Farallon slab detachment and deformation of the Magdalena Shelf, southern Baja California

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[1] Subduction of the Farallon plate beneath northwestern Mexico stalled by ∼12 Ma when the Pacific-Farallon spreading-ridge approached the subduction zone. Coupling between remnant slab and the overriding North American plate played an important role in the capture of the Baja California (BC) microplate by the Pacific Plate. Active-source seismic reflection and wide-angle seismic refraction profiles across southwestern BC (∼24.5°N) are used to image the extent of remnant slab and study its impact on the overriding plate. We infer that the hot, buoyant slab detached ∼40 km landward of the fossil trench. Isostatic rebound following slab detachment uplifted the margin and exposed the Magdalena Shelf to wave-base erosion. Subsequent cooling, subsidence and transtensional opening along the shelf (starting ∼8 Ma) starved the fossil trench of terrigenous sediment input. Slab detachment and the resultant rebound of the margin provide a mechanism for rapid uplift and exhumation of forearc subduction complexes. **Citation:** Brothers, D., A. Harding, A. González-Fernández, W. S. Holbrook, G. Kent, N. Driscoll, J. Fletcher, D. Lizarralde, P. Umhoefer, and G. Axen (2012), Farallon slab detachment and deformation of the Magdalena Shelf, southern Baja California, *Geophys. Res. Lett.*, *39*, L09307, doi:10.1029/2011GL050828.

1. Introduction

[2] Changes in subduction dynamics, surface deformation, volcanism and widespread tectonic reorganization have been attributed to slab detachment [*Dickinson and Snyder*, 1979; *Liu and Stegman*, 2012; *Severinghaus and Atwater*, 1990]. Between 20–16 Ma, the subducting Farallon Plate fragmented into the Guadalupe and Magdalena oceanic microplates as the Pacific-Farallon ridge approached the trench along the western margin of the modern-day Baja California (BC) peninsula [*Atwater and Stock*, 1998; *Lonsdale*, 1991]. Abyssal hill fabric and seafloor magnetic anomalies along the Magdalena Ridge suggest that seafloor spreading ceased by 12 Ma [*Lonsdale*, 1991]. Subsequent structural reorganization and post-subduction volcanism in Baja California (BC) and mainland Mexico [*Ferrari*, 2004; *Pallares et al.*, 2007] may be consequences of slab detachment as young, buoyant oceanic lithosphere approached the trench [*Burkett and Billen*, 2009; *Michaud et al.*, 2006]. Despite these observations, the following remain poorly understood: (1) the modern day architecture of BC continental crust and underlying relic slab, (2) the spatial relationship between post-subduction melts and relic slab geometry, (3) the geologic expression of slab detachment on the overriding plate (e.g., exhumation and erosion), and (4) the relative timing between subduction cessation and onset of transtensional deformation. Based on the integration of geological data with an active-source seismic reflection/refraction transect across the southern BC peninsula (Figure 1), we present new constraints on the two-dimensional crustal/upper mantle architecture of the BC microplate and interpretations for the isostatic response and tectonic reorganization of the BC microplate following slab detachment.

2. Geologic Background

[3] As the Pacific-North American plate boundary transformed from a convergent to translational margin the Farallon oceanic plate fragmented to the west of northwestern Mexico into the Guadalupe and Magdalena microplates [*Lonsdale*, 1991]. Between 14–12 Ma seafloor spreading and subduction of the Magdalena microplate slowed and ceased [*Lonsdale*, 1991]. Deformation associated with the evolving plate boundary was distributed between both sides of the BC peninsula, however the timing and kinematics of the deformation are debated [*Fletcher et al.*, 2007; *Oskin et al.*, 2001]. *Michaud et al.* [2006] proposed that complete capture of the Magdalena plate by the Pacific plate occurred progressively from 12 Ma to ∼8–7 Ma. Regardless, the total amount of relative displacement between the Pacific and North American plates since 14 Ma is ∼700 km and transtensional deformation appears to have been focused in the Gulf of California earlier than ∼6 Ma suggested by *Stock and Hodges* [1989].

