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Late Cretaceous to Miocene Seamount Accretion and Mélange Formation in the Osa and Burica Peninsulas (Southern Costa Rica): Episodic Growth of a Convergent Margin

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Abstract

Multidisciplinary study of the Osa and Burica peninsulas, Costa Rica, recognizes the Osa Igneous Complex and the Osa Mélange - records of a complex late Cretaceous - Miocene tectonic-sedimentary history. The Igneous Complex, an accretionary prism (sensu stricto) comprises mainly basaltic lava flows, with minor sills, gabbroic intrusives, pelagic limestones and radiolarites. Sediments or igneous rocks derived from the upper plate are absent. Four units delimited on the base of stratigraphy and geochemistry lie in contact along reactivated palaeo-décollement zones. They comprise fragments of a Coniacian-Santonian oceanic plateau (Inner Osa Igneous Complex) and Coniacian-Santonian to middle Eocene seamounts (Outer Osa Igneous Complex). The units are unrelated to other igneous complexes of Costa Rica and Panama and are exotic with respect to the partly-overthickened Caribbean Plate; they formed by multiple accretions between the late Cretaceous and middle Eocene, prior to the genesis of the Mélange. Events of high-rate accretion alternated with periods of low-rate accretion and tectonic erosion. The NW Osa Mélange in contact with the Osa Igneous Complex has a block-in-matrix texture at various scales, produced by sedimentary processes and later tectonically enhanced. Lithologies are mainly debris flows and hemipelagic deposits. Clastic components (grains to large boulders) indicate late Eocene mass wasting of the Igneous Complex, forearc deposits and a volcanic arc. Gravitational accumulation of a thick pile of trench sediments culminated with shallow-level accretion. Mass-wasting along the margin was probably triggered by seamount subduction and/or plates reorganisation at larger scale. The study provides new geological constraints for seamount subduction and associated accretionary processes, as well as on the erosive/accretionary nature of convergent margins devoid of accreted sediments.

(Introduction)

The Osa and Burica peninsulas lie in southern Costa Rica, on the southwestern edge of the Caribbean Plate, along the convergent margin between Central America and the subducting Cocos Plate (Fig. 1). The peninsulas lie directly above the submarine Cocos ridge, an aseismic volcanic ridge which rises ~2000 m above the adjacent sea floor and constitutes a significant topographic high entering the subduction zone (Walther 2003). The subducting ridge formed above the Galapagos hotspot 13.0-14.5 Ma ago (Werner *et al.* 1999) and is currently moving northeastward at a rate of ~90 mm/y (Trenkamp *et al.* 2002). It is believed to have started colliding with the Caribbean plate 8-1 Ma (most probably ~2 Ma) ago (MacMillan *et al.* 2004, and references therein), causing forearc shortening, large-scale block tilting and local cessation of volcanism (Kolarsky *et al.* 1995a; Fisher *et al.* 1998, 2004; Abratis & Wörner 2001; Gräfe *et al.* 2002; Morell *et al.* 2008; Sak *et al.* in press). The Osa and Burica peninsulas were uplifted and emerged in response to the Cocos Ridge subduction, with an estimated average long-term rate of uplift of 1-2 mm/y (Corrigan *et al.* 1990; Collins *et al.* 1995; Mann & Kolarsky 1995). Their morphology is controlled by active faults, interpreted to intimately relate to the morphology and roughness of the subducting plate, that define large tilted, variously uplifted blocks (Sak & Fisher 2004; Vannucchi *et al.* 2006; Sak *et al.* 2008) (Fig. 2b).

In southern Central America, subduction began in the late Campanian along a Coniacian-early Santonian oceanic plateau (Buchs *et al.* submitted, see also discussion of ages in Chapter 3.4.1). This plateau is exposed in the Azuero Peninsula (W Panama) and represents the first clear occurrence of arc basement in southern Central America. The Azuero Plateau may further represent the SW edge of a larger oceanic plateau that extends eastward into the Caribbean, generally defined as the Caribbean Large Igneous Province (CLIP) or Caribbean-Colombian Oceanic Plateau (CCOP) (*e.g.* Kerr *et al.* 2003; Hoernle *et al.* 2004) (Fig. 1). Due to (1) location of the South Central American Arc in the western Caribbean and (2) similar geochemistry and ages of the igneous rocks, many igneous complexes exposed along the forearc of Central America have been associated to the CLIP (*e.g.* Sinton *et al.* 1997, 1998). However these data do not rule out the possibility that complexes belonged to distinct volcanic edifices in the Pacific, subsequently amalgamated along the margin by accretionary processes. Tectonostratigraphic constraints are needed to better understand origins of the complexes.

The purpose of this study is to better characterize the age, tectonostratigraphy and internal arrangement of the exposed rocks from both the inner (isthmus side) and outer southwestern Osa and Burica peninsulas. The area of study lies only 15 km from the Middle American Trench and, thus represents one of the outermost parts of the Costa Rican margin. It provides onland access to rocks and structures that usually lie deep under the sea, close to the subduction zone. The rocks exposure on the Osa Peninsula are generally expected to be collected/observed during drilling and dredging only. Their significance in terms of accretionary processes and tectonic erosion is developed here on the basis of: (1) 6 months of field survey, (2) petrological characteristics of 455 samples, (3) geochemical analyses of the igneous rocks and (4) micropalaeontology. We show that igneous complexes exposed on the Osa and Burica peninsulas are exotic with respect to the Caribbean Plate and, as a consequence, are not part of the CLIP.

1. Geologic setting of the Osa and Burica peninsulas

In the literature the Osa Peninsula has been divided into two main units based on dominant lithology: (1) the Osa Igneous Complex (originally defined as the "Rincon Block" by Di Marco (1994)) and (2) the Osa Mélange (originally defined as the "Osa Caño Accretionary Complex" by Di Marco (1994) (Fig. 2). We first propose here the Osa Igneous Complex is not limited to the Osa Peninsula but extends toward the SE in the Burica Peninsula and, possibly, islands in the Montijo Gulf (W Panama). In the Burica Peninsula, the complex comprises a late Cretaceous igneous complex called "Burica Complex" or "Burica Terrane" by previous authors (*e.g.* Obando 1989; Di Marco 1994; Hauff *et al.* 2000). Exposures of the Osa Mélange are restricted in the outer part of the Osa Peninsula. Most of the area comprising the Osa Igneous Complex and Osa Mélange is unconformably overlain by Paleocene to Pleistocene sediments called herein "overlap sequences", in opposition to underlying rocks forming the "basement" (Fig. 2).

The basement rocks of the Osa Peninsula were seen for a long time to be part of the "Nicoya Complex", an accreted oceanic plateau cropping out in the NW Nicoya Peninsula (*e.g.* Denyer & Baumgartner 2006; Bandini *et al.* 2008). However, strong incompatibilities between the Nicoya Complex and the Osa area exist in terms of age, lithology, and tectonostratigraphy of igneous and sedimentary rocks, as well as geochemistry (*e.g.* Denyer *et al.* 2006). In this chapter we focus on the geology of the NW Osa Mélange and Osa Igneous Complex. A colored geological map of the area is given by Buchs & Baumgartner (2007). Fig. 2 is an updated grayscale version of this map.

1.1. The Osa Igneous Complex

The Osa Igneous Complex is limited on the trenchward, SW side by the Osa Mélange and on the landward, NE side by the late Cretaceous to early Tertiary Golfito Complex. The latter is broadly composed of: (1) a proto-arc that developed on the top of the CLIP in the late Campanian to Maastrichtian, and (2) younger overlapping sediments (*Buchs et al.*, submitted) (Fig. 2). The lateral extension of the Osa Igneous Complex toward the NW is not known. Toward the SE it extends in the Burica Peninsula and, possibly, in the Montijo Gulf (W Panama, Fig. 1.2).

The Igneous Complex comprises basalts, microgabbros, dolerites and minor gabbros, with rare (<1%) intercalations of radiolarian cherts, black shales, and pelagic limestones (Dengo 1962; Tournon 1984; Obando 1986; Berrangé & Thorpe 1988; Di Marco 1994; Di Marco *et al.* 1995; Buchs 2003). Radiolarian and foraminiferal assemblages from these sediments provide ages ranging from Campanian to Eocene (Di Marco 1994). K-Ar ages of the basalts range from late Cretaceous to Eocene (Berrangé *et al.* 1989). $^{40}Ar/^{39}Ar$ datings range from 54.5 ± 1.5 to 62.1 ± 0.6 Ma (Hauff *et al.* 2000; Hoernle *et al.* 2002). Basalt geochemistry indicates compositions ranging across NMORB-like, plateau-like and OIB-like affinities (Berrangé & Thorpe 1988; Di Marco 1994; Meschede & Frisch 1994; Hauff *et al.* 2000). Origins proposed until now for the Complex are: (1) a back-arc basin (Berrangé & Thorpe 1988), (2) a volcanic arc in the Osa Peninsula and an accreted Pacific seamount in the Burica Peninsula (Obando 1986; Di Marco 1994), (3) an uplifted western Caribbean Plateau (Meschede *et al.* 1999; Denyer *et al.* 2006), (4) an accreted aseismic ridge (Hauff *et al.* 2000; Hoernle *et al.* 2002, 2004; Denyer *et al.* 2006; Vannucchi *et al.* 2006), and (5) accreted seamounts (Buchs 2003). This wide range of interpretation is likely due to (1) development of analytical techniques in the last decades, (2) highly heterogeneous geochemical affinities of the igneous rocks, (3) low sedimentary content of the igneous complex, and (4) poor recognition of structures in absence of good stratigraphic markers.

1.2. The Osa Mélange

The Osa Mélange was recognized and differentiated from the Nicoya Complex by Baumgartner (1986) and Baumgartner *et al.* (1989), who postulated the presence of an Eocene accretionary prism cropping out on the outer Osa Peninsula and Caño Island. Di Marco (1994) and Di Marco *et al.* (1995) subdivided the Mélange into three tectonostratigraphic units, from NE to SW: (1) the San Pedrillo Unit, (2) the Cabo Matapalo Unit and (3) the Punta Salsipuedes Unit (Fig. 2).

The San Pedrillo Unit consists of a deformed matrix of detrital and siliceous sediments enclosing variable amounts of blocks of igneous rocks, pelagic sediments and resedimented shallow-water carbonates (Di Marco *et al.* 1995). The siliceous fraction of the matrix was dated as middle Eocene on the basis of radiolarian assemblages (Azéma *et al.* 1983). The igneous blocks have been interpreted as remnants of accreted seamounts by most authors (*e.g.* Di Marco *et al.* 1995; Vannucchi *et al.* 2006), but geochemical affinities of the lava blocks are not determined.

The Cabo Matapalo Unit comprises a detrital matrix containing blocks of late middle Eocene to middle Miocene pelagic limestones. Decimetric blocks of basalts occur within the pelagic limestones (Di Marco *et al.* 1995).

The Salsipuedes Unit contains "large bodies" of limestones in a fine-grained greywacke matrix (Di Marco *et al.* 1995). The ages of the limestones are poorly constrained; a single, Paleocene age was determined by Azéma *et al.* (1983). Interbedded dark shales and greywackes within the limestones (Di Marco *et al.* 1995) indicate that this unit is not a mélange sensu stricto, but more likely a dismembered sequence.

Various origins and genetic mechanisms have been proposed for the Osa Mélange. Di Marco *et al.* (1995) suggest the San Pedrillo Unit represents accreted Eocene trench-fill sediments associated with variable amounts of blocks of igneous and sedimentary rocks originally on the subducting plate. These authors see the most external parts of the Osa Peninsula (the Cabo Matapalo and Salsipuedes units) made by offscraped lenses of Eocene to Miocene pelagic limestones and distal detrital sediments. Meschede *et al.* (1999) postulate the Osa Mélange is a product of underplated material generated by tectonic erosion of an outer arc wedge structure at the interface between the descending and overriding plates. Vannucchi *et al.* (2006, 2007) interpret the Osa Mélange as a tectonically disrupted accreted package of oceanic lithologies that are exotic to the overriding Caribbean Plate. In this interpretation, the mélange suffered pervasive metamorphism and exhibit a "ghost stratigraphy suggesting dismemberment of a classic sequence of oceanic crust".

1.3. The overlap sequences

The overlap sequences rest unconformably upon the basement rocks of the Osa Igneous Complex and Osa Mélange. They are composed of: (1) the late Paleocene to late Eocene Pavones Formation, (2) the early Pliocene to early Pleistocene (or younger) Charco Azul Group, and (3) the mid to upper Pleistocene Osa Group (Fig. 2).

The late Paleocene to late Eocene Pavones Formation is the oldest overlap sequence in the area (Obando 1986; Di Marco 1994; Di Marco *et al.* 1995) (Fig. 2a). This formation crops out in the Burica Peninsula above deformed igneous rocks of the Osa Igneous Complex (Obando 1986; Di Marco 1994) (Fig. 2a). It comprises an association of periplatform, reworked shallow-water limestones and siliceous pelagic limestones (Obando 1986; Di Marco 1994). Although Di Marco (1994) considered this formation to be devoid of arc/continent-derived material and to have deposited on the slope of an intra-oceanic seamount, re-examination of Paleogene samples collected by Di Marco (1994) in the Rio La Vaca (Di Marco *et al.* 1995, p. 13, Fig. 7) revealed they contain quartz, zoned plagioclase and green amphibole grains. Similarly observations were made by Obando (1986). We propose that these grains indicate depositiona close to an arc, presumably a forearc slope. In the middle Eocene, the formation is characterized in the Quebrada Piedra Azul by the unusual occurrence of thick boulders beds reworking fragments of a carbonate platform (Di Marco *et al.* 1995).

The Charco Azul Group was comprehensively studied by Corrigan *et al.* (1990), Coates *et al.* (1992) and Collins *et al.* (1995). It has been subdivided into: (1) the early Pliocene Peñita Formation, which rests uncomformably upon the Pavones Formation and basement rocks, (2) the late Pliocene Burica Formation, conformableon the Peñita Formation and (3) the early Pleistocene or younger Armuelles Formation, conformable on the Burica Formation (Fig. 2a). The Peñita Formation is composed of as much of 1200 m of clayey, blue-green siltstone and litharenite consistently rich in benthic and planktic foraminifers, deposited in a forearc slope environment (Coates *et al.* 1992). The basal formation is coarse with locally channeled conglomerates, some of which form a distinctive suite defined as the La Vaca Member by Coates *et al.* (1992) (Fig. 2a). These coarse deposits record a detrital paralic and fan-delta depositional environment at the base of the Charco Azul Group. The Burica Formation consists of about 2800 m of mostly fine-grained, volcaniclastic turbidite deposits with local megabreccias formed by large-scale intraformational slumps (Coates *et al.* 1992). The La Chancha Member is a distinctive coarse facies interpreted to represent canyon fill within the trench slope on which the Burica turbidites were deposited (Coates *et al.* 1992) (Fig. 2a). Finally, the Armuelles Formation consists of ~370 m of channelled pebbly conglomerate and unconsolidated greenish-blue litharenite and siltstone in the lower part and predominant grey-blue, clayed siltstone and fine litharenites in the upper part (Coates *et al.* 1992).

The Osa Group rests on an erosional unconformity cut into the basement rocks in the northern and central Osa Peninsula (Berrangé 1989). This surface is covered by a veneer of paleosoils and continental deposits hosting the gold deposits of Osa (Berrangé 1989; Berrangé & Thorpe 1988). Mid to upper Pliocene sediments hosting the placer gold deposits give way upwards to thick turbidite fan deposits representing a deepening sequence, defining a sequence similar to the Charco Azul Group. Whereas Berrangé (1989) defined the Osa Group on the base of dissimilar sedimentary facies in Osa and Burica peninsula, Coates *et al.* (1992) suggested the Osa Group may rather represent a lateral extension of the Charco Azul Group. It seems to us initial subdivision between the Osa and Charco Azul groups by Berrangé (1989) should remain until new data from North and Central Osa Peninsula are provided.

In summary of this chapter we conclude that the overlap sequences exposed in the Osa and Burica peninsulas indicate at least two major tectonic events that occurred prior to the deposition of the sediments. The first preceded unconformable hemipelagic, forearc deposits of the basal Pavones Formation (late Paleocene) (Di Marco *et al.* 1995). The second preceded the unconformable, near-shore deposits of the lower Peñita Formation (early Pliocene) (Coates *et al.* 1992) and continental deposits of the Osa Group (mid to upper Pliocene) (Berrangé, 1989). The Charco Azul Group defines a transgressive-regressive cycle between the early Pliocene and the Pleistocene (Coates *et al.* 1992; Collins *et al.* 1995). In the middle Eocene, thick beds bearing shallow-water limestone boulders are observed in the Pavones Formation (Di Marco *et al.* 1995), which may also represent a record of a third tectonic event. The nature of the overlap sequences provides constraints on the tectonic evolution of the margin. Their significance is discussed below, along with the accretionary record of the Osa Igneous Complex and Osa Mélange.

2. Mélanges: nature and origins

In this study special emphasis is given to description and interpretation of the Osa Mélange. Mélanges are generally considered to be very complicated rock associations, frequently described as "chaotic rock bodies". We present below a succinct, non exhaustive review of the mélanges, their origins and commonly associated problems. We defined also a nomenclature for our descriptions of the Osa Mélange.

2.1. Mélange definition

A recognized definition of a mélange was introduced by Raymond (1984) as: "a body of rock mappable at a scale of 1:24 000 or smaller and characterized both by the lack internal continuity of contacts and strata and by the inclusion of fragments and blocks of all sizes, both exotic and native, embedded in a matrix of finer-grained material". The occurrence of fragments and blocks of all size is characteristic of the fractal nature of a mélange - repetition of the same block-in-matrix texture at various scales, or "scale independence" (Medley 1994).

The use of the term "mélange" following Raymond (1984) requires an *a priori* knowledge of the origin of the described rock body, because it is necessary to make a distinction between exotic and native blocks. When exotic blocks are not found in a rock body without internal stratal continuity, Raymond (1984) proposes the use of the term "dismembered unit". However, identification of genetic characteristics may be problematic in block-in-matrix rocks because it is sometime difficult to make a distinction between exotic and native blocks. Indeed, Raymond (1984) mentions and discusses this issue. Perhaps for this reason the term "mélange" in the literature is widely used with a broader, simpler meaning of "block-in-matrix rock". This use tends to be confusing because the term "mélange" has thus been attributed to rock bodies having very distinctive fabrics, compositions, origins and geological meanings.

The confusion arising from the use of the term "mélange" led Medley (1994, 2001) to propose the term "bimrock" for rock bodies that contain competent blocks of varied lithologies, embedded in sheared matrices of weaker rock. Medley (1994, 2001) introduces this term in a geological engineering purpose and defines the bimrock as "a mixture of rocks, composed of geotechnically significant blocks with a bonded matrix of finer texture". "Geotechnically significant blocks" means that there is mechanical contrast between blocks and matrix. Accordingly, Medley's definition is founded on geometric and mechanical parameters. This approach successfully avoids possible confusions related to genetic considerations. On the other hand, it emphasises deformation that may play a role in the formation of the block-in-matrix rocks by introducing a mechanical contrast between the blocks and the matrix as a fundamental parameter. However, some block-in-matrix rocks (such as the Osa Mélange) may locally lack a significant mechanical contrast between the blocks and the matrix.

In view of mélange definitions by Raymond (1984) and Medley (1994, 2001), it clearly appears that a precise characterization of block-in-matrix rocks is not straightforward and, in absolute, may actually be impossible. Along with complicated fabrics observed in block-in-matrix rocks this likely explains the significant variations in the meaning attributed to the term mélange in literature. In this chapter, we adopt the geologic terminology introduced by Raymond (1984) and use the terms "mélange" and "dismembered unit" in the sense presented in the beginning of this chapter. The terms "block" or "fragment" are used for geometric bodies regardless of their origins. "Grain" (size=125µm-2mm), "granule" (size=2-4mm), "pebble" (size=4-64mm), "cobble" (size=64-256mm) and "boulder" (size>256mm) are blocks/fragments of sedimentary origin. We arbitrarily use herein the sedimentary term "large boulder" as a rock fragment larger than 10m.

2.2 Recognizing the origin of a Mélange

A mélange may be produced by (1) purely sedimentary processes, (2) purely tectonic processes, or (3) combined sedimentary and tectonic processes (Raymond, 1984). Typical examples of mélanges produced by sedimentary processes are olistostromes or debris flow deposits which are commonly produced by erosion or gravitational reworking of older rocks and/or unlithified sediments along steep slopes (*e.g.* Hampton & Lee 1996). Tectonic mélanges are often produced at subduction zones along the interface between subducting and overriding plates. They are frequently composed of metamorphosed igneous/sedimentary fragments embedded in a shaley and/or serpentinitic matrix. Literature contains a wide diversity of names for these mélanges, such as flow mélange (Cloos 1984), mélange belt (Doubleday *et al.* 1994 a, b), serpentinite mélange (Chang *et al.* 2000) or suture zone ophiolitic mélange (*e.g.* Dupuis *et al.* 2005). Finally, mélange produced by both sedimentary and tectonic processes ("polygenetic mélanges" after Raymond (1984)) are generally a result of sedimentary mélange overprinted by tectonic deformation. Wildflysches are certainly the most illustrative example of a polygenetic mélange. They are produced in orogenic zones by deformation of olistostromic sediments deposited at the front of nappes (*e.g.* Alonso *et al.* 2006).

All these examples highlight that mélanges are produced by a large spectrum of geological processes encountered along convergent margins. General criteria allowing differentiation between several origins are given by Raymond and Terranova (1984): (1) the nature of contacts (depositional or structural), (2) the relationships to surrounding units, including paleogeographic considerations, (3) the nature of the matrix, (4) the internal structure of the rock body, (5) the presence or absence of features indicative of soft sediment deformation, and (6) the presence or absence of deformation and metamorphism within inclusions. In addition to these criteria a particular effort was made in our study to characterize the nature and ages of the blocks and matrix. This allowed us to make a precise comparison of the mélange with surrounding units.

2.3 Field work in the Osa Mélange

Due to high complexity generally associated to mélanges, particularly-detailed field work was made in the San Pedrillo Unit (inner Osa Mélange). Geological correlations and observations were made at scales ranging from a thin section to the entire unit (*i.e.* several km). We carried out detailed mapping at 1:5000 scale of the NW edge of the Osa Peninsula and Caño Island (Figs. 5, 6). Comprehensive maps are presented in Buchs & Stucki (2001). Lithologies of variously deformed rocks were characterized on the basis of a systematic sampling over the entire area (Fig. 6). Although our study was restricted in the NW part of the Osa Peninsula, it provides constraints applicable to the entire San Pedrillo Unit. Samples are listed in Table 1.

3. Results

3.1. The Osa Igneous Complex

A new tectonostratigraphy is proposed for the Osa Igneous Complex based on: (1) newly-recognized differences in geochemistry of the igneous rocks (Buchs 2008), (2) mapping of distinctive igneous and sedimentary rock formations, and (3) previous and new paleontologic dates from the sediments associated to the igneous rocks.

A comprehensive geochemical study of the Osa Igneous Complex is well beyond the scope of this Chapter and is presented in Buchs (2008). However, we choose here to use $(La/Sm)_{CIn}$ and $(Sm/Yb)_{CIn}$ ratios based on the geochemical study exposed in Buchs (2008) as representative parameters of the geochemical variations encountered in the Osa Igneous Complex. In tholeiitic and alkaline rocks of Costa Rica these ratios generally show a good correlation with Sm-Nd and Lu-Hf isotopic compositions (*e.g.* Hauff *et al.* 1997; Buchs 2008). Hence, they are considered here to represent useful discriminative parameters in terms of source composition and origins. In the text, these ratios are called "highly depleted" when $(La/Sm)_{CIn}$=0.3-0.4 and $(Sm/Yb)_{CIn}$=0.7-0.9, "NMORB-like" when $(La/Sm)_{CIn}$=0.5-0.6 and $(Sm/Yb)_{CIn}$=0.8-1.1, "plateau-like" when $(La/Sm)_{CIn}$=0.7-1.0 and $(Sm/Yb)_{CIn}$=0.8-1.3, and "OIB-like" when $(La/Sm)_{CIn}$=0.9-3.7 and $(Sm/Yb)_{CIn}$=1.4-4.9. Plateau-like igneous rocks are distinct from E MORB in terms of Nb and major element contents and resemble typical oceanic plateaus (Buchs 2008).

The Osa Igneous Complex is subdivided into: (1) the Inner Osa Igneous Complex, and an Outer Osa Igneous Complex composed of (2) the Güerra Unit, (3) the Ganado Unit, (4) the Riyito Unit and (5) the Vaquedano Unit (Figs. 2, 3). All these units are bounded by recent (active?) fault zones and are broadly oriented NW-SE, parallel to the Mid American Trench (Fig. 2b).

3.1.1. The Inner Osa Igneous Complex

The Inner Osa Igneous Complex is exposed on the isthmus side of the Osa Peninsula and on the Burica Peninsula. In the NE it is in contact with the arc-related Golfito Complex. In the northern Osa Peninsula it is in contact with the Güerra Unit, whereas in the southern Osa Peninsula it is bordered by the Osa Mélange (Figs. 2, 3B-B'). NW extension of the boundaries of the inner Osa Igneous Complex is poorly or not expressed on reflection profile P 1600 (NW Osa, Fig. 3A-A'). However on-land exposures in close vicinity (~15-30 km) tend to indicate the Osa Igneous Complexe and San Pedrillo Unit (inner Osa Mélange) are also present in this part of the margin.

The inner Osa Igneous Complex comprises over 99% of basaltic, massive-columnar lava flows and pillow lavas that constitutes a rock pile several km thick (Fig. 3). The lavas consist of sub-ophitic, intersertal and intergranular basalts and coarse basalts and microgabbros with plagioclase, clinopyroxene, oxides, interstitial glass, minor amounts of sulfides and occasionally altered olivine. Three clear occurrences of intrusive rocks have been observed in the Inner Osa Igneous Complex, which consist of a sill located along the shore close to Rincón (Golfo Dulce), dolerites exposed at Punta Banco (Burica Peninsula) and a gabbro in the Quebrada Sábalo (inner, isthmic side of Osa). The sill is characterized by an atypical microlitic texture with K-feldspar and acicular brown amphibole. The gabbro has a very peculiar poikilitic texture with plagioclase phenocrysts. Occasionally, lenses and layers, 1-3 m thick, of red cherts and black shales are observed between the lava flows. These sediments constitute a very minor amount of the Inner Osa Igneous Complex. Along the shore of the Golfo Dulce (Punta Esperanza, 539.9/291.3, Costa Rican coordinates), a 20 m thick intercalation of arenite, microbreccia and breccia, named "Esperanza Formation" by Mende (2001), crops out within the volcanic sequence. The sediments contain basaltic material similar to the lavas of the Inner Osa Igneous Complex. To date, this deposit constitutes a unique occurrence of detrital material in the Inner Osa Igneous Complex.

Lava flows and sediments dip predominantly NE. Orientation of the pillow lavas indicates that the volcanic sequences are both in normal and overturned position. Overturned pillow lavas are found over the entire unit but are much less frequent than rocks in normal position. A low-T submarine alteration in the zeolite facies is shown by low to moderate alteration of the glass and silicate minerals. Samples collected in the Inner Osa Igneous Complex are devoid of greenschist metamorphism. Strong deformation is locally observed and associated to intensive veining of the rocks. Veins are generally filled with calcite and zeolite. Small-scale structures potentially indicating folding of the rocks (*e.g.* cleavage in sediments) have not been observed. Deformation seems to have predominantly occurred in a brittle mode and resulted in the formation of fault-bounded lenses of relatively undeformed rocks. The lenses are well seen along the shore of the Burica Peninsula and are observed at scales ranging from several meters to possibly several hundreds of meter. In the Inner Osa Igneous Complex the presence of both overturned pillow lavas and lenses of rock bodies is indicative of a tectonic dismemberment of a very large unit or of an imbrication of several "smaller" rock bodies.

Age of formation of the basalts is defined by radiolarians associations found in intercalated cherts to the Coniacian-Santonian (~89-84 Ma) (Di Marco 1994; Diserens 2002; this study) (see Chapter 3.4.1 for more details). Two tholeiitic (low-K) basalts yield whole rock $^{40}Ar/^{39}Ar$ Ar total fusion isochron ages of 64.2 ± 1.1 and 54.5 ± 1.5 Ma (Hoernle *et al.* 2002). K-Ar ages on similar igneous rocks range from 78.0 ± 2 to 44.8 ± 8 Ma (Berrangé *et al.* 1989). Discrepancy between biochronological and radiometric ages is discussed in Chapter 4.3.

