Ridge-trench interactions and the Neogene tectonic evolution of the Magdalena shelf and southern Gulf of California: Insights from detrital zircon U-Pb ages from the Magdalena fan and adjacent areas

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ABSTRACT

The Magdalena fan is an apparently beheaded submarine depocenter that has figured prominently in reconstructions of middle to late Miocene Pacific–North American plate interactions. The deposit accumulated rapidly at the base of the continental slope on top of newly formed oceanic crust of the Magdalena microplate from 14.5 to 13 Ma. Subduction of this crust ceased as the Pacific-Magdalena spreading center encountered the trench. The widely accepted two-phase kinematic model for the formation of the Gulf of California holds that ~300 km of dextral shear between the Pacific and North American plates occurred along faults west of Baja California prior to the onset of dextral-transtensional shearing in the gulf ca. 6 Ma. We measured 1796 detrital zircon U-Pb ages from 65 samples in an effort to characterize the provenance of the fan, determine its source region, and define the cumulative dextral slip along faults offshore of southwestern Baja California. Zircons from the fan are dominantly 120–65 Ma with subordinate 15–35 Ma grains. Excellent matches to the fan can be obtained by mixing Magdalena shelf strata and/or adding detritus from the west-draining portion of the Los Cabos block. The same cannot be accomplished with zircons from the east-draining portion of the Los Cabos block and mainland Mexico. Our results favor a western Baja source region for the fan and suggest that cumulative dextral slip along faults west of Baja was <150 km, much less than previously believed. We propose that the fan was fed by erosional denudation of the Magdalena shelf produced by increased mantle buoyancy due to the ridge-trench juxtaposition. The fan's source was cut off when faults west of Baja California began to accommodate transtensional shearing and form rift basins that captured detritus that previously reached the trench.

Keywords: Magdalena fan, detrital zircon, U-Pb, Baja California, Mexico, Integrated Ocean Drilling Program, Gulf of California, Neogene.

INTRODUCTION

In the middle Miocene the paleo–East Pacific Rise closely approached the Baja California trench over a strike length of ~1000 km. This ridge-trench juxtaposition ultimately gave rise to the opening of the Gulf of California and the ongoing capture of the Baja California microplate. Pacific–North American plate margin shearing began affecting the region of Baja California in middle-late Miocene time as spreading ceased across offshore ridge segments, and the partially subducted Farallon-derived microplates were captured by the Pacific plate (Mammerickx and Klitgord, 1982). Global plate circuit reconstructions demonstrate that, depending on Euler latitude, the Pacific plate has been transported 640–720 km to the northwest relative to stable North America since 12.3 Ma (Atwater and Stock, 1998). It is generally thought that this deformation was partitioned into deformation belts on either side of the Baja California microplate, and most workers recognize two distinct kinematic phases of plate margin shearing (Fig. 1). During the first phase, it is thought that the Gulf of California began opening by orthogonal rifting and most of the dextral shear was partitioned into faults west of Baja (Fig. 1A). It is thought that ~300–350 km of displacement was accommodated west of Baja California before displacement along these faults waned and the modern deformational regime of integrated transtensional strain became established in the Gulf of California ca. 6 Ma (Fig. 1B). Oskin and Stock (2003) documented 296 km of displacement across the northern Gulf of California and reported that all but 20 ± 10 km of this accumulated after 6.3 Ma. Oskin and Stock (2003) inferred that the remaining ~350 km of displacement must have occurred outside of the Gulf of California, which is consistent with localization of most of the plate motion west of Baja California between 12.5 and ca. 6 Ma. However, palinspastic reconstructions carried out by Fletcher et al. (2003a) showed that 450–500 km of slip is necessary to close the southern half of the Gulf of California: if this estimate is correct, it requires the additional

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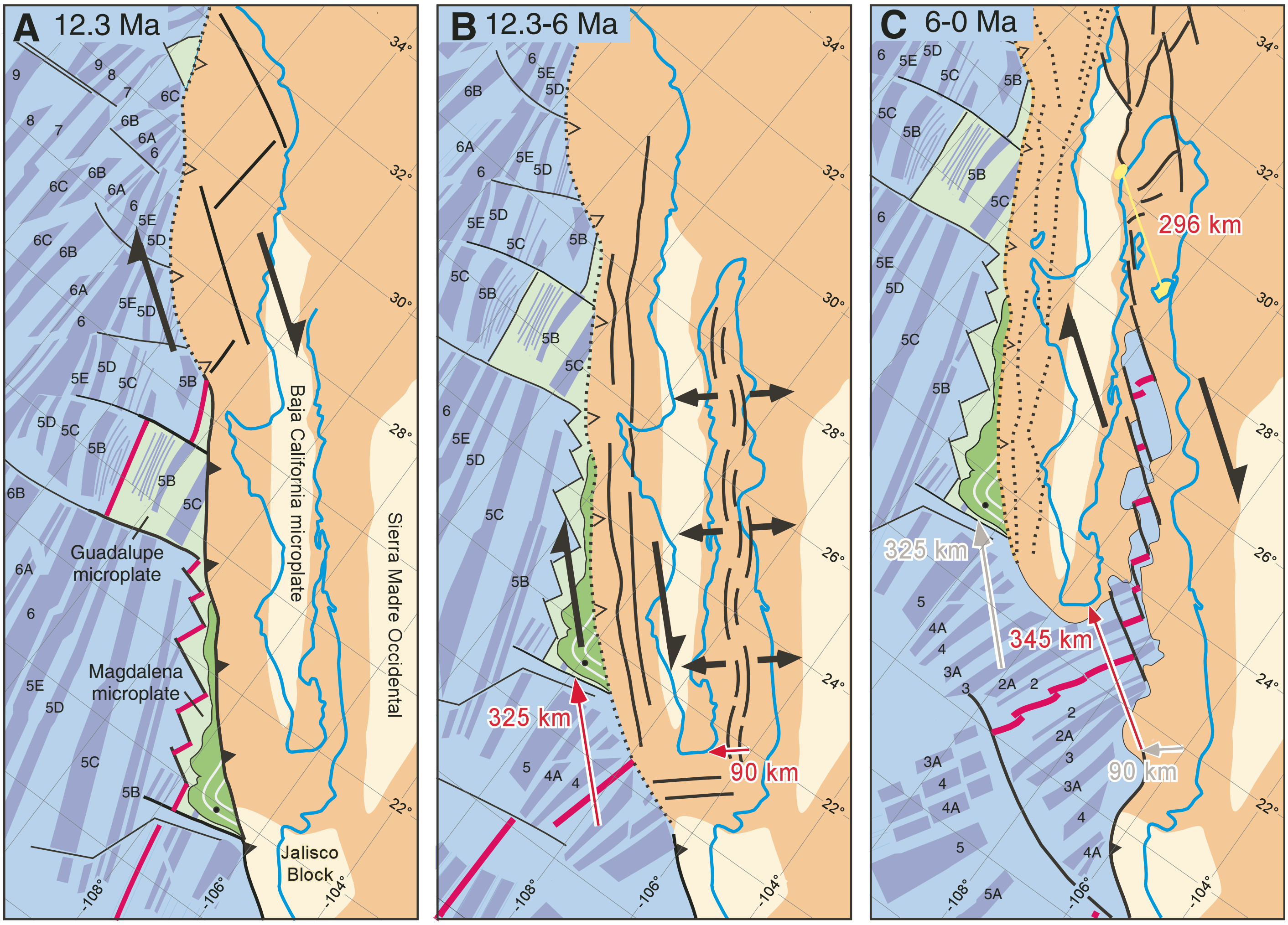

Figure 1. Map-view time slices showing the widely accepted model for the two-phase kinematic evolution of plate margin shearing around the Baja California microplate. (A) Configuration of active ridge segments (pink) west of Baja California just before they became largely abandoned ca. 12.3 Ma. (B) It is thought that plate motion from 12.3 to 6 Ma was kinematically partitioned into dextral strike slip (325 km) on faults west of Baja California and orthogonal rifting in the Gulf of California (90 km). This is known as the protogulf phase of rifting. (C) From 6 to 0 Ma faults west of Baja California are thought to have died and all plate motion was localized in the Gulf of California, which accommodated ~345 km of integrated transtensional shearing. Despite its wide acceptance, our data preclude this kinematic model. In all frames, the modern coastline is blue. Continental crust that accommodated post–12.3 Ma shearing is dark brown. Unfaulted microplates of continental crust are light tan. Farallon-derived microplates are light green. Middle Miocene trench-filling deposits like the Magdalena fan are colored dark green. Deep Sea Drilling Project Site 471 is the black dot on the southern Magdalena microplate. Yellow line (296 km) in the northern Gulf of California connects correlated terranes of Oskin and Stock (2003). Maps have Universal Transverse Mercator zone 12 projection with mainland Mexico fixed in present position.

~150–200 km of shear that is unaccounted for in the northern Gulf of California to have been accommodated by dextral transtensional shearing in mainland Mexico rather than by faults outboard of the Baja California margin.

One of the primary uncertainties regarding the transition from Andean-style convergence to the present regime involves the magnitude and location of middle to late Miocene slip between the North American and Pacific plates. There are two important fault systems along the Pacific margin of southern Baja California (Fig. 2): the well-known Tosco-Abreojos fault zone, which constitutes the dominant structural and geomorphic feature along the continental margin (Fig. 3; Spencer and Normark, 1979; Normark et al., 1987), and the more recently recognized Santa Margarita–San Lazaro fault zone, which is also an important structure and has an equivalent strike length (~400 km; Fig. 2; Fletcher et al., 2000a). Early workers recognized that the integrated middle Miocene to recent offset across all faults offshore of southern Baja California could be constrained by determining the magnitude of the northwest displacement of the apparently beheaded submarine Magdalena fan from its source region (Figs. 1 and 2). This submarine feature overlies oceanic crust at the base of the continental slope southwest of Bahia de Magdalena (Fig. 2). Although there is a broad consensus that Magdalena fan likely originated near the position where Baja California split away from the mainland (Fig. 1; Yeats and Haq, 1981; Lonsdale, 1991; Ferrari, 1995; Marsaglia, 2004), no specific areas have as yet been confidently identified as its source region.

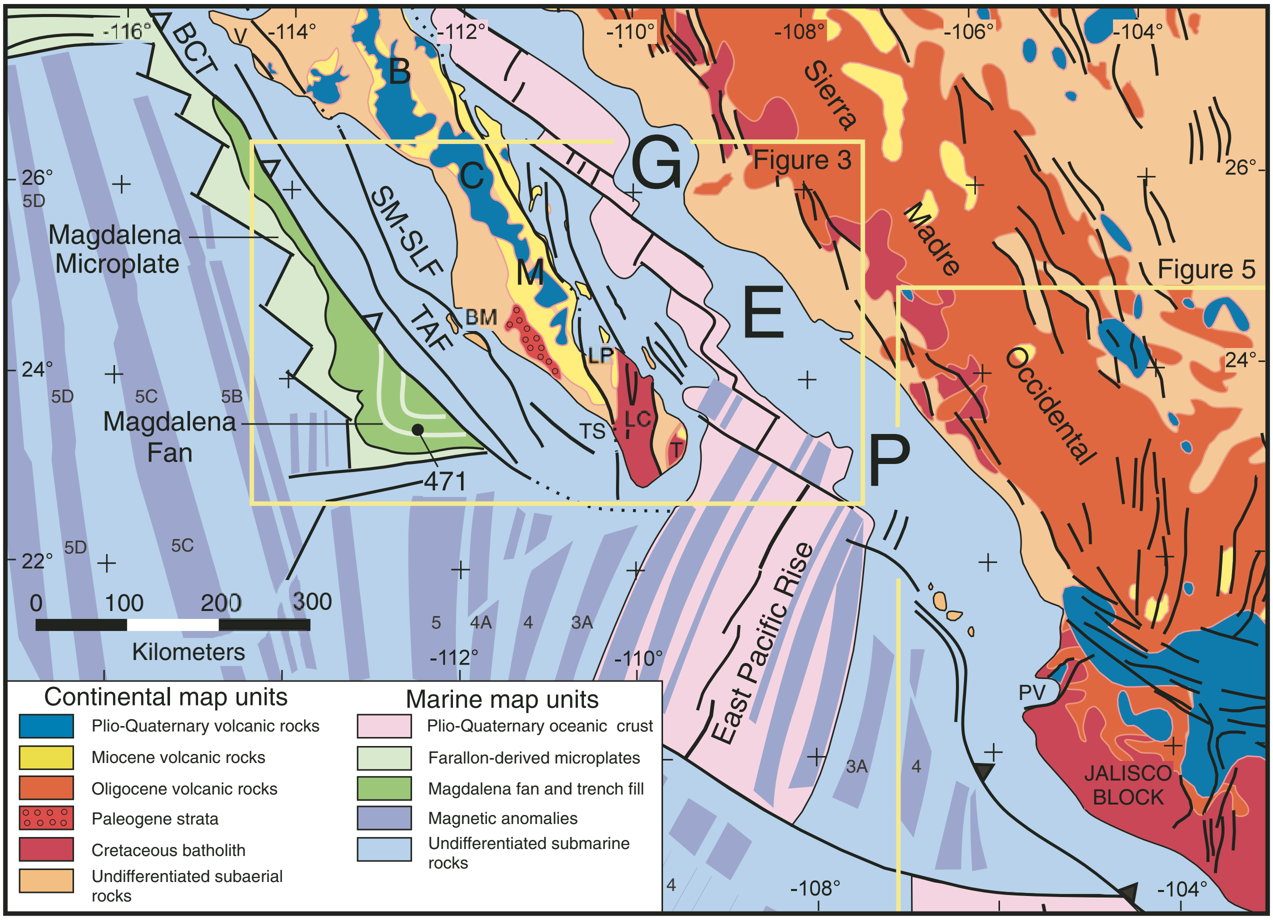

Figure 2. (A) Tectonic map of the southern Baja California microplate (BCM) and Gulf of California extensional province (GEP). The Magdalena fan is deposited on oceanic crust of the Farallon-derived Magdalena microplate located west of Baja California. Deep Sea Drilling Project Site 471 is shown as black dot on the Magdalena fan. Abbreviations: BCT—Baja California trench, BM—Bahia Magdalena, LC—Los Cabos block, T—Trinidad block, LP—La Paz, PV—Puerto Vallarta, SM-SLF—Santa Margarita–San Lazaro fault, TAF—Tosco-Abreojos fault, TS—Todos Santos, V—Vizcaino peninsula. Geology is simplified from Muehlberger (1996). Interpretation of marine magnetic anomalies, with numbers denoting the chron of positively magnetized stripes, is from Severinghaus and Atwater (1989) and Lonsdale (1991).

In this paper we present U-Pb detrital zircon ages that bear upon the provenance of the Magdalena fan and compare them with results from potential supracrustal and basement source regions from southern Baja California and formerly adjacent mainland Mexico. We conclude that the Magdalena fan formed off southern Baja California and was not displaced from a position near the original opening of the mouth of the Gulf of California, as originally thought (Yeats and Haq, 1981). Detrital zircon U-Pb age populations from the fan strongly resemble those contributed from the Magdalena shelf and adjacent crystalline rocks of the northwestern Los Cabos block. This outcome prompts us to reevaluate both the factors that triggered the deposition of the Magdalena fan and the total post–middle Miocene slip that occurred across faults west of Baja California. We summarize here the geologic attributes of the Magdalena fan and its potential source regions and describe the main faults that could have accommodated this movement between the fan and Baja California.

MAGDALENA FAN

The Magdalena fan is west of the base of the continental slope and was deposited shortly after formation of the underlying oceanic crust (Figs. 2 and 3). During Leg 63 of the Deep Sea Drilling Project (DSDP), an 823-m-deep borehole (DSDP Site 471) was drilled through the distal facies of the fan (Fig. 4). The oldest strata recovered (741.5 m depth) comprised a hemipelagic claystone deposited directly over oceanic crust. Its inferred age of 15–14.5 Ma is considerably older than magnetic anomalies found farther west and provided some of the first direct evidence that the fan was deposited on a stranded remnant of the former Farallon slab, as opposed to oceanic crust of the Pacific plate (Yeats and Haq, 1981). The lower half of the fan (438 m thick at Site 471) is within the *Coccolithius miopelagicus* subzone and was deposited rapidly from 14.5 to 13.0 Ma (Yeats and Haq, 1981; Yeats et al., 1981). The top of the lower submarine fan sequence occurs at a depth of 304 m in DSDP Site 471 and is marked by an unconformity representing both a depositional hiatus and angular discordance. After 13 Ma, the sedimentation rates diminished abruptly from 200 to 50 m/m.y. as porcellanite and diatomaceous claystone were deposited (Yeats et al., 1981).

