The Gulf of Mexico is a Jurassic backarc basin

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ABSTRACT

Any basin with seafloor spreading that forms over an active subduction zone is a backarc basin (BAB). The Gulf of Mexico (GoM) opened behind the 232–150 Ma Nazas arc over an east-dipping subduction zone in Late Jurassic time, beginning ca. 165 Ma, and thus is a BAB. The hypothesis that the Gulf of Mexico formed as a backarc basin explains two enigmas: (1) Why was the GoM opening pole (79–84°W, 23–30°N) so different from that of the central Atlantic (15–18°W, 65–67°N)? and (2) Why was the GoM opening so short-lived (ca. 165–142 Ma), when there was no collision or other obvious reason for seafloor spreading to stop? The GoM BAB hypothesis also illuminates the relationship between the GoM and the Border rift system, which can be traced from the GoM near the mouth of the Rio Grande >2000 km along the U.S.–Mexico border into the Independence Dike Swarm of eastern California. Late Jurassic rifting in the Border rift system was succeeded by thermotectonic subsidence through Early Cretaceous time. In addition, the segmentation of the transitional crust beneath the northern GoM into a magmatically robust segment beneath the Texas coast and a stretched margin beneath Louisiana is also consistent with BAB behavior: igneous activity is most prolific nearest the arc and diminishes with distance from the trench. A possible objection to the GoM BAB hypothesis is that the spreading ridge was oriented at high angles to the Nazas arc trend, whereas modern oceanic BAB spreading ridges generally parallel the associated arc. Continental BABs like the GoM develop spreading ridge orientations that are often at high angles to the associated convergent margin; for example, spreading ridges associated with the Miocene Sea of Japan and Andaman Sea BABs trend perpendicular to the associated arc. Such geometries reflect the presence of extensional stresses that are not orthogonal to the subduction zone, a situation that also existed in the GoM region during Late Jurassic time.

INTRODUCTION

The origins of most large marine basins are fairly well understood. The Gulf of Mexico (GoM) is a rare example where the origin of a sizable oceanic basin at low latitudes is still unclear. The GoM is a nearly enclosed basin, encompassing ~1.6×10^6 km^2, bounded on the north by North America, on the west by Mexico, and on the south by the Yucatan Peninsula and Cuba. We have only indirect information about its early evolution, due to thick sediments, including salt, and the lack of correlatable, spreading-related magnetic anomalies.

The GoM opened as part of the breakup of the late Paleozoic–early Mesozoic supercontinent Pangea (e.g., Pindell, 1985; Winterer, 1991; Adatte et al., 1996). The idea that the GoM opened with the central Atlantic as the westernmost arm of Tethys is partly driven by similar ages and geographic positions between fragments of Gondwana and Euramerica as well as by the fact that both GoM and central Atlantic exploited newly formed Pangean sutures (Alleghenian and Ouachita orogens). This would be a compelling interpretation if both the central Atlantic and GoM opened around a single pole of rotation, as once thought (e.g., Pilger, 1981; Klitgord and Schouten, 1986). However, it now appears that the GoM opened with a very different pole of rotation than that of the central Atlantic (15–18°W, 65–67°N versus 79–84°W, 23–30°N for the GoM; Fig. 1; Pindell, 1985; Pindell and Kennan, 2001, 2009; Bird et al., 2005), indicating that the two basins opened independently during Middle to Late Jurassic time. That the GoM opened independently and was isolated from the central Atlantic in Jurassic time is consistent with Late Jurassic GoM faunas that are either endemic or have stronger affinities to Pacific than Tethyan faunas (Adatte et al., 1996; Cantu-Chapa, 2001).

We discuss here the implications of the idea that the GoM formed as a backarc basin (BAB) behind the Permian–Jurassic Mexican arc. The "GoM = BAB" argument is simple. We begin by summarizing the distinctive characteristics of BABs and their tectonic kin, interarc basins (IABs). We discuss what causes these basins to sometimes form (not all convergent margins are associated with extensional stress regimes) and their brief lifespans. We then discuss age constraints for formation of the GoM. Next we summarize evidence that a continental magmatic arc existed in northeastern Mexico during Permian–Jurassic time, the result of eastward subduction of Pacific seafloor (Fig. 2; Torres et al., 1999; Barboza-Gudino et al., 1998, 1999, 2008). The existence of this magmatic arc to its west unequivocally places the GoM in a backarc tectonic setting, compelling consideration of it as a BAB. We then explore the relationship between the GoM, the Jurassic arc, and a Late Jurassic extensional system to the west, the Border rift system, which we interpret as an IAB that formed in response to the same subduction-related extensional regime that opened the GoM. The tectonic evolution of the GoM–Border rift system is compared to the evolution of other continental BAB examples. We hope these arguments are convincing, but trust regardless that the hypothesis serves to stimulate further research in this important and enigmatic region.

BACKARC BASINS AND INTERARC BASINS: CHARACTERISTICS AND CAUSES

The backarc basin concept has been confirmed and expanded on since Karig (1971) advanced the hypothesis that some convergent margins were spatially and temporally associated with zones of active seafloor spreading. BABs and IABs both reflect a strongly extensional stress regime above an active subduction zone (Table 1). Other extensional basins that form around the margins of ocean basins are not underlain by subduction zones; these are not BABs or IABs, but are known as marginal basins (Taylor and Karner, 1983).

The most important difference between BABs and IABs is that BABs form by seafloor spreading behind an active magmatic arc whereas IABs are rifts within an arc where seafloor spreading does not occur (Marsaglia, 1995). Some IABs evolve into BABs, but others

