Chapter 9

Convergent margin tectonics:
A marine perspective

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“These geological factors are important, but they only represent one fact of a complex set of relations that, although clearly related to ocean plate subduction, have yet to be investigated in adequate detail.” G.P. Woollard: The Status of Geophysical Research in Latin America. In: Geophysics in the Americas, 1977.

9.1 INTRODUCTION

The Central American convergent margin is a classic representative of the “Pacific Margin” in the nomenclature of Gutenberg and Richter [1] and early plate tectonics. It extends from the Gulf of Tehuantepec to Panama (Fig. 9.1). The dominant morphological feature is the Middle America trench (MAT) that was named by Heacock and Worzel [2], and runs from the Riviera fracture zone offshore Mexico to the Cocos ridge offshore south Costa Rica. Earthquakes clearly define a Wadati-Benioff zone of landward dipping seismicity or a subduction zone where Cocos plate and the older Farallón plate subducts beneath the Caribbean plate. Hypotheses regarding the MAT contributed to the evolution of concepts in the geosciences over the past 75 years.

The history of marine geoscience research along Central America margin (CAM) and the MAT is intimately interwoven with the evolution of concepts regarding convergent plate boundaries. Geophysical data tested with scientific ocean drilling along the CAM was significant in modifying ideas in the plate tectonic paradigm about convergent plate boundaries. This chapter is introduced with a narrative history of this evolution and then concentrates on the insights from modern bathymetry, potential field data, and improved seismic reflection information. A review of the marine geological and geophysical studies carried out along the convergent margin of Middle America shows that the area’s unique features have motivated research over the past 50 years that influenced the understanding of convergent plate boundary evolution. Interpretations of processes that shaped the CAM have been markedly modified as techniques and quality of data improved. Proposed in early models was a steady growth of the continent by long-term accretionary processes through which material from the incoming oceanic plate was tectonically transferred to the overriding plate. Subsequently, as the accretionary hypothesis was tested with scientific drilling, it was realized that the margin is non-accretionary. In the last ~10 years a wealth of new,
higher resolution data, have led to a consensus that the continental margin has been tectonically eroded during the Neogene–Quaternary periods (~23 Ma) and that a large mass of the overriding plate has been removed and probably recycled to the mantle. Modern data show the close correlation between the character of the incoming oceanic plate and the recent (~5 Ma) tectonic evolution of the arc-forearc system. Forearc tectonics, submarine sliding, arc magmatism and interplate seismicity differ in segments and those segments parallel segmentation of the oceanic plate subducting along the MAT. This understanding helps in assessments of the risk from natural hazards.

9.2 ACCRETION VERSUS NON-ACCRETION

9.2.1 Early studies offshore Guatemala

Investigations offshore Central America between 1950 and 1960 by scientific institutions were numerous for the time. Bathymetric data compiled in the early 1960s [3, 4] revealed the varied morphological character of the adjacent ocean basin. Soon afterwards, areas of the continental shelf were considered potentially petroliferous and were surveyed by industry explorationists who informally shared with academic colleagues that deformation on the slope indicated accretion. A concept of accretion was published by Dickinson [5] suggesting that although ocean crust is carried down with the descending lithosphere, lighter sediment is probably scraped off against a more durable overriding plate. These off-scraped sediments and ophiolitic scraps were presumably equivalent to the materials exposed in the Sambagawa formation of Japan and in the Franciscan formation in California, a vast tract of rock whose origin had long puzzled geologists. Dickinson proposed steady-state accretion and that the terrain between the arc and trench was proportional in width to the age of the arc-trench system. Dickinson summarized the model during his seminal workshop in Asilomar in 1971, where the concept was debated between marine and land geoscientists. He proposed a steady-state process of continental growth that was commonly referred to as “the plate tectonic margin model”. The origin of the ophiolites of the Nicoya peninsula thus became an interesting target of research.

Many proponents of plate tectonics were enthusiastic about the accretionary hypothesis, and when Exxon released a multichannel seismic reflection record across the MAT off Guatemala the model was convincingly backed by published data [6]. The Exxon record showed many landward dipping reflections but at the time it was difficult to differentiate between real reflections and diffractions without today’s more powerful processing software systems. The Guatemalan example elevated the accretionary hypothesis to broad consensus in the scientific community and the Guatemalan seismic record was commonly cited as a type accretionary section. At this time, drilling in the Nankai trough based mainly on industry records of JAPEX [7] provided further evidence supporting accretion [8] and a tendency to equate all convergent margins with accretion became common. With the Guatemalan record, Seely and his colleagues [6, 9] elevated the accretionary model from speculation to broad acceptance by geoscientists and other proprietary data were later integrated in an interpretation of the Oregon and Alaskan margins. Seely [9] interpreted reflection data off Oregon and Alaska as he had interpreted the Guatemalan record inferring that slices were detached, then rotated upward by younger underthrusting slices, to progressively build continental crust. The actively accreting prism uplifted the shelf edge forming the
Figure 9.1. Shaded relief map of Cocos and Caribbean plates. Areas of Deep Sea Drilling Program (DSDP) legs 66, 67, 84, 170 and Ocean Drilling Program (ODP) Leg 170 are indicated.
seaward flank of forearc basins. Single-channel marine seismic reflection data of the
academic community were grossly inadequate to reveal the complex structure along
active convergent margins. In hindsight, even the early multichannel Exxon record
processed with digital methods available only in industry was also over interpreted.

