeogene fore-arc sequence (Astorga, 1987) clearly indicate that a calc-alkaline island arc must have grown rapidly behind the outer arc suite at a distance that more or less corresponds to the present-day distance between outer arc and arc. In the present situation, however, the greater part of the Paleogene arc is deeply buried underneath younger volcanics and hardly accessible to direct observation. Thus the only evidence of Paleogene magmatic activity comes from the detritus that has been shed into the fore-arc basin. Owing to strong alteration, geochemical analyses of boulders taken from different stratigraphic levels have so far failed to give more insight into possible geochemical trends in arc evolution. According to Astorga (1988) and the chapter by Winsemann & Seyfried, the presence of autoclastic flow breccias and boulders of rhyolitic tuffs among coarse-grained late Eocene deep-water channel-fill deposits indicates that magma differentiation must have reached a first climax during the Eocene.

In southern Costa Rica, parts of the Paleogene calc-alkaline arc are exposed along the Cordillera de Talamanca. Weyl (1957) and Pichler & Weyl (1975) mainly report andesites. So far, rhyolitic rocks have not been reported from this area.

As to Oligocene magmatic rocks, there are almost no data. It seems probable that there was little activity throughout the entire isthmus.

Miocene volcanics and intrusions

Miocene calc-alkaline rocks have been studied in much detail by Pichler & Weyl (1973,1975), Kussmaul *et al.* (1982), Tournon (1984), Kussmaul (1987), and Appel (1990). An assemblage of plutonic rocks ranging from gabbros to alkali granites was intruded as laccoliths or batholiths mainly into the Cordillera de Talamanca and the Cordillera de Tilarán area (Fig. 2). K–Ar age determinations

spread around 19 Ma (gabbros; Appel, 1990) and 11.5–8 Ma (granitoids; Tournon, 1984; Appel, 1990). Volcanic rocks, mainly of andesitic composition, are reported from both early and late Miocene times (Tournon, 1984). Parts of a large late Miocene volcano (with intercalated shallow marine sediments) are still preserved in the Chirripó area (G.Calvo, 1987; Wunsch, 1988).

Pliocene and Quaternary volcanics

According to Pichler & Weyl (1975), Kussmaul *et al.* (1982), Tournon (1984), G. Alvarado (1985), Kussmaul (1987), Nyström *et al.* (1988), and Appel (1990), the Pliocene to Quaternary volcanics of the isthmus area cover a wide spectrum ranging from basaltic andesites to rhyolites. Most volcanoes correspond to the pyroclastic cone and the caldera type (O. Mora, 1989). Geochemically, the volcanic rocks can be subdivided into an alkaline and a calc-alkaline group. The alkaline group is mostly concentrated in the back-arc area, but sporadic occurrences in the arc region are also recorded. The calc-alkaline group still shows transitions towards IAT and displays extreme differentiations, which according to Pichler & Weyl (1975) and Kussmaul (1987) reveal that the island arc had entered into the 'mature' stage.

THE SEDIMENTARY SUITE

Figure 3 shows eight highly generalized, synthesized stratigraphic columns that correspond to the major tectonostratigraphic units of Costa Rica (for location, compare with Fig. 2). These columns reveal that the way in which sequences developed is comparable throughout the entire isthmus:

1 the overall pattern is shallowing upward (SU) (in the Osa–Burica Trough, there are two SU sequences);

2 during the late Paleocene, mid- to late Eocene, and latest Oligocene, carbonate ramps appear simultaneously along the flanks of both outer arc and arc;

3 major unconformities, which appear in the earliest Campanian, the late Oligocene, and the earliest Pliocene, are correlatable on a regional scale (900 km from southwestern Nicaragua to mid-western Panamá; see Fig. 3).

Biostratigraphic control is commonly very poor owing to strong diagenetic alteration, especially in fine sandstones (which account for approximately 70% of the total sediment volume of the island arc). Good control has been obtained with (1) pelagic and neritic limestones, (2) turbidites containing larger Foraminifera as grains, (3) some of the radiolaria-bearing sediments, and (4) some of the neritic shales. Again, this accounts for, at best, 5% of the total sediment volume. Fortunately, there are some regional marker horizons, for example an amber layer in the early Pliocene (Schmidt, 1989; Kolb, 1990). Further stratigraphic details are given in the papers by Winsemann & Seyfried, Schmidt & Seyfried, and Kolb & Schmidt.

Figures 4–14 summarize the main stages of development of the fore-arc area in the north Costa Rican arc segment from the Mid-Cretaceous until the present (for location of the cross-sections, see Fig. 2). At this stage of our investigations, the data base for an extension of these cross-sections into the back-arc area, or even into the south Costa Rican arc segment, is still insufficient. The sections were drawn mostly perpendicular to the present trench and are not to scale. The main structural elements and their internal facies architecture have been reconstructed on the basis of field observations by the authors, published sedimentological and biostratigraphical data, Costa Rican geological maps and 'licenciatura' theses (Escuela Centroamericana de Geología, University of Costa Rica), and seismic profiles (mainly Crowe & Buffler (1985), Shipley & Moore (1986), and Astorga *et al.* (1989)). As to the incorporation of geochemical data, it must be emphasized that there are still some open questions. Thus, in the course of drawing the cross-sections we had to adopt working hypotheses that are still subject to further proof.

Albian to early late Campanian (Figs 4, 5)

Observations

The first sedimentary unit that shows a genetic relationship to incipient island-arc magmatism ('primitive' IAT) is composed of black shales, siliceous mudstones, and tuffs. Azéma *et al.* (1979b) and Baumgartner (1987) assigned this formation an age between Albian and Santonian; Astorga (1987) provided sedimentological details and named the unit 'Loma Chumico Formation'.

The next sedimentary unit is a predominantly basaltic sedimentary breccia; the contact with the underlying sedimentary and magmatic rocks is a regional unconformity (cf. Fig. 3). This breccia