Drill core from DSDP Site 471 shows that the distal turbiditic facies of the submarine fan is

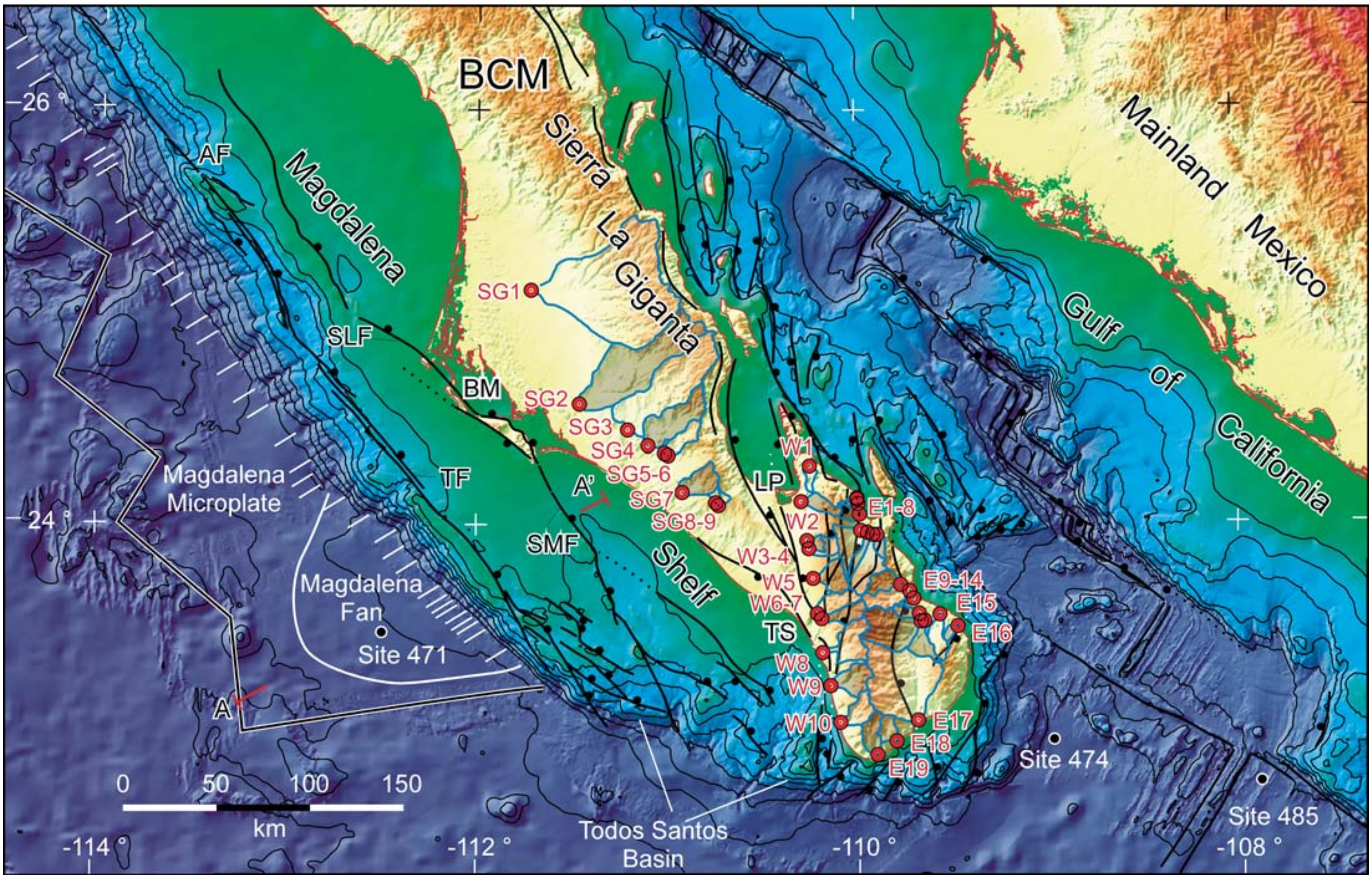

Figure 3. Shaded relief map of the southern Baja California microplate (BCM), which is between two main zones of plate margin shearing in the Gulf of California and the Magdalena shelf. Although these two zones are thought to have accommodated subequal amounts of plate margin shearing, obvious morphological differences suggest that most of the slip was partitioned in the Gulf of California. Modern sand sample locations and catchment basins are plotted. Magdalena fan is a semicircular lobe on the southern extreme of the Magdalena microplate. Series of white lines at the base of the continental slope mark channels that likely transported detritus from the shelf to backfill the paleotrench. Abbreviations: AF—Abreojos fault, BM—Bahia Magdalena, LP—La Paz, SLF—San Lazaro fault, SMF—Santa Margarita fault, TF—Tosco fault, TS—Todos Santos. Sources of digital elevation model include Instituto Nacional de Estadística Geografía e Informática (INEGI), Shuttle Radar Topography Mission, Sandwell and Smith (1997), and multibeam data collected by P. Lonsdale and B. Eakins (Scripps Institution of Oceanography), and D. Lizarralde (Woods Hole Oceanographic Institution), during four recent cruises of R/Vs *Revelle* and *Melville*, and one cruise of R/V *Ewing*.

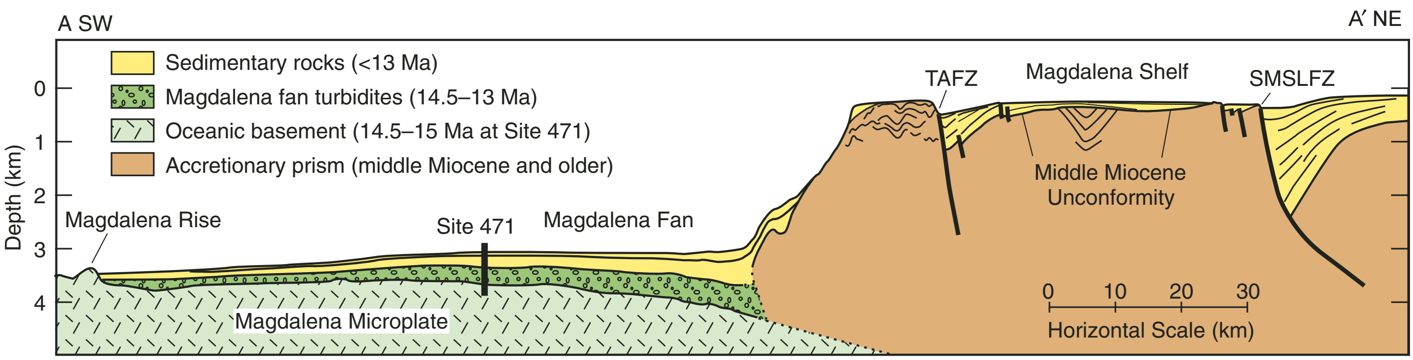

Figure 4. Representative cross section across the abandoned trench showing Magdalena fan and Magdalena shelf. Prominent erosional unconformity (contact between yellow and brown units) on the Magdalena shelf is likely to be the same age as Magdalena fan turbidites (see text). SMSLFZ—Santa Margarita–San Lazaro fault zone. Geologic relationships established from Deep Sea Drilling Project Leg 63, Normark et al. (1987), and González-Fernández et al. (2003) (see text).

dominated by siltstone and claystone with minor lenses of fine-grained to very fine grained calcareous sandstone (Marsaglia, 2004; Yeats et al, 1981). Although they are generally <1 cm thick, they can reach thicknesses of ~30 cm (Yeats et al., 1981). The sandstones contain subequal proportions of quartz, feldspar, and dominantly volcanic lithics with <15% metamorphic, sedimentary, and plutonic fragments (Yeats et al., 1981; Marsaglia, 2004). Marsaglia (2004) reported that the Magdalena fan sandstones are petrographically intermediate between dissected and undissected arcs (as defined by Dickinson et al., 1983). Based on the strong relative abundance of microlitic textures compared to felsitic and lathwork textures in the volcanic detritus, Marsaglia (2004) concluded that the volcanic lithics were more likely to have been derived from an intermediate to mafic volcanic province. The lower Magdalena fan contains a distinctive assemblage of reworked Cretaceous and Paleogene coccoliths, and Bukry (1981) inferred that the source area must have contained strata of this age. The fact that no reworked coccoliths are found in claystones above the unconformity was interpreted to indicate that the lower turbiditic portion of the fan was cut off from its source when sedimentation rates dramatically decreased (Yeats and Haq, 1981).

The Magdalena fan is not a unique feature along the Pacific margin of southern Baja California. Smaller distributed fans occur both to the north and south of the Magdalena fan and detritus has infilled the inactive trench everywhere along the margin of southern Baja California to water depths of 3000–3500 m below sea level (mbsl) (Figs. 2 and 3). Deposits correlative with the Magdalena fan have been observed in seismic sections hundreds of kilometers to the north (Michaud et al., 2004; Normark et al., 1987). Although the sedimentary apron does not extend as far from the trench as the Magdalena fan, its thickness is typically ~70% of the maximum thickness of the fan. Based upon available data we estimate that 3500 km^3 were deposited over a strike length of ~400 km between the Magdalena fan and the Cedros deep, which is adjacent to the Vizcaino peninsula. Hence the quantity of material infilling the trench (~8.8 km^3/km strike distance) is on average about one-third of that represented by the Magdalena fan (~29 km^3/km strike distance).

GEOLOGY OF THE MAGDALENA SHELF AND COASTAL PLAIN

The Magdalena shelf is a shallow, low-relief surface established along the western margin of Baja California Sur. It is bounded to the east by highlands of the Sierra La Giganta and extends ~100 km offshore to maximum water depths of 500 mbsl before abruptly terminating against the continental slope (Fig. 3). The shelf extends as far north as Isla Cedros, where it gives way to the highly dissected basin and ridge morphology of the Baja California borderland. To the south, the Magdalena shelf is bounded by a broad submarine basin southwest of the coastal town of Todos Santos (Fig. 3). We refer to this feature as the Todos Santos basin and note that the boundary between it and the Magdalena shelf coincides closely with the southern limit of the Magdalena microplate (Figs. 2 and 3). The Todos Santos basin contains numerous submarine canyons and fault scarps (Fig. 3; Normark and Curray, 1968; Normark et al., 1987; Eakins, 2000) and becomes deeper and more rugged toward the southeast. Because the Todos Santos basin is along the southern limit of the Magdalena microplate, it likely marks the location where the trench-fault-fault triple junction formed immediately after the cessation of spreading between the Pacific and Magdalena plates ca. 12.3 Ma (Eakins, 2000). We describe the pre–Magdalena fan stratigraphy and the possibly coeval and subsequent deformation that has affected the region.

Stratigraphy of the Offshore Region

Supracrustal rocks of the Magdalena shelf accumulated in a forearc setting floored by Mesozoic subduction-related accretionary rocks and rocks of ophiolitic and island-arc affinity (Rangin, 1978; Blake et al., 1984; Sedlock, 1993). These metamorphic rocks are exposed on the barrier islands that define Bahia Magdalena and structurally make up the footwall of a major northeast-directed detachment fault with multiple strands (Sedlock, 1993). Recent seismic reflection profiles measured across the Magdalena shelf in the PESCADERO project show that the overlying supracrustal rocks form two main sequences separated by a major unconformity (A. González-Fernández, 2005, personal commun.; Fig. 4).[1] The older portion of the sedimentary sequence is penetratively folded and faulted across the width of the Magdalena shelf (Fig. 4). A progressive decrease in contractional strain occurs toward onshore regions where temporally equivalent rocks are largely flat lying and only locally deformed. Deformed supracrustal rocks in the offshore region are presumed to be the distal facies of the Valle, Tepetate, San Gregorio, and Comondu Formations that are exposed throughout southern Baja California (see following). Offshore strata as young as middle Miocene were obtained in several dredge hauls from submarine ridges (Normark et al., 1987), that we infer to form part of the older sequence now exposed in the footwall of major Neogene faults.

Recent seismic profiles measured in the PESCADERO project (Gonzáles-Fernández et al., 2003) have revealed that the upper stratigraphic sequence forms two westward-thickening, wedge-shaped packages that reach ~3000 m adjacent to the major Neogene faults that control the extensional basins (A. González-Fernández, 2005, personal commun.; Fig. 4). Samples of this younger sequence obtained in dredge hauls are predominantly fossiliferous phosphatic mudstone and very fine grained sandstone that contains monocrystalline and polycrystalline quartz, feldspar, and sedimentary lithics (Normark et al, 1987).

Relationships described here indicate that contractional deformation of the accretionary wedge and overlying supracrustal rocks was as young as middle Miocene. We infer that the major unconformity imaged in the offshore portion of the Magdalena shelf (Fig. 4) represents a middle Miocene phase of deformation in which the folded strata were uplifted and beveled by erosion to form a broad peneplane surface. Sedimentation on the Magdalena shelf resumed in the late Miocene–Pliocene in two major half-graben basins. Therefore we interpret that the erosional unconformity marks a profound change in the tectonic regime of the Magdalena shelf from middle Miocene contraction to late Miocene–Pliocene extension.

Stratigraphy of the Onshore Region

Exposed sedimentary units that make up the coastal plain of the Magdalena shelf that predate and/or overlap deposition of the Magdalena fan include the Cretaceous Valle Formation, Eocene Tepetate Formation, Oligocene San Gregorio Formation, and Miocene Comondu Formation. Rocks younger than the Magdalena fan include the late Miocene–Holocene La Purisima volcanic field (Hausback, 1984; Sawlan, 1991) and Pliocene–Quaternary alluvial deposits (Fig. 2).

[1]PESCADERO stands for Profiling Experiments in the Sea of Cortez to Address the Development of Oblique Rifting. The PESCADERO project was a marine geophysical cruise to characterize the crustal structure of the Gulf of California in the fall of 2002. Multichannel and wide-angle seismic profiles were generated in three transects across the Gulf of California and one transect across the Baja California peninsula. Gravity, magnetics, and bathymetry were also collected. Two research vessels were used in coordination: the New Horizon and Maurice Ewing. Dan Lizarralde was the chief scientist. Co-principal investigators include: Gary J. Axen, John M. Fletcher, Antonio González-Fernández, Alistair J. Harding, W. Steven Holbrook, Graham M. Kent, and Paul J. Umhoefer.

The oldest supracrustal rocks of the Magdalena shelf are Albian–Aptian siliciclastic turbidites and deep-water conglomerates that are exposed in fault-bounded blocks in the outer islands of Bahia Magdalena (Figs. 2 and 3; Rangin, 1978; Blake et al., 1984; Sedlock et al., 1993; Bonini and Baldwin, 1998). Similar rocks present to the north in the Vizcaino region are capped by a continuous sequence of Late Cretaceous (Valle Formation) through Eocene forearc strata (Kimbrough et al., 2001, and references therein). Although onshore exposures of these rocks are not widespread in southern Baja California, we argue that the Late Cretaceous–early Tertiary forearc basin probably extended across much of the Magdalena shelf.

The Tepetate Formation is a sequence of marine sandstone and shale found on the western margin of Baja California and reaches more than 1000 m in thickness (Fig. 2; Heim, 1922). The sandstone facies is largely a feldspathic wacke derived from a western granitic source with very little volcanic detritus (Hausback, 1984; Ledesma-Vazquez et al., 1999). Based on early micropaleontologic studies, the Tepetate Formation was assigned a Late Cretaceous–early Eocene age (Fulwider, 1976; Coleman, 1979). However, abundant reworked Late Cretaceous–early Tertiary microfossils are found throughout the section and become more prevalent toward the top (Carreño, 2000; Garcia-Cordero and Carreño, 2005). Although the Tepetate Formation may be as old as Late Cretaceous, the most recent micropaleontologic studies conclude that most outcrops were deposited in the early-middle Eocene (Carreno, 2000; Garcia-Cordero and Carreno, 2005). Therefore, based on the abundance of reworked microfossils in the Tepetate Formation, we infer that it received sediment from Late Cretaceous–early Tertiary forearc strata that were exposed to the west (Fig. 2).

The San Gregorio Formation unconformably overlies the Tepetate and is a thin (100–127 m) shallow-marine sequence of interbedded siliceous shale, diatomite, pelletoidal phosphatic sandstone, and rhyolite tuff (Hausback, 1984). Thin beds (1 m) of metavolcanic conglomerate occur in the upper 15 m and along the basal unconformity (Hausback, 1984). Water-laid rhyolite tuffs (23.4–28.0 Ma) distributed throughout the sequence may be related to the voluminous Sierra Madre volcanic arc on the Mexican mainland (Hausback, 1984).

The Comondu Formation is a thick sequence (to 1500 m) of Miocene arc-derived volcanics and volcaniclastics of silicic to intermediate composition, and crops out over much of southern Baja, including the Sierra La Giganta (Fig. 2; Heim, 1922; Hausback, 1984). It contains interbedded volcanic sandstone and conglomerate, rhyolitic ash-flow tuffs, and andesitic lahars and lava flows (Heim, 1922; Hausback, 1984). The tuffs make up 70% of the section in the proximal facies of the Miocene volcanic arc (i.e., along the eastern coast of Baja California Sur and islands in the Gulf of California). These tuffs become systematically thinner and less abundant toward the west, where they eventually disappear midway across the peninsula (Hausback, 1984). The proximal facies of the Comondu arc dies out toward the south near Pichilingue (~20 km north of La Paz), and even the most distal deposits disappear ~20 km south of La Paz. Near this southern limit of the Comondu arc, paleocurrent indicators, isopach trends, and fining of clastic deposits rotate 90° from due west in the southern Sierra La Giganta to a southward direction near La Paz (Hausback, 1984). Whereas Hausback (1984) attributed this change in sediment transport to the influence of the uplifted western margin of the Los Cabos block, we believe that it represents the expected behavior at the southern termination of the Comondu volcanic arc.