[4] Volcanic rocks emplaced along southern BC record tectonic reorganization from ∼16 Ma to the present. Early to Middle Miocene calc-alkaline arc volcanism (i.e., Comondú Group; Figure 1) started to wane ∼15 Ma and ceased

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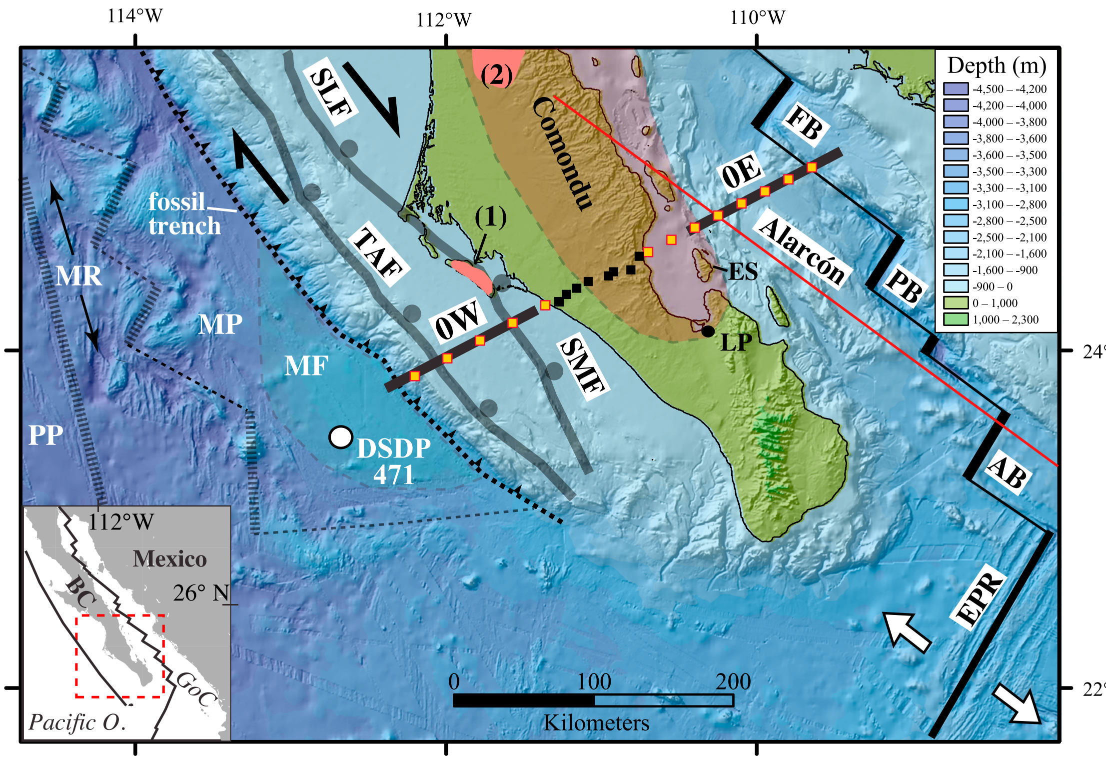

Figure 1. Inset: Study region (red box) and major fault systems around southern Baja California (BC; black lines). Ocean-bottom seismometers (orange squares) and land-based seismometers (black squares) are located along line zero. Black lines are multichannel seismic reflection profiles 0W and 0E. Alarcón profile is from *Lizarralde et al.* [2007]. Abbreviations: Magdalena Fan (MF), fossil Magdalena Ridge (MR), Tosco-Abreojos Fault (TAF), Santa Margarita Fault (SMF), Deep Sea Drilling Program (DSDP) Site 471, Pacific Plate (PP), Magdalena microplate (MP), East Pacific Rise (EPR). Post-subduction volcanism [*Calmus et al.*, 2011, and references therein]: (1) 6.2 $\pm$ 0.1 and 4.9 $\pm$ 0.1 Ma adakites on Isla Santa Margarita; (2) 9.7–8.8 Ma La Purisima magnesian andesites (i.e., "bajaites"). Orange region represents Comondú volcanics. Bathymetric data was downloaded with GeoMapApp (http://www.geomapapp.org).