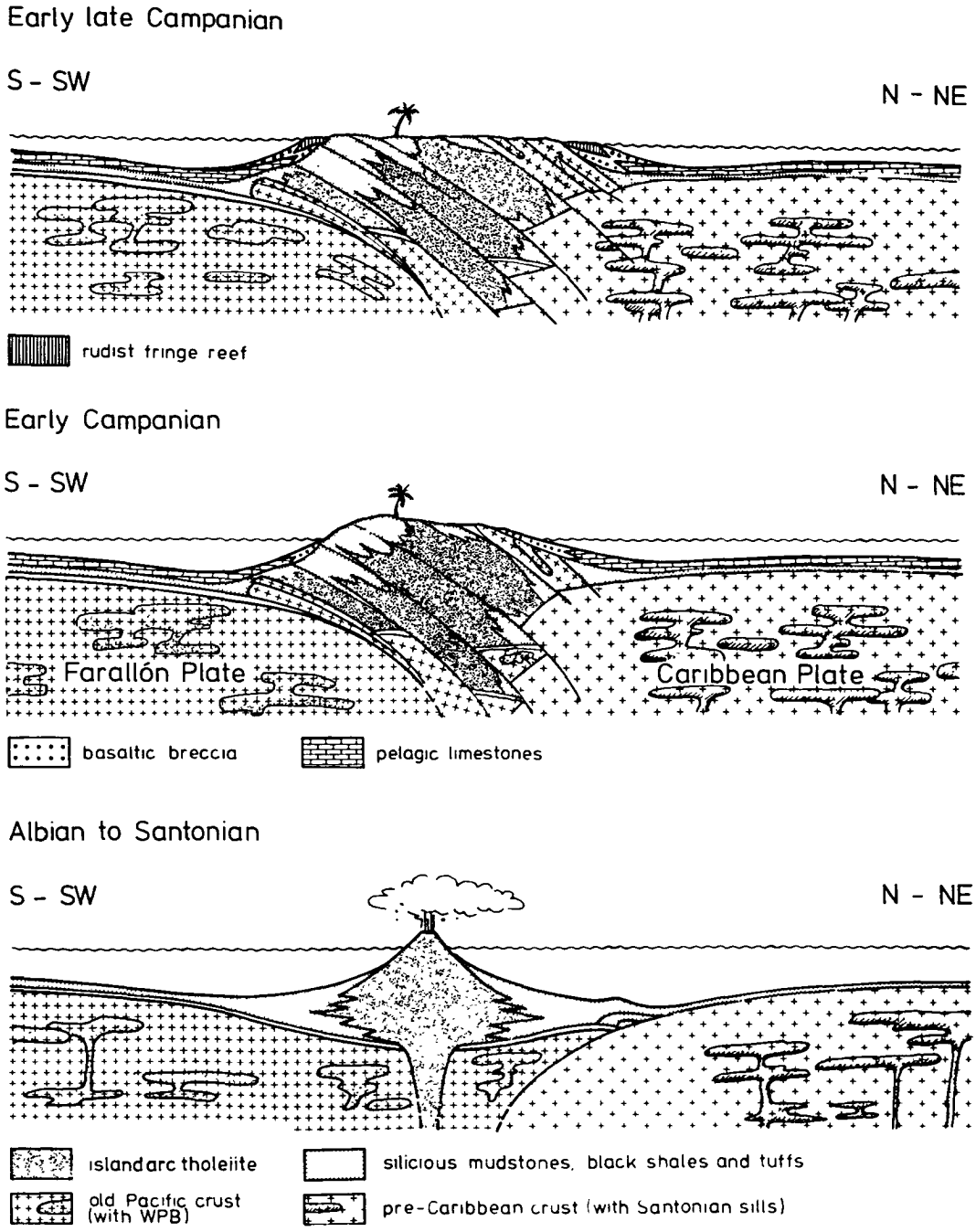

Fig. 4. Alternative A. Subduction reversal model as an explanation for the major tectonic event that affected the initial island arc during the early Campanian. The originally S–SW-directed subduction was reversed as the proto-Caribbean crust became unsubductable after the Santonian 'sill-event' The wedge between the reversing subduction zones was telescoped by décollement. During the early late Campanian, the first rudist fringe reefs established on the structural high

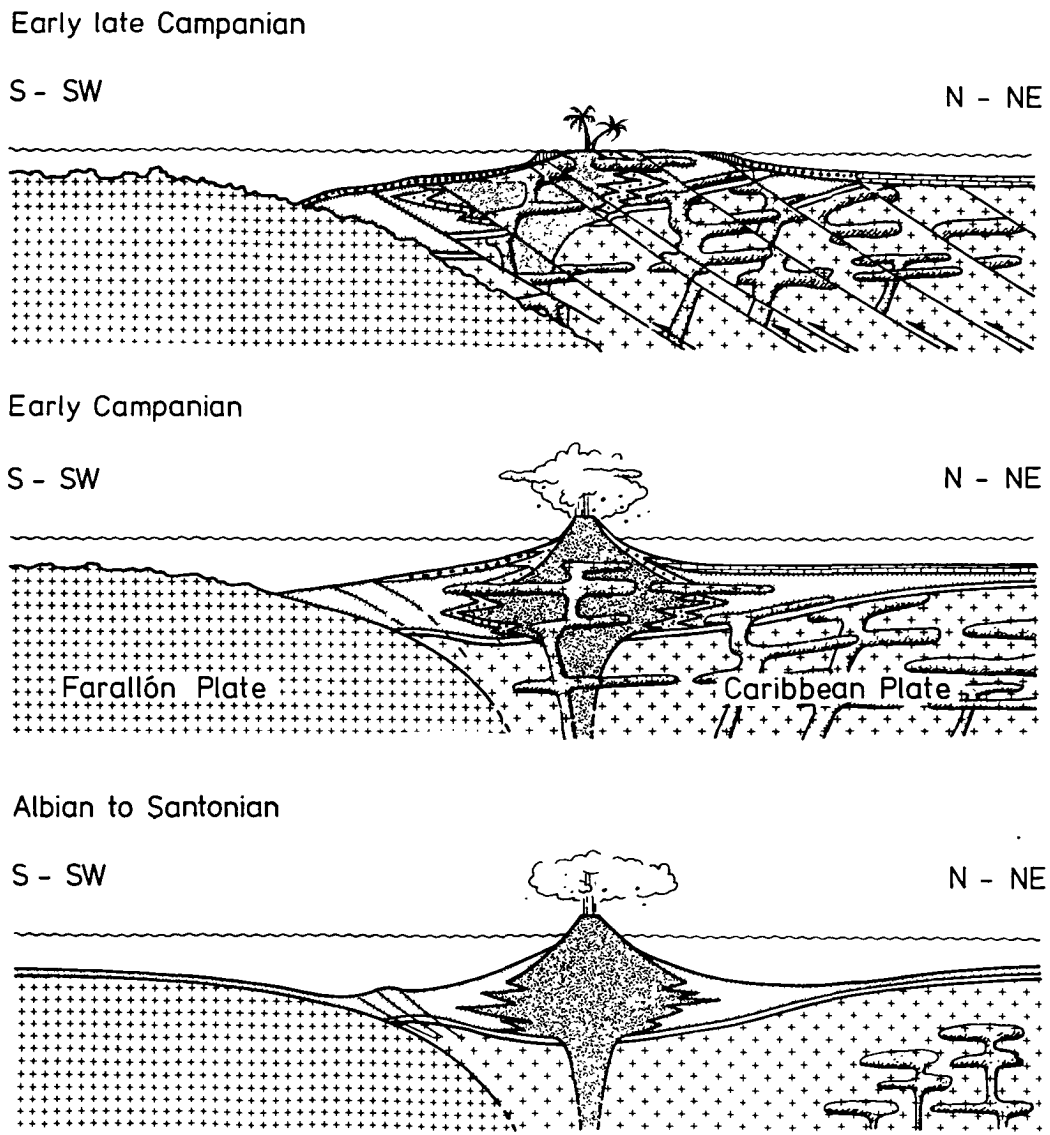

Fig. 5. Alternative B. Continuous subduction model as an alternative explanation for the major tectonic event that affected the initial island arc during the Campanian. In contrast to alternative A, continuous N–NE-directed subduction is assumed. Initial subduction would have been triggered by thickening of the proto-Caribbean crust during the Santonian 'sill-event'. Décollement is explained by strong plate coupling due to the arrival and initial subduction of an oceanic plateau. Symbols are the same as in Fig. 4.

spreads over both the 'Loma Chumico' unit and almost all units of the Nicoya Complex, even the oldest ones (Baumgartner *et al.*, 1984; Sprechmann, 1984). Seyfried & Sprechmann (1986) found that in some places the basal unit of the breccia consists entirely of reddish weathered, basalt rubble and gravel, which obviously formed a debris apron around islands. The upper unit of the breccia contains less-altered, probably cliff-derived basalt detritus and shows intercalations of rudist debris,

which points to initial colonization by rudist fringe reefs. An ammonite (*Canadoceras* sp.) from one of these intercalations allowed this unit to be dated as late Campanian. On a regional scale, these brecciated deposits laterally interfinger with pelagic limestones, which yielded both early and late Campanian ages (Schmidt-Effing, 1979; Baumgartner *et al.*, 1984; Astorga, 1988).

