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## From seamount accretion to tectonic erosion: Formation of Osa Mélange and the effects of Cocos Ridge subduction in southern Costa Rica

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[1] The Costa Rica portion of the Middle America Trench (MAT) is characterized by active tectonic erosion, a process that causes the removal of material from the base of the upper plate as the plate boundary migrates upward. Offshore studies demonstrate accelerated subduction erosion starting at the Miocene-Pliocene boundary, as the result of subduction of thickened Galapagos related crust, as presently represented by the Cocos Ridge. The subduction of the Cocos Ridge also caused uplift and exposure of the outer forearc on the Osa Peninsula, which offers a window to explore the tectonic evolution of the area. The rocks outcropping on Osa Peninsula are a middle Eocene–middle Miocene mélange dominated by basalt, chert, and limestone resulting from accretion of seamounts. The accretion-dominated period of the MAT evolution ended at the Miocene-Pliocene boundary, when thickened crust, a paleo-Cocos Ridge, produced at the Galapagos hot spot arrived at the trench. The thick crust caused uplift and severe tectonic erosion of the accretionary edifice allowing exhumation of the Osa Mélange. The change from accretion to erosion caused the outer forearc to be offset along subvertical faults that define small (kilometer to tens of kilometers size) blocks that are going through differential vertical movements in response to the morphology of the subducting ridge. Subduction accretion and erosion are two processes that can alternate in time and space or coexist along the same margin, so that mass removal can develop on a previously growing margin and completely remove an accretionary prism.

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### 1. Introduction

[2] Exploration of active convergent margins indicates that subduction is accompanied by either erosion or accretion of material to the upper plate [von Huene and Scholl, 1991; Clift and Vannucchi, 2004]. The two processes can coexist along the same margin or alternate in time, so that mass removal can develop on a previously growing margin and completely remove an accretionary prism. The cause for the temporal and spatial variations between tectonic accretion and erosion is poorly known. Subduction of seamounts, for example, could be one cause for this variation, being a punctuated anomaly on the incoming plate that introduces a local perturbation in the subduction zone and removal of material, as indicated by scarring of the lower slope [von Huene *et al.*, 2000]. Unfortunately active processes taking place in the outer part of the forearc are submarine and not easily accessible, while exposed fossil systems are rare, because erosive processes inherently do not lead to material preservation. However, on Osa Peninsula (Figure 1a), along the erosive plate boundary of the Middle America Trench (MAT) in Costa Rica [Ranero and von Huene, 2000; Vannucchi *et al.*, 2001, 2004], the outermost fore arc is exposed, providing a window into the tectonic evolution of the area. The greatest uplift and unroofing is occurring in the region inboard of prominent bathymetric highs on the subducting plate, most notably the Cocos Ridge [Gardner *et al.*, 1992; Fisher *et al.*, 1998] (Figure 1a). Directly inboard of the Cocos Ridge, the outer forearc is composed of a disrupted rock body known as the Osa Mélange [Di Marco *et al.*, 1995] (Figure 1b).

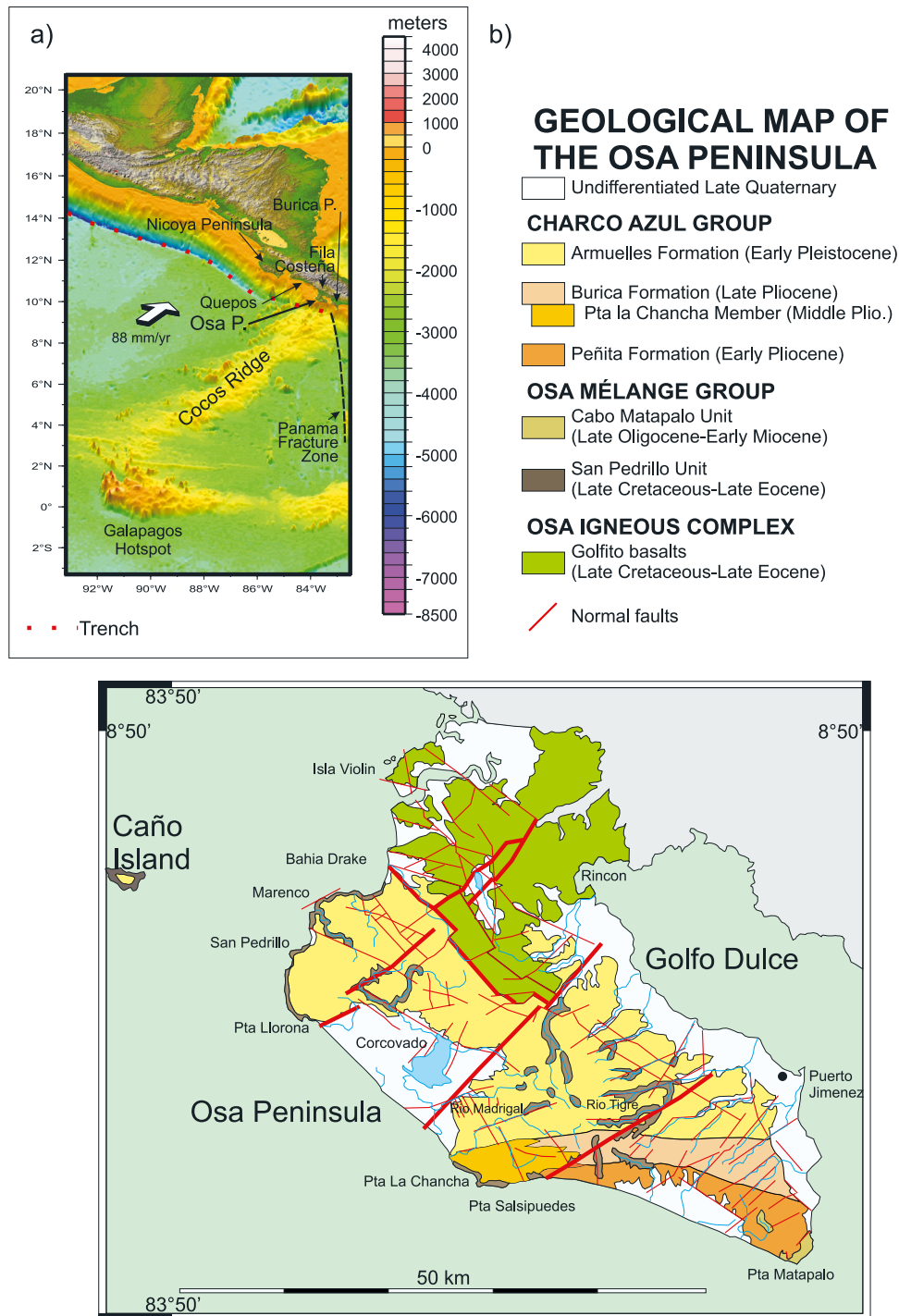
[3] The Osa Mélange is a middle Eocene–middle Miocene rock assemblage dominated by basalt, chert and limestone, whose origin and significance has been ascribed to debris flows subsequently accreted to the margin [Di Marco *et al.*, 1995], or to a tectonic mélange produced by subduction erosion and disruption of the preexisting margin wedge [Meschede *et al.*, 1999]. Our findings do not support either of these interpretations and rather point to a tectonic mélange that was accreted prior to the arrival of the Cocos Ridge during subduction, underthrusting and tectonic burial of seamounts and seamounts chains. The evidence for active, recent tectonic erosion of the forearc is compelling [Vannucchi *et al.*, 2003], and Osa Mélange does not reflect accretion from the currently subducting plate, given the southeastward migration of the Cocos-Nazca-Caribbean

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**Figure 1.** (a) Perspective map of the Cocos Ridge entering the Middle America Trench offshore the Osa Peninsula viewed from north to west. Elevation data are from *Smith and Sandwell [1997]*, onland topography from the Shuttle Radar Topography Mission (SRTM30). (b) Simplified geological map of the Osa Peninsula (modified after *Coates et al. [1992]*).

triple junction over the last 5 Myr [*Hey, 1977; Gardner et al., 1992; MacMillan et al., 2004*], possible transform jumps [*Lonsdale and Klitgord, 1978; Lowrie et al., 1979*], and the subduction of the Cocos Ridge [*Vannucchi et al., 2003*].

[4] In this paper we identify the deformation related to seamount subduction and underplating, and we describe the processes of disruption and fluid flow that characterize this tectonic environment. The accretion-dominated period of the Osa Mélange ended when the triple junction migrated to

offshore of the Costa Rica–Panama border and the leading edge of the Cocos Ridge arrived to the trench triggering the transition to tectonic erosion [Vannucchi *et al.*, 2003]. The thick crust of the ridge caused uplift and severe erosion of the accretionary edifice allowing the exhumation of the Osa Mélange and the exposure of structures that record the transition from accretion to erosion. This history has collectively resulted in perhaps the first example of a convergent margin where a transition from accretion to tectonic erosion is driven by the changes in subduction parameters that accompany triple junction migration. We show that the accretion/erosion switch was accompanied by displacement along subvertical faults that define small blocks that are experiencing ongoing differential vertical movements in response to subducting ridge morphology.

## 2. Tectonic Setting and Previous Study

[5] At the MAT, the Cocos plate is being subducted beneath the Caribbean Plate at an average rate of 88 mm/yr [DeMets, 1995]. This subduction front extends for about 1100 km from Mexico along Guatemala, El Salvador and Nicaragua to Costa Rica. Deep sea drilling [Vannucchi *et al.*, 2001, 2003, 2004] and geophysical exploration of the margin [Hinze *et al.*, 1996; Ranero and von Huene, 2000] indicate subduction erosion as the main process shaping the outer fore arc.

[6] The oceanic Cocos plate subducting at the MAT is sharply segmented due to Galapagos hot spot volcanism that intrudes oceanic lithosphere created at two ridges: the East Pacific Rise (EPR) and the Cocos Nazca spreading center (CNS) [Barckhausen *et al.*, 2001]. The main morphological feature on the Cocos plate is the Cocos Ridge formed by the passage of the Cocos plate over the Galapagos hot spot. The ridge stands 2.5 km high and has crust of Galapagos-type geochemistry about 12 km thick [Walther, 2003]. Bordering the ridge to the northwest is regular CNS oceanic crust, 40% of which is covered by younger seamounts (Figure 1a) also with Galapagos geochemistry [von Huene *et al.*, 2000]. Farther north, the EPR-generated crust has a smoother morphology.

[7] The effects of Cocos Ridge subduction are evident in Costa Rica and increases from the Nicoya Peninsula in the northwest to the Osa Peninsula to the southeast (~400 km; Figure 1a). These lateral variations correlate with an increase in the crustal thickness of the Cocos plate and a shallowing of the Wadati-Benioff Zone [Protti *et al.*, 1995]. The seismically active slab dips at ~65° near the Nicaraguan border and shallows to a few degrees inboard of the Cocos Ridge. When the Cocos Ridge arrived at the Middle America Trench is a debated issue, with estimates ranging from ~1 Ma [Lonsdale and Klitgord, 1978; Gardner *et al.*, 1992; Fisher *et al.*, 2004] to ~5 Ma [De Boer *et al.*, 1995; Grafe *et al.*, 2002; Vannucchi *et al.*, 2003; MacMillan *et al.*, 2004] to ~8 Ma [Rivier, 1985; Abratis and Worner, 2001] (Figure 2).