Neogene Faulting

Tosco-Abreojos Fault

The Magdalena shelf is cut by the Neogene Tosco-Abreojos fault system, which extends along the entire length of the Magdalena shelf (Fig. 3; Spencer and Normark, 1979; Normark et al., 1987). The northern segment is called the Abreojos fault and it controls the western wall of the 320°-striking, ~180-km-long, 10–15-km-wide Abreojos trough (Normark et al., 1987). Single channel seismic profiles indicate that the Abreojos fault cuts subsurface reflectors, but not the seafloor (Normark et al., 1987). Normark et al. (1987) called the southern segment of the composite structure the Tosco fault; it extends along the western edge of the southern Magdalena shelf for 220 km. Multibeam bathymetry collected on several recent cruises shows that the Tosco fault zone is composed of multiple closely spaced (~1 km) fault strands that bound linear ridges and strike ~320°. Southeast of lat 23.6°N the Tosco fault zone becomes wider and its strands splay out in a crude radiating pattern. The strands in this region are discontinuous, curvilinear, and appear to die within the northwest portion of the Todos Santos basin (Fig. 3).

Normark et al. (1987) inferred that the Tosco-Abreojos fault was a strike-slip fault based on the remarkable straightness of the fault trace over hundreds of kilometers. Normark et al. (1987) interpreted the deep submarine basin between the Tosco and Abreojos segments to be a pull-apart basin based on a small right step between the two fault segments, which is consistent with dextral shear. However, recent multibeam bathymetry shows that the entire length of the Tosco fault segment is dominated by an east-facing bathymetric escarpment (Fig. 3). Normark et al. (1987) described the uplifted ridge of the southwestern block as acoustically opaque basement, but noted that a seismic penetration of 4–6 s was observed on the northeastern block, which they inferred to be composed of a Neogene sedimentary sequence at least 2 km thick. We interpret the persistent east-facing bathymetric escarpment and structural basin to indicate a significant component of east-down normal shear across the fault.

Santa Margarita–San Lazaro Fault Zone

A second fault zone of equivalent strike length (400–500 km) is northeast of the Tosco-Abreojos fault on the Magdalena shelf (Fig. 3; Spencer and Normark, 1979; Normark et al., 1987). These previously unnamed faults have prominent east-facing bathymetric scarps and project laterally toward the Bahia Magdalena area from both the northwest and southeast (Fig. 3; Sedlock, 1993).

The barrier islands of Bahia Magdalena are cut by a major detachment fault system with northeast-directed transport (Sedlock, 1993). One of the main detachment strands defines crude structural corrugations of the northeast margin of Isla Santa Margarita (Fletcher et al., 2000a). In addition to the detachment, a prominent array of Quaternary scarps can also be followed for ~40 km along the entire length of Isla Santa Margarita. Fletcher et al. (2000a) noted that the Quaternary scarps make abrupt changes in strike of as much as 60° as they follow the synformal and antiformal corrugations of the detachment. Fletcher et al. (2000a) proposed that the northeast rooting detachment was still active and was the main structure responsible for uplift of the islands in Pliocene–Quaternary time.

Offshore faults present both north and south of Isla Santa Margarita both project laterally toward the trace of the northeast-rooting fault array exposed on the barrier island (Fig. 3). We infer that these fault segments link as a continuous, northeast-side-down fault zone. González-Fernández et al. (2003) presented seismic profiles across the offshore segment of the Santa Margarita–San Lazaro fault to the south of the Bahia Magdalena that clearly show that the northeast block is a major half-graben basin with a fanning sequence of late Neogene strata that are as thick as ~3000 m near the fault (Fig. 4). Like the Tosco fault, the Santa Margarita–San Lazaro fault appears to die out southward into the Todos Santos basin (Fig. 3). To the north of Bahia Magdalena, the Santa Margarita–San Lazaro fault controls the steep west flank of the ~25-km-long, ~10-km-wide

San Lazaro submarine depression developed parallel to the fault trace. The center of the basin is ~550 mbsl. The Santa Margarita–San Lazaro fault becomes difficult to follow toward the north, but magnetotelluric soundings across the Vizcaino peninsula show a major sedimentary basin ~10 km thick to the east of the uplifted coastal mountain range (Romo-Jones, 2002).

We propose that the strong curvilinear trace of the Santa Margarita–San Lazaro fault likely reflects antiformal and synformal corrugations similar to those observed on Isla Santa Margarita, but at a more regional scale. Likewise the overall kinematics of the Santa Margarita–San Lazaro fault are inferred to be dominated by northeast-directed normal displacement, which is indicated by striae on the detachment that bounds the northeast margin of Isla Santa Margarita and consistent with the east-facing escarpments and structural basins observed in the offshore fault segments. Therefore we infer that the dominant faults that cut the Magdalena shelf have accommodated integrated dextral transtension and not just the strike-slip component of plate margin shearing, as is commonly assumed in tectonic models.

Key Mesozoic Basement Massifs

Two formerly contiguous massifs of Mesozoic batholithic rocks that were exposed during the middle Miocene (Fig. 2) are on the conjugate rifted margins across the mouth of the Gulf of California. These include the Los Cabos and Trinidad blocks on Peninsular California and the Jalisco block on mainland Mexico (northern Jalisco block area). Although consideration of more distant granitic basement terranes that could have contributed to the Magdalena fan is beyond the scope of this paper, we emphasize that if a major extraregional river system responsible for development of the fan had emptied into the ocean at a position near the present-day opening of the Gulf of California, as is widely thought (Fig. 1; e.g., Yeats and Haq, 1981; Lonsdale, 1991; Ferrari, 1995; Marsaglia, 2004), this system would have traversed (and hence received sediment from) the middle to Late Cretaceous batholith.

Los Cabos and Trinidad Blocks

The geology and physiography of the southern extreme of the Baja California Peninsula is markedly different from the relatively undeformed forearc strata that blanket the rest of Baja California Sur (Fig. 2). Faults that define the rifted margin along the Gulf of Baja California cut southwestward across the peninsula. The broadly extended region can be subdivided into two main basement massifs and separated by the intervening Cabo Trough rift basin, which is bounded on the west by the east-dipping San Jose del Cabo fault. The radical north to south change in geology and physiography at the southern end of the peninsula coincides with the apparent southern termination of the Miocene volcanic field. Miocene volcanics, which dominate most of Baja California Sur, are only found in the northwesternmost exposures of the Los Cabos and Trinidad blocks, and there is no evidence that the granitic basement farther south was ever covered by the thick sequence of Comondu volcanics.

Prior to our study, information on the distribution of crystallization ages throughout Los Cabos and Trinidad blocks was sparse (e.g., Schaaf et al., 2000). Studies indicated that the northwestern portion of the Los Cabos block is underlain by dominantly 90–100 Ma and older intrusives, while the southeastern Los Cabos and Trinidad blocks are composed almost exclusively of Late Cretaceous granitoids younger than 90 Ma. Results presented in this paper confirm this relationship and more precisely delimit the crystallization-age domains.

Jalisco Block (Puerto Vallarta Batholith)

The northern Jalisco block represents the southeastern continuation of the middle Cretaceous to early Paleocene batholith on mainland Mexico (Figs. 2 and 5; Schaaf et al., 2000). The geology of mainland Mexico undergoes a major transition near the northern Jalisco block, where the thick Oligocene to Miocene volcanic pile of the Sierra Madre Occidental gives way to predominantly Mesozoic plutonic and metamorphic rocks of the Puerto Vallarta batholith (Fig. 2). Although this transition is now largely covered by the younger Transmexican volcanic field, these two main packages of rocks would have dominated this potential source region when the Magdalena fan was deposited. Limited data summarized by Schaaf et al. (2003) and Ortega-Rivera (2003) indicate that most of the intrusive rocks are Late Cretaceous to early Paleocene at more eastern positions.

METHODS

Sampling Strategy

We obtained 1796 U-Pb zircon analyses from 65 samples recovered from shipboard drilling, onland Tertiary strata, and modern sands from southernmost Baja California and formerly adjacent portions of mainland Mexico. Of these, 188 U-Pb analyses were from 4 widely spaced core samples recovered from the Magdalena fan at Site 471 (Figs. 2 and 6A). We measured 60 grains from each of 3 samples representing turbiditic sands from the lower portion of the fan (see Marsaglia, 2004, for additional details). In general, zircon could not be recovered from the much finer grained sediments that compose the upper portion of Site 471. However, sampling of coarser detritus concentrated within burrows formed by sediment-ingesting organisms (sample 471–05) yielded eight analyzable zircons.

In order to evaluate potential source regions for the Magdalena fan, we obtained additional zircon U-Pb age results from 9 sedimentary (n = 540; Table 1) and 53 modern sand samples (n = 1068; Table 2). We would have preferred to focus exclusively upon strata equivalent in age to the Magdalena fan; however, because the strata of the Comondu Group represent the only sedimentary rocks that are known to be age equivalent to the middle Miocene portion of the Magdalena fan, we elected to analyze a wide range of material to broadly characterize different source areas throughout the southern gulf region. The sedimentary rocks examined included (1) Miocene and older strata from the Magdalena shelf (Tepetate Formation, San Gregorio Formation, and Comondu Group); (2) Cenozoic strata deposited along the buttress unconformity developed at the western margin of the Los Cabos block; (3) late Miocene strata of the Cabo Trough rift basin that depositionally overlie the Trinidad block in the east; and (4) samples recovered from DSDP holes near the mouth of the Gulf of California.

Our sampling of modern sands involved a broad reconnaissance survey of materials sampled from the Magdalena shelf, the Los Cabos block, the northern Jalisco block, and the southern Sierra Madre Occidental (Figs. 3 and 5). Analysis of modern sands had the advantage of providing us with a rapid first-order assessment of detrital zircon age populations that could be directly related to potential supracrustal and crystalline source rocks over broad areas. Only limited results were obtained from individual drainages. To obtain statistically robust results, we combined data from individual drainages by scaling their normalized probability distributions by the map areas of their respective catchment basins (Table 2; see GSA Data Repository for additional details[2]). The total catchment-basin area sampled in this study is ~60,000 km^2, which is ~6–60 times greater than the inferred size of the source area of the Magdalena fan based on calculations presented in Appendix 1. Therefore, we are confident in our ability to evaluate multiple potential source areas of the Magdalena fan with this data set.

[2]GSA Data Repository item 2007194, ion microprobe analytical details, data tables, and details of data analysis, is available at http://www.geosociety.org/pubs/ft2007.htm or by request to editing@geosociety.org.

Analytical Approach

We used both ion microprobe and laser ablation multicollector inductively coupled plasma mass spectrometry (LA-MC-ICPMS) methods (e.g.,Gehrels et al, 2006) to measure detrital zircon age distributions to characterize provenance. (For analytical details for both approaches, see footnote 1.) Intercalibration experiments carried out with the University of California, Los Angeles (UCLA) Cameca ims1270 ion microprobe and the University of Arizona (UA) Micromass Isoprobe LA-MC-ICPMS that were performed with the same sample mount reveal that both approaches are capable of 1%–2% accuracy (see footnote 1). However, U-Pb ages produced by the UA LA-ICPMS are about twice as precise as those yielded by the UCLA ims1270 with procedures employed in this study.

In order to compare results from the Magdalena fan with these other areas, we utilized the Kolmogorov-Smirnov (K-S) statistic (Press et al, 1988). Although we generally applied the K-S statistic to compare the age distributions of individual samples with that of the Magdalena fan, we also employed it to compare the Magdalena fan results with composite samples intended to characterize broad areas that consisted of the weighted results from a number of individual modern drainages. In the latter case, we have defined the weighted distribution, X_w, as follows:

$$X_w = \sum_{i=1}^{m} \phi * X_i \text{ with } \sum_{i=1}^{m} \phi_i = 1\,, \qquad (1)$$

where ϕ_i is the weight assigned to the i^{th} modern drainage, X_i. Note that we have used catchment area (see Table 2) to calculate ϕ_i for the individual drainage basins. Calculation of the K-S statistic requires the size of the samples being compared to be specified. The effective sample size (N_{eff}) that we assigned to X_w is given by:

$$\frac{1}{N_{eff}} = \sum_{i=1}^{m} \frac{\phi_i^2}{N_i}\,, \qquad (2)$$

where $N_1, N_2, \ldots N_m$ are the number of samples analyzed from drainages $X_1, X_2, \ldots X_m$. Defining N_{eff} as specified by equation 2 for composite age distributions ensures that the null hypothesis is evaluated in a conservative manner.

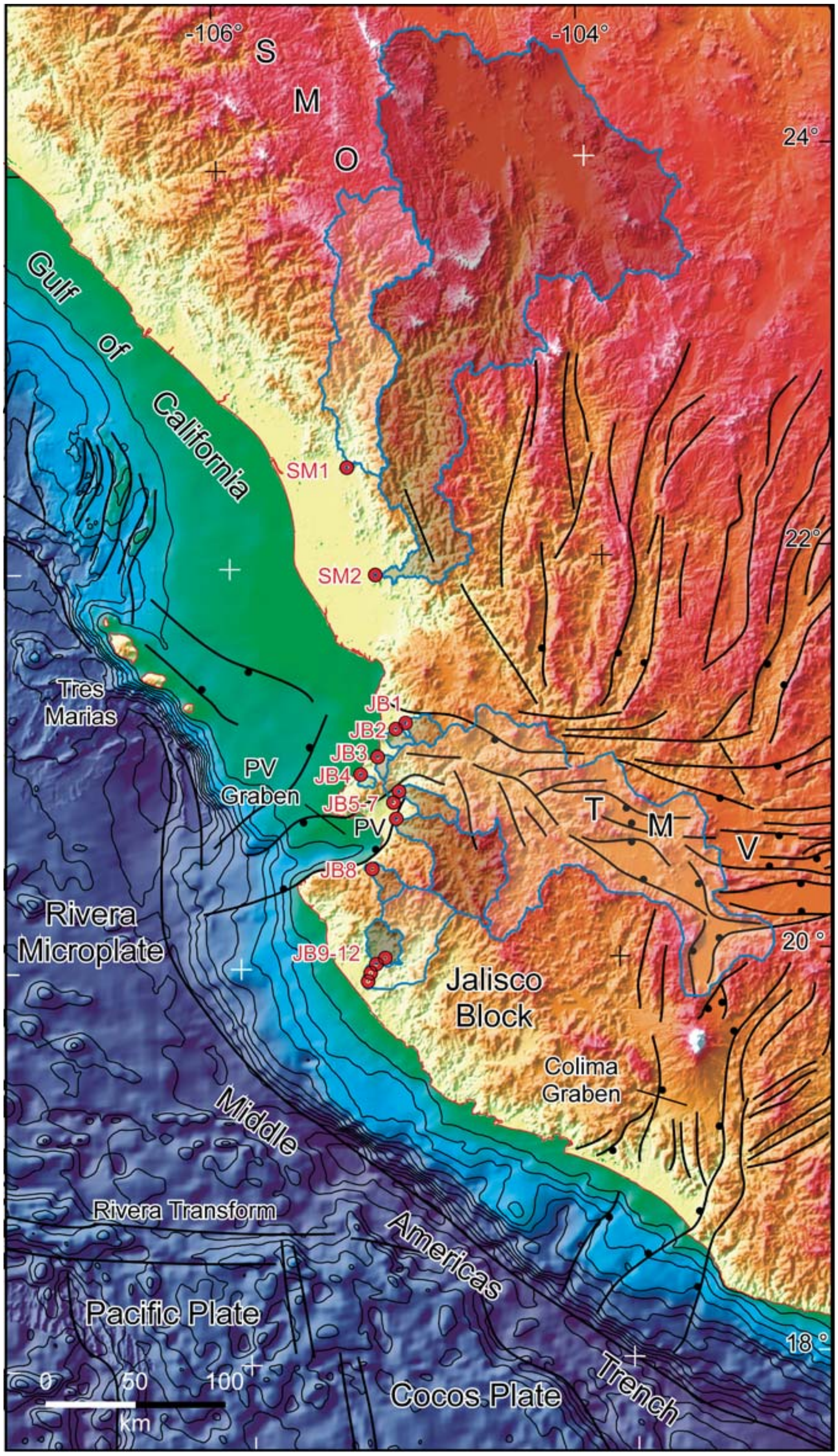

Figure 5. Shaded relief map of the southern Sierra Madre Occidental and northern Jalisco block showing modern sand sample locations, catchment basins, faults, and tectonic plates. Abbreviations: SMO—Sierra Madre Occidental, PV—Puerto Vallarta, TMV—Trans-Mexican volcanic field. Note lack of modern fans backfilling the Middle Americas trench adjacent to the Colima graben. Ameca River drainage mentioned in text has the largest catchment basin and corresponds to sample S26. Sources of digital elevation model include Instituto Nacional de Estadística Geografía e Informática (INEGI), Shuttle Radar Topography Mission, Sandwell and Smith (1997) and multibeam data from the R/V *Revelle*.