Interpretation

The indiscriminate exposure of both Lower and Upper Nicoya Complex units below the above-mentioned regional unconformity, the appearance of a widespread basaltic breccia above it, and the first appearance of upheaved islands indicate that a major tectonic process must have affected the area during the early Campanian. There are at least two possibilities.

Alternative A (subduction reversal model; Fig. 4). The edifice of primitive IAT was created by S–SW-directed subduction of proto-Caribbean crust underneath Pacific crust. Such a 'stationary' palaeogeographic model would be in accordance with the above-mentioned palaeomagnetic results (Sick, 1989). Crustal thickening during the Santonian 'sill event' rendered the Caribbean crust unsubductable. The ensuing reversal in subduction polarity telescoped the wedge in between, thus producing a stack of former plate-margin slices with the 'deep' units (Lower Nicoya Complex) on top and the 'shallow' units (Upper Nicoya Complex) underneath – which is exactly the situation found today in northern Costa Rica.

This model implies that (1) the entire Nicoya Complex, including radiolarites and WPB, has a Pacific origin, but now lies upon Caribbean crust – this would account for the anomalously thick crust underneath Costa Rica (40 km; Matumoto *et al.*, 1977); (2) the Caribbean sill event would not have had any direct effects upon the arc; (3) IAT volcanism would have stopped from the Santonian onward. Baumgartner *et al.* (1984) and Astorga (1988), however, report some minor volcanic activity from the early Campanian. The strong point of this model is that it explains satisfactorily the drastic spatial, temporal, and genetic separation between the Nicoya Complex and the calc-alkaline arc.

Alternative B (continuous subduction model; Fig. 5). This model starts with the assumption that the edifice of primitive IAT was created by N–NE-directed subduction of Pacific crust underneath proto-Caribbean crust. Such a suture could have developed elsewhere in the Pacific. The palaeogeographic model is not necessarily stationary and thus fits with the scenarios proposed by Burke *et al.* (1984) and Ross & Scotese (1988). The shortening of the overriding plate margin and stacking of slices of Lower Nicoya Complex over slices of Upper Nicoya Complex requires very strong plate coupling and deep-reaching transmission of compressive forces into the Caribbean plate. Such a situation could have developed during the initial collision and subduction of an oceanic plateau. According to the observations made in present-day southern Costa Rica (collision with the Cocos Ridge – see earlier section on tectonics), initial uplift should then be followed by isostatic relaxation (which indeed happened during the next episode).

The model implies that (1) the Upper Nicoya Complex formed at the Caribbean side of the suture upon the Lower Nicoya Complex, which originally was Pacific crust; (2) initial subduction was triggered by thickening of proto-Caribbean crust in the Santonian (evidence from the Loma Chumico Formation suggests, however, that IAT volcanism must have started much earlier); (3) continuous subduction allowed continuous IAT production until the early Campanian; (4) this in turn sets the telescoping event into the early late Campanian. It implies further that the Nicoyan WPB are either the product of the Caribbean sill event or represent accreted slices from a subducted oceanic plateau. Wildberg (1984) and Sick (1989) favour an origin as Caribbean sills; the latter even provided an indirect palaeomagnetic age determination (33r isochron = Campanian). In our opinion, however, it is difficult to imagine how these Caribbean sills should have penetrated during the entire Santonian to early Campanian timespan right into the leading edge of the Caribbean plate, where they interfered with active IAT volcanism.

As matters stand, neither of the alternatives presents unambiguous interpretations. In the following, we shall adapt model A as a working hypothesis.

Terminal Campanian to early late Maastrichtian (Fig. 6)

Observations

Seyfried & Sprechmann (1986) reported that the

first deposits that can be found upon the above-mentioned upheaved islands are thin patchy veneers of extremely coarse basaltic and ultramafic debris. Outcrops on the Santa Elena Peninsula and in the Tempisque Basin provide excellent evidence that large areas were overgrown by rudist reefs. Obviously, the biodetritus supplied by these reefs helped smooth the pre-existing relief. In places, the reefs even grew over rocky relief. A considerable portion of the former islands remained emerged, still exposing Nicoya Complex and rocks of the Loma Chumico Formation.

Subsequently, the entire relief was covered by a carbonate platform ('Barra Honda Formation'). Bio-