by ~12 Ma [*Umhoefer et al.*, 2001]. Post-subduction adakites and bajaites (ca. 12 Ma – Holocene) are found on BC between 24°N–27°N and ~100–250 km inboard of the paleo-trench [*Calmus et al.*, 2011, and references therein]. These rocks have been attributed to slab detachment and melting of young (< 5 m.y. old), subducted oceanic crust. Adakites dated between 6–5 Ma have been sampled near Line 0 on the footwall block of the Santa Margarita Fault [*Bonini and Baldwin*, 1998] (Figure 1). Their emplacement began at roughly the same time as the onset of dextral transtension along the Magdalena Shelf [*Michaud et al.*, 2006].

3. Seismic Reflection and Refraction Surveys

[5] Seismic surveys in 2002 aboard the *R/Vs Maurice Ewing* and *New Horizon* collected multichannel seismic reflection (MCS) and wide-angle refraction data across the BC peninsula [*Brothers*, 2009]. This paper is focused on the western half of the seismic transect. All shots used the *R/V Ewing*'s 20-gun, 140-L source array. Two multichannel seismic reflection profiles, lines 0W and 0E, both ~120 km in length were collected on either side of southern BC (Figures 1 and 2). Shots every 50 m were recorded using the *Ewing*'s 6-km-long, 480-channel seismic streamer. The MCS data processing sequence included common mid-point sorting, deconvolution, bandpass filtering, velocity analysis, normal move-out correction, stacking, and *f-k* migration [*Brothers*, 2009]. Seismic reflectors to the west of the Magdalena Shelf were correlated with drilling data from Deep Sea Drilling Project (DSDP) Leg 63 (Figures S1 and S2 in the auxiliary material) [*Fletcher et al.*, 2007; *Yeats et al.*, 1981].[1]

[6] A linear array of ocean-bottom and terrestrial seismometers spanning the BC microplate yielded an ~343 km-long wide-angle refraction profile (Figure 1). Shots were fired along lines 0W and 0E at 150 m spacing. Data were recorded by five ocean bottom seismometers (OBS) on the western continental borderland spaced ~25 km apart, eight RefTek seismometers onshore BC spaced between 6 and 13 km, and eight additional OBS instruments in the Gulf of California spaced ~17 km apart (Figures 1 and S3–S5). It is important to note that OBS receivers did not record useful data from shots on opposite sides of BC. All shot traces were minimum-phase bandpass filtered (4–15 Hz). The OBS closest to the western shoreline, OBS 5, was located in shallow water and had a very low signal to noise ratio, and thus data from OBS5 were not used in this analysis. With the exception of one instrument (RefTek 02), land-based receivers recorded shots from both sides of BC.

[7] Wide-angle seismic data were used to perform P-wave raytracing and travel time tomography following methods

[1]Auxiliary materials are available in the HTML. doi:10.1029/2011GL050828.

