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Seamount chain–subduction zone interactions: Implications for accretionary and erosive subduction zone behavior

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ABSTRACT

Sediment volume at the trench and topographic highs on the incoming plate are two of the main factors controlling whether a forearc will undergo subduction erosion or accretion. On oceanic plates, topographic highs such as large seamount complexes are commonly associated with significant volumes of flanking volcaniclastic sediments in the form of >100-km-wide debris aprons, with the largest deposits found in flexural moat basins. We propose that subduction of these sediment accumulations promotes localized frontal accretion, even in otherwise non-accretionary margins. The Osa mélange in southwestern Costa Rica is a field example that provides new insights into the nature and occurrence of this interaction. The southwestern margin of Central America is punctuated by accreted Late Cretaceous–middle Eocene seamounts that formed at the Galápagos hotspot and accreted throughout the late Miocene. In contrast to most accreted seamounts along this margin, which retained their overall structure, the Osa mélange is a chaotic mixture of seamount lithologies. It consists of basalt, chert, and carbonate blocks in a fine-grained pelitic matrix composed predominantly of feldspar and pyroxene grains with rare quartz. This lithology is consistent with sediment from a seamount chain's debris apron, such as the Hawaiian moat sampled during Ocean Drilling Program (ODP) Leg 136 and the Canary Islands moat sampled by ODP Leg 157. Subduction of seamounts and their debris aprons promotes concurrent accretion and erosion over short distances along the trench. This introduces heterogeneity into the subduction channel, with implications for deformation within the subduction zone plate interface.

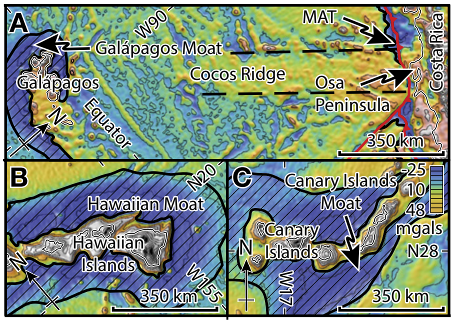

Figure 1. Gravity maps showing scale of seamount flexural moats (hachured areas) as low-gravity anomalies surrounding seamounts (Sandwell et al., 2014). A: Gravity map of Costa Rica, Galápagos Islands, and Cocos Ridge, showing Galápagos Moat as gravity low surrounding Galápagos Islands, Cocos Ridge as northeast-southwest–trending gravity high, and Middle America Trench (MAT) as gravity low along edge of Caribbean plate. B: Gravity map showing Hawaiian moat as gravity low surrounding Hawaiian chain. C: Gravity map showing Canary Islands moat as gravity low surrounding Canary Island chain.

INTRODUCTION

Subduction of bathymetric highs has traditionally been thought to be associated with tectonic erosion of the overriding forearc. Scars left on the forearc slope in the wake of subducting seamounts were the first convincing observations of material removal from the upper plate (Ranero and von Huene, 2000). However, seamount systems extend beyond the bathymetric high of the volcanic edifice to include broad sedimentary debris aprons, with the largest-volume deposits confined in flexural moat basins. Seamount flexural moats were first recognized by gravity measurements of the Hawaiian Islands (e.g., Vening Meinesz, 1941). These are several-hundred-kilometer-wide bathymetric depressions surrounding seamount chains (Fig. 1) that are caused by bending of the oceanic plate to flexurally compensate for the mass of the growing seamounts (e.g., Watts, 1994). Moat basins can accommodate the deposition of a thickness of up to 3 km of sediment from the adjacent seamounts through mass wasting of the igneous rocks and sedimentary cover (ten Brink and Watts, 1985). Even when a flexural moat is not obvious, major islands are typically surrounded by sedimentary debris aprons with up to 520-m-thick deposits extending >100 km away from the island (e.g., de Voogd et al., 1999). The subduction of a seamount chain's debris apron and/or moat sediments (hereafter referred to as "moat") offers a hitherto unconsidered opportunity for accretion of oceanic sediments at an otherwise "erosive" subduction margin. By this process, geologically significant volumes of volcaniclastic marine sediment may be transferred from the oceanic to the overriding plate.

Our recent work in southwest Costa Rica (Fig. 2) suggests that the subduction of a seamount chain can lead to the formation of a local frontal accretionary prism composed of sediments and igneous blocks initially deposited in the moat. Additional forearc material can be incorporated as the moat enters the trench. Accretion is prompted and/or enhanced by the local oversupply of thick, weak moat sediments to the trench.