[8] Figure 2 summarized the major events shaping the margin offshore Osa Peninsula. Here it is worth mentioning that the igneous complexes exposed in Costa Rica represent

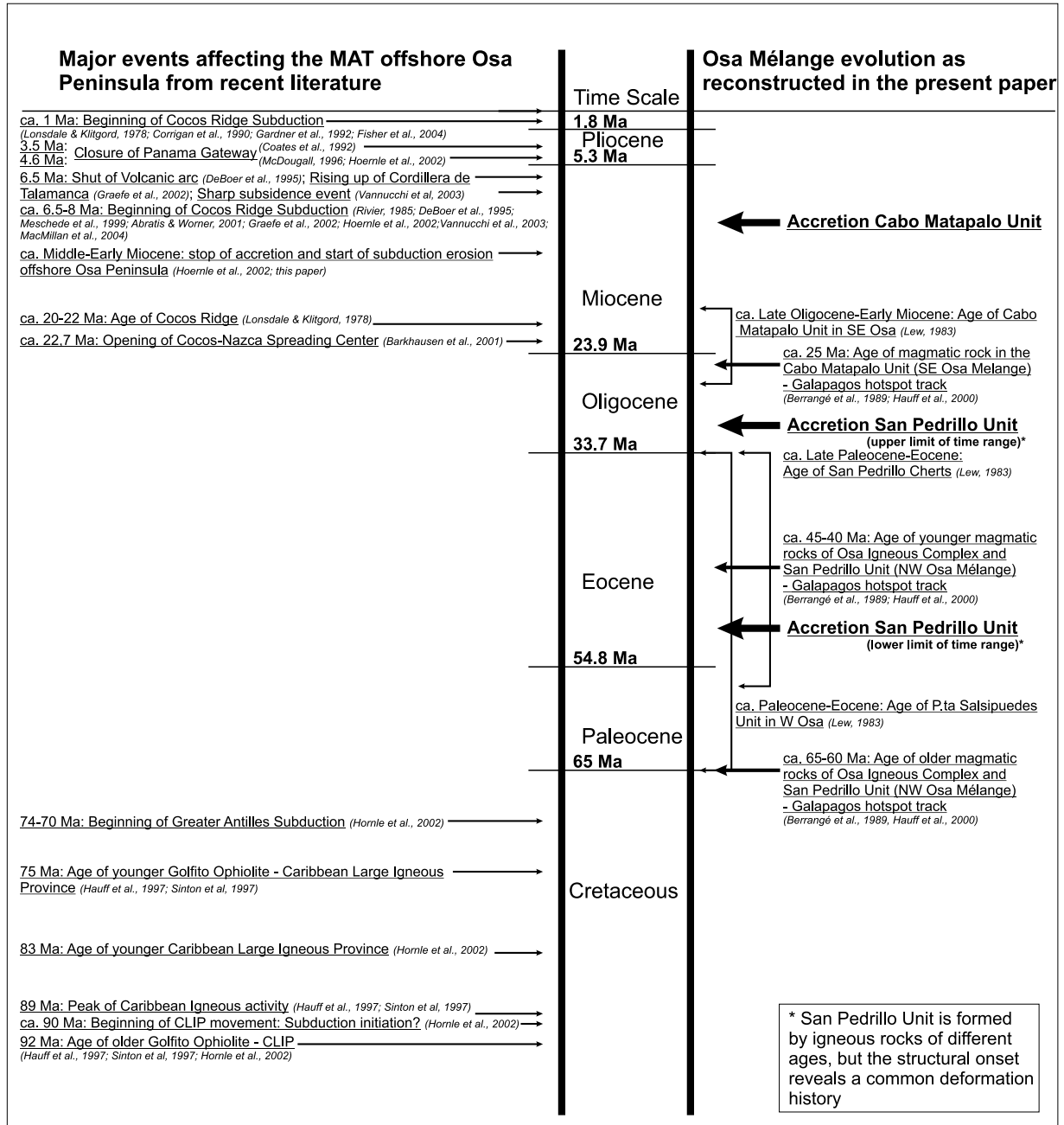
either the Caribbean Large Igneous Province (CLIP), emplaced between 74 and 94 Ma [Sinton *et al.*, 1998], or accreted ocean islands and aseismic ridge terranes [Hauff *et al.*, 1997; Sinton *et al.*, 1997; Hauff *et al.*, 2000] (Figure 2). The 60–25 Ma Quepos and Osa terrains, in fact, are interpreted to reflect rocks accreted from subducted edifices generated by the Galapagos hot spot [Hauff *et al.*, 1997, 2000] (Figures 1a and 2). Crucially there is no evidence that the Costa Rican forearc is composed of an accretionary complex of tectonized sediments offscraped from the currently subducting plate [Ranero and von Huene, 2000; Vannucchi *et al.*, 2001; Fisher *et al.*, 2004]. Plate reconstructions indicate that the Cocos-Nazca-Caribbean triple junction migrates to the southeast at a rate of ~50 km/Myr, implying that the Nazca plate was subducting beneath southeast Costa Rica in the late Neogene [Gardner *et al.*, 1992]. Arc volcanism and the presence of an accretionary prism in southwest Panama are consistent with active subduction of the Nazca plate to the southeast of the triple junction. Cocos Ridge subduction, after passage of the triple junction, has caused the exhumation of Late Cretaceous–early Eocene ophiolitic rocks cropping out along the Golfo Dulce and the middle Eocene–middle Miocene Osa Mélange on the Osa Peninsula.

## 3. Geologic Framework of the Osa Peninsula

### 3.1. The Osa Igneous Unit

[9] The inner part of the Osa Peninsula and the area around Golfo Dulce are characterized by an oceanic sequence composed of aphyric pillow lavas, massive basalts, gabbros, plagiogranites and radiolarian chert (Figure 1b). Until the mid-1980s the Osa and Golfo Dulce igneous complexes were interpreted together as an obducted back-arc basin sequence developed in association with an Oligocene southward dipping subduction system [Berrangé and Thorpe, 1988]. The back-arc hypothesis was supported by the geochemistry of the igneous rocks showing an affinity to large ion lithophile element-enriched oceanic crust. Wildberg [1984] proposed an island arc affinity for the ophiolites present in the inner part of the Osa Peninsula and around Golfo Dulce. Petrographic work since then, however, has documented that the oceanic igneous rocks of Golfo Dulce and Osa do not belong to the same oceanic environment [Hauff *et al.*, 1997, 2000; Hoernle *et al.*, 2002].

[10] Combined biostratigraphic, geochemical, petrological, and <sup>40</sup>Ar/<sup>39</sup>Ar age dating studies indicate that the vast majority of the igneous rocks of the Golfo Dulce ophiolites formed between 92 and 75 Ma from a source compatible with the Galapagos hot spot [Hauff *et al.*, 1997; Sinton *et al.*, 1997; Hauff *et al.*, 2000]. Moreover the volcanic facies of the extrusive rocks of the Golfo Dulce ophiolites and their high sulfur content in the fresh tholeiitic glasses indicate eruption in a deep marine environment [Sinton *et al.*, 1997; Hauff *et al.*, 2000]. Therefore the Golfo Dulce ophiolites are similar to the Nicoya Complex cropping out in the Nicoya Peninsula, Herradura and Burica, and mark the westernmost exposures of the Caribbean Large Igneous Province (CLIP) [Sinton *et al.*, 1997, 1998].



**Figure 2.** Summary of major tectonic events along the Costa Rica margin off Osa Peninsula as compiled by recent literature and by the present study.

[11] The Osa Igneous Unit represents rock bodies formed between 65–60 Ma (Paleocene) and 45–40 Ma (Eocene) [Berrangé et al., 1989; Hoernle et al., 2002] and subsequently accreted before ~25 Ma to the Pacific margin of Costa Rica after the eastward dipping subduction along the western margin of the CLIP initiated at ~90 Ma [Hoernle et al., 2002] (Figure 2). Volcanology, petrology, and sedimentology of igneous rocks and associated sediments suggest that the Osa Igneous Unit once formed part of an aseismic ridge similar to the Cocos Ridge presently being subducted beneath the Osa Peninsula. The Osa and Quepos igneous

complexes are interpreted to be part of the subsequent Galapagos hot spot track after the oceanic plateau migrated to the east [Hauff et al., 1997, 2000]. Younger, 20–38 Ma, accreted Galapagos terranes have been found in the western Panama Azuero Peninsula, where Hoernle et al. [2002] hypothesized the hot spot track to have been subducted between ~25 and 8–5 Ma. The volcanic stratigraphy in Quepos unit provides evidence for the emergence of a submarine volcanic edifice above sea level and the formation of an ocean island volcano [Hauff et al., 2000] prior to accretion in the inner fore arc. The Osa Igneous Unit,

although deformed, is not disrupted, and primary structures such as pillow basalts are well preserved.

### 3.2. The Osa Mélange

[12] Until the 1990s, the igneous rocks along the outer part of Osa Peninsula were considered to be volcanics intruding a more or less deformed CLIP basement and erupting at the time of carbonaceous ooze deposition, Eocene. This concept came originally from the idea that the basalts were of island arc affinity and that the pelagic sediments, the radiolarian cherts particularly, were older, Late Cretaceous, than the basalts of Eocene age [Lew, 1983; Berrangé and Thorpe, 1988]. Geochemical work and more accurate dating since then, however, has documented that the age of the basalt spans from Late Cretaceous to Miocene and that they have a volcanic island affinity [Berrangé et al., 1989; Hauff et al., 2000] indicating their exotic origin from the subducting plate. Moreover, the jaspers and cherts are in some cases observed in depositional contact with the basalts, indicating that the basalts were erupted and pelagic sediments deposited on top.

[13] Another question deals with whether the deformation is dominated by subduction accretion that occurred sub-perpendicular to the trench or with a strong oblique strike-slip component. The Osa Peninsula tectonics has been long considered, in fact, to be influenced by the boundary between the Cocos and the Nazca plates, the Panama Fracture Zone (Figure 1a). The Panama Fracture Zone is defined by a N-trending series of transform faults that enter the trench in the vicinity of the Burica Peninsula where they have been inferred to bend to the northwest forming a series of braided coast-parallel dextral or sinistral wrench faults [Berrangé and Thorpe, 1988; Corrigan et al., 1990]. The extent to which right-lateral slip along the Panama Fracture Zone produces strike-slip deformation in the upper plate is ambiguous. Fisher et al. [2004] demonstrated that strike-slip motion in the upper plate parallel to the margin is not consistent with the geometry of fault-related folds in the Fila Costeña. GPS measurements, moreover, indicate a stress regime with the maximum compression axis perpendicular to the coast [Dixon, 2003; Norabuena et al., 2004].

[14] The term *mélange* refers to a disrupted unit characterized by a block-in-matrix fabric, in some cases with occurrence of exotic blocks. In the Osa Peninsula the degree of disruption varies and in places deformation is not pervasive enough to break up the original layering; on the other hand, the igneous and sedimentary rocks in the assemblage are of volcanic island origin, so they are exotic to the CLIP [Hauff et al., 2000]. The present study, moreover, has resulted in identification of areas of concentrated shear strain and disruption that we interpret as thrust zones. The Osa Mélange is a chaotic assemblage of thrust slices and fault blocks with variable degree of internal disruption.

[15] The available data set permits recognition of at least two different units forming the Osa Mélange on the basis of lithological differences, age and degree of disruption.