Geochemistry of the igneous rocks is principally tholeiitic with plateau-like affinities showing consistency with an oceanic, intra-plate origin (Figs. 1a, 4). However, igneous rocks with distinct oceanic, intraplate affinities are locally observed, such as NMORB-like and OIB-like tholeiitic lava flows (Figs. 2a, 4a). Dolerites from Punta Banco (Burica) have NMORB-like tholeiitic, intraplate affinities and the sill close to Rincón is a basaltic trachyandesite with OIB-like, intraplate oceanic affinities. Local variations of the geochemical affinities point toward distinct origins for the igneous rocks that compose the Inner Osa Igneous Complex (Buchs 2008).

3.1.2. The Güerra Unit

The Güerra Unit is in contact with the Inner Osa Igneous Complex along its landward edge and with the Riyito and Ganado units along its seaward edge (Fig. 2). On a SW-NE cross section the transition from the Inner Osa Igneous Complex to the Güerra Unit is marked by changes in the topography (Fig. 3B-B'). In the NE side of the contact, the altitude progressively increases toward the contact and then suddenly drops seaward. This morphology is likely controlled by the presence of a major, possibly-active tectonic contact between the Güerra Unit and the Inner Osa Igneous Complex related to overthrusting of the Inner Osa Igneous Complex toward the SW. The contact seems to correlate with Osa shoreline along the Golfo Dulce, indicating that recent tectonic movements occurred along this basement suture (Fig. 2).

In contrast to the Inner Osa Igneous Complex, the Güerra Unit is characterized by stronger deformation and prehnite-pumpellyite to greenschist metamorphic facies. This metamorphism is unique in the area of study. The unit is broadly composed of metamorphosed/altered igneous rocks, marble, recrystallized micritic limestones and metamorphosed volcaniclastic sediments. These lithologies constitute a complicated arrangement of variously-deformed lenses extending at scales over 100 m that is interpreted to be a result of a tectonic imbrication of several large rock bodies. The less deformed lenses exhibit little deformed volcano-sedimentary textures, whereas the most deformed lenses are characterized by pervasive ductile deformation and associated schistosity that erased most pristine textures. There is good correlation between the intensity of the metamorphism and the degree of deformation (*i.e.* most deformed rocks exhibit highest metamorphic grades), pointing toward metamorphic reactions partly controlled by tectonics. Strike of the rock lenses is NW-SE with a NE moderate/subvertical dip. Similar orientations are marked by the schistosity in the most deformed rocks and by fabrics in the best preserved volcano-sedimentary rocks. This orientation is parallel to the contact of the Güerra Unit with the Inner Osa Igneous Complex.

As a consequence of locally strong deformation, many protoliths of the Güerra Unit are difficult to identify. However it is clear the unit comprises a wide range of rocks and contains a larger proportion of sediments than the Inner Osa Igneous Complex. In the less deformed areas we notably recognized preserved textures of vesicular pillow lavas interbedded with reddish, recrystallized limestones. These lavas consist of transitional basalts with OIB-like, intraplate affinities. However, due to sediment recrystallisation it was not possible to observe preserved fossils in our samples. In other places, spilitized porphyric pillow lavas were found. These lavas have tholeiitic affinities and highly-depleted incompatible element contents. These two examples of "preserved" volcano-sedimentary sequences are very similar in terms of sedimentary facies and geochemistry to some sequences of the Vaquedano and Riyito units (see below). Hence, by analogy with other units forming the Outer Osa Igneous Complex and the possible role of the unit in the construction of the Osa Igneous Complex (Chapter 3.1.5), formation ages of the rocks composing the Güerra Unit are probably encompassed between the late Cretaceous and the Eocene.

3.1.3. The Ganado Unit

The Ganado Unit is exposed in the SW side of the Güerra Unit. It is in contact with other units of the Outer Osa Igneous Complex and the Osa Mélange (Fig. 2).

This unit consists of pillowed and massive basaltic/basaltic-andesitic flows locally intruded by aphyric basaltic dykes, dolerites and gabbros. Intrusive rocks form a minor portion of the sequence (<10%) and are preferentially observed close to the Osa Mélange. Most common textures of the lavas are sub-ophitic, intersertal and intergranular with plagioclases, clinopyroxenes, oxides, interstitial glass and minor amounts of olivines and sulfides. Intrusive rocks have doleritic and ophitic textures with plagioclases, clinopyroxenes, oxides and co-magmatic amphiboles in some samples. In the volcanic rocks low-T submarine alteration in the zeolite facies is common. Strong alteration is also observed in the intrusive rocks and volcanic rocks at the contact. This is notably characterized by extensive argilitization of the plagioclases and epidote formation. It occurred in response to hydrothermal circulation triggered by the emplacement of the intrusive rocks prior to emplacement of the unit along the margin. In some gabbros, curvilinear cleavages are observed. This attests the gabbros were deformed by the time of their cooling, soon after emplacement. A ~2 m thick layer of red radiolarian chert, interbedded with coarse lava flows, was the sole occurrence of sediments encountered in the stratigraphic sequence. Radiolarians provided a Coniacian-Santonian (~89-84 Ma) age (see also Chapter 3.4.1 for more details).

The lava flows dip preferentially NE and are found both in inverse and normal positions. The volcanic rocks suffered deformation similar to the Inner Osa Igneous Complex. These observations and occurrences of intrusive bodies (*i.e.* deep crustal exposures) at the contact with surrounding units indicate the igneous rocks forming the Ganado Unit underwent a significant tectonic dismemberment. The unit may have formed through imbrication of distinct volcanic sequences or dismemberment of a single, very large rock body.

Two geochemically distinct groups of igneous rocks are found in the Ganado Unit. The first group comprises tholeiitic basaltic lava flows and aphyric dykes. It is characterized by plateau-like affinities consistent with an oceanic, intraplate origin (Fig. 4c). Although this group appears to be similar to the plateau-like lavas of the Inner Osa Igneous Complex, discriminative geochemical differences exist between the two, notably in terms of Nb content (Buchs 2008). One exception to this observation comes from a lava flow associated to the Campanian radiolarian chert. Although this lava has plateau-like affinities, it consists of a transitional tholeiite with Nb content similar to the tholeiites from the Inner Osa Igneous Complex. It is interpreted here to represent a record of a late stage of volcanism in the Ganado plateau-like "series". The second geochemical group of the Ganado Unit is mainly expressed in the dolerites and gabbros emplaced into the plateau-like group, as well as in a few massive lava flows. This group is composed of NMORB-like tholeiites with oceanic intraplate affinities similar to the NMORB-like tholeiites of the Inner Osa Igneous Complex (Fig. 4c).

3.1.4. The Riyito Unit

The Riyito Unit is a composite (non-contiguous) unit exposed at both the NW and SE edges of the Ganado Unit. It is in contact with the Güerra Unit in the NE and the Vaquedano Unit and Osa Mélange in the SW (Fig. 2).

The unit comprises volcano-sedimentary sequences including small, well-formed pillow lavas, sheet flows and minor occurrences of sediments and hyaloclastites. The lavas are basaltic in composition and locally vesicular. They ubiquitously contain plagioclase phenocrysts embedded in a subophitic-intersertal-microlitic matrix made of plagioclases, clinopyroxenes, oxides, matrix glass and minor amount of sulfides. The porphyric nature of these lavas has been used on the field to constrain the extension of the unit. Vesiculated hyaloclastites are locally observed between pillow lavas, possibly indicating eruption under shallower conditions for some parts of the volcanic rocks. Alteration of the igneous rocks is low to moderate and consistent to low-T oceanic alteration. The sediments represent less than 3% of the total volume of the sequence and are predominantly exposed along the Rio Riyito (central Osa). They comprise turbiditic beds reworking basaltic igneous rock fragments. Plagioclase-phyric dykes intruding lava flows occur in the lower part of the Rio Riyito. In the Punta Ganadito (western Osa) crustacean microcoprolites have been encountered in a deep ocean sequence (Buchs *et al.* in press).

The lava flows dip NE with pillow lavas in both normal and overturned positions. Exposures of the Riyito Unit are clearly non-contiguous and are separated by the Ganado Unit. Hence, similarly to the Inner Osa Igneous Complex, the Riyito Unit shows indications of dismemberment that possibly resulted from an imbrication of distinct rock bodies.

Hauff *et al.* (2000) provided a $^{40}Ar/^{39}Ar$ age of 62.1 ± 0.6 Ma (Paleocene, total fusion on whole rock matrix) for a basaltic sample of the Punta Ganadito. Fossils allowing a precise dating of the interlayered sediments have not been encountered.

Volcanic rocks are all tholeiitic and exhibit very consistent geochemistry. They are characterized by an unusual high depletion in the most incompatible elements that is consistent with an oceanic origin (Fig. 4b).

3.1.5. The Vaquedano Unit

The Vaquedano Unit is exposed along the Osa Mélange and is in contact with the Ganado and Riyito units (Fig. 2).

This unit comprises a complicated imbrication of volcano-sedimentary sequences exhibiting distinct lava morphologies, geochemistry, ages and sedimentary associations. It broadly consists of vesiculated, small-shaped pillow basalts and lava flows, reddish pelagic limestones, detrital sediments and hyaloclastites. Lavas form the bulk of the sequences (>85%) and consist of ophitic, subophitic, intersertal and spherulitic basalts with plagioclase, titanoaugite, olivine pseudomorphs, oxides, glassy matrix and minor amount of sulfides. A few pillow breccias and hyaloclastites are locally interbedded with the lavas. The pelagic limestones locally occur as deformed xenoliths embedded in massive lava flows, indicating an incorporation of unlithified sediments into the lavas by the time of their emplacement. Most commonly, the limestones form interbeds within the pillowed and massive lava flows. Occasional sponge spicules possibly indicate some of the limestones formed in nutrient-rich oceanic currents. A sample of late Cretaceous micritic limestone contained two badly-preserved fragments of red alga. In the Osa Igneous Complex, this is the sole occurrence of material originating from a shallow-water environment. Detrital basaltic sediments that consist of <50 m thick turbidites and pebbly-cobbly breccias are locally intercalated with volcanic rocks.

Ages of the volcano-sedimentary sequences are well constrained by fossil assemblages found in the pelagic limestones. These sediments contain late Cretaceous Inoceramus fragments and Campanian to middle Eocene Foraminifera (Di Marco 1994; Buchs 2003). This is the largest range of ages observed for the sequences of the Osa Igneous Complex, which spans ~40 Ma. The igneous rocks yielded K-Ar ages of 55.3 ± 6 to 40.8 ± 4 Ma that are broadly similar to biochronologic ages (Berrangé *et al.* 1989).

In both lava flows and sediments the layers predominantly dip NE, with both normal and reverse positions of pillow lavas. Although the lavas are ubiquitously reddish as a response to early, low-T, oceanic oxidization/alteration, no trace of higher temperature alteration or metamorphism has been encountered. The unit is composite and made of large (100 m length/width and bigger) rock bodies identified on the basis of distinct volcano-sedimentary associations, ages and geochemistry. Similarly to the Inner Osa Igneous Complex, the Güerra Unit and possibly the Riyito Unit, the Vaquedano Unit resulted from an imbrication of several rock bodies.

Volcanic rocks comprise transitional to alkalic basalts with OIB-like affinities (Fig. 4d). Although these rocks share intraplate oceanic affinities they are characterized by a wide range of immobile incompatible element contents throughout the unit. This is incompatible with a common origin of the volcanic rocks. However, good consistency of the geochemistry is observed in samples collected close to each others, at scales <250 m, which is in agreement with an imbrication of large rock bodies forming the Vaquedano Unit.

3.2. The NW Osa Mélange (San Pedrillo Unit)

3.2.1. Sedimentary fabric

Despite the existence of a highly pervasive deformation, the San Pedrillo Unit exhibits a relatively well-defined lithological arrangement (Buchs & Stucki 2001; Buchs & Baumgartner 2003). Compositional variations of the formations and recurrence of a finite number of lithologies are observed, providing the opportunity to map the mélange at 1:5000 and larger scales (Figs. 5, 6). In general, the NW Osa Mélange is characterized by alternations of (1) areas dominated by igneous blocks embedded within a deformed sedimentary matrix and (2) areas comprising deformed sedimentary layers lacking a significant amount of large (>1m) blocks and predominantly made by fine-grained (<5cm) detrital or hemipelagic sediments (Figs. 5, 7a). Alternations of lithologies trend NW-SE, with strong variation in dip (Fig. 7b). Sedimentary structures, such as layering, size grading and laminations are frequently observed throughout the unit and are oriented parallel to lithological alternations. The lithological arrangement and systematic orientation of layered sediments is interpreted to result from imbrication of distinct rock bodies characterized by a lenticular shape (Fig. 7b).

A detrital (sedimentary) fraction is ubiquitously observed in the San Pedrillo Unit. It is indicated by the presence of clasts ranging from grains to large boulders, embedded within sedimentary deposits (Fig. 5, see also Chapter 4.2.3.). Intense tectonic brecciation of large igneous blocks may lead locally to a possible confusion of the San Pedrillo Unit with a tectonic mélange sensu stricto (*e.g.* Meschede *et al.* 1999). However, we observed that (1) the large blocks are systematically found within debris flow layers and are rarely embedded within cataclased rocks and (2) geochemical compositions of the igneous blocks located close to each other and embedded within the same sedimentary deposits preclude a provenance from a unique volcanic series (see below). Thus, the igneous blocks of the San Pedrillo Unit are olistoliths pertaining to the detrital component of the mélange rather than preserved portions of tectonically-dismembered igneous sequences. A direct consequence of this observation is that there is a sedimentary fabric throughout the entire San Pedrillo Unit that predates a younger tectonic overprint.

3.2.2. Tectonic Fabric

Pervasive tectonic overprint in the San Pedrillo Unit may be divided into (1) active subvertical faulting and (2) earlier deformation. The former has been attributed to uplift and block tilting controlled by the morphology of the subducting Cocos Ridge (Sak *et al.* 2004). This implies that adjacent coastal exposures may actually represent different structural levels of the Osa Mélange.

Earlier deformation occurred in a low-grade metamorphic environment, below the field stability of greenschists. In a few cases, igneous olistoliths embedded in the sedimentary, low-grade metamorphic matrix show a higher metamorphic facies with the presence of epidote, prehnite and pumpellyite. These facies are likely inherited from their environment of formation prior to their incorporation to the San Pedrillo Unit. Although some deformed rocks are green due to chlorite formation, metamorphism observed in our samples from the Osa Mélange has not exceeded a prehnite-pumpellyite facies. This is an important dissimilarity of the Osa Mélange with other mélanges that commonly contain greenschist, amphibolite or blueschist grade blocks.

Tectonic deformation and related phases that occurred prior to the final exhumation of the San Pedrillo Unit are comprehensively described by Vannuchi *et al.* (2006). Their results are summarized and discussed conjointly with our observations in Chapter 5.3.

3.2.3. Lithologies

Large variation in lithologic composition occurs in the San Pedrillo Unit. During our 1:5000 mapping, a detailed characterization of the lithologies was performed (Fig. 5). However, the extent of the lithological variations is such that it is fundamentally not possible to constitute a complete report of all the rocks. Hence, we describe here only the most representative associations of lithologies.

The San Pedrillo Unit may be roughly divided into 3 types of lithologies: (1) sedimentary deposits containing shallow-water limestones (~20% volume of the San Pedrillo Unit), (2) debris flow deposits dominated by igneous olistoliths (~25% volume of the San Pedrillo Unit) and (3) fine-grain detrital sediments (~55% volume of the San Pedrillo Unit).

<u>Sedimentary deposits containing shallow-water limestones</u>

Shallow-water limestones occur mainly as pebbles and boulders embedded in a dark, tuffitic matrix (Plate 1a-d). They form matrix-supported breccias that are encountered on Caño Island and between Playa San Josecito and Punta Llorona (Fig. 6). This lithology appears as sedimentary layers that have an apparent thickness of 2 to 30 m and were probably emplaced by debris flow events. The matrix comprises altered ashy tuffites, intensively deformed during tectonic processes. The limestone clasts are frequently recrystallized and fragmented. Sometimes they comprise over 50% of calcite veins. The matrix was injected within and between the clasts, indicating the tuffites behaved softly and were poorly compacted during the beginning of the tectonic history within the mélange.

Limestone beds, 0.5 to 3m thick, are encountered in the areas of Agujitas, Marenco and Caño (Fig. 6, Plate 1a-b). These deposits represent an accumulation of largely dominant carbonate grains without a significant amount of tuffitic matrix. They are interpreted as calci-turbidites interbedded with tuffitic greywackes, volcarenites and microbreccias that notably contain fragments of mafic to differentiated volcanic sources. During tectonic deformation the beds underwent fracturing, brittle boudinage and injection of under- and overlying muddy sediments, creating networks of sedimentary dykes (Plate 1a). These limestones allowed us to date the deposition of the sediments forming the bulk of the mélange (see below).

The shallow-water limestone olitsoliths and turbidites contain carbonate grains and pebbles formed in a platform and/or peri-platform environment. They include mainly red algae, larger foraminifera, echinoderms and sponge spicules. An associated detrital fraction consists of fragments of pyroxene, zoned plagioclase, quartz, basalts and intermediate to acidic lavas. Detrital quartz and fragments of dacites occasionally occur as nuclei of red algal oncoliths. The larger foraminifera indicate a late Eocene age (see below). Thus, the depositional age of these shallow-water derived calcareous debris flows and calci-turbidites is late Eocene or younger.

Similarities of composition, faunal assemblages and age of the shallow-water carbonates of the San Pedrillo Unit likely indicate a common origin. In the NW Osa Mélange they are associated through primarily-sedimentary processes with products of a differentiated volcanism that is represented by ashy tuffites, quartz fragments, and silica-rich igneous blocks. The geochemical compositions of the silica-rich igneous blocks indicate an arc-related affinity (see below). Thus, it is clear that the carbonates must have formed in the vicinity of a volcanic arc.

<u>Debris flow deposits dominated by igneous olistoliths</u>

Debris flow deposits with large amounts of igneous boulders and large boulders are concentrated in the Marenco and San Pedrillo areas (Figs. 5b, 6, Plate 1h). The olistoliths locally exceed 50m in size, constraining thickness of the debris flow deposits to an equal or superior size. The olistoliths consist of basalts (~70%), intermediate-felsic igneous rocks (~25%), gabbros and hydrothermally-altered gabbros (~2%), radiolarites (~1%), limestones (~1%) and detrital sediments (~1%). They are embedded within a matrix of detrital sediments comprising mineral fragments, and grains, granules and pebbles of rock fragments. The matrix exhibits a composition analogous to the igneous blocks, indicating a similar provenance of the detrital material. The provenance of the igneous olistoliths is shown by their geochemical composition (see below), which points toward two main sources: (1) a highly heterogeneous basaltic source of oceanic intraplate origin and (2) an arc-related igneous source.

The olistoliths and the matrix are deformed and crosscut by a dense network of zeolite, calcite and quartz veins. An intensive brittle deformation affected the igneous blocks, resulting in strong tectonic brecciation. As a consequence, it may locally be particularly hard to make a distinction between the matrix and the blocks. This may explain the confusion of the Osa Mélange with a tectonically dismembered igneous sequence by some authors. However, association of well-rounded igneous and calcareous pebbles is locally observed in sedimentary layers, clearly indicating a primary sedimentary origin of the igneous blocks (see below). The sedimentary origin of the igneous blocks is further strengthened by the large variability of geochemical affinities observed within the igneous rocks that is clearly incompatible with disruption of a unique magmatic suites or several magmatic suites proceeding from a unique tectonic setting.

Radiolarites and pelagic limestones occur as isolated blocks or in sedimentary association with igneous olistoliths (Plate 1e-f). Within the igneous olistoliths radiolarites are in stratigraphic contact with lava flows. Pelagic limestones are interbedded within reddish pillow lava sequences. The radiolarians encountered in isolated blocks of sediments or in association with lava flows are Campanian-Maastrichtian in age. Radiolarian assemblages are dissimilar to those of the radiolarian cherts of the Osa Igneous Complex (see Chapter 3.4.1 for details). The pelagic limestones provided ages ranging from the Campanian to the middle Eocene, similar to the ages of the calcareous sediments found in the Outer Osa Igneous Complex (Vaquedano Unit). Faunal compositions of the pelagic limestones of the San Pedrillo Unit are similar to those of the Vaquedano Unit.

<u>Fine-grain detrital sediments</u>

Fine-grain detrital sediments form the predominant lithology in the San Pedrillo Unit (~55% of the mapped volume) (Fig. 6). They range from mudstone, greywacke, siltite, arenite to microbreccia (Plate 1g-i). The detrital fraction comprises mineral and lithic fragments (Fig. 5a). A matrix component predominantly of siliceous-calcareous-tuffitic oozes is observed in some samples (up to 95% of the mode). The mineral fragments consist of clinopyroxenes (~50%), plagioclases (~40%), opaque minerals (~10%) and quartz (<1%). Lithoclasts are predominantly fragments of basalts (~95%) and, to a lesser extent, intermediate-felsic igneous rocks (~5%) and limestones grains (<1%). When observed, the siliceous-calcareous matrix of the detrital sediments contains a few recrystallized radiolarians and planktonic foraminifera, which are not sufficiently preserved to allow age determination.

The occurrence of (1) pelagic faunas and (2) quartz fragments and tuffites within the fine-grain detrital sediments constrains their environment of deposition to a hemipelagic setting. The lithologies in this group range over a wide compositional field that is fully described by a mixing between two end-members: (1) siliceous-calcareous hemipelagic oozes (*e.g.* mudstones, biomicrites and radiolarian cherts) and (2) a detrital component (*e.g.* forming litharenites and arkosic arenites).

At Punta Campanario, <2m thick debris flow layers are intercalated with the fine-grained detrital sediments (Plate 1j). Within the debris flow deposits, shallow-water limestone pebbles occur in association with basaltic, andesitic and dacitic pebbles that are both angular and well rounded (Buchs & Baumgartner, 2007, p. 4, Fig. 2a). The association of mafic, intermediate and differentiated igneous material with grains of shallow-water limestones is in agreement with observations made in other, previously described lithologies of the mélange. In addition, the presence of well-rounded elements of basalts and dacites indicates this material was transported in a river system or was abraded along a shoreline. As a consequence, the sources of the detrital material encountered in the San Pedrillo Unit were at least partially emerged at the time of their erosion. Large foraminifera in the grains of shallow-water limestones provided late Eocene ages, similar to the age of the rest of the shallow-water limestones in the San Pedrillo Unit (see below). Late Eocene is thus a limit age of formation of the fine-grained detrital sediments (*i.e.* they are late Eocene or younger).

A minor fraction (<2%) of lenses of radiolarian cherts, intercalated within the fine-grained detrital sediments, occurs in the San Pedrillo Unit. These sediments contain <10% of plagioclase, clinopyroxene and glass fragments. Radiolarians are early Eocene in age, apparently in disagreement with the ages of the calcareous grains. Occurrence of these sediments and significance of their age are discussed below.

3.2.4. Geochemistry of the igneous olistoliths

Pervasive dense networks of hydrothermal veins within the San Pedrillo Unit indicate that (hydrothermal) fluids circulated throughout the mélange. The fluids may have altered some of the igneous rocks. However, we observed that, in some cases, the cores of the biggest igneous olistoliths remained surprisingly well-preserved (Fig. 5b). We sampled those cores and relatively unaltered igneous blocks to perform geochemical analyses (Tables 2.1, 2.2, 2.3).

Four groups of igneous rocks have been recognized within the Osa Mélange on the basis of immobile trace element contents. We subdivided them into intermediate-felsic igneous rocks and basaltic igneous rocks.

The intermediate-felsic rocks are represented by blocks and megablocks of dacites, rhyodacites, monzonites and granophyres. Three samples of dacites and monzonite were selected in this group for their apparent freshness. Their incompatible element patterns are highly variable, indicating both enrichment and depletion in the LREE and highly incompatible elements (Fig. 4e). We note a systematic $(Nb/La)_{nCI} < 0.6$ and $(Ce/Pb)_{nPM} < 1$ (Fig. 4e). Since La and Nb are known to be immobile during alteration processes (*e.g.* Verma, 1992), the La/Nb ratio is believed to represent a primary feature consistent with an arc-related origin of the samples. A positive Pb anomaly is also observed, which may be due to sediment-derived fluids within the accretionary prism or represent a primary feature. In the light of the high incompatible element contents in the samples, the Pb positive anomaly could hardly be related to secondary processes because it would require a strong alteration that is not observed in the analyzed rocks. Accordingly, these rocks have both primary La/Nb and Ce/Pb consistent with a near-arc origin. Indeed, their composition is similar to Miocene high-Fe (tholeiitic) and low-Fe ("calc-alkalic") suites of the Costa Rican forearc (Fig. 4e) (Abratis 1998).

The olistoliths of basaltic rocks span a large domain in terms of geochemical composition (Fig. 4a-d). Groups showing similar affinities on the basis of their immobile element composition were recognized, which point toward oceanic, mostly intraplate origins of the basaltic olistoliths. Three groups of volcanic rocks were recognized with characteristic REE contents: (1) tholeiitic plateau-like basalts with $(La/Sm)_{CIn}\approx1.0$ and $(Sm/Yb)_{CIn}\approx1.0$, (2) highly depleted tholeiitic basalts and gabbros with $(La/Sm)_{CIn}=0.2\text{-}0.4$ and $(Sm/Yb)_{CIn}\approx0.9$ and (3) OIB-like alkali-transitional basalts with $(La/Sm)_{CIn}=1.0\text{-}2.6$ and $(Sm/Yb)_{CIn}=1.6\text{-}4.6$. Igneous samples from the San Pedrillo Unit are compared in terms of REE content to the igneous rocks of the Osa Igneous Complex on Fig. 4. Strong geochemical similarities exist between these two groups of rocks. It seems that most of the igneous olistoliths present in the San Pedrillo Unit have an equivalent in the Osa Igneous Complex (Fig. 4), but not in other forearc igneous complexes of South Central America (not shown, see Hauff *et al.* 2000 for a representative dataset of South Central American igneous complexes). Similarities between mafic igneous sequences in the Osa Igneous Complex and mafic igneous blocks in the San Pedrillo Unit are detailed below, conjointly with sedimentary associations.

3.2.5. Similarities between the basaltic olistoliths and the Osa Igneous Complex

Igneous olistoliths occur in debris flow deposits throughout the San Pedrillo Unit. Some of them include a sedimentary cover and interlayered sediments. Hence, both geochemistry and sedimentary associations may be used to point out possible origins for the olistoliths. We make here a detailed description for a representative selection of these olistoliths, with emphasis on the similarities between these rocks and sequences observed in the Osa Igneous Complex.

Basalt DJ01-085, with plateau-like affinities and OIB-like alkali basalt DJ01-082 were both collected in an olistostromic deposit at the Rio Claro (Fig. 5). An atypical microlitic texture with K-feldspar and acicular brown amphibole is recognized in the alkali basalt that is similar to the texture of the sill exposed close to Rincón in the Inner Osa Igneous Complex (Chapter 3.1.1.). The two samples of the San Pedrillo Unit from the Rio Claro debris flow deposit show strong geochemical similarities with igneous rocks of the Inner Osa Igneous Complex (Fig. 4a).

Plateau-like gabbro DJ01-129 from San Pedrillo area has a very distinctive poikilitic texture and REE content similar to the poikilitic gabbro sampled in the Inner Osa Igneous Complex (Chapter 3.1.1., Fig. 4a).

Basalt DJ01-094 from Marenco area has geochemical affinities similar to plateau-like igneous rocks of the Ganado Unit (Fig. 4c). These rocks are also characterized by a lower Nb/Y ratio than plateau-like igneous rocks from the Inner Osa Igneous Complex, pointing toward distinct origins (Buchs 2008).

Highly depleted tholeiitic lavas DJ01-023 and DJ01-097 were sampled in olistotromic deposits close to Marenco (Fig. 5). They are characterized by plagioclase-phyric textures and REE contents highly similar to lavas from the Riyito Unit (Fig. 4b). The sample DJ01-023 was embedded in a sedimentary layer conjointly with a cobble of sediment containing *Palaxius osaensis* coprolites. This species was first identified in the sediments of the Riyito Unit (Buchs *et al.* in press) and tus may be considered as a highly-specific marker of this unit.

Reddish alkali/transitional basalts DJ01-131 and DJ01-133 were sampled in olistostromic deposits close to the San Pedrillo ranger station. These samples have similar geochemical affinities to igneous rocks of the Vaquedano Unit (Fig. 4d). They are associated to late Cretaceous to Eocene pelagic sediments similar to the limestones of the Vaquedano Unit.

