Long-term non-erosive nature of the south Costa Rican margin supported by arc-derived sediments accreted in the Osa Mélange

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Abstract

Understanding the erosive and accretionary nature of convergent margins is significant to understand tectonics and the crustal mass balance at subduction zones. The Costa Rican margin is commonly regarded as an archetypal example of an erosive margin, where subduction of sediments and basal removal of the upper plate in the subduction zone have occurred for most of the Cainozoic. This view is supported by structural constraints from 3D seismic reflection data in the outer forearc, as well as periods of forearc subsidence at ODP/DSDP/IODP drill sites. However, determining the origin of the Upper Eocene-Miocene Osa Mélange that is exposed in south Costa Rica only 10–30 km from today's trench offers another opportunity to constrain the long-term erosive, accretionary, and/or non-erosive evolution of the margin. Existing models for formation of the mélange propose that it resulted from (i) accretion of arc-derived trench-fill sediments, (ii) punctual accretion of the clastic apron of an ocean islands system, (iii) local dismemberment of the margin due to tectonic erosion, or (iv) in-situ deformation of a forearc sedimentary cover. To test the validity of these models and provide new constraints on the accretionary and/or erosive nature of the margin we studied the provenance of volcaniclastic material in the Upper Eocene San Pedrillo Unit of the Osa Mélange using geochemical analysis of detrital pyroxenes, amphiboles and igneous rocks. This innovative approach to determine the origin(s) of dismembered sedimentary sequences reveals that the volcaniclastic fraction of the mélange is, without ambiguity, predominantly composed of forearc material that preserves an assemblage of arc basement, proto-arc and arc sequences of the pre-Oligocene Costa Rican margin. This result and previous geological constraints show that the Osa Mélange formed through accretion of arc-derived trench-fill deposits in the Late Eocene to Miocene, with possibly minor tectonic incorporation of intra-oceanic material (ocean floor and seamount sequences). Therefore, consistently with recent seismic observations in south Costa Rica that document a phase of accretion within the past ~5m.yr., preservation of arc-derived sediments in the Osa Mélange shows that the margin was predominantly non-erosive over the past ~35m.yr. Cycles of subsidence and uplift in the south Costa Rican forearc during this period could represent a tectonic response to episodic subduction of seamounts formed at the Galapagos Hotspot, without causal link to short-term subduction erosion or accretion. Fundamentally, new results from the Osa Mélange show that large (10 km-thick) accretionary complexes can form durably due to local sedimentary recycling of the forearc in seamount collisional settings. The recycled component of the NW Osa Mélange exemplifies that quantifying the extent of local recycling vs net crustal addition through accretion of intra-oceanic sequences or net crustal loss due to tectonic erosion poses a serious challenge to determine the crustal mass balance at subduction zones.

1. Introduction

Convergent margins can be subdivided into accretionary and erosive types depending on whether sediments on the subducting plate are tectonically scraped off in the subduction zone to form an accretionary complex, or whether the sediments are subducted entirely and the upper plate undergoes long-term tectonic erosion along the subduction interface (von Huene and Scholl, 1991; Clift and Vannucchi, 2004). Accretionary and erosive margins are equally abundant (von Huene and Scholl, 1991), with long-term accretionary or erosive behaviour primarily correlated to plate con-vergence and thickness of sediments on the downgoing plate (Clift and Vannucchi, 2004). Distinguishing between accretionary and erosive margins and characterising their nature and evolution are critical to our understanding of the recycling of continental crust, carbon cycle, subduction zone seismogenesis, as well as arc magmatism.

The Costa Rican margin is commonly regarded as a classical example of erosive margin, where considerable offshore research has been conducted (e.g., Ranero and von Huene, 2000; Vannucchi et al., 2003; Clift and Vannucchi, 2004; von Huene et al., 2004; Ranero et al., 2007; Vannucchi et al., 2013). The erosive nature of the margin since the Miocene has been supported by 3D seis-mic observations in the outer forearc of north and central Costa Rica (Ranero and von Huene, 2000; von Huene et al., 2004) and subsidence patterns determined based on benthic foraminifera collected by DSDP/ODP/IODP drilling in the outer forearc of north and south Costa Rica (Vannucchi et al., 2003, 2013) (Fig.1) [note: all figures are in the end of this document]. However, retreat of the volcanic front that is associated with long-term sub-duction erosion at some other convergent margins (Clift and Vannucchi, 2004) has not occurred in Costa Rica during the Cainozoic (Fig.1). Migration of the volcanic front in nearby Panama during 1159683the Eocene (Lissinna, 2005; Wegner et al., 2011) was most likely associated with oroclinal bending of the Panamanian volcanic arc during collision with South America (Montes et al., 2012). Significantly, recent 3D seismic observations in south Costa Rica show that at least parts of the forearc have experienced a phase of accretion within the past ∼5m.yr. (Bangs et al., 2016). This shows that the erosive nature of the Costa Rican margin during the Neo-gene is not as continuous or ubiquitous as previously considered, and that new data are needed to better determine the accretionary vs erosive or non-accretionary nature of the margin both spatially and temporally.

Another interesting observation that contrasts with the original definition of erosive margins (sensu von Huene and Scholl, 1991) is that the forearc of Costa Rica and Panama exposes a large number of accreted fragments of seamounts, ocean islands and possibly oceanic plateau(s) that were emplaced along the south Central American island arc during the Palaeocene to Mid Eocene (e.g., Hauff et al., 2000; Buchs et al., 2009, 2011a, 2016; Trela et al., 2015; Baumgartner-Mora and Baumgartner, 2016) (Fig.1). However, unlike typical accretionary complexes that include abundant accreted sediments, pre-Late Eocene accreted sequences in south Central America predominantly include igneous sequences that are juxtaposed with an igneous autochthonous backstop com-posed of the volcanic arc and its Upper Cretaceous oceanic plateau basement (Buchs et al., 2009, 2011b). In west Panama, a clear ex-ample of subduction erosion is exposed on the Azuero Peninsula in the form of accreted Eocene ocean islands that are juxtaposed with Upper Cretaceous arc sequences along a km-thick mélange interface (Kolarsky et al., 1995; Buchs et al., 2011a, 2011b). There-fore, despite ubiquitous exposures of accreted oceanic sequences in Costa Rica and Panama, regional geological constraints suggest that the margin was mostly erosive or non-accretionary before the Late Eocene, because it lacks large volumes of accreted sediments defining accretionary margins sensu von Huene and Scholl (1991). In this geological context, accreted seamounts, oceanic islands and oceanic plateau(s) can be interpreted to reflect only spatially-and temporally-restricted accretionary pulses along a predominantly erosive (or non-accretionary) margin (e.g., Vannucchi et al., 2006; Clarke et al., 2018).

In contrast to the Palaeocene to Mid Eocene geology of the Costa Rican-Panamanian margin, thick sedimentary sequences are exposed in the Osa Mélange in south Costa Rica, which have been interpreted by several studies as a Late Eocene-Miocene accretionary complex (Di Marco et al., 1995; Vannucchi et al., 2006; Buchs et al., 2009; Clarke et al., 2018) (Figs.1–2). However, the provenance of the sequences is still debated, with accretionary models favouring either a predominantly ocean island origin (Vannucchi et al., 2006; Clarke et al., 2018) or a predominantly trench-fill, margin-derived origin (Di Marco et al., 1995; Buchs et al., 2009). Determining the origin(s) of these sequences is critical to defining the erosive, accretionary and/or non-erosive nature of the margin in the Eocene-Miocene. If the mélange represents an assemblage of intra-oceanic volcano-sedimentary sequences em-placed during the collision and accretion of ocean islands (Vannucchi et al., 2006; Clarke et al., 2018), this would be consistent with the long-term, overall erosive behaviour of the margin with only punctual (i.e., short-term and spatially-restricted) seamount collisions, as described above during the Palaeocene-Mid Eocene. In contrast, if the mélange is composed of accreted sediments pre-dominantly derived from the margin (Di Marco et al., 1995; Buchs et al., 2009), this would document a phase of accretion typical of an accretionary margin sensu von Huene and Scholl (1991), therefore questioning the overall erosive nature of the Costa Rican mar-gin. Here we test these two hypotheses as well as other erosive models of formation of the Osa Mélange through a provenance study of volcaniclastic sequences exposed on the NW Osa Peninsula (Figs. 1–2). We show that the volcaniclastic fraction of the studied mélange is predominantly composed of material derived from the margin, and discuss why these new results and other regional geological constraints suggest that the present-day south Costa Rican margin might be best described as a non-erosive or "collisional" margin.

2. Geological background

2.1. Composition and possible origins of the Osa Mélange

The Osa Mélange is exposed on the Osa Peninsula, south Costa Rica, only 10–30 km from the present-day Middle American trench, above the subducting Cocos Ridge that represents an aseismic ridge that formed at the palaeo-Galapagos Hotspot (Fig.1). The mélange was subdivided into 3 units with contrasted lithologies by Di Marco et al. (1995), with from NE to SW, the San Pedrillo, Cabo Matapalo, and Salsipuedes Units. All these units have been preserved below the greenschist metamorphic facies. The Cabo Matapalo and Salsipuedes Units are predominantly composed of a greywacke matrix that includes blocks of Palaeocene to Middle Miocene pelagic limestone (Di Marco et al., 1995). The San Pedrillo Unit that is the focus of this study is composed of an assemblage of pelagic to hemipelagic sediments, including locally abundant igneous blocks (sometimes >10 m in size) and breccias of shallow-marine limestone (Di Marco et al., 1995; Buchs et al., 2009; Clarke et al., 2018; Bolz and Calvo, 2019). The age of the mélange's matrix is constrained by radiolarian assemblages to the Late Palaeocene-Mid Eocene, whereas blocks of siliceous and carbonate pelagic sediments range in age between the Late Cretaceous and Mid Eocene (Buchs et al., 2009 and references therein). Clasts of shallow-marine limestone include larger foraminifera of Mid to Late Eocene ages (Buchs et al., 2009; Bolz and Calvo, 2019). These biostratigraphic constraints ascribe the age of formation of the San Pedrillo Unit to the Late Eocene.