#### 3.2.1. San Pedrillo Unit

[16] The northeastern package, the San Pedrillo unit [Di Marco et al., 1995], is the largest subunit, cropping out from

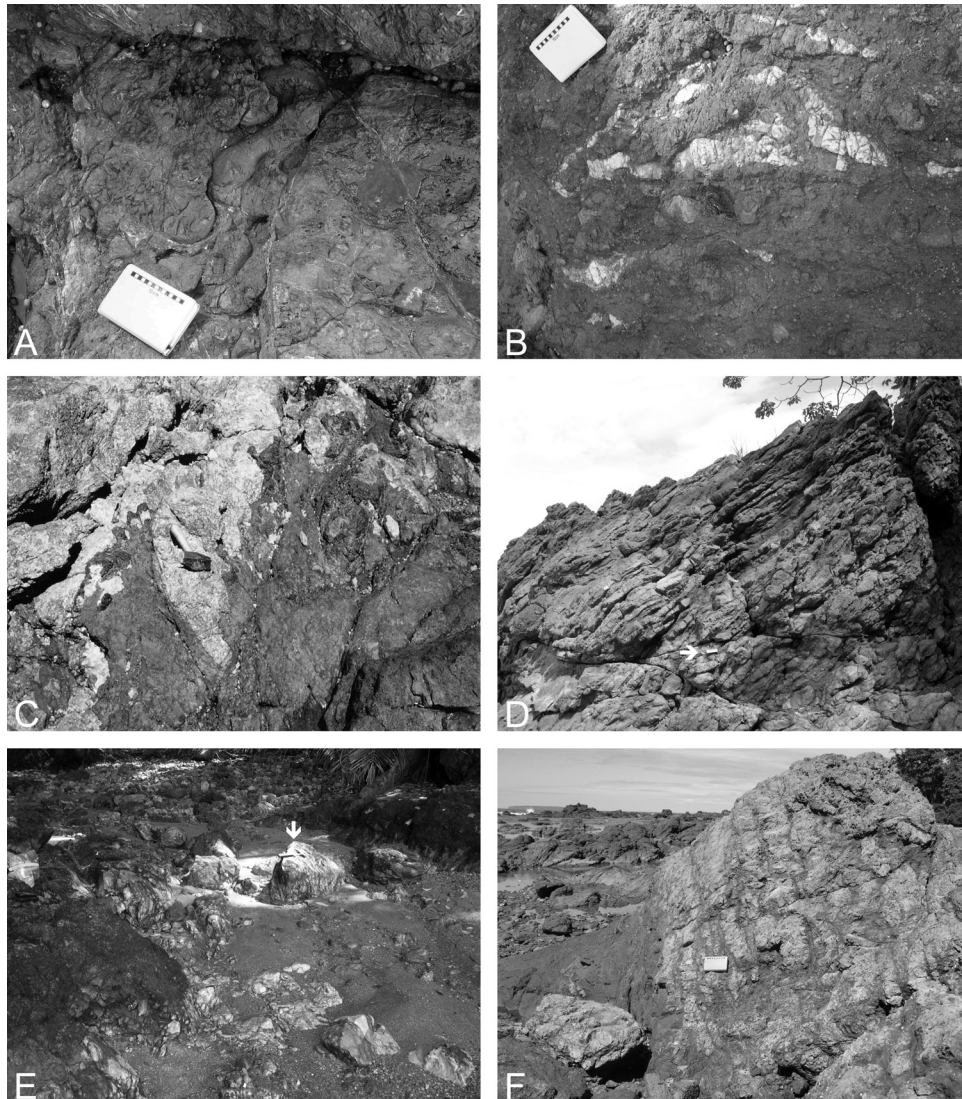
Bahia Drake to Punta Llorona, on the N-NW part of the peninsula and on Caño Island (Figure 1b). Isolated outcrops along the Rio Cedral, Rio Rincon and Rio Tigre are also ascribed to the San Pedrillo Unit. The San Pedrillo Unit is composed of tectonic blocks of low-grade metamorphic rocks of the zeolite to greenschist facies. Basalt, gabbro, and pelagic sediments show recrystallization in low PT conditions; equilibrium mineral assemblages are not always present. The basalts are usually massive, but pillow basalt and extrusion breccias are also present (Figures 3a and 3b). The basalt contains few phenocrysts of plagioclase, mainly albite, olivine and clinopyroxenes in an almost completely chloritized groundmass. Spilitization, widespread chloritization and zeolite veins in the basalt reveal hydrothermal alteration. Actinolite, epidote, calcite veins, hematite and pyrite are also common. Meschede et al. [1999] also describe pumpellyite.

[17] The gabbros and the dolerites occur in blocks ranging in thickness from less than a meter to tens of meters and it is common also to find discordant dikes, usually extended in boudins. Pegmatites, consisting of quartz, plagioclase (albite) and hornblende, occur as boudins in the massive basalts and gabbros. Red and green chert interlayers are common in the basalt. Basaltic dikes and sills are particularly common around Punta Salsipuedes (Figure 3c).

[18] The K/Ar dating on the basalts has differentiated three different events: the first one  $78 \pm 2$  Ma, Santonian, the second  $60.2 \pm 7.6$  Ma Paleocene, and a third one  $44.1 \pm 4.4$  Ma, Eocene [Berrangé et al., 1989].

[19] Packages of layered and massive red radiolarian cherts in thin (3 to 20 cm) layers (Figure 3d) are often associated with the basalts, where they also occur as xenoliths. The cherts vary from radiolarites, mainly composed by quartz and recrystallized radiolaria replaced by quartz or calcite, and tuffaceous cherts, that consists of laminated very fine to fine-grained sands. Primary laminations are still visible. The cherts exhibit boudinage and pinch-and-swell. Foliation is locally present at the meso-scale and also in thin section there is an incipient preferred orientation of the lenticular mineral aggregates. Veins filled with quartz, calcite, barite, epidote, hematite, chlorite and zeolites cut the incipient metamorphic foliation. The age of the cherts has been attributed to the late Paleocene–early to late Eocene [Lew, 1983].

[20] In the San Pedrillo Unit, both shallow water and pelagic limestones are observed [Di Marco et al., 1995]. Deep-water limestones are massive to thinly bedded alternating with clay as in Figure 3e, or cherts, the latter being originally ash layers. These limestones are particularly exposed around Punta Salsipuedes (Figure 3c), where Lew [1983] defined the Punta Salsipuedes Formation as ivory-mottled in appearance, partially to completely recrystallized and with intensely deformed bedding. Foraminifera and radiolaria are poorly preserved and define a general Paleocene to Eocene age [Lew, 1983; Di Marco et al., 1995]. Widespread evidence of pressure solution is present together with common brecciation. It is worth mentioning that in some outcrops, brecciation in limestone has been observed to be depositional and associated with a fore-reef environ-



**Figure 3.** Field photographs of various lithologies and observed mesoscopic structures in the San Pedrillo Unit. (a) Pillow basalt; (b) slump fold developed in cherts and extrusion basaltic breccia; (c) basalt intruding limestone at Punta Salsipuedes; (d) layered radiolarian cherts showing pinch-and-swell (arrow indicates a compass for scale); (e) deep-water limestones (arrow indicates a hammer for scale); and (f) mélangé block formed by a portion of clastic, mainly tuffaceous cherts and graywackes, sequence.

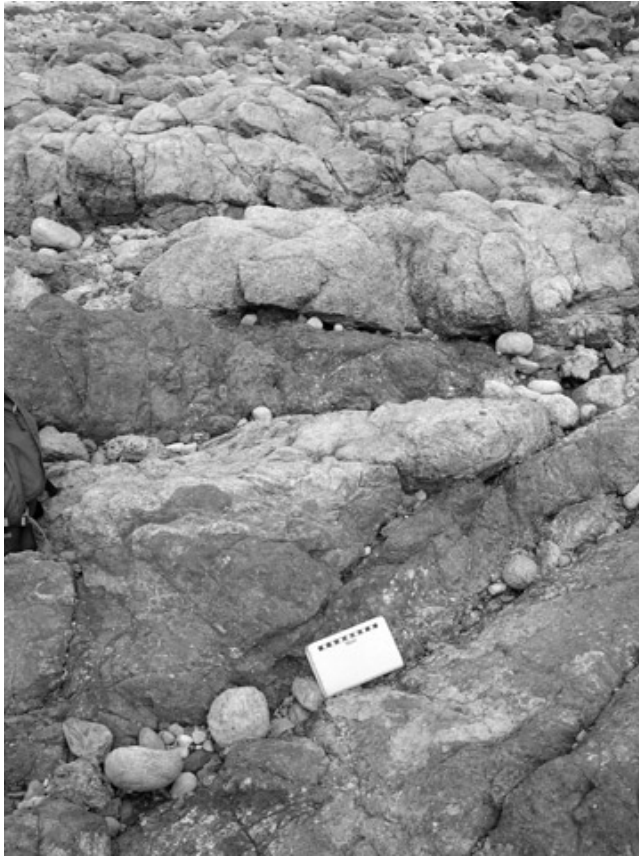
ment. In the San Pedrillo area the clasts composing the breccia are elongated and show some preferred orientation (Figure 3e). The calcite is completely recrystallized, while the clay mineral impurities are not yet micas. Basalts intrude the limestones, but they do not cause contact metamorphism, indicating that the carbonates were still un lithified and water-rich at the time of intrusion (Figure 3c). Shallow water carbonates are common in the Bahia Drake (Playa Colorado) area close to the Osa Igneous Unit [Di Marco *et al.*, 1995; Hoernle *et al.*, 2002]. These limestones have been interpreted as clastic aprons associated with island volcanoes suggesting drowning of former ocean island volcanoes before they were accreted [Hoernle *et al.*, 2002].

[21] Mudstone to fine-grained volcanoclastic graywackes and, rarely, coarse-grained/conglomerate are also present

(Figure 3f). They often occur interbedded with thin chert layers, and less commonly with the basalts and the limestones. They rarely preserve thin laminations. Highly convoluted to folded laminations and thin layers are indicative of soft sediment deformation, and slumps suggest sediment instability on the slope of the seamount or in the proximity of the trench (Figure 3b). On the other hand, the volume of terrigenous sediment and the fine grain size suggests deposition within a sediment-starved trench far from the major landmass according to Berrangé and Thorpe [1988].

### 3.2.2. Cabo Matapalo Unit

[22] The Cabo Matapalo unit, cropping from Punta Carbonera to Cabo Matapalo on the SE tip of Osa Peninsula, is distinguished from San Pedrillo Unit because of a



**Figure 4.** Field photograph of the youngest, middle Miocene pelagic limestones (light gray) at Cabo Matapalo.

younger age of about late Oligocene–early Miocene [*Di Marco et al.*, 1995], a large volume of limestones, and a fair amount of clastic material relative to the basalts. The rock assemblage at Cabo Matapalo is composed of limestone, siltstone and mudstone. Sparse cherts beds are also observed.

[23] The limestones of the Cabo Matapalo unit are very similar to those of Punta Salsipuedes (Figure 4). They have an ivory-mottled appearance and they are partially to completely recrystallized, yet they display remnants of fossils that document a pelagic origin. Bedding is intensely deformed and pressure solution is widespread. Paleontological evidence indicates that the limestones are late Oligocene–middle Miocene [*Berrangé et al.*, 1989; *Di Marco et al.*, 1995] so significantly younger than the Late Cretaceous–middle Eocene of the San Pedrillo Unit.

[24] Interbedded basaltic lava flows and doleritic sills and dikes intrude the limestones, without contact metamorphism, here again testifying to the lack of lithification. These basalts have to be post-early Miocene, indicating an igneous event different from those described for the San Pedrillo area.

[25] Fine-grained graywacke and conglomerate are abundant in this unit. They occur interbedded with the limestones and sometimes they also inject the latter, indicating soft sediment deformation. Conglomerate and sedimentary breccias contain basalt and gabbro clasts.

[26] Thus, at Cabo Matapalo-Punta Carbonera, the sedimentary component is larger than the igneous component, but the presence of volcanic island basalt suggests that the sediments are overlying an oceanic basaltic basement.

### 3.3. Plio-Quaternary Sedimentation

[27] The Osa Mélange is overlain by a clastic sequence of Pliocene-Quaternary age. A formal definition of the lithostratigraphy of this sedimentary sequence has been proposed several times. *Berrangé* [1989] proposes to use a local Osa Group stratigraphy, even though former work refers to the Charco Azul Group as described on Burica Peninsula [*Sprechmann*, 1984]. The most recent descriptions by *Corrigan et al.* [1990] and by *Coates et al.* [1992] also refer to the Charco Azul Group. Following this classification, the Plio-Quaternary sedimentary sequence is subdivided into the basal Peñita Formation, the Burica Formation, including the Punta La Chancha Member extensively cropping out in Osa Peninsula, and the Armuelles Formation [*Sprechmann*, 1984; *Berrangé*, 1989; *Corrigan et al.*, 1990; *Coates et al.*, 1992; *Sak et al.*, 2004]. The Charco Azul Group is then overlain by the late Pleistocene to Recent sediments of the Marengo Formation and Puerto Jiménez Group.

