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Formation of continental fragments: The Tamayo Bank, Gulf of California, Mexico

R. Abera[1], J. van Wijk[1]*, and G. Axen[1]
[1]Department of Earth and Environmental Science, New Mexico Institute of Mining and Technology, 801 Leroy Place, Socorro, New Mexico 87801, USA

ABSTRACT

We present a model for microcontinent formation that is based on the structure of the Tamayo trough in the Gulf of California, Mexico. Potential field modeling of a transect through the Tamayo trough and Tamayo Bank suggests that the crust of the Tamayo trough is oceanic, and that the Tamayo Bank is a detached continental fragment. The oceanic crust that separates the Tamayo Bank from the mainland of Mexico is thin (5 km), so oceanic spreading was probably magma starved before it ceased. Such a thin crust has also been described on the Aegir Ridge in the North Atlantic, which became extinct after the Jan Mayen microcontinent separated from Greenland. In our model for the origin of microcontinents, the locus of plate spreading jumps to the weakened continental margin when the spreading ridge becomes amagmatic and the force required for continued extension at the ridge increases. A microcontinent is formed when the ridge jumps into a continental margin, and an asymmetric ocean basin or microplate is formed when the ridge jumps within oceanic crust.

INTRODUCTION

Microcontinents are continental fragments surrounded by oceanic lithosphere. They usually are created when rifts form in continental lithosphere near young rifted margins (Vink et al., 1984). The existing spreading ridge is abandoned, and a new ridge forms in a nearby continent where a sliver of continental crust is rifted off of the continental mass. Microcontinents are transported within oceanic plates and will eventually arrive at convergent margins as accreted terranes (Vink et al., 1984).

At least a dozen microcontinents have been described (Gudlaugsson et al., 1988; King and Barker, 1988; St-Onge et al., 2000; Gaina et al., 2003) in various ocean basins of differing ages. They vary in size and continental crust thickness; the Jan Mayen microcontinent (Norwegian Basin), for example, is ~150 km wide and as much as ~15 km thick (Gaina et al., 2009); the East Tasman Rise (southern Pacific Ocean) is ~12 km wide and ~2.5–3 km thick (Gaina et al., 2003). When continental fragments are separated from the main continent, the old oceanic spreading ridge sometimes continues to be active. In the North Atlantic, the Aegir Ridge continued to spread up to ca. 25 Ma, while the newly formed Kolbeinsey Ridge started to open the Greenland Basin before ca. 33 Ma, separating Jan Mayen from Greenland (Nunns, 1983; Müller et al., 1997). Other microcontinents form following the abandonment of an old spreading ridge: The Seychelles microcontinent (Indian Ocean) was separated millions of years after seafloor spreading in the Mascarene Basin stopped (Masson, 1984).

Ridge migration, which isolates the microcontinent, is often into continental lithosphere, because the rifted margin is usually weaker than oceanic lithosphere (Vink et al., 1984). Why spreading ridges jump is less well understood. Most studies focus on finding the optimum location for renewed rifting and changes in the lithospheric strength of the young margin (i.e., Müller et al., 2001; Yamasaki and Gernigon, 2010). This continental lithospheric strength depends on the geotherm, composition, crustal thickness, magma (magmatic intrusions), and strain rate of the lithosphere (Ranalli and Murphy, 1987). Young margins are thinned, warm, and sometimes magmatically active, and therefore weak. Since microcontinents have been found near continental margins in close proximity to hotspots (Borissova et al., 2003), further weakening of continental lithosphere by a mantle plume is considered a driving force for ridge jumps (Müller et al., 2001). However, mantle plume heads are thought to have areas much larger (Campbell, 2005) than that of most microcontinents, so we question applicability to smaller microcontinents. In an alternative model, a redistribution of lithospheric strength by magmatic underplating may direct the location of renewed rifting (Yamasaki and Gernigon, 2010). Oceanic lithospheric strength depends mainly on its thermal structure (Ranalli and Murphy, 1987) and magmatic activity (Cannat et al., 2006), and it is therefore lowest at magmatically active spreading ridges. Ridges increase in strength when the magma supply is limited (Buck et al., 2005).