Detailed mapping of coastal exposures of the San Pedrillo Unit outline the occurrence of contrasting, albeit internally consistent lithologies at the km scale (Buchs et al., 2009; Clarke et al., 2018) (Fig.2and Supplementary Fig. S1). Most of the mélange is com-posed of silty-sandy hemipelagic sediments (55% of the mélange, Lithofacies 1 in Fig.2), with subordinate igneous breccia to mega-breccia (∼25% of the mélange, Lithofacies 2 in Fig.2), and minor breccia of shallow-marine limestone (∼20% of the mélange, Litho-facies 3 in Fig.2). Four main models have been proposed to ex-plain the formation of this lithological assemblage, as illustrated in Fig.3: (A) Accretion of trench-fill deposits predominantly derived from sedimentary erosion/gravitational collapse of the mar-gin (Di Marco et al., 1995; Buchs et al., 2009); (B) Dismemberment of the base of the outer margin and formation of a block-in-matrix (mélange) fabric through subduction erosion (Meschede et al., 1999); (C) Local, temporally restricted accretion of ocean island igneous to volcaniclastic material along a predominantly erosive margin (Vannucchi et al., 2006; Clarke et al., 2018); and (D) In situ deformation of forearc trench slope sediments controlled by fore-arc tectonics in the absence of accreted oceanic sequences (Bolz and Calvo, 2019). To test the validity of these models we synthesise previous regional geological constraints and study the geo-chemical affinity of igneous minerals (blocks, clinopyroxenes and amphiboles) in Lithofacies 1 and 2 to determine the provenance of the volcaniclastic fraction that is found in ∼80% of the NW Osa Mélange. As further discussed below, the geochemical diversity/peculiarity of igneous units encountered in south Costa Rica offers a unique opportunity to determine whether volcaniclastic material in the San Pedrillo Unit originated from a nearby backstop (model B), a range of forearc to arc sources (models A and D), or ocean is 1159685lands still partly preserved in other accreted units of south Costa Rica (model C) (Fig.3).

2.2. Geological context of the Osa Mélange

The Osa Mélange occurs next to basaltic oceanic sequences of the Osa Igneous Complex (OIC) (Fig.1B). Although these sequences were originally considered to represent a lateral extension of the south Central American volcanic arc (Berrangé and Thorpe, 1988; Meschede and Frisch, 1994), new geochemical, geochronological and biostratigraphic constraints show that they represent a series of accreted Upper Cretaceous to Middle Eocene seamounts and an Upper Cretaceous oceanic plateau (Di Marco et al., 1995; Hauff et al., 2000; Buchs et al., 2009, 2016). The OIC was subdivided into an outer and inner OIC complexes based on distinctive lithological, geochemical and age constraints (Buchs et al., 2009, 2016) (Fig.1B). The outer OIC is composed of accreted palaeo-Galapagos seamounts with tholeiitic to alkali basalts and gabbros stratigraphically interbedded with rare Upper Cretaceous to Middle Eocene pelagic sediments. In contrast, the inner OIC is composed of oceanic plateau tholeiitic basalts that are stratigraphically interbedded with rare Upper Cretaceous pelagic sediments, and that belong to a terrane or form the basement of the volcanic arc (Hauff et al., 2000; Buchs et al., 2009, 2016). The contact between the OIC and the Osa Mélange (observed in exposures of inland rivers) corresponds to a mélange-like zone that grades from deformed seamount basalts of the outer OIC to a sediment-rich block-in-matrix unit typical of the San Pedrillo Unit in the Osa Mélange (Buchs et al., 2009). Significantly for our provenance study, the seamounts in the outer OIC are characterised by 3 distinctive geo-chemical signatures (Buchs et al., 2016) that can offer excellent control on the provenance of volcaniclastic material in the Osa Mélange. Notably, Middle Eocene alkali basalts of seamount origin with a steep (OIB-like) pattern in normalised multielement diagrams form a distinctive unit at the contact with the mélange across Osa Peninsula. In addition, Palaeocene accreted seamounts of the outer OIC have an unusual depleted geochemical signature with low light REE contents that is almost unique among igneous sequences documented to date in Central America, the Caribbean area, and the eastern Pacific Ocean (Buchs et al., 2016). Critically, this unique geochemical signature offers a robust means of deter-mining whether volcaniclastic sequences of the San Pedrillo Unit formed due to basal erosion of the forearc after accretion of the depleted seamounts (similar to Model B, Meschede et al., 1999), or whether they were part of the volcaniclastic apron of seamounts accreted in the OIC (Model C, Vannucchi et al., 2006; Clarke et al., 2018). Similarly, the composition of oceanic plateau basalts in the inner OIC is sufficiently distinctive (e.g., flat patterns in normalised multielement diagrams, Buchs et al., 2016) to determine whether the Osa Mélange includes material reworked from this unit. Because the inner OIC is separated from the Osa Mélange by the outer OIC, recognising oceanic plateau material in the NW Osa Mélange would support the occurrence of sedimentary material that sourced in the margin (Models A and D; Buchs et al., 2009; Bolz and Calvo, 2019).

Further east, the OIC is in tectonic contact with the Golfito Complex that consists of Upper Cretaceous (Campanian) proto-arc sequences. These sequences are predominantly composed of tholeiitic basalts with a geochemical signature intermediate be-tween that of oceanic plateau and early arc sequences, with generally flat patterns and variable Nb-Ti negative and Th positive anomalies in normalised multielement diagrams; this signature is unique in the region (Buchs et al., 2010) and to our knowledge unreported from intra-oceanic settings. Lateral analogues of the Golfito Complex can be found on the Azuero Peninsula in west Panama, where proto-arc tholeiites overlap Upper Cretaceous oceanic plateau basalts similar to those of the inner OIC. These sequences are in turn underlying Upper Cretaceous to Eocene calc-alkaline and tholeiitic basalts to dacites from the early volcanic arc (Buchs et al., 2010; Wegner et al., 2011; Corral et al., 2011). Early arc sequences similar to those of Panama have not been documented yet in south Costa Rica (e.g., Abratis and Wörner, 2001), where they are likely buried under post-Eocene forearc deposits and younger (compositionally distinct) volcanic arc sequences. Be-cause of their characteristic geochemical signature, proto-arc igneous rocks (Golfito Complex) and pre-Oligocene arc igneous rocks (Azuero Arc) constitute two additional sources of volcaniclastic material that could be recognised in the Osa Mélange. Should volcanic arc material be found in abundance in the NW Osa Mélange, this would support formation of this unit predominantly through accretion or accumulation of margin-derived sediments, as suggested by Models A and D (Fig.3).

In summary, existing geological and geochemical data from south Costa Rica and nearby west Panama define 6 possible sources for the volcaniclastic material preserved in the NW Osa Mélange: (1–3) Three types of seamount basalts/gabbros accreted in the outer OIC and in tectonic contact with the mélange; (4)Oceanic plateau basalts in the inner OIC; (5) Proto-arc basalts in the Golfito Complex; and (6) Arc basalts to dacites in the pre-Oligocene volcanic arc. The occurrence of these sources in the mélange is tested below with the analysis of a broad selection of detrital minerals and igneous blocks from the San Pedrillo Unit.

3. Methods

Samples of the San Pedrillo Unit were selected among 113 samples of sedimentary and igneous rocks collected during mapping of coastal exposures of the NW Osa Mélange at the 1:5000 scale as described in Buchs et al. (2009). The detail of the mapping is illustrated in Fig.3 of Buchs et al. (2009), with original sampling coverage given in Supplementary Fig. S1. Seven turbidite samples were selected from the matrix of the mélange in both block-rich and block-poor areas of Lithofacies 1 (Fig.2). Polished thin sections were prepared from these samples to carry out Scanning Electron Microscope -Energy Dispersive Spectroscopy (SEM-EDS) analysis of detrital clinopyroxene and amphibole. In addition, 15 samples of igneous blocks were selected from Lithofacies 2 of the San Pedrillo Unit to complement original geochemistry of Buchs et al. (2009) with an extended set of trace elements. The location of all samples considered in this study is given in Fig.2.

Chemical microanalysis of clinopyroxenes and amphiboles was carried out using a Zeiss Sigma HD Analytical Scanning Electron Microscope at Cardiff University equipped with dual 150 mm2ac-tive area EDS detectors and Oxford Instruments Aztec software. Abeam energy of 20 kV was used with a nominal beam current of ~1nA. The analyses were fully standardised with elements calibrated using mineral standards from Astimex Standards Ltd and Smithsonian Microbeam Standards. Accuracy and precision were measured using repeated analysis of chrome diopside, augite, and Kakanui hornblende. All measurements used spot analyses. Beam drift was measured every 15 min using Co as a reference standard. SEM results and the results of standards analysed during this study are given in Supplementary File 2. All reported clinopyroxene and amphibole compositions are averages of 2 spot analyses per mineral. The analysis of standards shows that elements in clinopyroxenes like those encountered in this study have a relative error generally <10%, specifically of ∼2% for Ca, ∼4% for Na, ∼6% for Ti, and ∼10% for Cr. The detection limit of Cr was ∼0.02 wt.%. Although many analysed clinopyroxenes have a lower Cr content, this has no impact on our use of discrimination diagrams that are based on Ti +Cr values (Fig.5C). Amphiboles typically show relative errors of ∼4% for Ti and ∼3% for Na and K. Thus, SEM analytical errors are significantly lower than the natural variability of our samples.