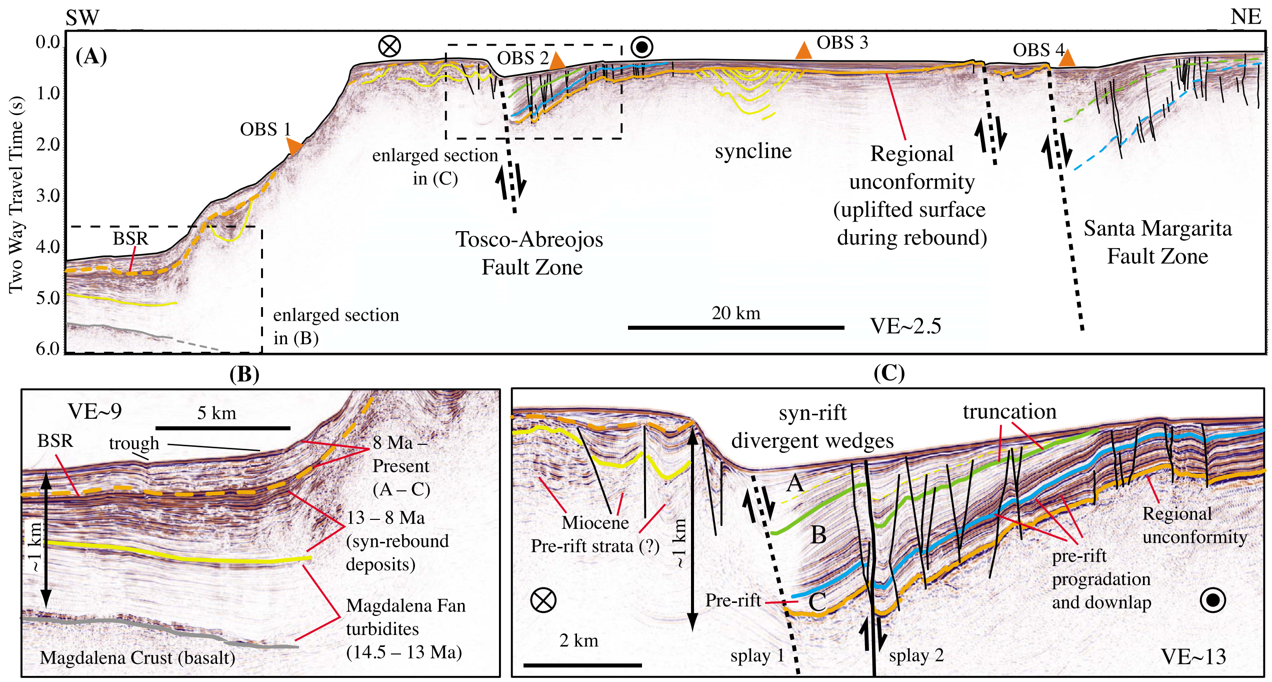

Figure 2. Seismic reflection profile 0W. (a) Line 0W (total length = 111 km) and locations of OBS receivers 1–5. (b and c) Enlarged sections show stratigraphy in the paleo-trench and TAF basin. Estimates for stratal ages are based on correlation with DSDP Site 471 [*Yeats et al.*, 1981].

described by *Van Avendonk et al.* [2006].Travel time residuals between predicted and observed values were minimized through an iterative process of raytracing and linearized inversion until the χ^2 data misfit approached a value of 1. Errors assigned to arrival picks ranged from 24 to 250 ms, depending on the strength and coherency of the signal. Basement topography and sediment velocities were refined using results from MCS reflection data. An initial velocity model was constructed using more than 12,000 Pg, Pn and PmP arrivals. The final velocity model used just over ten thousand arrival picks (Figure 3a) and 25 iterations of ray tracing and inversion to yield a $\chi^2 = 2.5$ and an RMS misfit of 80 ms [*Brothers*, 2009] (Figures S6 and S7). The reason $\chi^2 > 2$ is that many of the residual misfits come from short-wavelength features (few km long), such as basins, fault zones and steep forearc structures to