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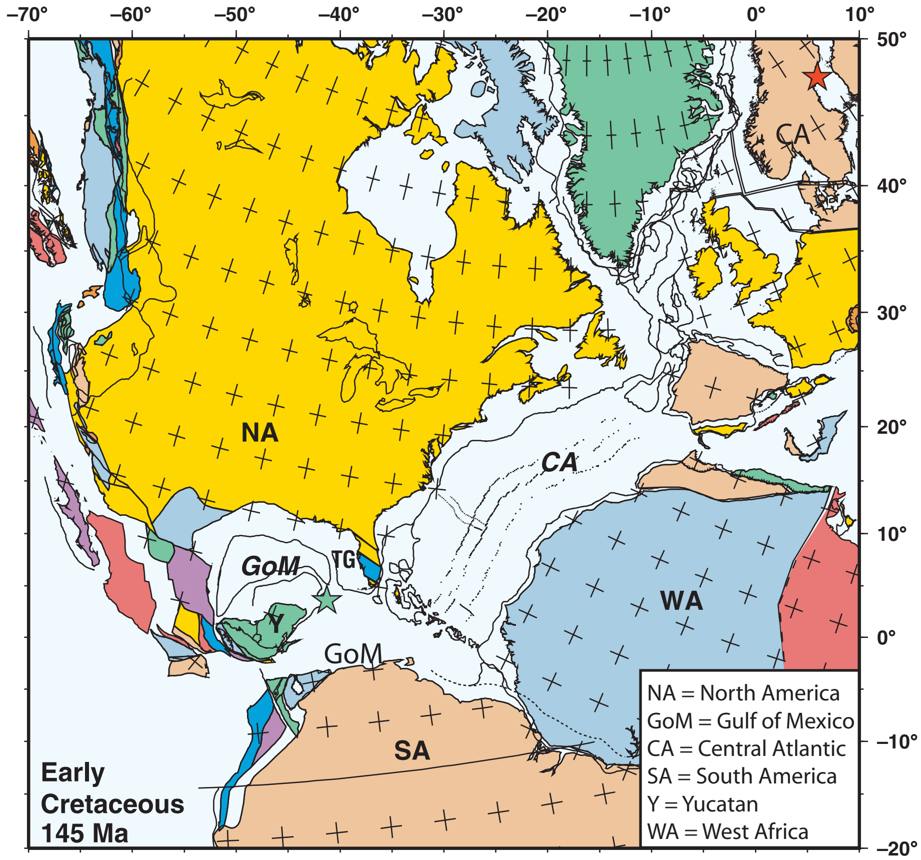

Figure 1. Configuration of continents and ocean basins around the central Atlantic and Gulf of Mexico ca. 145 Ma (Late Jurassic, courtesy Lisa Gahagan, University of Texas Institute for Geophysics PLATES project: http://www.paleogis.com/dotnetnuke/PlateModels/ThePLATESProjectatUTIG/tabid/84/Default.aspx). Note the very different positions of Euler poles for the Gulf of Mexico (Yucatan–North America, 23.0°N, 85.2°W; green star) and central Atlantic (West Africa–North America, 66.2°N, 18.3°W, red star).

do not, analogous to the way that some continental rifts evolve into ocean basins and others become extinct before they do. Regardless of its ultimate fate, if a suprasubduction zone extensional basin does not have seafloor spreading, then it must be regarded as an IAB.

Active BABs and IABs today are concentrated around the western Pacific Ocean, but also occur elsewhere (Fig. 3; Table 2). BABs and IABs result whenever tensional forces sunder the overriding plate. There is no single cause for extension, but slab rollback is often invoked, especially for arcs subducting old, dense lithosphere (Mariana-type margins of Uyeda and Kanamori, 1979). This is driven by the negative buoyancy of the subducting lithospheric slab with respect to the underlying asthenosphere (Elsasser, 1971; Molnar and Atwater, 1978; Garfunkel et al., 1986; Hamilton, 1988; Wortel and Spakman, 2000; Schellart and Lister, 2004; Clark et al., 2008). The negative buoyancy force causes the slab to sink more steeply than the dip of the subduction zone (i.e., to have a vertical as well as a downdip component of motion). Slab rollback is an important reason that most BABs and IABs form where crust older than ca. 55 Ma is being subducted (Sdrolias and Müller, 2006). Other BABs form in association with a deeply anchored subducted slab because the overriding plate is being stretched for other reasons (Heuret and Lallemand, 2005). For example, the Mariana Trough BAB is opening because the Philippine Sea plate is being subducted beneath the Philippines (Stern et al., 2003). If the arc on the overriding plate cannot follow this retreat, it will sunder to form a BAB or IAB.

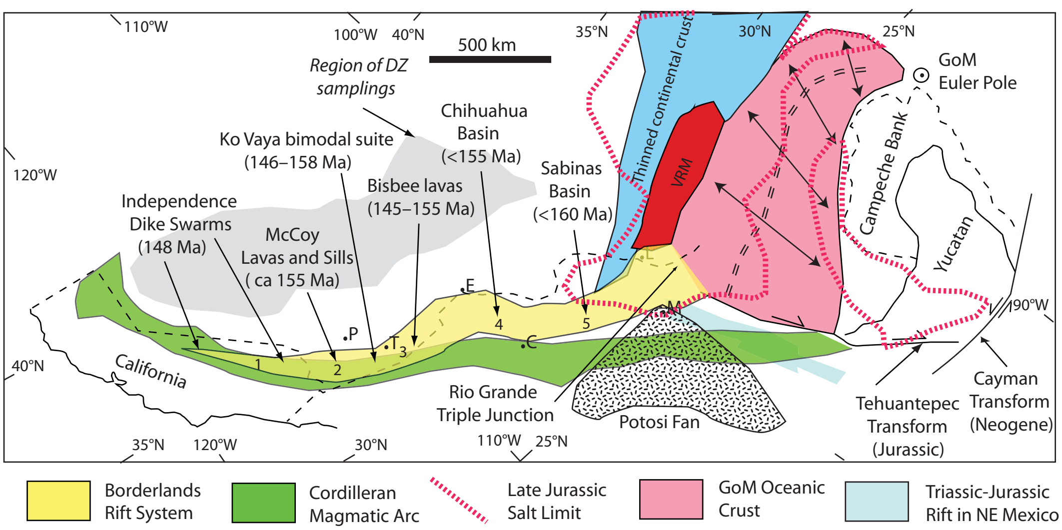

Figure 2. Late Jurassic configuration of the Gulf of Mexico (GoM), modified after Dickinson and Lawton (2001a). Border rift system is after Dickinson and Lawton (2001b). Ages for Bisbee lavas are after Lawton and McMillan (1999) and for McCoy lavas and sills are after Gleason et al. (1999) and Spencer et al. (2011). Cities (open circles) for orientation are Phoenix (P), Tucson (T), El Paso (E), Chihuahua (C), Laredo (L), and Monterrey (M). Location of Mesozoic detrital zircons (DZ) used to generate spectra in Figures 5 and 6B are shown in gray, and trend of Triassic–Jurassic Cordilleran arc is after Dickinson and Gehrels (2010). Locations of generalized stratigraphic sections shown in Figure 7 are listed (1–5). Limit of Late Jurassic salt and general location of Late Triassic–Jurassic rifts in northeastern Mexico is modified after Gray et al. (2008). Note also approximate position of volcanic rifted margin (VRM) and stretched continental crust after Mickus et al. (2009).