Notwithstanding the focus on accretion in the published literature, evidence was
building that convergent margins were also subjected to tectonic erosion. As Miller
[10] and Rutland [11] pointed out, some older arc-trench systems have narrow forearcs
seaward of an exposed Mesozoic continental framework. This observation was not lost
on Creighton Burk. At the time, Burk was Director of the University of Texas Marine
Science Institute (UTMSI). In 1974, he formulated a program to investigate the
tectonics of the MAT from the Cocos ridge to the Riviera fracture zone. He and
colleagues on the Deep Sea Drilling Project (DSDP) Active Margins Panel reasoned
that investigating two adjacent areas one of which appeared accretionary and the other
erosional would yield insights greater than those derived from studies of either margin
type alone. In contrast to the accretionary Guatemalan margin, the southwestern
Mexico margin appeared to have no older accreted mass because Mesozoic rock crops
out along the coast as observed along the Chilean margin. Thus the volume of a
possible accretionary prism cannot accommodate all incoming sediment on the lower
plate and part of the prism must be missing. Site surveys by UTMSI produced the first
multichannel seismic reflection data off Acapulco Mexico and off Guatemala,
Nicaragua, and Costa Rica. These surveys formed a basis for selecting two transects
that were drilled during DSDP Legs 66, 67, and 84 (Fig. 9.1). Much to everyone’s
surprise, the Guatemalan margin proved non-accretionary [12, 13] and the Mexican
margin was interpreted as accretionary [14]. The Guatemalan margin yielded
Cretaceous limestone resting on igneous oceanic rocks of the upper plate within 4 km
of the trench axis. Clearly, steady accretion had not affected the margin during Tertiary
time [12, 15]. Although many of the landward dipping reflections interpreted as
accretionary thrusts were shown to be diffractions by later pre-stack depth processing,
rare landward dipping reflections do occur in the margin wedge. The shortcomings of
géophysics alone to assess basic convergent margin tectonic processes was also
experienced along the Japan, Marianas, Tonga, Peru, and most recently the Costa Rica
margins. Although the seismic reflection technique and the information content of the
seismic reflection method have improved greatly in the past 40 years, the accretionary
model that guided interpretations of geophysical data was appropriate only along some
margins. We return to this point after recounting the great advances made over the past
10 years with multibeam bathymetry (Fig. 9.2) and seismic reflection investigations
that include advanced pre-stack-depth processing.

9.2.2 Contribution of bathymetric mapping

Investigators at the Scripps Institution of Oceanography compiled bathymetric
information along the CAM most of which are summarized in Fisher [16].
Geoscientists compiling conventional bathymetric data in the late 1950s were mindful
of seafloor processes in constructing maps from widely spaced data. Fisher’s maps
showed numerous seamounts along the northern flank of the Cocos ridge. The many
transit legs of research vessels from ports in the area and through the Panama canal
became data of opportunity that Lonsdale and Klitgord [17] later compiled, data
included in the independent compilation of Case and Holcombe [18]. The latter
Figure 9.2. Shaded relief map of the bathymetry and topography of Costa Rica and Nicaragua. The oceanic plate has four segments with different morphological character. Segments 1–3 were formed at the Cocos-Nazca spreading center and segment 4 at the East Pacific rise. ODP Leg 170 sites are indicated by black circles filled white. DSDP Leg 84 site 565 is a white circle filled black. Oil exploration drills sites onshore and offshore Nicaragua are indicated by black filled circles. Black lines represent tracks of seismic profiles.

compilation included continental geology and both compilations depicted the seamount covered ocean floor off central Costa Rica and the adjacent smooth ocean floor and less complicated slope off Nicoya peninsula. This was termed the rough-smooth boundary by Hey [19] who correlated it with the change in origin of ocean crust. The subducting Cocos ridge was positioned opposite the uplifted Osa peninsula and off both Costa Rican peninsulas the shelf is very narrow. At this time a first order morphology of the continental margin was known as well as could be expected from conventional bathymetry without GPS navigation.

A short multibeam bathymetric survey of the trench off Guatemala made with the French R/V Jean Charcot demonstrated the more coherent information acquired with multibeam [20]. Revealed were details of horst and graben as the plate bends into the trench. These horst and graben underthrust the base of the continental slope, and are
roughly mimicked by lower-most slope morphology where the plate interface forms a scarp parallel to the trench axis. Disruption of the lower slope by seafloor relief of ~300 m is minor but the slope morphology has a restless character that matches the poor coherence of reflectivity in seismic reflection records. Tectonism of the middle and lower slope is apparent from seismic data but without 100% coverage the tectonic significance of multibeam bathymetry is not obvious. Nonetheless, Aubouin and co-workers correctly interpreted extensional tectonism and drilling established the non-accretionary nature of all but the slope toe. With 100% coverage, extensive mass wasting and extensional tectonics shaping slope morphology becomes apparent but this was not achieved until 2003.

A multibeam system was installed on the Scripps R/V *Thomas Washington* during a port stop in Puntarenas, Costa Rica in 1984. The instrument test data was preceded by a survey off the Nicoya peninsula where the continental slope morphology is least complicated [21]. It showed that even the simplest morphology was generously endowed with small-scale gravity sliding as noted in DSDP drill cores [22]. Off Guatemala the *Charcot* survey was expanded by R/V *Thomas Washington* and combined with high-resolution seismic data the indications of sediment folding, interpreted as accretion across the slope toe, were emphasized [23]. A small frontal prism was in evidence despite upper plate basement sampled during Legs 67 and 84.

The GEOMAR Geodynamics group selected Costa Rica for investigation because of a possible subducting seamount that had been partially mapped inadvertently by the R/V *Thomas Washington* test survey. Scientific questions to investigate included the fate of large seamounts in a subduction zone, whether they remain on the lower plate or are sheared off, whether they form earthquake asperities, and whether they mechanically erode the continental margin. R/V *Sonne* mapped about 400 km of the CAM bathymetry with near 100% [24]. These data were expanded during several subsequent cruises and current maps include detailed morphology of the continental slope and incoming oceanic plate from northern Nicaragua to the Cocos ridge offshore southern Costa Rica (Fig. 9.2).