[28] On the Osa Peninsula, the Peñita Formation, of early Pliocene age, crops out near the south coast along the Leona Creek where it sits unconformably on the mélange through a basal conglomerate. Peñita Formation is formed by clayey siltstone with turbiditic layers, and it is laterally discontinuous. The Burica Formation is late Pliocene in age and conformably overlies the Peñita Formation. It consists of fine-grained, volcanoclastic turbidites with local megabreccias originated by slumps. On Osa Peninsula, the Burica Formation crops out on the eastern coast, while moving west toward Punta Salsipuedes, it laterally passes to Punta La Chancha Member of middle Pliocene age [*Lew*, 1983]. The latter consists of 850 m thick, fining upward terrigenous sequence, with well-bedded calcareous graywacke turbidites cut by a thick channel system with conglomerates (Figure 5) indicating a provenance from the Cordillera de Talamanca, in accordance also with the direction toward SSE pointed out by slumped layers. The conglomerates of Punta La Chancha Member also contain clasts of Osa Mélange, suggesting that the latter was also already exposed above sea level in the middle Pliocene.

[29] The early Pleistocene Armuelles Formation is formed by siltstones and pebbly conglomerates containing large boulders encrusted with oysters. The Charco Azul Group defines a sedimentary sequence from shallow to deep water, to shallow environment again.

[30] The late Pleistocene, Marengo Formation, is exposed on the northwestern part of Osa Peninsula [*Sak et al.*, 2004]. The Marengo Formation is composed of poorly to well-sorted sands with a general fining-upward trend indicative of deposition in an environment characterized by rapid vertical tectonic variations that include subsidence faster than sea level fall from 48ka to 26ka (fining upward from wave base to subwave base deposits) and subsequent uplift at a rate greater than sea level rise to present elevations of >75 m [*Sak et al.*, 2004]. The Marengo Formation has been



**Figure 5.** Field photograph of graywacke turbidites and conglomerate of the Punta La Chancha Member. The gravels are from Osa Melange.

used to interpret the response of the upper plate to the subduction of the Cocos Ridge [Sak *et al.*, 2004]. Late Pleistocene to Holocene sediment also outcrop extensively on top of the Osa Group along the southeastermost part of the peninsula, where they have been referred to as the Puerto Jimenez Group [Berrange, 1989] and also used to document a net vertical uplift and landward block rotation of the Osa Peninsula [Gardner *et al.*, 1992].

#### 4. Origin of Osa Melange

[31] The origin of Osa Melange has been attributed either to gravitational [Di Marco *et al.*, 1995] or tectonic [Meschede *et al.*, 1999] mechanisms. Our beginning considerations deal with the identification of the process responsible for the disruption. The disruption appears to have been developed during different, but continuous stages of deformation. The sedimentary part of the sequence presents evidence for disruption occurring during lithification, as described in the following paragraph. This observation is in agreement with a progressive tectonic event occurring gradually at a rate comparable with diagenesis, since gravitational events are, instead, short and episodic so that they punctuate the diagenetic history [Maltman, 1995]. Deformation during progressive lithification, combined with the exotic origin of oceanic lithologies, argues against disruption of the margin wedge during subduction erosion [Meschede *et al.*, 1999] and instead points to disruption during underthrusting and tectonic burial.

[32] Another diagnostic observation regards the melange fabric. Sedimentary assemblages, as debris and mudflows, are characterized by clasts dispersed in a detrital matrix produced by disaggregation and new deposition, a “clastic fabric”. During disruption induced by tectonic stresses, instead, the fine-grained material embedding the blocks is made up of sheared shales which, strictly, can be considered a matrix only from a rheological point of view [Bettelli and Vannucchi, 2003]. Deposits characterized by clastic fabric are dispersed and intercalated in the oceanic sedimentary rocks of the Osa Melange (Figure 6), but they are volumet-

rically limited. Moreover there is evidence of original stratigraphic contacts between the debris flow and the overlying sediments. The chaotic rocks produced by sedimentary processes are cut by the later tectonic deformation responsible for the disruption of the Osa Melange.

[33] A final argument for tectonic disruption of the melange is that similar asymmetric structures indicating the sense of shear are observed ubiquitously both at mesoscopic and microscopic scales throughout the Osa Peninsula.

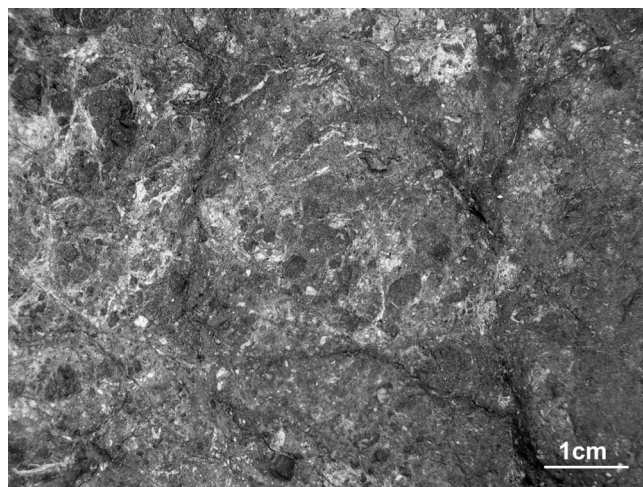
### 5. Structural Setting of the Osa Melange

#### 5.1. Outline

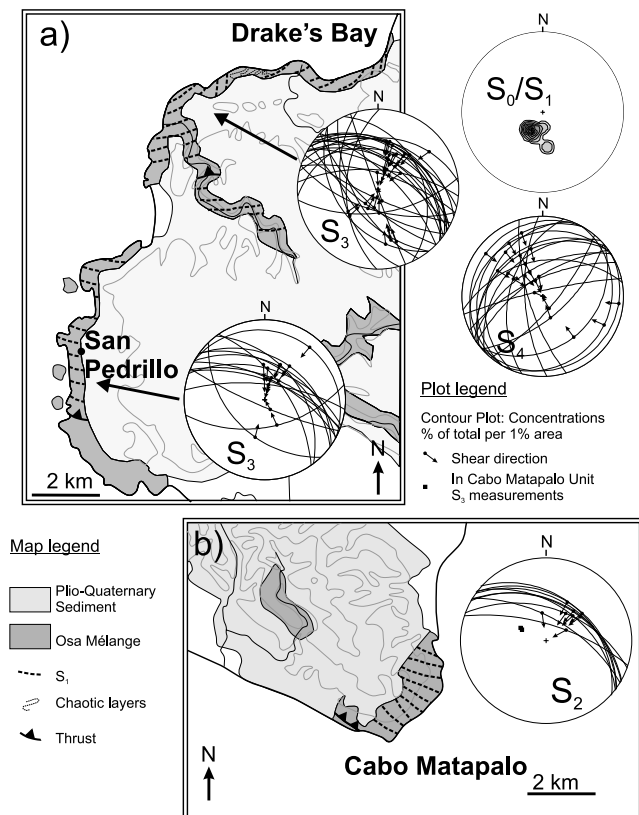
[34] The San Pedrillo Unit of the Osa Melange crops out for ~50 km along the NW coast of the peninsula, between Bahia Drake and Punta Llorona, and in limited areas of the SW, Punta Salsipuedes, area, while the Cabo Matapalo Unit is present to the SE Cabo Matapalo–Punta Carbonera region (Figure 1b). Exposures of the melange are also present inland along river cuts along the Rio Tigre and Rio Madrigal (Figure 1b). The data discussed here are coming from the well-exposed coastal outcrops and based on field and microstructural analysis of these exposures, the structural history can be broadly characterized in terms of (1) early structures and fabrics that reflect the subduction regime and (2) later, brittle structures that overprint these fabrics and record the structural history of the forearc during the unroofing and exhumation of the Osa Melange. The relative ages of the deformation events are established on the basis of crosscutting relationships, the metamorphic environment, and operative deformation mechanisms. In the following sections we describe the structures related to the two phases of the structural history and then we discuss the implications of these results for the tectonic evolution of the area.

#### 5.2. Structure of the San Pedrillo Unit

[35] Along the Bahia Drake–Punta Llorona section, the San Pedrillo Unit presents imbrications along two main



**Figure 6.** Debris flow with evidence of hydrothermal alteration within the San Pedrillo Unit.



**Figure 7.** Detailed structural maps of the coastal exposures of the (a) San Pedrillo and (b) Cabo Matapalo units. Pole and contoured stereograms, lower hemisphere, represent foliations, faults, and shear sense directions of kinematic indicators.

ESE-WNW thrust faults characterized by thick (>500 m) NE dipping shear zones associated with a scaly fabric (Figure 7a). Thrust-related deformation overprints boudinage and pinch-and-swell structures associated to the first deformation event, SP(San Pedrillo)-D<sub>1</sub>, and the layer-perpendicular dissolution cleavage developed during the SP-D<sub>2</sub> event. SP-D<sub>3</sub> thrust-related deformation is extremely heterogeneous with areas of intensely disrupted mélangé grading into more coherent igneous rocks or sedimentary strata. Within the more disrupted areas, we have recognized successive, transitional stages in the structural history with breakup of igneous bodies or sedimentary layers along cataclastic shear zones and development of the block-in-matrix fabric. Structural heterogeneity is also introduced by the lithology; the igneous rocks, massive and hard at the time of deformation, record mainly cataclastic deformation, whereas the sedimentary rocks, where bedding is still visible, show a whole sequence of deformation events that span the progressive history of lithification and record the transition from ductile noncohesive sediment to brittle rocks.

[36] A later SSE thrust-related deformation event, SP-D<sub>4</sub>, develops localized features, which represent the last evi-

dence of compression. Widespread high-angle faulting, primarily normal, implies the final exhumation and unroofing of the San Pedrillo Unit, as described in section 6.