TABLE 1. CHARACTERISTICS OF BACKARC BASINS, INTERARC BASINS, GULF OF MEXICO, AND BORDER RIFT SYSTEM

Characteristic	BAB	IAB	GoM	BRS
Extensional basin, formed over an active subduction zone	Y	Y	Y	Y
Form by seafloor spreading	Y	N	Y	N
Occur behind active magmatic arc	Y	N	Y	N
Occur within active magmatic arc	N	Y	N	Y
Lifespan	12.5 ± 4.7 m.y. (extinct) 11.2 ± 8.9 m.y. (active)		<23 m.y.	

Note: BAB—backarc basin; IAB—interarc basin; GoM—Gulf of Mexico; BRS—Border Rift System; Y—yes; N—no.

There is no universal reason that BABs and IABs form. Taylor and Karner (1983) identified three general causes: mantle diapirism, induced asthenospheric convection, and global plate kinematics. Sdrolias and Müller (2006) rephrased these causes: plate kinematics, behavior of the downgoing slab, the effect of lateral asthenospheric flow on the slab, or mantle wedge dynamics. The important point is that the origin of the extensional stress is not part of the BAB-IAB definitions, only tectonic setting and extension style (rifting versus spreading).

All BABs begin as IABs, and rifting begins where the plate is weakest. Because lithospheric thickness and tensile strength is strongly controlled by temperature (Kohlstedt et al., 1995), arc lithosphere is weakest above the region of melt generation, along the magmatically active part of the arc; IAB rifting begins near here. Rupture can occur in front (trenchward) of the magmatic arc, behind the magmatic arc, or along the magmatic arc (Martinez and Taylor, 2006).

It has long been recognized that arc igneous activity may cease for all or part of the time that a BAB is active. Crawford et al. (1981) were perhaps the first to note that arc and BAB igneous activity were asynchronous. Arc magmatism is often disrupted by IAB formation because the extension axis captures the arc magmatic budget (Clift, 1995). For most modern arc-backarc systems (e.g., Scotia, Mariana, and Lau/Tonga), the magmatic arc resumed activity once the BAB widened sufficiently to separate the two magmatic systems. However, there is clear hiatus in the Izu-Bonin-Mariana arc tephra record ca. 15–25 Ma, indicating that the Izu-Bonin-Mariana arc shut down while the Shikoku and Parece Vela Basins opened (Straub et al., 2003). Even though we do not yet understand why different arc and BAB systems behave differently in this regard, it appears that arc and BAB volcanism may or may not coexist. When arc magmatic activity resumes, the magmatic arc is always situated trenchward of the BAB spreading axis.

We understand intraoceanic BABs much better than continental BABs. Because continental crust is compositionally distinct from the mafic crust of intraoceanic arcs, where the best-studied BABs occur, it will have a different rheology (e.g., strength profiles that are quartz dominated as opposed to olivine dominated) and thermal structure. It is thus likely that continental BABs will evolve in ways that differ from intraoceanic BABs. These differences are shown by the best examples we have of continental BABs, the Andaman Sea, the Black Sea, and the Sea of Japan (discussed later herein).

The GoM formed in association with extensional stresses associated with Pangea break-up, but what caused this in the GoM is controversial. This controversy centers on whether rifting was active or passive, in the sense of Sengor and Burke (1978). Explanations for Pangea breakup range from active causes such as mantle plumes (Dalziel et al., 2000) or upper mantle instability

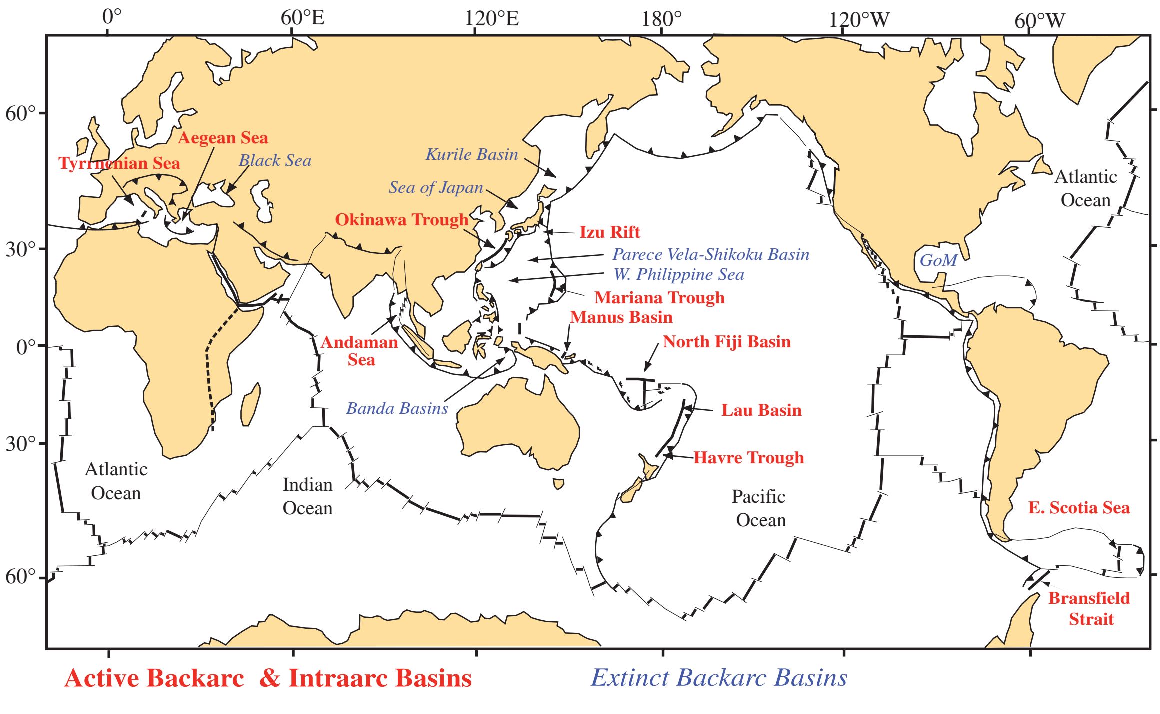

Figure 3. Active (red lettering) and extinct (blue italics lettering) backarc basins and interarc basins of the world, listed in Table 2. GoM—Gulf of Mexico.