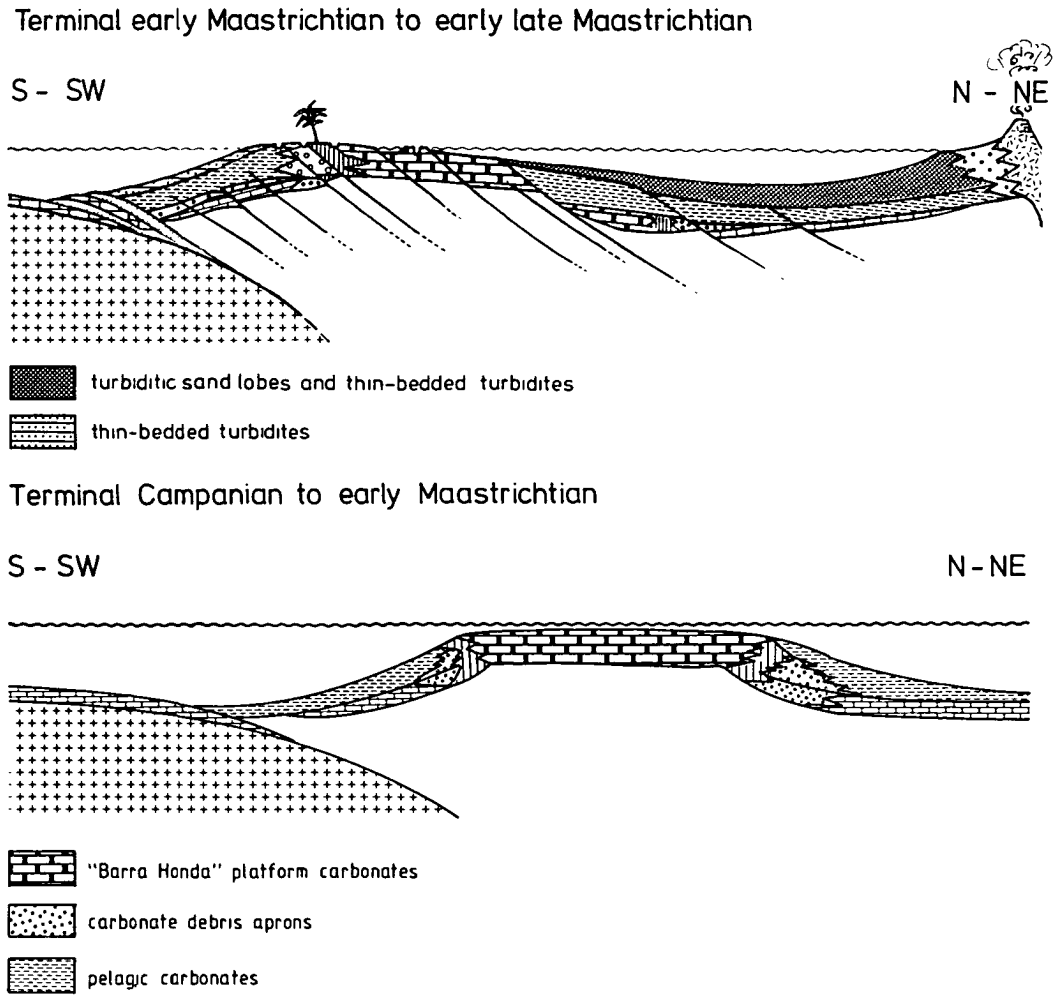

Fig. 6. During the latest Campanian to early Maastrichtian episode, a carbonate platform became established upon the subsiding structural high. Subsidence is explained by isostatic relaxation. The bank sequence, however, records several phases of short-term exposure, which means that carbonate production compensated subsidence. During the early to late Maastrichtian transition, a final karstification occurred, which most probably represents a eustatic overprint over steady uplift due to incipient accretion. During that episode, the activity of a calc-alkaline arc becomes increasingly evident. By now, the classical subdivision into trench slope, outer arc, fore-arc, and calc-alkaline arc is clearly established. Connections between the fore-arc and the trench slope, however, must have existed as sand lobes obviously correlate with thin-bedded turbidite systems.

stratigraphical data (C. Calvo, 1987; Sprechmann *et al.*, 1987) prove that this platform was initiated in the latest Campanian and ended shortly before the end of the early Maastrichtian. Microfacies analysis (C. Calvo, 1987) revealed that micritic facies types predominate; towards the windward side, they were protected by fringing coral reefs. The bank sequence records several minor meteoric diagenetic events and a final karstification episode.

In basinal areas, during the early Maastrichtian, turbiditic sand lobes and thin-bedded turbidite systems, composed of andesitic material, gradually replaced carbonate oozes. Thin-bedded turbidites, which are also typical of the trench slope area, have been observed to prograde diachronically over the eastern parts of the 'Barra Honda' platform.

Interpretation

The gradual overgrowth, firstly by fringing rudist reefs, and then by a carbonate platform, of the formerly upheaved islands clearly points to subsidence by isostatic relaxation, probably aided by a relative rise of sea level. Several minor meteoric diagenetic events recorded in the bank sequence might correspond to small-scale, short-term sea-level fluctuations. The final karstification event could be explained by uplift of the outer arc. Seismic data reveal (though not very clearly) that accretion must have started more or less during this episode and thus could have provoked the uplift.

During later development (see Figs 7, 8) the most uplifted parts of the platform became the nucleus of the outer arc. The less uplifted eastern parts subsided and were rapidly buried underneath thick units of fore-arc turbidites, derived from a rapidly rising calc-alkaline arc. Thus, the differences in tectonic style between outer arc and fore-arc must have started to develop during this episode. In addition to this purely tectonic explanation it must be emphasized, however, that a significant drop of sea level could also have produced the karstification event. In our opinion, a eustatic overprint over steady uplift in the outer arc and continuing subsidence in the fore-arc would best explain the given situation.

Latest Maastrichtian to early late Paleocene (Fig. 7)

Observations

At the beginning of this episode, the pattern of sedimentation was still dominated by turbidites spreading over the entire area. During the early Paleocene, however, parts of the former trench-slope turbidite sequence were removed along deep incisions. In the earliest late Paleocene these features were being filled with debris deriving from both the arc and the former 'Barra Honda' platform (Baumgartner *et al.*, 1984; Astorga, 1988). Simultaneously, a carbonate ramp began to develop discontinuously along both sides of the outer arc, shedding grainflows of larger Foraminifera into the adjacent basins. In the fore-arc trough, turbidite systems became increasingly coarser.

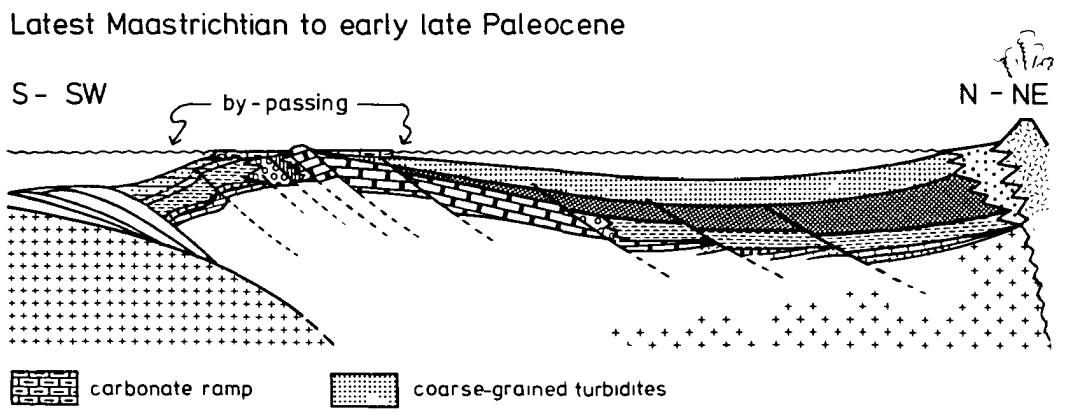

Fig. 7. During this episode, the outer arc was first overgrown by a carbonate ramp and then undercut by canyons. The growth of the ramp is considered as a highstand signal, whereas the canyon cuts are believed to represent a lowstand signal. The uplift of the outer arc is attributed to accretion.

Interpretation

The incisions at the edge of the outer arc can be interpreted as canyon cuts. Their filling proves both a direct connection to the fore-arc and exposure of parts of the 'Barra Honda' platform in the outer arc. Thus, it may be assumed that the outer arc was tilted towards the arc and cross-cut by canyons that allowed bypassing of debris coming from the arc. Concomitant with tilting, carbonate ramps started to form along the edges of the outer arc. Boulders from that ramp are found in the canyon fill debris, where they occur with boulders from the 'Barra Honda' platform. As to the causes of tilting, again a combination of continuing accretion and eustatic overprint could have produced the observed situation. The occurrence of carbonate megabreccias along the inner edge of the outer fore-arc, however, might be considered as a strong tectonic signal indeed (C. Calvo, 1987; Seyfried *et al.*, 1987; Astorga, 1988; for further details, see paper by Winsemann & Seyfried).

Terminal late Paleocene (Fig. 8)

Observations

The carbonate ramp continued to grow during this episode. In the fore-arc, turbidites became again predominantly thin-bedded. Along the trench slope, sedimentation turned to siliceous limestones.

Interpretation

No obvious structural changes are observed during this episode. The continuing growth of the ramp, together with the onset of siliceous limestone deposition on the trench slope, and the return, in the fore-arc basin, from coarse-grained to fine-grained turbidites clearly indicate that the situation was controlled by rising sea level. The overall trend signals an increasing separation between fore-arc and trench slope (Lundberg, 1982; Astorga, 1988; see paper by Winsemann & Seyfried). Continuing accretion in the trench is indicated by seismic data (Crowe & Buffler, 1985).