### 5.2.1. SP-D<sub>1</sub> Structures

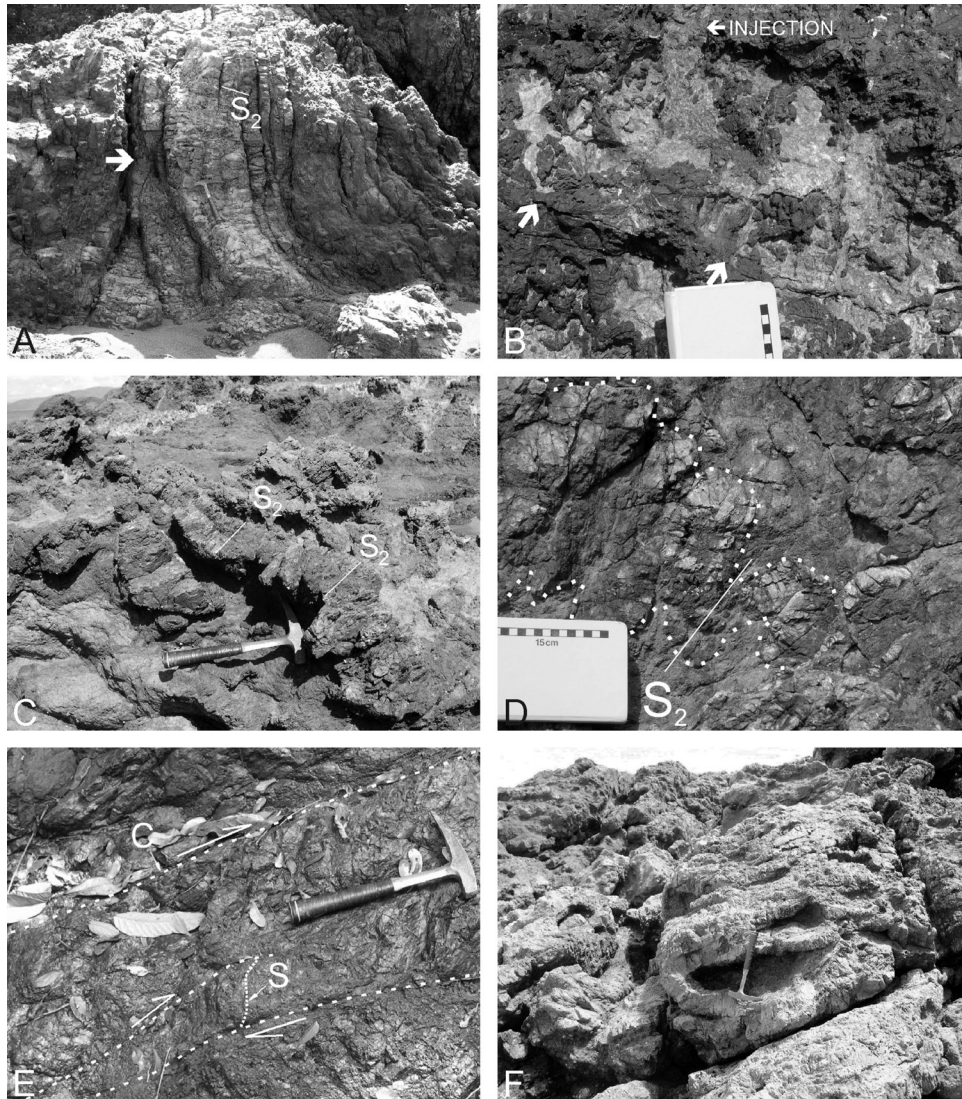
[37] The earliest deformation event resulted in the development of boudinage and pinch-and-swell structures involving single layers or packages of layers in the sedimentary rocks (Figure 8a). SP-D<sub>1</sub> is pervasive and regionally extended. Boudins have symmetric shapes with necks defined by conjugate normal faults. Most of the rocks composing the San Pedrillo Unit are massive igneous rocks that develop planar fractures, whereas the pelagic and hemipelagic sediments have been disrupted during lithification, with different lithologies showing distinct variations in strength as strain accumulated. Tuffs, for example, display sediment injections dikes and complex swirls and wisps that have a distinct seahorse shape (Figure 8b) testifying that SP-D<sub>1</sub> occurred during lithification with fluid pressures in excess of hydrostatic. Red radiolarian chert packages, hemipelagic and clastic sequences show common pinch-and-swell. Boudins with cataclastic terminations are here very rare indicating a prevalence of plastic over brittle behavior at the outcrop and thin section scale. Evidence for bedding parallel fissility associated with compaction is also present. Extensional fractures perpendicular to bedding are most probably present, but difficult to recognize, because they are overprinted by SP-D<sub>2</sub> structures. We interpret the earliest deformation event SP-D<sub>1</sub> as resulting from compaction and layer parallel extension (Figure 9).

### 5.2.2. SP-D<sub>2</sub> Structures

[38] As SP-D<sub>1</sub>, also SP-D<sub>2</sub> is ubiquitous to the entire volume of the San Pedrillo Unit. SP-D<sub>2</sub> is associated with a closely spaced foliation ( $S_2$ ) defined by dissolution surfaces that define a penetrative cleavage (Figures 8a and 8c). Although  $S_2$  surfaces vary considerably in orientation because of later deformation, they are always oriented subperpendicular to bedding. Single rows of rectangular blocks, possibly SP-D<sub>1</sub> boudins, show compression parallel to layering forming symmetric buckle folds with  $S_2$  as axial plane cleavage (Figures 8c and 8d). Symmetric to slightly asymmetric folds are present and characteristic of deformed cherty layers in hemipelagic and clastic sequences (Figure 8d), indicating that layering was quasi-parallel to slightly oblique to the maximum shortening orientation at the time of SP-D<sub>2</sub> deformation (Figure 9).

### 5.2.3. SP-D<sub>3</sub> Structures

[39] Brittle thrust faults and associated structures of the SP-D<sub>3</sub> event progressively overlap SP-D<sub>2</sub> by localizing the deformation and crosscutting SP-D<sub>2</sub> structures. SP-D<sub>3</sub> structures are widespread, well developed and represented by faults normally occurring as discrete shear surfaces or zones grading toward cataclasis and recording minor displacement, S-C structures, duplexes and asymmetric folds. SP-D<sub>3</sub> is also the main deformation event responsible for the disruption of the San Pedrillo Unit. Disruption is particularly well developed in the igneous rocks, where it is recorded by bands and planar shear surfaces ( $S_3$ ) dipping from 40° to 70° to the NNE and, subordinately, to the SSW (Figure 7a). Observable sense of shear indicators provide

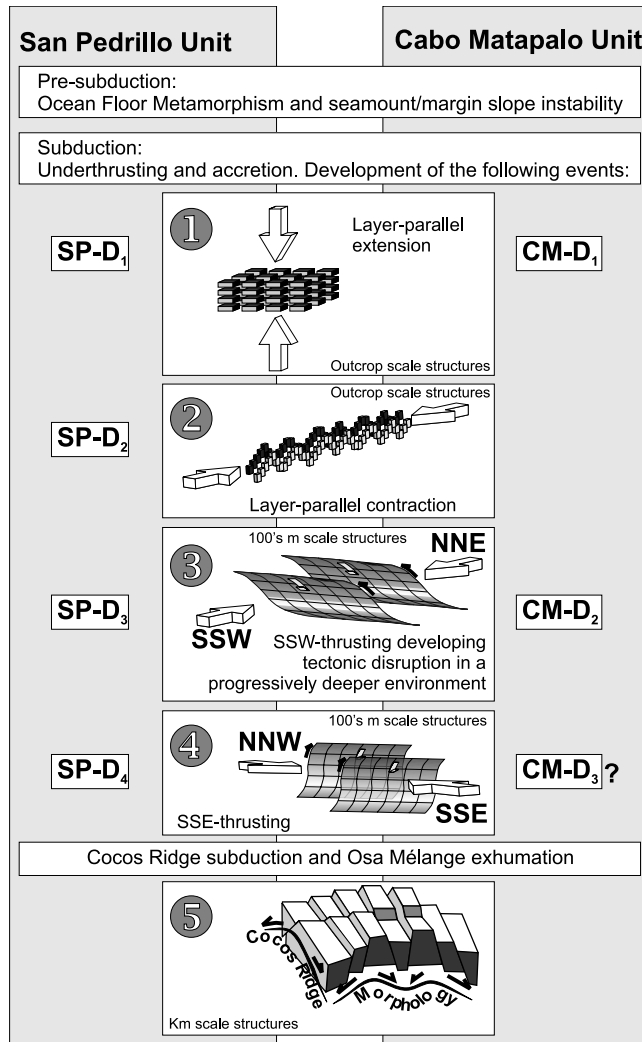


**Figure 8.** (a) SP-D<sub>1</sub> pinch-and-swell structures (indicated by the arrow) involved in the hinge of a SP-D<sub>3</sub> fold. SP-S<sub>2</sub> foliation defined by dissolution cleavage in the cherty layers is also visible. (b) Tuff layers showing swirls (indicated by arrows) and sediment dike injection. (c) SP-S<sub>2</sub> dissolution cleavage and SP-D<sub>2</sub> buckle fold. (d) Symmetric SP-D<sub>2</sub> folds with associated SP-S<sub>2</sub> axial plane cleavage. Note that in the SP-D<sub>2</sub>, hinge below the arrow folds SP-D<sub>1</sub> boudins. (e) S-C structures in the clay-rich sediments marking a SP-D<sub>3</sub> thrust area along Rio Claro. (f) SP-D<sub>3</sub> fold showing rotation of SP-S<sub>2</sub> along the hinge.

constraints on the kinematics of SP-D<sub>3</sub>, revealing a predominant dip-slip orientation and reverse movement (Figure 7a). SP-D<sub>3</sub> shear zones have been interpreted to accommodate overall thickening of the disrupted unit during noncoaxial deformation. SP-D<sub>3</sub> deformation bands are pervasive in the clastic sediments and are defined by a preferred orientation of clay minerals. These shear surfaces are parallel to scaly fabric bands of around 50 m thick, and to C surfaces of S-C structures, similar to those occurring in mylonites [Lister and Snoke, 1984]. S-C bands develop showing obliqueness of S fabric, represented by flattening surfaces composed of continuous coarse foliation or scaly fabric, to the C shear surfaces (Figure 8e). S-C structures are preferentially developed in the phyllosilicate-rich portions

of the mélangé, but a coarser S fabric is present also in the strong (cherts or clastic) layers, where aligned quartz grains and phyllosilicate films define the fabric. Calcite, quartz and, less commonly, zeolite veinlets are associated to the deformation bands, in accordance with the observations of Berrangé and Thorpe [1988].

[40] Folds do not occur uniformly throughout the mélangé, but rather range from isolated, isoclinal to close fold hinges that postdate the development of boudinage, to asymmetrical, often recumbent in the cherts sequences (Figure 8f), to noncylindrical and with axis plunging 30° to 45° indicating tectonic transport toward SSW and, subordinately, to NNE suggesting they were formed under SP-D<sub>3</sub> stress geometry. Refolding of pinch-and-swell struc-



**Figure 9.** Synoptic interpretation of deformation phases, D, as visible in the San Pedrillo and Cabo Matapalo units. The scale of the drawings is indicated in each sketch.

tures and boudins (Figure 10b) confirms a shear of top to the SSW.

[41] Well-exposed thrust zones along the Rio Claro and in the San Pedrillo area are consistent with SP-D<sub>3</sub> deformation features and a shear direction toward the SSW (~20°). SW thrusting within the San Pedrillo Unit are also associated to duplex structures (Figure 10a). We interpret SP-D<sub>3</sub> as a compressional phase associated to the ESE-WNW trending thrust faults (Figure 9).

**5.2.4. SP-D<sub>4</sub> Structures**

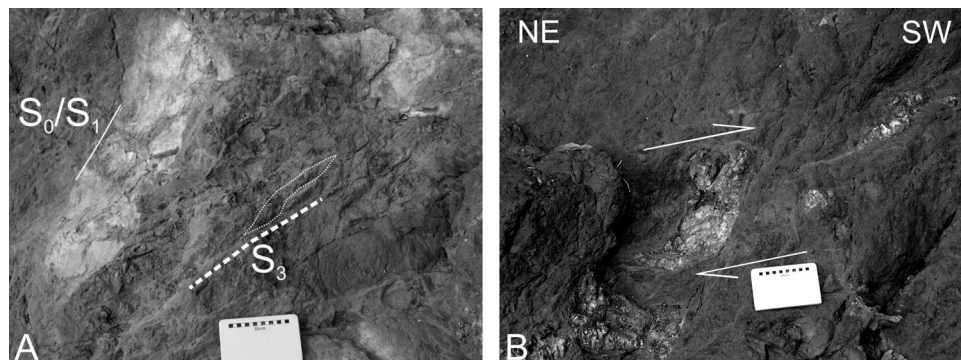
[42] Locally and in the areas of major disruption, the blocks characterized by S<sub>3</sub> shear zones are cut by a later, heterogeneously developed foliation, S<sub>4</sub>. S<sub>4</sub>, trending NE and plunging steeply northwestward (Figure 7a), carries NW-SE trending structural and mineral lineations, such as intersections, slickenlines and slickenfibres. S<sub>4</sub> foliation is parallel to mesoscopic shear zones indicating compression along the western segment of the outcropping San Pedrillo Unit. Riedel shear surfaces in shear zones associated to the S<sub>4</sub> foliation are also consistent with a shear direction top to the SSE (~310°). The relationship between S<sub>3</sub> and S<sub>4</sub> indicates that the shear direction rotated of around 90° (Figure 7a). We interpret SP-D<sub>4</sub> as a compressional phase associated to ENE-WSW trending thrust faults (Figure 9).