TABLE 2. LIFESPANS OF ACTIVE AND EXTINCT BACKARC BASINS

Backarc basin	Start (Ma)	End (Ma)	Duration (Ma)	Transtensional?	References
Extinct					
Banda Sea	6	3	3		Honthaas et al. (1998)
Shikoku-Parece Vela	30	15	15		Sdrolias et al. (2004)
W. Philippine	53	33	20		Deschamps and Lallemand (2002)
Sea of Japan	25	12	13	Yes	Kimura et al. (2005)
Kurile					Tararin et al. (2001)
Coral Sea	62	52	10		Schellart et al. ESR (2006)
N. D'Entrecasteaux	80	66	14		Schellart et al. ESR (2006)
Black Sea					Shillington et al. (2008)
N. Loyalty Basin	44	35	9		Sdrolias et al. (2003)
S. Loyalty Basin					Schellart et al. (2006)
Santa Cruz Basin					Schellart et al. (2006)
Solomon Basin		28			Hall (2002)
S. Fiji Basin	35	24	11		Sdrolias et al. (2003)
Caspian Sea					Brunet et al. (2003)
Gulf of Mexico			<23		This study
Grenada Basin	56	38	18		Bird et al. (1999)
Komanodrsky	20	10	10	Yes	Scholl (2007)
Ligurian Basin	30	15	15		Rollet et al. (20020
Mean ± std. dev.			12.5 ± 4.7		
Active					
Mariana Trough	10				Fryer (1996) RoG
E. Scotia Sea	15				Barker (2001)
Bransfield Strait	4				Barker (2001)
Tyrrhenian Sea	9				Sartori (2003)
Aegean	25			Tectonic Escape	Jolivet et al. (1999)
Okinawa Trough	6				Nai-Shang (2001)
Izu Rifts	3				Ishizuka et al. (1998)
Andaman Sea	32			Yes	Curray (2005)
Manus	4			Yes	Martinez and Taylor (1996)
N. Fiji	12				Schellart et al. (2002)
Lau Basin	7				Parson and Hawkins (1994)
Havre Trough	7				Parson and Hawkins (1994)
Mean ± std. dev.			11.2 ± 8.9		

Note: std. dev.—standard deviation.

due to thermal blanketing (Gurnis, 1988) to passive, including far-field stresses due to trench retreat (cf. Dalziel et al., 2000 and Gutiérrez-Alonso et al., 2008). Because the causes of extension have nothing to do with the BAB and IAB definitions, we do not need to resolve this controversy.

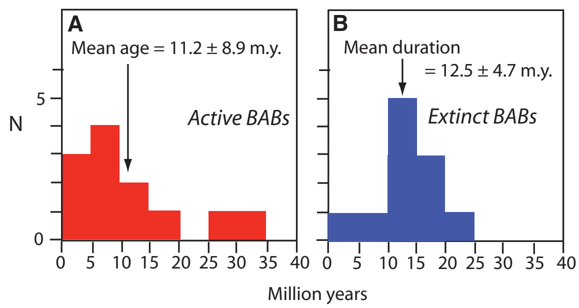

Figure 4. Histograms showing lifespans of (A) active and (B) extinct backarc basins (BABs) and interarc basins (IABs) of the world, from Table 2. The maximum lifespan of <23 m.y. inferred for the Gulf of Mexico is similar to that expected for a BAB.

SHORT LIVES OF BACKARC BASINS

An important characteristic of BABs is a short lifespan; they typically continue to spread for only 10–30 m.y. (Schellart et al., 2006). Figure 3 shows the location of 12 active BABs and IABs and 18 extinct BABs (including the GoM); Table 2 lists these and summarizes their tectonically active lifespans, which are graphically displayed in Figure 4. This compilation is intended to encompass all uncollapsed Cenozoic and some Mesozoic basins that formed by extension above a subduction zone. Extinct BABs had lifespans that range from <23 m.y. to 3 m.y., with a mean and standard deviation of 12.5 ± 4.7 m.y (Fig. 4B). Active BABs and IABs have been active for 35 m.y. or less, with a mean and standard deviation of 11.2 ± 8.9 Ma (Fig. 4A). Typical lifespans of IABs are not compiled here, but Woodcock (2004) reported a mean of 8.7 ± 4.4 m.y. Note that, although BABs and IABs are characterized by short tectonic lifespans, we do not imply that all short-lived basins are BABs or IABs.

Why do BABs have such short lifespans? This question has never been convincingly answered. Changing stress fields provide part of the answer, but this does not explain the behavior of modern western Pacific BABs. Extensional stresses there mostly reflect trench rollback due to subduction of old (Mesozoic) seafloor; trench rollback is not likely to cease until significantly more buoyant (thicker crust and/or younger) lithosphere is subducted, and that is not expected to occur on the ~15 m.y. time scales of BAB activity. Furthermore, the presence of multiple BABs associated with the Izu-Bonin-Mariana (e.g., progressively older Mariana Trough, Parece Vela–Shikoku Basin, and West Philippine Sea Basin) and Tonga-Kermadec convergent margins indicates that extensional stresses persist beyond the lifespans of individual BABs. These observations suggest that something other than the duration of extensional stress regimes in the upper plate is important for determining BAB lifespans.

The supply of hydrated mantle, which rises beneath the BAB spreading ridge and melts to form BAB oceanic crust, may be the important control. The main difference between mid-ocean ridge and BAB basalt is that the latter is much wetter (1.14% ± 0.64% versus <0.5% H_2O; Stern, 2002). Water lowers the mantle melting temperature and thus controls the supply of hydrated mantle for BAB mantle melting and seafloor spreading. Exhausting the supply of hydrated mantle beneath the spreading axis may signal the end of BAB seafloor spreading. The supply of water to the mantle wedge will diminish as a BAB widens and the spreading ridge becomes increasingly distant from the trench and overlying a progressively deeper, thus drier, slab with time. BAB widening taps progressively drier mantle, so water is removed by melting faster than it can be added from the subduction zone, and this deficit will increase as the BAB widens. At some point, magma generation ceases completely and BAB spreading stops, perhaps to jump trenchward back to the arc to form a new BAB. Such a progression from magma-rich to magma-poor spreading just prior to BAB shutdown is consistent with the Miocene evolution of the Parece Vela Basin in the western Pacific. This now-extinct BAB began by arc rifting (29–26 Ma), then spread approximately east-west (26–19 Ma) before the spreading ridge reorganized to northeast-southwest opening (19–15 Ma). The change from east-west to northeast-southwest spreading produced rough bathymetry and giant megamullions due to magma starvation in the terminal phase of seafloor spreading (Okino et al., 1998; Ohara, 2006). This evolution from magma-rich to magma-poor spreading to extinction could reflect diminished water supply, although this suggestion needs to be tested.

WHEN DID THE GULF OF MEXICO FORM, AND HOW LONG WAS IT ACTIVE?