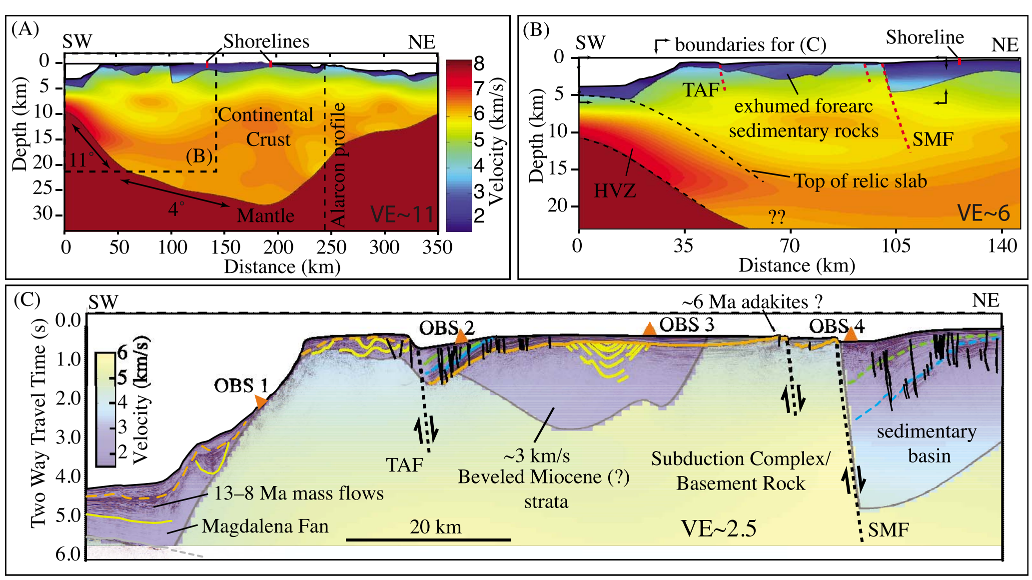

Figure 3. (a) Velocity model for BC. (b) Expanded region of dashed box in Figure 3a. The high velocity zone (HVZ) extending beneath the western half of the Magdalena shelf and is interpreted to be Magdalena oceanic crust. (c) Merged seismic reflection profile and velocity model of the Magdalena Shelf.

the west of BC, that are not fit as well as longer wavelength features. Hence the goodness of fit differed slightly between the western and eastern margins ($\chi^2 = 3.2$ on the west; $\chi^2 = 1.3$ on the east).

4. Crustal and Stratigraphic Architecture

[8] Line 0W crosses the fossil trench and two asymmetric fault-bounded basins on the Magdalena Shelf (Figures 1 and 2). Seismic reflection horizons at the toe of the continental slope can be correlated with lithostratigraphy sampled at DSDP Site 471 [*Fletcher et al.*, 2007; *Yeats et al.*, 1981]. Distal turbidites of the Magdalena Fan (MF) mantle basaltic crust and are age-dated to be ~13–14.5 Ma (Figure 2b). MF turbidite deposition ended approximately at the same time that subduction dramatically slowed [*Fletcher et al.*, 2007; *Yeats et al.*, 1981]. Above the MF turbidites, seismic horizons become lenticular, discontinuous and show higher amplitudes (i.e., impedance contrasts), particularly along the base of the continental slope. This section thickens landward with maximum thicknesses observed along the base of the slope. Up-section, a bottom simulating reflection (BSR) marks a transition to slightly less chaotic and lower amplitude layering. The BSR corresponds to a diagenetic boundary with an age of ~8 Ma [*Yeats et al.*, 1981].

[9] Two asymmetric, transtensional basins on the shelf are bounded by the Tosco-Abreojos Fault (TAF) and Santa Margarita Fault (SMF), respectively (Figures 1 and 2). A larger impedance contrast is associated with a shelf unconformity that progressively increases in amplitude moving eastward, separating young, less consolidated sediment from older, consolidated sediment (see syncline in Figures 2 and 3). The older sediments below the unconformity are >2 km thick and have velocities up to 3 km/s. The age of strata below the unconformity is unknown, but *Fletcher et al.* [2007] proposed that the surface represents a Miocene abrasion surface that was exposed subaerially during subduction of young oceanic crust. In the TAF basin, stratigraphic offset is concentrated along two fault splays (Figure 2c). Vertically offset and divergent strata suggest that at least 1 km of basin subsidence was syn-depositional. Strike-slip faulting is inferred based on mismatched horizons and appears to be distributed across several fault splays within the TAF zone. Cumulative horizontal offset cannot be measured with these data. Based on stratal geometry and acoustic character, three primary stratigraphic packages are identified that infill the basin. Package-C horizons overlie the shelf unconformity and are characterized by high acoustic reflectivity, downlap, and seaward progradation (Figures 2a and 2c). Flattening along the top of package-C reveals little to no divergence or thickening into the faults. Reflectors within packages B and A diverge and thicken towards the major fault splays. The SMF basin contains reflector packages that thicken and diverge westward; the basin-bounding fault separates young sediments from uplifted, high velocity footwall blocks that crop out at the seafloor. The SMF basin is more than 3.5 km deep, and the uplifted footwall block has velocities of ~5 km/s (Figure 3). Tentative correlations between reflector packages in the two basins are made based on acoustic character and stratal geometry (Figure 2a).