In this study, we explore the factors and processes that cause the locus of extension and rifting to jump, a requirement for microcontinent formation. We used potential field data to interpret the crustal structure and composition of an extensional segment in the Gulf of California (Mexico), and we discuss a transect that crosses the Alarcón basin (cf. Lizarralde et al., 2007). The potential field data models point to the existence of a small continental fragment (the Tamayo Bank) in the Alarcón basin. The microcontinent is flanked on the southeast by thin oceanic crust (interpreted as continental by Lizarralde et al., 2007), and on the northwest by normal-thickness oceanic crust. This suggests that an older, southeastern spreading ridge (Tamayo trough) became magma starved and was abandoned, with a new ridge subsequently formed farther northwest. This mechanism is a likely cause of microcontinent formation elsewhere on Earth as well.

TAMAYO BANK: A CONTINENTAL FRAGMENT IN THE GULF OF CALIFORNIA

The Gulf of California is an oblique extension zone between the Mexican mainland and the Baja California Peninsula (Fig. 1). Opening of the Gulf of California followed the cessation of subduction and microplate capture west of southern Baja California at ca. 12 Ma (Atwater, 1970; Oskin et al., 2001). At ca. 6 Ma, the Pacific–North America plate boundary shifted inland into the present-day Gulf of California (Lonsdale, 1989), followed by seafloor spreading in the central and southern Gulf.

A seismic transect in the Gulf of California (Lizarralde et al., 2007; Sutherland et al., 2012) crossed the Alarcón basin (A-A′ in Fig. 1) parallel to the Tamayo transform fault, which separates the short Alarcón spreading segment from the East Pacific Rise. The Tamayo trough, southeast of the Alarcón basin, was interpreted as thinned continental crust separated from the Alarcón oceanic crust by the Tamayo Bank (Fig. 1B). Our alternative interpretation is based on potential field data described herein (Fig. 1C). These data suggest instead that the Tamayo Bank is a continental fragment, separated from the Mexican mainland by oceanic crust of the Tamayo trough. Tamayo trough oceanic crust is thin, suggesting that seafloor spreading was magma starved before the ridge became extinct.

*E-mail: jvanwijk@nmt.edu

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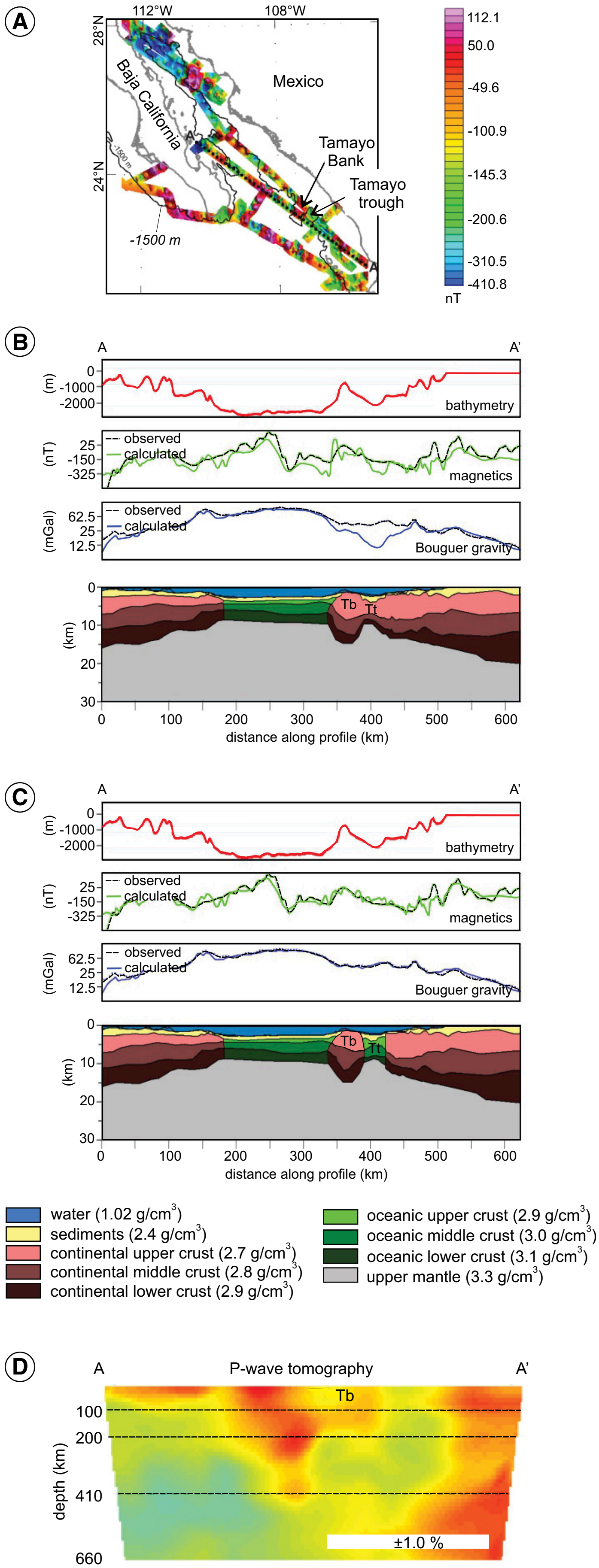