GoM crust is buried beneath 15 km or more of sediments along its northwest margin. More distal parts of the basin have ~1 km of sediment. Jurassic oceanic crust is thought to be present in the GoM, but no correlatable spreading-related magnetic anomalies are known. Nevertheless, the deepest part of the GoM, the Sigsbee Deep, is 4384 m below sea level. This and other parts of the abyssal GoM seafloor are at depths only observed for old oceanic crust. Early geophysical surveys concluded that oceanic crust underlies the central GoM (Antoine et al., 1974; Worzel, 1974), and most tectonic models for its origin infer that a wedge-shaped tract of oceanic crust underlies the central GoM (Pindell and Kennan, 2009). In the following we outline evidence that GoM opening occurred after early uplift, about the time that the Louann Salt was deposited, and at the same time that the Yucatan (which was then part of Gondwana) moved away from Laurentia, between 165 and 142 Ma.

Evidence for Early Uplift

Seafloor spreading in the GoM occurred during or after Late Triassic time (ca. 225 Ma), when precursory doming or accompanying rift flank uplift in what is now central Texas shed a flood of clastic sediments to the west and southwest (Dickinson and Gehrels, 2008a; Dickinson et al., 2010). Eagle Mills rift grabens with basalts also formed in Late Triassic time in what is now southern Arkansas (Moy and Traverse, 1986). There is similar evidence of Late Triassic–Early Jurassic rifting, preserved as redbeds that are now exposed along the front of the Sierra Madre Oriental in northeastern Mexico. The La Boca–Huizachal redbeds are Late Triassic–Early Jurassic and the La Joya–Cahuasas redbeds are Late Jurassic (Salvador 1991). The two redbed units are separated in the north by an unconformity and in the south by marine sediments (Salvador, 1991).

Salt

Early stages in the evolution of marine basins often result in narrow passages to the larger ocean so that seawater flow is prone to disruption by tectonic or volcanic activity, and the embryonic basin dries out episodically. Consequently, salt is commonly deposited during early stages of rifting and seafloor spreading, especially at low latitudes (like that of the GoM formation), and the age of salt deposits thus approximates when the incipient ocean basin formed. Widespread salt (Louann Salt) of Jurassic age underlies much of the U.S. and Yucatan GoM continental shelves and slopes, but not the area of inferred oceanic crust, implying that at least some seafloor spreading occurred after the salt blanket was deposited (Salvador, 1987). However, this argument is not compelling because salt can be deposited with early oceanic basalts (e.g., Mohr, 1978; Jackson et al., 2000; Torsvik et al., 2009). Salvador (1991) reviewed the Louann Salt and its age, and concluded that the salt could not be directly dated but that it could be stratigraphically bracketed as post–Early Jurassic to pre–late Oxfordian, between 176 and 156 Ma. With this constraint for the Louann Salt, some seafloor spreading occurred after 176–156 Ma. Salt is also found as domes in the Sabinas and La Popa Basin, the southeastern part of the Border rift system (Eguiluz de Antuñano, 2001), but there is no evidence for seafloor spreading there.

Yucatan Motion

Another independent constraint on when the GoM opened comes from the rotation of Yucatan, which separated (with the rest of Gondwana) from Texas. Yucatan rotated as it moved south along the Tehuantepec transform (Fig. 2; Pindell, 1985; Marton and Buffler, 1994), which marks the boundary between continental and oceanic crust along the east coast of Mexico. Most workers consider that a total of 42°–60° counterclockwise rotation took place (Pindell and Dewey, 1982; Bird et al., 2005). Paleomagnetic data (Guerrero et al., 1990) indicate that this rotation ended by middle Berriasian time (ca. 142 Ma). After the Yucatan moved into its final position, Gondwana separated and the proto-Caribbean Seaway opened (Pindell, 1985; Klitgord and Schouten, 1986; Ross and Scotese, 1988; Pindell and Kennan, 2009).

These three constraints together indicate that seafloor spreading occurred between 165 and 142 Ma, for a total maximum opening duration of 23 m.y. This chronology is consistent with the conclusion of Marton and Buffler (1994), that seafloor spreading in the GoM began during Callovian time (165–161 Ma) and ended by ca. 135 Ma, and with the conclusions of Bird et al. (2005), that seafloor spreading occurred between 160 and 138 Ma.

PERMIAN–JURASSIC CONTINENTAL ARCS IN NORTHEASTERN MEXICO

An important tectonic element that is often overlooked in efforts to understand GoM evolution is the active magmatic arc that persisted in Mexico from Permian through Jurassic time. This arc developed along the southwestern flank of conjoined Laurentia and Gondwana following truncation of older tectonic fabrics along the Permian–Triassic California-Coahuila transform or Mojave-Sonora megashear (Burchfiel and Davis, 1972; Dickinson and Lawton, 2001a). The igneous rocks of this arc are not well exposed, due to younger sedimentary and volcanic cover and subsequent deformation.

Pre-Cretaceous arcs of northeastern Mexico include the Permian–Triassic East Mexico arc (Torres et al., 1999) and the Jurassic Nazas arc (Dickinson and Lawton, 2001a). The East Mexico arc existed prior to the breakup of Pangea, whereas the Nazas arc was coeval with Pangea breakup and GoM formation. Both arc systems were due to subduction of oceanic crust eastward beneath westernmost Pangea (and its fragments) in the region now occupied by Mexico. The relationship between northeastern Mexican arcs, the GoM, and other tectonic elements is summarized in Figure 2.

The Permian–Triassic East Mexico arc trended approximately north-south in today's coordinates. Today it is manifested by felsic plutons along the trend of the Tampico block (Torres et al., 1999) that can be traced southward into the Chiapas massif and the Del Sur block (Dickinson and Lawton, 2001a). The trend of Permian–Triassic arc plutons crossed the Chiapas massif of the Yucatan-Chiapas block, as restored prior to opening of the Gulf of Mexico, and continued north as an arcuate belt of isolated plutons emplaced both within the Coahuila block and into Laurentian crust across the Ouachita suture (Torres et al., 1999). Iriondo and Arvizu (2009) suggested that the Permian arc continued westward into northwestern Mexico, where it is covered by the Jurassic Nazas arc assemblage.

Figure 5. Comparison of U-Pb ages (age-probability plots) for detrital zircon grains in (A) Colorado Plateau strata with fluvial paleocurrents or eolian paleowinds indicating sediment derivation from the south or southwest, (B) sedimentary assemblages within or adjacent to the Cordilleran magmatic arc in northern Mexico, (C) Colorado Plateau and High Plains strata with fluvial paleocurrents or eolian paleowinds indicating sediment derivation from the east or southeast, and (D) superimposed curves of A, B, and C. Data are from Dickinson and Gehrels (2008a, 2008b, 2009, 2010). Data for B are from Barboza-Gudino et al. (2010), Gonzáléz-Léon et al. (2009), and Lawton et al. (2009). (Note: there are no Colorado Plateau or High Plains strata of Cretaceous age derived from the east or southeast, hence only three curves in C.)