### 9.2.3 Accretion versus non-accretion models

Seismic records acquired offshore Costa Rica by UTMSI in 1978 showed a thicker slope sediment section off Costa Rica than offshore Nicaragua and Guatemala. Beneath that sediment section is a rough yet strong reflective top of the rock comprising the bulk of the continental margin, the so-called margin wedge. The base of the margin wedge is defined by strong reflections paralleling the plate interface (Figs. 9.3 and 9.4). Within the margin wedge are landward dipping reflections clearly differentiated from diffractions [25]. A hole drilled offshore Costa Rica during DSDP Leg 84 failed to reach basement for safety reasons and thus the accretionary model was not tested. The seismic records off Nicaragua and Costa Rica were interpreted in accord with the accretionary model [21, 25–27] although a non-accretionary Costa Rican model was also proposed [13, 28]. The UTMSI seismic data offshore the Nicoya peninsula showed some of the strongest coherent plate interface reflections of any collected at the time and this area was chosen for the first academic 3-D reflection seismic experiment across a convergent margin. The 3-D survey was collected across the lower slope and extended with 2-D lines shot from the continental shelf to the ocean plate [25, 30, 31]. Within the 3-D volume of rock, landward dipping reflections were traced from the top
of the margin wedge to the plate interface (Fig. 9.3). They were interpreted as recently formed structures representing thrust faults, duplex structures, and “out-of-sequence” faults. “Out-of-sequence” fault is a generic term derived from the constant accretionary model to explain landward dipping reflections that exceed the length of initial accretionary thrust faults. They are longer than the initially detached sections of accreted oceanic sediment and are proposed to cut the accretionary prism once the first thrust faults are rotated and become too steep to continue thickening the prism. Other structures were interpreted as underplated duplexes seaward of a post-Eocene accretionary prism forming the bulk of the continental margin (Figs. 9.3 and 9.4). A major shortcoming of the interpretation was the lack of reliable velocity data and the difficulty to balance structure in the context of an accretionary model [31].

During the 1991 and 1992 R/V Sonne cruises 76 and 81, not only multibeam echosounding but also magnetic data [32], seismic refraction data [33], and multichannel seismic reflection sections [34] were acquired. The refraction data indicated higher acoustic velocity in margin wedge rock (~5–6 km/s) than that derived from time processing of the 3-D seismic reflection data. These velocities were similar to those in upper plate crustal rock of the Guatemalan margin [35] where the margin...
wedge had been shown to be igneous rock, and not indicative of young accreted sediment [31, 33]. In addition to the high velocities, the bathymetry offshore Central Costa Rica indicated only a small frontal prism. The subducting plate with seamounts and ridges appeared to erode the margin because opposite the seamounts the slope was indented [24] (Fig. 9.5). A non-accretionary origin explained most readily the structure imaged in reflection sections [34]. Modeling of magnetic anomalies was consistent with a margin wedge composed of igneous rather than sedimentary rock [32]. Drilling results from ODP Leg 170 confirmed that all sediment in the incoming plate is underthrust and no classical accretionary prism occurs, although the margin wedge rock was not unequivocally sampled [36]. In fact, the small “accretionary prism” at the lower slope was shown to consist only of tectonized slope sediment without transfer of oceanic sediment from the lower to the upper plate (Fig. 9.4). Thus the former accretionary prism is now termed a frontal sediment prism. Consequently, the steady state accretionary model for Costa Rica was no longer the consensus interpretation.

9.3 Changes in the Paradigm

9.3.1 Long-term subsidence and subduction erosion

Tectonic processes controlling the past 5 m.y. evolution of the CAM became much clearer once multibeam bathymetry was available and structure was imaged in true depth with multichannel seismic reflection sections (Figs. 9.5 and 9.6). DSDP and ODP drill holes provided a lithostratigraphy of sedimentary units and benthic microfossil fauna documented paleo bathymetry to reveal a history of massive subsidence. These data indicated that a large mass of the CAM was missing and was presumed to be tectonically eroded during Neogene time. Evidence for Neogene margin subsidence offshore Costa Rica, Nicaragua and Guatemala supports the structural evidence for subsidence observed in the seismic data and this evidence is discussed below.

In Costa Rica, large-scale Neogene subsidence and upper plate extension has been interpreted from structure in seismic images and it is recorded in DSDP Leg 84 and ODP Leg 170 cores. The top of the margin wedge is a rough low-relief surface overlain by sedimentary strata that locally show onlap (Fig. 9.6). The upper plate landward of the frontal prism appears extended [30, 37]. Numerous normal faults offset the sedimentary strata and some appear to continue as discrete reflections deep into the margin wedge. Most likely, the surface at the top of the margin wedge is an erosional unconformity that subsided from the surf zone to its current depths beneath the outer shelf and the middle and lower slope (Fig. 9.6).