3.3. Contact between the Osa Igneous Complex and the Osa Mélange

The Osa Mélange is in contact with the Osa Igneous Complex along a NW-SE fault zone that extents through the Osa Peninsula (Fig. 2). In NW Osa, the Mélange is directly in contact with the Vaquedano Unit, whereas in the SE Osa the Mélange it borders the Inner Osa Igneous Complex. The nature of the contact is similar in both NW and SE Osa. This contact probably extends further toward the NW but has not been imaged on a seismic line ~35km off the Osa Peninsula (Kolarsky *et al.* 1995b) (Fig. 3). Like the fault zone at the Güerra Unit-Inner Osa Igneous Complex interface, te topography is indicative of a major, possibly-active tectonic contact between the Osa Igneous Complex and the Osa Mélange (Fig. 3B-B'). In the Outer Osa Igneous Complex, altitude broadly increases toward the contact where it reaches a high and then descends strongly toward the Osa Mélange. This may be caused by thrusting of the Osa Igneous Complex upon the Osa Mélange along an inverse fault.

Deformation of the rocks from the Osa Igneous Complex progressively increases toward the fault zone and marks a transition to the Osa Mélange. The deformation is characterized by the appearance of a pervasive intense brecciation of the igneous rocks associated to a complicated vein network. In an area of <300m from the Mélange, the igneous sequences were brittlely deformed and reduced to a tectonic mélange with "preserved" igneous blocks embedded within cataclased igneous rocks. In the Vaquedano Unit higher volumes of sediments are intercalated with igneous rocks and preferentially accommodated the deformation, leading to a better preservation of the igneous rocks.

The edge of the San Pedrillo Unit in contact with the Osa Igneous Complex is globally similar in terms of geology and structure to the rest of the San Pedrillo Unit. Tectonic incorporation of brecciated blocks of the Osa Igneous Complex in a ~100 m thick layer may occur at the transition between the two complexes. However, the small thickness of this layer indicates that no significant tectonic incorporation of the Osa Igneous Complex into the Osa Mélange has occurred.

3.4. Biostratigraphy

New paleontologic determined for the Osa Igneous Complex and San Pedrillo Unit (inner Osa Mélange) are documented in this chapter. Radiolarian ages from the Osa Igneous Complex given by Diserens (2002) are newly evaluated using updated fossil ranges. Radiolarian ages from the Azuero Plateau (Azuero Complex, western Panama, Buchs *et al.* submitted) given by Kolarsky *et al.* (1995b) are reappraised following the same method so as to provide reliable comparisons of biochronologic ages for some Costa Rican-Panamean igneous complexes predominantly composed of plateau-like igneous rocks.

3.4.1. Radiolaria in the Osa Igneous Complex and San Pedrillo Unit

The radiolarian biostratigraphy (Fig. 8, Plates 3, 4) for the late Cretaceous is based on work by Riedel and Sanfilippo (1974), Dumitrica (1975), Foreman (1975, 1977), Pessagno (1976), Taketani (1982), Sanfilippo and Riedel (1985), Schaaf (1985), Thurow (1988), O'Dogherty (1994), Hollis & Kimura (2001), Vishnevskaya (2001, 2007), while Foreman (1973), Sanfilippo & Riedel (1973), Nishimura (1987, 1992), Sanfilippo & Nigrini (1998) were used in dating the Paleogene samples. For more details on the technique used to date samples see Bandini *et al.* (2006, 2008).

Azuero Complex, western Panama

Sample JC-86-A7 (Torio shore, Kolarsky et al. (1995b)): occurrence of *Crucella plana* and *Alievium praegallowayi* gives a Turonian-early Santonian age. This fauna was illustrated in Kolarsky *et al.* (1995b) and is used herein for comparison with the radiolarian assemblages from the Osa Igneous Complex illustrated in this study (see discussion below).

Inner Osa Igneous Complex

Sample GDM 9116 (Punta Banco, Burica Peninsula, Diserens (1994)): The occurrence of *Theocampe urna* and *Praeconocaryomma universa* gives an early Turonian-early Maastrichtian age. Sample FBJ 90174 (Punta Esquinas, eastern coast of Golfo Dulce, Diserens (1994)): occurrence of *Lithatractus pusillus*, *Acanthocircus yaoi* and *Crucella cachensis* gives a Coniacian-Santonian age.

Ganado Unit

Sample DB02-199 (~505.6/297.3 Costa Rican coordinates, this study): occurrence of *Archaespongoprunum bipartitum*, *Eostichomitra* sp. and *Theocampe salillum* gives a Coniacian-Santonian age.

San Pedrillo Unit (inner Osa Mélange)

Sample DJ01-114 (this study): occurrence of *Lithatractus pusillus*, *Acanthocircus yaoi* and *Crucella cachensis* gives a late Campanian-early Maastrichtian age. Sample DJ01-141 (this study): occurrence of *Archaedictyomitra napaensis* gives a Maastrichtian age.

Sample GDM 9020 (Diserens (2002)): occurrence of *Periphaena heliasteriscus* gives a Thanetian-Bartonian age. Sample DJ01 (this study): occurrence of *Phormocyrtis striata striata* and *Buryella tetradica* gives a late Thanetian-Ypresian age. Sample DJ01-140 (this study): occurrence of *Phormocyrtis turgida* and *Buryella tetradica* gives an Ypresian age. Sample DJ01-118 (this study): occurrence of *Phormocyrtis turgida* gives an Ypresian age. Sample DJ01-043 (this study): occurrence of *Theocotylissa alpha*, *T. auctor*, *Buryella clinata*, *B. tetradicta* and *Lychnocanium carinatum*, gives a late Ypresian age. Sample GDM 90126 (Diserens (2002)): occurrence of *Dictyoprora mongolfieri* and *Buryella clinata* gives a Lutetian-Bartonian age.

Discussion

Radiolarian cherts of similar ages (Coniacian-Santonian) have been found in the Azuero Plateau (Kolarsky *et al.* 1995b), the Inner Osa Igneous Complex (Di Marco 1994; this study) and the Ganado Unit (this study). All these units are predominantly composed of igneous rocks with plateau affinities (see also Buchs 2008). Despite poor radiolarian preservation and weak abundance in the studied sediments, samples proceeding from these units yielded different faunal assemblages. The fauna of sample JC-86-A7 (Azuero Plateau, Azuero Complex, W Panama) is characterised by the association of *Hemicryptocapsa polyhedra*, *Praeconocaryomma universa*, *Pseudoaulophacus lenticulatus*, *P. venadoensis*, *Crucella plana* and *Alievium praegallowayi* (Kolarsky *et al.* 1995b). The assemblage of sample FBJ 90174 (Inner Osa Igneous Complex) is characterised by the association of *Dictyomitra formosa*, *Theocampe tina*, *T. urna*, *Acanthocircus yaoi*, *Praeconocaryomma universa*, *Crucella cachensis*, *Gongylothorax verbeeki* and *Lithatractus pusillus*. The assemblage of sample DB02-199 is characterised by the association of *Amphipternis stocki*, *Dictyomitra formosa*, *Halesium amissum*, *Praeconocaryomma universa*, *Theocampe urna*, *T. salillum*, *Archaespongoprunum bipartitum* and *Eostichomitra* sp. These three assemblages, from three different units, share only two commonly illustrated species in the published Late Cretaceous radiolarian faunas (*Dictyomitra formosa*, *Praeconocaryomma universa*). Some precautions are required in the interpretation of faunal assemblages since preservation and methodology may differ between samples and workers. However, we note that in samples of similar ages, associated on the field with similar igneous rocks, faunal assemblages possibly point toward distinct palaeoenvironments. This observation is in good agreement with occurrences of partly distinct sedimentary facies among the units.

Radiolaria occur in a variety of lithologies in the Osa Mélange. Ribbon-bedded red cherts associated with basalts in seamount-derived blocks (samples DJ01-114 and DJ01-141) contain Campanian-Maastrichtian radiolarian assemblages. Samples DJ01-141 occurs on the field in association with large blocks of basalt containing interbeds of pelagic limestones of similar ages.

The San Pedrillo Unit contains an important amount of pelitic hemipelagic to pelagic lithologies that range from originally ribbon-bedded muddy chert to siliceous and tuffaceous mudstones that partly form the mélange matrix. Radiolaria and sponge spicules are locally abundant in all these lithologies. Faunal assemblages indicate in general a late Paleocene-middle Eocene age, in broad agreement with middle Eocene ages from Azéma *et al*. (1983). However, the better preserved samples (DJ01-140 and DJ01-043) restrict the age to the early Eocene.

3.4.2. Larger benthic Foraminifera in the San Pedrillo Unit

Larger benthic foraminifera occur together with other shallow-water benthic bioclasts in limestone clasts-olistoliths and calciturbidites of the San Pedrillo Unit in the NW Osa Peninsula and Caño Island. The well-lithified samples only allowed determination in thin sections, studied in light microscopy and cathodoluminescence. Although there are some compositional variations from one outcrop to another, faunal assemblages are similar and, in general, have a late Eocene age according to larger foraminifera (see also *Azéma et al.* 1983). On the NE and SE coasts of Caño island, redeposited shallow-water material occurs in isolated blocks of calcarenites and calcirudites showing clasts of lime packstone, grainstone and bindstone and grains of basalt, chert, and feldspar (Mora *et al.* 1989). The limestone clasts contain the following bioclasts: articulate coraline algae (dominant), larger foraminifera, smaller planktonic and benthic foraminifera, crinoids, siliceous sponge spicules, bryozoans and green algae. The clasts show stylolitized contacts and several phases of fracturing and vein infill by opal-quartz and then calcite. Although the larger foraminifera found at the studied localities are recrystallized, partly silicified and fractured, we could identify the following assemblage (*Mora et al.* 1989): *Amphistegina grimsdalei*, *Amphistegina lopeztrigoi*, *Amphistegina parvula*, *Asterocyclina* sp., *Discocyclina* sp., *Eoconuloides* sp., *Eofabiania cushmani*, *Eofabiania* sp., *Fabiania cubensis*, *Lepidocyclina* sp., *Linderina* sp., *Nummulites floridensis*, *Pararotalia* sp., *Sphaerogypsina globulus*. This indicates a late Eocene age with reworking of some middle Eocene forms.

At Punta Campanario (Fig. 6) limestone clasts occur in a variety of debris flow breccias with a tuffitic mudstone to greywacke matrix (Plate 2). Lithoclasts are calcarenites to calcirudites with volcanic content (Plate 2). Samples DB02-024/026 contain well-preserved, but abraded and sometimes broken Larger Foraminifera that are clearly size sorted (in general forms of less than 4mm size). The assemblages include *Operculinoides* sp., small globulose and small flat forms of *Nummulites* sp. such as: *Nummulites dia, Nummulites cf. macquiaveri*, *Orthophragmina* sp., neolepidine *Lepidocyclina* sp., such as *Lepidocyclina chaperi*, *Lepidocyclina* cf. *antillea, Lepidocyclina canellei, Lepidocyclina pustulosa, Sphaerogypsina globules*, *Amphistegina* sp., *Discocyclina* sp., *Pseudophragmina* sp. Most of these forms indicate middle to late Eocene age; some are restricted to late Eocene.

One sample yielded Late Cretaceous shallow water bioclasts. A spiculite from Agujitas (sample DJ01-019) contains poorly preserved *Pseudorbitoides sp.*, *Sulcoperculina sp.*, *Omphalocyclus sp.*, this material is reworked from a probable Late Cretaceous carbonate bank.

3.4.3. Planktonic Foraminifera in the San Pedrillo Unit

Planktonic foraminifera occur in pelagic limestones mostly associated with basaltic olistoliths. Rocks were studied in polished thin sections by light- and cathodoluminescence microscopy. No isolated forms could be obtained, which leaves the specific determinations somewhat uncertain. The ages range from Campanian-Maastrichtian for a majority of blocks to middle Eocene. Similar ages and sedimentary facies are observed in the pelagic limestones of the Vaquedano Unit (Di Marco 1994; Buchs 2003; this study).

4. The Osa Igneous Complex: discussion and interpretation

4.1. A well-organized highly-composite complex

The Osa Igneous Complex is an imbricate of several rock bodies, recognized on the basis of converging lines of observation: (1) pillow lavas are frequently overturned, (2) strong deformation is locally observed that is very likely related to thrust zones, (3) small-scale (<100m) tectonic lenses clearly occur in some units, (4) biochronologic dating provides late Cretaceous to middle Eocene ages of formation for the igneous rocks and (5) geochemistry points toward a large diversity of mostly intraplate, oceanic origins for the igneous rocks (Fig. 4, Buchs 2008).

Although geochemical and age characteristics are strongly heterogeneous at a scale of the complex (*i.e.* tens of km), detailed characterization of the volcano-sedimentary sequences allowed us to recognize five units that define composite rock belts with similar trench-parallel strikes (Fig. 1b). This arrangement and the presence of various intra-oceanic volcanic rocks are typical of accretionary complexes, or accretionary belts (*e.g.* Dickinson 2008). This suggests the Osa Igneous Complex is an accretionary complex made up of several pieces of accreted igneous sequences, which may have initially pertained to several oceanic islands, seamounts, and oceanic plateaus. Absence of significant amounts of pelagic sediments and/or geochemical affinities of the igneous rocks (Hauff *et al.* 2000, Buchs 2008) indicates the Osa Igneous Complex does not comprise "normal", unthickened oceanic crust (*i.e.* MORB sensu stricto).

4.2. Size and arrangement of accreted rock bodies

Due to a lack of extended exposures and limited occurrences of stratigraphic markers, size of imbricated rock bodies and imbrication mechanisms are poorly constrained. However, contrary to amalgamated terranes of North America (*e.g.* Coney 1989), indication of large strike-slip motion has not been observed in the Osa Peninsula. Large fault zones associated to left-lateral strike-slip motion were recognized in western Panama (Kolarsky & Mann 1995), but no precise quantification of possible displacement was provided. The geology of western Panama does not exhibit evidence of large strike-slip displacements (Buchs *et al.* submitted). Hence, it seems the Osa Igneous Complex provides opportunity to recognize accretion-related structures that normally tend to be altered during later tectonics.

With the exception of the Ganado Unit, large igneous intrusive rocks are lacking in the Osa Igneous Complex. This probably indicates the imbricated rock bodies represent superficial sequences of volcanic edifices, probably originally restricted in the few uppermost km or hundred of meters of the crust. Dolerites and gabbroic rocks of the Ganado Unit are devoid of significant crystal accumulations and were possibly originally located in superficial levels of one or several volcanic edifice(s). As a consequence, we propose an estimate of less than 4 km for the maximal thickness of the imbricated, dismembered rock bodies forming the Osa Igneous Complex.

In the Vaquenano and Güerra units, distinct geochemical affinities, volcano-sedimentary sequences and biochronologic ages are encountered at scales ~500 m. Thus, these units comprise thin, probably ~250 m tick, accreted sequences. The units are characterized by a high content of accreted sediments (~20%) compared to other units of the Osa Igneous Complex. Hence, we propose the Vaquedano and Güerra units are made up of several seamount slices accreted by scrapping off thin layers of "strong" igneous rocks along "weak" sedimentary layers. In absence of sediment interbeds in the volcanic sequences of subducting seamounts several km-thick piles of igneous rocks may detach and accrete to the overriding plate, as notably imaged in Japan (Park *et al.* 1999). Such a mechanism may have been effective for the Ganado Unit, Riyito Unit and Inner Osa Igneous Complex. Hence, several km (<4 km) thick piles of rock probably compose these units. Relatively good preservation of the rocks bodies and frequent occurrences of overturned pillow lavas may be related to an emplacement by duplexing or fault propagation folding at large scale. However, detailed structural observations are still required to better constrain this hypothesis.

Three major sutures bound the Inner and Outer Osa Igneous Complexes and mark the contact with the island arc (Golfito Complex) and the Osa Mélange (Fig. 3B-B'). These sutures correlate to the landscape morphology (incised valleys and slope variations over broad areas). They are interpreted here as ancient tectonic contacts conducting recent and/or active faulting. Although the sutures are well seen in on-land exposures they are not visible on nearby seismic profile P 1600 (Kolarsky *et al.* 1995a) (Fig. 3A-A'). Proximity between on-land exposures and profile P 1600 (~15-30 km) certainly indicates allochtonous and accreted igneous rocks forming the outer forearc and the San Pedrillo Unit is also present northwest of the Osa Peninsula. Failure of offshore seismic imaging probably results from small velocity and structural contrasts between the units. Location of possibly-active fault zones along the edge of the units indicates the compressive regime associated to the incoming of the Cocos Ridge (*e.g.* Kolarsky *et al.* 1995a; Morell *et al.* 2008) or, more generally, topographic irregularities on the top of the oceanic floor, develop faulting preferentially along weaknesses in the crust, such as ancient sutures in the forearc basement. The landscape morphology in the Osa Peninsula is representative of an overthrust of landward units onto seaward units. Although formation of fault-bounded blocks in the outermost S Costa Rican forearc is triggered by vertical tectonics associated the topography of the subducting plate (*e.g.* Sak *et al.* 2004, in press, Vannucchi *et al.* 2006), this mechanism alone does not account for the existence of recent and/or active large inverse fault zones along unit boundaries. Hence, similarly to deformation patterns of the S Costa Rican innermost forearc (Fila Costeña), we suggest here that block faulting is related to compressive stress in the outermost forearc, in response to the subducting Cocos Ridge. Inverse faulting preferentially develop along weak crustal zones. In the Osa Peninsula these zones correspond to boundaries between accreted units and, hence, to palaeo-décollements exposed in the forearc basement. A direct implication of these observations is that recognition of fault-bounded blocks by remote imaging is a very useful tool for geological mapping of the S Central American forearc, because faulting in the igneous basement tends to develop along unit boundaries.

4.3. Argon loss induced by tectonics?

In the Inner Osa Igneous Complex ages of lava formation are given by sediments and $^{40}Ar/^{39}Ar$ dates. Coniacian-Santonian (~89-84 Ma) siliceous pelagic sediments are interbedded with the lavas in several places. Two basalts from the Burica Peninsula and Isla Violín gave dissimilar $^{40}Ar/^{39}Ar$ ages of 54.5 ± 1.5 Ma (late Paleocene-early Eocene) and 64.2 ± 1.1 Ma (early Paleocene), respectively (total fusion on whole rock matrix) (Hoernle *et al.* 2002).

It may be considered that occurrence of basalts formed at different times is not a big issue in a composite complex, but it is troubling that (1) there is no overlap between the radiometric and biochrononologic ages and (2) the radiometric method provides the youngest ages. Furthermore, the 54.5 ± 1.5 Ma (late Paleocene-early Eocene) intra-oceanic basalt sampled in the

Burica Peninsula is stratigraphically covered by the ~56-59 Ma (late Paleocene) arc-derived sediments of the Pavones Formation. Older ages of the overlap sediments indicate that the $^{40}Ar/^{39}Ar$ age does not represent an age of formation. As a consequence, the basalt certainly experienced Ar loss after its formation. This loss may be related to syn- or post-accretion tectonics and deformation. Hence, it appears clearly the age of formation of the lava is more efficiently defined by the biochronologic dates in the Osa Igneous Complex.

Fig. 9 illustrates a comparison between radiometric ages of the igneous rocks and ages of corresponding units based on paleontological data. Although there is a large variability in the biochronologic ages due to heterogeneity of the unit and/or poor age accuracy of the fossil assemblages, many samples from the Inner Osa Igneous Complex and Golfito Complex (considered here solely for the Ar-loss issue) have lower radiometric than biochronologic ages. Moreover, we note on Fig. 9 that mean ages are globally shifted to the left of a line of similar biochronologic and radiometric ages. This indicates that there is a tendency of Ar loss among dated samples. In the view of the geological heterogeneity and tendency of Ar loss in the dated samples, it appears that good agreement between $^{40}Ar/^{39}Ar$ ages and the range of K/Ar ages as pointed out by Hoernle & Hauff (2007) is most likely a result of randomness rather than a convergence of radiometric ages obtained by different methods.

Interestingly, lowest radiometric ages point toward a ~40 Ma (middle Eocene) age (Fig. 9). This age corresponds broadly to the age of accretion of the Outer Osa Igneous Complex (see below), potentially indicating that massive Ar loss from the igneous rocks may occur in response to increased tectonics along the margin, such as that induced by seamount accretion.

In the light of preceding remarks, it appears that $^{40}Ar/^{39}Ar$ or K/Ar ages have to be interpreted with much precaution in the case of the Osa Igneous Complex Hence, we choose here to consider radiometric dates to represent minimal ages of formation only. Biochronologic and radiometric discrepancies pointed out in this study further raise an important interrogation about the interpretation of ages determined by $^{40}Ar/^{39}Ar$ dating for other (low-K) basaltic samples reported for south Central America (*e.g.* Sinton *et al.* 1997; Hauff *et al.* 2000; Hoernle *et al.* 2002, 2004). Thes ages should be used with a lot of caution and controlled by stratigraphic data.

4.4. Origin and Significance of the Units

The units forming the Osa Igneous Complex consist of mostly unmetamorphosed accreted fragments of igneous rocks that range from a few hundred of meters to several km in size. In this section, we make a summary of the units and discuss their probable origin and implication in terms of accretionary processes.

One of the most intriguing features of the Osa Igneous Complex is the low occurrence of intercalated arc-derived or continental sediments. Such detrital deposits are very commonly observed in other accretionary complexes (*e.g.* Isozaki *et al.* 1990; Dickinson 2008). Furthermore, with the exception of the Güerra Unit, the Osa Igneous Complex has apparently not suffered metamorphism (greenschist facies and higher) while metamorphism is very commonly observed in accreted rocks (*e.g.* Maruyama & Liou 1989; Isozaki *et al.* 1990; Dickinson 2008). Accretionary complexes predominantly composed of poorly metamorphosed igneous rocks are scarce and examples from the Alexander Island in Antarctica (Doubleday *et al.* 1994a, b) and Northern California Coast Ranges (Shervais *et al.* 2005) show that greenschists may locally represent a significant portion of the accreted material. Indeed, to our knowledge, oceanic terranes of the Solomon Islands (*e.g.* Petterson *et al.* 1997, 1999) are the sole known occurrence of an accretionary complex similar to the Osa Igneous Complex, *i.e.* essentially composed of oceanic sequences devoid of significant metamorphism and trench-fill sediments. Below, we point out other similarities between these two complexes.

4.4.1. The Inner Osa Igneous Complex

The Inner Osa Igneous Complex predominantly comprises Coniacian-Santonian (~89-84 Ma) tholeiitic basalts with plateau-like, oceanic intraplate affinities. Minor NMORB-like and OIB-like igneous rocks occur as sills, small intrusions and, possibly, interlayered lava flows. The volcano-sedimentary sequences are almost devoid of detrital material and, hence, indicative of submarine volcanism. Rare, thin interbeds of siliceous pelagic sediments point toward high effusive rates for the lavas. Absence of carbonate banks indicates the lavas probably formed below the CCD. Detrital sediments of the Esperanza Formation are interpreted to be a product of submarine erosion of the plateau-like lavas prior to the accretion. Consistency of rocks forming the Inner Osa Igneous Complex tends to indicate that they initially belonged to a unique volcanic edifice, most probably an oceanic plateau.

The Azuero Plateau (Azuero Complex, W Panama) is made up of tholeiitic, plateau-like basalts and minor intercalations of siliceous pelagic sediments. It represents a Coniacian-early Santonian (~89-85 Ma) oceanic plateau that forms the arc basement (Buchs *et al.* submitted). On this basis, it appears the Inner Osa Igneous Complex and Azuero Plateau are highly similar and could be considered to have the same origin. This interpretation has to be discarded because: (1) dissimilarities exist in terms of sedimentary facies andfaunal assemblages between the two units, (2) the Inner Osa Igneous Complex contains NMORB-like and OIB-like igneous rocks not observed yet in the Azuero Plateau, (3) lavas from both units have dissimilar ranges of Mg# (Buchs 2008) and (4) proto-arc igneous rocks crosscut the Azuero Plateau, but have not been observed in the Osa Igneous Complex. Absence of proto-arc dykes in the Inner Osa Igneous Complex which are frequently seen in the Azuero Plateau is a key feature that points toward an allochthonous, Pacific origin for the Inner Osa Igneous Complex. Hence, we propose here the sequences of the Inner Osa Igneous Complex were part of a Pacific oceanic plateau distinct from the CLIP, which formed prior arc initiation in South Central America and was later accreted to the South Central American Arc and CLIP-related basement.

It is important to note that despite striking geochemical and age similarities between the Azuero Plateau and Inner Osa Igneous Complex, the former is strictly part of the CLIP whereas the later is exotic and unrelated to the CLIP. Hence, it appears that systematic association of Central American exposures of oceanic plateau with the CLIP on the basis of geochemistry and radiometric dating only (*e.g.* Sinton *et al.* 1998) is inappropriate. Our results suggest possible genetic links of plateau-like igneous complexes with the CLIP should be carefully constrained by tectono-stratigraphy and field observations.

The Malaita accretionary prism (Solomon Islands), known to have formed by accretion of the subducting Ontong-Java Plateau (Petterson *et al.* 1999; Mann & Taira 2004; Phinney *et al.* 2004; Taira *et al.* 2004), shares many similarities with the Inner Osa Igneous Complex: (1) accreted rocks are in a very-low metamorphic facies (Petterson *et al.* 1997), (2) occurrences of trench-fill deposits lack (Petterson *et al.* 1997), (3) sequences of the Malaita Volcanic Group (Malaita Island) contain predominantly igneous rocks with plateau affinities and minor interbeds of siliceous sediments (Petterson *et al.* 1997), (4) sequences partly overturned during accretion and development of fault-propagation folds (Petterson *et al.* 1997; Phinney *et al.* 2004) and (5) the Makira Terrane (Makira Island) contains igneous rocks having NMORB signatures interbedded with plateau igneous rocks (Petterson *et al.* 1999). These similarities are another argument for an accreted oceanic plateau origin for the Inner Osa Igneous Complex. Thick (900-1770 m) pelagic limestones observed on the top of the Malaita Volcanic Group (*e.g.* Petterson *et al.* 1995) have no apparent equivalent in the Inner Osa Igneous Complex. We interpret this dissimilarity as a possible consequence of (1) distinct travel times of the two oceanic plateaus on the oceanic floor before their accretion (*i.e.* < 25 Ma for the Inner Osa Igneous Complex (see Chapter 4.5) and ~94-105 Ma for the Ontong-Java Plateau (Petterson *et al.* 1999, and references therein)), which resulted in few occurrences and preservation of calcareous sedimentary covers in the Inner Osa Igneous Complex, and/or (2) summital areas of the Inner Osa Igneous oceanic plateau were below the CCD, pointing toward a lower crustal thickness for the Inner Osa Igneous plateau or distinct paleo-oceanographic conditions.

4.4.2. The Güerra Unit

The Güerra Unit is characterized by the highest metamorphic and deformation grades observed in the Osa Igneous Complex and Osa Mélange. It marks the contact between the Inner and Outer Osa Igneous Complexes and comprises various rock bodies, similar to the Riyito and Vaquedano units in terms of igneous geochemistry and sediment facies. The Güerra Unit is exposed along the Outer Osa Igneous Complex but is apparently lacking along the contact between the Outer Osa Igneous Complex and the San Pedrillo Unit (Fig. 2b). This geometrical arrangement and compositional similarities with some units of the Outer Osa Igneous Complex indicate that the Güerra Unit formed after the formation of the Inner Osa Igneous Complex and prior to the emplacement of the Outer Osa Igneous Complex. Along-strike disappearance of the unit may be an artefact due to poor exposures in southern and northern Osa or linked to tectonic erosion at some places along the margin, prior to the accretion of the San Pedrillo Unit. Compositional heterogeneity of the Güerra Unit indicates it was likely triggered by low rates of accretion and several seamount subductions before the emplacement of the Vaquedano, Ganado and Riyito Units. In this interpretation, the Güerra Unit remained close to the décollement zone for a relatively long time, potentially recording some of the processes that occur at the interface between the overriding and subduction plates. As suggested in the case of sediment underplating (Moore 1989), long duration of residence close to the décollement may result in strong deformation of accreted material, similar to that of the Güerra Unit. Deformation and/or fluid flows through the unit may have been a source of metamorphic catalysis, in a similar way than formation of metabasalts in the Franciscan complex (*e.g.* Nelson 1995).