The southwestern margin of North America was tectonically truncated in Permian–Triassic time (Dickinson, 2006). Subduction along the foreshortened continental margin produced a nascent continental margin arc in California by Early Triassic time (Barth and Wooden, 2006). By Early Jurassic time, the magmatic arc was continuous from California across southern Arizona and into adjacent Sonora. Coeval arc assemblages are also present farther southeast on the Tampico block in east-central Mexico. Although Triassic–Jurassic intrusions are also present farther south (Sedlock et al., 1993), Triassic–Jurassic arc rocks are missing from the Del Sur block of southern Mexico (Morán-Zenteno et al., 1993). The Nazas arc may have continued along strike into Colombia (Dickinson and Lawton, 2001a) before opening of the proto-Caribbean seaway separated North and South America.

Because the East Mexico and Nazas magmatic arcs are not well exposed, the age spans of Mesozoic arc activity in southwestern North America were examined using detrital zircons from Mesozoic sedimentary rocks of the backarc region exposed within the shaded area of Figure 2. The zircons were derived in part from areas of northeastern Mexico now largely masked by Cretaceous and younger sedimentary cover. Although we cannot know the precise sources of zircons in any sedimentary rock, we know of no magmatic system other than the East Mexico and Nazas arcs and their western continuations that could have generated significant quantities of zircons of Permian–Jurassic age. Detrital zircons presumably reached the backarc region via streams that flowed northward from Mexico across the region west of the Tehuantepec transform, at least during Triassic time. Late Triassic strata in particular are dominated by zircons older than 300 Ma shed from the Paleozoic Ouachita orogenic belt and the Texas Mesoproterozoic craton (Dickinson et al., 2010); these older zircons are not considered here.

Figure 5 shows age-probability plots for detrital zircon populations younger than 300 Ma from Mesozoic strata of the Colorado Plateau and High Plains divided into 6 successive stratigraphic intervals, each lasting 10–25 m.y. Detrital zircon populations (300–50 Ma) from the Colorado Plateau (and High Plains) in the backarc region were deconvolved into component subpopulations for which fluvial paleocurrent indicators or paleowind vectors document derivation from the east and southeast (Fig. 5C), in the direction of the GoM, or from the south and southwest (Fig. 5A). Detrital zircon age data from others are also used to evaluate detrital zircon populations in sedimentary assemblages of northern Mexico directly south of the Colorado Plateau (Fig. 5B). The superimposed curves of Figure 5D suggest no major differences in times of arc igneous activity across Mexico from west to east, implying that arc magmatism west of the GoM persisted from Permian through Middle Jurassic time, both before and during initial phases of seafloor spreading within the GoM.

Some aspects of the detrital zircon age spectra of Figure 5 deserve comment. In Figure 5C, the detrital zircon age peak at 250–260 Ma in Middle to Late Jurassic strata of the backarc region derived from the east (eolian) or southeast (fluvial) probably reflects sources in the Permian–Triassic East Mexico arc preserved just west of the GoM. The age peak at 211–217 Ma for Early Jurassic backarc strata sourced from the south (Fig. 5A) derives from a single sample, and probably only reflects local vagaries in shifting arc provenance. The prominent peak at 163–168 Ma for Middle to Late Jurassic strata deposited in northern Mexico (Fig. 5B) within or near the arc provenance apparently reflects proximity to source. The modest 135 Ma peak in Late Cretaceous strata of northern Mexico (Fig. 5B) is not seen on the other curves, and probably reflects derivation of some detritus from Early Cretaceous igneous rocks of the Guerrero terrane of westernmost Mexico too distant to contribute to the other sedimentary assemblages shown in Figure 5. For other age spectra (Figs. 5A, 5B), the absence of any peaks within the interval 150–125 Ma suggests a major reorganization of the Mexican convergent margin during Early Cretaceous time.

A few other issues are noteworthy. First, the detrital zircon record could be biased because East Mexico arc detritus samples zircon-rich plutonic rocks, whereas Nazas arc detritus samples volcanic rocks, which tend to be poorer in zircons. The only place in Mexico where there are extensive exposed Jurassic plutons is in western Sonora, where Laramide uplift exhumed the Jurassic arc roots (T.F. Lawton, 2008, personal commun.). Nevertheless, independent support for our conclusions about East Mexico and Nazas arc activity comes from a study of detrital zircons from Mexico by Gray et al. (2008). Here, Permian–Triassic zircons dominate the Jurassic and Lower Cretaceous strata and Jurassic grains are subordinate. Again, part of the reason might be the difference between the Permian–Triassic arc, which is deeply eroded down to the batholith (in its Cretaceous subcrop), and the Jurassic arc, which typically consists of supracrustal rocks, redbeds, and interbedded tuffs and flows. The Permian–Triassic arc may have been an Andean-type massif, high-standing and thus an excellent source for detritus, whereas the Triassic–Jurassic arc developed in an extensional environment and thus had lower relief and less erosion. It is not clear what caused the arc to shut down ca. 150 Ma, apparently for 30 m.y. in places. The arc may have jumped westward atop the Guerrero terrane (Alisitos-Peninsular arc of northwestern Mexico) after it collided with Mexico. Alternatively, arc shutdown may have been linked to the GoM opening. Initial stages in the formation of many Cenozoic backarc basins sometimes interrupt magmatic activity in associated arcs, as discussed herein. It is clear that a magmatic arc grew in the region almost immediately following collision to form Pangea and continued essentially in place and without significant interruption until after the Gulf of Mexico began to form immediately east of the Nazas arc.