The margin wedge lower boundary, the plate interface, is imaged as a reflective interface that retains a high amplitude signature for about 50 km from the trench and to about 12 km depth. Reflection and onshore-offshore refraction velocities constrain determinations of upper plate thickness from the lower slope (±200 m) to the coast (±500 m). If the margin wedge unconformity was formed by surf zone erosion near a former coast, the crust there may have been 14–16 km thick, similar to upper plate thickness beneath the current coast [33, 38, 39]. The margin wedge in central Costa Rica is currently only 10 km thick beneath the outer shelf and about 3.5 km thick beneath the middle lower slope (e.g., km 35 on Fig. 9.6). If the unconformity was formed near sea-level, the upper plate must be thinned. Although faulting of the upper plate may account for some of the thinning, the small offsets along these faults is not sufficient to explain the much larger thinning observed and thus basal erosion and
removal of material is a plausible explanation for subsidence. Upper plate extension is an apparent response to basal erosion and thinning rather than the main cause of margin subsidence. The margin wedge unconformity and normal faulting has been mapped across the entire slope of Costa Rica [30, 37, 40] and a similar unconformity separating igneous basement from overlying strata has been observed beneath the continental slopes of Nicaragua and Guatemala. Since onlap produces a time-transgressive unconformity, the age of the unconformity probably varies along the CAM.

Although the distinctive unconformity at the top of the margin wedge is seen regionally across the middle–upper slope, it becomes more irregular farther down slope and the upper plate is increasingly dismembered. Locally the unconformity is more disrupted where lower plate relief (seamounts and ridges) has subducted and...
stratigraphy is poorly imaged in seismic records because of the deformation [37]. The margin wedge dismemberment beneath the lower slope is consistent with subduction erosion there.

Consistent with geophysical evidence for subsidence of the CAM in Costa Rica are results from studies of DSDP Leg 84 site 565 cores, and site 1041 of ODP Leg 170 cores. The lithologies of rock from the unconformity at the top of the margin wedge currently at ~4 km (site 1042, Leg 170), have shallow-water affinities [41, 42]. The latter sites recovered igneous basement. The site 1042 cores just above the margin wedge unconformity recovered ~25 m of carbonate cemented limestone breccia underlain by ~10 m of a breccia composed of clasts of red chert, doleritic basalt and mafic rock [36]. The contact between material from the high velocity body and sediment was not recovered because the site 1042 was located at the frontal tip of the margin wedge and a thrust truncated the stratigraphic section. The chert and igneous rock from the breccia are similar to rocks found in the Nicoya complex cropping out onshore [36]. Analysis of the carbonate cemented limestone breccia indicates a beach to near shore depositional environment [41]. Drilling at Sites 565 and 1041 penetrated much of the sediment overlying the margin wedge and good recovery provided a relatively continuous benthic foraminiferal stratigraphy. The depth at which the foraminiferal assemblages lived changes from shallow water at the base of the section, to abyssal fauna in the upper section consistent with the present depth of the sites [43]. The beach to near shore carbonate cemented limestone breccia is ~16 Ma old and neritic fauna (water depth < 300 m) appears in sediment older than 5–6.5 Ma indicating slow average subsidence. However, the more detailed depth information from benthic foraminifera shows a sudden acceleration in subsidence offshore Nicoya peninsula starting at ~5–6.5 Ma when that area of the margin subsided rapidly to upper-middle bathyal depth (< 800 m water depth). A renewed increase in subsidence rate occurred at ~1.8 Ma when the slope deepened to abyssal depths (> 2000 m) or the current core depth of ~3200 m. [43]. These observations are explained by long-term margin subsidence caused by subduction erosion and thinning of the upper plate.

In Nicaragua, drill hole information along a seismic reflection/refraction transect across the Sandino basin shows that the basin depocenter was located beneath the current continental shelf during Cretaceous to ~Middle Eocene time (Fig. 9.7). The Cretaceous–Paleogene sediment units rapidly pinch out along the basin seaward flank. Beneath the current upper continental slope, a thin Cretaceous–Early Paleogene sediment sequence becomes indistinct down slope [44] but probably extends to the middle slope where dredging recovered fragments of igneous basement rock and Cretaceous limestone [45]. From about Late Eocene to latest Oligocene or Early Miocene time (~26–23 Ma) the outer shelf seafloor was sufficiently elevated to form a barrier to sediment transport and most deposition was restricted to the inner shelf area where a stable depocenter accumulated sediment about 5 km thick. A major change in basin configuration and the beginning of long-term regional subsidence of the seaward part of the margin occurred in latest Oligocene or Early Miocene time. When the outer shelf subsided, Neogene sediment unconformably covered the Cretaceous–Early Paleogene units. Since Early Miocene, a 70-km-wide swath of the Nicaraguan margin forming the current upper continental slope subsided about 2 km at the position of the current shelf break, and probably 3–4 km along the middle to-upper slope transition (Fig. 9.7).

In Guatemala, paleo-depths from benthic foraminifera of sites 568–570 on the middle-upper slope yield similar evidence for long-term subsidence as off Costa Rica
Figure 9.6. Pre-stack depth migration of *Sonne*-81 line 4 projected on bathymetry. Line 4 is 58 km long from the slope toe to the outer continental shelf. The top of the margin wedge is an unconformity cut by normal faults with small offset. Thrust faulting occurs only at the lower continental slope in the small frontal sediment prism where the slope drainage system is disrupted. Location on Figure 9.2. Modified from Ranero and von Huene [37].
Benthic foraminiferal assemblages indicate a progressive subsidence of the slope that might have started in latest Oligocene or Early Miocene (~26–23 Ma) time. Subsidence began earlier (~26 Ma) in the middle slope (site 569 currently at 2799 m depth). Subsidence at site 568 (currently at 2030 m deep) started about 19 Ma and at site 570 (currently at 1720 m deep) about 11 Ma. The record of vertical tectonism shows a migration of margin subsidence toward the continent.