4.4.3. The Ganado Unit

The Ganado Unit is composed of Coniacian-Santonian plateau-like and NMORB-like tholeiites emplaced in an oceanic intraplate setting. The plateau-like lavas have lower Nb/Y ratios than similar rocks of the Inner Osa Igneous Complex, indicating that these two units have dissimilar origins (Buchs 2008). The Ganado Unit may represent a large fragment of accreted seamount that originally developed in submarine conditions on the Pacific Plate. The occurrence of large intrusive rocks in the unit likely indicates that the seamount underwent a severe dismemberment in the vicinity of the trench as a response to slab flexuration (*e.g.* Kobayashi *et al.* 1987) and/or during the accretion due to coupling between the overriding and subducting plates. Dismemberment of the seamount in the trench environment may have caused a removal of pelagic sediments initially capping the edifice, presently lacking in the unit.

4.4.4. The Riyito Unit

The Riyito Unit is mostly composed of Paleocene or older (?) highly-depleted tholeiites. It represents an assemblage of various seamount fragments. Peculiar geochemical affinities indicate these seamounts were generated very close to a mid-ocean ridge (Buchs 2008). Although the top of the seamounts may have reach relatively shallow water, allowing formation of highly-vesiculated hyaloclastite, all accreted lavas and detrital material issued from the erosion of the seamounts were emplaced in submarine conditions. Similarly to the Ganado Unit, pelagic sediments deposited on the top of the seamounts before their arrival at the subduction zone may have been removed close to the trench through gravitational collapsing.

4.4.5. The Vaquedano Unit

The Vaquedano Unit principally comprises Campanian to Eocene alkali-transitional basalts with OIB-like signatures. These igneous rocks are an example of igneous rocks generally regarded as typical "Oceanic Island Basalts". Geochemical and age variations indicate the unit is composed of an imbricate of relatively thin (<250 m) volcano-sedimentary sequences with distinct origins. The unit is devoid of shallow-water limestones, showing the accreted rock bodies initially formed in submarine environments.

Interbeds of pelagic limestones are common among the lavas of the Vaquedano Unit. Alkaline igneous rocks and frequent sedimentary intercalations indicate low eruption rates, generally associated with the latest stage of eruption of large oceanic intraplate volcanoes (*e.g.* Clague & Dalrymple 1987). Alternatively some seamounts of the Vaquedano Unit were possibly small edifices, which never experienced intense volcanism. In both cases, the Vaquedano Unit comprises superficial layers of seamounts peeled off at shallow-level during subduction.

Important differences exist between the Vaquedano Unit and the Riyito Unit, Ganado Unit and Inner Osa Igneous Complex: (1) accreted seamount fragments are much smaller in the Vaquedano Unit, (2) detachment of rock bodies was easier in the Vaquedano Unit,due to the occurrence of weak layers in the superficial parts of the subducting seamounts, (3) the Vaquedano Unit has more heterogeneous geochemical affinities and (4) ages of the accreted material spans a longer period of time (~40 Ma). External position of the Vaquedano Unit (*i.e.* in contact with the Osa Mélange) may be attributed to an emplacement during the latest stage of growth of the Osa Igneous Complex. These observations tend to indicate that the Vaquedano Unit has a particular significance in terms of accretionary processes. We propose this unit marks a transition between two subduction regimes: (1) a regime characterized by strong coupling between overriding and underlying plates and accretion of thick/large rock bodies proceeding from subducting seamounts (Ganado and Riyito units) and (2) a regime characterized by a lower coupling and/or an absence of large seamount subduction leading to little accretion or tectonic erosion. Similarities in the size of accreted rock bodies and composition between the Vaquedano and Güerra Units arise very likely from the transitional character of these two units in terms of subduction regime. We suggest the Güerra Unit marks a transition from little seamount accretion to seamount accretion and the Vaquedano Unit from seamount accretion to little seamount accretion (see also below). The Vaquedano Unit has remained mostly undeformed and poorly metamorphosed in comparison to the Güerra Unit. This may be due to a rapid emplacement of the Osa Mélange on the edge of the Vaquedano Unit and to a shorter time of residence of the Vaquedano Unit in the vicinity of the décollement relatively to the Güerra Unit.

4.5. Construction of the Osa Igneous Complex

Our model for the construction of the Osa Igneous Complex is principally constrained by the tectonostratigraphy of the area (Fig. 10), assuming that the complex did not suffer from post-accretion reorganisation due to along-strike displacements. There are several regional, stratigraphic and structural aspects that have been taken into account to constrain the model: (1) accretion may have occurred since the late Campanian only (~73-70 Ma), after the initiation of the subduction in southern Central America (Buchs *et al.* submitted), (2) the oldest possible age of accretion of a volcano-sedimentary sequence is defined by the youngest age of formation of the sequence, (3) units in external (seaward) position accreted after units in internal (landward) position, (4) overlap sequences (*i.e.* arc-derived sediments unconformably resting on accreted rocks) define a minimal age of accretion of underlying accreted rocks, (5) tectonic erosion may possibly occur between periods of accretion, and (6) deformed, metamorphosed volcano-sedimentary sequences remained longer in the vicinity of the décollement than undeformed, unmetamorphosed volcano-sedimentary sequences. Growth of the margin by successive stacks of rock bodies is well documented in the Osa area by a chiefly progressive decline of ages toward the trench (Fig. 10).

Construction of the Osa Igneous Complex may be summarized as follows. Subsequent to subduction initiation along the southwestern Caribbean Plate in the late Campanian (event 1 on Fig. 10), portions of arc basement and proto-arc were removed from the margin by subduction erosion. This resulted in progressive migration of the trench toward the Caribbean. Due to this erosion the Golfito Complex was located close to the trench in the early Paleocene and sediments proceeding from the arc were entirely subducted (Fig. 11a). In the early-middle Paleocene the Inner Osa Igneous Complex formed by partial accretion of a subducting oceanic plateau (Fig. 11b, event 2 on Fig. 10). Subsequent to emplacement of the Inner Osa Igneous Complex, possible tectonic erosion and/or subduction of the oceanic plateau caused the outer margin to subside, allowing deposition of arc-derived hemipelagic sediments of the late Paleocene Pavones Formation (Fig. 11b). From the late Paleocene to the early Eocene, the subduction regime was characterized by low rates of superficial accretion of small seamounts that led to the formation of the Güerra Unit and continuous deposition of the Pavones Formation on the forearc slope (Fig. 11c). In the middle Eocene, a group of late Cretaceous-Paleocene seamounts entered the subduction zone and accreted, resulting in the formation of the Ganado and Riyito units (Fig. 11d, event 3 on Fig. 10).Seamount accretion squeezed the previously-formed Güerra Unit between the Inner Osa Igneous Complex and newly-accreted Ganado and Riyito units, preserving it from subsequent tectonic erosion. This event may have been recorded in the Pavones Formation by deposition of the limestone boulders found in the Quebrada Piedra Azul (Di Marco *et al.* 1995) (Fig. 10). The area comprising the Golfito Complex was possibly uplifted, partly eroded and subsided, leading to subsequent deposition of peri-platform deposits of the Monita Unit (Fig. 10, Buchs *et al.* submitted). After this event, the subduction regime was again characterized by low rates of accretion with possible tectonic erosion that led to the construction of the Vaquedano Unit and removal of some portions of the margin (Fig. 11e).

In summary, we observe the construction of the Osa Igneous Complex by multiple events of high-rate accretion alternating with low-rate accretion and/or tectonic erosion. Although this is broadly similar to other well-studied convergent margins (*e.g.* North America: Byrne & Fisher 1987; Dickinson 2008; Japan: Isozaki *et al.* 1990) the Osa Igneous Complex is characterized by pulses of high-rate accretion, or episodic accretionary events, that are associated with the emplacement of fragments of an oceanic plateau and seamounts. Such events may be facilitated by incoming of large topographic highs into the subduction zone and, possibly, regional tectonic changes in the middle Eocene that resulted in a stronger coupling between the overriding and subducting plates (Buchs 2008). Arc-derived sediments lack in the Osa Igneous Complex. This indicates the sedimentary supply in the trench remained low or the convergence rate between the overriding and subducting plates was sufficiently high to allow entire subduction of the trench-fill deposits (see discussion on the San Pedrillo Unit below). Whether these characteristics are symptomatic of an erosive or accretionary margin, they are discussed below along with constraints from the Osa Mélange.

5. Construction of the Osa Mélange

5.1. The San Pedrillo Unit: an unusual polygenetic mélange

The San Pedrillo Unit is a complex of lenticular, dismembered sequences composed of variously-clastic sediments (Fig. 7). Although the sediments may contain blocks very similar to portions of the Osa Igneous Complex, some components such as shallow-water limestones, differentiated igneous rocks, ash deposits or finer hemipelagic sediments are clearly lacking in the Osa Igneous Complex. The unit appears to be derived from a volcanic arc. In a thin, ~100 m thick layer along the Osa Igneous Complex, the San Pedrillo Unit tectonically incorporates some material of the igneous complex. Extension of this tectonic incorporation is however very limited in comparison to the size of the San Pedrillo Unit. Hence, in regard to ubiquitous occurrence of sediments forming the San Pedrillo Unit and poor tectonic incorporation of the Osa Igneous Complex at the contact with the mélange, it appears the Osa Mélange was not simply produced by tectonic, or basal erosion of the Osa Igneous Complex as suggested by Meschede *et al.* (1999).

Vannucchi *et al.* (2006, 2007) proposed the rocks forming the San Pedrillo Unit are dominated by basalt, chert, and shallow-water limestone resulting from accretion of seamounts.

In this interpretation, the Osa Mélange is a dismembered unit characterized by a pervasive metamorphism (partly in greenschist facies) that formed by accretion at depth of a "classic sequence of oceanic crust". According to the same interpretation the material forming the San Pedrillo Unit consists of uppermost crustal sequences initially part of a "seamount system" that accreted to form the Osa Igneous Complex (Vannucchi *et al.* 2006, p. 16, Fig. 14). This interpretation is inconsistent with our results for several reasons. Lithologies ofthe San Pedrillo Unit were studied in detail in the field during more than two months (Buchs & Stucki 2001) (Fig. 5) and were further constrained by microscope observation of 134 samples. Our mapping shows the San Pedrillo Unit comprises detrital sediment that incorporates various amounts of clasts ranging from grains to large boulders. This is atypical in classic sequences of Pacific oceanic crust. Furthermore, rocks forming the San Pedrillo Unit are not dominated by basalt, chert and shallow-water limestones but by fine-grain detrital sediments and olistostromic deposits (Fig. 6). A significant portion of the material forming the San Pedrillo Unit proceeded from a volcanic arc. Arc-related and seamount-related olistoliths sedimentarily embedded in the same debris flow deposits are observed throughout the San Pedrillo Unit, indicating the mélange is not a product of the dismemberment/erosion of the Osa Igneous Complex only. The Osa Igneous Complex is not a "seamount system" accreted at the same time of the San Pedrillo Unit but is a composite accretionary complex that developed between the early-middle Paleocene and middle Eocene. Hence, accretion of the bulk of the Osa Igneous Complex cannot have triggered the formation of the San Pedrillo Unit. Although some deformed rocks are green due the presence secondary chlorite, we have not observed metamorphosed rocks in the greenschist facies. Hence, it seems the San Pedrillo Unit remained at relatively shallow depth during its formation.

We propose here the occurrence of highly deformed sedimentary deposits throughout the San Pedrillo Unit is representative of a polygenetic mélange, with a block-in-matrix texture primarily controlled by clastic sedimentation and subsequently deformed during accretion. Numerous subduction mélanges around the world are characterized by hard metamorphic blocks embedded in a weaker metamorphosed matrix generally made up of shales or serpentinite (*e.g.* in the: Franciscan Complex,Dickinson 2008, and references therein; Kodiak Convergent Margin,Byrne & Fisher 1987; Japanese convergent margin,Isosaki *et al.* 1990; Alexander Island of Antartica,Doubleday *et al.* 1994a, 1994b; Lichi Mélange of Taiwan, Chang *et al.* 2000 and Burma-Java Subduction Complex,Pal *et al.* 2003). Unlike these mélanges, the San Pedrillo Unit is predominantly composed of unmetamorphosed hard blocks embedded in an unmetamorphosed hard matrix. This specificity of the San Pedrillo Unit with respect to other mélanges worldwide is further discussed in the following sections.

5.2. The sedimentary record in the San Pedrillo Unit

5.2.1. Origins of the sediments

We have shown the San Pedrillo Unit is composed of three main types of lithologies that form the bulk of the inner Osa Mélange: (1) sedimentary deposits containing shallow-water limestones, (2) debris flow deposits dominated by igneous olistoliths and (3) fine-grain detrital sediments (Fig. 6). All these lithologies are characterized by a detritic, clastic component that range from grains to large boulders embedded within a finer sedimentary matrix. On the basis of composition of the matrix and clasts, three main, distinct sources are recognized for the material composing the San Pedrillo Unit: (1) a palaeo-Osa Igneous Complex, (2) a subaerial volcanic arc and (3) pelagic-hemipelagic sediments.

Striking similarities exist between the basaltic olistoliths embedded in the sedimentary matrix of the San Pedrillo Unit and the volcano-sedimentary sequences of the Osa Igneous Complex. These similarities are well-defined in terms of geochemistry, age (late Cretaceous to middle Eocene), faunal assemblages encountered in the sediments associated with the lava flows and facies of the sediments. Although the Osa Igneous Complex is a composite unit made up of a wide range of late Cretaceous to middle Eocene igneous and sedimentary rocks, some of these rocks have very unusual geochemical affinities or contain very particular fossils such as Crustacean microcoprolites. Indeed, similarities between the San Pedrillo basaltic olistoliths and the Osa Igneous Complex are very specific in some cases. Hence, the bulk of the basaltic olistoliths encountered in the San Pedrillo Unit were very likely originally part of the palaeo-Osa Igneous Complex. The sedimentary mode of emplacement of the olistoliths is well constrained by the sedimentary fabric recognized throughout the San Pedrillo Unit and points toward mass wasting along the margin by the time of formation of the Osa Mélange. Parts of the finer detrital material of the San Pedrillo Unit (*e.g.* unidentifiable rock fragments and crystals) may also be sedimentarily related to the palaeo-Osa Igneous Complex.

A subaerial volcanic arc is believed to have provided significant parts of the material forming the San Pedrillo Unit. Arc-derived material consists of fragments (grains to large boulders) of felsic volcanic rocks and reworked and interlayered late Eocene shallow-water limestones, as well as dark ashy tuffites in the mélange matrix. The association of dark ashy tuffites with fragments of shallow-water limestones form one of the three principal lithologic associations recognized in the San Pedrillo Unit, described here as the "sedimentary deposits containing shallow-water limestones" (Fig. 6). This recurrent rock association further constrain the origin of the shallow-water limestones to an arc environment. The felsic and basaltic olistoliths are locally associated within the same debris flow deposits, indicating that these rocks proceeded from a similar paleo-environment. This is another argument pointing toward a paleo-Osa Igneous Complex for the bulk of the basaltic olistoliths.

The pelagic-hemipelagic sediments consist of undated siliceous-calcareous hemipelagic oozes intercalated with fine-grained detrital sediments and deformed lenses of early Eocene radiolarian cherts. We relate the hemipelagic oozes to background sedimentation commonly observed in near-trench environments (Carter 1979). The detritic fraction variously expressed in these sediments has a composition pointing toward a predominant basaltic source and a minor differentiated source that may represent an erosion of the palaeo-Osa Igneous Complex and a subaerial volcanic arc, respectively. The early Eocene radiolarian cherts are devoid of arc-derived material and, thus, may have originated in a pelagic environment, presumably on the slope of a seamount or on the ocean floor. Scarce igneous olistoliths associated to Campanian-Maastrichtian radiolarites (not found yet in the Osa Igneous Complex), may have been tectonically incorporated from subducting seamounts into the San Pedrillo Unit in a process similar to that proposed by Okamura (1991) for some mélanges in the Mino Terrane (Japan).

5.2.2. Emplacement of the sediments into the trench

The sedimentary record preserved in the San Pedrillo Unit is a highly valuable source of information, allowing a better understanding of the southern Costa Rican margin at the time of the mélange formation (Fig. 12).

Sediments of the San Pedrillo Unit are indicative of a significant detrital input variously expressed among the lithologies, which culminates in the debris flow deposits and the sedimentary deposits containing shallow-water limestones. Large boulders of igneous rocks derived from both the paleo-Osa Igneous Complex and a subaerial volcanic arc were embedded together in thick debris flow layers prior to accretion of the mélange. Hence, the San Pedrillo Unit was partly produced by removal of large portions of the forearc area through mass wasting. At the time of deposition of the sediments, the palaeo-Osa Igneous Complex was presumably undergoing a strong uplift that led to disaggregation of unstable slopes by gravity. The material was gravitationally driven to the trench, partly incorporating arc-derived sediments transiting through by-passes, and ultimately formed thick pile of sediments close to the subduction zone. The carbonate material was displaced or reworked either grain by grain or as limestone clasts and gravitationally transported together with ashy tuffites toward the trench. Grain by grain displacement/reworking, possibly triggered by storm events or earthquakes, resulted in calci-turbidites relatively poor in ashy material owing to hydrodynamic winnowing. Limestone clast reworking occurred together with the mobilization of abundant arc-derived volcanic material, possibly triggered by earthquakes and/or slope instabilities and resulted in debris flows with a variable amount of carbonates.

Fine-grain detrital sediments and hemipelagic siliceous limestones deposited on the forearc slope and in the vicinity of the trench during periods of lower detrital input. In this view, the hemipelagic limestones represent the background sedimentation in the forearc environment that was sporadically affected by catastrophic events leading to deposition of significant amounts of detrital material (*e.g.* Underwood & Bachman 1982). Hence, the sedimentary fabric of the San Pedrillo Unit, characterized by layers of various clast size (*i.e.* grains to large boulders) (Fig. 5, 3.5), may be regarded as a consequence of variations in degree of clastic input in the trench environment.

The age of deposition of the sediments of the San Pedrillo Unit in the trench is constrained to the late Eocene by the limestone beds containing shallow-water fauna. This age is in agreement with the age of the youngest rocks of the Cabo Matapalo Unit (middle Miocene), which were accreted subsequently to the San Pedrillo Unit. This age is also in relatively good agreement with the stratigraphy of the forearc area inboard of the Osa Peninsula that contains >1000 m-thick arc-derived turbidites deposited during the Oligocene-early Miocene (Henningsen 1963). Occurrence of these deposits points toward high rates of clastic sediment production close to the arc at this time, which has remained preserved from erosion.

5.3. Deformation

Vannucchi *et al.* (2006) provided a detailed structural analysis of the San Pedrillo Unit and outlined four tectonic phases that occurred prior to the exhumation. According to their results and our observations, the tectonic record indicates the clastic sediments were not lithified at the beginning of subduction. During the first stages of underthrusting, the sediments progressively lost their fluid content and deformation changed from an underthrust regime to underplating and shortening within the upper plate wedge. After the constitution of the San Pedrillo Unit and prior to its uplift, new tectonic events occurred, possibly in response to repeated collisions of seamounts with the margin.

Shear planes presumably related to the SP-D_3 and SP-D_4 phases (Vannucchi *et al.* 2006), which may correspond to an underplating regime, are defined by the precipitation of calcite, zeolites and quartz minerals. They crosscut the stratification and trend NE-SW with steep dips and, in conjunction with the orientations of stratification, they delimit lenses of consistent sedimentary facies (Fig. 7). Calcite, zeolites and quartz veins are ubiquitously encountered within the San Pedrillo Unit. This indicates pervasive fluid circulation took place during the first stages of the tectonic history of the mélange (SP-D_1), as previously suggested by Vannucchi *et al.* (2006). The density of the veins locally increases and may exceed 50% in the formations. It is thought to be associated with hydrofracturation. Preferential fluid drainage is indicated by high density of vein networks and occurred within areas dominated by igneous and calcareous olistoliths. These observations likely indicate fluids associated to poorly lithified sediments plaid a predominant role during accretion of the San Pedrillo Unit.

5.4. Accretion of the San Pedrillo Unit

5.4.1. An accretion primarily triggered by catastrophic sediment supply

The presence of debris flow deposits containing large boulders of igneous rocks in the San Pedrillo Unit has to be considered as a record of highly catastrophic events that affected the trench environment in the late Eocene. We propose that a rapid increase of the sediment supply in the trench triggered the formation of the San Pedrillo Unit (Fig. 11f, g).

Cloos & Shreve (1988) first proposed the existence of an inlet, or "subduction channel", at the interface between the subducting and overriding plates. In their model, the geometry of the inlet is temporally linked to the tectonic environment and tends to accommodate the subducting plate morphology, the sedimentary supply and the fluid content of the subducting sediments. A rapid increase of the sediment supply may fill topographic depressions and dramatically increase the sediment pile in the vicinity of the subduction zone. With sufficiently low rates of convergence and/or sufficient sediment supply, trench deposits may outgrow the subducting capacity of the subduction channel and ultimately lead to growth of an accretionary prism (*e.g.* Moore 1989; Le Pichon *et al.* 1993; Lallemand *et al.* 1994). Recent geological evidence from Italy shows the subduction channel at shallow depth may be exposed in uplifted ancient convergent margins (Vannucchi *et al.* 2008).

It is generally considered that convergence between the Farallon and Caribbean Plate was nearly orthogonal in the Eocene (Meschede & Barckhausen 2001; Pindell *et al.* 2005). The rate of convergence may thus have been similar or faster to present day (~10 mm/y, DeMets 2001) so sediments in the trench were driven quickly (most probably in less than 500 ky) into the subduction zone. This is corroborated by the presence of low sediment induration in the San Pedrillo Unit at the onset of deformation (Vannucchi *et al.* 2006). In this context, deposition of large volumes of sediments over a short period of time in the trench provided an excess of material in the subduction zone, which over-filled the subduction channel. The excess sediments accumulated at shallow level, progressively lost fluid content and accreted to form the San Pedrillo Unit. Whereas this kind of process is generally associated to frontal accretion of the sediment (Le Pichon *et al.* 1993; Lallemand *et al.* 1994), structures in the San Pedrillo Unit may indicate the sediments accreted by underplating (Vannucchi *et al.* 2006).

The structural fabric of the NW Osa Mélange indicates massive sediment fluid loss at the beginning of underthrusting, provoking changes in the regime of deformation (Vannucchi *et al.* 2006). Along erosive margins, fluid content within subducting sediments plays an important role in the control of subduction erosion. Fluids released from the subducting plate may increase hydrofracturing of the upper plate and trigger the removal and subduction of lenses of several kilometres in width and length (Ranero & von Huene 2000). High fluid content of subducting sediments tends to prevent accretion and enhance subduction (Cloos & Shreve 1988; Moore, 1989; Seno, 2007, 2008). Thus rapid fluid expulsion likely occurred during underthrusting of the San Pedrillo Unit. Large amount of clastic sediments and low argileous component in the unit likely enhanced the ability of the subducted material to quickly dewater. Fluid expulsion caused a migration of the décollement toward the subducting plate and, consequently, accretion of subducting material. Due to strongly disturbed internal arrangement of the San Pedrillo Unit, it is unclear if this process repeatedly occurred or not to form the unit. For a similar reason it is not possible to know if significant portions of accreted material were removed between possible multiple events of accretion. Nonetheless, the presence of the San Pedrillo Unit indicates overall net accretion in southern Costa Rica during the late Eocene continuing until at least the middle Miocene with the subsequent emplacements of the Cabo Matapalo and Salsipuedes units.

5.4.2. The San Pedrillo Unit: a record of a margin collapse in response to seamount subduction

Large volumes of sediment deposited in the trench and produced by mass wasting along the Costa Rican margin during the late Eocene indicate that significant changes in subduction dynamics took place in the area at that time. This event was likely caused by seamount subduction along the palaeo-Osa Igneous Complex.

Seamount subduction is a common process along many active margins. It has been notably observed along the Nankai Trough (Park *et al.* 1999; Kodaira *et al.* 2000), the New Hebrides Trench (Collot & Fisher 1989), the New Zealand margin (Collot *et al.* 2001) and the Mid American Trench (von Huene *et al.* 1995). Subduction of a seamount is accompanied by a zone of tectonic deformation in the upper plate and a re-entrant in the margin on the steep slope behind the subducting seamount (von Huene *et al.* 1995). This process creates a zone of slope failure that migrates upward and generates the deposition of reworked sediments in the trench area (Dominguez *et al.* 2000; Hühnerbach *et al.* 2005). The amount of material disrupted in the margin by seamount subduction is about four to five times the volume of the subducting seamount, of which about three quarters seems to be recycled downslope, backfilling the scar (Hühnerbach *et al.* 2005). The volume of reworked material of the margin may be even larger, depending on the brittleness of the margin (*e.g.* Collot *et al.* 2001). For example, along the Hikurangi margin (New Zealand), Collot *et al.* (2001) reported the presence of (1) a giant debris avalanche constituted by up to 2 km thick blocky deposits covering an area of ~3400 km^2 and (2) a 65-170 m thick debris flow covering an area of ~8000 km^2 that extends over 100 km from the trench fill. According to these authors, the deposits were generated in response to oblique seamount subduction that removed several thousands km^3 of material from the margin and created an indentation of the slope 65 km landward from the trench. Such present-day observations indicate a seamount subduction may generate large volumes of clastic material redepositing into the trench and forming deposits similar to the sediments of the San Pedrillo Unit. Therefore, we propose the sediments of the San Pedrillo Unit were triggered by the subduction of a seamount (or several seamounts) during the late Eocene. The presence of subducting seamounts along the Central American margin during this period is in good accordance with the presence of accreted seamounts in the Azuero Peninsula (western Panama) (Buchs 2008).

Subducting seamount along the paleo-Osa Igneous Complex in the late Eocene may have possibly enhanced the ability of the San Pedrillo Unit to accrete by underplating at shallow-level, rather than in the greenschist metamorphic facies or by frontal off-scrapping. Sandbox experiments have shown subducting seamounts may trigger temporary migration of the décollement upward (Dominguez *et al.* 2000), thus temporarily and locally increasing the thickness of the subduction channel. Such mechanism may allow partial subduction of sediments in the wake of downing seamounts and underplating at shallow level (Bangs *et al.* 2006) (Fig. 11f). If this mechanism led to the accretion of the San Pedrillo Unit it may indicate the unit formed very rapidly, possibly through a unique event of accretion.

The bulk of the reworked material in the San Pedrillo Unit proceeded from the partial collapse of the upper plate. It remains possible, however, that some igneous and sedimentary blocks were tectonically incorporated into the mélange matrix directly from disaggregating subducting seamounts. If a similar process is involved in the genesis of some mélanges (*e.g.* Okamura, 1991), this was nonetheless an insignificant process in the formation of the San Pedrillo Unit because (1) the fabric is primarily controlled by sedimentary processes and (2) the bulk of the basaltic blocks and associated pelagic sediments proceeded from an older accretionary prism (the palaeo-Osa Igneous Complex). Early Eocene radiolarian cherts sporadically encountered in the mélange as deformed lenses and minor proportion of basaltic olistoliths associated to Campanian-Maastrichtian radiolarites may represent a record of partial tectonic incorporation of subducting seamounts into the San Pedrillo Unit.

5.5. Accretion of the Cabo Matapalo and Salsipuedes units

The Cabo Matapalo and Punta Salsipuedes units constitute the outermost extension of the Osa Mélange, presumably emplaced onto the San Pedrillo Unit by accretion processes (Di Marco 1994; Di Marco *et al.* 1995) (Fig. 2). Review and interpretation of these units is not the aim of this study, but their presence indicates that accretionary processes may have continued until the Miocene, prior to the exhumation of the Osa basement and subsequent deposition of the Charco Azul Group (Fig. 10).

According to Di Marco (1994), the Cabo Matapalo Unit may have formed similarly to the San Pedrillo Unit, whereas the Salsipuedes Unit may represent sediments detached from the subducting plate that accreted onto the Cabo Matapalo Unit. Further stratigraphic, structural and geochemical data are nonetheless required to better constrain these interpretations.

6. The southern Central American margin: erosive or accretionary?

6.1. Erosive and accretionary margins

Since early work by von Huene & Lallemand (1990) it has been widely recognized that convergent margins may be subdivided into two classes, one dominated by accretion and net growth of accretionary prisms and the second characterized by tectonic erosion, absence of accreted material and trench retreat (von Huene & Scholl 1991; Clift & Vannucchi 2004). Each type composes approximatively half of the convergent margins observed at the present time around the world. Distinction between these two types of margins has been initially based on long-term forearc subsidence and associated landward retreat of the trench (von Huene & Lallemand 1990). New contributions have shown erosive or nonaccretionary margins are notably characterized by higher forearc slope angle, higher rate of orthogonal convergence between the descending and overriding plates, and lower rate of sediment delivery into the trench than accretionary margins (Clift & Vannucchi 2004). The higher forearc slope angle in accretionary margins has been attributed to material removal at the base of the overriding plate, causing subsidence and normal faulting of the forearc taper (Ranero & von Huene 2000). Lower rate of trench sediment supply and higher degree of orthogonal convergence between the plates is intrinsically related to the ability of the subduction zone to accommodate and subduct the sedimentary input. Basal erosion of the overriding plate has been attributed to hydrofracturation induced by percolating slab-related fluids (Le Pichon *et al.* 1993; von Huene *et al.* 2004) or abrasion/tunnelling by subducting seamounts and ridges (Clift & Vannucchi 2004, Kukowski & Oncken 2006). It is important to note here that the long term distinction between erosive and accretionary margins has been principally based on the recognition on seismic profiles of the occurrence or non-occurrence of an accretionary prism composed of sedimentary material (von Huene & Scholl 1991, Fig. 3; Clift & Vannucchi 2004, Fig. 1).