Early to mid-Eocene (Fig. 9)

Observations

In the trench slope area, sedimentation continued with siliceous limestones. Intercalations of allodapic limestones are reported from the mid-Eocene (Baumgartner *et al.*, 1984; C. Mora, 1985; C. Calvo, 1987). The carbonate ramp on the outer arc continued growing along the inner flank. During the mid-Eocene, it extended on to the outer flank (C. Calvo, 1987). Sedimentation in the fore-arc was still characterized by thin-bedded turbidites. Towards the mid-Eocene, volcaniclastic influx increased gradually, creating minor lobe systems in the inner fore-arc. There is some field evidence

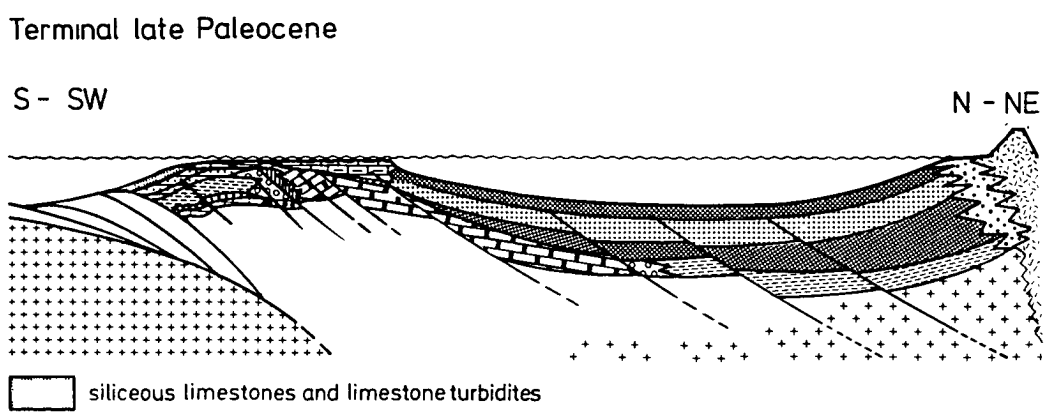

Fig. 8. No major structural changes have been deduced for this episode. The onset of siliceous limestone and limestone turbidite deposition on the trench slope indicates morphologic separation between trench slope and fore-arc. The overall situation suggests control by a rising sea level, with the growing carbonate ramps shedding fore-arc detritus.

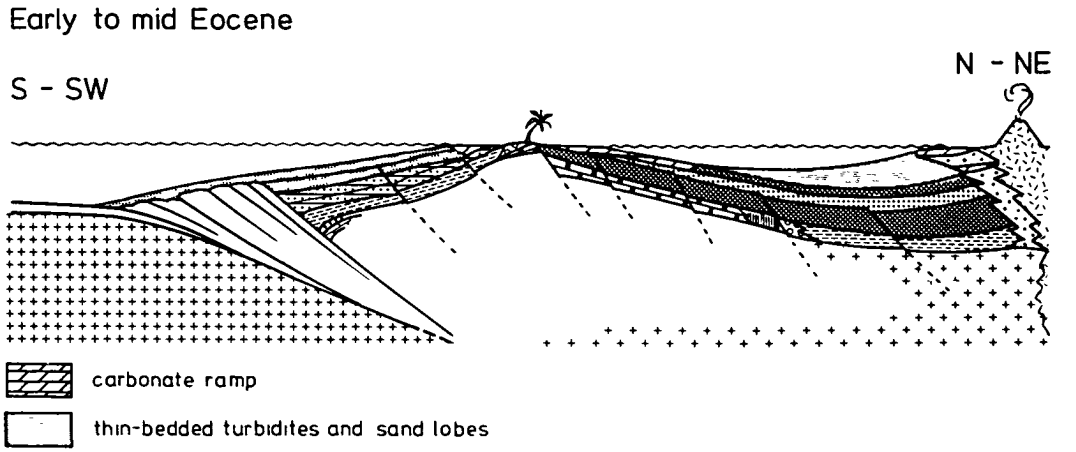

Fig. 9. The outer arc continued to be uplifted (erosion of parts of the previous sequence); consequently, separation between trench slope and fore-arc increased. The outer arc was again overgrown intermittently by carbonate ramps.

(larger foraminiferal grainflows) that carbonate ramps must have developed intermittently along the inner margin of the fore-arc basin.

Interpretation

The more or less continuous growth of the carbonate ramp along the inner edge of the outer arc can be explained by differential movements between outer arc (uplift by accretion) and fore-arc (subsidence by loading). Seismic data (Crowe & Buffler, 1985) indicate that accretion continued. The extension, during the mid-Eocene, of the carbonate ramp on to the outer edge of the outer arc may be interpreted as a strong signal of rising sea level.

Late Eocene to early Oligocene (Fig. 10)

Observations

During the late Eocene, both flanks of the outer arc were again overgrown by a carbonate ramp (Baumgartner *et al.*, 1984; C. Mora, 1985; C. Calvo, 1987). There is little information on sedimentation in the trench slope; seismic data (Crowe & Buffler, 1985) show that sedimentation continued. Late Eocene fore-arc sedimentation is characterized by very coarse-grained channel-lobe systems. Submarine canyons were deeply incised into the volcanic flanks (or small internal clastic/carbonate ramp shelves) of the arc. Volcaniclastic flows with enormous andesite boulders moved directly into canyon heads (Astorga, 1988; see paper by Winsemann & Seyfried). Finally, the entire fore-arc basin was filled up by prograding slope apron systems. There is some evidence that compressional deformation of the fore-arc area started during this episode (Kuypers, 1980; Rivier, 1983; Denyer *et al.*, 1987).

Little information is available on early Oligocene sedimentation. The outer arc and the outer margin of the fore-arc basin do not show early Oligocene deposits at all. Recent field observations made by one of us (Astorga) suggest that sedimentation may have persisted along the inner margin, but no biostratigraphic proof has been obtained so far.

Interpretation

The existence of carbonate ramps on the outer arc in the late Eocene, their demise during that substage, and the lack of early Oligocene deposits in this area suggest that the outer arc became emergent during the early Oligocene. The gradual filling (with very coarse clastic detritus), shoaling, and narrowing of the fore-arc basin, as well as the indications of compressional deformation indicate that the fore-arc area became uplifted as well. Seismic data provided by Crowe & Buffler (1985) clearly prove that accretion stopped towards the end of the Eocene. In this context, the overall uplift and compressional deformation could be interpreted as a consequence