**5.3. Structure of the Cabo Matapalo Unit**

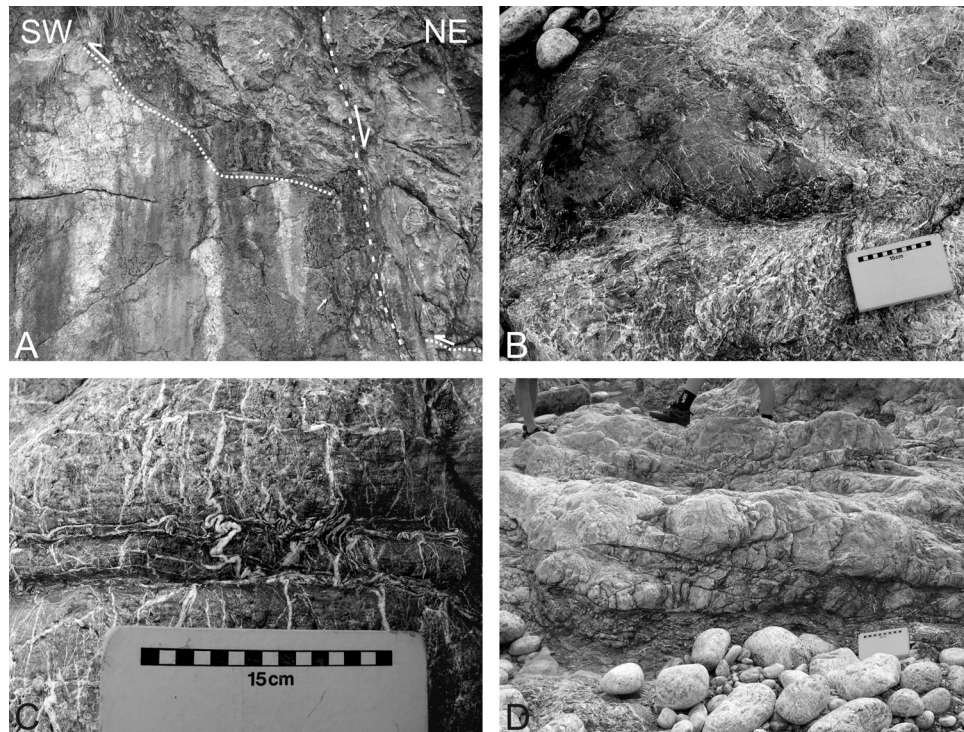
[43] In the Cabo Matapalo area, ghost bedding and preferential orientation of blocks define a first deformation event, CM (Cabo Matapalo)-D<sub>1</sub>, responsible for boudinage and pinch-and-swell structures (Figure 9). CM-D<sub>1</sub> is associated with pervasive calcite and quartz veins that we interpret as hydrofractures. NW-SE trending foliation (S<sub>2</sub>), associated with a NE dipping mesoscopic thrust, crosscuts the boudins (Figure 7b and 11a). Associated shear zones indicates tectonic transport toward the SW. Evidence of a subsequent deformation associated to a SSE thrusting event are present, but very localized and rare (Figure 7b), while a later deformation phase, CM-D<sub>4</sub>, related to normal faults is present also here and described in section 6 (Figure 9).

**5.3.1. CM-D<sub>1</sub> Structures**

[44] CM-D<sub>1</sub> is ubiquitous to the Cabo Matapalo Unit and it involves to development of boudinage and pinch-and-



**Figure 10.** (a) SP-D<sub>1</sub> boudin showing, involved in SP-D<sub>3</sub> shearing developing duplex structures. (b) Folded SP-D<sub>1</sub> pinch-and-swell structures showing top to the right movement associated to SP-D<sub>3</sub>.



**Figure 11.** (a) Mesoscopic CM-D<sub>2</sub> thrust cut by a high-angle normal fault. (b) Sandstone boudin within carbonate rocks with abundant hydrofracturing deformation and development of tectonic brecciation. (c) Cabo Matapalo limestone with intense hydrofracturing cut by CM-D<sub>1</sub> pressure solution cleavage buckling the veins. (d) CM-D<sub>2</sub> cataclasis of limestone of the Cabo Matapalo Unit.

swell structures, similar to the first deformation event observed in the San Pedrillo Unit. In the disrupted sedimentary sequence, the preferred orientation of blocks is parallel to bedding in the coherent portions, and both bedding and the block-in matrix fabric dip to the northeast. This layering is also parallel to the contacts between igneous and sedimentary rocks. The abundant limestone shows evidence of both soft sediment deformation and hydrofracturing associated with tectonic brecciation reflecting heterogeneity in diagenesis (Figure 11b). Boudinage and brecciation develops through synthetic normal faults (Figure 11b). At the edge of boudins, these faults curve into parallelism with the foliation defined by the alignment of phyllosilicates in the matrix, and thin veins are locally observed along these surfaces. The lack of sharp breakage and the gentle convergence with phyllosilicates indicate that these shears are kinematically consistent with the unit thinning and have been interpreted as synthetic Riedel R shears developed during CM-D<sub>1</sub> since they appear to be related to the earliest fabric. Although cataclasis is locally developed, the fractures that define the boudinage commonly record small offsets, as in the San Pedrillo Unit.

[45] In the limestone, though, the most regionally pervasive structures are those related to pressure solution and mineral precipitation. Veins oriented perpendicular and parallel to  $S_1$  are the earliest and most widespread structures (Figure 11c). There are several generations of these veins, suggesting a protracted history of fracturing and precipita-

tion.  $S_1$ -parallel stylolites with an amplitude of roughness at the centimeter-scale record the transition from deformation by particulate flow to deformation by pressure solution, suggesting that the deformation spans a progressive history of lithification and increasing cohesion so that they mark the evolution from sediment compaction to tectonic deformation. Some of the  $S_1$ -perpendicular and oblique veins show crosscutting relationship with stylolites indicating the formation of shortening structures that alternate with the thrust-parallel veins (Figure 11c). Multiple generations of veins perpendicular to  $S_1$  are buckled while other veins just crosscut the stylolites, indicating a close association between sets of veins, which record fracturing under ambient stress conditions but subsequently deform, and stylolites, which record continuous viscous deformation throughout the history of CM-D<sub>1</sub> veining. Folded veins record internal deformation and recrystallization. Cross veins, oblique to  $S_1$ , are also observed. In places, a complex assemblage of diverse veins orientations gives the rock a brecciated appearance. A greater concentration of veins in fault zones, together with a consistent orientation to the regional sub-horizontal shortening direction, suggests they are genetically related to the development of thrusts. The combination of  $S_1$ -parallel and  $S_1$ -perpendicular veins, and the growth of extensional calcite, suggests that the overpressure condition,  $P_f > \sigma_3$ , was widely achieved with deformation occurring under near-lithostatic fluid overpressure [Cosgrove, 1995; Maltman, 1995], according to the failure and mineralization

supply in a compressive regime [Maltman, 1995]. The evidence for competition between  $S_1$ -parallel veins, representing new permeable channels along fracture surfaces subsequently sealed by precipitation, and the  $S_1$ -parallel stylolites, implies permeability, and fluid pressure, cyclically increasing and decreasing.

[46] In total these observations suggest that early stage CM-D<sub>1</sub> reflects overall layer parallel extension and shear zone thinning occurring during high fluid pressure and suggesting different strength to deformation and faulting (Figure 9).

### 5.3.2. CM-D<sub>2</sub> Structures

[47]  $S_1$  foliation, veins, and stylolites are cut by arrays of faults and well-developed shear surfaces associated with top to the SSW thrusting (Figure 7b). Shear zone-parallel  $S_2$  foliation is widespread, while locally shearing is also related to a solution cleavage and tension gashes oriented at high angle to  $S_2$  (Figure 11d). In thin section, synkinematic recrystallization of chlorite and preferred orientation of platy minerals are observed along  $S_2$ . Progressive deformation develops S-C fabric to cataclastic shear zones.  $S_2$  trends NW-SE (Figure 7b) and surface lineations, as slickenlines and slickenfibres, indicate a sense of shearing toward the SW (Figure 8b) in agreement also with the geometry and kinematics of detachment observed along an outcropping mesoscopic thrust (Figure 11a). The same kinematics has been observed in the SP-D<sub>3</sub> event in the San Pedrillo Unit (Figure 9) and reflects the modern convergent vector suggesting overall shortening associated with incorporation in the subduction complex. The occurrence of NE-SW trending shear zones suggests a later compressional phase that may be similar to SP-D<sub>4</sub> (Figure 7b).

### 5.4. Deformation Environment of the Osa Melange

[48] The interpretations of combined field and microstructural data for both units composing the Osa Melange, show that the rocks preserve evidence for a temporal change from layer-parallel extension (SP and CM-D<sub>1</sub> in Figure 9) to later shortening features. During layer-parallel extension, both units of the Osa Melange developed bedding parallel or subparallel fabric,  $S_1$  (Figure 9). In this phase the sediments seem to have bypassed the compressional regime that dominates the upper plate in a subduction margin [Maltman, 1995] and rather experienced progressive loading associated with underthrusting. These observations suggest that the disruption of the Osa Melange formed already in the downgoing plate prior to accretion. Field evidence also suggests that D<sub>1</sub> occurred while the clastic sediments were still unlithified and deformation was contemporaneous with consolidation and changes in mechanical properties of the sediments. Development of high fluid pressure is indicated by sedimentary dikes, while veins are rare in the San Pedrillo Unit, and abundant in the Cabo Matapalo Unit. The igneous rocks, which were hard rocks at the time of deformation, show pervasive cataclastic deformation responsible for disruption, with fractures typically filled with phyllosilicates or red opaque minerals. The presence of cataclasis and evidence of fluid flow may suggest that initial fracturing of the basalt allowed fluid

infiltration that created high fluid pressure on further burial, which lowered the effective stress and promoted cataclasis. After repeated fracturing, the basalts develop a pervasive fracture-dominated permeability that allows widespread hydration.

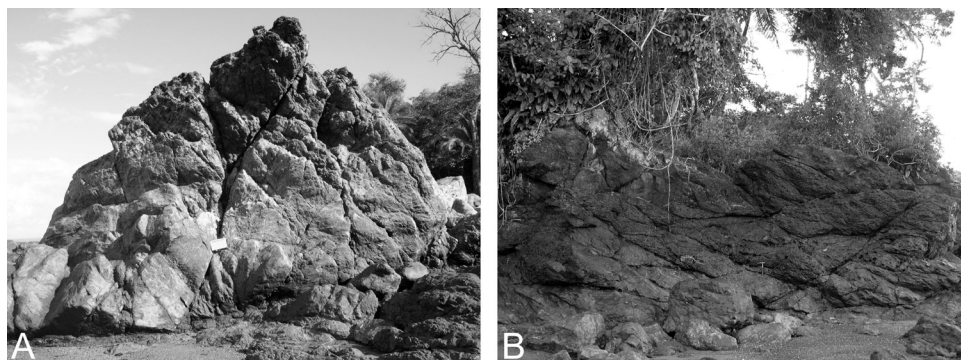
[49] In the San Pedrillo Unit D<sub>1</sub> is followed by layer-parallel contraction with buckle folding and development of pressure solution cleavage constantly oriented subperpendicular to bedding and intersecting  $S_1$  (Figure 9). SP-D<sub>2</sub> compression results in thickening of the underthrust pile. The transition from SP-D<sub>1</sub> to SP-D<sub>2</sub> represents a switch from vertically to horizontally oriented principal stress. We interpret this rotation as occurring just before thrusting associated with plate boundary migration and underplating [Moore and Byrne, 1987; Kimura and Mukai, 1991; Hashimoto and Kimura, 1999]. The cause of the principal stress switch is either strain hardening during consolidation allowing downward migration of the plate boundary [Moore and Byrne, 1987] or footwall collapse of the underthrusting sediment pile along a ramp in the plate boundary leading to duplex accretion and incorporation of slices of the underthrusting sequence into the overriding plate [Sample and Fisher, 1986]. SP-D<sub>2</sub> deformation is largely coaxial subhorizontal contraction based on kinematic analysis of structures. In contrast, SP-D<sub>3</sub> shows pervasive noncoaxial strain related to imbricate thrusting and duplexing.