Trace elements of the 15 selected samples of igneous rocks were measured at ALS Global laboratory in Loughrea, Ireland, using lithium borate fusion ICP-MS technique (ISO accreditation 17025:2005). Sample and standards powders (0.200 g) were added to lithium metaborate flux (0.90 g), mixed well and fused in a furnace at 1000◦C. The resulting melt was then cooled and dissolved in 100 mL of 4% HNO3/2% HCl3solution. This solution was then analysed by inductively coupled plasma -mass spectrometry (ICP-MS) on an Agilent 7700. Geochemical results (samples, standards, and blank) are provided in Supplementary File 3. This table also includes a synthesis of previous geochemical data from igneous blocks in the mélange (Buchs et al., 2009). Because rock powders were prepared in a tungsten carbide mill Ta and W were not included in the results.

4. Results

4.1. Sediment petrography

All selected sedimentary samples are fine to coarse sandy lithic arenite from Lithofacies 1 in the San Pedrillo Unit (Fig.2). Although these sedimentary rocks are plastically deformed and faulted with abundant calcite veins, they sometimes preserve grading that is consistent with a turbidite origin. Zones within our thin sections that have a similar petrography were treated as separate samples during acquisition of SEM-EDS mineral data (Fig.4A). Preservation of zones with a similar petrography in the deformed sediments indicate that the studied assemblages of detrital minerals are pristine and preserve original sediment source(s). Fresh to partly altered clinopyroxene, amphibole and epidote form 2–19 vol.% (commonly ∼5%) of the sedimentary rocks. Coarser lithic fragments are dominantly composed by porphyritic igneous rocks with feldspar phenocrysts, with subordinate subophitic coarse basalt, and altered sideromelane (Fig.4B). By analogy with other igneous sequences in the region, this lithic assemblage suggests a mixed provenance from calc-alkaline arc and tholeiitic basalt (oceanic plateau and/or proto-arc?) sources. Olivine ±Cpx porphyritic basalts that are typical of ocean island settings have not been observed in our samples. An arc source is suggested by pervasive, albeit rare, occurrence of zoned feldspars and quartz, as well as occasional zircon. Some of the quartz is polycrystalline (Fig.4C), which documents provenance from granitoids and/or metamorphic rocks. Reworking of the sediment from subaerial source(s) is attested by occurrence of rounded minerals and lithics.

4.2. Geochemistry of detrital pyroxenes and amphiboles

All analysed detrital pyroxenes (n=432, 13 petrographic samples) have augite to diopside compositions (Supplementary Files 2 and 4). They have Mg# >60 (Mg# =Mg/[Mg +Fe]) and an in-creasing Ti content with decreasing Mg#, indicating magmatic differentiation without fractionation of ilmenite (Fig.5A). The provenance of the detrital clinopyroxenes (Cpx) was assessed using tectonic discrimination diagrams of Leterrier et al. (1982). In these diagrams, only sample DJ01-080 includes a significant number of Cpx with alkaline affinities (Figs.5B–D). This affinity is typically associated with igneous rocks formed in intraplate settings such as ocean islands. All other analysed Cpx have almost exclusively subalkaline affinities that can be further discriminated between tholeiitic non-orogenic (MORB-like) and volcanic arc settings in a Ca vs Ti +Cr diagram (Fig.5C). This shows that 60% of subalkaline Cpxs (and the majority of all analysed Cpxs) have a volcanic arc affinity. Discrimination of Cpx within individual samples (Supplementary File 5) shows that several sandstones have mixed Cpx populations with MORB-like and arc affinities (e.g., samples DJ01-100 and DJ01-122). Although the origin of some MORB-like Cpx remains unclear (see below) these are significant observations that suggest that most analysed turbidites were sourced in a compositionally heterogeneous forearc environment.

In order to better constrain the origin of MORB-like detrital Cpx, we compared our results with 3 Cpx populations representative of potential volcanic sources in south Costa Rica: (1) basalts from depleted accreted seamounts in the outer OIC (sample DB02-216 of Group 3 in Buchs et al., 2016, new data presented in Supplementary File 2); (2) oceanic plateau basalts from western Colombia (data from Buchs et al., 2018, compositionally similar to the inner OIC); and (3) proto-arc basalts to basaltic andesites from the Golfito Complex (data from Buchs, 2008). As shown in Supplementary File 6 and Fig.5C, these reference datasets plot across the MORB-like – Arc discrimination boundary in the Ca vs Ti +Cr diagram of Leterrier et al. (1982). Although this suggests that some of (but not all) detrital Cpx with arc affinities were not sourced in arc sequences, a significant fraction of the detrital Cpx has very low Ti +Cr that unambiguously supports an arc origin. Comparison with reference datasets additionally shows that detrital Cpx that plot in the MORB-like field of the Ca vs Ti +Cr diagram (Fig.5C) most likely come from an oceanic plateau source, with possible proto-arc and/or depleted seamount source(s) similar to those exposed in the forearc of south Costa Rica.

Detrital amphiboles of the Osa Mélange were encountered in 5 of our 13 analysed samples, all of which also include arc-derived Cpx (Supplementary File 5). Most of the amphiboles are Magnesio-ferri-hornblende and Magnesio-hastingsite (based on Hawthorne et al., 2012and Locock, 2014) (Fig.6, Supplementary File 2). Considering that amphiboles have not been reported from the OIC and Golfito Complex, and that ocean island amphiboles generally are kaersutite with a high Ti content, the composition of the detrital amphiboles from the Osa Mélange is best explained by an arc origin. Three amphiboles are Ferro-actinolite, which suggests re-working from a metamorphic source, e.g., metamorphic aureoles around granitoid intrusions.

4.3. Whole rock geochemistry

New trace element analyses of 15 whole rock samples were combined with previous geochemical data from Buchs et al. (2009)for a total of 18 igneous blocks analysed in the NW Osa Mélange (Supplementary File 3). These blocks range in size from 10 cm to several tens of metres and were collected in both Lithofacies 1 and 2 of the San Pedrillo Unit (Fig.2). Petrographic observations indicate that these blocks predominantly include fine to coarse subophitic basalt, with subordinate gabbro, quartz-bearing dacite, and feldspar-phyric porphyritic andesite. The occurrence of intermediate-felsic igneous rocks is consistent with the SiO2con-tent of our samples, which ranges between 42 and 74 wt.% (Supplementary File 3). However, due to pervasive alteration of the igneous rocks embedded in the mélange and high abundance of veins in the blocks we only use here immobile trace elements to constrain the origins of selected samples.

Primitive mantle-normalised multielement diagrams reveal the occurrence of at least 5 types of igneous rocks preserved in the NW Osa Mélange (Fig.7). Type 1 corresponds to 4 andesites/dacites with arc signatures like those of the pre-Oligocene Azuero volcanic arc (Fig.7A). Type 2 is represented by 2 samples of basalt with arc signatures like those of Golfito Complex (Fig.7B). Type 3 is composed of 3 basalts and 1 andesite with an unusual, depleted arc signature (Fig.7C). An arc origin is attested by a negative Nb anomaly that is not seen in depleted basalts of the outer OIC. This unusual rock type has not been found yet in south Costa Rica but corresponds to a new member of the proto-arc that was recently recognised in nearby Panama (Brims et al., 2019). Type 4 corresponds to 2 basalts with an oceanic plateau signature (Fig.7D). The pattern and overall enrichment of trace elements suggest an inner OIC origin. Type 5 includes 4 basalts with ocean island affinities (Fig.7E). Two of these basalts are akin to some of the accreted seamounts in the outer OIC, whereas 2 others have no known equivalent in south Costa Rica. Finally, another type of igneous rock is suggested by a cumulate gabbro with very low light REE concentration (sample DJ01-063, Fig.7F). Th and Nb of this sample were below the detection limit of the ICP-MS, making determination of its origin uncertain. This sample could be similar to the depleted proto-arc (Type 3), or could be an unusual gab-bro from depleted seamounts accreted in the outer OIC (without known equivalent in these units).

In addition to multielement diagrams, the interpretation of the provenance of selected igneous blocks from the Osa Mélange is in good agreement with a large range of geochemical discrimination diagrams, including $(La/Sm)_n$ vs $(Th/Nb)_n$ diagram (Fig.8A), Zr/Y vs Nb/Y diagram (Fig.8B, after Fitton et al., 1997), and Nb/Yb vs Th/Yb and Nb/Yb vs TiO2/Yb diagrams (Figs.8C–D, after Pearce, 2008). As explained above, pre-Oligocene igneous sequences of the south Costa Rican and nearby Panamanian forearc area have very specific geochemical signatures. Recognition of these signatures in igneous blocks of the San Pedrillo Unit provides therefore unambiguous evidence for the occurrence of material recycled from the early arc in the NW Osa Mélange.