GEOLOGY OF THE OSA MÉLANGE

The Osa mélange constitutes up to 24.6 × 10^3 km^3 of the Costa Rican forearc and contains 10^{-2}–10^2-m-scale blocks of carbonate, chert, and basalt, with rare blocks of gabbro, serpentinite, and granodiorite. The isotope geochemical character of the basalt in the Osa mélange has been used to interpret a Galápagos ocean island basalt (OIB) geochemical affinity like that of the Osa Igneous Complex (Hauff et al., 2000; Vannucchi et al., 2006). Rare dacitic blocks, instead, have an ambiguous geochemical signature resembling that of the early stages of a volcanic arc (Buchs et al., 2009). The matrix consists of clay minerals (smectite and illite) and angular to subrounded grains of feldspar and clinopyroxene; quartz grain content varies from 0% to 5% ± 2%. This mélange exhibits notable variation of the matrix and block populations and their relative proportions; the matrix to block ratio is high throughout. The general structure is layered, with alternating packages containing high proportions of clastic debris intercalated with those dominated by pelagic sediment (Fig. 2). Clastic-dominated units contain meter- to hundred-meter-sized blocks of carbonate, chert, basalt, and gabbro with low aspect ratios, whereas pelagic-dominated units exhibit a tectonic block-in-matrix fabric consisting of high-aspect-ratio centimeter- to meter-sized blocks of chert and carbonate with

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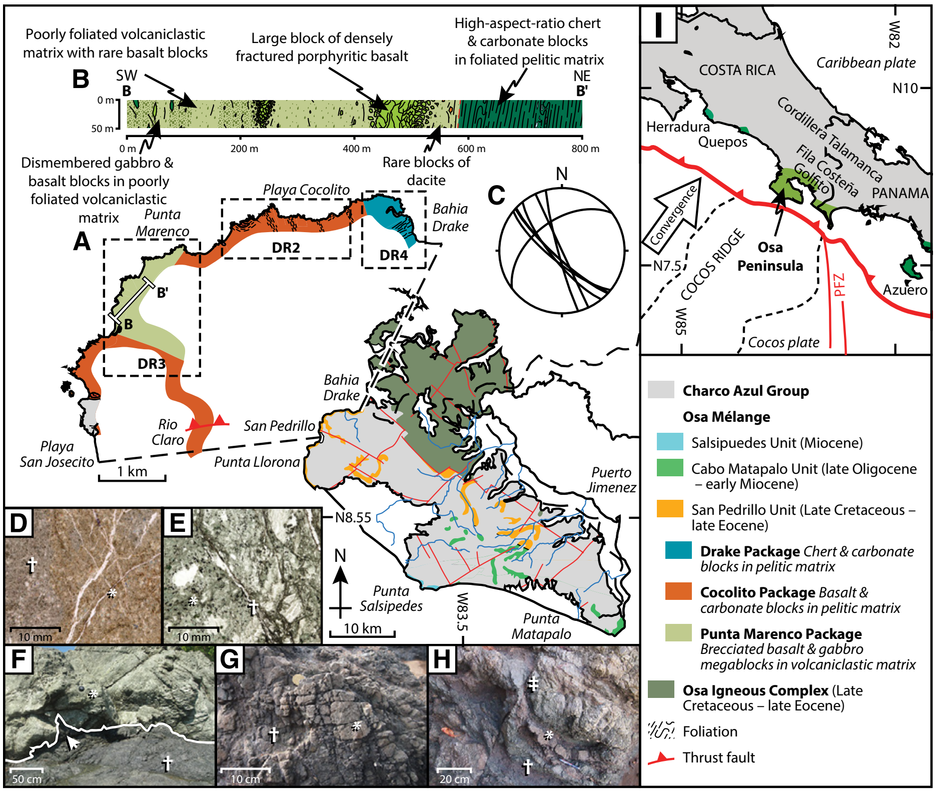