The Neogene subsidence record in Guatemala and Nicaragua (~26–23 Ma) begins at approximately the same time but is somewhat later in Costa Rica offshore Nicoya peninsula (~17 Ma). The rapid subsidence pulse at ~5–6.5 Ma in the latter area is not observed in Nicaragua or Guatemala. Initiation of widespread subsidence in the CAM might be related to a major kinematic reorganization of the plates in the eastern Pacific. Soon after the Farallón-Pacific spreading center collided with the North American plate in the Late Oligocene [46] a latest Oligocene or Early Miocene (26–23 Ma) change in plate kinematics led to the opening of the Cocos-Nazca spreading center [46, 47]. The plate kinematic reorganization produced a change from oblique to normal convergence along the MAT and was accompanied by an increased rate of spreading along the East Pacific rise [48] adjacent to the newly formed Cocos plate. Fast convergence rates and arrival of a younger and shallower slab at the trench may have induced subduction erosion along the plate boundary [42, 44]. The rapid pulse of subsidence at 5–6.5 Ma recorded locally offshore Nicoya peninsula is coeval with the arrival of the topographic swell associated with the Cocos ridge [43]. Studies of the Talamanca cordillera opposite the subducting Cocos ridge indicate that widespread calcalkaline volcanism ceased about 3.5–5 Ma [49, 50]. Adakitic rocks probably produced by partial melting of ocean crust were emplaced ~3.5 Ma [51] and denudation ages from fission track analysis indicate uplift of the cordillera to about this same time [52]. These observations indicate a 5–7 Ma arrival time of Cocos ridge at the trench. The arrival of Cocos ridge further decreased the subduction angle of the incoming plate as far north as Nicoya peninsula and after an initial uplift a former shelf area subsided to its current abyssal depth [43].

9.4 THE FOREARC SANDINO BASIN

Sandino forearc basin is located beneath the broad continental shelf from the Gulf of Tehuantepec to Costa Rica (Figs. 9.7 and 9.8). This basin has been subsiding active since Late Cretaceous and contains a 9–15 km thick sediment accumulation at its depocenter [44, 53]. The structure of the basin is similar from Guatemala to Nicaragua. Its depocenter is located near the current coastline and the infill progressively shallows towards a basement outer high located beneath the current shelf edge. Evolution of the basin from Nicaragua to Guatemala was similar during the Tertiary. Although there may be a difference in the pre-Eocene tectonics at each segment of the margin, it is also possible that previous interpretations are different because of incomplete data [44]. The pre-Middle Eocene basin imaged near the present coastline off Nicaragua (Fig. 9.7) was not clearly imaged off Guatemala. Offshore Nicaragua, seismic stratigraphy and backstripping indicate that rapid basin subsidence occurred during early development of the Sandino basin (Cretaceous–Paleocene). In Costa Rica, Late Cretaceous deep water sediment rests over Nicoya complex igneous rock, and deformation of the basin has uplifted similar strata that crop out along the coastal region of Nicaragua [28, 54] indicating a single development of the entire forearc basin along Middle America.
Figure 9.7. Pre-stack depth migration of a cross section composed of three multichannel seismic reflection profiles across the Nicaragua margin. Seismic stratigraphy has been calibrated with Corvina-2 and Argonaut-1 wells. The continental shelf is underlain by the more than 9 km deep Sandino basin. Location on Fig. 9.2. Modified from Ranero et al. [44].
The Late Eocene and Oligocene section in Nicaragua and Guatemala have similar structure. The strata show landward thickening and are absent from the outer high and upper slope probably indicating subsidence restricted to the shelf. A transition from deep to shallow water sediment in Guatemala [55] Costa Rica [28, 56] and Nicaragua Pacific margin in the Late Eocene indicates similar conditions regionally. From Nicaragua to Guatemala a phase of renewed subsidence from the latest Oligocene to the Quaternary is documented by sediment deposition across the outer high and upper slope. In Early–Middle Miocene time tectonic shortening deformed strata in the Nicaraguan segment (Fig. 9.7) creating an angular unconformity beneath the shelf. A similar unconformity locally separates Oligocene from Miocene sections in Guatemala (Fig. 9.8). Therefore, the entire Sandino basin developed as a unit and the similar Late Cretaceous to Oligocene tectonic histories indicate a major regional tectonic event.

Along the CAM, the basement of the forearc basin is probably composed of igneous rocks of oceanic origin. The Nicoya complex onshore Costa Rica belongs to the Caribbean basaltic province [57–59] and it is possible that the basement underlying the forearc basin of the CAM is part of a single volcanic province. Landward of the MAT, the magnetic anomalies offshore Nicaragua and Costa Rica include a broad positive anomaly (Fig. 9.9). Magnetic modeling has shown that this can be explained with an offshore extension of the igneous rocks that crop out on the Nicoya peninsula [32]. Wide-angle seismic studies also show that the igneous complex extends seaward to near the continental slope toe [33, 39]. The continuity of the magnetic anomalies across the forearc of Costa Rica and Nicaragua indicates that the same igneous basement extends across the entire region (Fig. 9.9). The origin of a sharp magnetic boundary across the coastline of northern Costa Rica in the Nicoya peninsula area is not yet clear but may be related to the Chortis-Chorotega block transition and is older than the development of the forearc basin. The Caribbean basaltic province is interpreted as formed largely by initial melting of the head of the Galápagos plume (~90 Ma) and subsequent obduction (~80 Ma) [57, 58, 60, 61]. This large igneous body was obducted along at the Antilles easterly dipping subduction zone. It is proposed that this obduction terminated subduction and eventually caused inversion of subduction polarity [60].

Subduction along the Middle America trench probably began on the western edge of the Caribbean basaltic province at ~75 Ma, as suggested by the oldest volcanoclastic Cretaceous sediment overlying the igneous complexes [54]. Subduction initiation is associated with rapid subsidence of the upper plate [62, 63] that might have caused the initial development of the Sandino basin along the western rim of the Caribbean plate. Subduction initiation is associated with rapid subsidence to several-km depth at 150–200 km from the trench, driven by sinking of the slab into the mantle [62, 64, 65]. As subsidence rates decreased after initial subduction, the basin was filled with sediment (Middle–Late Eocene) from a developing volcanic arc. Subsidence seems to be currently active across the continental shelf and slope.