5. Discussion

5.1. Source and origin of the NW Osa Mélange

Recognition of ubiquitous arc-derived clinopyroxenes, amphiboles and basalts-dacites in the studied turbidites and igneous blocks of the San Pedrillo Unit is a significant result that allows us to test the validity of existing models of formation of the Osa Mélange (Fig.3). Our results show that a large fraction of the NW Osa Mélange originated from the convergent margin, with alkaline Cpx and OIB-like basalt indicative of ocean island volcaniclastic material restricted to only 5 (out of 31) of our samples (Fig.2). When present, blocks of OIB (or margin-derived oceanic plateau) are closely associated in the field with arc-derived mate-rial (Fig.2). Also, arc-related Cpx are associated with seamount and/or oceanic plateau-related Cpx in several turbidite samples (Fig.4A, Supplementary File 5). This demonstrates that the volcaniclastic sequences in the NW Osa Mélange cannot represent significant volumes of ocean island debris formed in an intra-oceanic setting (Model C in Fig.3, Vannucchi et al., 2006; Clarke et al., 2018). This result is also consistent with the origin of Lithofacies 3 in the San Pedrillo Unit, which is composed of breccia of Middle to Upper Eocene shallow-marine limestone with petrographic and palaeontological evidence for reworking from the shelf of the volcanic arc (Buchs and Baumgartner, 2007; Bolz and Calvo, 2019).

Model C also proposes that accreted igneous sequences in the outer OIC are ocean island fragments that were originally stratigraphically associated with volcaniclastic material of the San Pedrillo Unit (Vannucchi et al., 2006; Clarke et al., 2018). How-ever, in contrast to other accretionary complexes in Costa Rica and Panama that include abundant geological evidence for subaerial intra-oceanic environments (e.g., Buchs et al., 2011a; Baumgartner-Mora and Baumgartner, 2016), oceanic sequences in the outer OIC are exclusively composed of submarine lava flows with rare hyaloclastites and pelagic sediments (Berrangé and Thorpe, 1988; Di Marco et al., 1995; Buchs et al., 2009). This indicates that the outer OIC includes accreted seamounts (Hauff et al., 2000; Buchs et al., 2016), without ocean islands and their associated carbonate platforms and volcaniclastic apron. In addition, our geochemical results show that igneous blocks in the NW Osa Mélange include only a minor fraction of material potentially derived from the outer OIC (samples DJ01-133 and DJ01-144, possibly sample DJ01-063, Figs. 7–8). This observation and evidence for abundant arc-derived material and pelagic-hemipelagic sediments in the San Pedrillo Unit also demonstrate that the mélange was not produced by tectonic dismemberment of the outer OIC during subduction erosion (Model B in Fig.3, Meschede et al., 1999).

Widespread occurrence of arc-derived volcaniclastic materials in the San Pedrillo Unit is consistent with both accretion of trench-fill sediments (Model A in Fig.3, Di Marco et al., 1995; Buchs et al., 2009) and in-situ deformation of trench slope sediments (Model D in Fig.3, Bolz and Calvo, 2019). However, as pointed out by most regional studies (Baumgartner et al., 1989; Di Marco et al., 1995; Meschede et al., 1999; Vannucchi et al., 2006; Buchs et al., 2009; Clarke et al., 2018), the structural fabric of the mélange is typical of subduction zone deformation as observed in accretionary complexes globally. Although Model D proposes that igneous rocks of Lithofacies 2 in the San Pedrillo Unit emplaced and mingled with slope sediments (Bolz and Calvo, 2019), peperitic textures have not been recognised during detailed mapping of the mélange (Buchs et al., 2009; Clarke et al., 2018). In addition, our geochemical results from debris flow deposits reveal complex assemblages of igneous blocks with intraplate oceanic to supra-subduction origins. This cannot be explained without older accretionary events and sedimentary reworking in the forearc, as suggested in Model A and several studies on the origins of igneous sequences in south Costa Rica (Hauff et al., 2000; Buchs et al., 2009, 2016).

We conclude based on preceding observations that the studied NW Osa Mélange records accretion of pelagic-hemipelagic sediments and trench-fill deposits (Model A in Fig.3). These deposits predominantly originated from sedimentary reworking of igneous sequences of the volcanic arc (Upper Cretaceous proto-arc and pre-Oligocene arc sequences) and from carbonate platforms bordering the arc. Subordinate reworking occurred from an Upper Cretaceous oceanic plateau (inner OIC, accreted or basement of the arc) and accreted Upper Cretaceous to Middle Eocene seamounts (outer OIC), which all emplaced along the margin before Late Eocene formation of the Osa Mélange. Two igneous blocks (samples DJ01-042 and DJ01-082) have OIB signatures without known equivalent in igneous sequences of the south Costa Rican margin (Figs.7–8). These blocks, and turbidite DJ01-080 that contains abundant alkaline Cpx and was collected close to basalts DJ01-42 and DJ02-082 in the field (Fig.2), could reflect minor tectonic incorporation of a subducting seamount during assembly of the mélange in the subduction zone. Alternatively, this unusual OIB material could represent gravitational collapse of a seamount in the trench, as il-lustrated in Fig.3A.

The cause for the accretion of large volumes of arc-derived volcaniclastic materials found in the San Pedrillo Unit of the Osa Mélange remains poorly understood. However, it is interesting to note that the emplacement of this unit in the Late Eocene followed, or was partly synchronous to, major geological changes in Costa Rica and Panama (Buchs et al., 2011b). At this time, volcanic fronts were displaced up to ∼100 km in Panama (Wegner et al., 2011), and major unconformities developed in forearc and back-arc basins in Costa Rica and Panama (Kolarsky et al., 1995; Brandes and Winsemann, 2018). This shows that important changes occurred in the dynamics of subduction at this time, which could have been caused by plate re-organisation in the Pacific (Buchs et al., 2011b) and/or collision of Panama with South America (Montes et al., 2012). These events are associated with regional forearc up-lift(s) that could have accelerated the production of margin-derived clastic sediment and promote accretion. In addition to these regional events, palaeo-Galapagos oceanic islands that accreted during the Middle Eocene in Panama (Hoernle et al., 2002; Buchs et al., 2011a) suggest that collisional events could also have occurred in south Costa Rica due to subduction of seamounts. Seamounts collision could have increased local production of margin-derived clastic sediments to promote formation of the San Pedrillo Unit (Buchs et al., 2009). Although the exact cause of formation of the San Pedrillo Unit remains obscure, it is possible that this unit developed at least partly in response to regional tectono-sedimentary changes. Should this be correct, this unit could have a regional ex-tent that remains to be documented in other, submarine parts of the Costa Rican-Panamanian forearc.

5.2. Implications for the non-erosive nature of the south Costa Rican margin and determining crustal mass balance in subduction zones

The long-term, presumably on-going erosive nature of the south Costa Rican margin has previously been considered in agreement with the origin of the Upper Eocene to Miocene Osa Mélange (Vannucchi et al., 2006; Clarke et al., 2018) as well as fast subsidence of the forearc in the Pleistocene at IODP Site U1379 in south Costa Rica (Vannucchi et al., 2013). As mentioned above, the lack of accreted sediment in the forearc in Costa Rica-Panama before the Late Eocene (e.g., Buchs et al., 2009, 2011b; Baumgartner-Mora and Baumgartner, 2016; Andji´c et al., 2019) is consistent with net tectonic erosion (or non-accretion) along the early margin. In west-ern Panama, subduction erosion is well documented by accreted Eocene oceanic islands juxtaposed with the Upper Cretaceous volcanic front (Buchs et al., 2011b). Conspicuous accreted seamounts, oceanic islands and oceanic plateaus in Costa Rica and Panama (e.g., Hauff et al., 2000; Buchs et al., 2011a, 2016; Trela et al., 2015; Andji´c et al., 2019) suggest that only large topographic features on the ocean floor could accrete before the Late Eocene. This could have been facilitated by increased collisional behaviour of subducting seamounts with the margin in the absence of thick packages of accreted/subducting sediment in the shallow subduction zone (e.g., Cloos and Shreve, 1996). However, accretion (and preservation) of arc-derived sediments in the Upper Eocene Osa Mélange as documented in this study disagrees with long-term tectonic erosion. Instead, our results, together with Middle Miocene blocks of pelagic limestone accreted in the SW Osa Mélange (Di Marco et al., 1995) and a recent (<5 Ma) phase of accretion near the Osa Peninsula (Bangs et al., 2016), provide growing evidence for net accretionary and non-erosive behaviour of the south Costa Ri-can margin in the past ∼35m.yr. Although it is possible that the margin underwent periods of non-accretion in the Cainozoic, the nature of the geological record considered in this and previous studies in Costa Rica and Panama has not yielded yet supporting evidence for this process. This has however no implication for the long-term non-erosive behaviour of the margin that is supported by our new results on the preservation of recycled arc-derived material accreted in the Upper Eocene San Pedrillo Unit.