[10] Along the western margin of BC, the Moho dips ~11° for nearly 40 km east of the trench then dips 3–4° until it reaches its deepest point (~27 km), which underlies the highest topography along the profile (Figure 3a). Pg rays turning in the lower crust along the western margin reveal a 6–7 km thick high-velocity zone (HVZ; Vp = 6.5–7.5 km/s) along the trench and extending ~40 km beneath the shelf, in the region where Moho has a steeper dip (Figure 3b). Reflections off the upper boundary of the HVZ are not observed east of the Moho bend (Figure S8) and the high-velocity zone cannot be resolved farther east of this point. Although the velocity structure in the Gulf of California is not discussed here, a good fit was needed to constrain the model beneath the terrestrial stations. The velocity model is consistent with results from the previously published Alarcón transect that intersects Line 0 in the Gulf of California (Figures 1 and 3) [*Lizarralde et al.*, 2007].

5. Discussion

[11] Although direct age control on shelf stratigraphy is unavailable, there is potential to establish a relative chronostratigraphy for the shelf sediments with the dated material at the toe of the slope [*Fletcher et al.*, 2007; *Yeats et al.*, 1981]. At the drill site, the distal turbidites of the Magdalena Fan are separated from overlying upper mid-Miocene porcelanite and porcelaneous silty claystone by a depositional hiatus [*Yeats et al.*, 1981]. There is a sharp decrease in both deposition rate and supply of terrigenous material above the hiatus. This boundary is traced to the toe of the slope where it appears to separate regionally laminated, low-amplitude Magdalena Fan turbidite layers (14.5–13 Ma) from the overlying high-amplitude and irregular layers of the middle unit (13–8 Ma; Figures 2a and S2). At the drill site the BSR is concordant with the hemipelagic beds and approximately delineates the upper boundary of the middle unit. As the BSR is followed landward, the middle unit thickens markedly into the paleotrench, which is consistent with emplacement by gravity flows (Figures 2b and S2). The package above the BSR contains irregular bedding and disrupted strata that appear to be confined to a small trough at the base of the slope; farther seaward, the same layers become laminar and have relatively low amplitude. This change in character may record the cut-off of shelf sediment and the transition to fine-grained, gravity flows sourced from failed hemipelagic deposits on the adjacent continental slope.

[12] The high velocities of the sediments (~3 km/s; Figures 3b and 3c) imaged on the shelf beneath the regional unconformity suggests that at least 1 km of overburden has been removed by erosion [*Brocher*, 2008]. We present the following explanation: the 13–8 Ma sedimentary wedge (Figure 2b) represent deposits that were shunted off the margin when the shelf was exposed to wave-base erosion. The prograding shelf strata resting above the unconformity (package – C) indicate that widespread erosion was followed by subsidence and sequestration of terrigenous sediment on the shelf. Divergent layers within Packages B and A (Figure 2c) record the opening of transtensional basins on the shelf, leading to further isolation of the paleotrench from terrestrial sediment sources. Sediment deposited above the BSR along the fossil trench shows a dramatic decrease in deposition rate and change in acoustic character. This