Figure 1. A: Map of Gulf of California (Mexico) with magnetic anomalies (data from 2002 RV *Maurice Ewing* PESCADOR expedition cruise EW0210), and location of Alarcón (A-A′) transect shown in B and C. Coastline is in gray, and 1500 m bathymetry (black line) is indicated. B: Topography/bathymetry, potential field data, and crustal model of Alarcón transect with Tamayo trough modeled as 7-km-thick continental crust. C: Same as B, but with Tamayo trough modeled as 5-km-thick oceanic crust. Tt—Tamayo trough, Tb—Tamayo Bank. D: P-wave tomography of Burdick et al. (2014) along transect A-A′ (Alarcón). Slow seismic wave velocities (–1% minimum anomaly) are in red, and fast velocities (+1% maximum) are in blue/green.

Potential Field Models of the Alarcón Segment

We constructed crustal transects using gravity and magnetic data, constrained by seismic reflection and refraction studies (Fig. 1). Densities and magnetic susceptibilities of different layers are listed in Table 1. Seismic refraction and reflection results (Persaud et al., 2007; Lizarralde et al., 2007; Sutherland et al., 2012) were used to constrain the Moho depth and sediment thickness. The continental crustal layers follow the velocity structure of Lizarralde et al. (2007) where possible; the sediment base was taken from Sutherland et al. (2012) and Lizarralde et al. (2007). In the continental model, the Tamayo trough has a 7-km-thick continental basement; in the oceanic model, the trough is underlain by 5-km-thick oceanic crust (Figs. 1B and 1C).

Topography/bathymetry data are from the ETOPO1 Global Relief Model (Amante and Eakins, 2009). Magnetic anomaly data (reduced to pole) are from the RV *Maurice Ewing* PESCADOR expedition cruise EW0210 (Lizarralde et al., 2007). Terrain-corrected Bouguer gravity anomalies are from the Bureau Gravimétrique International (http://bgi.omp.obs-mip.fr/), calculated from EGM2008 (Pavlis et al., 2008); Bouguer gravity anomalies were used to avoid strong topographic effects on free-air anomalies.

The Alarcón transect starts on Baja California and extends southeastward to Mexico (Fig. 1A). The Tamayo trough is characterized by a positive Bouguer gravity anomaly that is ~40 mGal smaller than that of the oceanic crust west of the Tamayo Bank (Figs. 1B and 1C) and a bathymetric low. According to Lizarralde et al. (2007) and Sutherland et al. (2012), the Tamayo trough is highly thinned continental crust with a thickness of ~7 km; we show herein that the potential field data are a better fit with a model where the Tamayo trough is underlain by 5-km-thick oceanic crust.

We were not able to fit the gravity data with a crustal model that has a 7-km-thick continental crust and the sedimentary infill imaged by Sutherland et al. (2012), shown in Figure 1B. We were also not able to fit the magnetic anomalies of the Tamayo Bank and trough with this model. The gravity data can be modeled well with a crustal model consisting of a 5-km-thick layer of oceanic crust (Fig. 1C) and the sediment thickness as imaged by Sutherland et al. (2012), and this crustal architecture has the added advantage of fitting the magnetic data slightly better than the continental crust model. Syn- and postrift sediments thicken dramatically into the Tamayo trough (Sutherland et al., 2012), consistent with cooling and thermal contraction of the underlying young oceanic lithosphere.