Although the long-term non-erosive behaviour of the south Costa Rican margin was possibly punctuated by short periods of tectonic erosion (e.g., Buchs et al., 2011b; Vannucchi et al., 2013), subsidence patterns along the forearc are unlikely to offer a reliable indication of erosion. The geological record, neotectonic constraints and the present-day morphology of the south Central American margin provide numerous examples of spatially-and temporarily-restricted phases of uplift and subsidence in response to the collision of seamounts and other topographic highs on the subducting Cocos and Nazca Plates (Corrigan et al., 1990; Fisher et al., 1998; Sak et al., 2009; Buchs et al., 2011b; Morell, 2016; Andji´c et al., 2018; Brandes and Winsemann, 2018; Morell et al., 2019). Events of uplift and subsidence along the forearc have most likely been abundant during the long-term history of the forearc considering that, since inception of the subduction zone in the Late Cretaceous (Buchs et al., 2010; Wegner et al., 2011; Andji´c et al., 2019), the margin has continuously been impacted by the arrival of seamounts formed at the Galapagos Hotspot (Hoernle et al., 2002). In south Costa Rica, a recent cycle of forearc subsidence and uplift is well documented by Plio-Pleistocene marine sediments of the Osa/Charco Azul Group that disconformably overlaps on the Osa Mélange and OIC (Berrangé, 1989; Coates et al., 1992; Corrigan et al., 1990; Gardner et al., 2013) (Fig.2). Pliocene-Pleistocene trench-slope turbidites exposed on the Burica Peninsula were raised several kilometres during collision/subduction of the Cocos Ridge, with an average uplift rate of ∼1 mm/m.yr. (Corrigan et al., 1990). In addition, late Quaternary uplift rates (1.7 m/k.yr. to 8.5 m/k.yr.) determined from the sedimentary record on the Osa Peninsula could directly mirror the bathymetry on the Co-cos Ridge (Gardner et al., 2013). Yet, the exact timing of initial collision/subduction of the ridge in south Costa Rica remains obscured by limited understanding of the Cocos Plate geometry at the leading edge of the Cocos Ridge close to Caribbean-Cocos-Nazca triple junction (Morell, 2016). Because this is key to determine the timing and extent of the effects of the ridge in the outer forearc, Pleistocene subsidence along the northern side of the Cocos Ridge is difficult to interpret. Although it is possible that this subsidence reflects a fast pulse of tectonic erosion (Vannucchi et al., 2013), it could also more directly relate to bathymetric adjustments of the upper plate due to the seafloor roughness of the subducting plate, consistent with the long-term accretionary to non-erosive period documented by the nearby Osa Mélange (Di Marco et al., 1995; this study) and outer forearc (Bangs et al., 2016).

This study shows that determining the origin of mafic to felsic volcaniclastic material preserved in subduction mélanges can provide a significant insight into local tectonics at the time of mélange formation. This approach is particularly useful to deter-mine whether a mélange reflects (i) local recycling of the margin through sedimentary erosion and tectonic accretion (this study), (ii)net addition of intra-oceanic volcaniclastic material to the mar gin by accretion (e.g., Clarke et al., 2018), or (iii) net loss due to subduction erosion and, possibly, development of a block-and-matrix fabric due to local dismemberment of the base of the fore-arc (e.g., Meschede et al., 1999). These 3 modes of mélange formation are associated with variable amounts of crustal addition/removal in the forearc environment, but could share similar litho-logical and geometrical properties or undergo a complex structural evolution. This makes their recognition and accretionary and erosive interpretation from indirect geophysical data challenging (e.g., Bangs et al., 2016). Similarly, without knowledge of the original geometry of the convergent margin it is impossible to assess the amount of material that might have been lost through subduction erosion (e.g., Buchs et al., 2011b). Difficulties to reconstruct the original geometry of the convergent margin also limit our ability to assess crustal addition/removal associated with the formation of a mélange from local sedimentary recycling, even when the origin of the accreted material can be determined through field observation or drilling (e.g., Buchs et al., 2009; Clarke et al., 2018; this study). Overall this means that reconstructing the crustal mass balance at convergent margins faces a significant challenge, which could tentatively be addressed through further integration of in-direct geophysical constraints with regional geological constraints, local field observations, and drilling. Critically, new results from the NW Osa Mélange warn us that this approach will require the use of detailed provenance studies to successfully characterise the intra-oceanic vs locally recycled or tectonically eroded origin of subduction mélanges.

6. Conclusions

Detailed provenance study of the fine to coarse volcaniclastic fraction of the Upper Eocene San Pedrillo Unit in the NW Osa Mélange provides a novel insight into the erosive vs accretionary nature of the south Costa Rican margin. This study shows that this unit preserves a complex assemblage of volcaniclastic material recycled from the early volcanic arc and nearby pre-Oligocene accretionary complexes, as well as breccias of Eocene shallow-marine limestone reworked from the early arc shelf. These deposits and blocks of Miocene pelagic limestone in the SW Osa Mélange (Di Marco et al., 1995) belong to an accretionary prism that attests for net accretion along the south Costa Rican margin during the Late Eocene-Miocene. Although only reported from the Osa Peninsula, the mélange could form large parts of the outer, submarine fore-arc in Costa Rica and Panama. Together with seismic evidence for a recent (<5Ma) phase of accretion in south Costa Rica (Bangs et al., 2016), the geological record of the Osa Mélange documents long-term, possibly continuing, non-erosive behaviour of the south Costa Rican margin since the Late Eocene. Although forearc subsidence in south Costa Rica has been suggested to reflect tectonic erosion during the Pleistocene, cycles of uplift and subsidence in the forearc since the Miocene suggest that the subduction of topographic highs on the ocean floor might have played a dominant control on the bathymetric evolution of the margin. This and widespread occurrence of pre-Oligocene seamounts and oceanic is-lands accreted in Costa Rica and Panama suggest that the Costa Rican margin might be best described as a collisional (rather than erosive, accretionary, or non-erosive) margin. Even during possible phases of erosion, regional geological observations show that this intra-oceanic margin differs significantly from the original erosive model developed from continental margins (von Huene and Scholl, 1991). Notably, the Costa Rican-Panamanian margin offers a unique and significant opportunity for the study of the impact of subducting seamounts on the short-to long-term tectonic, seismic and magmatic evolution of convergent margins. In addition, this study shows that a detailed provenance study is critical in discriminating between intra-oceanic, local sedimentary recycled, or local tectonically eroded origins of materials preserved in subduction mélanges. A broader use of this approach will be required to determine crustal mass balance at convergence margins globally.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

Supplementary material related to this article can be found on-line at https://doi.org/10.1016/j.epsl.2019.115968.

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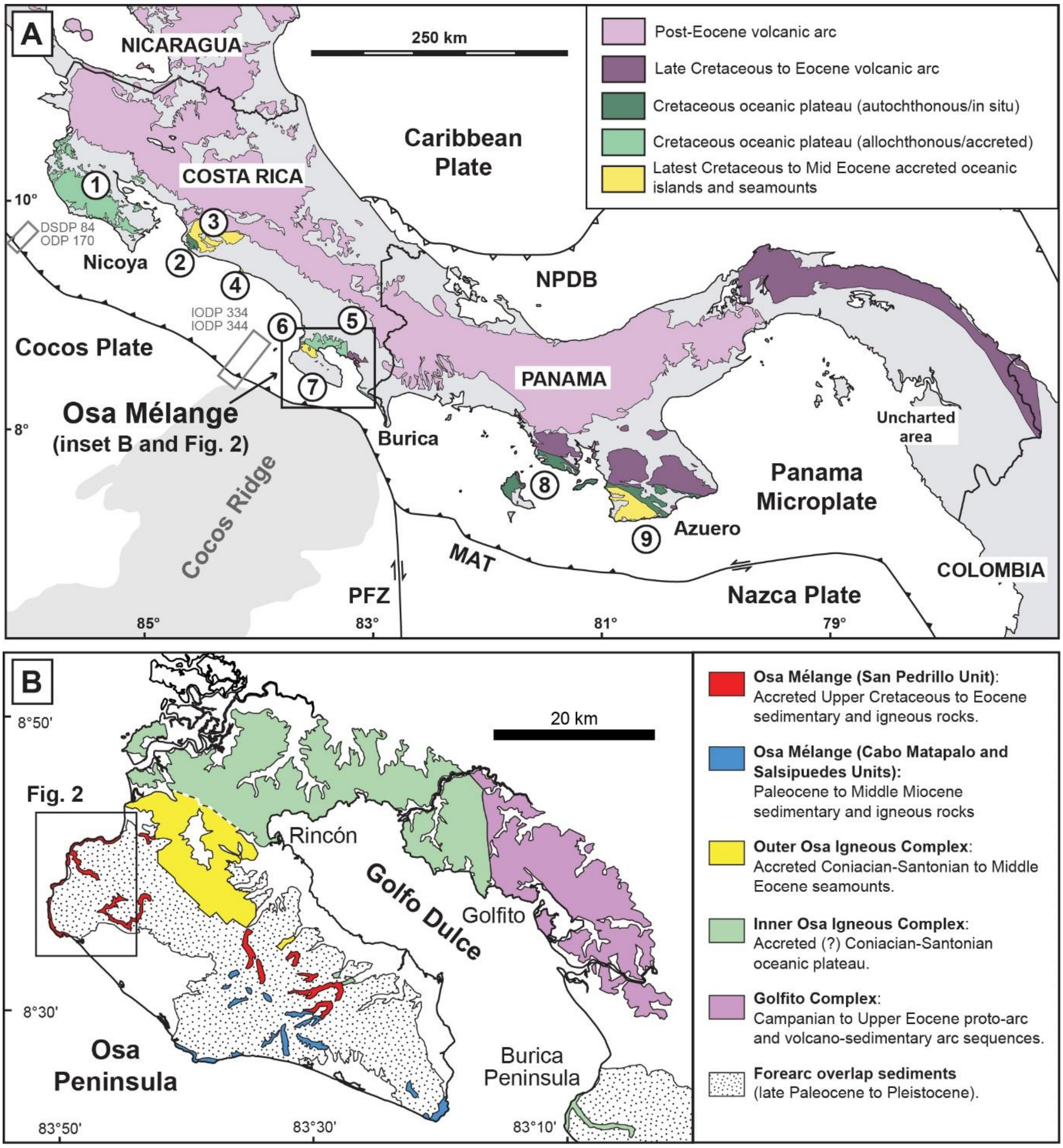

Fig.1. Simplified geological map of the Costa Rica-Panama convergent margin (modified from Buchs et al., 2010), with Cretaceous to Cainozoic exposed forearc basement complexes: (1) Nicoya Complex, Manzanillo Terrane, and Tortugal komatiitic suite; (2) Herradura Complex; (3) Tulin Formation; (4) Quepos terrane; (5) Inner Osa Igneous Complex; (6) Outer Osa Igneous Complex; (7) Osa Mélange; (8) Azuero Plateau; and (9) Azuero Accretionary Complex and Mélange. MAT =Middle America Trench, NPDB =North Panama Deformed Belt, and PFZ =Panama Fracture Zone. Fig.1B is modified from Buchs et al. (2009).