There is a significant body of geochronological data for arc igneous rocks that supports the inferences drawn from detrital zircons; these ages are summarized in Figure 6A. Torres et al. (1999) summarized 45 radiometric ages, ranging

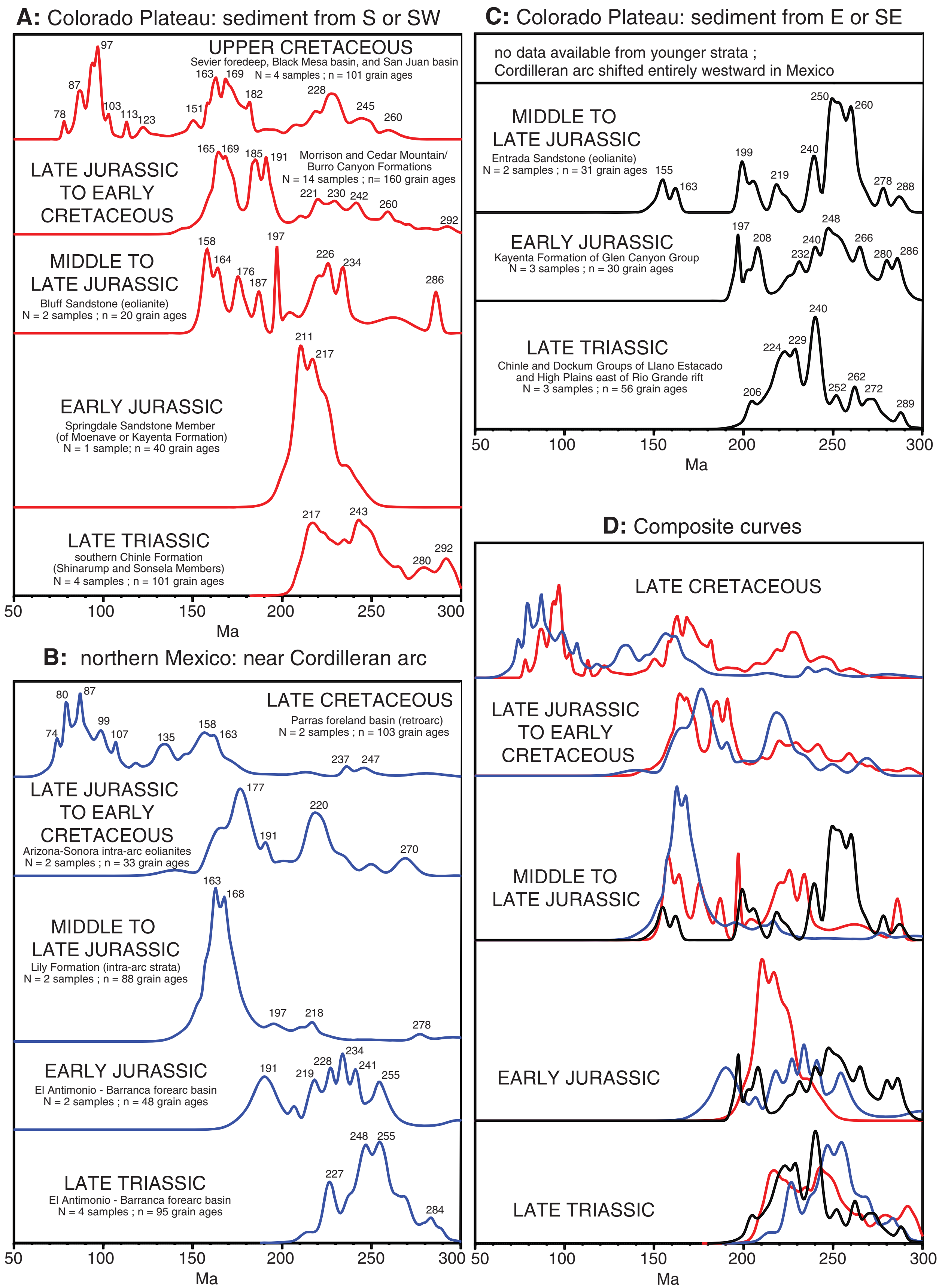
A: Colorado Plateau: sediment from S or SW
UPPER CRETACEOUS
Sevier foredeep, Black Mesa basin, and San Juan basin
N = 4 samples ; n = 101 grain ages
LATE JURASSIC TO EARLY CRETACEOUS
Morrison and Cedar Mountain/ Burro Canyon Formations
N = 14 samples ; n= 160 grain ages
MIDDLE TO LATE JURASSIC
Bluff Sandstone (eolianite)
N = 2 samples ; n = 20 grain ages
EARLY JURASSIC
Springdale Sandstone Member (of Moenave or Kayenta Formation)
N = 1 sample; n = 40 grain ages
LATE TRIASSIC
southern Chinle Formation (Shinarump and Sonsela Members)
N = 4 samples ; n = 101 grain ages
Ma
B: northern Mexico: near Cordilleran arc
LATE CRETACEOUS
Parras foreland basin (retroarc)
N = 2 samples ; n = 103 grain ages
LATE JURASSIC TO EARLY CRETACEOUS
Arizona-Sonora intra-arc eolianites
N = 2 samples ; n = 33 grain ages
MIDDLE TO LATE JURASSIC
Lily Formation (intra-arc strata)
N = 2 samples ; n = 88 grain ages
EARLY JURASSIC
El Antimonio - Barranca forearc basin
N = 2 samples ; n = 48 grain ages
LATE TRIASSIC
El Antimonio - Barranca forearc basin
N = 4 samples ; n = 95 grain ages
Ma
C: Colorado Plateau: sediment from E or SE
no data available from younger strata ; Cordilleran arc shifted entirely westward in Mexico
MIDDLE TO LATE JURASSIC
Entrada Sandstone (eolianite)
N = 2 samples ; n = 31 grain ages
EARLY JURASSIC
Kayenta Formation of Glen Canyon Group
N = 3 samples ; n = 30 grain ages
LATE TRIASSIC
Chinle and Dockum Groups of Llano Estacado and High Plains east of Rio Grande rift
N = 3 samples ; n = 56 grain ages
Ma
D: Composite curves
LATE CRETACEOUS
LATE JURASSIC TO EARLY CRETACEOUS
MIDDLE TO LATE JURASSIC
EARLY JURASSIC
LATE TRIASSIC
Ma
50 100 150 200 250 300

Figure 5.