[50] The SP-D<sub>3</sub> phase, together with CM-D<sub>2</sub> in Cabo Matapalo Unit (Figure 9), is associated with development of landward dipping thrusts and mesoscale duplexes. The reconstructed shear direction is consistent with the present-day convergence vector toward NNE in both units. This deformation phase implies a switch from the underthrust regime to underplating and shortening within the upper plate wedge. The depth of underplating is based on the calcite and chlorite recrystallization and quartz mobilization should have reached 150°–200°C. On the basis of temperature at the plate boundary calculated from heat flow probes and depth to the BSR along the modern trench from Nicoya to Osa Peninsula the depth during the peak temperature could have spanned from 4 to 8 km (C. R. Ranero et al., The relationship between fluids, tectonics and seismogenesis during subduction erosion, submitted to *Nature*, 2005).

[51] A younger thrusting event oriented perpendicular to the previous event and to the convergence vector (Figure 1a), cuts through the San Pedrillo Unit and, to some extent, the Cabo Matapalo Unit. Trench-parallel thrusting could be local and related to the presence of accreting seamounts so that repeated punctual collisions to the margin could have produced lateral ramps as envisioned by Dominguez et al. [1998].

## 6. Postsubduction Deformation: Osa Melange Exhumation

[52] The younger deformation features cutting the Osa Melange are throughgoing brittle fractures and faults (Figure 12). These form a spaced network that cuts the melange at scales ranging from several meters to several kilometers. Faults record dip-slip movements, with mostly



**Figure 12.** (a) High-angle normal fault cutting through the San Pedrillo Unit. (b) Conjugate normal faults in the San Pedrillo Unit.

normal faults (Figure 12a). Measurements of late, mesoscopic normal faults in the mélangé and in the Plio-Quaternary sequence depict two distinct fault systems: the most common one striking NW-SE, parallel to the trench, and the other striking NE-SW, perpendicular to the trench. Figure 13 shows normal faults that cut the Pliocene-Quaternary sediments overlying the Osa Mélangé, and these faults are geometrically and kinematically consistent with faults observed cutting through the Osa Mélangé itself (Figure 12b). The fault dips can range from subhorizontal to subvertical, with shallow dips more typical in the steep-dipping Osa Mélangé, and steep dips more common in the Plio-Quaternary sediments. Each fault system can be characterized in terms of two conjugate sets (Figure 12b and 13).

[53] An analysis of fault slip indicators reveals that some of the faults have been reactivated with opposite movements during their evolution. This observation is consistent with analyses of marine deposits of the Marengo Formation on Osa Peninsula that indicate up-and-down tectonics, possibly related to variations in topography along the axis of the Cocos Ridge [Gardner *et al.*, 1992; Sak *et al.*, 2004].

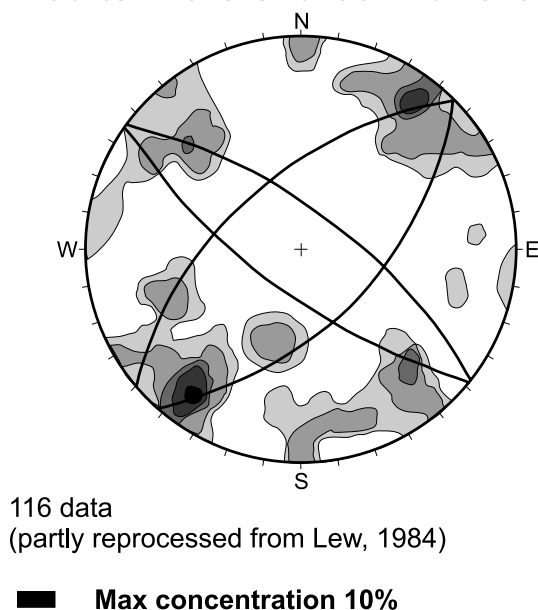
[54] The surface trace of regional discontinuities were compiled from the Costa Rica topographic maps 1:50,000 and the relief map produced by the Shuttle Radar Topography Mission (STRM30), and these lines cluster around two orientations: one parallel and one perpendicular to the trench. The discontinuities outline four major blocks oriented NE-SW (Figure 1b) with two of them crosscut by a main trench-parallel fault. A comparison of the onland topography with the bathymetry reveals that some morphological features of the Osa Peninsula conform to the bathymetry along the axis of the Cocos Ridge. For example, the Laguna Corcovado is the upper plate morphological expression of the axial graben of the indenting Cocos Ridge.

[55] The analysis carried out in the present study implies that the last deformation stage recorded on Osa Peninsula is strongly linked with Cocos Ridge subduction (Figure 9). The intense faulting produced on Osa Peninsula defines independent blocks that have been freely moved up and down to accommodate the roughness of the incoming Cocos Ridge (Figure 9).

[56] Dip-slip faults are the superficial expression of the great damage caused by Cocos Ridge subduction, that can

be better envisioned through geophysical imaging of the margin. The Caribbean overriding plate, for example, shows a dramatic thinning from 16 km at the coastline in Guatemala [Ye *et al.*, 1996], far and not influenced by Cocos Ridge subduction [Vannucchi *et al.*, 2004], to 12–14 km in Nicoya [Christeson *et al.*, 1999; Sallares *et al.*, 2001], where the sharp increase in subduction erosion rate is in agreement with the beginning of thickened crust subduction [Vannucchi *et al.*, 2003], to 3 km in Osa Peninsula [Walther, 2003]. A general increase in erosional rates along the margin toward Cocos Ridge can also be inferred from the trench morphology, where a sudden landward shift of the trench axis strike occurs coincident with the area of

### Contour of pole to NORMAL faults in the Charco Azul Group



**Figure 13.** Equal-area, lower hemisphere contour plot of pole to normal faults in the Plio-Quaternary sediments of the Charco Azul Group. Data from Lew [1983] have been incorporated to original measurements.

seamount subduction (Figure 1). Both, the thin upper plate and trench retreat indicate that subduction of Cocos Ridge intensifies erosion of the continent, even though, the thick, buoyant crust of the ridge caused inboard uplift of Osa Peninsula. *Sak et al.* [2004] describe the response of the forearc to underthrusting bathymetric roughness as analogous to the hanging wall deformation associated with a fault bend [*Knipe*, 1985]. The geodynamic model presented by *Gardner et al.* [1992], instead, consider the overriding plate as a continuous elastic plate. Both models are quite different from the brittle behavior of the forearc as exposed in Osa peninsula.

## 7. From Tectonic Accretion to Tectonic Erosion: Discussion

[57] Several authors have discussed timing and effects of the entrance of Cocos Ridge in the Central America subduction zone (see Figure 2 and references therein). We bring another line of evidence, namely the effects of subduction of thick and buoyant crust on the Osa Peninsula accretionary edifice as displayed on Figure 14.

[58] Accretion of the Osa Igneous Complex and Osa Mélange from the Farallon to the Caribbean plate is implied by the geochemical and isotopic composition of the their igneous component [*Hauff et al.*, 1997; *Hoernle et al.*, 2002].

[59] Several authors have been discussed the mechanisms of seamount accretion and subduction with conclusions suggesting complete transfer of the intact mass to the upper plate [*Cloos*, 1992; *Park et al.*, 1999], complete subduction [*Yamazaki and Okamura*, 1989; *Kodaira et al.*, 2000; *Husen et al.*, 2002; *Soh and Tokuyama*, 2002] or a combination of the two through the nucleation of thin-skinned duplexes [*Ueda*, 2005] or flank fracturing [*Cloos and Shreve*, 1996; *Baba et al.*, 2001]. These different results have been explained by the varying amount of lubrication at the subduction thrust interface [*Seno*, 2006].

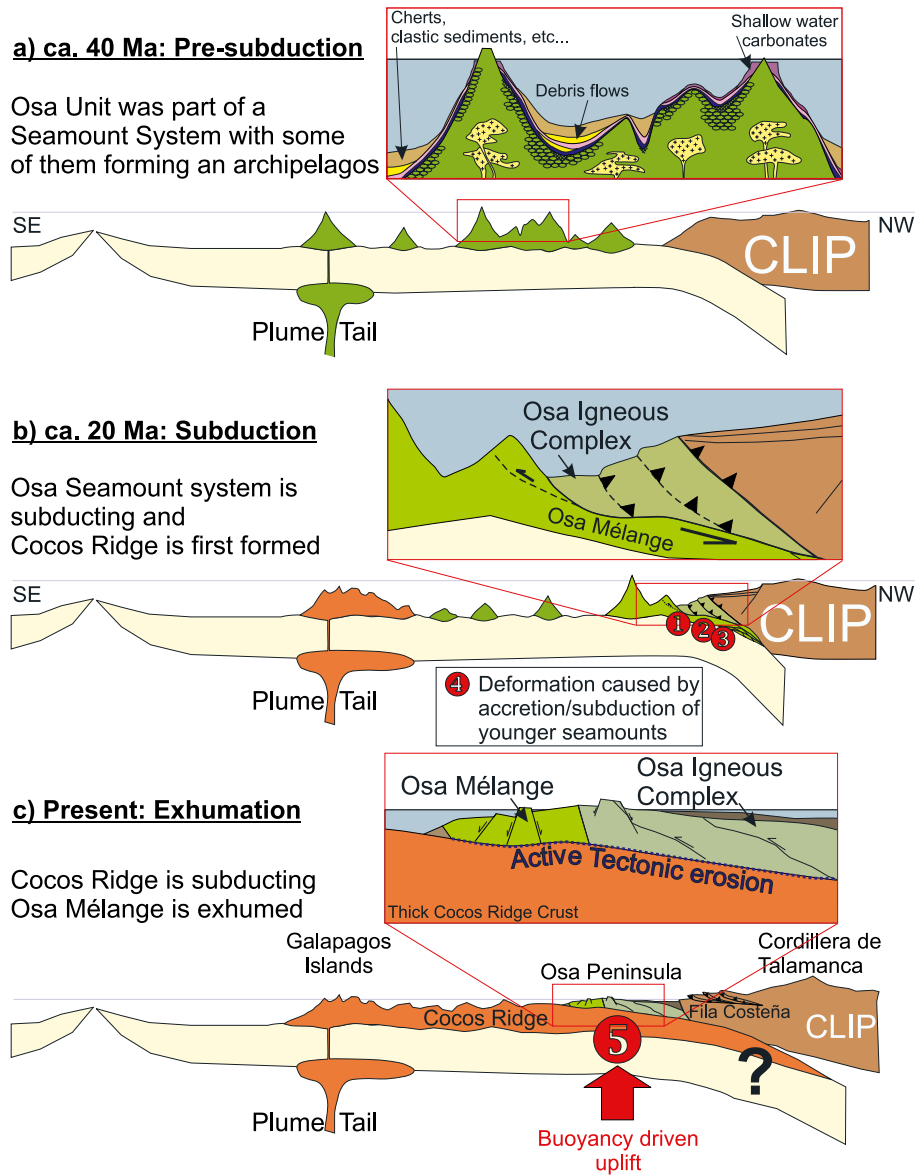
[60] Although there is no obvious difference in metamorphic mineral assemblage among the Osa Mélange and the Osa Igneous Complex, their structural setting and deformation structures reveal a different deformation pathway within the subduction zone. The Osa Mélange, in fact, indicates an evolution from underthrusting to underplating, while the little internal deformation and coherency of the Osa Igneous Complex suggest incorporation to the upper plate by frontal accretion or shallow level processes (Figure 14). Numerical modeling [*Baba et al.*, 2001] suggests shear stress concentration at both flanks of the subducting seamount can induce breakage of the seaward flank, if the confining pressure there is sufficiently low, and the upper part of the seamount to be thrust trenchward. Breakage of a subducting seamount at shallow level, though, occurs easier if the subducting plate carries a thin (<500 m) sediment succession [*Cloos and Shreve*, 1996] and if the seamount abuts a hard upper plate basement [*Cloos*, 1992]. Field indication confirms the little sedimentary component forming the Osa Mélange, while the hard upper plate assumption sheds light on the subduction zone

and the nature of accretion prior to the arrival of the Cocos Ridge. In particular it is worth mentioning that the Osa Igneous Complex outcrops adjacent to the basalts of the Caribbean Large Igneous Complex and that there are no evidence for an early Tertiary “sedimentary” accretionary prism. Following this line, we can further speculate that the margin offshore Osa Peninsula was not characterized by a typical, Nankai-type accretion, but the margin was rather punctuated by accretionary events of igneous edifices.