Figure 2. A: Geological map of Osa mélange from Bahia Drake (as shown in the figure) to Playa San Josecito (Costa Rica) (thrust fault from Vannucchi et al. [2006], and inland mapping of Rio Claro valley from Buchs et al. [2009]). Location of this map segment is shown on geological map of Osa Peninsula (lower right). (Modified from Vannucchi et al., 2006, and references therein.) B: Schematic cross-section from B to B′ (see A) showing megablocks and block-in-matrix texture. Lithological variation shown in cross section is mapped in the Data Repository (see footnote 1). C: Stereoplot of dominant foliation in Punta Marenco package. D: Photomicrograph of altered basalt showing "fresh" cores (*) containing unaltered feldspars and altered matrix (†) predominantly composed of clays. E: Photomicrograph of deformed volcaniclastic matrix showing phacoids (*) and localized shear zones (†). F: Gabbro megablock (*) in volcaniclastic matrix (†) with matrix injections into fractures (indicated by arrow) (8°40′50.5″N, 83°42′43″W). Line indicates boundary of block. G: Brecciated basalt megablock displaying brick-like geometric regularity (*) with "matrix" of comminuted basalt gouge (†) (8°41′22.7″N, 83°42′13.3″W). H: Dismembered chert and pelite with high-aspect ratio-blocks (*) in pelitic matrix (†) cut by minor fault (‡) (8°41′30.8″N, 83°40′18.0″W). I: Map of southern Central America showing location of Osa Peninsula in tectonic context and proximity to Middle America Subduction Zone, Cocos Ridge, and Panama Fracture Zone (PFZ).

a strongly developed lenticular fabric (see the GSA Data Repository[1]; Fig. 2).

The Osa mélange experienced significant deformation during and subsequent to accretion, which overprinted any preexisting sedimentary structures. Thrust faults are present within the mélange (Fig. 2). Mapped thrusts are separated by ~5–10 km, but poor exposure limits our ability to detect all of them. The chaotic nature of the mélange prevents us from estimating their offsets (Vannucchi et al., 2006). However, it appears that most deformation is accommodated by distributed shear within the matrix, which appears as a pervasively well-developed lenticular fabric with abundant anastomosing shear bands. Clastic-dominated units feature a chaotic fabric with discrete bands displaying moderate foliation, while pelitic layers are strongly foliated and feature high-aspect-ratio chert blocks formed by tectonic dismemberment of bedding. Basalt and gabbro olistoliths are densely fractured and feature pervasive matrix injection at their margins (see Fig. 2F), resulting in their dismemberment. The Osa mélange lacks pervasive recrystallization or greenschist facies minerals and contains abundant veins with calcite showing twinning types indicating the maximum experienced temperature was ~200–250 °C (Burkhard, 1993; Meschede et al., 1999).

DISCUSSION OF FORMATION MODELS AND COMPARISON TO VOLCANICLASTIC SEDIMENTS FLANKING SEAMOUNT CHAINS

High-resolution mapping, and geochemical and petrological analyses, reveal that the Osa mélange is mostly composed of igneous rocks and sediments typical of oceanic seamounts and their flanking debris aprons, but also contains rare blocks of granodiorite and dacite with an arc signature (Buchs et al., 2009). Deformation and metamorphic pressure-temperature (*P-T*) conditions of the Osa mélange are consistent with accretion in a frontal accretionary prism. The prevalence of OIB-affinity basalt and ubiquitous volcaniclastic sediment preclude an origin of the Osa mélange by tectonic dismemberment of the lower plate during subduction, or the upper plate by tectonic erosion, as suggested by Meschede et al. (1999). Vannucchi et al. (2006) interpreted the Osa mélange, together with the Osa Igneous Complex landward of the mélange, as an accreted seamount chain that preceded the arrival of the Cocos Ridge at ca. 6.5–8 Ma (Vannucchi et al., 2006, and references therein). In this model, the Osa mélange would have formed by tectonization of the seamount flanks during direct accretion while the tops of these seamounts were off-scraped to form the Osa Igneous Complex. This hypothesis requires that the composition of the Osa mélange resemble the composition of seamount flanks, which are dominantly zones of sediment bypass with low sediment proportions (cf. Morgan et al., 2007). This condition contrasts with the large (75%–90%) amount of sediment forming the Osa mélange. Alternatively, Buchs et al. (2009) interpreted that the Osa mélange formed by mass wasting of a previously accreted Osa Igneous Complex into the Middle America Trench combined with normal terrigenous sediment input. They attributed the source of rare felsic blocks to gravitational transport from the arc. However, arc-derived clasts are absent in the Eocene–Pliocene forearc basin—now exhumed in the Fila Costeña fold-and-thrust belt (Fisher et al., 2004)—and arc-derived plutonic rocks are absent from the Late Cretaceous–Eocene forearc rocks of the Golfito Complex (Buchs, 2008), adjacent to the Osa Igneous Complex. Minor input from the forearc as the seamount's moat met the trench would be anticipated due to surface transport and tectonic erosion above the adjacent subducting seamounts. Such tectonic erosion beneath the Golfito Complex may have supplied the granodiorite blocks found in the mélange.