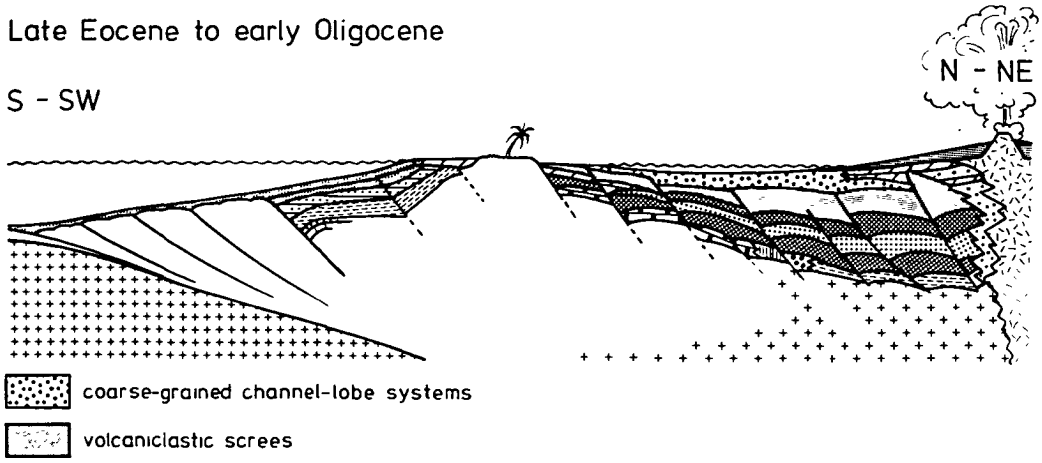

Fig. 10. During this episode a major tectonic event affected the entire island arc. Volcanism increased, accretion stopped, and both the outer arc and the fore-arc were subjected to compressional stress. In the course of the late Eocene, the fore-arc basin became filled up with coarse volcaniclastic debris. In the more protected areas of the external outer arc, a carbonate ramp developed during the late Eocene. The almost complete lack of early Oligocene sediments suggests that the entire area became uplifted during this time.

of increased plate coupling. If strong enough, this process would stop further accretion and transmit considerable compressional forces into the fore-arc. The present-day situation in southern Costa Rica demonstrates that the arrival and initial subduction of an oceanic plateau produces precisely such a situation.

Alternatively, according to Astorga *et al.* (1989), compression could also have been caused by the rotation of the southern segments with respect to the northern one (Sick, 1989), which in turn may have been a result of the tectonic rearrangements that affected the Caribbean plate during the episode in question (Burke *et al.*, 1984; Mann & Burke, 1984; Pindell *et al.*, 1988).

Late Oligocene to early Miocene (Fig. 11)

Observations

Late Oligocene to early Miocene deposits have only been found so far along the outer edge of the outer arc. Seismic data (Crowe & Buffler, 1985) prove they extend downslope towards the trench. On the peninsula of Nicoya, the sequence starts with mixed carbonate–clastic coastal bar systems which rest unconformably on different older rock units ranging from Paleocene trench-slope deposits to late Eocene carbonate ramps. The coastal deposits in turn are overlain by delta deposits (Baumgartner *et al.*, 1984; C. Mora, 1985; Seyfried *et al.*, 1987; Laurito, 1988; Schmidt, 1989; see paper by Schmidt & Seyfried). Field observations recently made by one of us (Astorga) suggest that sediments of this episode might also exist in the inner fore-arc but no biostratigraphic proof has been obtained so far.

Interpretation

The fact that sedimentation started on an angular unconformity along the outer edge of the outer arc suggests previous uplift and subsequent subsidence. As large parts of the outer arc and fore-arc remained emergent there can be no doubt that subsidence was tectonic. Isostatic relaxation after the late Eocene to early Oligocene compressive event could be an explanation of this phenomenon. As with previous uplift events (Campanian, Paleocene), the overprint of a eustatic signal can be detected again, with the coastal deposits representing transgressive and the delta deposits indicating regressive conditions; poor biostratigraphic control does not allow more detailed conclusions. It must be emphasized, however, that the basal angular unconformity is regional (cf. Fig. 3). Evidence from adjacent basins puts onset of

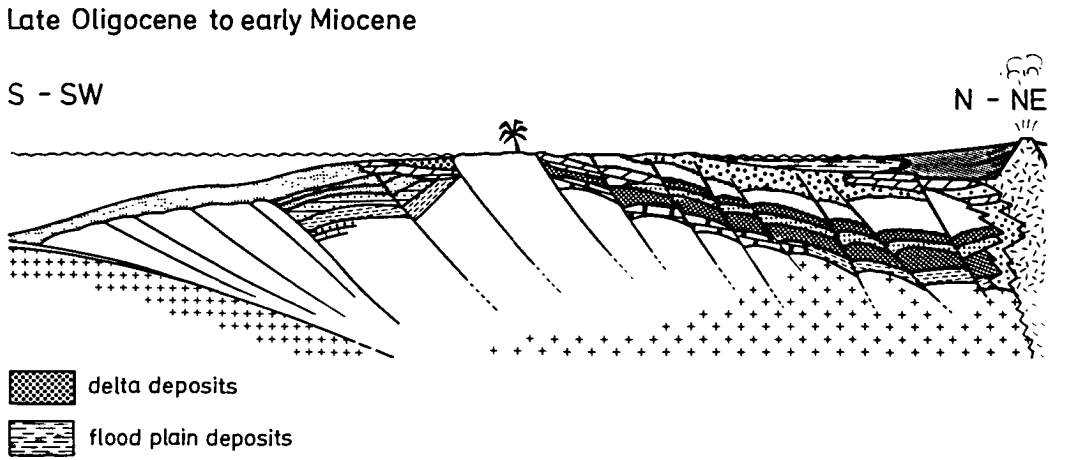

Fig. 11. Sedimentation started again in the latest Oligocene on a regional unconformity produced by the previous uplift. The transgressive episode, however, was of short duration; early Miocene delta and floodplain deposits soon overfilled the small sedimentary basins, prograding most of their detritus on to the trench slope.

sedimentation into the latest Oligocene; several pulses of deltaic sand supply are recorded from early Miocene shallow-shelf sequences (Schmidt, 1989).

Mid-Miocene (Fig. 12)

Observations

At the outer edge of the outer arc, mid-Miocene sediments are separated from early Miocene deposits by a disconformity. The sequence is made up by some few tens of metres of estuarine, fan-delta, and shallow-shelf deposits (Schmidt, 1989). Similar facies types could be observed in the inner fore-arc (Kuypers, 1979; Schmidt, 1989); there, they interfinger with tephritic layers.

Interpretation

The combination of estuarine, fan-delta, and shallow-shelf deposits is typical of the coastal embayments along the present-day Pacific coastline of Costa Rica.

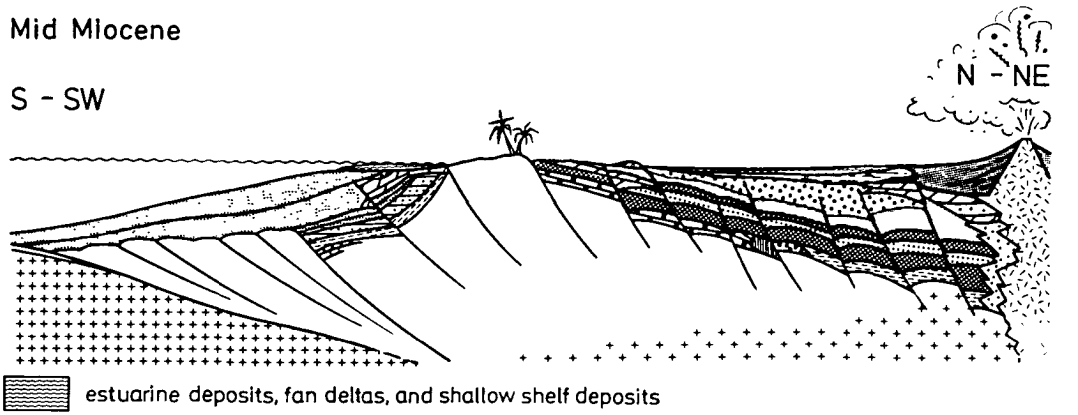

Fig. 12. The outer arc continued rising, whereas fore-arc and trench slope subsided. The basins depicted in this cross-section contain estuarine deposits, which means that highstand deposits were preserved by local subsidence