Potential field models are nonunique, and we cannot exclude the possibility that the Tamayo trough is underlain by very thin, heavily intruded, and hence, denser ($\rho_{average}$ ~3.0 g/cm^3 to fit the potential field data) continental crust. If the Tamayo Bank is a detached fragment of continent, it may have formed by the northward propagation of the East Pacific Rise. At ca. 4 Ma (Lonsdale, 1989), the present Tamayo trough was aligned to the northeast of the Maria Magdalena Rise and occupied the Mazatlán Embayment. Subsequently, the Maria Magdalena Rise was abandoned, and it now lies south-southeast of the Tamayo trough. The Maria Magdalena Rise is interpreted as a series of short extinct spreading ridges that formed oceanic crust in a zone ~50 km wide (Lonsdale, 1989). This ridge may have propagated further into the continent, forming the Tamayo

TABLE 1. MODEL DENSITIES AND MAGNETIC SUSCEPTIBILITIES OF SEDIMENTS, CRUSTAL LAYERS, AND MANTLE

Layer	Sediments	UCC	MCC	LCC	UOC	MOC	LOC	Mantle
Density (kg m^{-3})	2400	2700	2800	2900	2900	3000	3100	3300
Magnetic susceptibility	1.3×10^{-5}	1.3×10^{-5}	5.7×10^{-2}	5.7×10^{-2}	1.3×10^{-1}	7.5×10^{-2}	7.5×10^{-2}	8.5×10^{-3}

Note: UCC, MCC, and LCC denote upper, middle, and lower continental crust, respectively; UOC, MOC, and LOC are upper, middle, and lower oceanic crust, respectively. Density and magnetic susceptibility values are from Fuis and Kohler (1984), Schnetzler (1985), and Arkani-Hamed and Strangway (1986). Values are held constant within each of the modeled layers.

trough. No seafloor magnetic anomalies are present, which led Lonsdale (1989) to interpret this area as a failed rift. The Maria Magdalena Rise did not detach a continental sliver; it propagated into the continent-ocean boundary (Lonsdale, 1989). Because of its high density and lower seismic P-wave velocities (Fig. 1D), we favor a model in which the Tamayo trough is oceanic crust. The Tamayo Bank, which was interpreted partly as a continent-ocean transition zone, partly as continental crust (Lizarralde et al., 2007; Sutherland et al., 2012), is a small continental fragment. We suggest that it detached from Baja California by a ridge jump when the magma-starved spreading ridge in the Tamayo trough (Fig. 2; discussed later herein) was abandoned. Closely spaced faults in the Tamayo trough (Sutherland et al., 2012) are also consistent with ridge shutdown.

P-wave tomography of Burdick et al. (2014) shows that P-wave velocities are close to average (i.e., no anomaly) at depths <100 km where the Tamayo Bank continental fragment is interpreted, and they are lower below the Tamayo trough and the currently active spreading center (Fig. 1D). This supports an interpretation where the regions surrounding the Tamayo Bank consist of young, warm oceanic lithosphere where seismic wave velocities are lower.

MODEL FOR THE FORMATION OF MICROCONTINENTS

The modeled oceanic crust southeast of the Tamayo Bank is relatively thin (~5 km) compared to typical oceanic crust (~7 km), which suggests that magma supply to the ridge was probably limited before the ridge was abandoned. Similarly, thin oceanic crust is found east of the Jan Mayen microcontinent in the Norwegian Basin (Greenhalgh and Kusznir, 2007). Here, the extinct Aegir Ridge produced oceanic crust that is generally <4 km thick, and locally only 2 km (Greenhalgh and Kusznir, 2007). The crust west of Jan Mayen that is formed by the Kolbeinsey Ridge, is, in contrast, normal to thick (~7–10 km; Greenhalgh and Kusznir, 2007). Magma-limited spreading ridges (such as the present Gakkel Ridge) accommodate plate separation by tectonic deformation when magma supply is low (Cannat et al., 2006). Magmatic intrusions at a spreading ridge are the primary cause of plate weakening (Buck et al., 2005; Cannat et al., 2006), so ridges may strengthen considerably during periods of limited magma supply, when intrusions are presumably sparse. In young oceanic lithosphere (<~3–4 m.y.), the strongest layer is in the crust (Bohannon and Parsons, 1995), and we suggest that a similar strength distribution is applicable to that of magma-starved spreading ridges: When the magma supply below the ridge is shut off, the strength of the crust and ridge increases quickly as intrusions cool (Buck et al., 2005), while the mantle lithospheric strength increases rapidly with time as it cools and thickens (Bohannon and Parsons, 1995). The force needed to cause extensional yielding of the lithosphere is an order of magnitude larger when rifting is not magma-assisted (Buck, 2004), and it is likely that more force is required to continue opening a magma-starved oceanic ridge than to rift a nearby weakened continental margin. At that point, it may be relatively easy for the spreading ridge to jump to a new location, forming a microcontinent (Steckler and ten Brink, 1986). An arriving plume head would weaken the continental margin lithosphere further, making a ridge jump more likely (i.e., Gaina et al., 2003), but this is not a necessary condition in our model, and seems unlikely in the Gulf of California. Alternatively, the ridge may jump within oceanic crust (Mittelstaedt et al., 2008). This would create an asymmetric ocean basin (Fig. 2C) or an oceanic microplate. Such spreading ridge jumps within young oceanic lithosphere are common (Mittelstaedt et al., 2008; many others).