Here we propose that the Osa mélange in southwestern Costa Rica is the first-recognized example where the flexural moat–debris apron package typically flanking an island chain has been accreted to the upper plate. Sedimentation into island moats consists of debris-avalanche

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[1] GSA Data Repository item 2018109, Item DR1 (detailed geological map of the San Pedrillo Unit), Items DR2–DR4 (photographs, thin sections, cross sections, and lithological descriptions of the Cocolito, Punta Marenco, and Drake packages, respectively), and Item DR5 (comparative Scale of the Osa Mélange and seamount moats/debris aprons), is available online at http://www.geosociety.org/datarepository/2018/ or on request from editing@geosociety.org.

deposits caused by mass wasting from unstable island flanks and pelagic sedimentary deposits derived from background pelagic sedimentation (Leslie et al., 2002; Morgan et al., 2007). Large-scale flank collapse can transport 100-m- to kilometer-scale megablocks into the moats (e.g., Moore et al., 1994). The moat has a maximum of 3 km thickness by up to 160 km width at Hawaii (e.g., ten Brink and Watts, 1985; Moore et al., 1994), a maximum of 455 m thickness by up to 250 km width at the Canary Islands (Collier and Watts, 2001; Gee et al., 2001), and a maximum of 520 m thickness by up to 130 km width at La Réunion island (southwestern Indian Ocean; de Voogd et al., 1999; Oehler et al., 2008) (widths as measured from Figure 1 and from Oehler et al. [2008]). Relatively little sediment is deposited on the flanks of the actual seamounts; these are dominated by sediment erosion and bypass into the moat (Leslie et al., 2002). Deepwater flexural moats are the dominant depositional environment for seamount-derived sediments. These deposits consist predominantly of mafic igneous clasts, carbonate clasts, highly immature grains of pyroxene and feldspar, and clays interbedded with pelagic sediment deposited during periods of quiescence (Leslie et al., 2002). Scientific drilling of the moat of the Hawaiian chain during Ocean Drilling Program (ODP) Leg 136 (Tribble et al., 1993) and the Canary Islands during ODP Leg 157 (Carey et al., 1998), as well as submersible surveys of the Hawaiian flank (Morgan et al., 2007), all reveal clay-dominated sediment containing high proportions of plagioclase and clinopyroxene clasts and lithic volcanic debris, with low proportions of quartz. Detailed seafloor mapping at Hawaii finds that late slump-related tectonics during the intrusive growth of islands can tectonically stack the debris apron sediment package, a mode analogous to accretionary stacking at a subduction frontal toe (cf. Morgan et al., 2007).

Moat sediments contrast with ocean trench sediments, where sediments are mostly compositionally mature with high volumes of quartz and lithic clasts from the adjacent arc and forearc (Underwood and Bachman, 1982). Trenches starved of typical terrigenous sediment are still subject to mass wasting from the forearc and typically have a small frontal prism of disrupted forearc material (von Huene et al., 2004). In the Osa mélange, the dominance of plagioclase, clinopyroxene, and volcaniclastic grains over quartz argues against its source material being typical ocean trench sediments; instead, it is diagnostic of a moat deposit.

ACCRETION OF MOAT SEDIMENTS

At a subduction zone, marine sediment is typically accreted by the development of imbricate thrusts at the toe of the wedge and underplating of subducted sediment above the décollement (Silver et al., 1985). Given sufficient volumes of its flanking moat sediments, the arrival of a seamount chain to the trench may therefore result in net accretion to the margin, even when the subducting seamounts themselves are associated with local subduction erosion (Ranero and von Huene, 2000; Dominguez et al., 2000).

Incorporation of oceanic igneous material from the incoming plate within accretionary complexes has previously been attributed to tectonic dismemberment of high-bathymetry features such as seamounts within the subduction channel (Cloos and Shreve, 1996) or backstepping of subduction resulting in accretion of intact sections of oceanic crust (Wakabayashi and Dilek, 2003). However, incorporation of large blocks of oceanic material within accreted moat sediments must also be considered. Such a model effectively explains the hundreds-of-meters-thick blocks of basalt found within the predominantly fine-grained Osa mélange. Moreover, in the case of Osa, previously intact igneous material from the seamounts themselves was also accreted, now forming a geologically distinct Osa Igneous Complex on the landward side of the mélange (Buchs et al., 2016). The data at Osa cannot discriminate whether sedimentary apron stacking occurred during island growth (e.g., Morgan et al., 2007) or during forearc off-scraping and accretion. All thrusts mapped in the Osa mélange have an WNW–ESE to ENE–WSW trend (Vannucchi et al., 2006; see the Data Repository) consistent with the direction of long-term plate convergence in this region and an origin linked to an accretionary subduction system.