RESULTS: MAGDALENA FAN

The four sampled intervals of the Magdalena fan are all dominated by 60–110 Ma zircon (75%; Fig. 6). Other distinctive features include

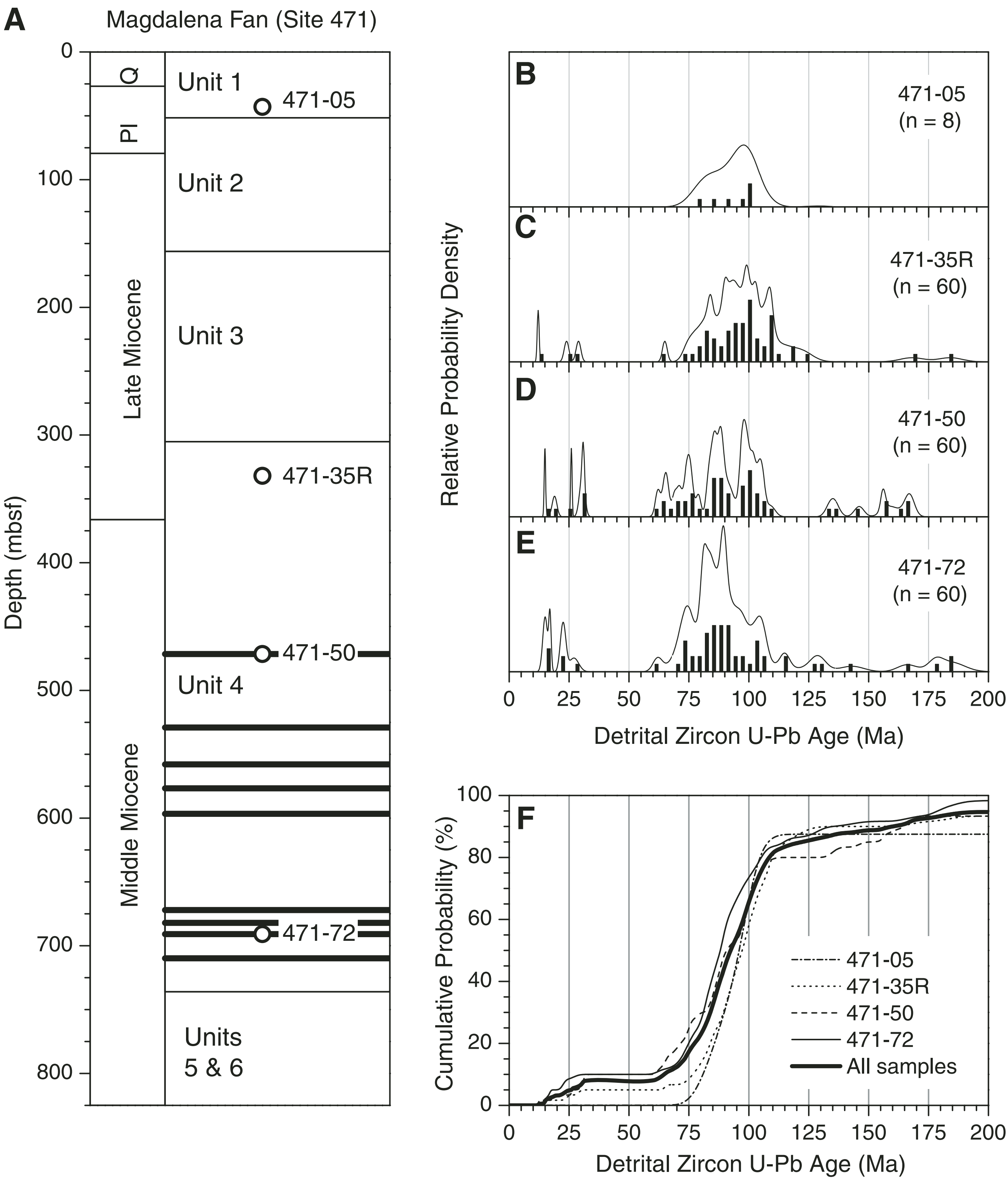

Figure 6. (A) Simplified stratigraphy of Site 471 illustrating sampling horizons from the Magdalena fan (mbsf—m below seafloor). (B–E) Probability density plots of detrital zircon U-Pb results from four sampling horizons. (F) Cumulative probability plot for all four samples and the combined result. Note that we employ a 0–200 Ma scale because 95% of the measured U-Pb ages are younger than 200 Ma.

TABLE 1. SANDSTONE SAMPLES

Sample	UTM zone	UTM northing	UTM easting	N	Stratigraphic age	Description
471-05	12Q	347189	2597542	8	Pliocene	Site 471, Magdalena Fan
471-35R	12Q	347189	2597542	60	Middle Miocene	Site 471, Magdalena Fan
471-50	12Q	347189	2597542	60	Middle Miocene	Site 471, Magdalena Fan
471-72	12Q	583521	2585874	60	Middle Miocene	Site 471, Magdalena Fan
LP03-78	12R	543712	2660130	76	Late Miocene	Comondu Group (Magdalena Shelf)
LC03-08	12R	516032	2671586	82	Oligocene	San Gregorio Formation (Magdalena Shelf)
LP03-83	12R	507705	2672860	75	Eocene	Tepetate Formation (Magdalena Shelf)
LP03-85A	12R	486652	2697348	14	Eocene	Tepetate Formation (Magdalena Shelf)
LC0306	12R	581542	2655504	65	Eocene(?)	Un-named basal conglomerate (Western Los Cabos block)
TS0376	12Q	578253	2606168	61	Pliocene	Salada Formation (Western Los Cabos block)
LC0302	12Q	590408	2632622	62	Late Miocene	La Calera Formation (Eastern Los Cabos block)
474-xx	12Q	707036	2540589	53	Pliocene	Site 474, Offshore Southeastern Los Cabos block
485-xx	12Q	818032	2518932	51	Quaternary	Site 485, Rivera Plate, mouth of Gulf of California

Note: UTM—Universal Transverse Mercator; N—number.

TABLE 2. MODERN SAND SAMPLES

Sample	UTM zone	UTM easting	UTM northing	Catchment area (km^2)	N
SG1	12R	427323	2780120	3017	96
SG2	12R	453059	2719221	1385	36
SG3	12R	478791	2705360	1191	26
SG4	12R	489670	2696997	519	26
SG5	12R	498518	2692985	172	27
SG6	12R	500418	2691831	–	25
SG7	12R	507947	2672201	240	20
SG8	12R	525902	2666685	33	12
SG9	12R	527328	2665237	34	12
W1	12R	575919	2686361	58	11
W2	12R	571502	2667325	126	11
W3	12Q	574685	2646486	48	10
W4	12Q	575674	2642157	94	10
W5	12Q	577987	2626264	204	10
W6	12Q	580270	2607433	193	10
W7	12Q	582638	2604696	169	10
W8	12Q	583161	2586576	318	10
W9	12Q	587526	2568919	241	10
W10	12Q	592805	2549278	188	10
E1	12R	601355	2669467	9.7	4
E2	12R	601412	2668691	–	5
E3	12R	601944	2666391	18	5
E4	12R	602691	2660705	68	5
E5	12R	603363	2652010	248	5
E6	12R	606924	2651029	87	5
E7	12R	609781	2649915	87	10
E8	12Q	612061	2649804	59	17
E9	12Q	624809	2623100	154	9
E10	12Q	629557	2619828	199	10
E11	12Q	631762	2615784	22	10
E12	12Q	634779	2607735	72	12
E13	12Q	635756	2603573	504	10
E14	12Q	637698	2603921	17	25
E15	12Q	645717	2607500	72	20
E16	12Q	655328	2601203	69	30
E17	12Q	634365	2550589	1233	95
E18	12Q	622821	2539353	117	10
E19	12Q	612653	2532038	182	10
SM1	13Q	463543	2487035	5132	57
SM2	13Q	476918	2426937	26,656	60
JB1	13Q	490529	2344356	243	10
JB2	13Q	484970	2341206	115	10
JB3	13Q	474384	2326389	81	10
JB4	13Q	464594	2317079	52	14
JB5	13Q	485487	2306877	345	23
JB6	13Q	482193	2300861	13,025	101
JB7	13Q	483382	2291809	2032	27
JB8	13Q	469127	2264491	240	26
JB9	13Q	474509	2214909	–	10
JB10	13Q	469455	2211720	380	17
JB11	13Q	466097	2206885	1517	13
JB12	13Q	464544	2202358	–	10

Note: UTM—Universal Transverse Mercator; N—number.

TABLE 3. KOLMOGOROV-SMIRNOV RESULTS

Comparison*	*N*	D_{max}§	*PROB***
471-005	8	0.17	0.980
471-35R	60	0.14	0.322
471-50	60	0.08	0.915
471-72	60	0.12	0.476
Comondu Group	76	0.17	0.098
San Gregorio Formation	82	0.57	2E-16
Tepetate Formation	89	0.20	0.018
Un-named basal conglomerate	65	0.21	0.026
Salada Formation	61	0.20	0.058
La Calera Formation	62	0.34	4E-05
Site 474	53	0.44	2E-07
Site 485	51	0.66	8E-16
Rio Bramonas (SG1)	96	0.13	0.23
Rio San Jose (E17)	95	0.31	7E-6
Rio Ameca (JB6)	101	0.63	5E-24
Rio San Pedro (SM1)	60	0.90	1E-33
Magdalena shelf sand†	200	0.32	2E-9
Western Los Cabos block sand†	81	0.14	0.23
Eastern Los Cabos block sand†	149	0.27	5E-6
Jalisco block sand†	166	0.46	1E-18
Southern Sierra Madre Occidental sand†	82	0.89	6E-41

*Relative to all results from Magdalena Fan.

†Composite results calculated from individual drainages weighted by catchment area. Effective number of analyses (N_{eff}) calculated from equation 2 in text.

§Maximum vertical separation of the cumulative probability spectra of the indicated sample and the Magdalena Fan.

**Probability of valid null hypothesis (*PROB* > 0.05 indicates that the distributions being compared are indistinguishable at the 95% confidence level).

middle Tertiary zircon (14–34 Ma zircon; 8% overall). Eocene zircon is conspicuously absent, although there are a few Paleocene grains (2%). The comparatively high proportion of 90–120 Ma grains (41% overall) is an important factor for differentiating among granitic massifs that may have contributed detritus to the fan. Although we managed to obtain very limited results (n = 8) from the stratigraphically highest (Pliocene) sample, the overall similarity of its detrital zircon age distribution to those yielded by samples from the lower turbiditic section implies that all portions of the Magdalena fan were derived from the same source region. Kolmogorov-Smirnov analysis of the results from the four individual samples reveals that they cannot be distinguished at the 95% confidence level (Table 3). This homogeneity is consistent with the strikingly similar modal compositions reported by Marsaglia (2004) for unaltered sandstone throughout the lower turbiditic section of Site 471.

MAGDALENA SHELF AND SIERRA LA GIGANTA

Tertiary Strata

Tepetate Formation

We obtained 89 zircon U-Pb analyses from 2 samples of the Tepetate Formation (Fig. 7A). The youngest zircon measured (51 ± 2 Ma) is consistent with the reported Eocene depositional age for this unit (Heim, 1922; Garcia-Cordero and Carreño, 2005). The distribution of Cretaceous zircon U-Pb ages from the Tepetate Formation are similar to those of the Magdalena fan in that 70% of the grains examined yielded middle to Late Cretaceous zircon ages (i.e., between 65 and 120 Ma) with 60% of the results between 90 and 120 Ma. The Magdalena fan and Tepetate zircon U-Pb age distributions can just barely be resolved at the 95% confidence level (Table 3). Minor differences include the presence of a few early Eocene zircons and the absence of middle Tertiary grains in the Tepetate Formation.

San Gregorio Formation

We examined 82 zircons from the upper San Gregorio Formation (Fig. 7B; Table 1). These yielded abundant (54% of total) late Oligocene to earliest Miocene U-Pb ages that are consistent with the depositional age determined by Hausback (1984). While late Oligocene–early Miocene zircon is a distinctive component within the Magdalena fan, its extreme abundance allows us to distinguish the age distributions of the San Gregorio Formation and the Magdalena fan (Table 3). Nevertheless, 29% of the zircons measured are within the 65–120 Ma age range. Like the Tepetate Formation, the San Gregorio contains appreciable (13%) Eocene and Paleocene zircon, which was not abundant in the Magdalena fan.

Comondu Group

Zircons (n = 76) from one sample of a late Miocene sample of the Comondu Formation yielded a U-Pb age distribution remarkably similar to that determined from the Magdalena fan (Fig. 7C). While 19% of the zircons yielded Miocene ages as young as 9 Ma, 67% of the grains yielded U-Pb ages between 65 and 120 Ma, with 39% between 90 and 120 Ma. A smattering of zircon yielded earlier Cretaceous and Jurassic ages while 7% yielded ages between 35 and 65 Ma. Although this upper portion of the Comondu slightly postdated the deposition of the Magdalena fan, the overall zircon U-Pb age distribution is indistinguishable from that of the Magdalena fan (Table 3).

Modern Sands

We sampled 9 west-flowing drainages with a collective catchment area of 6500 km^2 along the western flank of the Sierra La Giganta between Bahia Magdalena and the Los Cabos block (Figs. 2 and 3). These fluvial systems largely transport material derived from the erosion of the Tepetate, San Gregorio, and Comondu Formations, which are the dominant constituents of the Magdalena shelf. Detrital zircon ages from these drainages exhibit the characteristic

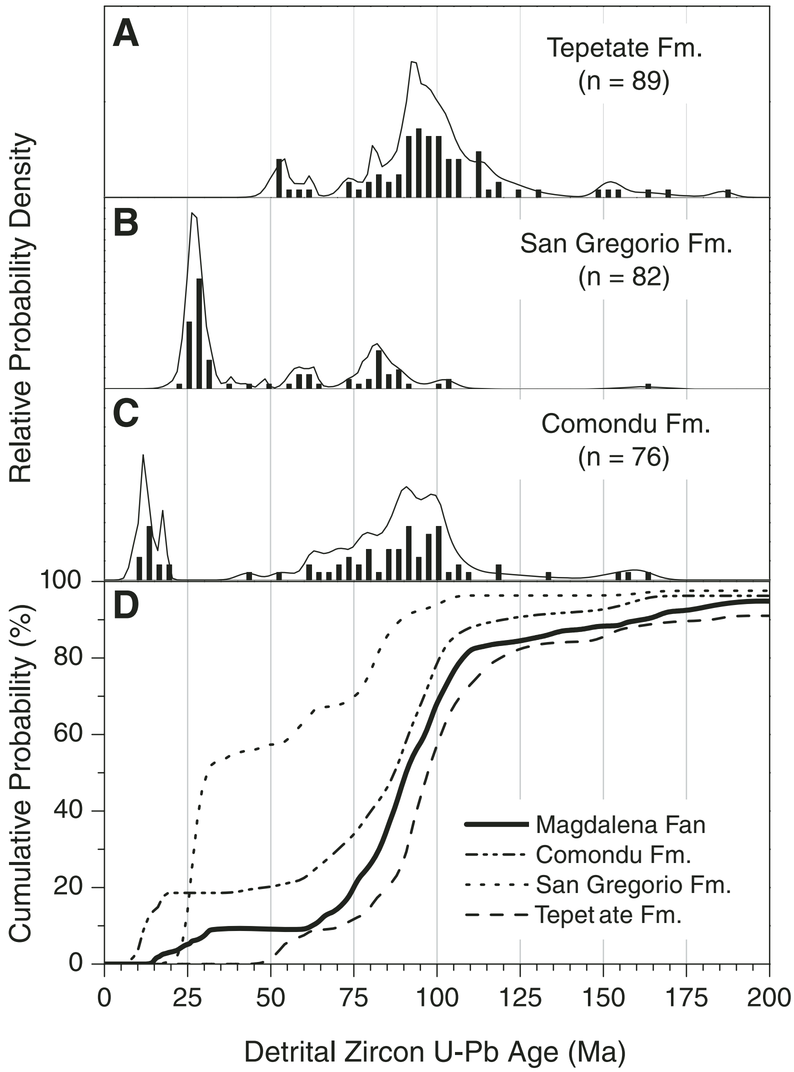

Figure 7. (A–C) Probability density plots portraying detrital zircon U-Pb results from the Tepetate, San Gregorio, and Comondu Formations. (D) Cumulative probability plots for all three samples. Note strong similarity of the results from the Tepetate and Comondu Formations to the Magdalena fan.

bimodal distribution of zircon ages seen in the Magdalena fan (Figs. 8A–8H; Table 2). Moreover, the proportion of 90–120 Ma zircon (relative to 65–90 Ma zircon) present in many samples is reminiscent of the Magdalena fan. The principal difference is that middle Tertiary grains were disproportionately more abundant than they are within the fan. The most northern and southern drainages sampled yield zircon age distributions that are the most similar to that of the Magdalena fan (Fig. 8B). By weighting results from individual drainages according to catchment areas (Table 2), we calculated a composite U-Pb age distribution for all modern sands from the Magdalena shelf (Fig. 8I). Although the age components present as the same as those within the Magdalena fan, the composite age distribution from the western Sierra La Giganta is readily distinguished from that of the fan due to the overabundance of Tertiary grains in the former (Table 3).