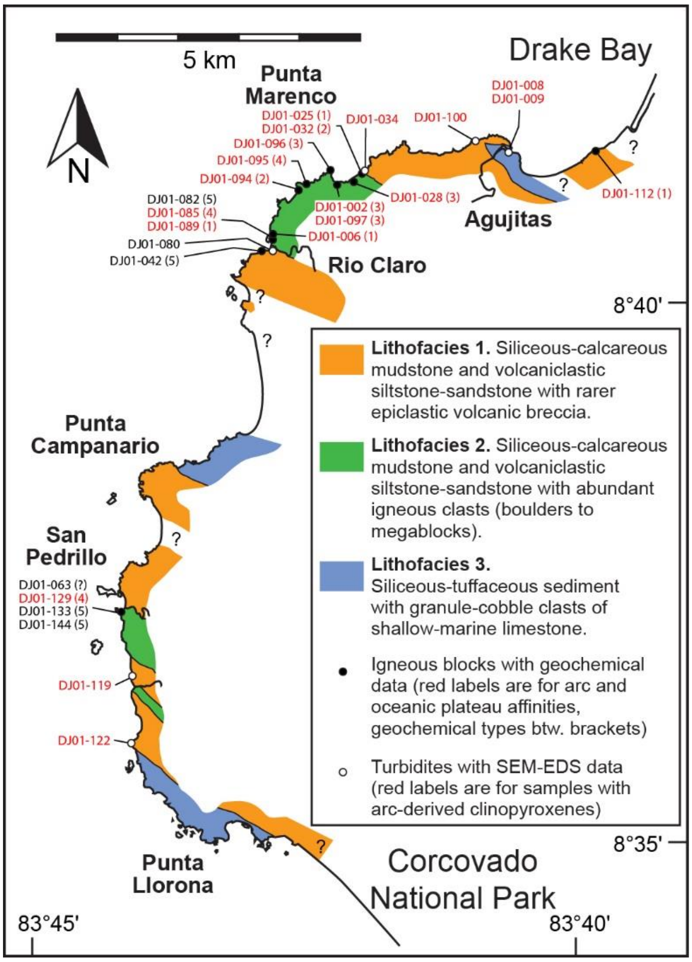

Fig.2. Geological map of coastal exposures of the San Pedrillo Unit in the NW Osa Mélange (modified from Buchs et al., 2009), with samples considered in this study. This geological map interpretation is compared with that of Clarke et al. (2018) in Supplementary Fig. S1.

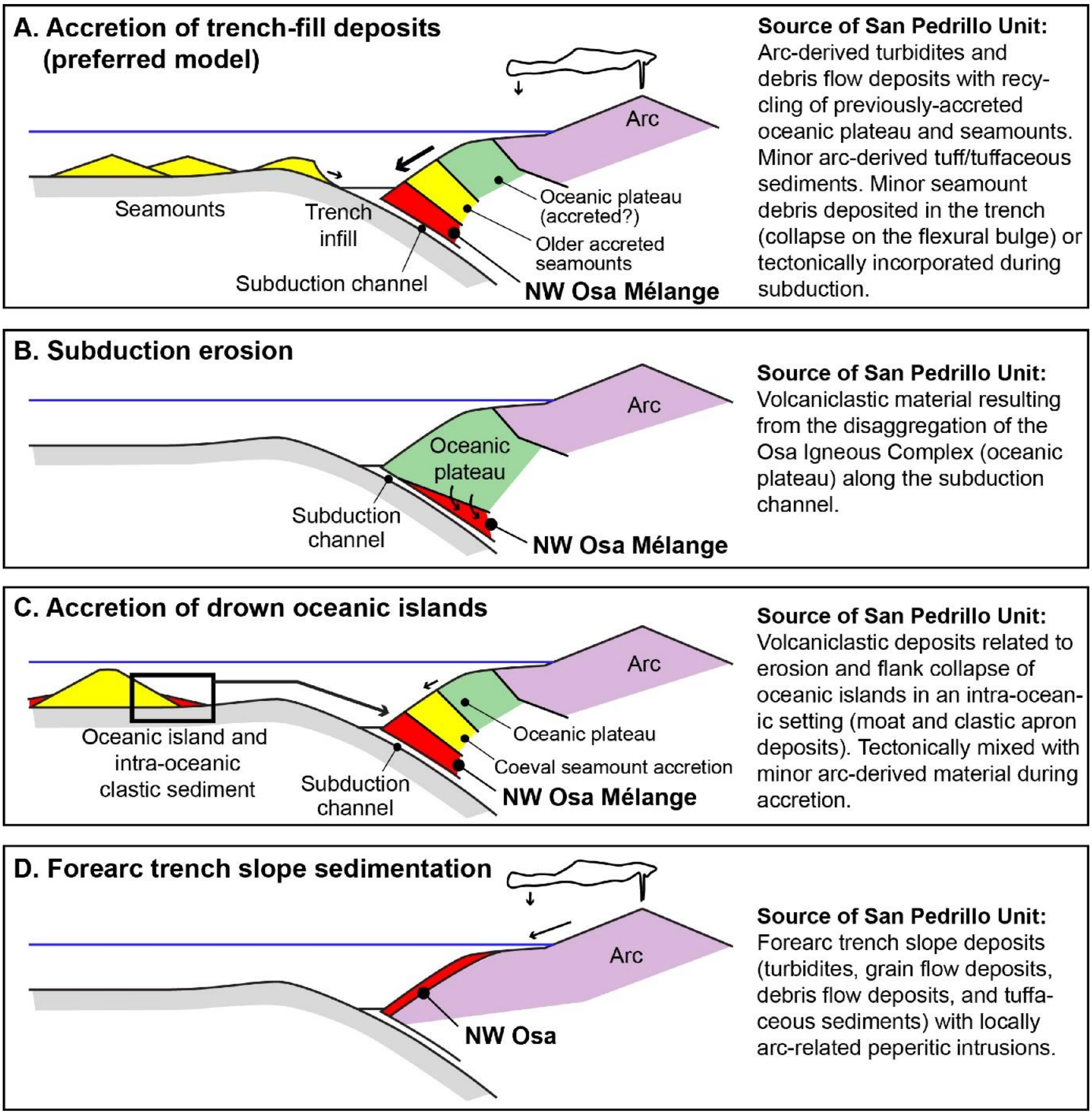

Fig.3. Models of formation of the NW Osa Mélange. Model (A) is based on Di Marco et al. (1995)and Buchs et al. (2009), model (B) is based on Meschede et al. (1999), model (C) is based on Vannucchi et al. (2006)and Clarke et al. (2018), and model (D) is based on Bolz and Calvo (2019).