9.5 QUATERNARY TECTONICS

A compilation of multibeam bathymetry ~600-km-long and 100–150 km-wide offshore Costa Rica and Nicaragua provides an unprecedented map of the active tectonics exhibited as seafloor relief (Figs. 9.2 and 9.5). Data were acquired with the Hydrosweep system during R/V Sonne cruises 76, 81, 107, 144 and 150, R/V M. Ewing cruises 0005 [66] and 2001 [67], and with a Simrad system during R/V Sonne cruise
Figure 9.8. Post-stack time migration of line GUA2 across the Guatemala margin. The line was collected in 1977 by R/V Ida Green. Re-processing includes post-stack deconvolution, frequency-wavenumber noise attenuation, dip-dependent trace interpolation and migration. The Sandino basin may be more than 10 km deep underneath the continental shelf and thins rapidly towards the outer shelf. Basement extends underneath the continental slope to a point very close to the trench and is covered by a thin and disrupted sediment section. The top of the basement is indicated by the black-filled circles where observed. The pelagic sediment section of the oceanic plate is strongly tilted at the trench axis indicating that faults are active across the entire oceanward trench slope. Turbidites partially fill a half graben being underthrust at the deformation front. The top of the subducting plate can be followed ~35 km underneath the overriding plate and it shows that the half graben structure is preserved.
Editing with MB system software [68] eliminated spurious soundings and accepted soundings were converted to depth with water velocities measured during different cruises. There data allowed gridding at ~100 m node spacing. This bathymetry resolves tectonic structure less than 0.5 km wide from which sedimentary and tectonic processes can be interpreted. A compilation of magnetic data shows the structure of the incoming oceanic plate formed at the East Pacific rise and Cocos-Nazca spreading center (Fig. 9.9). The comparison of magnetic and bathymetric data shows the control of structure formed at the spreading centers on the configuration of the oceanic plate and on the deformation during bending at the trench.

The emphasis of previous Costa Rica margin studies was on segmentation of the ocean plate, which correlates, with large-scale tectonic segmentation of the upper plate [37, 40, 47]. The current bathymetric and magnetic compilations sharpen the correlation between lower ocean plate segmentation and upper plate tectonics. Expanded coverage offshore Costa Rica and Nicaragua shows this upper/lower plate similarity that we interpret as a cause-and-effect relation between lower plate character and upper plate tectonism.

### 9.5.1 Segmentation of the incoming oceanic plate

The along strike variability in ocean plate relief and water depth result from a combination of magmatic and tectonic processes. The oceanic Cocos plate subducting beneath much of CAM is divided into two provinces that were generated at different mid-ocean spreading centers (Fig. 9.1). Most of the oceanic lithosphere entering the MAT today originates from the East Pacific rise (EPR) and has the low relief morphology and low-amplitude magnetic anomalies common to fast-spreading ridges [19, 48]. Along the southern boundary of the Cocos plate, crust was generated along the Cocos-Nazca spreading center (CNS) by intermediate spreading with a rough topography and high-amplitude magnetic anomalies [69]. The resulting “rough-smooth boundary” that separates these two provinces enters the MAT offshore the Nicoya peninsula in northern Costa Rica [47]. Detailed magnetic mapping (Fig. 9.9) clearly defines the location of this feature, other tectonic boundaries and seafloor spreading magnetic lineations in the Cocos plate which resulted from the break-up of the Farallón plate at 23 Ma and the early history of the subsequent Cocos-Nazca spreading (Fig. 9.10).

The identification of seafloor spreading anomalies provides the age of the Cocos plate along the MAT. The oldest plate of 24 m.y. is found offshore Nicaragua. To the north, the EPR-generated crust becomes progressively younger until it is almost zero at 18°N where the EPR meets the MAT offshore Mexico. To the south of Nicaragua, the age of the Cocos plate decreases rapidly to ~13 Ma offshore the Costa Rica-Panama border where the Cocos plates terminates at the Panama fracture zone against the Nazca plate. No clear Wadati-Benioff seismicity is observed underneath Panama and lithospheric underthrusting may not be active in that region.

Magmatic processes at the Cocos-Nazca spreading center and the Galápagos hotspot govern crustal formation from the 20 km beneath the crest of Cocos ridge to ~6 km offshore central Costa Rica [33, 70, 71]. The high heatflow on and adjacent to Cocos ridge and the much lower than normal heatflow offshore Nicoya peninsula [67] are probably also related to magmatic history and fluid circulation in ocean crust but causes for strong lateral changes have not yet been determined. Magmatism also
Figure 9.9. Magnetic anomalies in Nicaragua and Costa Rica compiled from R/V Sonne cruises 76, 107 and 144, R/V M. Ewing cruises 0005 [66] and 0104 [67], and R/V R. Revelle delivery cruise [90]. Data processing includes corrections for daily variations of the magnetic field. In addition, detailed maps of an aeromagnetic survey across Costa Rica were digitized and merged with the marine data. The contour interval is 100 nT. Different patterns of magnetic anomalies result from the different types of oceanic crust.