RESULTS: WESTERN LOS CABOS BLOCK

Modern Sands

We analyzed 102 zircons from 10 modern sand samples collected from west-draining arroyos between La Paz and the southern tip of Baja California (Fig. 3; Table 2). Collectively, these systems drain an area of >1600 km^2. Weighting the results by catchment area yields a bimodal zircon U-Pb age distribution (Fig. 9A) that is just barely distinguished from that of the Magdalena fan at the 95% confidence level (Table 3). Zircon age distributions from the southwestern area are overwhelmingly 65–90 Ma, whereas those from the northwestern flank of the Los Cabos blocks are dominantly 90–120 Ma U-Pb with subordinate earlier Cretaceous and Jurassic ages (Table 2; Fig. 9D). The approximate boundary between the older and younger basement is near Todos Santos.

Tertiary Strata

Salada Formation

Pliocene marine arkosic sandstone and conglomerate crop out along the southwestern margin of the Los Cabos block near Todos Santos (Figs. 2 and 3; Aranda-Gómez and Pérez-Venzor, 1989). These deposits are tentatively correlated with the Salada Formation (Aranda-Gómez and Pérez-Venzor, 1989). We measured 61 zircons (Fig. 9B). Like the modern sands from western Baja, its age distribution was dominated by 65–120 Ma zircon (90%), 28% of these between 90 and 120 Ma. While no middle Tertiary grains were detected, the Sala-

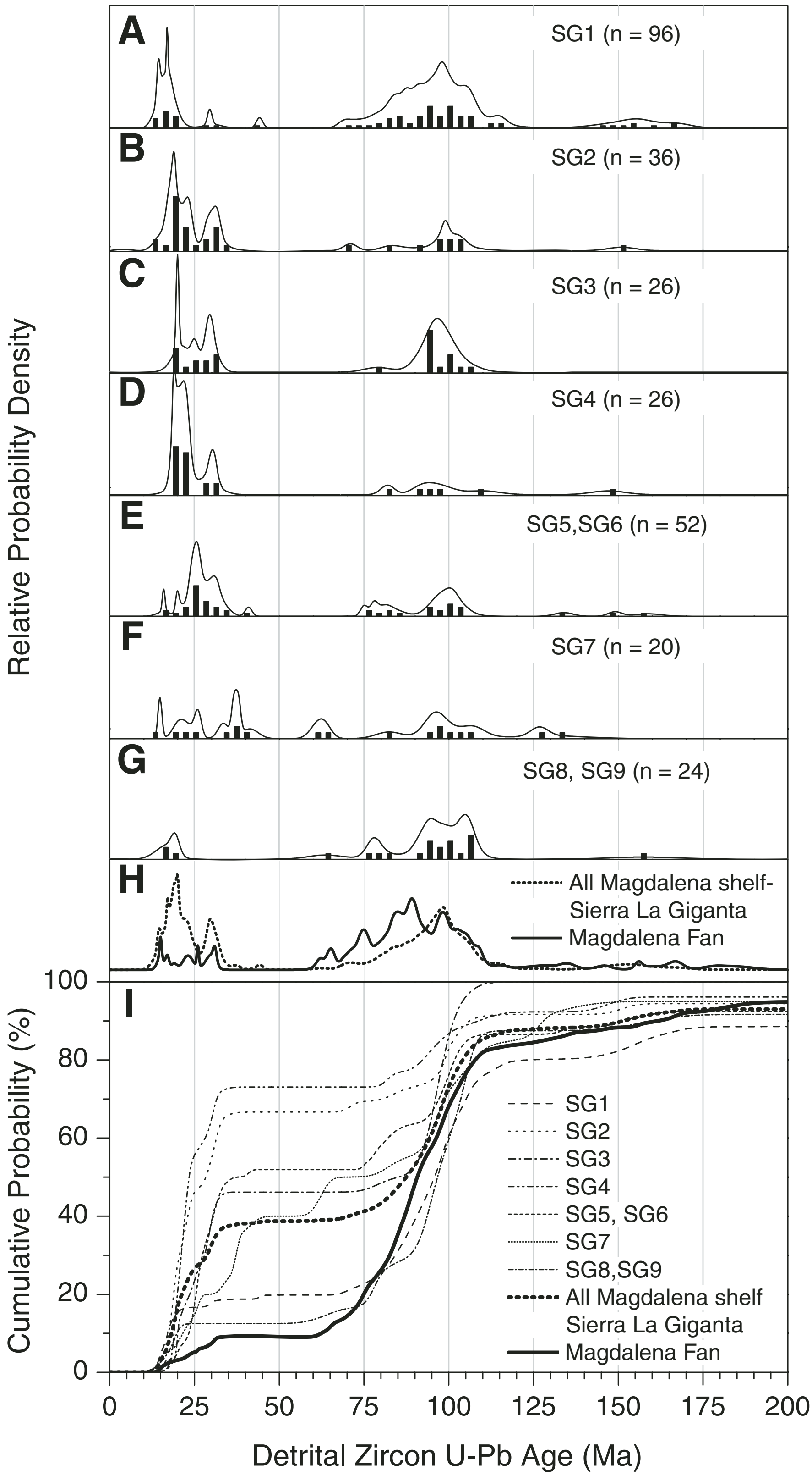

Figure 8. (A–H) Probability density plots illustrating detrital zircon U-Pb results from nine modern sand samples from the Magdalena shelf–Sierra La Giganta domain. (I) Cumulative probability plots for all samples are compared to Magdalena fan. Note that modern sands from the Magdalena shelf contain the required age components but in proportions that differ from the Magdalena fan.

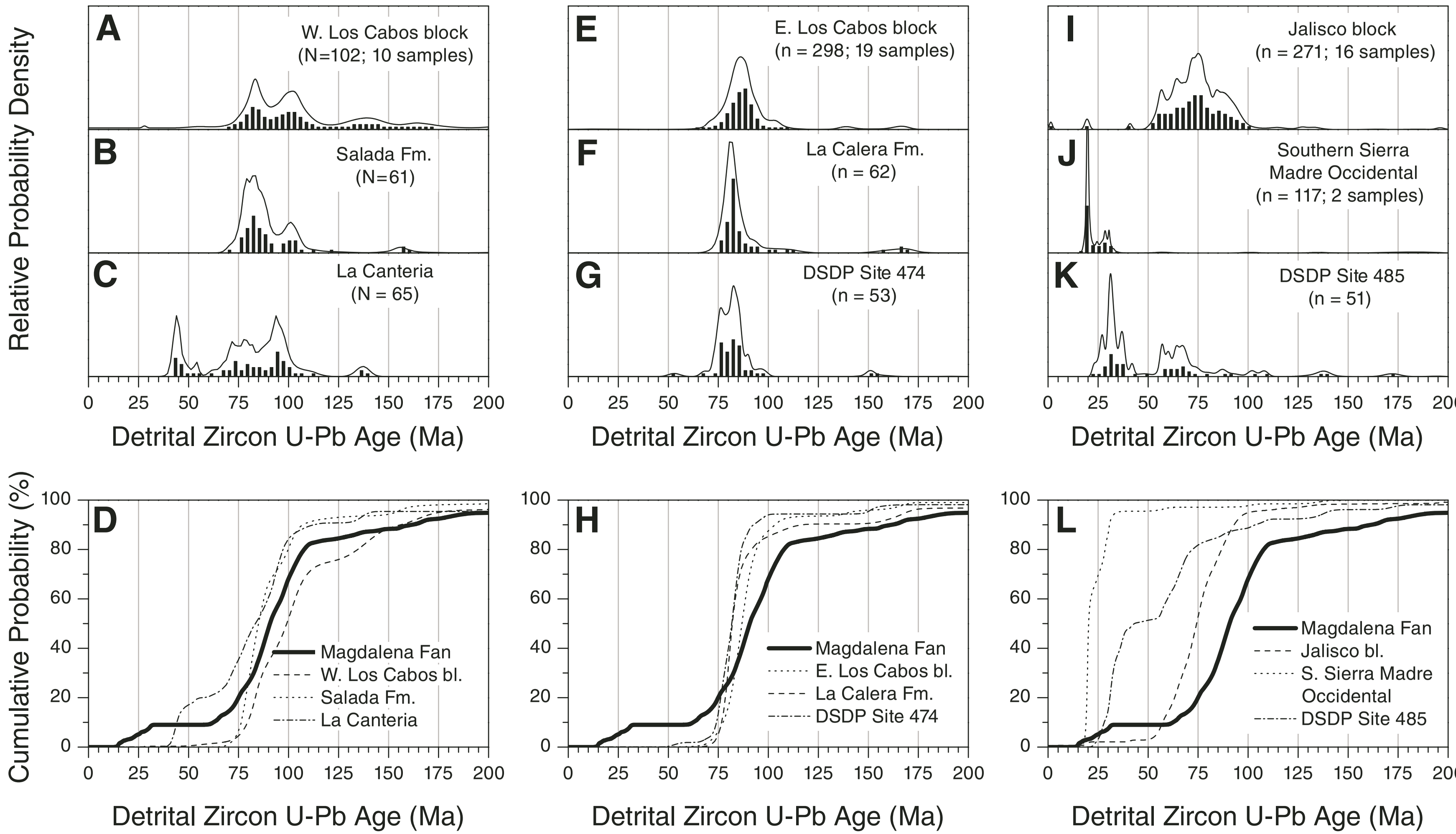

Figure 9. Probability density plots of detrital zircon results. (A) Composite of all modern sands from W. Los Cabos block. (B) Pliocene Salada Formation. (C) Unnamed middle Tertiary conglomerate along the northwestern margin of the Los Cabos block southwest of La Paz. (D) Cumulative probability plot of A–C illustrating strong similarity to Magdalena fan. (E) Composite of all modern sands from eastern Los Cabos block. (F) Late Miocene La Calera Formation. (G) Pliocene strata from Deep Sea Drilling Project (DSDP) Site 474A-37R. (H) Cumulative probability plot of E–G showing discernible deficit of 90–120 Ma zircon relative to Magdalena fan. (I) Composite of all modern sands from northern Jalisco block. (J) Composite of all southern Sierra Madre Occidental modern sands. (K) Quaternary strata from DSDP Site 485. (H) Cumulative probability plot of I–K showing discernible deficit of 90–120 Ma zircon relative to Magdalena fan. Note that results from individual modern sands have been combined in proportions weighted by the relative areas of their catchment basins.

da's measured age distribution was sufficiently similar to the Magdalena fan that it could not be distinguished from it (Table 3; Fig. 9D).

Middle Tertiary Conglomerate

An unnamed sequence of basement-derived conglomerate is exposed west of the Sierra El Novillo along the northwestern margin of the Los Cabos block (Fig. 2). Although the depositional age of the unit is poorly delimited, it overlies the Cretaceous batholith and is overlain by strata of the Miocene Comondu Group. We analyzed 65 zircons from one sample (Fig. 9C). In similar fashion to the modern sands from western Baja, nearly 70% of the grains gave U-Pb ages between 65 and 120 Ma with 34% between 90 and 120 Ma. However, a significant number (20%) of Eocene zircons differentiates it slightly from the Magdalena fan (Table 3; Fig. 9D).

RESULTS: EASTERN LOS CABOS BLOCK

Modern Sand

U-Pb ages were measured from 308 zircons from 19 east-draining arroyos from the eastern Los Cabos block between La Paz and Cabo San Lucas representing a combined area of ~3218 km^2, about twice as large as that of the western Los Cabos block (Fig. 3; Table 2). Approximately 40% of this area is drained by the Rio San Jose (e.g., sample E17; Fig. 3). With the exception of the results from comparatively small drainages in the northeast region, 65–90 Ma age zircons predominate (Table 2; Fig. 9E). While the eastern portion of the topographically subdued Trinidad block is poorly represented by our survey of modern sands, reconnaissance field work indicates that the area is dominated by a few large intrusive phases, and thus we do not expect significant differences in ages in the unsampled portions of the block. The deficiency of 90–120 Ma zircon is the principal reason why the eastern Los Cabos block is so easily distinguished from the Magdalena fan (Table 3; Fig. 9H).

Tertiary Strata

La Calera Formation

The late Miocene La Calera Formation contains red beds that directly overlie Cretaceous basement and represents the oldest known strata in southeastern Baja California (McCloy, 1984; Martínez-Gutiérrez and Sethi, 1997). Although the 62 zircons we measured were overwhelmingly Cretaceous, only 13% yielded U-Pb ages in the 90–120 Ma category, with most of these near 90 Ma (Fig. 9F). Similar to modern sand samples from the eastern Los Cabos block, 65–90 Ma zircons dominate the age distribution (77% in the case of the La Calera sample). The paucity of 90–120 Ma zircon allows us to easily distinguish the La Calera age distribution from that of the Magdalena fan (Table 3; Fig. 9H).

DSDP Site 474

DSDP Site 474 is located off the southern tip of Baja California adjacent to the continent-ocean transition on what was considered to be some of the oldest oceanic crust on this side of the mouth of the Gulf of California (Curray et al., 1982). Holes 474 and 474A were drilled through a submarine fan that is one of many found around the southern tip of Baja California (Fig. 2). The section is largely composed of mud turbidites with minor arkosic sand, and reaches a total thickness of ~500 m before basalt flows of the oceanic basement are encountered. The lowermost strata are late Pliocene, approximately the same age as the underlying oceanic crust. Previous petrographic work on sandstones from Site 474 revealed close similarities to the turbidites of the Magdalena fan (Marsaglia, 2004). Our analysis of 53 zircons from one of the turbidite layers revealed a strongly eastern Los Cabos block provenance (85% 65–90 Ma zircon but only 7% 90–120 Ma grains; Fig. 9G). The overall distribution obtained from Site 474 is easily distinguished at the 95% confidence level from the Magdalena fan (Table 3; Fig. 9H).

RESULTS: MAINLAND MEXICO

Modern Sand

Northern Jalisco Block

The northern Jalisco block of mainland Mexico was formerly adjacent to the eastern Los Cabos block prior to rifting (Schaaf et al, 2000). We measured 271 U-Pb zircon ages from 12 samples of west-draining arroyos in this area (Fig. 5; Table 2). Although the net drainage area represented by all samples is much larger than that covered by the Los Cabos block (>16,000 km^2), >80% of this is accounted for by the Rio Ameca (see sample JB6; Fig. 5). Similar to the eastern Los Cabos block, 65–90 Ma zircon U-Pb ages predominate over zircons of other age ranges (Fig. 9I). In addition, abundant Eocene and Paleocene zircons contributed by the Rio Ameca shift the entire distribution to younger ages relative to the Magdalena fan. The abundance of Late Cretaceous and early Tertiary grains is the main reason modern sands from this region of mainland Mexico are so readily distinguished from the Magdalena fan (Table 3; Fig. 9L).

Southern Sierra Madre Occidental

To further characterize the nature of zircons shed from portions of mainland Mexico adjacent to the mouth of the Gulf of California, we sampled two major river systems that drain the southern Sierra Madre Occidental (Fig. 5), and found the drainages to be dominated by middle Tertiary zircon (Fig. 9J). Distinct peaks occur at 19 and 30 Ma. Middle Miocene zircon present within the Magdalena fan was absent from these two drainages (i.e., the youngest zircons were 18 Ma). Only three zircons were older; two of these yielded late Paleocene ages. The observed age distributions are completely dissimilar to the Magdalena fan (Table 3; Fig. 9L)

Submarine Strata Near the Opening of the Gulf of California (DSDP Site 485)

DSDP Site 485 is near the axis of the mouth of the Gulf of California on young oceanic crust of the Rivera plate (Fig. 1), and samples sediment shed from mainland Mexico. The upper 153 m of the drill hole is composed of a Pleistocene very fine grained hemipelagic section that contains turbiditic layers that become more abundant and coarser grained toward the base of the unit (Lewis et al, 1983). Detrital zircons from DSDP Site 485 form a bimodal U-Pb age distribution (Fig. 9K) that is completely dissimilar to the Magdalena fan (Table 3; Fig. 9L). Oligocene grains represent more than a third of the total measured, and Paleocene–Eocene grains account for an additional third. Our results are consistent with Marsaglia's (2004) assessment that Site 485 sediments were derived primarily from volcanic rocks of the Sierra Madre Occidental.

EVALUATION OF POTENTIAL SOURCE REGIONS FOR THE MAGDALENA FAN

Global plate circuit reconstructions (Atwater and Stock, 1998) place limits upon the position of the Magdalena fan relative to the North American margin in the middle Miocene, and provide a useful framework for evaluating our detrital zircon U-Pb age results from the Magdalena fan in terms of potential source regions. Using the paleopositions of the network of arbitrary points on the Pacific plate defined by Atwater and Stock (1998), we were able to reconstruct the position of the Magdalena microplate for chron 5a (12.3 Ma), which slightly postdated the 13.0 Ma cessation of deposition of the lower turbidites from the Magdalena fan (Fig. 10A). This reconstructed position shows significant overlap with the continental margin of northern Jalisco block (Fig. 10A). If we assume that the paleotrench was a relatively straight tectonic feature, then most of the Magdalena fan would plot east of the trench along the western margin of the Jalisco block, which is impossible. The most plausible explanation for the apparent overlap is that it is a consequence of intraplate deformation that was not considered in the global plate circuit reconstruction (Joann Stock, 2005, personal commun.). Although the post–12.3 Ma intraplate deformation could have affected any of the plates employed in Atwater and Stock's (1998) global circuit, the southwestern corner of North America is a prime suspect. Numerous deformation belts were active in this region after 12.3 Ma, including the Mexican segment of the Basin and Range province, the Transmexican volcanic belt, the Colima graben, dextral transtension along the northwest boundary of the Jalisco block, and perhaps even structures related to the Caribbean plate like the Tehuantapec fault, which cuts southern Mexico from the Gulf of Mexico to the Pacific coast. Any post–12.3 Ma spreading across the Magdalena rise as proposed by Michaud et al. (2006) could contribute to the overlap problem.