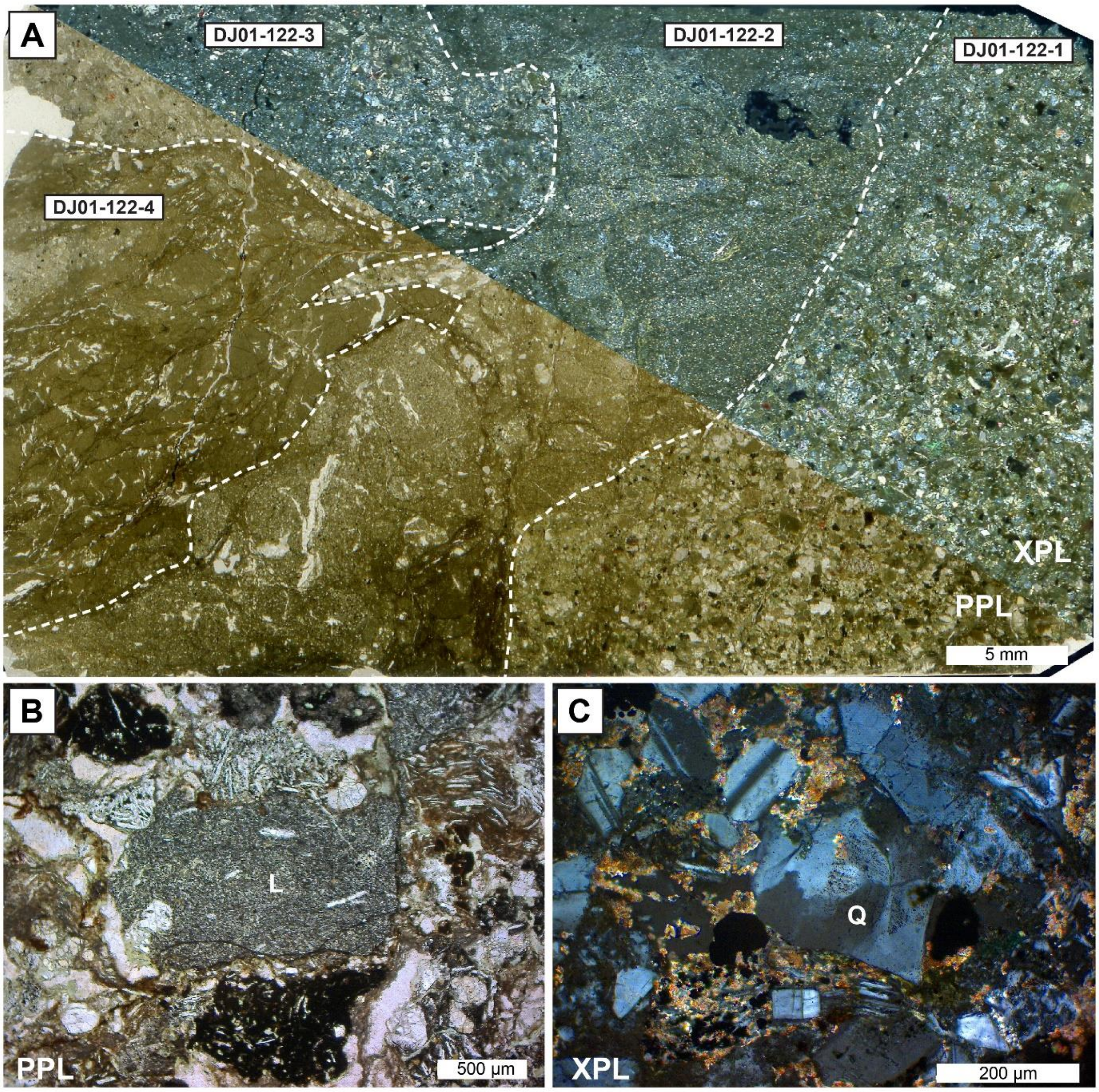

Fig.4. Key microscope petrographic observations in Lithofacies 1 and 2 of the NW Osa Mélange (PPL =plane polarised light, XPL =crossed polarizers). (A) Coherent zones created by soft sediment deformation without loss of the original mineralogical content of the distinct zones (Lithofacies 1, Sample DJ01-122, PPL/XPL). (B) Arc-related porphyritic (L) and fluidal lithics (Lithofacies 2, DJ01-091, PPL). (C) Detrital polycrystalline quartz (Q) and feldspars from lithofacies 1 (Lithofacies 1, DJ01-034, XPL).

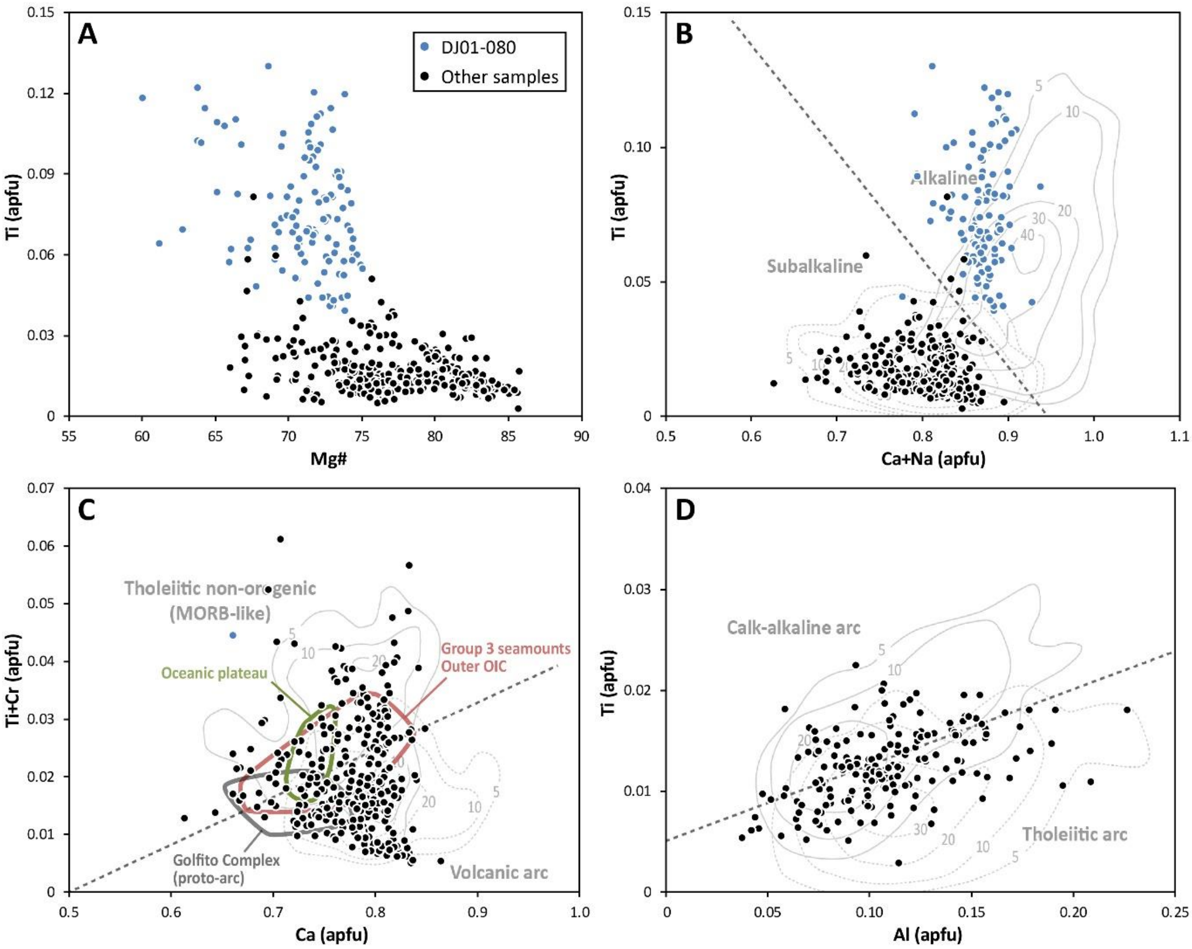

Fig.5. Geochemical composition of detrital clinopyroxenes from the NW Osa Mélange. Diagrams (B-D) with discrimination lines and density contours of reference datasets are based on Leterrier et al. (1982). Additional reference clinopyroxene data in (B) include clinopyroxenes from depleted (Group 3) basalts of accreted Palaeocene seamounts in the outer Osa Igneous Complex (sample DB02-216 in Supplementary File 2), proto-arc basalts and basaltic-andesite of the Golfito Complex (microprobe data from Buchs, 2008, also reported in Supplementary File 2), and oceanic plateau basalt from Upper Cretaceous oceanic sequences accreted in W Colombia (SEM-EDS data from Buchs et al., 2018).

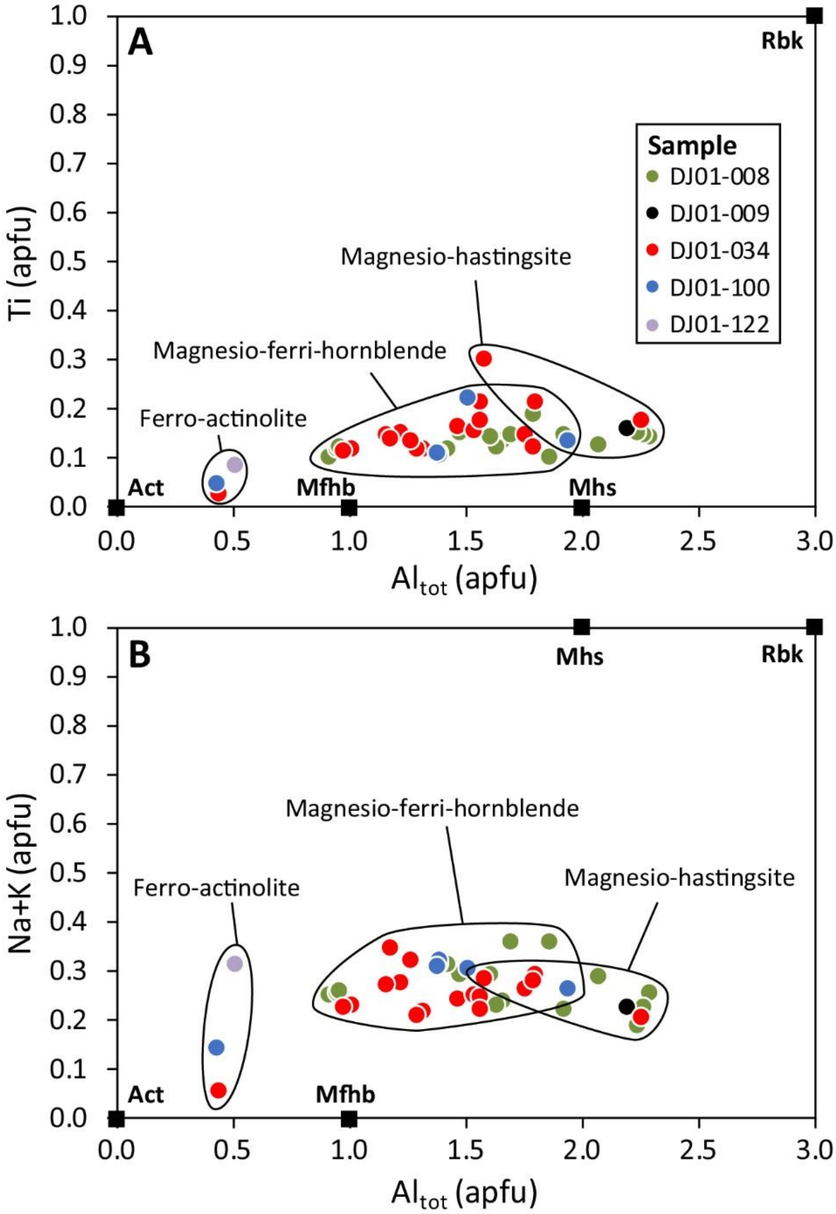

Fig.6. Geochemistry of detrital amphiboles encountered in turbidite samples of the NW Osa Mélange. The nomenclature of amphiboles follows 2012 IMA classification scheme (Hawthorne et al., 2012) and was determined using the algorithm of Locock (2014). Ideal compositions are shown for Actinolite (Act), Magnesio-ferri-hornblende (Mfhb), Magnesio-hastingsite (Mhs), and Riebeckite (Rbk).