Our proposed model for the formation of a continental fragment outlines three stages (Fig. 2):

(1) During the first phase, seafloor spreading follows continental breakup. The young rifted margin slowly cools and strengthens. Magma supply to the ridge is sufficient, and plate spreading is accommodated at the divergent plate boundary.

(2) As magma supply to the ridge decreases, the plate boundary strengthens until its strength is comparable to or larger than that of the adjacent rifted margin. During this phase, the ridge may be abandoned while tectonic extension begins elsewhere (on the young rifted margin; Fig. 2C), or spreading may continue while a new ridge starts to develop (thick black arrow, Fig. 2C).

(3) Eventually the old ridge is abandoned, and seafloor spreading initiates elsewhere. If the ridge jumps within oceanic lithosphere, an

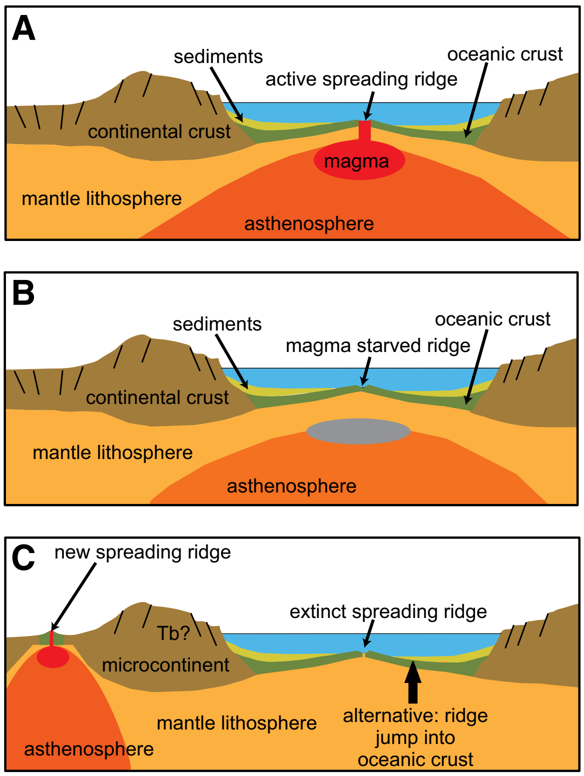

Figure 2. Conceptual model for microcontinent formation. A: Magma-compensated seafloor spreading following continental breakup. When magma supply decreases, oceanic crust that is formed is thin, and eventually (B) plate spreading is accommodated by tectonic extension during phases of amagmatic spreading. Plate boundary gains strength, and a larger force is needed to continue rifting. At this point, locus of rifting may jump into weak rifted margin (C) to form a microcontinent, or to another location within oceanic lithosphere (thick black arrow) to form an asymmetric ocean basin. Tb—Tamayo Bank.

asymmetric ocean basin is formed; if the ridge jumps into a rifted margin, a microcontinent is formed (Fig. 2). Reduced magma supply to a spreading ridge may be caused by along-strike cooling of the ridge. Where short spreading segments are separated by long transforms, as in the Gulf of California and other sheared margins, this process may be important. The Tamayo trough may have been the cold tip of a short-lived (~1 m.y.; Lonsdale, 1989) oceanic spreading center (Maria Magdalena Rise), where magma supply was reduced. Greenhalgh and Kusznir (2007) proposed that colder sublithospheric mantle may have caused the reduced magma supply to the Aegir Ridge in the Norwegian Basin. Depletion (from earlier [arc-] volcanism, for example) that reduces mantle fertility and magmatism is another possible factor contributing to the slowing down of magmatic spreading.

CONCLUSIONS

Potential field data indicate that the Tamayo Bank in the Gulf of California is a microcontinent, separated from the Mexican mainland by thin oceanic crust of the Tamayo trough. We propose that this microcontinent formed after the Tamayo trough spreading ridge became magma starved and the nascent plate boundary increased in strength. The spreading ridge consequently jumped toward the stretched and weakened crust of Baja California, forming the small continental fragment. This model for formation of continental fragments is applicable to other regions as well, eliminating the need for a mantle plume to weaken and facilitate rifting of a young continental margin and microcontinent formation.

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