constructed large volcanic edifices adjacent to Cocos ridge. The tectonic process of bending-related normal faulting seems greatly influenced by crustal thickness and the orientation of tectonic fabric created at the spreading center with respect to the axis of bending [72]. Seafloor relief in the study area defines 4 distinct oceanic plate segments (Figs. 9.2 and 9.5). The lithosphere of segments 1–3 was formed at the Cocos-Nazca spreading center whereas the crust of segment 4 was formed at the East Pacific rise. Segment 1 consists of the broad Cocos ridge whose crest is the shallowest seafloor area (water depth 2.5–1.5 km) of the MAT. The shallow seafloor corresponds to the anomalously thick ocean crust of Cocos ridge produced ~14 Ma ago by the interaction of the Galápagos hotspot with the Cocos-Nazca spreading center [73]. Paralleling Cocos ridge are large tilted normal fault blocks indicating extension perpendicular to the ridge axis along segment 1. Steep normal fault scarps dip toward the Cocos ridge axis and bound a large graben over the thickest crust (Figs. 9.2 and 9.5). The sediment strata in the graben are not tilted, indicating that the large faults are not recent and related to the bending of the plate, but probably old structures formed during the creation of the Cocos ridge. Smaller ridges, conical seamounts, and the Quepos plateau characterize segment 2. The conical seamounts and Quepos plateau are 13–15 Ma old.
Figure 9.10. Isochron map of the Cocos plate offshore Nicaragua and Costa Rica with ages derived from identification of seafloor spreading anomalies [47]. Numbers indicate ages in m.y. of identified magnetic lineations. Dotted lines show tectonic boundaries, double arrows indicate crust formed at the East Pacific rise and at the Cocos-Nazca spreading center. Triangles show the locations of volcanoes. The 100 km isodepth contour of the Wadati-Benioff zone is shown [47].

[73] and are emplaced on 21–18 Ma old lithosphere [47]. The age and geochemistry of the seamounts is essentially the same as Cocos ridge indicating emplacement during the hotspot activity in the adjacent segment 1 lithosphere [73]. The ocean crust of segment 2 is 7–8 km thick [33, 71] and it is flexed into the trench more than the contiguous segment 1. Bending at segment 2 is partially relieved by normal faulting near the trench axis (Figs. 9.2 and 9.5), that strikes obliquely to the trench axis and to the seafloor spreading magnetic anomalies (Figs. 9.9 and 9.10). Segment 3 with a 6 km thick crust [33] has the smoothest morphology displaying a few bending-related faults with relatively small vertical displacement. Bending-related faults strike roughly parallel to the trench and are perpendicular to the magnetic anomalies, implying that bending, rather than reactivating the inherited tectonic fabric, forms new faults. The boundary between segment 3 and segment 4 is a low ridge that strikes perpendicular to the trench and marks the juncture between the lithosphere formed at the Cocos-Nazca spreading center and at the East Pacific rise. The crust in segment 4 is ~5–6 km thick [33, 74] and is pervasively faulted as it bends into the trench. Faulting is roughly parallel to the trench axis and to magnetic lineations (Figs. 9.9 and 9.10) and thus parallel to the fabric formed at the East Pacific rise (Figs. 9.2 and 9.5). In this segment, trench depth and the width of the faulted area increase to the NW to ~5500 m depth.

Bending-related faulting produces a profound geochemical and mechanical change of the incoming oceanic lithosphere. The pervasive system of faults cuts across the entire crust and into the upper mantle to at least 20 km below the seafloor [72].
Figure 9.11. Perspective shaded relief view of the bathymetry from central Costa Rica showing seamount subduction and the Nicoya slide.
Faulting remains active across the entire trench oceanic slope and as the plate continues bending new faults form up to the trench axis. This extensional system provides open paths for fluid percolation deep into the oceanic plate, leading to serpentinization of the peridotites of the mantle and perhaps also important hydration of the crust [72]. As the oceanic plate subducts, the progressive pressure-temperature increase leads to metamorphic dehydration reactions liberating fluids from the slab that are released into the mantle wedge of the overriding plate, triggering arc volcanism [75]. The segmentation of the oceanic plate is also displayed in the variability of the amount of bending-related faulting at the trench which might also imply differences in the amount of hydration of the plate along the subduction zone.

In summary, the morphology of the subducting oceanic plate, the amount of bending and the associated increase in trench depth, change greatly in segments of the CAM studied. Controlling parameters appear to be the changes in crustal thickness, its age and thermal structure, and the angle between seafloor spreading fabric and the axis of bending. This segmentation of the incoming plate is parallel by a similar spatial segmentation in the character of the overriding plate.

9.5.2 Parallel segmentation of subducting and overriding plates

Remarkable is the parallelism between morphotectonics of the continental slope, the shelf, the land, and the morphological segmentation of the ocean plate. Active forearc tectonism is influenced by local uplift over subducting seafloor relief and the subsidence from subduction erosion at the front and along the base of the upper plate. Thus, changes in character of the subducting oceanic plate influence differences in the Quaternary tectonic evolution of the continental margin. The influence of the subducting oceanic plate character is additionally correlated to distinct differences in seismic activity occurring along the four segments of the margin. The volcanic arc also displays along-strike variability that corresponds to changes in the character of the incoming plate.

Segment 1 of the incoming plate subducts offshore the Osa peninsula of southeastern Costa Rica. It contains the thick and buoyant Cocos ridge and correlates with singular morphotectonic features landward of the continental slope to the arc. Retreat of the margin is greatest opposite the colliding Cocos ridge which implies accelerated Quaternary erosion (Figs. 9.2 and 9.5). Opposite the subducting ridge, uplift of a broad area of the continental shelf culminates in the Osa peninsula. The peninsula displays margin perpendicular topography parallel to the large tilted fault blocks on the ridge [40]. Landward of Osa peninsula, the Fila Costeña thrust and fold belt is the only area along the margin where active contraction is significant. Further landward, arc volcanism is extinguished and the Talamanca cordillera has been uplifted [76, 77] exposing mid crustal granodioritic plutons [49]. Rough relief from river incision characterizes the region where arc volcanism ceased and a drainage system developed (Fig. 9.5). Large earthquakes of MW 7–7.5 have nucleated in this area but during the past 20 years small earthquakes in this segment have been relatively few compared to those in the adjacent middle segment [78].