Structurally, these basins are fault-angle depressions. Estuarine and paralic facies are located along the hinge zone, whereas fan-deltas and cliff-bound deposits accumulate along the opposite fault-scarped coasts, with the shelf deposits (mainly fine sands) lying in between. As this facies pattern can be recognized in most of the Neogene basins, an analogous interpretation has been proposed by Seyfried *et al.* (1987). Detailed palaeoecological and sedimentological studies confirmed this hypothesis (Seyfried *et al.*, 1985; Laurito, 1988; Schmidt, 1989). In contrast to most other Neogene troughs, the basins shown in Fig. 12 did not accumulate large thicknesses of sediment (some tens of metres in comparison to almost 1 km in the Parrita Basin). Under these circumstances, sequences are expected to register densely stacked eustatic signals. Field studies recently carried out by one of us (Amann) in the Tarcoles Basin indeed revealed the existence of four shallowing upward parasequence sets. Seismic profiles (Crowe & Buffler, 1985) indicate that there was no accretion during this episode. Both seismic data and Deep Sea Drilling Project results (von Huene *et al.*, 1985) verified the existence of a thick carbonate–clastic turbidite sequence that overlies the ancient accretionary prism (see Fig. 12). This points to trench-slope subsidence through continuing tectonic erosion in the subduction zone.

Late Miocene to early Pliocene (Fig. 13)

Observations

Late Miocene marine deposits are rare in the area. At the outer edge of the outer arc, some tens of metres of braid-delta deposits occur together with shoreface sandstones (Schmidt, 1989). In the inner fore-arc, a flood-plain–braid-delta sequence 100 m thick, which contains abundant volcanic debris and shows intercalations of lahars, has been assigned a late Miocene age (Fischer, 1981). Strong volcanic activity has also been reported from other basins (Astorga *et al.*, 1989; Kolb, 1990). Compressional phenomena within the outer arc (overthrusts and karstification of uplifted slices of 'Barra Honda' limestones) have been dated as late Miocene by Dengo (1962), Kuypers (1980), C. Calvo (1987), and Denyer *et al.* (1987). Accordingly, Silver *et al.* (1985) relate seismically observed 'duplex' phenomena to compression in the trench (cf. Fig. 13).

The boundary between upper Miocene and lower Pliocene deposits is again a regional angular unconformity (cf. Fig. 3). In the outer arc area, lower Pliocene deposits have only been recognized from one small basin ('Montezuma Basin' in southwest Nicoya), which filled with a sequence 35 m thick composed of cliff-derived debris, fan-delta deposits, shoreline and floodplain sands, and shallow-shelf sediments (Chinchilla, 1989). These deposits rest unconformably on both Nicoya Complex and Paleocene trench-slope sediments. Palaeoecological aspects point to initial deepening followed by shoaling. From the inner fore-arc area, only borehole data are available. Astorga *et al.* (1989) described a Plio-Pleistocene sequence 600 m thick composed of shallow-shelf, shoreface, floodplain or lagoonal, and lacustrine facies types that rests unconformably on upper Miocene rocks. Similar sequences are known from adjacent basins (see papers by Kolb & Schmidt and Schmidt & Seyfried). A common feature of these sequences is a basal shell-lag deposit, which in places contains high concentrations of amber pebbles. An enormously thick Plio-Pleistocene section (3 km) is known from the Burica Peninsula (Corrigan *et al.*, 1990). The filling pattern is comparable to the above-mentioned Montezuma Basin (although thicknesses differ by a factor of 100): the sequence starts with cliff-derived debris and channel-lobe systems and passes through slope apron deposits to shallow-shelf and estuarine sediments (cf. Fig. 3).

Interpretation

The predominance of braid-delta and flood-plain deposits as well as the occurrence of karstification phenomena in the late Miocene indicate general uplift of the entire outer-arc–fore-arc system. This is corroborated by compression observed both in the outer arc and in the trench. The lower Pliocene basin-fill sequences, in contrast, suggest the reappearance of the same type of fault-angle depressions as occurred in the mid-Miocene. Such a succession of tectonic events recalls the situations that existed during the Campano-Maastrichtian and Oligo-Miocene episodes: compression is followed by relaxation; uplift, emersion, and erosion precede the creation of new basins, which display the fault-angle depression pattern. From this point of view, the three major regional unconformities shown in Fig. 3 testify that something unusual happened to the subduction zone. A further common characteristic is the fact that eustatic changes overprint the tectonic signal only when isostatic relaxation allowed

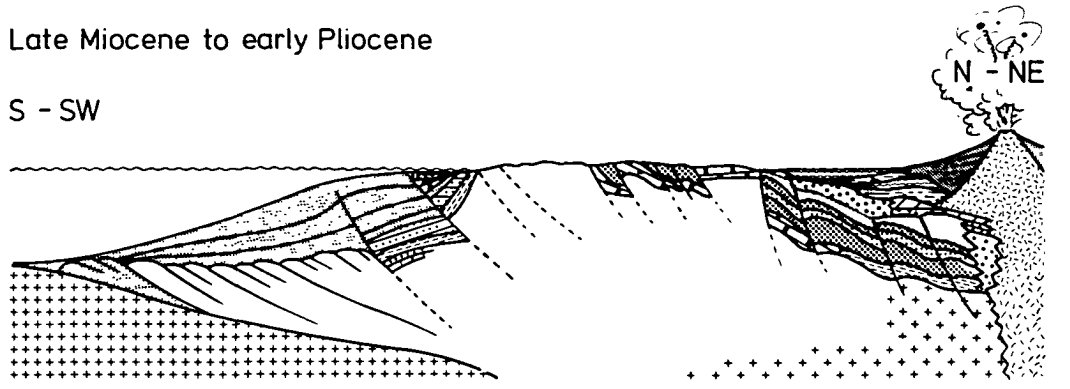

Fig. 13. During the late Miocene, strong regional compression led to exposure and erosion of large areas. The third and last regional unconformity shown in Fig. 3 developed during this episode. The last episode of basin formation started in the early Pliocene. In the area covered by the present cross-section, there is only one comparatively small basin in the inner fore-arc. In neighbouring regions, Pliocene troughs subsided by as much as 3 km. Seismic information indicates small 'duplex' structures, which could mean temporary resumption of accretion.

them to do so. In the early Pliocene, this seems to be particularly true for the basal shell-lag concentrations that contain high amounts of amber pebbles.

Late Pliocene to Recent (Fig. 14)

Observations

The only record of sedimentation relative to this episode comes from a borehole in the Tempisque area (inner fore-arc) where upper Pliocene floodplain and lacustrine deposits (diatomites) have been described by Astorga *et al.* (1989). These deposits are overlain by > 300 m of Quaternary ignimbrites, which relate to the volcanic chain of the Guanacaste and Tilarán cordilleras (O. Mora, 1989). According to Crowe & Buffler (1985), there is no further accretion, but sedimentation continues along the trench slope. Geomorphologic criteria, such as uplifted wave-cut terraces and rivulets falling into active cliffs, point to ongoing uplift of the outer arc (Hare & Gardner, 1985).