The post–12.3 Ma deformation affecting southwestern North America is not sufficiently quantified to permit accurate refinement of Atwater and Stock's (1998) reconstruction. For our purposes it is sufficient to point out that there are two important correction vectors that could logically be applied to the global plate circuit reconstruction to eliminate the observed crustal overlap. The first possibility, option 1, is simply defined by the shortest possible vector displacement that would serve to align the existing trench segments (Fig. 10B). Option 1 restores the Magdalena fan to a position adjacent to the mouth of the proto–Gulf of California at 12.3 Ma. Option 2 would define a correction vector oriented parallel to the relative Pacific–North American slip vector for the time interval between chron 5a and the present (Fig. 10C). Option 2 positions the Magdalena fan adjacent to the Magdalena shelf at 12.3 Ma. These two correction vectors may effectively represent realistic extremes in the range of possible solutions to the overlap problem, but, more important, they can be readily tested with our detrital zircon data. Note that slip across the Gulf of California is restored 350 km for option 1 and 475 km for option 2. Both of these restoration magnitudes are valid, albeit mutually exclusive, and are used here only to accentuate the differences between option 1 and option 2.

Option 1: Source Region near the Mouth of the Proto–Gulf of California

There is a broad consensus among previous workers that the Magdalena fan was derived from the mouth of the Gulf of California in a configuration similar to that shown in Figure 10B (e.g., Yeats and Haq, 1981; Ferrari et al., 1999; Marsaglia, 2004). Due to the lithologic diversity of the Magdalena fan, Yeats and Haq (1981) proposed that it was derived from the mouth of the proto–Gulf of California when Baja was still largely attached to the mainland and extraregional river systems could have extended well into the continental margin. Ferrari (1995) proposed that the onset of extension in this region likely triggered the rapid deposition of the turbidites. Building on this hypothesis, Marsaglia (2004) proposed that a graben similar to the Colima graben extended perpendicular to the continental margin in this region and acted to focus the flow of continental fluvial systems as well as the submarine channels that would have transported the turbidite flows. Most workers concur that, as proposed by Yeats and Haq (1981), the abrupt decrease in sedimentation rates and the change in character of sedimentary facies across the 13.5 Ma unconformity marks the time when the fan became cut off from this source and began traveling northward with the Farallon-derived microplates to its present position. Nearly all major tectonic models of the day incorporate this history to describe the tectonic evolution of the Pacific–North American plate margin, and it is widely thought that the Magdalena fan has been displaced ~300 km to the northwest by offshore faults on the Magdalena shelf (e.g., Spencer and Normark, 1979; Hausback, 1984; Lonsdale, 1991; Lyle and Ness, 1991; Stock and Lee, 1994; Ferrari, 1995; Marsaglia, 2004).

Although the two major batholith terranes found on either side of the mouth of the Gulf of California are now separated by ~520 km, numerous lithological, geochemical, and geochronological correlations support the idea that these terranes formed a continuous batholith prior to rifting across the Gulf of California (Ortega-Rivera, 2003; Schaaf et al., 2003). Our new results clearly indicate that batholithic rocks on the formerly opposing margins of the Gulf of California are overwhelmingly younger than 90 Ma. While the region adjacent to the proto-mouth of the gulf clearly represents a source of Late Cretaceous–early Tertiary (Ortega-Rivera, 2003; Schaaf et al., 2003), and even Miocene zircon (Chinas, 1963; McCloy, 1984; Martínez-Gutiérrez and Sethi, 1997), the paucity of 90–120 Ma grains revealed by our extensive sampling of modern arroyos from the eastern Los Cabos block and northern Jalisco block area make it highly unlikely that these rocks contributed to the Magdalena fan. The simplest example supporting this conclusion is provided by our results from the three largest modern drainages we sampled adjacent to the proto-mouth of the gulf (Fig. 10B). These include the Rio San Jose (E17), the Rio Ameca (JB6), and the Rio San Pedro (SM2), that drain the southeastern Los Cabos block, the Jalisco block, and the southern Sierra Madre Occidental, respectively. While the configuration of middle Miocene drainages was undoubtedly somewhat different, the >40,000 km^2 area collectively represented by these three modern drainages requires that they provide a good first approximation of the nature of the sediment that would have been supplied to the proto-mouth of the gulf at the time the Magdalena fan was deposited. The cumulative probability age spectra of zircons sampled from these three drainages are compared to that of the Magdalena fan in Figure 11A. The dissimilar nature of each relative to the Magdalena fan is reflected by extremely low values of the Kolmogorov-Smirnov statistic (Table 3). Similar conclusions are provided by smaller drainages in this area.

The Colima graben analogy proposed by Marsaglia (2004) is well tested by our results from the Ameca River, which extends eastward from the Puerto Vallarta graben to the highest elevations of the Transmexican volcanic field (Fig. 5). The catchment area (13,025 km^2) of the Ameca River is comparable to (or perhaps even much larger than) that required by the Miocene Magdalena fan based on our sediment load calculations (Appendix 1). Both our results (Table 2) and those of previous studies (Schaaf et al., 2000; Henry et al., 2003; Ortega-Rivera, 2003) clearly indicate that a major east-to-west flowing, middle Miocene extraregional river system would have produced an overall younger zircon U-Pb age distribution than that observed for the Magdalena fan. Moreover, there is little reason to believe that a major Tertiary depositional system existed in this region, because the adjacent trench is not significantly backfilled and there is no recognizable sedimentary deposit that is even close to the size of the Magdalena fan (Fig. 5).

We carried out mixing calculations with our modern sand results from the eastern Los Cabos block, Jalisco block, and southern Sierra Madre Occidental, and found no way to combine these results to reproduce the detrital zircon age distribution of the Magdalena fan. The results of our mixing calculations (Fig. 12A) involved modern sand results from nearly 36 drainages. Results from these drainages were grouped into three domains (eastern Los Cabos, Jalisco, and southern Sierra Madre Occidental) with the age distributions weighted according to catchment area. The maximum vertical separation of the age distribution of the mixture and that of the Magdalena fan in cumulative probability space is given by D_{max}. Figure 12A shows contours of D_{max} for all possible ternary mixtures. For this

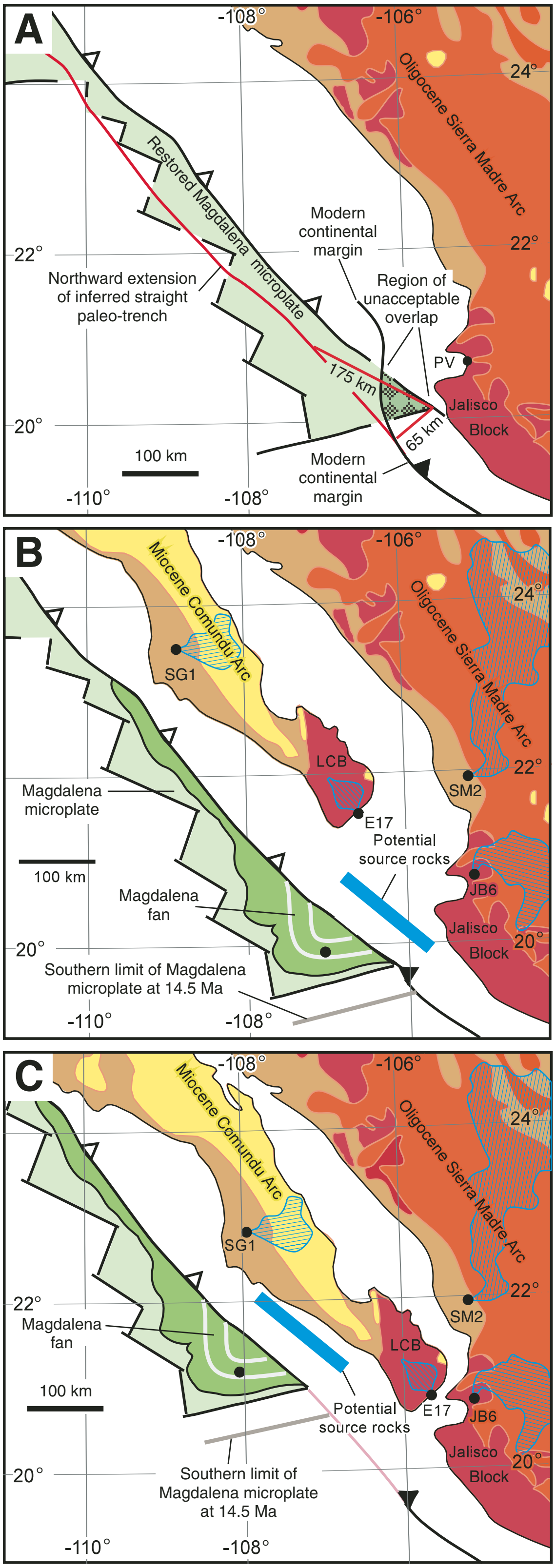

Figure 10. Tectonic reconstructions for chron 5a (12.3 Ma). (A) Based on global plate circuit reconstructions of Atwater and Stock (1998), paleoposition of Magdalena microplate shows unacceptable overlap (crossing blue diagonal lines) with continental crust of the western margin of the Jalisco block. A correction must be made to the global plate circuit reconstructions such that the Magdalena microplate restores east of an originally straight paleotrench (pink line). Two possible correction vectors, here considered realistic extremes, are shown in red. (B) First correction vector of 65 km locates Magdalena fan adjacent to the proto-mouth of the Gulf of California. Baja California is restored by 360 km. (C) Second correction vector of 175 km locates Magdalena fan adjacent to the Magdalena shelf. Baja California is restored by 475 km. Note that different magnitudes of restoration of Baja California are permitted by existing data and are depicted this way only to accentuate differences in potential source areas of the Magdalena fan. Maps have Universal Transverse Mercator zone 12 projection with mainland Mexico fixed in present position. The southern limit of Magdalena microplate is determined by interpolating between its reconstructed position at chrons 5a and 5b (see text). Potential source rocks are defined as region directly upslope from the paleopositions of Site 471 (black dot) between 14.5 and 13.0 Ma. LCB—Los

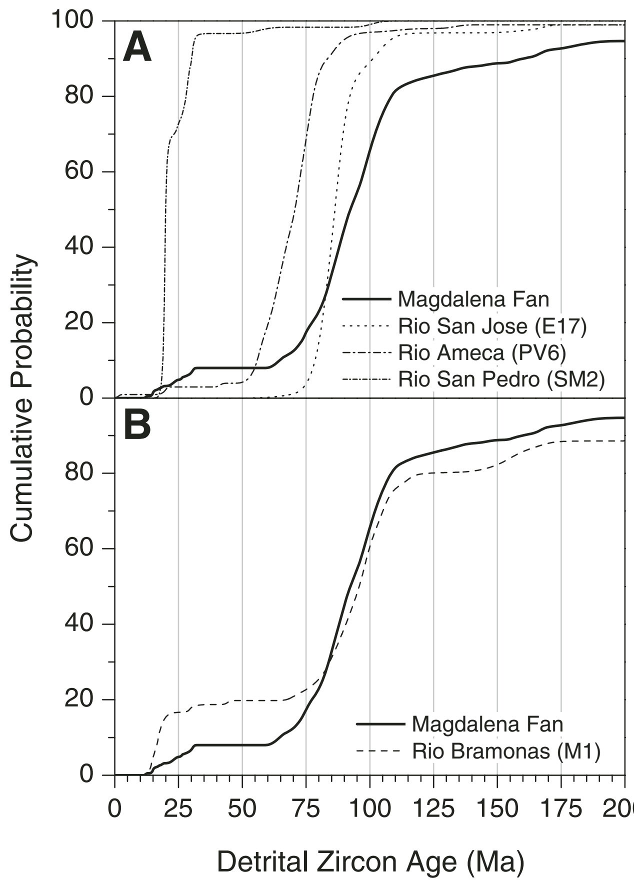

Figure 11. (A) Cumulative probability plots of detrital zircon age distributions from three major drainages proximal to the proto-mouth of the Gulf of California (see Fig. 10B for possible reconstructed drainage location). All can be readily distinguished from the Magdalena fan (Table 3). (B) Cumulative probability plots of the detrital zircon age distribution from the largest drainage sampled from the Magdalena Shelf (see Fig. 10C for possible reconstructed drainage location). Distribution overlaps that of the Magdalena fan within 95% confidence (Table 3).

set of calculations, the best approximation was simply the eastern Los Cabos block end member (Fig. 12B). Adding the results from the Jalisco block and southern Sierra Madre Occidental in any proportions to the eastern Los Cabos block end member only serves to degrade the fit to the Magdalena fan.

To determine the statistical significance of the results shown in Figure 12A, we used equation 2 to determine the effective number of analyses corresponding to a given mixture and applied the Kolmogorov-Smirnov approach. Although the K-S statistic is not strictly applicable to composite age distributions, our Monte Carlo simulations indicate that the null hypothesis is evaluated in a conservative manner when the effective number of analyses of the mixture, N_{eff}, is calculated according to equation 2. Applying this approach, there is a critical value of D_{max} (D_{crit}) that will just satisfy the null hypothesis (i.e., the distributions being compared can just be distinguished at 95% confidence). For the mixing calculations depicted in Figure 12A, D_{crit} ranged between 0.15 and 0.18. Because these values are considerably smaller than the lowest D_{max} (0.27; see Fig. 12B), we have >95% confidence that all possible age distributions calculated from the eastern Los Cabos block, Jalisco block, and southern Sierra Madre Occidental end members will fail to reproduce the age distribution of the Magdalena fan.

Continent-derived marine deposits like those of DSDP Sites 474 and 485 overlie young oceanic crust that has formed across the mouth of the gulf and arguably could be younger equivalents of the Magdalena fan. Marsaglia (2004) noted a remarkable similarity in modal sandstone compositions of the Magdalena fan and those in DSDP Site 474. This was viewed as consistent with the proposal that this area was the original source region of the Magdalena fan. Our detrital zircon data show that this similarity is only lithologic. Zircon U-Pb age distributions from these are highly deficient in the 91–120 Ma age component in the fan and lack Miocene age zircons (Table 1; Fig. 9K). Therefore the detrital zircon age distributions from these deposits reconfirm our conclusion that it is unlikely that the mouth of the Gulf of California formed the source area of the Magdalena fan.

Option 2: Source Region near the Magdalena Shelf

The existence of the Tosco Abreojos fault combined with proposals of large-scale dextral offset (Fig. 3; Spencer and Normark, 1979; Normark et al., 1987) has represented a serious impediment for considering the Magdalena shelf as a legitimate potential source area for the Magdalena fan. Although Marsaglia's (2004) limited sampling of alluvial deposits on the coastal plain of the Magdalena shelf demonstrated that materials from this region could be combined to reproduce the quartz:feldspar:lithics ratio of the Magdalena fan, she discarded the Magdalena shelf as a viable source because the modern sands had higher plagioclase:K-feldspar ratios and were more enriched in lathwork volcanic textures than were materials preserved within the Magdalena fan. While it is true that these compositional differences indicate a more mafic volcanic source within the modern sand (e.g., Marsaglia, 1991), the distinction is not likely to be meaningful. Specifically, our observations of detritus within modern drainages that cross the Magdalena shelf from the western Sierra la Giganta indicate that it is likely that the material analyzed by Marsaglia (2004) contained abundant rock fragments derived from the late Miocene–Quaternary La Purisima volcanic field. These basaltic cinder cones and flows postdate deposition of the Magdalena fan and are widely exposed in drainage basins that emanate from the western Sierra La Giganta and extend to the coastal region of the Magdalena shelf (Hausback, 1984; Sawlan and Smith, 1984; Sawlan, 1991).

Our systematic sampling of materials derived from the on-land portion of the Magdalena shelf and western Los Cabos block (Fig. 3) clearly demonstrates that this broad region contains all of the main age components of detrital zircon ages observed in the Magdalena fan (Tables 1–3; Figs. 6–9). More important, detrital zircon age components (e.g., Eocene) that are notably absent in the fan also tend to be scarce within the region. For example, in contrast to the situation for the region surrounding the proto-mouth of the gulf (Fig. 11A), the largest modern drainage that we sampled from the Magdalena shelf–Sierra La Giganta domain (SG1; Rio Bramonas) yields a detrital zircon age distribution that is indistinguishable from the Magdalena fan at the 95% confidence level (Fig. 11B; Table 3). Although the critical age components exist in nearly all individual drainages, they are not always present in proper proportions (Fig. 8). Hence the primary question that must be addressed is whether a compelling geological argument can be made for how materials from individual settings could have been mixed to produce the observed age distribution within the Magdalena fan. Although we discuss two possibilities, it is easy to mix materials derived from the Magdalena shelf and adjacent areas to produce the age proportions exhibited by the fan.