[61] Magnetic anomalies on the Cocos and Nazca plates [*Barckhausen et al.*, 2001] support the first-order approximation that the current northeastward Cocos plate motion of ~90 mm/yr with respect to the Caribbean plate [*DeMets*, 2001] well agrees with the inferred motion prior of Cocos-Nazca Spreading Center was formed (Figure 2) and did not change during the Tertiary. With this hypothesis we can infer that the circa 65–40 Ma San Pedrillo seamount and the circa 25 Ma Cabo Matapalo seamount, both formed at the Galapagos hot spot, arrived at the trench circa 50–30 Ma and circa 11 Ma, respectively (Figure 2). This hypothesis agrees with the age of the youngest sediment on the Osa Mélange dated to the early Miocene [*Di Marco et al.*, 1995]. The submarine upper plate basement of the margin offshore Osa Peninsula is thought to be similar to the Osa Mélange as implied by seismic velocities (*C. R. Ranero*, written communication, 2004), and it can carry other accreted seamount edifices.

[62] The structural onset of Osa Mélange implies that following subduction and underplating the mélange reached about 4 to 8 km depth before exhumation. The burial of Osa Mélange could have been provided by progressive accretion of younger seamounts presently missing due to the concurrent action of subduction erosion and strong uplift triggered by Cocos Ridge subduction. This hypothesis brings to the matter of what happened to the material subaerially eroded to exhume Osa Mélange. Cocos Ridge is characterized by a 15 km wide, ridge parallel graben filled by ~1 km thick sediment indicating a Caribbean source [*von Huene et al.*, 2000], while efficient sediment subduction is inferred by the active tectonic erosion. Sediment generated by Osa Mélange exhumation may have ponded along the ridge graben and progressively and efficiently subducted, as involved in an erosive margin.

[63] A second hypothesis regarding the Osa Mélange burial takes into account the Osa Igneous Complex, which was accreted at the margin toe and remained at shallow level implying that it might have formed the overriding plate on top of Osa Mélange. The two units are presently separated by normal faults (Figure 1). The overriding plate of erosive convergent margins is often characterized by extension [*McIntosh et al.*, 1993; *Calahorrano et al.*, 2004]. In the case of the Costa Rica margin off Nicoya peninsula, normal faults are either recent or inherited features, but both seems to be associated to the occurrence of subduction erosion [*Vannucchi et al.*, 2003]. The severe subduction erosion and abrupt upper plate thinning off Osa peninsula might have triggered large offsets and the occurrence of an exhumation mechanism active at the inner forearc. More-over mass removal by subduction erosion striped off fault



**Figure 14.** Diagram of the Eocene to Present tectonic evolution along the Costa Rica convergent margin offshore Osa Peninsula. (a) Eocene time (circa 40 Ma). The Osa Igneous Complex and the Osa Mélange are forming a seamount system with sediments of both deep and shallow water environment. (b) Miocene time (circa 20 Ma). The seamount system is subducting; Osa Igneous Complex and Osa Mélange are entering different deformation environment; the upper plate for the coherent unit frontally accreted, and the lower plate underthrust and lately underplated for the mélangé. Numbers in the red dots are indicating different deformation stages as described in Figure 9. (c) Present time. Cocos Ridge is subducting, the thick and buoyant crust of the ridge caused a decrease of the slab dip, exhumation of the deeper part of the margin, now represented by the Osa Mélange, and severe basal tectonic erosion.

roots and the normal faults separating the Osa Igneous Complex and the Osa Mélange may represent remnant portions of larger features. At present we do not have the data to discriminate between the two hypotheses, but both include subduction erosion as a major component in the process as stated in Figure 14.

[64] The marine conglomerates of the Punta La Chancha Member unconformably overlies the Osa Mélange and

contains clasts of the mélangé itself inferring that the complex was exposed on the surface in the middle Pliocene time [Lew, 1983]. Exhumation is best explained with the entrance of the thick and buoyant crust of the Cocos or Proto-Cocos Ridge crust that caused a dramatic slab dip shallowing [Vannucchi et al., 2003] (Figure 14). When the Cocos Ridge entered the subduction zone is an unresolved issue. The thick crust which approached the trench at the

Miocene-Pliocene boundary were presumably formed ~20 Myr ago when the Cocos-Nazca spreading center was already opened [Barckhausen *et al.*, 2001] (Figure 2). At that time also the Cocos-Nazca-Caribbean triple junction was migrating through the Osa peninsula portion of the margin and that might have been amplified the effect of the thick crust subduction which altered the dynamic margin equilibrium triggering basal erosion of the upper plate as testified by the thin upper plate wedge of about 7 km beneath the coast [Ranero and von Huene, 2000] and the subsidence record of the adjacent Nicoya Peninsula area [Vannucchi *et al.*, 2003]. Furthermore, subduction erosion, with removal of Osa Igneous complex and Osa M elange rocks from the upper plate and their transport to depth of magma generation, can explain the Galapagos signature in the geochemical and isotopic composition of the adakitic and alkalic back-arc lavas erupted between 5.8 and 2 Ma [Abratis and Worner, 2001; Goss *et al.*, 2004]. Adakitic magmas can be explained by eruption through thinner crust as flat subduction is triggered by the ~5 Ma subduction of the Cocos Ridge under Central American plate [Goss *et al.*, 2004].

[65] The switch from subduction accretion to erosion triggered the uplift of the Osa M elange. Ridge subduction caused contrasting consequences as uplift inboard of the Cocos Ridge and subsidence recorded offshore Nicoya Peninsula, ~300 km to the northwest [Vannucchi *et al.*, 2001, 2003], both in a subduction erosion regime. This diversity is best explained through the severe damages caused by the ridge to the margin, as suggested by the disrupted topography [von Huene *et al.*, 2000]. Moving south from Nicoya Peninsula, where the subducting plate is smoother and the trench retreat has been estimated to be ~50 km since 16 Ma [Vannucchi *et al.*, 2001], to Osa Peninsula the slope has retreated up to 20 km (Figure 1a). In Osa, upper plate thinning by subduction erosion is counteracted by horizontal shortening and internal deformation of the wedge to produce uplift. Onshore, for example, uplift has been accompanied by shortening and the formation of a coastal, shallowly rooted, fold-and-thrust belt, the Fila Coste a [Fisher *et al.*, 2004] (Figure 14).

[66] The Osa Peninsula is presently characterized by steeply dipping normal faults developed perpendicular and parallel to the convergence vector suggesting an extensive tectonic effect of the Cocos Ridge on the overriding plate. Cocos Ridge subduction, thus seems to increase tectonic erosion of the margin by breaking up the upper plate into kilometer-wide blocks, which are fragmented at the front of the margin, and eventually dragged in the subduction channel.

## 8. Conclusions

[67] The Osa M elange is a tectonically disrupted accreted package of oceanic lithologies that are exotic to the overriding Caribbean plate. The m elange records the accretion of at least two seamount complexes that originated at the Galapagos hot spot between 65 and 25 Ma [Berrang e *et al.*, 1989; Di Marco *et al.*, 1995; Hauff *et al.*, 1997; Hoernle *et*

*al.*, 2002]. The evolution of the Osa M elange can be described in three stages as illustrated in Figure 14: pre-subduction, subduction, and exhumation.

[68] During the presubduction phase the seamount systems experienced ocean floor metamorphism associated with hydrothermal fluid circulation as indicated by multiple generations of zeolite and calcite veins and shear zones. The occurrence of deformation features contemporaneous with ocean floor metamorphism is evidence for a tectonically active environment close to the spreading center. The Galapagos hot spot, in fact, has a long history of interaction with the Cocos-Nazca Spreading Center (Figure 1a), which opened in the early Miocene, circa 22.7 Ma [Barckhausen *et al.*, 2001]. The seamounts have been accreted with the associated pelagic and hemipelagic sediment and these sedimentary sequences show debris flows and slump deposits indicating gravitational mass movements and slope instabilities (Figure 14), while it is not clear, because of the disruption, if the mass movements are associated with instabilities triggered by near-trench processes. In any event they are formed by material coming from the seamount system and they have experienced all the deformation phases linked to the subduction processes and described in Figure 9. The petrological and sedimentological indication coming from the Osa Igneous Complex reveals the presence of a seamount system, probably reaching the sea level (Figure 14).

[69] The subduction stage of the Osa M elange started with the arrival of the seamounts at the trench and ended with the subduction of the Cocos Ridge (Figure 14). Underthrusting of the Osa M elange is testified by layer parallel extension which suggest that the unit bypassed the compressional regime that dominates the upper plate in a subduction margin, while underplating produced the thrust staking (Figure 14). The San Pedrillo and the Cabo Matapalo Unit were underplated from the subducting seamounts during temperature conditions of 150–200 C., implying a range of possible burial depth from 4 to 8 km.

[70] Here we suggest that the Osa Igneous Complex and the Osa M elange, although parts of the same seamount system, were originally located at different structural levels and followed different deformation paths. In particular the Osa Igneous Complex carries a small amount of sediment, among which debris flow deposits are missing, while shallow water carbonates are present. On the contrary the San Pedrillo Unit is characterized by abundant debris flow deposits and generally deep water sediments, suggesting that the Osa M elange has been formed by relatively lower portions of the seamount system if compared to the Osa Igneous Complex (Figure 14). Their present location and the disrupted vs. coherent fabric of the two units suggest that while the Osa M elange experienced underthrusting and underplating, the Osa Igneous Complex might have been accreted at the front or in a fairly shallow part of the subduction system (Figure 14). This hypothesis, based on sedimentary, petrographic and structural evidence, envisions a possible scenario of the still poorly known mechanism of deformation within a seamount during accretion. The seamount accretion, on the other hand, might have occurred

through a plate boundary characterized by a complex geometry, or even not fitting the model of a thin frictional décollement, but rather that of a relatively thick shear zone, or subduction channel [Cloos and Shreve, 1996] where seamounts can either subduct or accrete or a combination of the two depending on the available source of fluids [Seno, 2006]. The nature of the upper plate during the Osa Mélange underplating phase is a matter of discussion, although the Osa Igneous Complex could have formed a cap for the Osa Melange itself (Figure 14). The Osa Mélange exhumation is purely brittle with dip-slip subvertical faults cutting the Osa Mélange at all scales (Figure 14). The uplift is associated with the entrance of the thick and buoyant crust of the Cocos or Proto-Cocos Ridge that caused a dramatic slab dip shallowing. The slab geometry introduces an important feedback on the upper plate wedge, which maintains a large taper altering its dynamic equilibrium [Davis *et al.*, 1983]. The unstable taper triggers basal erosion of the upper plate [Vannucchi *et al.*, 2003] removing most of the early Tertiary accretionary complex and leaving a thin wedge [Walther, 2003]. Upper plate thinning and

margin uplift are elements usually correlated to ridge subduction [Soh and Tokuyama, 2002].

[71] The interpretation that the Osa Mélange records past accretion to the plate margin and the switch to tectonic erosion has implications for our understanding of forearc deformation at convergent margins. Plate margins are generally divided into those showing long-term mass removal and those dominated by accretion of sediments from the subducting plate. Despite this simple separation, some margins may be more complicated and even where basal subduction erosion may thin the crust of the upper plate, a forearc can preserve evidence of changes in subduction-related processes.

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