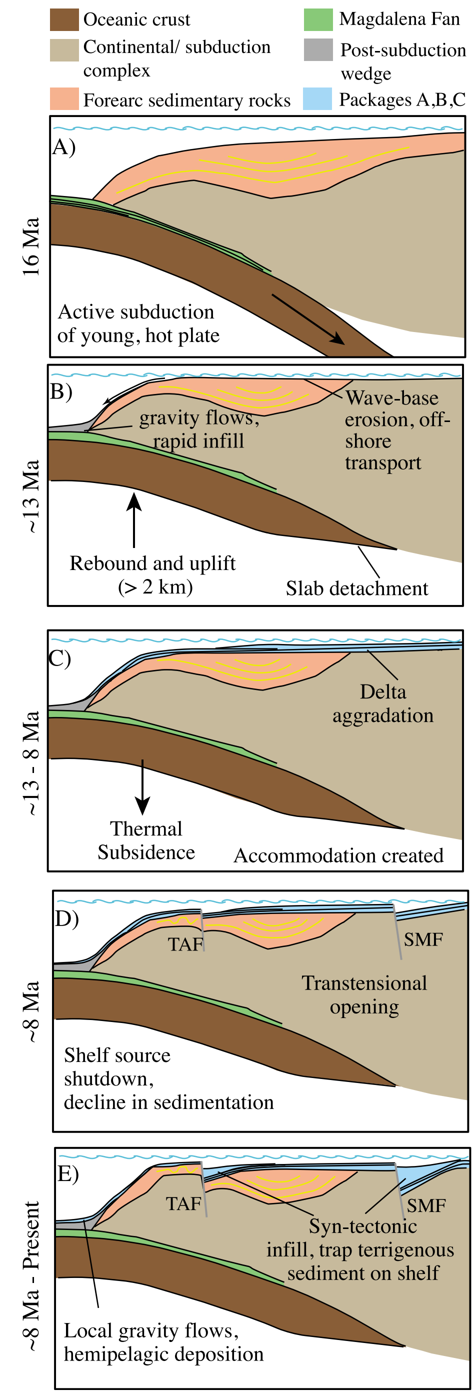

Figure 4. (a–e) Proposed tectonic evolution from ∼16 Ma to present, respectively. See Discussion.

change appears to be associated with the opening of basins on the shelf, and thus a transition to hemipelagic and locally sourced debris flow deposition along the slope and paleotrench. Correlating shelf packages A–C to the post-BSR strata in the trench provides a maximum age of shelf subsidence and transtensional opening along the TAF of ∼8 Ma.

[13] Based on the seismic evidence for high-velocity oceanic slab beneath the Magdalena Shelf, stratigraphic interpretations on the shelf and toe of the slope, transtensional deformation on the shelf and adakite volcanism on Isla Santa Margarita [*Bonini and Baldwin*, 1998], we propose that the slab detached near the break in Moho inclination (Figures 3 and 4). Although the eastward extent of the high-velocity zone is not resolved due to limited ray coverage in the lower crust and upper mantle, slab reflections and/or other seismic evidence for remnant slab extending below the root of the BC microplate are not observed [*Brothers*, 2009]. As the dense slab broke away and sank into the mantle, the overriding plate was isostatically uplifted and exposed to wave-base erosion. The age of blueschist exhumation along western BC is poorly constrained, but there is evidence for increased uplift of the subduction complex during the Middle Miocene [*Baldwin and Harrison*, 1989]. Numerical models of rebound immediately after slab detachment estimate that 2 to 6 km of uplift may occur [*Buiter et al.*, 2002] and geologic evidence in the Apennines, Northern Italy, documents a minimum of 500 m of post-detachment uplift [*van der Meulen et al.*, 1999]. After slab detachment and isostatic rebound, the stalled Magdalena ridge complex cooled, the margin subsided and Package C was deposited on the shelf. Transtension initiated along the TAF and SMF zones created shelf accommodation and trapped terrigenous sediment (packages B and A) and starved the paleotrench from terrestrial sediment sources.

[14] In summary, we propose the following sequence of events beginning at ∼16 Ma. (*1; ∼16–13 Ma*): Subduction slowed and the Magdalena slab became unstable as young, hot lithosphere approached its yield strength, eventually breaking off at a point below the Magdalena Shelf (Figures 4a and 4b). (*2; ∼13 Ma*): Rebound and uplift of the Magdalena Shelf occurred, exposing the margin to wave-base erosion and formation of a regional unconformity. Eroded shelf rock and terrigenous material were initially transported to the deep sea, forming a thick wedge of onlapping strata along the toe of the slope. (*3; ∼13–8 Ma*): As the stalled ridge complex cooled, the Magdalena Shelf subsided, creating accommodation for fan-delta progradation that predates opening along the TAF (Package-C; Figure 4c), although pure strike-slip could go undetected in 2-D seismic profiles. (*4; ∼8 Ma–present*): The Magdalena microplate became completely welded to the Pacific Plate and motion along the TAF and SMF systems began (Figure 4d). Terrigenous sediment was routed away from uplifted footwall blocks and into the incipient shelf basins, further starving the slope of sediment (Figure 4e).