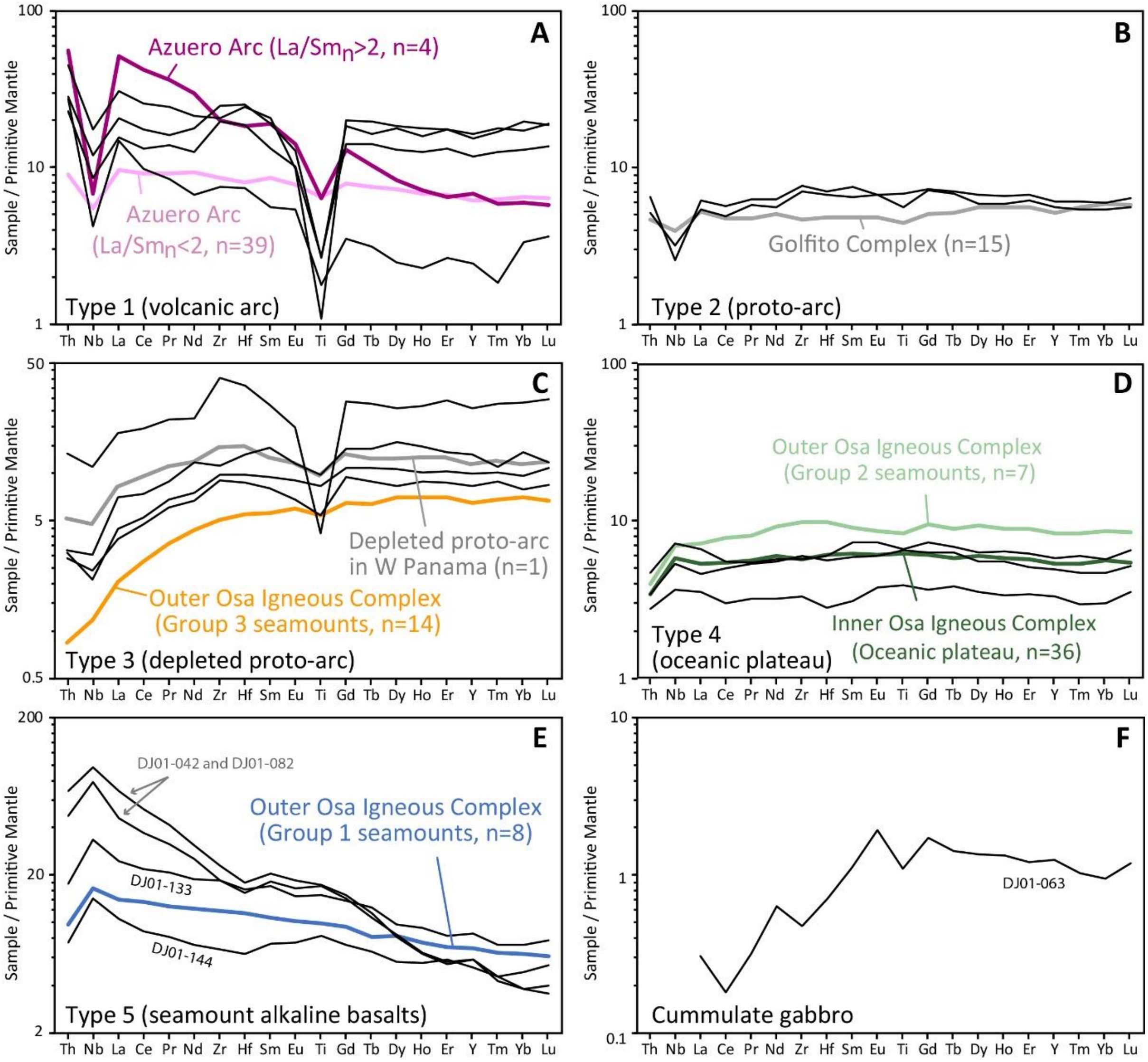

Fig.7. Primitive mantle-normalised multielement diagrams to determine the provenance of igneous blocks in the San Pedrillo Unit of the NW Osa Mélange. Data is from Buchs et al. (2009) and this study as synthesised in Supplementary File 3. Data from the Azuero Arc is from Lissinna (2005) and Buchs et al. (2010), data from the Golfito Complex is from Buchs et al. (2010), and data from the Osa Igneous Complex is from Buchs et al. (2016). A depleted proto-arc sample (B) is from an on-going geochemical study in the proto-arc of west Panama (Brims et al., 2019). Primitive mantle values are from McDonough and Sun (1995). Information on the lithology of the igneous blocks is provided in the text.

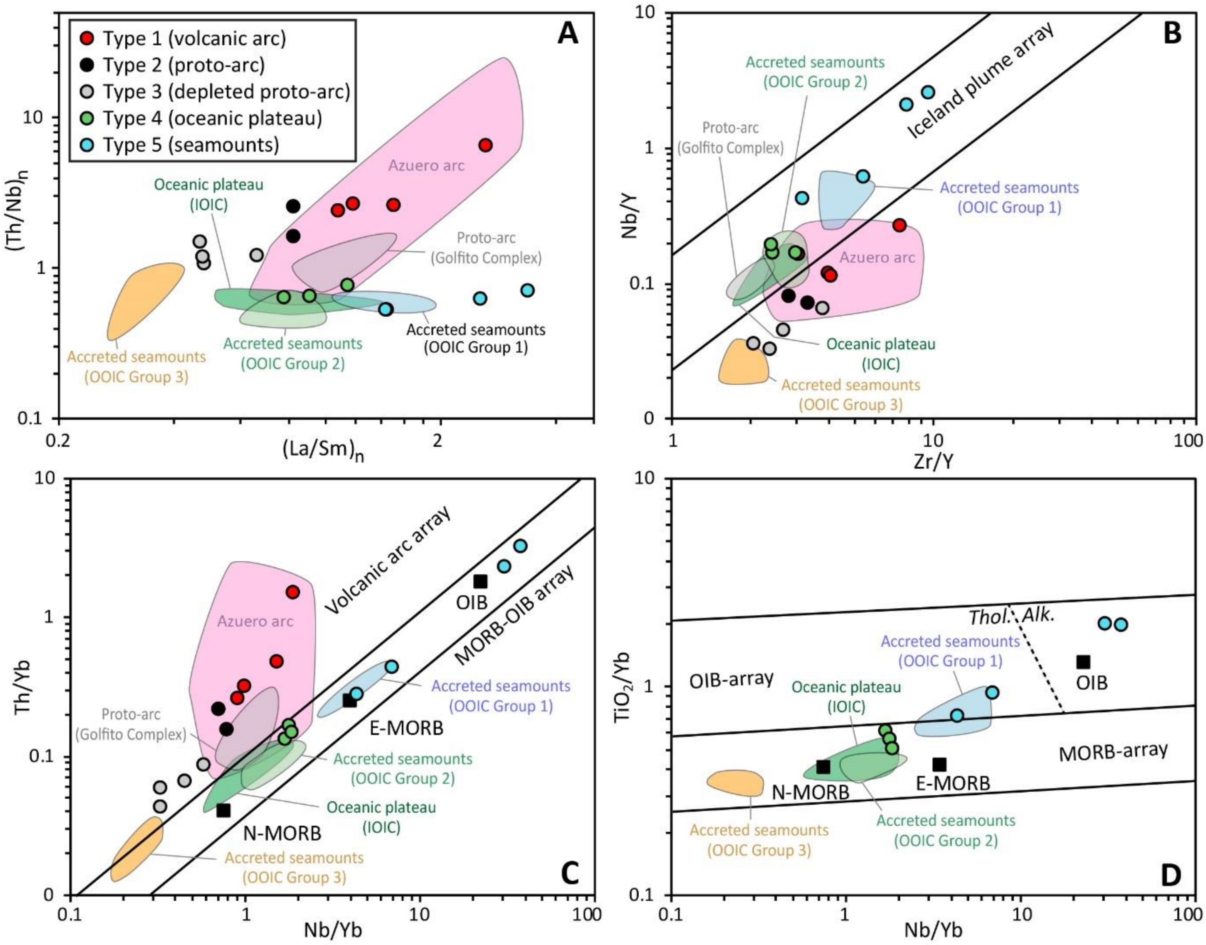

Fig.8. Selected geochemical diagrams to determine the provenance of igneous blocks in the San Pedrillo Unit of the NW Osa Mélange. IOIC =Inner Osa Igneous Complex, OOIC =Outer Osa Igneous Complex, MORB =Mid-Ocean Ridge Basalt, and OIB =Ocean Island Basalt.