The Central American margin is generally considered to be currently nonaccretionary (Ranero & von Huene 2000; Meschede, 2003; Ranero *et al.* 2007). In northern Costa Rica, recent active subduction erosion has been demonstrated on the basis of geophysical studies and drilling that shown that the outer forearc underwent a recent, rapid subsidence associated to normal faulting (Vannucchi *et al.* 2001, 2003). On the other hand, late Cretaceous-Tertiary accretionary complexes are commonly observed along the margin (for review see Denyer *et al.* 2006). This apparent contradiction between present-day observations and the geological record is commonly attributed to a hypothetical recent change of the subduction regime from accretion to erosion (Vannucchi *et al.* 2006). We show below that mechanisms presently observed along the margin are on the contrary in good agreement with the geological record and are actually extremely difficult to interpret in terms of subduction accretion/erosion over long periods of time.

6.2. Hidden accretionary complexes along intra-oceanic subduction systems

We have shown exposed forearc in southern Costa Rica records several accretion events, indicating that the margin developed seaward through episodic growth. The Osa Igneous Complex records two events of significant growth by seamount accretion in the Maastrichtian/early Paleocene with the emplacement of the Inner Osa Igneous Complex and, probably, in the middle Eocene with the emplacement of the Ganado and Riyito units (Figs. 10, 11). The San Pedrillo Unit was emplaced onto the Osa Igneous Complex in the late Eocene subsequently to rapid, large sedimentary supply into the trench possibly in response to seamount subduction. To our knowledge, development of convergent margins over long periods of time (late Cretaceous to middle Eocene) by accretion of mostly igneous rocks has not been observed elsewhere. Whether this is due to observation bias or to a peculiarity of the Costa Rican margin is difficult to assess. It is possible the unusual nature of the Costa Rican margin (an arc built on an oceanic plateau, Buchs *et al.* submitted) has led to unusual accretionary processes between the late Cretaceous and middle Eocene. Alternatively, igneous accretionary complexes may be very common along intra-oceanic convergent margins and only poorly exposed.

While sediment accretion along convergent margins is easily demonstrated by seismic imaging of accreted sediments, seamount accretion as recorded in the Osa Igneous Complex may be difficult to recognize in intra-oceanic subduction systems.Density and velocity contrasts between basaltic terranes and arc-related igneous rocks inboard of accretionary complexes may be very low and reflectors poorly developed in the igneous rocks. Density and velocity contrasts may be particularly low along the Costa Rican margin because the arc basement comprises an oceanic plateau highly similar to accreted volcanic rocks (Buchs *et al.* submitted). Seismic profiles over the seaward extension of the Nicoya Peninsula (Sallarès *et al.* 1999, 2001) failed to image the composite, partly accretionary nature of the area, well documented by on-land, tectonostratigraphic reconstructions (Flores 2003; Bandini *et al.* 2008). Magnetic signatures of upper plate structures investigated between Nicoya and Osa peninsulas point toward a composition of the margin wedge similar to the igneous complex found onshore on the Nicoya Peninsula (Barckhausen *et al.* 1998). However, accreted material exposed in southern Costa Rica on the Osa Peninsula has not been recognized on seismic profiles in close proximity (Kolarsky *et al.* 1995a; Ranero & von Huene 2000) (Fig. 3), although these profiles very likely comprise accreted igneous rocks and mélanges containing igneous olitholiths similar to those expose in the Osa Peninsula.

Observations from Costa Rica show that, along intra-oceanic convergent margins, igneous accretionary complexes may remain unobservable in numerous cases and their occurrence widely underestimated. This raises an important interrogation about the validity of the consensual model of erosive margin (*e.g.* von Huene & Scholl 1991; Clift & Vannucchi 2004), because unidentified (seamount) accretion may have occurred along many intra-oceanic convergent margins devoid of accreted sediments. Hence, some intra-oceanic subduction systems presently regarded as erosive may actually be accretionary over long periods of time, even if accreted sediment lacks and local and/or temporary erosion presently occurs.

6.3. Accretion vs erosion: the case of the southern Central American margin

Development of the Osa Igneous Complex in cross-section view (Figs. 3, 11) illustrates the southern Costa Rican margin experienced at least two events of episodic growth (emplacement of the Inner Osa Igneous Complex and Riyito-Ganado Units) separated by periods of tectonic erosion or low-rate accretion (erosion of the arc basement and formation of the Güerra and Vaquedano Units). On map views of southern Central America (Fig. 1.2) and southern Costa Rica (Fig. 2b) it appears igneous accretionary complexes characterised by distinct geochemical affinities (Hauff *et al.* 2000; this study) are randomly distributed along the forearc. They have a fairly limited along-strike extension at the scale of the entire margin that relates to smaller size of accreted seamount fragments. Old events of tectonic erosion are well illustrated on a map view by arc-related and arc basement rocks occurring close to the present-day trench on Coiba Island or to the Osa Igneous Complex in southern Costa Rica (Buchs *et al.* submitted, this study). They may also be marked by limited along-strike extension of the Güerra and Vaquedano units in Osa. Hence, without implying any sediment accretion, it seems the southern Central American margin experienced variations in accretion/erosion rates in both time (*i.e.* seaward-landward variations seen on cross-section view) and space (along-strike variations seen on map view).

Exposed igneous complexes along the forearc of Costa Rica and Panama record subduction from the Maastrichitian to the Eocene. Over this ~25 Ma-long period, the regime was globally characterized by no sediment accretion, seamount subduction as and subduction erosion. This is a situation very similar to the present-day margin. However, it is clear that in some parts of the old margin, seamount accretion led to the construction of several km thick accretionary complexes (Fig. 2). Therefore, understanding the erosive/accretionary nature of the margin between the Maastrichtian and Eocene is only achievable by estimating the amount of material added to and removed from the margin over the period of interest. This seems however to be extremely difficult to carry out in the case of the southern Central American margin for four main reasons: (1) occurrences of on-land arc basement and accretionary complexes are scarce relative to margin length, (2) current geophysical techniques cannot make a clear, precise distinction between composite, igneous accretionary complexes and the arc basement, (3) precise estimation of the total amount of eroded material is not possible because the shape of the margin prior to erosive events is unknown, and (4) the eroded material subducted into the mantle (?) cannot be observed with current geophysical techniques, prohibiting estimation of the exact volume of this material.

Since the late Eocene, evolution of the margin is poorly constrained by the geological record. Sole on-land occurrence of late Eocene and younger accretionary complex comes from the Osa Peninsula where the Osa Mélange indicates an overall growth of the margin by sediment accretion. Other areas close to the trench have been imaged trough seismic profile and apparently lack large, sedimentary accretionary wedges and are composed by basaltic rocks (Ranero & von Huene 2000). Accreted fragments of seamounts may actually compose most of the younger part of the margin. Hence, difficulties similar to older south Central American accretionary complexes exist in quantifying net accretion or erosion along the margin since the Eocene.

In conclusion to preceding observations, it seems that even if the present-day margin apparently lacks active accretionary prisms composed of sediments, seamount accretion and tectonic erosion may coexist and/or quickly alternate through time. This is in very good accordance with older geological record present in exposed accretionary complexes along southern Central America. Due to possible local growths of the margin by seamount accretion and difficulties in estimating volumes of eroded material, it is not clear if seamount subduction is associated to net growth or erosion of the margin over long periods of time. As a consequence, there is currently no way to unequivocally define the southern Central American margin as erosive or accretionary.

7. Summary and conclusions

The Osa and Burica Peninsulas are parts of the outer forearc of southern Central America that were recently uplifted in response to the subduction of the Cocos Ridge. Rocks exposed in these peninsulas are of significant interest for understanding key processes of convergent margins such as tectonic accretion, tectonic erosion and seismogenesis along the subduction zone. The basement rocks of the Osa and Burica Peninsula were studied through a multidisciplinary approach combining a geological survey, sedimentology, palaeontology, geochemistry, structural observations and remote tectonic analyses.

The basement comprises the Osa Igneous Complex that extends from the inner Osa Peninsula to the Burica Peninsula and, possibly, further into the Montijo Gulf (western Panama) and NW off Osa and the Osa Mélange, exposed in the seaward side of the Osa Peninsula and Caño Island (Figs. 2, 3). The Osa Igneous Complex is an accretionary complex made up of late Cretaceous to middle Eocene fragments of an oceanic plateau and seamounts. The Inner Osa Igneous Complex comprises fragments of a Coniacian-Santonian oceanic plateau that accreted in the early-middle Paleocene and was followed by emplacement of the Outer Osa Igneous Complex. The Outer Osa Igneous Complex comprises Coniacian-Santonian to middle Eocene seamount fragments that accreted during (1) a period of low rate accretion / tectonic erosion between the middle-late Paleocene and the middle Eocene (Güerra Unit), (2) a period of net growth in the middle Eocene (Ganado and Riyito Units) and (3) another period of low rate accretion / tectonic erosion in the middle-late Eocene, prior to the emplacement of the Osa Mélange.

The Osa Mélange is an accretionary complex comprising (1) the San Pedrillo Unit, (2) the Cabo Matapalo Unit and (3) the Punta Salsipuedes Unit (Figs. 2, 3). The San Pedrillo Unit is a polygenetic mélange predominantly made up of deformed fine-grain detrital sediments and olistostromic deposits including late Cretaceous to late Eocene material. This material was sedimentarily removed from the forearc area in the late Eocene and essentially comprises rocks derived from the palaeo-south Central American volcanic arc and the palaeo-Osa Igneous Complex. Landslide formation along the margin was presumably triggered by seamount subduction. Underplating at shallow level of the San Pedrillo Unit resulted from a combination of high, catastrophic sediment supply into the trench and quick dewatering of the subducted sediments, possibly driven to depth on the trailing edge of subducting seamounts. The Cabo Matapalo Unit may have formed in a similar way during the Miocene, whereas the Punta Salsipuedes Unit was formed by off-scrapping and frontal accretion of pelagic sediments in the Miocene (Di Marco *et al.* 1995). Further work is required to better constrain the origins of these two later units.

Detailed study of the southern Costa Rican margin shows that faulting induced by the subducting Cocos Ridge is not solely controlled by the topography of the descending plate (*e.g.* Sak *et al.* 2004, in press), but equally by compression and possible reactivation of ancient suture zones between the units, leading to the formation of recent and/or active backthrusts. Faulting associated with the thrusts may greatly contribute to the morphology of the area but is not clearly seen on offshore seismic profiles. Suture zones were initially located along palaeo-décollements, which therefore represent fossil subduction zones. In Osa they provide an interesting on-land opportunity to study some remote processes of convergent margins such as fluid flows along the décollement or, possibly, through the outer crystalline forearc (Ranero *et al.* 2008).

The Osa Igneous Complex accreted onto the Caribbean Plate south western margin, which is composed of an arc built on an oceanic plateau (Buchs *et al.* submitted). Hence, the Osa Igneous Complex is exotic with respect to the Caribbean Plate and should no longer be considered as being part of the CLIP. No clear genetic link exists between the oceanic plateau forming the arc basement and the igneous rocks exposed in the Osa Igneous Complex. It is unclear if these lavas were emplaced above the same hotspot or not. This raises questions about the association of accreted igneous complexes of northern South America with the CLIP.

Similarly to other well-studied convergent margins in the world, the southern Costa Rican margin shows the accretionary prisms develop by episodic growth. In the case of the Osa Igneous Complex, we identified pulses of accretion of large fragments of oceanic plateau and seamounts presumably related to episodic arrival of an oceanic plateau and seamounts and/or tectonic changes at a regional scale, separated by periods of low-rate accretion and tectonic erosion. Accretion of the San Pedrillo Unit was triggered by a catastrophic event along the margin, presumably a seamount subduction.

The geological record of the south Central American forearc between the late Cretaceous to middle Eocene is similar to and consistent with the current situation. No significant amount of sediment accretion occurred during the early stages of margin evolution when several seamounts arrived at the subduction zone. In the Osa Igneous Complex, northern Costa Rica and western Panama, growth of the margin is attested by the presence of accreted seamount fragments that certainly extend offshore and have not been recognized on seismic profiles. As a consequence, it is clear that net growth of the margin over time is not restricted to sediment accretion but may result from the presence of incoming seamounts along the margin. In absence of precise information concerning the amount of material removed from the margin by tectonic erosion, this indicates the present-day margin may be accretionary rather than erosive.

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References

Abratis, M. 1998. *Geochemical variations in magmatic rocks from southern Costa Rica as a consequence of Cocos Ridge subduction and uplift of the Cordillera de Talamanca*. PhD tesis, University of Gottingen, Germany.

Abratis, M. & Worner, G. 2001. Ridge collision, slab-window formation, and the flux of Pacific asthenosphere into the Caribbean realm. *Geology*, **29**, 127-130.

Arias, O. 2003. Redefinición de la Formación Tulín (Maastrichtiano-Eoceno inferior) del Pacífico Central del Costa Rica. *Revista Geológica de America Central*, **28**, 47-68.

Azéma, J., Butterlin, J., Tournon, J. & de Wever, P. 1983. Presencia de material volcano-sedimentario de edad Eoceno medio en la Península de Osa (provincia de Puntarenas, Costa Rica). *10a Conferencia Geológica del Caribe, Cartagena, Colombia*.

Bandini, A. N., Baumgartner, P. O. & Caron, M. 2006. Turonian radiolarians from Karnezeika, Argolis Peninsula, Peloponnesus (Greece). *Eclogae Geologicae Helvetiae*, **99**, 1-20.

Bandini, A. N., Flores, K., Baumgartner, P. O., Jackett, S.-J. & Denyer, P. 2008. Late Cretaceous and Paleogene Radiolaria from the Nicoya Peninsula, Costa Rica: a tectonostratigraphic application. *Stratigraphy*, **5**, 3-21.

Bandy, O. L. & Casey, R. E. 1973. Reflector Horizons and Paleobathymetric History, Eastern Panama. *Geological Society of America Bulletin*, **84**, 3081-3086.

Bangs, N. L. B., Gulick, S. P. S. & Shipley, T. H. 2006. Seamount subduction erosion in the Nankai Trough and its potential impact on the seismogenic zone. *Geology*, **34**, 701-704.

Barckhausen, U., Roeser, H. A. & von Huene, R. 1998. Magnetic signature of upper plate structures and subducting seamounts at the convergent margin off Costa Rica. *Journal of Geophysical Research, B, Solid Earth and Planets*, **103**, 7079-7093.

Baumgartner, P. O. 1986. Discovery of subduction-related melanges on Cano Island and Osa Peninsula (Pacific, Costa Rica, Central America). *Onzième réunion annuelle des sciences de la terre*, *Réunion Annuelle des Sciences de la Terre*, *Clermont-Ferrand*, *France*, 12.

Baumgartner, P. O., Obando, J. A., Mora, C. R., Channell, J. E. T. & Steck, A. 1989. Paleogene accretion and suspect terranes in southern Costa Rica (Osa, Burica, Central America). *Transaction of the 12th Caribbean geological Conference, St croix, Virgin Islands*, 529.

Baumgartner, P. O., Flores, K., Bandini, A. N., Baumgartner-Mora, C. & Buchs, D. M. 2008. Terranes of NW-Costa Rica and the Hess Escarpment: A Pre-Campanian paleo-plate boundary. *18th Caribbean Geological Conference, March 2008, Santo Domingo, Dominican Republic*.

Berrangé, J. P. & Thorpe, R. S. 1988. The Geology, Geochemistry and Emplacement of the Cretaceous Tertiary Ophiolitic Nicoya Complex of the Osa Peninsula, Southern Costa-Rica. *Tectonophysics*, **147**, 193-220.

Berrangé, J. P. 1989. The Osa group: an auriferous Pliocene sedimentary unit from the Osa Peninsula, southern Costa Rica. *Revista Geológica de America Central*, **10**, 67-93.

Berrangé, J. P., Bradley, D. R. & Snelling, N. J. 1989. K/ Ar age dating of the ophiolitic Nicoya Complex of the Osa Peninsula, southern Costa Rica. *Journal of South American Earth Sciences*, **2**, 49-59.

Buchs, D. M. 2003. *Etude géologique et géochimique de la région du Golfo Dulce (Costa Rica):*

Genèse et évolution d'édifices océaniques accrétés à la marge de la plaque caraïbe. DEA thesis, Université de Lausanne, Switzerland.

Buchs, D. M. 2008. *Late Cretaceous to Eocene geology of the South Central American forearc area (southern Costa Rica and western Panama): Initiation and evolution of an intra-oceanic convergent margin*. PhD thesis, Université de Lausanne, Switzerland.

Buchs, D. M. & Stucki, J. 2001. *Etude géologique, géochimique et structurale du prisme d'accrétion de la péninsule d'Osa, Cosa Rica.* Diploma thesis, Université de Lausanne, Switzerland.

Buchs, D. M. & Baumgartner, P. O. 2003. The mélange of Osa-Caño (Costa Rica): an access to the sedimentary processes recorded in an emerged middle Eocene to middle Miocene accretionary prism. *10th Meeting of Swiss Sedimentologists (SWISS SED), Fribourg, Switzerland.*

Buchs, D. M. & Baumgartner, P. O. 2007. Comment on "From seamount accretion to tectonic erosion: Formation of Osa Mélange and the effects of Cocos Ridge subduction in southern Costa Rica" by P. Vannucchi *et al. Tectonics*, **26**, TC3009, doi:3010.1029/2006TC002032.

Buchs, D. M., Guex, J., Stucki, J., and Baumgartner, P. O. in press. Paleocene Thalassinidea colonization in deep-sea environment and the coprolite Palaxius osaensis n. ichnosp. in Southern Costa Rica. *Revue de Micropaléontologie*.

Buchs, D. M., Arculus, R., Baumgartner, P. O., Baumgartner-Mora, C., Ulianov, A., Flores, K. & Bandini, A. N. submitted. Late Cretaceous arc development on the SW margin of the Caribbean Plate: insights from the Golfito Complex (Costa Rica) and Azuero Complex (Panama). *Geochemistry Geophysics Geosystems*.

Byrne, T. & Fisher, D. 1987. Episodic Growth of the Kodiak Convergent Margin. *Nature*, **325**, 338-341.

Carter, R. M. 1979. Trench-Slope Channels from the New-Zealand Jurassic - Otekura Formation, Sandy Bay, South Otago. *Sedimentology*, **26**, 475-496.

Chang, C. P., Angelier, J. & Huang, C. Y. 2000. Origin and evolution of a melange: the active plate boundary and suture zone of the Longitudinal Valley, Taiwan. *Tectonophysics*, **325**, 43-62.

Clague, D. A. & Dalrymple, G. B. 1987. The Hawaiian-Emperor volcanic chain, *in* Decker, R. W., Wright, T. L. & Stauffer, P. H. (eds), Volcanism in Hawaii, 5-54.

Clift, P. & Vannucchi, P. 2004. Controls on tectonic accretion versus erosion in subduction zones: Implications for the origin and recycling of the continental crust. *Reviews of Geophysics*, **42**.

Cloos, M. 1984. Flow melanges and the structural evolution of accretionary wedges, Melanges: their nature, origin and significance, *in* Raymond, L. A. (eds), *Geological Society of America, Special Paper*, **198**, 71-79.

Cloos, M. & Shreve, R. L. 1988. Subduction-channel model of prism accretion, melange formation, sediment subduction, and subduction erosion at convergent plate margins, Part 1, Background and description. *Pure and Applied Geophysics*, **128**, 455-500.

Coates, A. G., Jackson, J. B. C., Collins, L. S., Cronin, T. M., Dowsett, H. J., Bybell, L. M., Jung, P. & Obando, J. A. 1992. Closure of the Isthmus of Panama, the near-shore marine record of Costa Rica and western Panama. *Geological Society of America Bulletin*, **104**, 814-828.

Collins, L. S., Coates, A. G., Jackson, J. B. C. & Obando, J. A. 1995. Timing and rates of emergence of the Limon and Bocas del Torro basins: Caribbean effects of Cocos Ridge subduction? *In:* Mann, P. (ed.) *Geologic and tectonic development of the Caribbean Plate boundary in southern Central America*, *Geological Society of America, Special Paper*, **295**, 263-289.

Collot, J. Y. & Fisher, M. A. 1989. Formation of forearc basins by collision between seamounts and accretionary wedges: an example from the New Hebrides subduction zone. *Geology*, **17**, 930-933.

Collot, J. Y., Lewis, K., Lamarche, G. & Lallemand, S. 2001. The giant Ruatoria debris avalanche on the northern Hikurangi margin, New Zealand: results of oblique seamount subduction. *Journal of Geophysical Research, B, Solid Earth and Planets*, **106**, 19271-19297.

Coney, P. J. 1989. Structural Aspects of Suspect Terranes and Accretionary Tectonics in Western North-America. *Journal of Structural Geology*, **11**, 107-125.

Corrigan, J., Mann, P. & Ingle, J. C., Jr 1990. Forearc response to subduction of the Cocos Ridge, Panama-Costa Rica. *Geological Society of America Bulletin*, **102**, 628-652.

DeMets, C. 2001. A new estimate for present-day Cocos-Caribbean Plate motion; implications for slip along the Central American volcanic arc. *Geophysical Research Letters*, **28**, 4043-4046.

Dengo, G. 1962. Tectonic-igneous sequence in Costa Rica. *In:* Engel, A.E.J., James, H.J. & Leonard, B.F. (eds) *Petrologic studies (A volume in honor of A. F. Buddington), Geological Society of America*, 133-161.

Denyer, P. & Baumgartner, P. O. 2006. Emplacement of Jurassic-Lower Cretaceous radiolarites of the Nicoya Complex (Costa Rica). *Geologica Acta*, **4**, 203-218.

Denyer, P., Baumgartner, P. O. & Gazel, E. 2006. Characterization and tectonic implications of Mesozoic-Cenozoic oceanic assemblages of Costa Rica and Western Panama. *Geologica Acta*, **4**, 219-235.

Di Marco, G. 1994. Les terrains accrétés du Costa Rica: évolution teconostratigraphique de la marge occidentale de la Plaque Caraïbe. *Mémoires de Géologie, Lausanne*, **20**.

Di Marco, G., Baumgartner, P. O. & Channell, J. E. T. 1995. Late Cretaceous-early Tertiary paleomagnetic data and a revised tectonostratigraphic subdivision of Costa Rica and western Panama., *In:* Mann, P. (ed.), *Geologic and Tectonic Development of the Caribbean plate boundary in southern Central America, Geological Society of America, Special Paper*, **295**, 1-27.

Dickinson, W. R. 2008. Accretionary Mesozoic-Cenozoic expansion of the Cordilleran continental margin in California and adjacent Oregon. *Geosphere*, **4**, 329-353.

Diserens, M.-O. 2002. *Upper Cretaceous and Paleogene Radiolarian Biostratigraphy of Southern Costa Rica; Radiolarian faunas from the Rincon Block, Golfito and Burica Terranes, Osa-Cano Accretionary Complex and Herradura Block*, DEA thesis, Université de Lausanne.

Dominguez, S., Malavieille, J. & Lallemand, S. E. 2000. Deformation of accretionary wedges in response to seamount subduction: Insights from sandbox experiments. *Tectonics*, **19**, 182-196.

Doubleday, P. A., Leat, P. T., Alabaster, T., Nell, P. A. R. & Tranter, T. H. 1994. Allochthonous Oceanic Basalts within the Mesozoic Accretionary Complex of Alexander Island, Antarctica

- Remnants of Proto-Pacific Oceanic-Crust. *Journal of the Geological Society*, **151**, 65-78.

Dumitrica, P. 1975. Cenomanian Radiolaria at Podul Dimbovitei. Micropaleontological guide to the Mesozoic and Tertiary of the Romanian Carpathians, paper presented at *14th European Micropaleontological Colloquium, Romania, Bucharest, Institute of Geology and Geophysics*.

Dupuy, C., Vidal, P., Maury, R. C. & Guille, G. 1993. Basalts from Mururoa, Fangataufa and Gambier Islands (French-Polynesia) - Geochemical Dependence on the Age of the Lithosphere. *Earth and Planetary Science Letters*, **117**, 89-100.

Fisher, D. M., Gardner, T. W., Marshall, J. S., Sak, P. B. & Protti, M. 1998. Effect of subducting sea-floor roughness on fore-arc kinematics, Pacific Coast, Costa Rica. *Geology*, **26**, 467-470.

Fisher, D. M., Gardner, T. W., Sak, P. B., Sanchez, J. D., Murphy, K. & Vannucchi, P. 2004. Active thrusting in the inner forearc of an erosive convergent margin, Pacific Coast, Costa Rica. *Tectonics*.

Flores, K. 2003. *Propuesta tectonoestratigráfica de la región septentrional del golfo de Nicoya, Costa Rica*. Licenciatura thesis, Escuela Centroamericana de Geología, Universidad de Costa Rica.

Foreman, H. P. 1975. Radiolaria from the North Pacific, Deep Sea Drilling Project, Leg 32. *Initial Reports of the Deep Sea Drilling Project*, **32**, 579-676.

Foreman, H. P. 1977. Mesozoic Radiolaria from the Atlantic Basin and its borderlands. *In:* Swain, F. M. (Ed.) *Stratigraphic micropaleontology of Atlantic Basin and borderlands,* Elsevier, *Developments in paleontology and stratigraphy*, **6**, 305-320.

Foreman, H. P., Heezen, B. C., MacGregor, I. D., Forristall, G. Z., Hekel, H., Hesse, R., Hoskins, R. H., Jones, E., John, W., Krasheninnikov, V., Okada, H. & Ruef, M. H. 1973. Radiolaria from DSDP Leg 20, Initial reports of the Deep Sea Drilling Project, covering Leg 20 of the cruises of the drilling vessel Glomar Challenger, Yokohama, Japan to Suva, Fiji September-November 1971. *Initial Reports of the Deep Sea Drilling Project*, **20**, 249-303.

Graefe, K., Frisch, W., Villa, I. M. & Meschede, M. 2002. Geodynamic evolution of southern Costa Rica related to low-angle subduction of the Cocos Ridge: constraints from thermochronology. *Tectonophysics*, **348**, 187-204.

Hauff, F., Hoernle, K. A., van den Bogaard, P., Alvarado, G. E. & Garbe-Schonberg, D. 2000. Age and geochemistry of basaltic complexes in Western Costa Rica: Contributions to the geotectonic evolution of Central America. *Geochemistry Geophysics Geosystems*, **1**, 5, doi:10.1029/1999GC000020.

Henningsen, D. 1963. Notes on stratigraphy and paleontology of upper Cretaceous and Tertiary sediments in southern Costa Rica. *American Association of Petroleum Geologists Bulletin*, **50**, 562-566.

Hoernle, K., & Hauff, F. 2007. Oceanic Igneous Complexes, *In:* Bundschuh, J. & Alvarado, G. (eds) *Central America, geology, resources, hazards*, **1**, 523-548.

Hoernle, K., Hauff, F. & van den Bogaard, P. 2004. 70 m.y. history (139-69 Ma) for the Caribbean large igneous province. *Geology*, **32**, 700.

Hoernle, K., van den Bogaard, P., Werner, R., Lissinna, B., Hauff, F., Alvarado, G., and Garbe-Schonberg, D. 2002. Missing history (16-71 Ma) of the Galpapagos hotspot: Implications for the tectonic and biological evolution of the Americas. *Geology*, **30**, 795-798.

Hollis, C. J. & Kimura, K. 2001. A unified radiolarian zonation for the Late Cretaceous and

Paleocene of Japan. *Micropaleontology*, **47**, 235-255.

Isozaki, Y., Maruyama, S. & Furuoka, F. 1990. Accreted Oceanic Materials in Japan. *Tectonophysics*, **181**, 179-205.