Segment 2 of the incoming plate subducts offshore central Costa Rica. The subducting ridges and chains of seamounts that are 2 to 3 km high breach the margin front and leave seafloor grooves up the slope indicating material removal. Subducting seamounts breach the lower slope during initial collision with the margin (Fig. 9.11)
Figure 9.12. Prestack depth migration of Sonne-81 line 6 indicating active tectonic erosion above a subducting seamount as it tunnels underneath the continental plate. Dots mark the plate boundary, with black dots delineating the seamount flanks. This segment of line 6 is parallel to the continental margin and shows the lateral variations in margin wedge thickness. The margin wedge is 0.5–0.7 km thinner above the subducting seamount than on either side. Tectonic extension of the overriding plate caused by uplift above the seamount is too small to explain the thinning. The thinning is probably due to ongoing tectonic erosion by the seamount. Location on Fig. 9.2. Modified from Ranero and von Huene [37].

and as they tunnel beneath it they apparently erode the underside of the upper plate (Fig. 9.12). The continental slope is uplifted above the subducting seamount causing mass wasting at the seafloor. Mass wasting produces slumps and slides locally several tens of km long. The largest slide is the Nicoya slide with a headwall detachment running more than 50 km across the middle slope (Fig. 9.11). The slide toe runs about 5 km up the ocean trench slope and it could have created a tsunami wave about 30 m high [79]. Seamounts and ridges remain attached to the subducting plate beneath the continental shelf where they produce uplift (Fig. 9.13). Subducted basement highs beneath the shelf induce local increase of the stress on the plate interface and are areas of earthquake nucleation [37, 80–82]. The largest events associated with chains of subducting seamounts are \( M_w < 7 \) [37]. Some seamounts are associated with local uplift on land that may separate the Panama block from northern Costa Rica along margin perpendicular faults [83, 84]. In this segment the volcanic output is greater than along other segments of the arc, and the arc volcanoes have recently migrated landward [85] perhaps related to the accelerated tectonic erosion associated with seamount subduction here [37, 40]. Where large seamounts on the ocean plate are sparse and small, roughness of seafloor forms from bending-related normal faulting. Segment 3 and the contiguous portion of segment 4 exhibit a relatively smooth subducting oceanic plate morphology (Figs. 9.2 and 9.5) mainly opposite the Nicoya peninsula. There the continental slope displays the most stable morphology of the margin with gentle dips and well-developed canyon systems in the upper-middle slope (Fig. 9.5). Heatflow at the trench and lower slope is exceptionally low [67, 86]. Some of the largest historic earthquakes have nucleated in this segment [78] adjacent to the smoothest subducting topography in the area. The oceanic plate of segment 4 displays more bend-faulting and morphological roughness that increases towards the NW (Figs. 9.2 and 9.5). The vertical displacement of individual faults increases progressively NW from a few tens of m to as much as 500 m. A parallel change in continental slope morphology occurs along the margin. The slope of the margin changes gradually from the simplest structure offshore Nicoya peninsula to a margin characterized by an upper, middle and
lower slopes with different morphologies and dips. The upper slope dips gently and its many canyons develop at the slope break and coalesce downslope. A change to steeper dips defines the transition to the middle slope, characterized by many normal faults and the mud diapirs associated with fluid flow [87] and chemosynthetic fauna [88]. Also, the middle slope dip increases progressively towards the NW, where slump scars become abundant (Figs. 9.2 and 9.5). The lower slope is an area characterized by terraces that display an en echelon pattern that mimic and strike parallel to the morphology of the half grabens in the subducting oceanic plate. The terraces are formed by the riffling of the thin apex of the overriding plate over subducting topography indicating a largely dismembered upper plate. Segment 4 ocean floor subducts in the area where the damaging 1992 large tsunami earthquake occurred [89].

9.6 SUMMARY

Early in the exploration of the Pacific basin the CAM was recognized as a Pacific type margin with a trench and Wadati-Benioff zone. It was recognized as a subduction zone when the plate tectonic paradigm first developed. Later it was significant in developing the knowledge to correctly differentiate between accretionary and erosional convergent margin end-members. When only seismic data are available the constant accretionary end-member model must be applied with greater care than it was invoked in the past. Landward dipping reflections in seismic records are not only derived from accretionary processes but in erosional margins they may represent extensional structures or inherited fabric and their origin requires further investigation. The CAM displays the effects of subducting lower plate character on tectonics of the upper plate. The effects of relief, crustal thickness, thermal structure, and the orientation of original oceanic crustal fabric also shape continental slope structure, induce a pattern of earthquake seismicity, influence the potential for tsunamigenic submarine sliding, and correlate with changes in the volcanic arc. Oceanic crustal thickness and temperature correlate with trench depth and bending of the incoming plate. Orientation of oceanic crustal fabrics subdue or accentuate bend faulting which imparts subducting plate roughness and correlates with rates of erosion. These interactive geological processes are not yet fully understood and are the topics of ongoing research. The differences in the character of the subducting plate are sharply segmented along the CAM and segment.
boundaries in the lower plate correspond with features in the upper plate. This segmentation also separates earthquake magnitude and epicentral patterns. Subducting seamounts are commonly associated with large submarine slides. Thus, the forefront research along the CAM continues to contribute significantly to a basic understanding of natural hazards and promotes progress towards the mitigating of their damaging effects.

REFERENCES


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