Interpretation

The late Pliocene situation evolved into the present-day situation by steady uplift of the outer arc. The portion of the inner fore-arc shown in the cross-section of Fig. 14 most probably subsided until the late Pleistocene and became uplifted during the Holocene. This can be deduced from the geomorphology of the Tempisque valley, which shows inselbergs (= heads of thrust units) sticking out of a floodplain, and only recently being eroded along river banks. The recent Gulf of Nicoya, situated southeast of the cross-section (compare with Fig. 2) represents an inner fore-arc fault-angle basin inherited from Pliocene times. The fact that it still remains open may be due to the intersection with the Trans-Isthmic Fault System (cf. Fig. 2).

CONCLUSIONS

Albian to early late Campanian

The southern part of the Central American isthmus was created at a suture between the Farallón plate and proto-Caribbean crust. From the Albian to the Santonian, this intra-oceanic suture produced a ridge of IAT that was partly covered by siliceous mudstones, black shales, and tuffs.

During the Campanian, a major tectonic event destroyed this configuration. We conclude that subduction reversal was responsible for the décollement tectonics that produced the stacking of different units of the former plate margin. This model explains the drastic spatial, temporal, and genetic separation between the older Nicoya Complex (which subsequently became the basement of the outer arc) and the younger calc-alkaline arc.

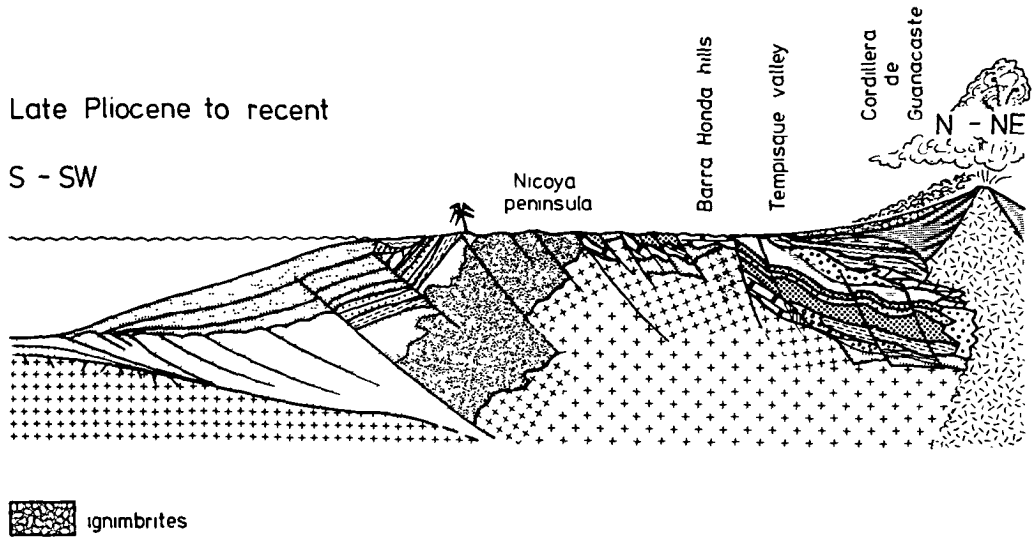

Fig. 14. This figure shows the present-day situation in the Costa Rican fore-arc–outer-arc area, which by now is fully emerged and evolved from the early Pliocene configuration by general uplift and strong explosive volcanic activity, which produced large amounts of volcaniclastic debris, overfilling the remnants of the former basins.

Late Campanian to late Eocene

During the late Campanian to early Maastrichtian, a carbonate platform established on the gradually subsiding tectonic high. From the late Maastrichtian onward, continuous subduction produced both accretion and a continuous growth of the calc-alkaline arc. This resulted in a relatively stable morphotectonic configuration (trench-slope/outer-arc/fore-arc/calcalkaline-arc), which persisted until the late Eocene.

Sedimentation on the trench slope was largely controlled by the morphologic evolution of the outer arc. Thin-bedded turbidite systems or coarse-grained channel-lobe systems developed when canyons cut across the outer arc, allowing the bypass of arc debris towards the trench slope. Siliceous limestones (or calcareous turbidites) predominated during episodes of relative isolation. They correlate with carbonate ramps that repeatedly overgrew the outer arc. Thus, it may be concluded that though outer arc uplift (and morphology) controlled the general pattern of sedimentation in the trench slope, eustatic changes left a remarkable overprint by over-deepening and back-cutting pre-existing depressions during lowstands and by allowing carbonate ramps to grow and shed fore-arc clastics during highstands.

Sedimentation in the fore-arc was strongly influenced by volcanic activity and by tectonic activity along the outer margins of the basin (which most probably had a transcurrent component). Volcanic activity is expressed by the occurrence of coarse-grained channel-lobe systems, which may contain andesite boulders with diameters of up to 4 m as well as autoclastic flow breccias. Tectonic activity is mainly indicated by debris flows with carbonate ramp components. Eustatic control is expressed in the style of turbiditic sedimentation: during lowstands, huge amounts of first-cycle sands were mobilized along internal clastic shelf areas and ponded into the basin; during highstands, thin-bedded turbidite systems prevailed. The predominant eustatic signal, however, is the lowstand signal (for more details, see the paper by Winsemann & Seyfried). Towards the end of the Eocene, the fore-arc basin became almost entirely filled, mainly as a result of increased volcanic activity of the calc-alkaline arc.

Oligocene to Recent

At the beginning of this episode, two important events affected the area in question: accretion stopped and the north and south Costa Rican arc segments began to decouple along the Trans-Isthmic Fault System. During most of the Oligocene, large

parts of the outer arc and fore-arc of the northern block became uplifted and eroded. As to the process responsible for this widespread uplift, there are two possibilities: (1) collision with an oceanic plateau (with general initial uplift and subsequent differential isostatic relaxation); (2) compression as a consequence of rotation of the southern blocks, which in turn may have resulted from tectonic rearrangements within the Caribbean plate.

From the latest Oligocene until the Pliocene, differential tilting and (to a minor degree) strike-slip faulting created several fault-angle depressions along both the outer arc and the fore-arc area. Each basin-fill sequence starts on an unconformity, which in most cases is correlatable on a regional scale. Cliff-bound deposits, fan-deltas, and braid-deltas are characteristic of the fault-scarped coastlines of these basins, whereas estuarine facies, mixed carbonate–clastic coastal bars, and floodplain deposits are common along the hinge zone. Characteristically, the shallow-shelf sands which commonly lie in between show bimodal compositions: first-cycle components (feldspars, calc-alkaline volcanic rock fragments) are intricately mixed with strongly altered 'Nicoya Complex grains' derived from weathered structural highs.

In most basins, subsidence was fairly strong, but water depth seldom fell below shallow-shelf depths. Some few basins, especially those in the outermost fore-arc, display extremely complex subsidence/uplift histories. The present-day situation is the result of a general slight uplift of the entire island arc. Strong explosive volcanic activity during the Pleistocene–Holocene also led to shoaling of most of the pre-existing basins.

The cycle: compression – uplift – erosion – unconformity – subsidence (tilting) – basin-filling has occurred three times since the late Eocene (Oligocene to early Miocene, latest early Miocene to early late Miocene, latest Miocene to Pleistocene). These repetitive phases of compression might be related to changes in the intra-plate stress field, which in turn are the result of such factors as convergence of the North and South American plates and changing spreading rates, respectively.

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