Kerr, A. C., White, R. V., E., T. P. M., Tarney, J. & Saunders, A. S. 2003. No oceanic plateau; no Caribbean Plate? The seminal role of an oceanic plateau in Caribbean Plate evolution. *In:* artolini, C., Buffler, R.T. & Blickwede, J. (eds) *The circum-Gulf of Mexico and the Caribbean, hydrocarbon habitats, basin formation, and plate tectonics, AAPG Memoir*, **79**, 126-168.

Kobayashi, K., Cadet, J. P., Aubouin, J., Boulegue, J., Dubois, J., Vonhuene, R., Jolivet, L., Kanazawa, T., Kasahara, J., Koizumi, K., Lallemand, S., Nakamura, Y., Pautot, G., Suyehiro, K., Tani, S., Tokuyama, H. & Yamazaki, T. 1987. Normal Faulting of the Daiichi-Kashima Seamount in the Japan Trench Revealed by the Kaiko-I Cruise, Leg-3. *Earth and Planetary Science Letters*, **83**, 257-266.

Kodaira, S., Takahashi, N., Nakanishi, A., Miura, S. & Kaneda, Y. 2000. Subducted seamount imaged in the rupture zone of the 1946 Nankaido earthquake. *Science*, **289**, 104-106.

Kolarsky, R. A. & Mann, P. 1995. Structure and neotectonics of an oblique-subduction margin, southwestern Panama. *In:* Mann, P. (ed.) *Geologic and tectonic development of the Caribbean Plate boundary in southern Central America, Geological Society of America, Special Paper*, **295**, 131-157.

Kolarsky, R. A., Mann, P. & Montero, W. 1995a. Island arc response to shallow subduction of the Cocos Ridge, Costa Rica *In:* Mann, P. (ed.) *Geologic and tectonic development of the Caribbean Plate boundary in southern Central America, Geological Society of America, Special Paper*, **295**, 235-262.

Kolarsky, R. A., Mann, P., Monechi, S., Meyerhoff, H. D. & Pessagno, E. A., Jr. 1995b. Stratigraphic development of southwestern Panama as determined from integration of marine seismic data and onshore geology *In:* Mann, P. (ed.) *Geologic and tectonic development of the Caribbean Plate boundary in southern Central America, Geological Society of America, Special Paper*, **295**, 159-200.

Kukowski, N. & Oncken, O. 2006. Subduction Erosion - the "Normal" Mode of Fore-Arc Material Transfer along the Chilean Margin? *In:* Oncken, O., Chong, G., Franz, G., Giese, P., Götze, H.-J., Ramos, V., Strecker, M., Wigger, P. (eds) *The Andes - Active Subduction Orogeny*, Springer, 217-236.

Lallemand, S. E., Schnuerle, P. & Malavieille, J. 1994. Coulomb theory applied to accretionary and nonaccretionary wedges; possible causes for tectonic erosion and/ or frontal accretion. *Journal of Geophysical Research, B, Solid Earth and Planets*, **99**, 12033-12055.

Le Pichon, X., Henry, P. & Lallemant, S. J. 1993. Accretion and erosion in subduction zones: the role of fluids. *Annual Review of Earth and Planetary Sciences*, **21**, 307-331.

MacMillan, I., Gans, P. B. & Alvarado, G. 2004. Middle Miocene to present plate tectonic history of the southern Central American volcanic arc. *In:* Dilek, Y. & Harris R. (eds) *Continental margins of the Pacific Rim*. *Tectonophysics*, **392**, 325-348.

Mann, P. & Kolarsky, R. A. 1995. East Panama deformed belt: structure, age, and neotectonic significance *In:* Mann, P. (ed.) *Geologic and tectonic development of the Caribbean Plate boundary in southern Central America, Geological Society of America, Special Paper*, **295**, 111-130.

Mann, P. & Taira, A. 2004. Global tectonic significance of the Solomon Islands and Ontong Java Plateau convergent zone. *Tectonophysics*, **389**, 137-190.

Maruyama, S. & Liou, J. G. 1989. Possible Depth Limit for Underplating by a Seamount. *Tectonophysics*, **160**, 327-337.

Medley, E. W. 1994. *The Engineering Characterization of Melanges and Similar Block-in-Matrix Rocks (Bimrocks)*. PhD thesis, University of California.

Medley, E. W. 2001. Orderly Characterization of Chaotic Franciscan Melanges. *Engineering Geology*, **19**, 20-33.

Mende, A. & Astorga, A. 2007. Incorporating geology and geomorphology in land management decisions in developing countries: A case study in Southern Costa Rica. *Geomorphology*, **87**, 68-89.

Meschede, M. 2003. The Costa Rica convergent margin: a textbook example for the process of subduction erosion. *Neues Jahrbuch Fur Geologie Und Palaontologie-Abhandlungen*, **230**, 409-428.

Meschede, M. & Barckhausen, U. 2001. The relationship of the Cocos and Carnegie ridges: age constraints from paleogeographic reconstructions. *International Journal of Earth Sciences*, **90**, 386-392.

Meschede, M. & Frisch, W. 1994. Geochemical characteristics of basaltic rocks from the Central American ophiolites. *Profil*, **7**.

Meschede, M., Zweigel, P., Frisch, W., and Voelker, D. 1999. Melange formation by subduction erosion; the case of the Osa melange in southern Costa Rica. *Terra Nova*, **11**, 141-148.

Moore, J. C. 1989. Tectonics and hydrogeology of accretionary prisms: Role of the decollement zone. *Journal of Structural Geology*, **11**.

Mora, C., Baumgartner, P. O. & Hottinger, L. 1989. Eocene shallow water carbonate facies with larger foraminifera in the Caño Accretionary Complex, Caño Island and Osa Peninsula (Costa Rica, Central America). *12th Caribbean Geological Conference, St. Croix, Virgin Islands,* 122.

Morell, K. D., Fisher, D. M. & Gardner, T. W. 2008. Inner forearc response to subduction of the Panama Fracture Zone, southern Central America. *Earth and Planetary Science Letters*, **265**, 82-95.

Nelson, B. K. 1995. Fluid-Flow in Subduction Zones - Evidence from Nd and Sr-Isotope Variations in Metabasalts of the Franciscan Complex, California. *Contributions to Mineralogy and Petrology*, **119**, 247-262.

Nishimura, A. 1992. Paleocene Radiolarian Biostratigraphy in the Northwest Atlantic at Site-384, Leg-43, of the Deep-Sea Drilling Project. *Micropaleontology*, **38**, 317-362.

Nishimura, K. &Ishiga, H. 1987. Radiolarian biostratigraphy of the Maizuru Group in Yanahara area, Southwest Japan. *Memoirs of the Faculty of Science, Shimane University*, **21**, 169-188.

O. Dogherty, L. 1994. Biochronology and paleontology of Mid-Cretaceous radiolarians from Northern Apennines (Italy) and Betic Cordillera (Spain). *Mémoires de Geologie Lausanne, Switzerland*.

Obando, J. A. 1986. *Sedimentología y tectónica del Cretácico y Paleógeno de la region de Golfito, Península de Burica y Península de Osa, Provincia de Puntarenas, Costa Rica*. Licenciatura thesis, Escuela Centroamericana de Geología, Universidad de Costa Rica.

Okamura, Y. 1991. Large-scale melange formation due to seamount subduction; an example from the Mesozoic accretionary complex in central Japan. *Journal of Geology*, **99**, 661-674.

Pal, T., Chakraborty, P. P., Gupta, T. D. & Singh, C. D. 2003. Geodynamic evolution of the outer-arc-forearc belt in the Andaman Islands, the central part of the Burma-Java subduction complex. *Geological Magazine*, **140**, 289-307.

Park, J. O., Tsuru, T., Kaneda, Y., Kono, Y., Kodaira, S., Takahashi, N. & Kinoshita, H. 1999. A subducting seamount beneath the Nankai accretionary prism off Shikoku, southwestern Japan. *Geophysical Research Letters*, **26**, 931-934.

Pessagno, E. A., Jr. 1976. Radiolarian zonation and stratigraphy of the upper Cretaceous portion of the Great Valley Sequence, California Coast Ranges. *Micropaleontology, Special Publication*, **2**, 1-95.

Petterson, M. G., Babbs, T., Neal, C. R., Mahoney, J. J., Saunders, A. D., Duncan, R. A., Tolia, D., Magu, R., Qopoto, C., Mahoa, H. & Natogga, D. 1999. Geological-tectonic framework of Solomon Islands, SW Pacific: crustal accretion and growth within an intra-oceanic setting. *Tectonophysics*, **301**, 35-60.

Petterson, M. G., Neal, C. R., Mahoney, J. J., Kroenke, L. W., Saunders, A. D., Babbs, T. L., Duncan, R. A., Tolia, D. & McGrail, B. 1997. Structure and deformation of north and central Malaita, Solomon Islands: tectonic implications for the Ontong Java Plateau Solomon arc collision, and for the fate of oceanic plateaus. *Tectonophysics*, **283**, 1-33.

Phinney, E. J., Mann, P., Coffin, M. F. & Shipley, T. H. 2004. Sequence stratigraphy, structural style, and age of deformation of the Malaita accretionary prism (Solomon Arc-Ontong Java Plateau convergent zone). *Tectonophysics*, **389**, 221-246.

Pindell, J., Kennan, L., Maresch, W. V., Stanek, K. P., Draper, G. & Higgs, R. 2005. Plate kinematics and crustal dynamics of circum-Caribbean arc-continent interactions; tectonic controls on basin development in proto-Caribbean margins.; Caribbean-South American plate interactions, Venezuela. *Special Paper - Geological Society of America*, **394**, 7-52.

Ranero, C. R. & von Huene, R. 2000. Subduction erosion along the Middle America convergent margin. *Nature*, **404**, 748-755.

Ranero, C. R., von Huene, R., Weinrebe, W. & Barckhausen, U. 2007. Convergent margin tectonics: A marine perspective. *In:* Bundschuh, J. & Alvarado, G. E. (eds) *Central America - Geology, Resources and Hazards*, 239-276.

Ranero, C. R., Grevemeyer, I., Sahling, H., Barckhausen, U., Hensen, C., Wallmann, K., Weinrebe, W., Vannucchi, P., von Huene, R. & McIntosh, K. 2008. Hydrogeological system of erosional convergent margins and its influence on tectonics and interplate seismogenesis. *Geochemistry Geophysics Geosystems*, **9**, Q03S04, doi:10.1029/2007GC001679.

Raymond, L. A. 1984. Classification of melanges. *In:* Raymond L. A. (ed.), *Melanges: their nature, origin and significance, Geological Society of America, Special Paper*, **198**, 7-20.

Raymond, L. A. & Terranova, T. 1984. Prologue: The melange problem: a review. *In:* Raymond L. A. (ed.), *Melanges: their nature, origin and significance, Geological Society of America, Special Paper*, **198**, 1-5.

Sak, P. B., Fisher, D. M. & Gardner, T. W. 2004. Effects of subducting seafloor roughness on upper plate vertical tectonism; Osa Peninsula, Costa Rica. *Tectonics*, **23**, TC1017, doi:1010.1029/2002TC001474.

Sak, P. B., Fisher, D. M., Gardner, T. W., Marshall, J. S. & LaFemina, P. C. in press. Rough crust, forearc kinematics, and Quaternary uplfit rates, Costa Rican segment of the middle

American Trench. *Geological Society of America Bulletin*.

Sallares, V., Danobeitia, J. J., Flueh, E. R. & Leandro, G. 1999. Seismic velocity structure across the middle American landbridge in northern Costa Rica. *Journal of Geodynamics*, **27**, 327-344.

Sallares, V., Danobeitia, J. J. & Flueh, E. R. 2001. Lithospheric structure of the Costa Rican Isthmus: Effects of subduction zone magmatism on an oceanic plateau. *Journal of Geophysical Research, B, Solid Earth*, **106**, 621-643.

Sanfilippo, A. & Riedel, W. R. 1973. Cenozoic Radiolaria (exclusive of theoperids, artostrobiids and amphipyndacids) from the Gulf of Mexico, DSDP Leg 10. *In:* Worzel, J. L., Bryant, W., Beall, A.-O. J., Capo, R., Dickinson, K., Foreman, H. P., Robert, L., McNeely, B. W. & Smith, L.-A. (eds) *Initial Reports of the Deep Sea Drilling Project*, **10**, 475-611.

Sanfilippo, A. & Riedel, W. R. 1985. Cretaceous Radiolaria. *In:* Bolli, H. M., Saunders, J. B. & Perch-Nielsen, K. (eds), *Plankton Stratigraphy*, 573-630.

Sanfilippo, A. & Nigrini, C. 1998. Upper Paleocene-lower Eocene deep-sea radiolarian stratigraphy and the Paleocene/ Eocene series boundary: Late Paleocene-early Eocene climatic and biotic events in the marine and terrestrial records. *In:* Aubry, M.-P., Lucas, S. G. & Berggren, W. A. (eds) *Late Paleocene-Early Eocene Biotic and Climatic Events in the Marine and Terrestrial Records*, 244-276.

Schaaf, A. 1985. Un nouveau canevas biochronologique du Crétacé inférieur et moyen: les biozones à radiolaires. *Sciences Géologiques (Strasbourg)*, **38**, 227-269.

Seno, T. 2007. Collision vs. subduction: from a viewpoint of slab dehydration. *In* Dixon, T. H. & Moore, C. (eds) *The Seismogenic Zone of Subduction Thrust Faults, MARGINS Theoretical and Experimental Earth Science Series*, 601-623.

Seno, T. 2008. Conditions for a crustal block to be sheared off from the subducted continental lithosphere: What is an essential factor to cause features associated with collision? *Journal of Geophysical Research, B, Solid Earth*, **113**, B04414.

Shervais, J. W., Schuman, M. M. Z. & Hanan, B. B. 2005. The Stonyford volcanic complex: A forearc seamount in the northern California Coast Ranges. *Journal of Petrology*, **46**, 2091-2128.

Sinton, C. W., Duncan, R. A. & Denyer, P. 1997. Nicoya Peninsula, Costa Rica: A single suite of Caribbean oceanic plateau magmas. *Journal of Geophysical Research, B, Solid Earth*, **102**, 15507-15520.

Sinton, C. W., Duncan, R. A., Storey, M., Lewis, J. & Estrada, J. J. 1998. An oceanic flood basalt province within the Caribbean plate. *Earth and Planetary Science Letters*, **155**, 221-235.

Smith, W. H. F. & Sandwell, D. T. 1997. Global sea floor topography from satellite altimetry and ship depth soundings. *Science*, **277**, 1956-1962.

Taira, A., Mann, P. & Rahardiawan, R. 2004. Incipient subduction of the Ontong Java Plateau along the North Solomon trench. *Tectonophysics*, **389**, 247-266.

Taketani, Y. 1982. Cretaceous radiolarian biostratigraphy of the Urakawa and Obira areas, Hokkaido. *Science Reports of the Tohoku University*, **52**, 1-76.

Thurow, J., Moullade, M., Brumsack, H. J., Masure, E., Taugourdeau, L. J., Dunham, K. W., Boillot, G., Winterer, E. L., Meyer, A. W., Applegate, J., Baltuck, M., Bergen, J. A., Comas, M. C., Davies, T. A., Evans, C. A., Girardeau, J., Goldberg, D., Haggerty, J. A., Jansa, L. F., Johnson, J. A., Kasahara, J., Loreau, J. P., Luna, E., Ogg, J. G., Sarti, M., & Williamson, M. A. 1988. The Cenomanian/ Turonian boundary event (CTBE) at Hole 641A, ODP Leg 103 (compared with the CTBE interval at Site 398). Proceedings of the Ocean Drilling Program, Scientific Results, **103**, 587-634.

Tournon, J. 1984. Magmatisme du Mésozoïque à l'actuel en Amérique Centrale: l'exemple du Costa Rica, des ophiolites aux andésites. *Mémoire des sciences de la terre, Université Pierre et Marie Curie*, **84**, 335.

Trenkamp, R., Kellogg, J. N., Freymueller, J. T. & Mora, H. P. 2002. Wide plate margin deformation, southern Central America and northwestern South America, CASA GPS observations. *Journal of South American Earth Sciences*, **15**, 157-171.

Underwood, M. B. & Bachman, S. B. 1982. Sedimentary facies associations within subduction complexes. *Geological Society, London, Special Publications*, **10**, 537-550.

Vannucchi, P., Scholl, D. W., Meschede, M. & Kristin, M. R. 2001. Tectonic erosion and consequent collapse of the Pacific margin of Costa Rica; combined implications from ODP Leg 170, seismic offshore data, and regional geology of the Nicoya Peninsula. *Tectonics*, **20**, 649-668.

Vannucchi, P., Ranero, C. R., Galeotti, S., Straub, S. M., Scholl, D. W. & McDougall-Ried, K. 2003. Fast rates of subduction erosion along the Costa Rica Pacific margin: Implications for nonsteady rates of crustal recycling at subduction zones. *Journal of Geophysical Research, B, Solid Earth*, **108**.

Vannucchi, P., Fisher, D. M., Bier, S. & Gardner, T. W. 2006. From seamount accretion to tectonic erosion; formation of Osa melange and the effects of Cocos Ridge subduction in southern Costa Rica. *Tectonics*, **25**, TC2004, doi:2010.1029/2005TC001855.

Vannucchi, P., Fischer, D. M. & Gardner, T. W. 2007. Reply to comment by David M. Buchs and Peter O. Baumgartner on ''From seamount accretion to tectonic erosion: Formation of Osa Mélange and the effects of the Cocos Ridge subduction in southern Costa Rica''. *Tectonics*, **26**, TC3010, doi:3010.1029/2007TC002129.

Vannucchi, P., Remitti, F. & Bettelli, G. 2008. Geological record of fluid flow and seismogenesis along an erosive subducting plate boundary. *Nature*, doi:10.1038/nature06486.

Vishnevskaya, V. S. 2001. *Jurassic to Cretaceous radiolarian biostratigraphy of Russia*.Type thesis Thesis.

Vishnevskaya, V. S. 2007. New radiolarian species of the family pseudoaulophacidae riedel from the upper cretaceous of the volga region. *Paleontological Journal*, **41**, 489-500.

von Huene, R. & Lallemand, S. 1990. Tectonic Erosion Along the Japan and Peru Convergent Margins. *Geological Society of America Bulletin*, **102**, 704-720.

von Huene, R. & Scholl, D. W. 1991. Observations at Convergent Margins Concerning Sediment Subduction, Subduction Erosion, and the Growth of Continental-Crust. *Reviews of Geophysics*, **29**, 279-316.

von Huene, R., Bialas, J., Flueh, E., Cropp, B., Csernok, T., Fabel, E., Hoffmann, J., Emeis, K., Holler, P., Jeschke, G., Leandro, M. C., Perez Fernandez, I., Chavarria, S. J., Florez, H. A., Escobedo, Z. D., Leon, R. & Barrios, L. O. 1995. Morphotectonics of the Pacific convergent margin of Costa Rica.; Geologic and tectonic development of the Caribbean Plate boundary in southern Central America. *In:* Mann, P. (ed.) *Geologic and tectonic development of the Caribbean Plate boundary in southern Central America*, *Geological Society of America,* *Special Paper*, **295**, 291-307.

von Huene, R., Ranero, C. R. & Vannucchi, P. 2004. Generic model of subduction erosion. *Geology*, **32**, 913-916.

Walther, C. H. E. 2003. The crustal structure of the Cocos Ridge off Costa Rica. *Journal of Geophysical Research, B, Solid Earth and Planets*, **108**, 2136, doi:2110.1029/2001JB000888.

Werner, R., Hoernle, K., van den Bogaard, P., Ranero, C., von Huene, R. & Korich, D. 1999. Drowned 14-m.y.-old Galapagos Archipelago off the coast of Costa Rica: implications for tectonic and evolutionary models. *Geology*, **27**, 499-502.

Figure Captions

Fig. 1: A) Geologic setting of the South Central American Arc. PAN=Panama Microplate, Mesquito=Mesquito Composite Oceanic Terrane (after Baumgartner *et al.* 2008). Dark grey areas represent igneous complexes generally associated to the Caribbean Large Igneous Province (CLIP) or Colombian-Caribbean Oceanic Plateau (CCOP). B) Simplified geological map of southern Central America based on national geological maps of the area and results from this study. Bathymetry based on Smith and Sandwell (1997). Autochtonous and accreted oceanic complexes are defined on the basis of our new results (*e.g.* Bandini *et al.* 2008; Buchs 2008; Buchs *et al.* submitted; this study) and stratigraphic data from previous contributions (Bandy & Casey 1973; Baumgartner *et al.* 1984, 2008; Di Marco 1994; Arias 2003; Flores 2003).

Fig. 2: A) Geological map of the Golfo Dulce area modified after Buchs & Baumgartner (2007) and references therein. Analyzed igneous rocks: circles = samples from this study, squares = samples from Hauff *et al.* (2000), triangles = samples from Di Marco (1994), partly re-analyzed in this study. B) Geological map of the Golfo Dulce area illustrating basement rocks (*i.e.* underlying recent alluvial deposits, as well as overlap sediments of the Charco Azul and Osa Groups). Lineaments are based on satellite imagery (pixel size of 28.5 m) and DEM (3 arc seconds). Lineaments in the Golfito area are from Mende & Astorga (2007).

Fig. 3: Comparison of seismic and on-land interpretations for the NW Osa Mélange and Osa Igneous Complex. A-A') Depth converted interpretation of multichannel reflection profile P 1600 from the upper plate basement (modified after Kolarsky *et al.* (1995a), full references and data in Kolarsky *et al.* (1995a), vertical exaggeration: 2x). The profile is only ~15 and ~30 km distant from the San Pedrillo Unit exposed on Caño Island and other units exposed on the Osa Peninsula, respectively. Dashed lines represent possible extensions of unit boundaries projected from cross-section B-B'. B-B') SW-NE cross-section through the Osa Peninsula and forearc slope (vertical exaggeration: 2x). Topography is from GeoMapApp (online georeferred database). Note particular changes in topography correlating with suture zones between the Inner Osa Igneous Complex, Outer Osa Igneous Complex and San Pedrillo Unit (Inner Osa Mélange).

Fig. 4: A-D) REE diagrams for the basalts and gabbros of the Osa Igneous Complex (grey areas, organised per unit) and basaltic olistoliths of the San Pedrillo Unit (black lines with sample references). Samples from the San Pedrillo Unit were individually associated with most similar unit of the Osa Igneous Complex. Normalisation values are from McDonough & Sun (1995). "Highly-depleted", "NMORB-like", "plateau-like" and "OIB-like" denominations are defined in Chapter 3.1. E) Multielement diagram of two dacitic olistoliths from the San Pedrillo Unit. Normalisation values are from Mac Donough & Sun (1995). For comparison, 11-17 Ma high-Fe (tholeiitic) basalts-andesites and 8-12 Ma low-Fe (calc-alkalic) basalts-dacites from Costa Rican forearc volcanics are plotted (grey areas, Abratis (1998)). Note that the dacitic olistoliths and igneous rocks from the Osa Igneous Complex have dissimilar affinities in terms of REE, notably.

Fig. 5: Detail geological map of the Rio Claro area. A) Basalt olistolith embedded within a cataclasite matrix. B) Microphotograph of a volcanic microbreccia principally made of basaltic grains. A-B) highlight the large variability in the clast size observed in the San Pedrillo Unit. Costal exposures of NW Osa and Caño Island have been integrally mapped in a similar way (Buchs & Stucki 2001).

Fig. 6: Simplified geological map of the NW San Pedrillo Unit illustrating recurrent lithologic associations.

Fig. 7: A) Structural model of the NW Osa Mélange illustrating the block-in-matrix texture and disrupted sedimentary layers at a small scale. At a larger scale, the chaotic arrangement of the mélange is replaced by lithologically-coherent lenses. B) Orientations of principal shear planes observed in the mélange. (1) and (2) are shear planes mainly parallel to the orientation of the trench, that crop out on the Osa Peninsula, respectively on the Caño Island. (3) and (4) represent shear planes predominantly perpendicular to the orientation of the trench, that are exposed on the Osa Peninsula, respectively on the Caño Island. The two families of shear planes show a large variability in their orientation that is consistent with a lenticular arrangement of the lithologies in the San Pedrillo Unit.

Fig. 8: Ranges and occurrences of Cretaceous and Paleogene radiolarian species from samples of the Azuero Complex (Azuero plateau, data from Kolarsky *et al.* (1995b)), the Osa Igneous Complex (inner Osa Igneous Complex and Ganado Unit, data from Diserens (2002) and this study) and the San Pedrillo Unit (inner Osa Mélange, data from Diserens (2002) and this study). Ages of sample formation are given by grey fields (details in Chapter 3.4.1).

Fig. 9: Radiometric vs. biochronologic ages for some igneous samples of the Osa Igneous Complex and Osa Mélange, with error bars. Biochronologic ages are inferred from the tectonostratigraphy as defined in this study. Whole rock K/Ar ages are from Berrangé *et al.* (1989) and whole rock 40Ar/39Ar total fusion isochron ages from Hauff *et al.* (2000) and Hoernle *et al.* (2002). Large variability in the biochronologic ages is due to large range of formation ages for some units and/or poor age accuracy of fossil assemblages. Some samples have inconsistent biochronologic and radiometric ages within the incertitude range that is attributed to Ar loss.

Fig. 10: Tectonostratigraphy of the Osa and Burica Peninsulas (partly based on data from Berrangé & Thorpe, 1988; Coates *et al.* 1992; Di Marco *et al.* 1995). Horizontal lines represent major tectonic events along the south Costa Rican margin: (1) subduction initiation (Buchs *et al.* submitted), (2) accretion of the Inner Osa Igneous Complex, (3) accretion of the Ganado and Riyito Units, (4) possible seamount subduction leading to formation of the San Pedrillo Unit, (5) subsidence of the margin (unidentified origin, tectonic erosion?), and (6) possible incoming of the Cocos Ridge. Grey areas represent age ranges of possible accretion for corresponding units. Note that ages of the accreted units roughly define a development of the margin toward the trench through time. Dark bars represent age ranges of possible tectonic erosion. Succinct definition of the formations and units is provided on Fig. 2.

Fig. 11: Model of accretionary processes in the Osa transect of the mid-American Trench (middle Campanian to Oligocene, not to scale). A) Margin just after the subduction initiation, undergoing overall tectonic erosion. B) Accretion by large-scale duplexing of pieces of a Coniacian-Santonian oceanic plateau; initiation of the construction of the Osa Igneous Complex. C) Period of low-rate accretion; formation of the metamorphic, highly composite Güerra Unit. D) Various fragments of large seamounts accrete and squeeze the Güerra Unit onto the Inner Osa Igneous Complex; Ganado and Riyito Units are emplaced. E) Period of low-rate accretion and intermittent tectonic erosion; formation of the highly composite Vaquedano Unit. F) a seamount subduction causes a strong uplift of the forearc, leading to the gravitational collapse of the paleo-Osa Igneous Complex and large production of sediments. Large volumes of sediment proceeding form the forearc quickly deposit into the trench and lead to the formation of the San Pedrillo Unit. G) Possible growth of the San Pedrillo Unit by successive accretion of sediments derived from the forearc and arc areas.

Fig. 12: Palinspastic reconstruction of the south Costa Rican margin in the late Eocene, based on the sedimentary record observed in the San Pedrillo Unit. The forearc area undergoes an important uplift possibly in response to seamount subduction. Large amount of sediments are deposited in the trench and quickly accreted to form the San Pedrillo Unit. The sediments are composed of volcanic fragments of the arc (1), late Eocene shallow-water carbonates originally deposited/produced along the arc (2), late Cretaceous-middle Eocene clasts (grains to large boulders) of the paleo-Osa Igneous Complex (3), and early-middle Eocene hemipelagic and tuffaceous sediments of the forearc slope-basin (4). Minor reworking of previously accreted portions of the San Pedrillo Unit is possible (5). Minor volumes of sediments and basalt derived from collapsing seamounts may have been deposited into the trench or may be tectonically incorporated into the mélange during the subduction of the seamounts (6), but remain very limited in comparison to the volume of detrital material coming from the upper plate.