In the first set of calculations we attempted to reproduce the zircon age distribution exhibited by the Magdalena fan simply by mixing the results from Tertiary strata of the Magdalena shelf (Figs. 12C, 12D). The dashed line in Figure 12C (D_{crit}) is the boundary of the region that yields age distributions that satisfy the null hypothesis (i.e., are distinguishable from the Magdalena fan at 95% confidence). As indicated in Figure 12C, ~25% of the possible mixtures yield D_{max} values lower than D_{crit} (i.e., are indistinguishable from the Magdalena fan). These include a mixture of the Tepetate, San Gregorio, and Comondu age results weighted by relative stratigraphic thickness (stratigraphic proportions in Figs. 12C, 12D). The best-fit mixture has ~56% Comondu Group and ~44% Tepetate Formation and yields a D_{max} value of 0.06 (Fig. 12D). Note that minor input from the Oligocene zircon-rich San Gregorio Formation does not overly degrade the match. The fact that the stratigraphically youngest material would be most prominently represented is not a problem for model I given the close similarity between the Comondu Group results and the Magdalena fan (Tables 1 and 3). Moreover, older strata are certain to have been previously exposed in this potential source area due to the folding and deformation that become progressively more intense toward the western edge of the Magdalena shelf (Fig. 4). Therefore, erosion of this type of tectonically disturbed source area need not have produced a simple unroofing sequence that followed an inverted stratigraphic order, as might have been expected from erosion of a source area with flat-lying stratigraphy.

Additional evidence for a predominantly sedimentary source comes from abundant reworked Late Cretaceous and Paleogene microfossils that are present within the fan (Bukry, 1981; Yeats et al., 1981). Existence of these materials is best explained by reworking of preexisting strata in the source region of the fan. The fact that the Eocene Tepetate Formation contains significant reworked Late Cretaceous–early Tertiary microfossils supports the notion that sediment eroded from it contributed to the deposition of the fan. Perhaps the most compelling evidence for significant erosion of the Tertiary strata on the Magdalena shelf is the laterally persistent Miocene unconformity that is observed both on land in incised arroyo walls (Heim, 1922) and offshore in seismic sections of the PESCADERO project (González-Fernández et al., 2003).

In the second set of calculations, we mixed modern sands of the Magdalena shelf with equivalent data from the eastern and western Los Cabos block to obtain the proper blend of Cretaceous and Tertiary zircon (Figs. 12E, 12F). There is excellent evidence that such mixing of Cretaceous granitic and Miocene volcanic-rich sediment occurred on the Magdalena shelf in

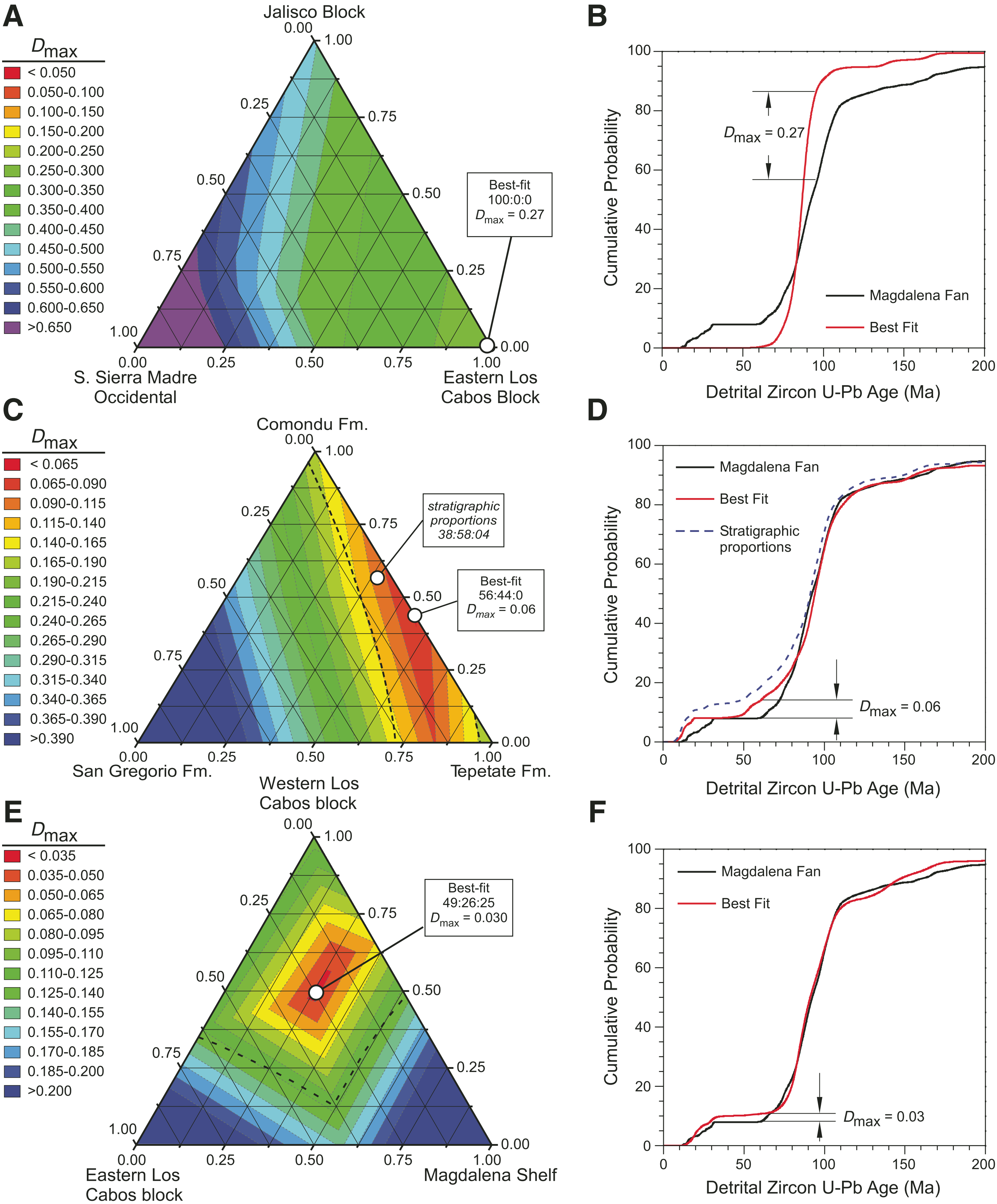
A
Dmax
< 0.050
0.050-0.100
0.100-0.150
0.150-0.200
0.200-0.250
0.250-0.300
0.300-0.350
0.350-0.400
0.400-0.450
0.450-0.500
0.500-0.550
0.550-0.600
0.600-0.650
>0.650
Jalisco Block
S. Sierra Madre Occidental
Eastern Los Cabos Block
Best-fit 100:0:0 Dmax = 0.27
B
Cumulative Probability
Dmax = 0.27
Magdalena Fan
Best Fit
Detrital Zircon U-Pb Age (Ma)
C
Dmax
< 0.065
0.065-0.090
0.090-0.115
0.115-0.140
0.140-0.165
0.165-0.190
0.190-0.215
0.215-0.240
0.240-0.265
0.265-0.290
0.290-0.315
0.315-0.340
0.340-0.365
0.365-0.390
>0.390
Comondu Fm.
San Gregorio Fm.
Tepetate Fm.
stratigraphic proportions 38:58:04
Best-fit 56:44:0 Dmax = 0.06
D
Cumulative Probability
Magdalena Fan
Best Fit
Stratigraphic proportions
Dmax = 0.06
Detrital Zircon U-Pb Age (Ma)
E
Dmax
< 0.035
0.035-0.050
0.050-0.065
0.065-0.080
0.080-0.095
0.095-0.110
0.110-0.125
0.125-0.140
0.140-0.155
0.155-0.170
0.170-0.185
0.185-0.200
>0.200
Western Los Cabos block
Eastern Los Cabos block
Magdalena Shelf
Best-fit 49:26:25 Dmax = 0.030
F
Cumulative Probability
Magdalena Fan
Best Fit
Dmax = 0.03
Detrital Zircon U-Pb Age (Ma)

Figure 12. (A) Results of ternary mixing calculations involving modern sands from the eastern Los Cabos block, Jalisco block, and Southern Sierra Madre Occidental. The ternary plots illustrate the variation of the maximum separation (D_{max}) of cumulative probability plots corresponding to mixtures of the indicated compositions relative to the Magdalena fan. The modern sand spectra used in calculations are composites from individual samples weighted according to catchment area. Note that all of the possible solutions, including the best fit (100% eastern Los Cabos block), yield D_{max} above the critical value (D_{crit} ~0.15) required to be resolved from the Magdalena fan at 95% confidence. (B) Cumulative probability plot of best-fit solution in A. Mismatch primarily reflects deficit of 90–120 Ma zircon. (C) Variation of D_{max} in ternary mixing calculations involving Tertiary strata of the Magdalena Shelf (Tepetate Formation, San Gregorio Formation, and Comondu Group). Dashed line represents D_{max} values that correspond to the critical separation in which the model age spectra are just resolved from the Magdalena fan at the 95% confidence level. Approximately 25% of the mixtures are indistinguishable from the Magdalena fan. This includes a mixture of the results of the Tertiary strata weighted by stratigraphic thicknesses of the units (see text). (D) Cumulative probability plot of best-fit solution in C. (E) Variation of D_{max} in ternary mixing calculations involving modern sands from the Magdalena shelf–Sierra La Giganta, western Los Cabos block, and eastern Los Cabos block. Dashed line same as in C. Approximately half of the ternary mixtures are indistinguishable from the Magdalena fan. (F) Cumulative probability plot of best-fit solution in E. Note the excellent fit to Magdalena fan when significant components of the western Los Cabos block are involved in the mix. All binary mixtures of the Magdalena Shelf and eastern Los Cabos block modern sands can be distinguished from the Magdalena fan.

the middle Miocene. Rocks of the Comondu arc form the most elevated portions of the Sierra La Giganta throughout southern Baja California. However, prior to gulf rifting, the elevated western margin of the Los Cabos block formed a long-lived buttress unconformity (Hausback, 1984) that can be regionally correlated to the north throughout islands in the Gulf of California (Fletcher and Munguía, 2000). Although the detailed nature of the crystallization history of the northern extension of the Los Cabos blocks is not well known, basement studies by Henry et al. (2003) in western Sinaloa on the Mexican mainland, and reconnaissance results from the Loreto area east of Magdalena Bay on the peninsula exhibit strong age similarity to the western Los Cabos block and hence indicate that our simulation is reasonable.

As indicated in Figure 12E, more than half of the possible solutions yield an acceptable fit to the Magdalena fan (i.e., those solutions above the dashed line). An excellent fit to the fan results when 26% Magdalena shelf modern sands are mixed with 48% western Los Cabos block and 25% eastern Los Cabos block (D_{max} = 0.03; Fig. 12F). Note that while the distinction between western and eastern Los Cabos block is somewhat artificial (i.e., pertains to the modern drainage divide), it is not possible to obtain satisfactory solutions from binary mixtures involving the Magdalena shelf and eastern Los Cabos block as end members because of the paucity of 90–120 Ma zircon in the latter. Alternatively, half of the mixtures between the western Los Cabos block and the Magdalena shelf yield acceptable fits. These results strongly support our conclusion that the source of the Magdalena fan was derived from the western margin of Baja California.

It has long been recognized that the Peninsular Ranges batholith is strongly zoned, the western portion being characterized by plutons that are smaller, more mafic, and have older crystallization ages of 90–120 Ma (Gastil, 1975; Silver and Chappell, 1988; Todd et al., 2003). Plutons throughout the more mafic western belt of the Peninsular Ranges batholith contain magnetite, and the belt as a whole shows a strong magnetic anomaly that has been mapped along most of the length of Baja California, but ends near Todos Santos and is not observed on the Mexican mainland (Langenheim and Jachens, 2003). The southern limit of the western belt magnetic anomaly coincides perfectly with a prominent transition in detrital zircon age distributions, and drainages south of this transition have a paucity of 90–120 Ma zircons. The southern limit of rocks that contain abundant 90–120 Ma zircons, a key component of the Magdalena fan, is yet another strong argument in favor of a relatively local source region in western Baja California.

MIDDLE MIOCENE EVOLUTION OF THE MAGDALENA SHELF

Our identification of a western Baja California source area for the Magdalena fan requires significant rethinking about the depositional and tectonic environment in which it formed. Most previous workers have attributed deposition of the Magdalena fan to a single extraregional river system with a presumably large catchment basin that drained into the proto-mouth of the gulf (e.g., Yeats and Haq, 1981; Lonsdale, 1991; Ferrari, 1995; Marsaglia, 2004). An idea of the dimensions of the drainage system required to form the Magdalena fan can be obtained if the annual sediment load can be calculated and compared with the suspended sediment discharge from modern rivers worldwide as reported by Milliman and Syvitsky (1992). Based upon calculations presented in Appendix 1, we conclude that the catchment basin area of the Magdalena fan was likely 10^3–10^4 km^2. If the source region had a width similar to the Magdalena fan (140 km) it could have extended as far as 70 km to the east and encompassed an area that fit within the Miocene arc-trench gap.

Given the apparent absence of a major feeder channel along the southwestern margin of Baja California, the question becomes whether multiple feeder channels of smaller dimension could have acted in unison to infill the trench and form the fan. The multibeam data of Figure 3 show that the continental slope is dissected by a series of closely spaced channels. The larger of these are generally ~1–2 km wide and spaced at 10–20 km (Fig. 3). We believe that it was these distributed channels, and not a single major drainage, that was responsible for the backfilling of the trench and formation of the Magdalena fan.

In our view, infilling of the trench and formation of the Magdalena fan likely resulted from regional uplift of the Magdalena shelf that occurred in direct response to the ridge-trench interactions that began ca. 16 Ma, when the Magdalena ridge approached the Baja California trench. This encounter was the culmination of a long-lived history of convergence between the paleo–East Pacific Rise and North America, which eventually consumed most of the intervening Farallon plate (e.g., Atwater, 1970; Bohannon and Parsons, 1995). Most of the contractional deformation of the lower sedimentary sequence observed on the Magdalena shelf probably occurred during the period of rapid subduction of progressively younger oceanic lithosphere prior to the ridge-trench encounter ca. 16 Ma (Fig. 13A). Immediately following chron 5b or 15 Ma, the Magdalena ridge fragmented and rotated clockwise (Fig. 2; Mammerickx and Klitgord, 1982; Lonsdale, 1991). This radical change in spreading direction likely occurred after the subducting slab was severed from its mantle roots (Fig. 13B). Severing of the slab probably occurred in response to the large

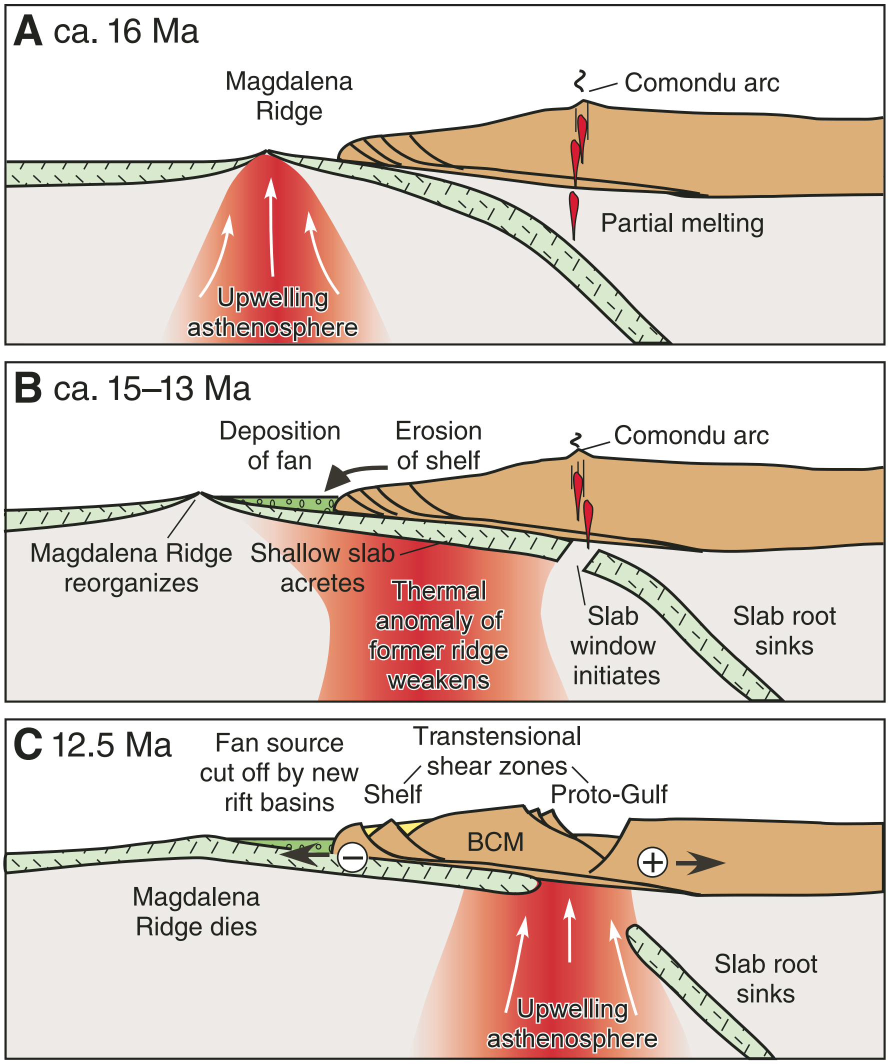

Figure 13. Schematic cross sections of the paleotrench showing tectonic evolution of the Magdalena shelf. (A) Magdalena ridge converges on Baja California trench by ca. 16 Ma. (B) Oceanic slab severs beneath North America and shallow portion begins to accrete to the base of continent. Continued spreading forces Magdalena ridge to migrate west, but thermally perturbed asthenosphere (red) continues its eastward convergence and becomes overridden by North America. Magdalena shelf undergoes uplift and erosion due to increased mantle buoyancy, which causes deposition of the Magdalena fan. (C) Spreading rate across Magdalena ridge dramatically decreases, perhaps due to misalignment of the ridge with thermally perturbed feeder zone in the upper mantle. Pacific–North America shearing initiates in deformation belts on either side of the Baja California microplate (BCM). Opening of slab window beneath North America causes renewed asthenospheric upwelling and focuses most of the plate margin deformation in the proto–Gulf of California. Magdalena fan becomes cut off from its source by the formation of intervening rift basins on the Magdalena shelf.

gradient in body forces that was set up between the nascent, and hence relatively buoyant, shallow slab underlying the Magdalena shelf and the older, more dense oceanic crust that was descending into the mantle beneath the continent in the direction of the previous Magdalena–North America convergence vector (Fig. 13B).