CONCLUSIONS AND IMPLICATIONS

The moats that flank seamount chains can provide a significant local volume of sediment to the trench when subducted. Mass wasting and large-scale flank collapse from growing islands provide volcaniclastic material that includes very large igneous blocks. Accretion of flanking moat deposits appears favorable even at otherwise non-accretionary margins. This provides a simple means to transfer large volumes of seamount-derived volcaniclastic material to the upper plate. Here we recognize the Osa mélange to be a fossil example of an accreted moat deposit, explaining why it contains hundreds-of-meters-scale igneous blocks within a fine-grained quartz-poor matrix.

Unlike sediment accretion at typically accretionary margins, accretion of moat fill may occur concurrently with adjacent forearc erosion caused by subduction of the seamount chain (Fig. 3). This lateral heterogeneity of tectonic processes affecting the forearc would also influence the composition of the plate boundary shear zone at depth. In regions where seamounts are subducted, subduction erosion would be active

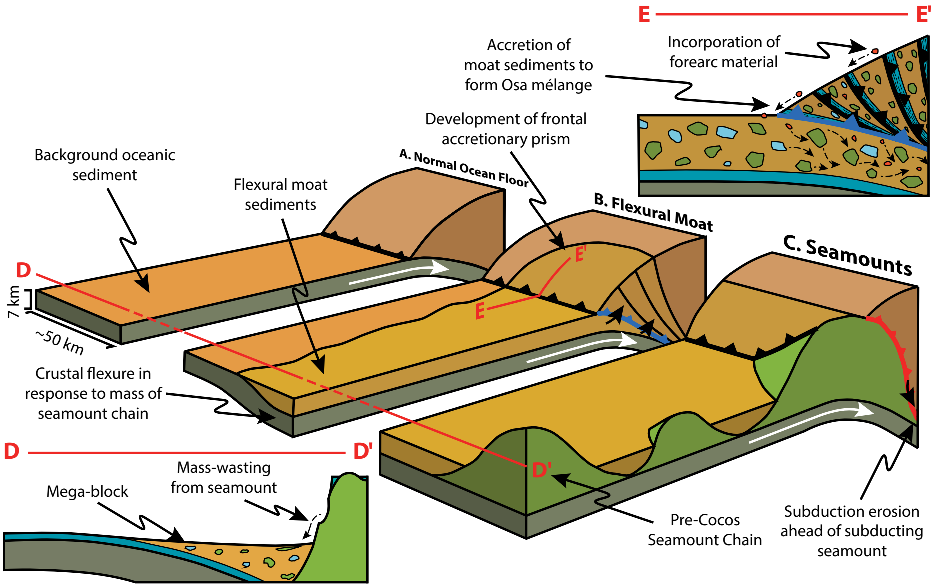

Figure 3. Conceptual model of frontal accretion of seamount moat sediments adjacent to subduction erosion by subduction of seamount. White arrows indicate convergence direction. A: Subduction of oceanic plate under conditions normal for this margin. B: Subduction of moat leading to increased accretion and development of frontal accretionary prism, even in otherwise non-accretionary subduction zones. This is the setting in which Osa mélange formed. Blue ticked line shows subduction accretion. C: Subduction of seamount (green) leading to increased local subduction erosion of upper plate (e.g., Ranero and von Huene, 2000; Vannucchi et al., 2016). Material eroded from base of forearc may be mixed with subducted moat sediments and reaccreted. Red ticked line shows subduction erosion. Insets show cross-sections beneath lines D-D′ and E-E′; D-D′ shows mass wasting from volcanic edifice into moat; E-E′ shows accretion of flexural moat into localized accretionary prism (see B) and mixing with upper-plate blocks.

and the plate boundary shear zone would be localized within material coming from the upper plate. Adjacent subduction accretion would drive localization of the plate boundary within former moat sediments. In this scenario, forearc material tectonically eroded above subducting seamounts may be mixed with subducted moat sediments within the plate boundary shear zone, accounting for the incorporation of exotic blocks from both settings, such as the rare upper-plate granodiorite blocks mixed into the moat-derived sediments of the Osa mélange.

Seamounts and aseismic ridges are common features of oceanic plates. They interact with subduction zones—e.g., where the Louisville Ridge subducts at the Tonga-Kermadec trench—and it has been estimated that ~17% of the total length of modern subduction systems are subducting major high-relief features (Vannucchi et al., 2016). Raymond's (1984) map of global distribution of mélanges shows good correlation between mélanges and modern subducting seamount chains. The above evidence suggests that the accretion of seamount flexural moats is a previously unrecognized and globally significant mechanism for transferring seamount-derived sediments to the upper plate.

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