Plates Captions

Plate1
Outcrops of the principal rock types of the Osa mélange. NW Osa and Caño Island

a. An originally well-bedded, laminated, calciturbidite interbedded with tuffaceous mudstones. The late Eocene limestone bed lithified before the mudstone, became hydrofractured and intruded by the soft mudstone. Agujitas, Bahia Drake, Osa.
b. Individual limestone interbeds became boudinaged and faulted Agujitas, Bahia Drake, Osa.
c. Limestone-tuffite breccia. This pebbly mudstone is of probable debris flow origin. It is highly deformed as most rocks in the Osa Mélange. Punta Campanario, Osa.
d. Boudinaged limestone beds in a siliceous tuffitic mudstone matrix, Caño Island.
e. Basalt/radiolarite contact in a late Cretaceous megablock of probable seamount origin. San Pedrillo, Osa. Scale bar 22 cm.
f. Detail of a late Cretaceous-Paleocene cherty limestone associated with a seamount block. The early lithified chert beds suffered from brittle fracturing, while the limestones responded by pseudo ductile deformation to stress. River mouth of Rio Claro, Marenco, Osa.
g. Red and dark green cherty mudstones and cherts that show boudinage in bundles. Between Marenco and Agujitas, Osa. Length of hammer 45 cm.
h. Mass flow deposit. Base of a basalt block (upper side of the photograph) and boulder breccia including clasts of basalts, dacites and shallow-water limestones within a detrital hemipelagic sediment matrix. Scale bar 22 cm.
i. Fine grained, volcaniclastic greywackes and mudstones with well preserved bedding and lamination of turbiditic origin. Punta Campanario, Osa. Scale bar 22 cm.
j. Polymict boulder breccia including angular clasts of cherts, rounded clasts of dacites - basalts and tuffites. Punta Campanario, Osa.

Plate 2
Transmitted light photomicrographs of thin sections of late Eocene shallow-water limestone clasts from the San Pedrillo Unit, Osa Peninsula.

a. Calcarenite rich in Larger Foraminifera (f). Red algal rhodoliths (rh), green volcanic tuffites (t), dark volcanics (v) and angular feldspars set in a calcareous matrix. In addition there are rare radiolarite (r) and spicultite (sp) clasts. Punta Campanario, Osa.
b. Packstone with fragments of Larger Foraminifera, red algae, crinoids and volcaniclastic material. Ps: Oblique and vertical section of *Pseudophragmina*. Nm: small globular Nummulites. Sample DB02-026. Punta Campanario, Osa.
c. Packstone with *Lithotamnium*, Larger Foraminifera and volcanic lithoclasts. Ds: equatorial section of *Discocyclina* with a megalospheric embryon of semi-isolepidine type.
d. Packstone with fragments of vertical sections of *Pseudophragmina* (ps), *Lepidocyclina* (lp), *Operculinoides* (op) and crinoids (cr).
e. Packstone with larger forams. Lp: fragments of equatorial section of *Lepidocyclina* showing the arcuate shape of the equatorial chambers. Sample CM-Caño98F from the Caño Island.
f. Bioclastic packstone with Larger Foraminifera and abundant fragments of echinoderms both very recristalizaded. The clasts show mechanic erosion. ps: *Pseudophragmina* in vertical section . hg: *Helicostegina* in oblique section. Sample: POB 3060 coastal outcrops of Llorona, Corcovado.

Plate 3
SEM-illustrations of Late Cretaceous and Paleogene Radiolaria from the Osa Peninsula, Costa Rica:
The numbers of illustrations in this plate correspond to those in Fig. 8. Marker = 100 µm.

1. ***Amphipyndax* sp. Cf. A. *pseudoconulus*** Pessagno, Sample DJ01-141, San Pedrillo.

2-4. ***Archaeodictyomitra napaensis*** Pessagno, Sample DJ01-141, San Pedrillo.

5. ***Alievum gallowayi*** (White), Sample DJ01-114, Agujitas.

6. ***Praeconocaryomma universa*** Pessagno, Sample DJ01-114, Agujitas.

7-8. ***Calocyclas hispida*** (Ehrenberg), Sample DJ01-043, between Rio Claro and San Jocesito.

9. ***Lychnocanium carinatum*** Ehrenberg**,** Sample DJ01-043, between Rio Claro and San Jocesito.

10. ***Theocotyle (Theocotylissa) auctor*** Foreman, Sample DJ01-043, between Rio Claro and San Jocesito.

11. ***Theocotyle (Theocotylissa) alpha*** Foreman, Sample DJ01-043, between Rio Claro and San Jocesito.

12. ***Lithelius* sp**., Sample GDM 90126, Punta Agujitas

13-14. ***Amphisphaera* spp**., Sample GDM 90126, Punta Agujitas

15. ***Calocycloma castum*** (Haeckel), Sample GDM 90126, Punta Agujitas.

16-18. ***Phormocyrtis turgida*** (Krasheninnikov), Sample DJ01-140, San Pedrillo.

19-21. ***Podocyrtis (Podocyrtis) papalis*** Ehrenberg, 19 & 20, Sample DJ01-043, between Rio Claro and San Jocesito, 21, Sample DJ01-140, San Pedrillo.

22-23. ***Buryella tetradica*** Foreman**,** 22, Sample DJ01-140, 23, Sample DJ01-098, Agujitas.

24-26. ***Buryella clinata*** Foreman, Sample GDM 90126, Punta Agujitas.

27. ***Tristylospyris* spp.**, Sample GDM 90126, Punta Agujitas

28. ***Spongodiscus* sp.**, Sample GDM 90126, Punta Agujitas.

29. ***Phormocyrtis striata striata*** Brandt, Sample DJ01-098, Agujitas.

30. ***Spongurus* (?) *regularis*** (Borisenko), Sample DJ01-098, Agujitas.

31. ***Periphaena heliastericus*** (Clark and Campbell), Sample GDM 9020, Rio Cedral.

Plate 4
SEM-illustrations of Late Cretaceous and Paleogene Radiolaria from the Osa Peninsula, Costa Rica: The numbers of illustrations in this plate correspond to those in Fig. 8. Marker = 100 µm, except for fig. 25 where marker equals 50 µm.

1. ***Alievium* sp.**, Sample DB02-199.

2. ***Halesium amissum*** (Squinabol), Sample DB02-199.

3. ***Acanthocircus* sp. b.**, Sample DB02-199.

4. ***Pseudoaulophacus* sp.**, Sample DB02-199.

5. ***Archaeospongoprunum bipartitum*** Pessagno, Sample DB02-199.

6. ***Praeconocaryomma universa*** Pessagno, Sample DB02-199.

7. ***Napora* sp.**, Sample DB02-199.

8. ***Rhopalosyringium* sp.**, Sample DB02-199.

9. ***Theocampe* aff. *urna*** (Foreman), Sample DB02-199.

10. ***Theocampe salillum*** (Foreman), Sample DB02-199.

11. ***Tugurium* sp.**, Sample DB02-199.

12. ***Pseudodictyomitra* sp.**, Sample DB02-199.

13. ***Dictyomitra formosa*** Squinabol, Sample DB02-199.

14. ***Amphipternis stocki*** (Campbell and Clark), Sample DB02-199.

15. ***Eostichomitra* sp.**, Sample DB02-199.

16. ***Alievium* aff. *gallowayi*** (White), Sample FBJ 90174.

17. ***Dictyomitra formosa*** Squinabol, Sample FBJ 90174.

18. ***Archaeospongoprunum* sp.**, Sample FBJ 90174.

19. ***Crucella cachensis*** Pessagno, Sample FBJ 90174.

20. ***Praeconocaryomma universa*** Pessagno, Sample FBJ 90174.

21. ***Gongylothorax verbeeki*** (Tan Sin Hok), Sample FBJ 90174.

22. ***Theocampe tina*** (Foreman), Sample FBJ 90174.

23. ***Theocampe urna*** (Foreman), Sample FBJ 90174.

24. ***Acanthocircus yaoi*** (Foreman), Sample FBJ 90174.

25. ***Lithatractus pusillus*** (Campbell and Clark), Sample FBJ 90174.

26. ***Amphipternis stocki*** (White), Sample GDM 9116.

27. ***Theocampe urna*** (Foreman), Sample GDM 9116.

28. ***Praeconocaryomma universa*** Pessagno, Sample GDM 9116.

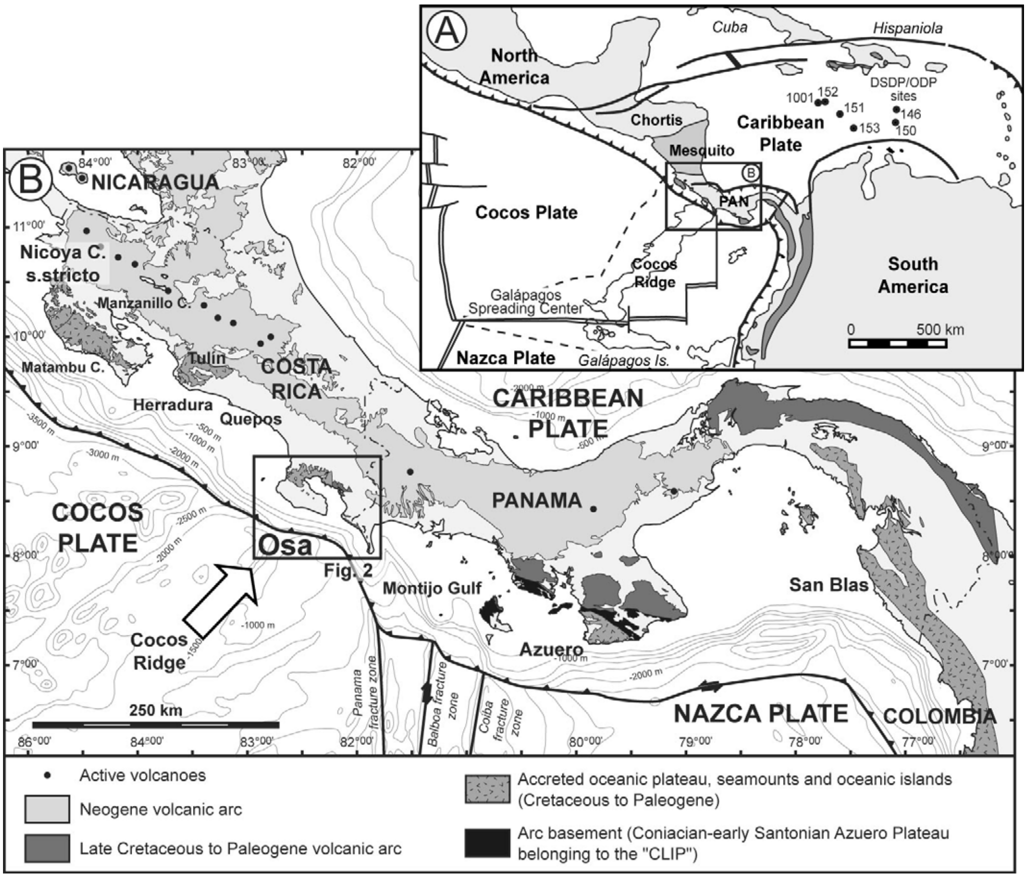

FIGURE 1

Buchs et al., Late Cretaceous to Miocene Seamount Accretion and Mélange Formation in the Osa and Burica Peninsulas (Southern Costa Rica): Episodic Growth of a Convergent Margin, accepted in “Geology of the area between North and South America, with focus on the origin of the Caribbean Plate”, GSL Special Publication, in preparation, edited by K.H. James, M.A. Lorente and J. Pindell

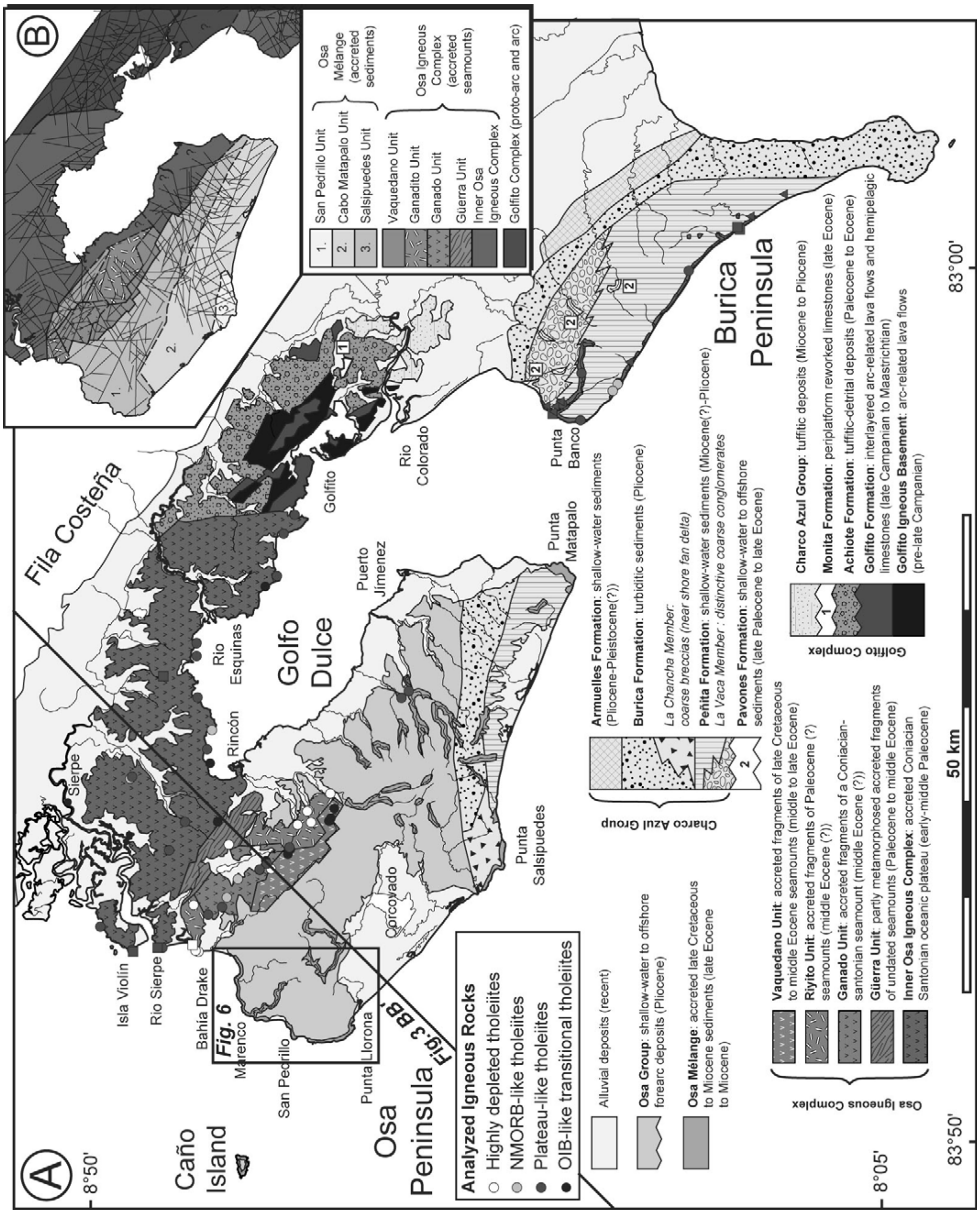

FIGURE 2

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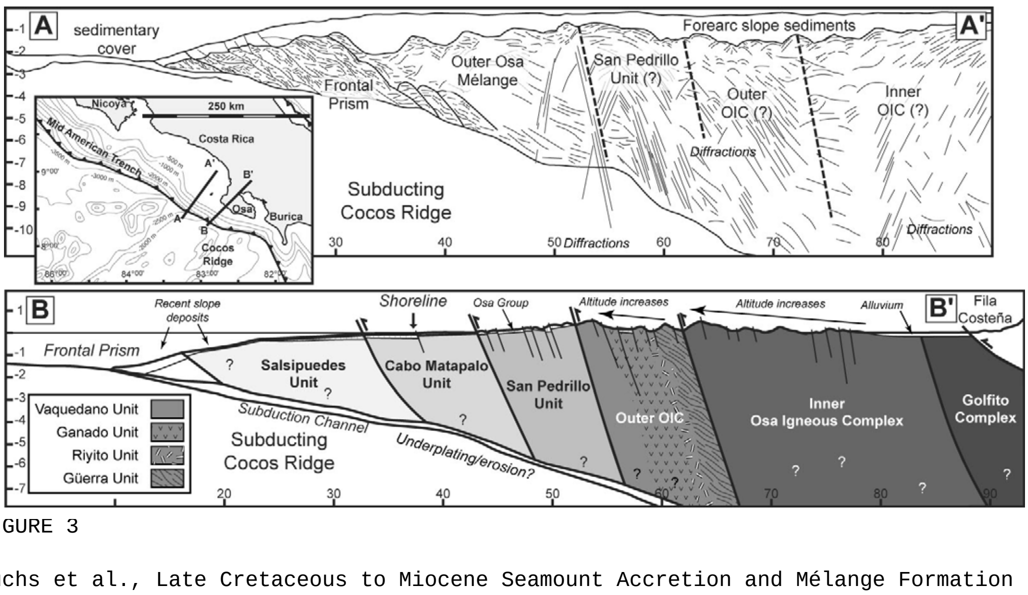

FIGURE 3

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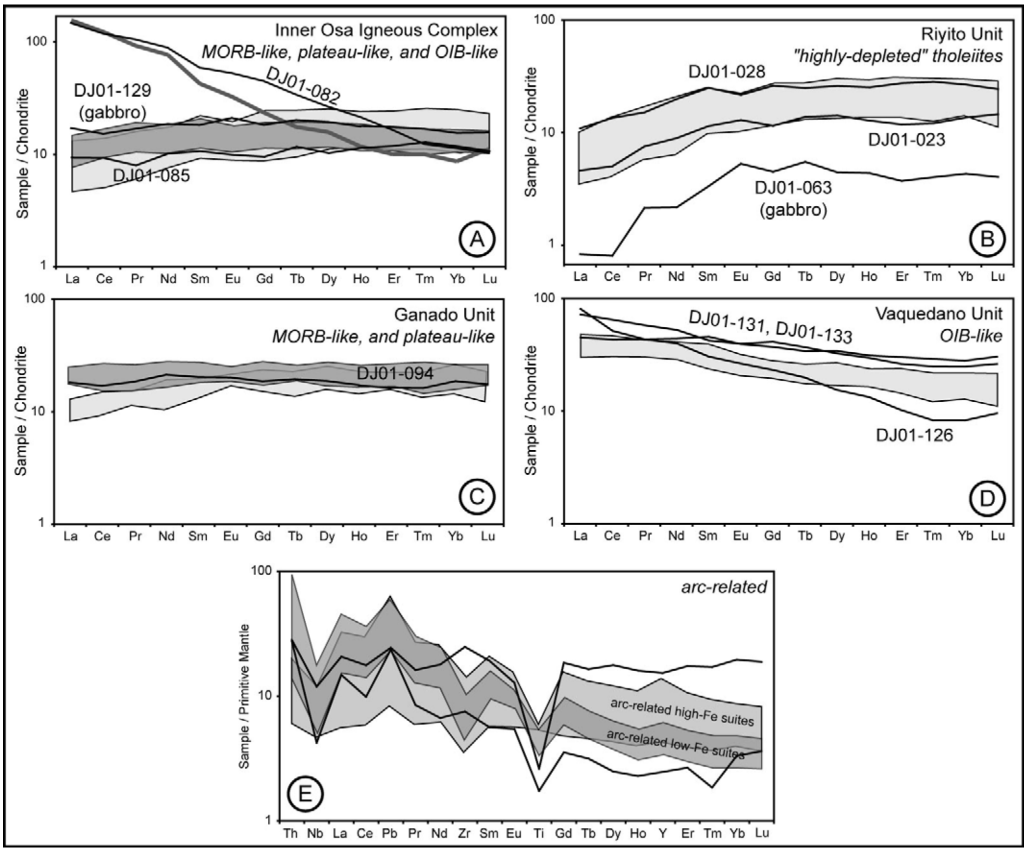

FIGURE 4

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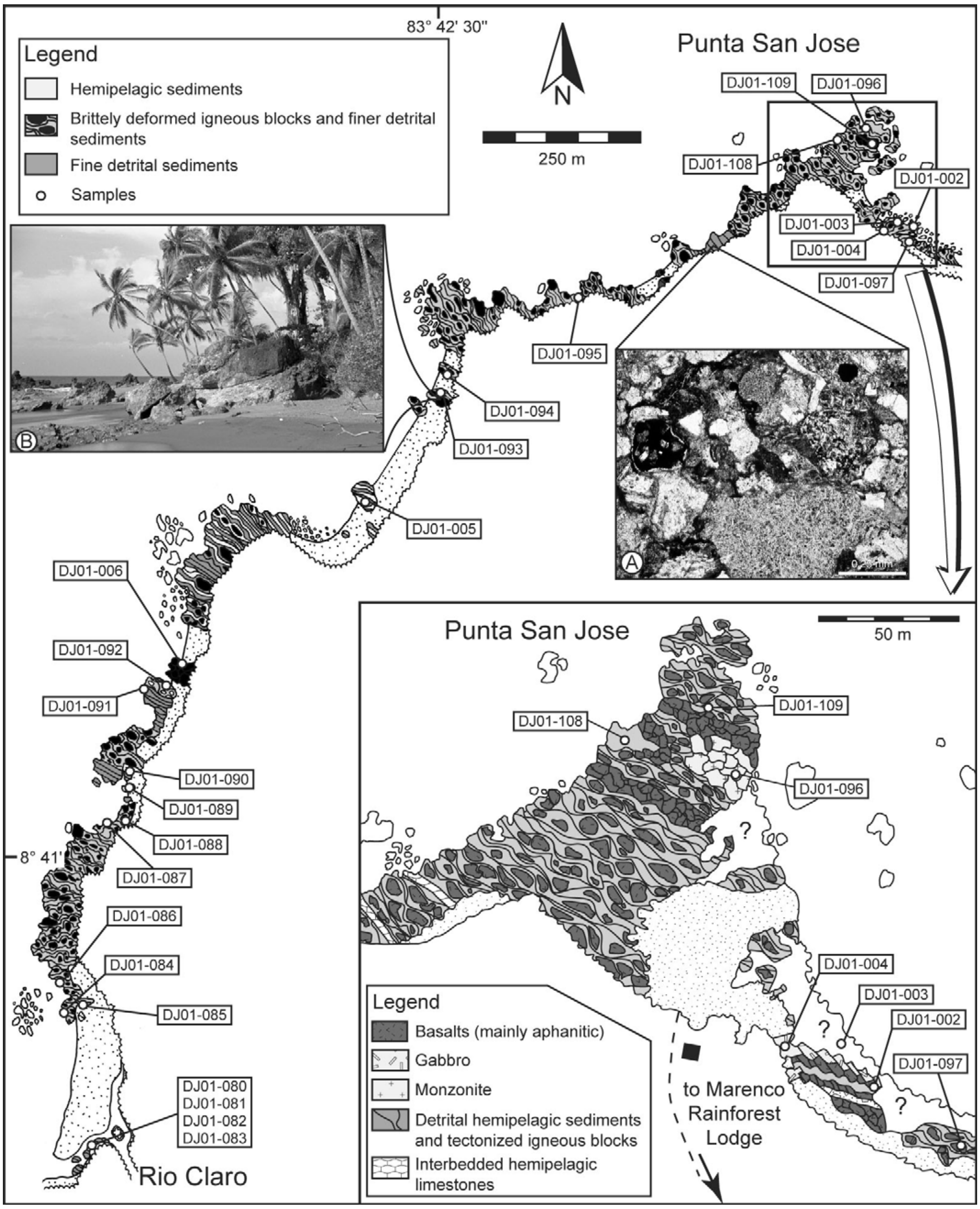

FIGURE 5

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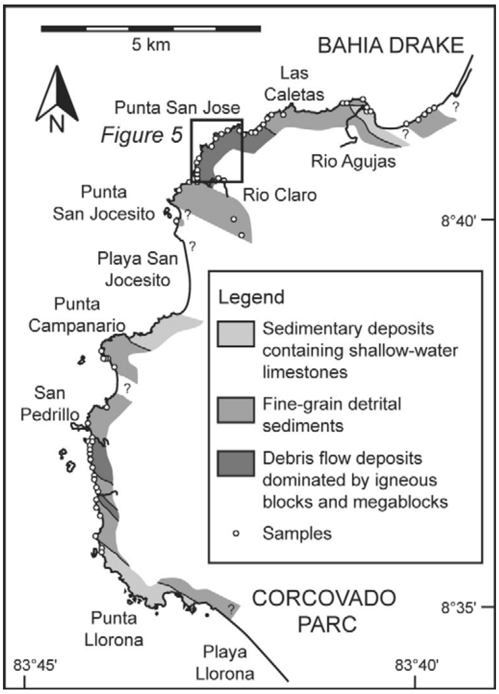

FIGURE 6

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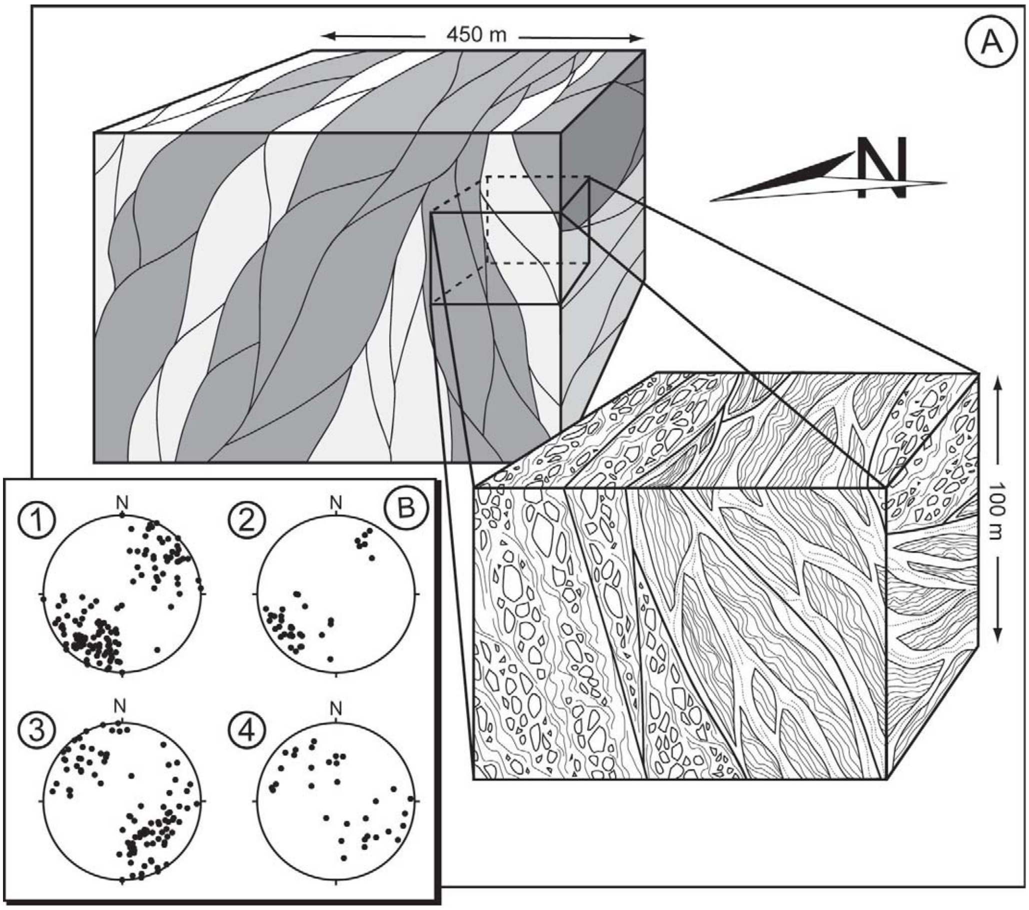