[15] The approximately 4 million-year lag between the end of full-rate spreading and the onset of transtension along the Magdalena Shelf could represent a reorganization of the plate boundary as the relic slab gradually became welded to BC [*Atwater and Stock*, 1998; *Bohannon and Parsons*, 1995]. In this model, transtensional faulting in the BC forearc occurs much later in time (8 Ma versus 12 Ma) than suggested by *Stock and Hodges* [1989]. If these faults systems formed ∼8 Ma and accommodated 3–7 mm/yr of slip since their initiation [*Michaud et al.*, 2011; *Plattner et al.*, 2007], their cumulative displacement would be 24–56 km, in agreement with estimates by *Fletcher et al.* [2007]. Since 12.3 Ma the total displacement between the Magdalena microplate and North America is ∼610 km. At least 460 km was accommodated in the southern Gulf of California [*Fletcher et al.*, 2007], which leaves ∼100 km of unaccounted relative plate motion. Although seafloor magnetic

anomalies that post-date 12 Ma are equivocal [*Lonsdale*, 1991], it is possible that post-subduction spreading and rotation of the Pacific-Magdalena ridge segments accommodated some portion of the missing displacement prior to the onset of transtension on the Magdalena Shelf [*Michaud et al.*, 2006].

[16] High shear wave velocities (50–90 km depth) imaged beneath the BC peninsula to the north of Line 0 may represent remnants of the stalled Magdalena microplate [*Wang et al.*, 2009]. The high velocity anomaly disappears in the vicinity of Line 0 and is replaced by a low velocity anomaly that underlies the Magdalena Shelf and the proposed location of slab detachment. If traction forces along the interface between the slab and overriding plate influenced the rifting process and aided the transfer of BC to the Pacific Plate, one might expect a change in kinematics to the south of Line 0 where the slab is either diminutive or nonexistent. Prior to detachment, westward migration and steepening of the Farallon slab [*Umhoefer et al.*, 2001] may have led to enhanced upwelling and replacement of mantle material that provided additional forces to "push" the BC peninsula toward Pacific plate velocities, thus explaining, in part, how BC may have been "pulled" by traction forces between a stump of hot, weak oceanic lithosphere.

6. Conclusions

[17] Our results support a tectonic model for margin reorganization and oceanic slab detachment beneath the western margin of the BC microplate. Slab detachment and the consequent uplift of the overriding plate may be an important mechanism for rapid exhumation and erosion of subduction complexes [e.g., *Ring et al.*, 1999]. Without deep sea drilling and additional lower-crust and upper-mantle seismic imagery below the western margin of BC, the precise timing and location of slab detachment will remain less certain. Based on these combined factors, it appears likely that older, denser slab broke away from its younger, weaker and more buoyant section beneath the Magdalena Shelf near its interface with the overriding continental crust. Subsequent to detachment, basal shear applied to the continental margin of North America by stalled Farallon microplates may have constituted a key influence in the dynamic evolution of the BC microplate and its subsequent capture by the Pacific plate.

[18] **Acknowledgments.** Neither the U.S. Government, the Department of the Interior, nor the USGS, nor any of their employees, contractors, or subcontractors, make any warranty, express or implied, nor assume any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, nor represent that its use would not infringe on privately owned rights. The act of distribution shall not constitute any such warranty, and no responsibility is assumed by the USGS in the use of these data or related materials. Any use of trade, product, or firm names is for descriptive purposes only and does not imply endorsement by the U.S. Government. We thank Uri ten Brink and two anonymous reviewers for assisting in the evaluation of this paper. This work was funded by the NSF Margins Program, grant number OCE-0112058.

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