High heat flow and elevated mantle buoyancy along the continental margin due to the close proximity of the Magdalena spreading center likely persisted until ca. 12.3 Ma (Mammerickx and Klitgord, 1982). Therefore it is probable that much of the Magdalena shelf was subaerially exposed and eroded between 15 and 12 Ma, forming the prominent erosional unconformity on the Magdalena shelf (Fig. 13B). The resulting sediment pulse from the Magdalena shelf would have flowed directly down the continental slope to backfill the trench segment adjacent to the Magdalena microplate (Figs. 4 and 13B). Enhanced accumulation of turbidites upon the southern portion of the microplate (i.e., in the vicinity of the Magdalena fan) may have occurred due to its proximity to the Los Cabos block, which was topographically elevated throughout the Tertiary (Fig. 2; Hausback, 1984; Fletcher and Munguía, 2000).

Previous workers have argued that the cessation of turbidite deposition occurred due to the lateral tectonic transport of the Magdalena fan away from its extraregional river source (e.g., Yeats and Haq, 1981; Lonsdale, 1991; Lyle and Ness, 1991; Ferrari, 1995; Marsaglia, 2004). We believe that the shelf source was shut off when the Tosco-Abreojos and San Lazaro–Santa Margarita faults began accommodating transtensional shearing and forming rift basins that captured detritus that previously had been transported to the trench (Fig. 13C). We attribute the onset of transtensional rifting of the Magdalena shelf to be due to the dramatic decrease and eventual cessation of spreading rate across the Magdalena ridge (Michaud et al., 2006). Transtensional rifting in the southern gulf region initiated ca. 12 ± 2 Ma, and Fletcher et al. (2000b) proposed that this occurred in response to the dying Magdalena ridge system west of Baja.

An interesting geodynamic problem is understanding why Miocene spreading along the Magdalena ridge system was reestablished ~8–12 m.y. later as the series of nascent ridges and transforms along the axis of the gulf (cf. Figs. 14A, 14C). A key observation toward understanding this problem is that although the ridge system west of Baja was never subducted, the mantle beneath the ridge may have continued to converge with North America, as it had done throughout most of the Cenozoic, to eventually become overridden. In contrast, continued spreading after severing of the Magdalena slab would cause the Magdalena ridge to stall or even reverse its direction of migration relative to the western margin of North America (Figs. 13A, 13B). We hypothesize that the Magdalena ridge eventually died due to the progressive misalignment of the ridge with its mantle roots, which would have been hotter than surrounding mantle due to the long Cenozoic history of advective heat flux due to melt migration to the surface (Figs. 13A, 13B). Once separated from the ridge, advection in the mantle would cease and the thermal anomaly would

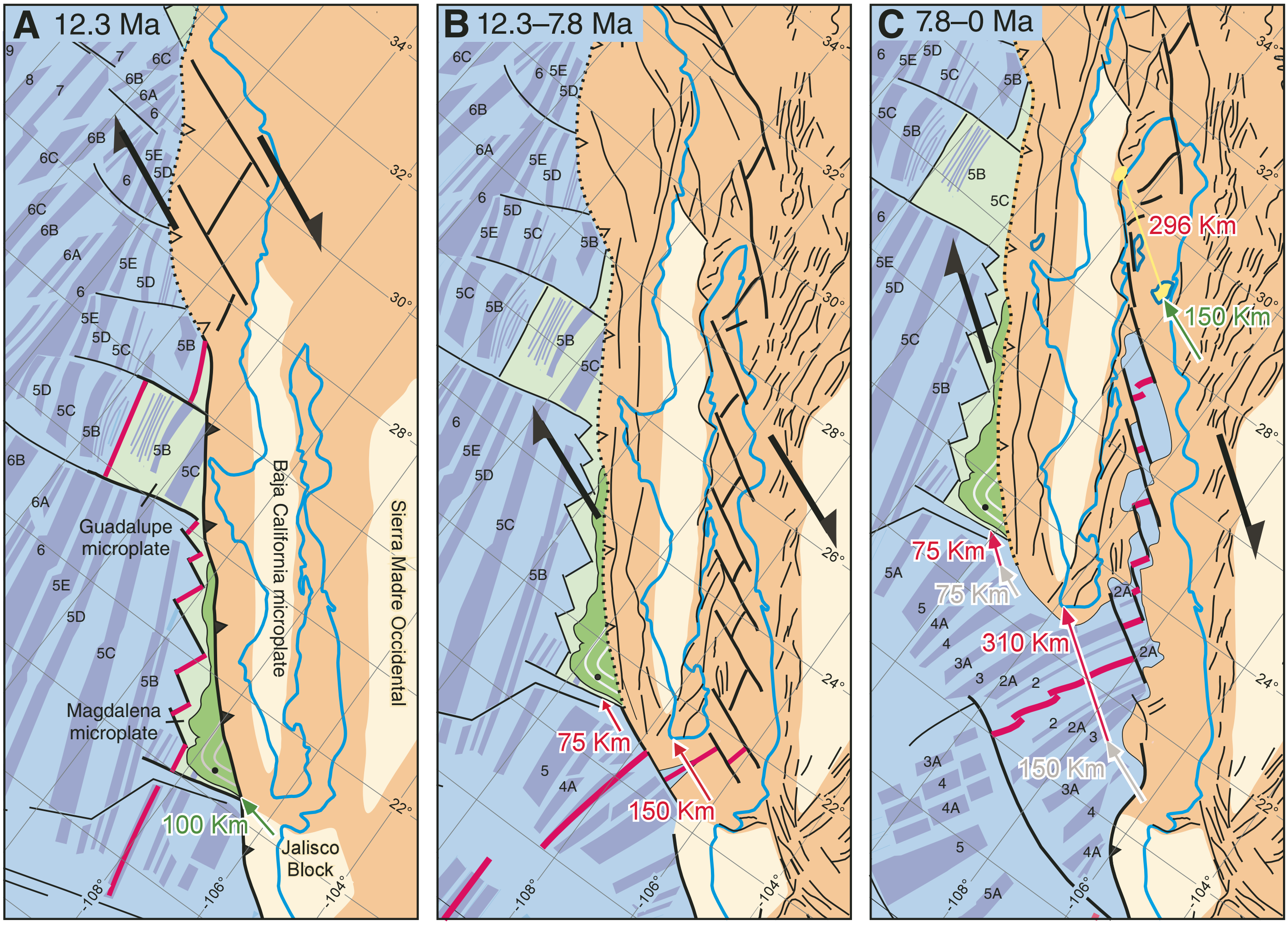

Figure 14. Revised kinematic model for shearing around the Baja California microplate. Our maximum displacement estimate (150 km) across the Magdalena shelf requires 460 km of shear in the Gulf of California extensional province, which suggests that slip rates have gradually decreased in the former and increased in the latter for the past 12.3 m.y. (see text). We assume that the Pacific–North American plate motion maintained a constant rate, but became more northward in direction after chron 4 (7.8 Ma), as reported by Atwater and Stock (1998). (A) Magdalena microplate restored for chron 5a (12.3 Ma) with correction vector (100 km) positioned midway between the two extremes shown in Figure 10A. Spreading ridges west of Baja California just prior to their effective abandonment are shown in pink. (B) From 12.3 to 7.8 Ma, 75 km and 150 km of integrated transtensional shearing should have accumulated across the Magdalena shelf and Gulf of California extensional province, respectively. (C) From 7.8 to 0 Ma, 75 km and 310 km of transtensional shearing accumulated across the Magdalena shelf and Gulf of California extensional province, respectively. A new system of en echelon oceanic spreading systems (shown in pink) formed in the southern Gulf of California extensional province with much the same orientation as the one that was abandoned west of Baja California. Color scheme is the same as in Figure 1. Maps have Universal Transverse Mercator zone 12 projection with mainland Mexico fixed in present position.

conductively decay, unless it was affected by a new system of upwelling such as the opening of the slab window beneath North America (Figs. 13B, 13C). Along-strike variations in the Pliocene–Pleistocene magnitude and style of seafloor spreading in the Gulf of California (e.g., Fletcher et al., 2004) could be related to the previous configuration of spreading centers west of Baja California and subsequent eastward migration of thermally perturbed mantle, as depicted in Figures 13B and 13C.

TECTONIC IMPLICATIONS FOR MIDDLE-LATE MIOCENE PACIFIC–NORTH AMERICAN DEXTRAL SHEARING

Our new detrital zircon data allow us to place a crude upper bound upon the cumulative displacement on late Neogene faults along the southwestern margin of the peninsula. These results clearly favor the Magdalena shelf and area west of the Los Cabos block as the source of the Magdalena fan (Figs.10B, 11A, and 12C–12F), not the mouth of the Gulf of California, as previously thought (Fig. 10C). The maximum cumulative late Neogene displacement that we believe compatible with our results is ~150 km, which is obtained by positioning the Magdalena fan such that its southern limit coincides with the southern tip of Baja California. However, the existence of individual drainages with detrital zircon populations that strongly resemble those of the Magdalena fan indicate that shear across faults west of Baja may be only a few tens of kilometers (e.g., samples SG1, SG8, and SG9; Figs. 3, 8, and 11B). This minimum slip estimate is consistent with the apparent termination of the Tosco-Abreojos and San Lazaro–Santa Margarita faults in the Todos Santos basin (Fig. 3). Therefore our study suggests that faults west of Baja have accommodated 100 ± 50 km since the onset of turbiditic backfilling of the trench and formation of the Magdalena fan ca. 14.5 Ma.

Our revised estimate of total Neogene shear (100 ± 50 km) is one-third of the ~300–350 km of dextral shear that was previously inferred to have taken place west of Baja California between 12.3 and 6 Ma. A significant amount of northward transport of the Magdalena fan probably occurred by dextral convergence across the subduction interface prior to 12.3 Ma. Based on Euler poles derived by Atwater and Stock (1998), the Shirley fracture zone, which forms the northern edge of the Magdalena microplate, traveled ~60 km northwest, parallel to the trench, between 14.5 and 12.3 Ma. However, northwest transport of the southern Magdalena microplate, which contains the Magdalena fan, should be <60 km due to the clockwise rotation of spreading across the Magdalena rise during this time interval. Another important aspect of the total Neogene slip across the Magdalena shelf is that it continues to accumulate at rates of 4–5 mm/yr, based on global positioning system studies (Dixon et al., 2000; Gonzalez-Garcia et al., 2003) and displacement of marine terraces (Fletcher et al., 2000a). Therefore only a fraction of our new estimate of total Neogene shear could have occurred between 12.3 and 6 Ma, the supposed time that 300–350 km of deformation accumulated west of Baja California. We conclude that it is unlikely that faults west of Baja could ever have served as the principal Pacific–North American boundary for any significant period of time since 12.3 Ma. We propose that, since their inception, faults west of Baja only accommodated a small fraction of the total Pacific–North American slip rate, and they have undergone a gradual reduction to the modern rates of 4–5 mm/yr, which is ~10% of the total slip rate.

Our lower estimate of total displacement across the Magdalena shelf must be balanced by an increase of shear across the Gulf of California. Euler poles from Atwater and Stock (1998) show that the southern edge of the Magdalena microplate was displaced ~700 km relative to North America after 12.3 Ma. However, this restoration leads to unacceptable overlap with the continental margin (Fig. 10A). If we assume a correction vector positioned midway between the two extremes shown in Figures 10B and 10C, then 610 km of shear must have accumulated across the Gulf of California and Magdalena shelf. Therefore, our maximum slip estimate of 150 km for the Magdalena shelf requires a minimum of 460 km of shear across the Gulf of California, which is consistent with new estimates of total displacement (450–500 km) across the southern Gulf of California based on palinspastic reconstructions of serial profiles using an Airy isostatic model of crustal thickness (Fletcher et al., 2003a, Fletcher et al., 2004). The disparity in shear estimates between the southern (450–500 km) and northern Gulf of California (296 km; Oskin and Stock, 2003) is likely to be balanced by late Neogene deformation along the Sonoran rifted margin (e.g., Gans, 1997). Therefore, in addition to the 296 km of displacement documented by Oskin and Stock (2003), ~150 km of displacement parallel to relative plate motion has probably occurred across the Sonoran margin since 12.3 Ma (Fig. 14).

The new kinematic model shown in Figure 14 has three important implications for understanding the geodynamic evolution of plate-margin shearing around the Baja California microplate. (1) Our data preclude kinematic partitioning of strike-slip and orthogonal rifting into separate deformation belts on either side of the Baja California microplate as schematically depicted in Figure 1. Although we recognize that both of these deformation belts have undergone internal kinematic partitioning (e.g., Fletcher and Munguía, 2000), it is most likely that regional slip across each belt has been dominated by integrated transtensional shearing that has deviated little from the direction of relative plate motion, which, as shown by Atwater and Stock (1998), became slightly more northward 8 m.y. ago (Fig. 14). (2) Our results require that the Gulf of California extensional province has been the site of most plate margin shearing since the onset of the major plate reorganization 12.3 m. y. ago. Therefore, this area must have contained the weakest lithosphere, and/or it was the site of the greatest applied tectonic stress. Strong arguments can be made for both. The axis of the middle Miocene volcanic arc coincides well with the western margin of the Gulf of California extensional province (Hausback, 1984), and thus, as proposed by Fletcher et al. (2003b), it is likely that mechanical and thermal weakening of the crust around the arc helped to focus early plate margin shearing in this area. In addition, as modeled by Bohannon and Parsons (1995) and shown schematically in Figure 13, the formation of a deep slab window beneath the protogulf also would have significantly weakened the lithosphere. We propose that after cooling of the Magdalena ridge, tectonic stress must have been transmitted well east of the trench to the trailing edge of the severed Magdalena slab (Figs. 13B, 13C). The localization of a smaller fraction of plate margin deformation in the Magdalena shelf implies that the forearc and subduction interface were also weaker than surrounding rocks, but not to the same extent as the Gulf of California extensional province. Our lower slip estimates suggest that it is unlikely that a significant slab window formed beneath the Magdalena shelf. (3) Our data are compatible with gradual changes in displacement rate, which has increased in the Gulf of California extensional province and decreased in the Magdalena shelf. Therefore, progressive plate margin shearing has reduced lithospheric strength more in the former, which is to be expected if it had greater slip rates from the beginning.

APPENDIX 1. ESTIMATION OF CATCHMENT AREA FOR MAGDALENA FAN

Global bathymetry modeled by Sandwell and Smith (1997) combined with reflection bathymetry collected on several recent oceanographic cruises document that the Magdalena fan has a broad semicircular shape (Fig. 3). It reaches water depths of 3000 m, and has a vertical relief of 200–400 m above the adjacent seafloor. The elevated semicircular lobe of the fan is widest right along the trench where it extends ~150 km, and it covers an area of ~8800 km^2. Seismic profiles perpendicular to the trench show that the thickness of the deposit decreases systematically with distance from the trench (Fig. 4). Assuming an average thickness of ~500 m, which is slightly thicker than the section at Site 471, we estimate the volume of the lower turbiditic portion of the fan to be ~4400 km^3. Because this lower section of the fan is thought to have been deposited over 1.5 m.y. and likely has an average density of 2.3 g/cm^3, total sediment load of the system feeding the fan was ~7 × 10^6 t/yr.

Using the power-law relationship between suspended sediment load and drainage area as reported by Milliman and Syvitsky (1992) for North and South American rivers and assuming 1000–3000 m of relief as appropriate for convergent margin settings, the drainage area that supplied the Magdalena fan is only ~2000 km^2. While this is considerably less than the aerial extent of the fan, reducing topography results in increasingly larger catchment areas. Based upon the available data, we conclude that the catchment basin of the Magdalena fan was probably 10^3–10^4 km^2, and note that this is well within the documented range of drainage areas of modern rivers that have suspended sediment discharge as high as 30 × 10^6 t/yr.

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