FIGURE 7

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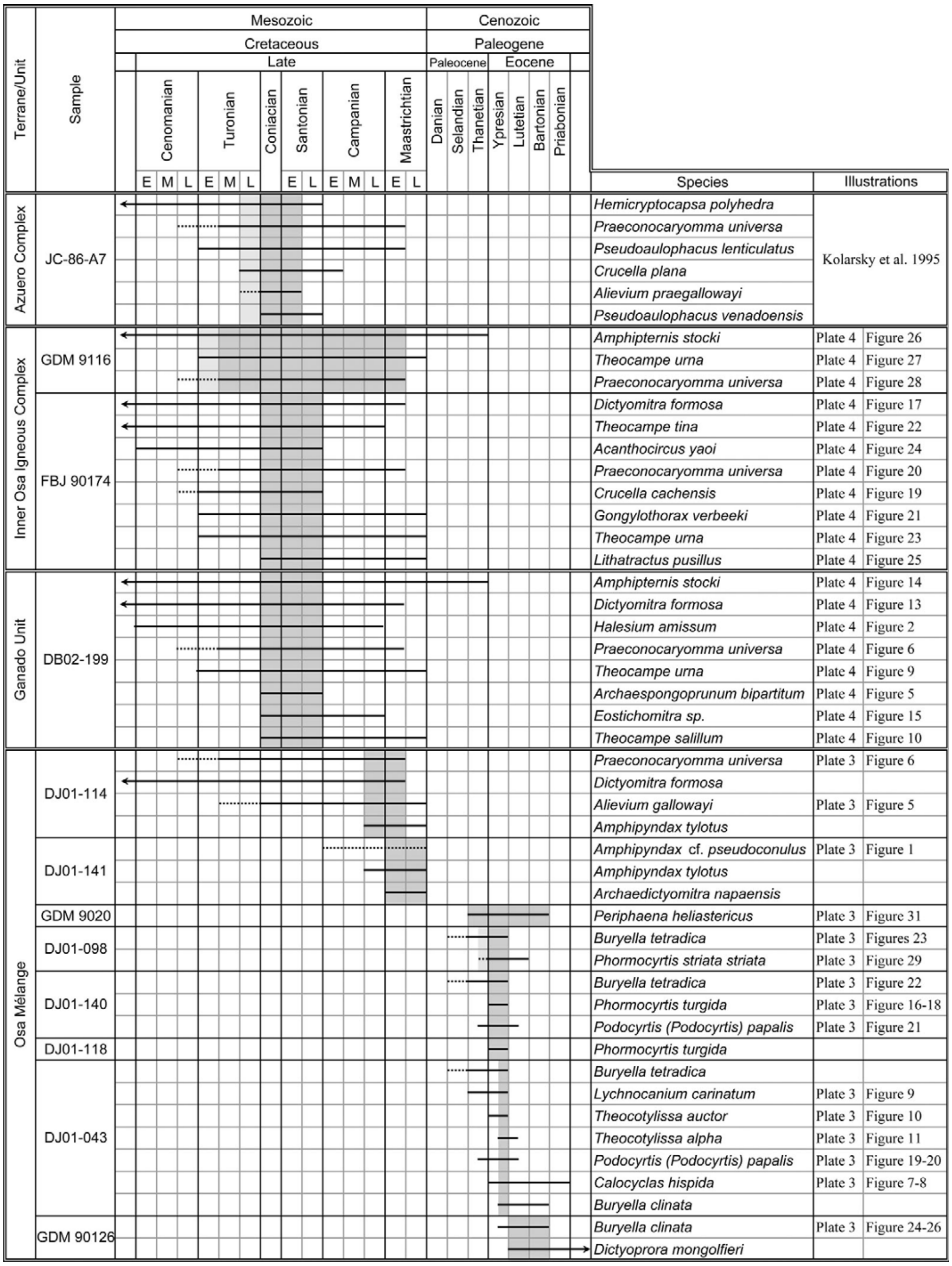

FIGURE 8

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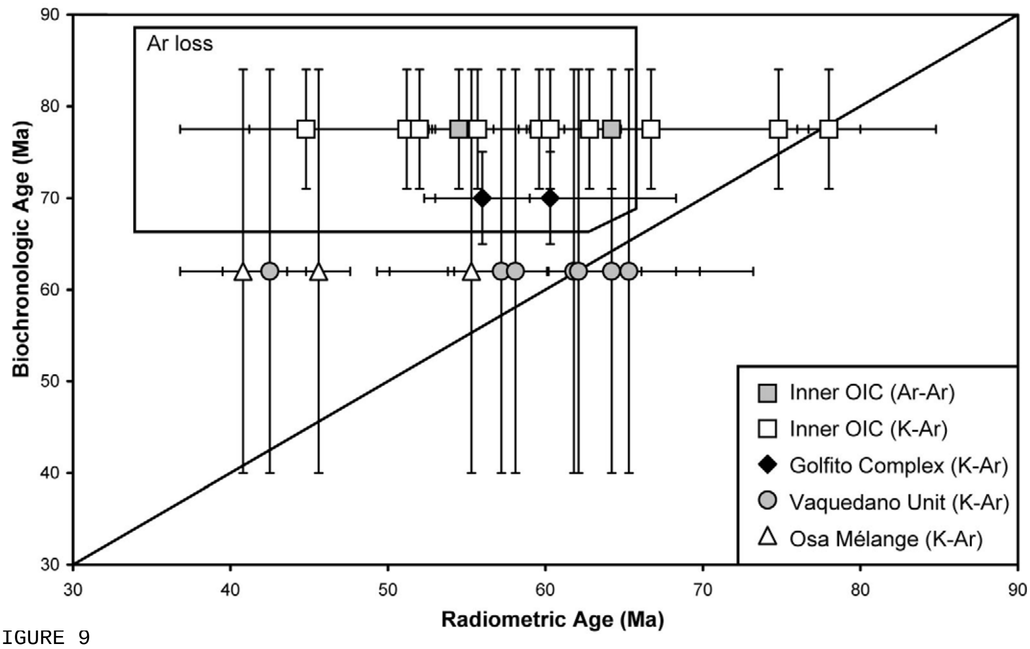

FIGURE 9

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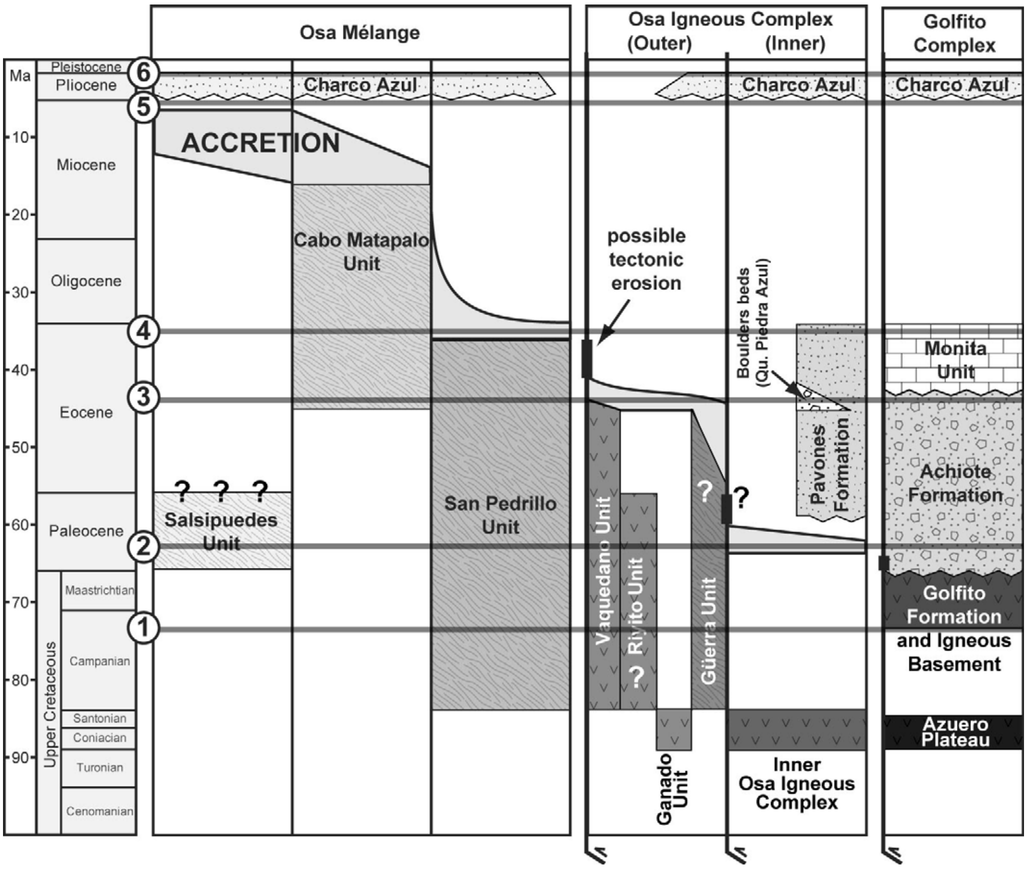

FIGURE 10

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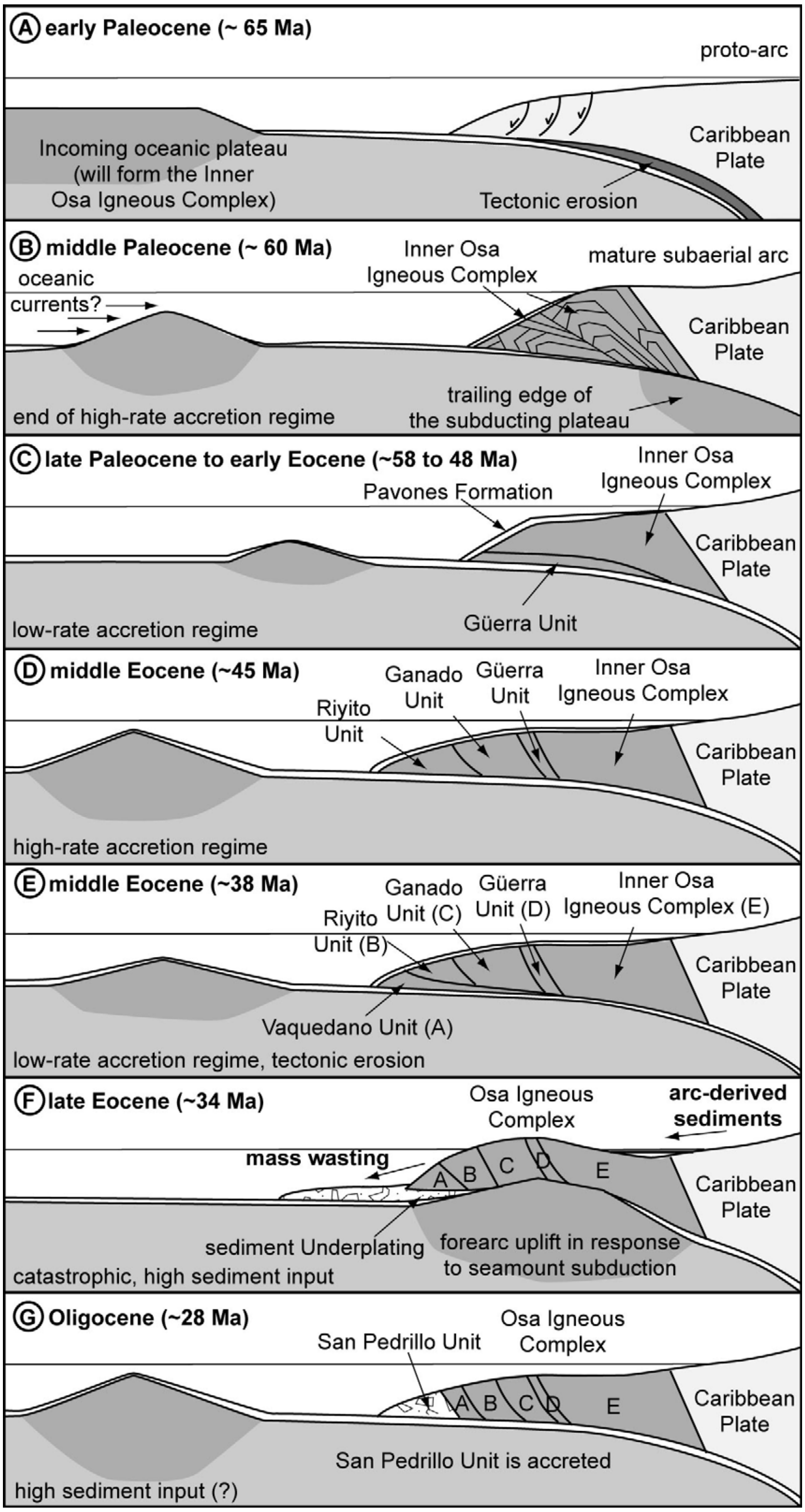

FIGURE 11

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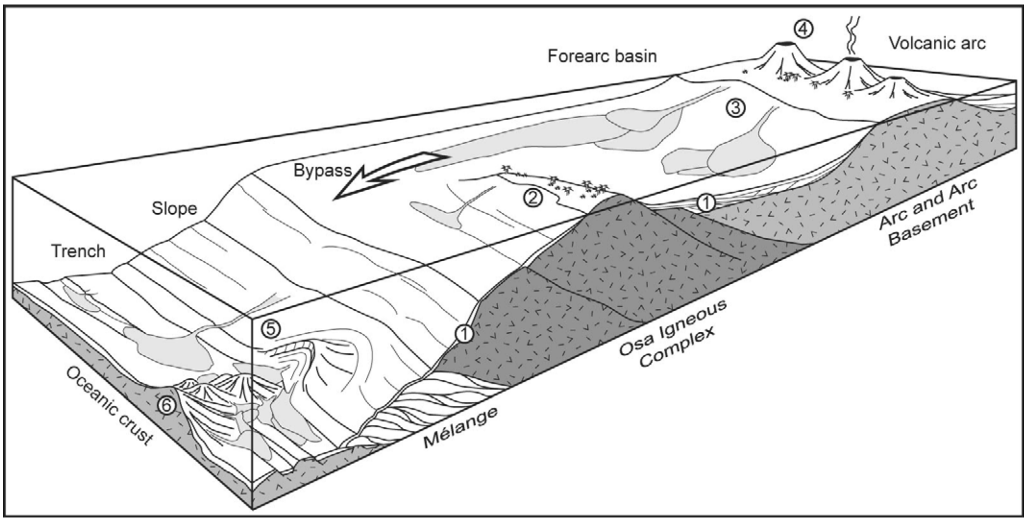

FIGURE 12

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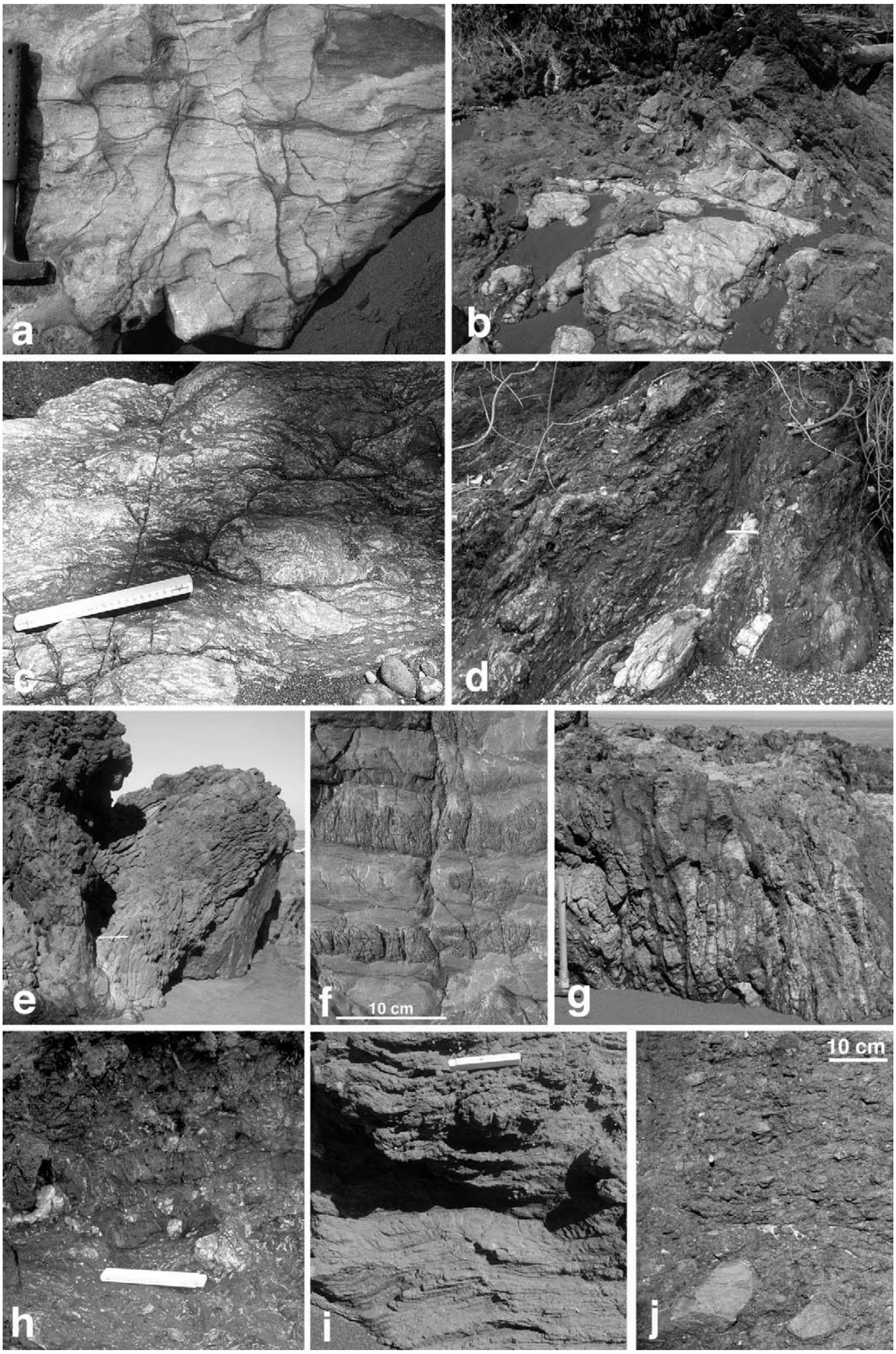

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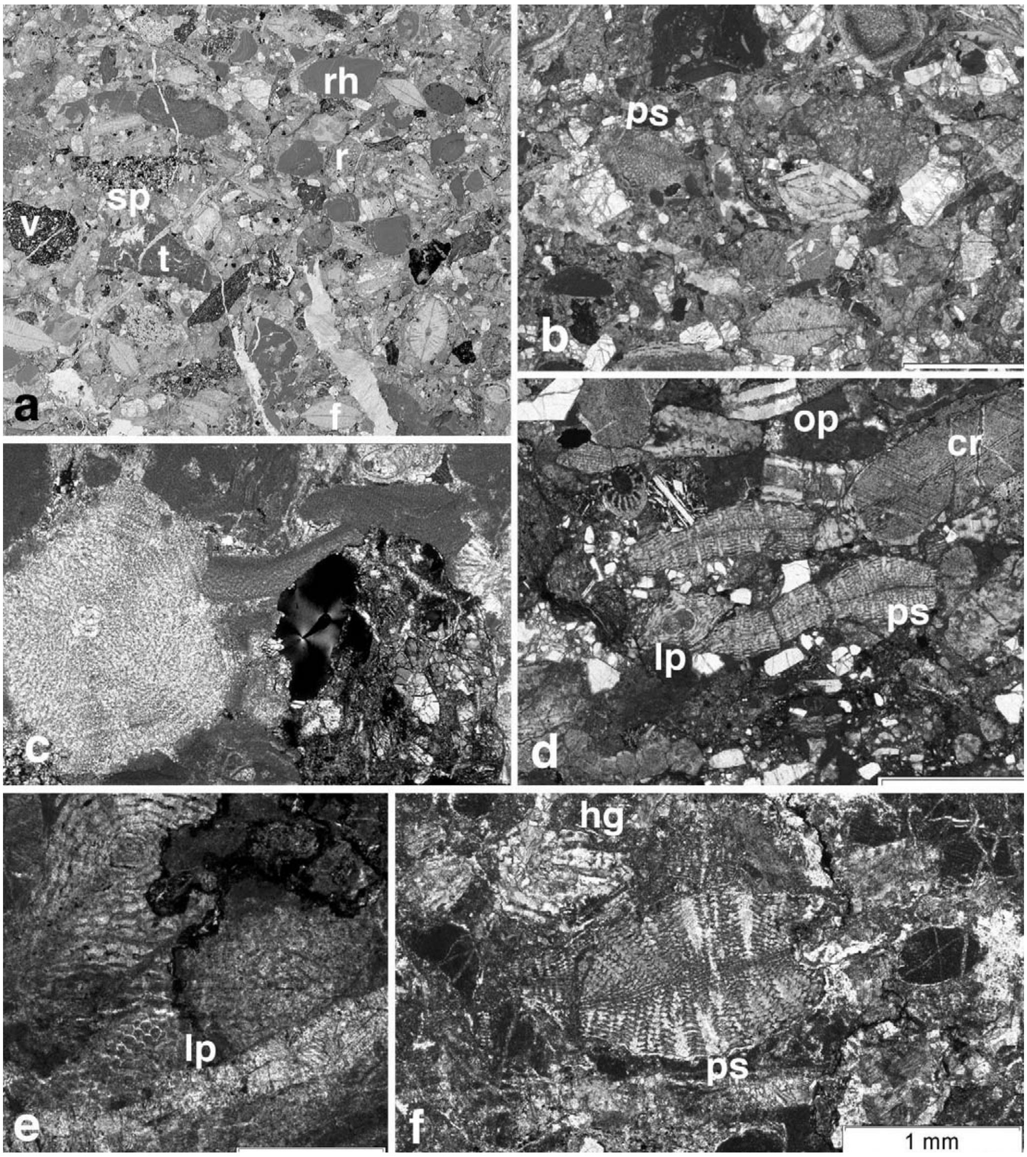

PLATE 2

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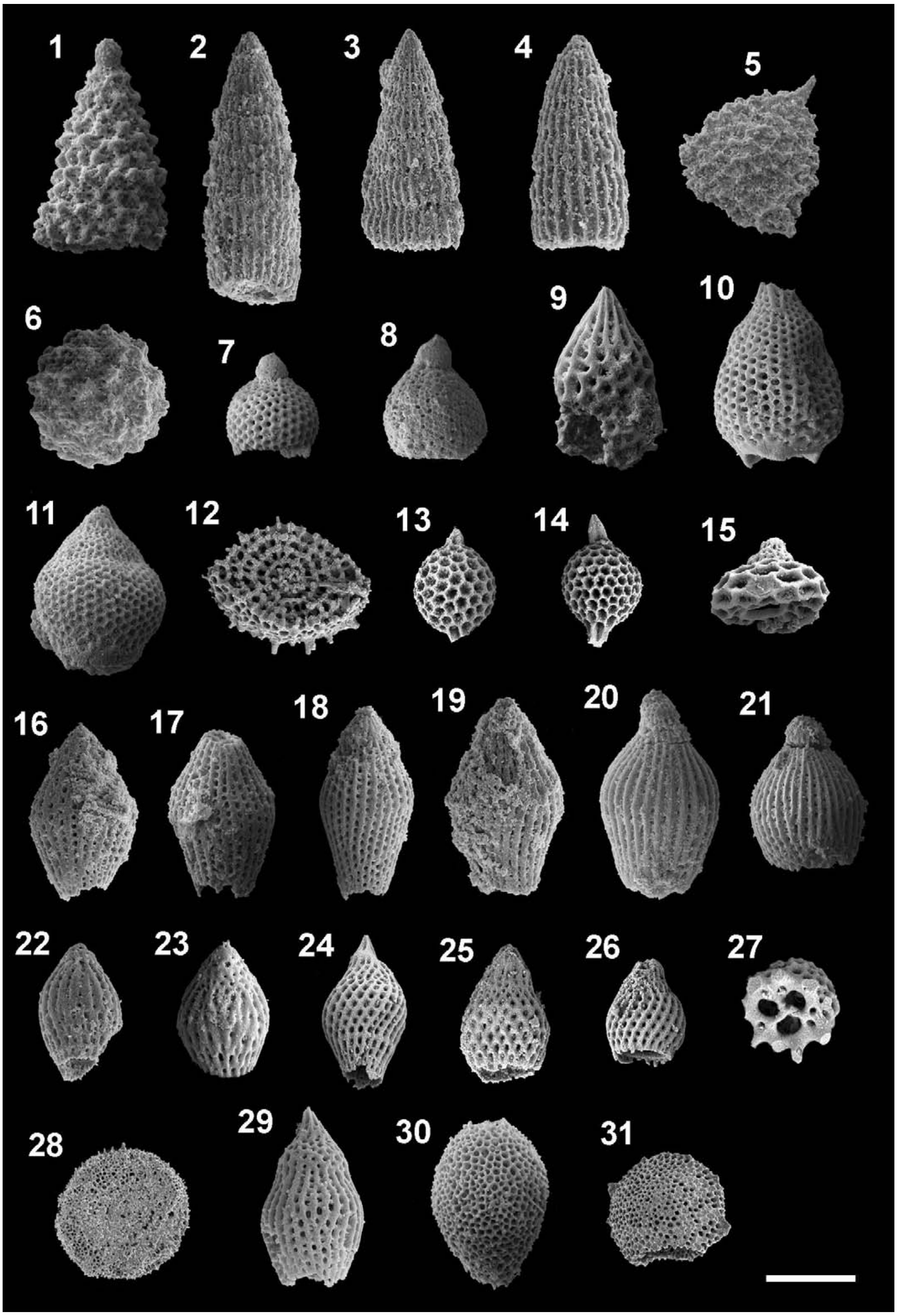

PLATE 3

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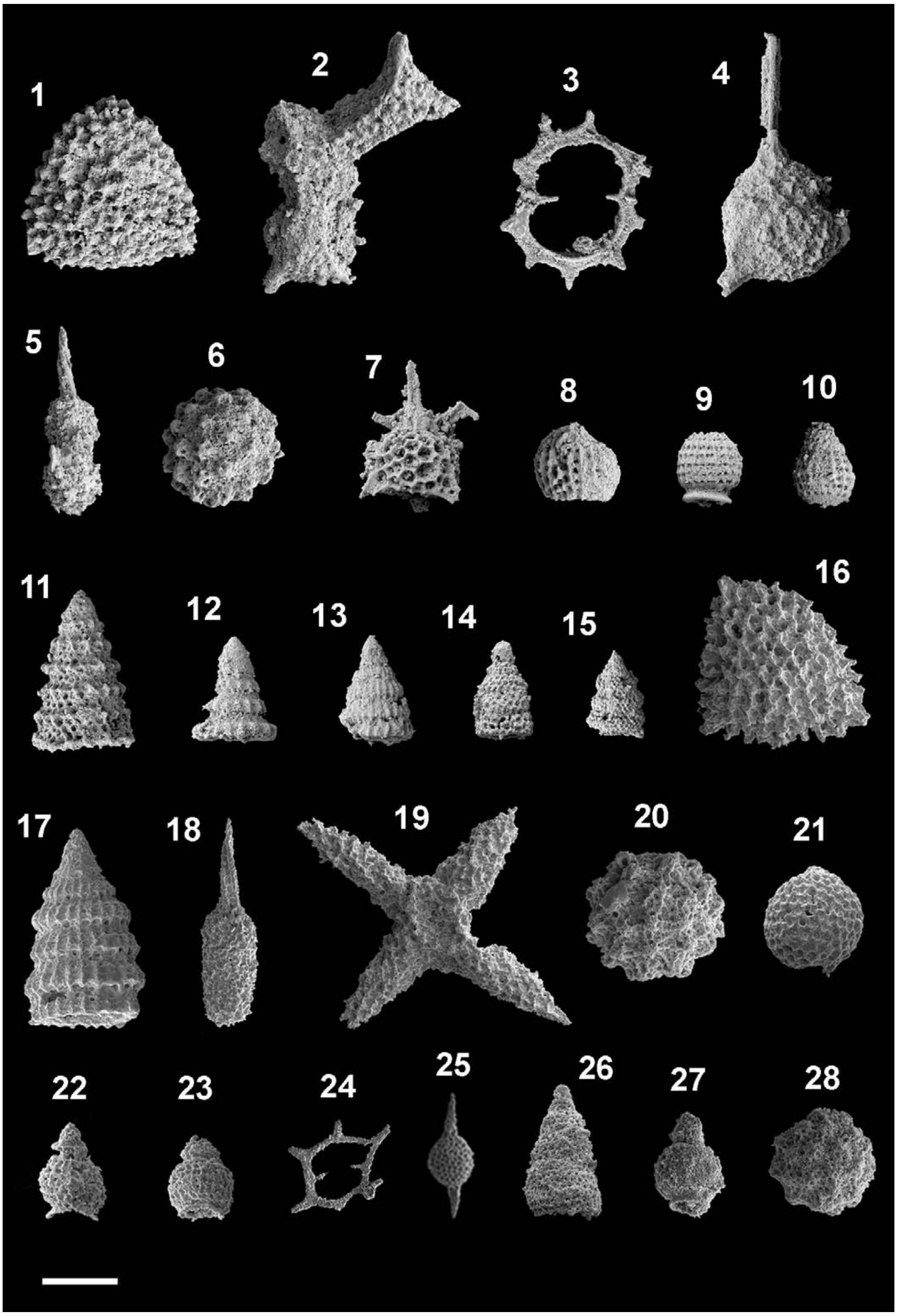

PLATE 4

Buchs et al., Late Cretaceous to Miocene Seamount Accretion and Mélange Formation in the Osa and Burica Peninsulas (Southern Costa Rica): Episodic Growth of a Convergent Margin, accepted in “Geology of the area between North and South America, with focus on the origin of the Caribbean Plate”, GSL Special Publication, in preparation, edited by K.H. James, M.A. Lorente and J. Pindell