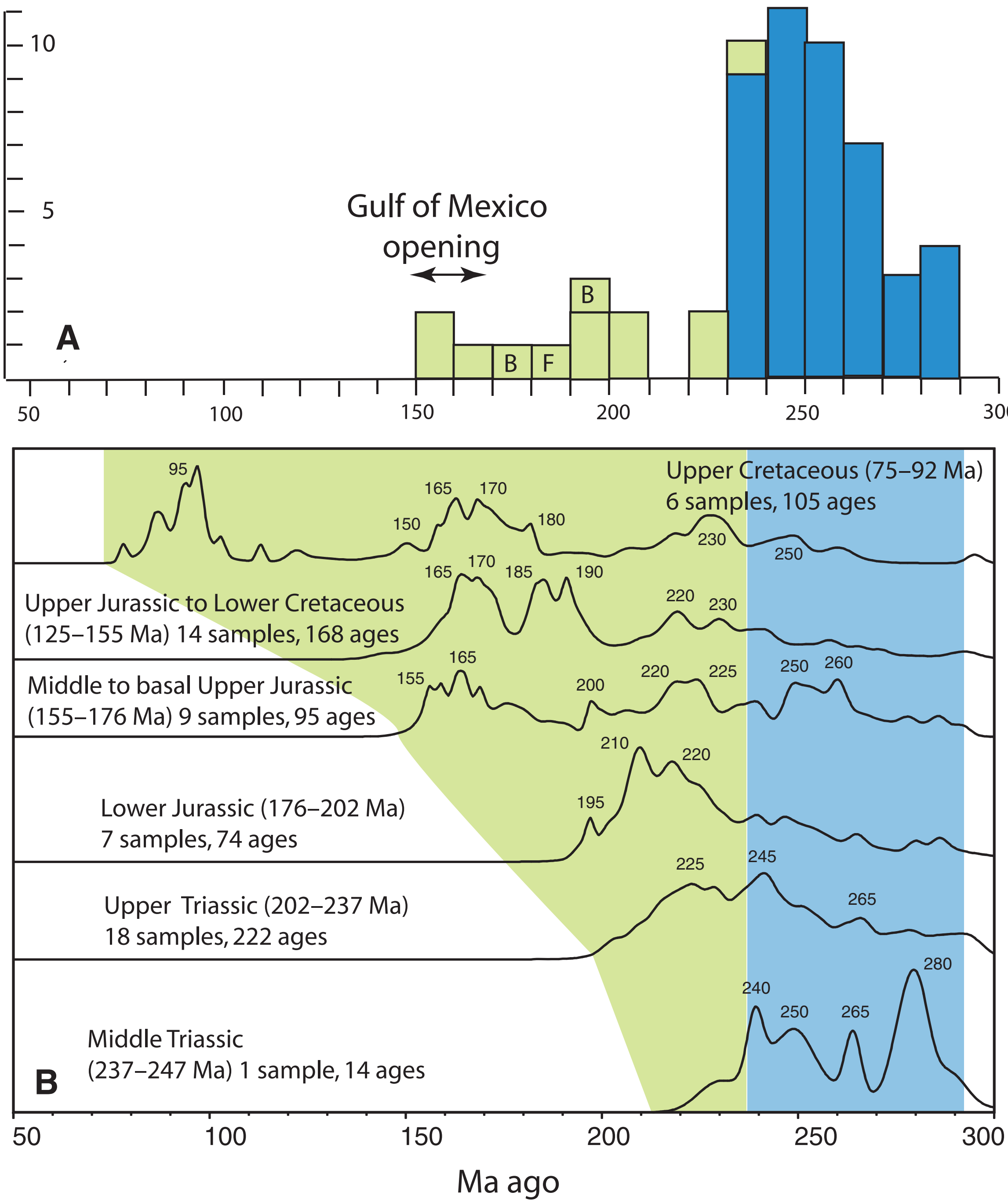

Figure 6. Two glimpses of the age of Permian–Jurassic arc magmatic rocks on the western flank of the Gulf of Mexico. (A) Histogram of radiometric ages for northeastern Mexican arc plutonic and volcanic rocks (blue—Permian–Triassic granitoids of the East Mexico Arc; Torres et al., 1999; green—Triassic–Jurassic felsic lavas of the Nazas arc; Barboza-Gudiño et al., 1999). Box F is U-Pb zircon age of Fastovsky et al. (2005); boxes B are U-Pb zircon ages of Barboza-Gudiño et al. (2004, 2008). (B) Age-probability plots of U-Pb ages for 678 detrital zircon grains younger than 300 Ma in 55 samples of Mesozoic sandstone from the Colorado Plateau and High Plains of the southwestern U.S. (region shown in gray in Fig. 2). Data sources are the same as for Figure 5. Data are plotted for six stratigraphic intervals deposited during time intervals each lasting 10–35 m.y. Age peaks are denoted to the nearest 5 Ma. Shaded green field shows the time that could be sampled by sediments of a particular stratigraphic level; zircon grains younger than the ages of host sediments are not expected. The curves are (from bottom to top) Middle Triassic (Moenkopi); Late Triassic (from Texas Ouachita direction); Early Jurassic; Middle to early-Late Jurassic; Late Jurassic to Early Cretaceous; and Late Cretaceous. See text for further discussion.

from 287 Ma (Early Permian) to 232 Ma (early-Late Triassic), with a mean of 254 Ma (Fig. 6A). Initial ε_{Nd} values of +2.5 to –4.4 imply emplacement of mantle magmas through continental crust (Torres et al., 1999). Barboza-Gudiño et al. (1999, 2008) summarized 13 radiometric ages for mostly felsic volcanic rocks from the Nazas arc, ranging from 230 Ma (Middle Triassic) to 156 Ma (Late Jurassic) (mean = 189 Ma). Initial ε_{Nd} values (–1.5) indicate the involvement of underlying continental crust or derivative sediment (Centeno-García and Silva-Romo, 1997). There is good agreement between these ages and composite detrital zircon spectra, summarized in Figure 6B.

Several features of the detrital zircons spectra and igneous rock ages are noteworthy. First, Late Triassic zircons are more abundant in the Late Triassic and Early Jurassic sediments from the U.S. than from Mexico, whereas Jurassic zircons are more abundant in Early and Middle Jurassic sediments from Mexico relative to U.S. sediments of similar age. We speculate that this indicates a shifting locus of most intense igneous activity southward into Mexico with time. Second, radiometric ages of East Mexico and Nazas arc plutons and lavas (Fig. 6A) and detrital zircon composite spectra (Figs. 5D, 6B) indicate significant diminution of arc activity ca. 150 Ma. This strongly suggests that the Mexican convergent margin underwent a major reorganization about that time. Third, dating of isolated outcrop and subcrop samples from the arc assemblage suggests a gap between episodes of East Mexico and Nazas arc magmatism (Fig. 6A), but the detrital zircon compound age spectra (Fig. 5D) indicate continuous arc igneous activity from Permian to Jurassic time in southwestern North America. For example, the age spectrum for detrital zircons in the Upper Triassic backarc strata of Figure 5C implies continuous arc activity throughout both Permian (290–252 Ma peaks) and Triassic time (235–206 Ma peaks).

We reiterate that the detrital zircon record integrates the distribution of zircons in the source region; that both eolian and fluvial transport operated at different times at differing intensities; and that the record of Permian and Mesozoic igneous activity in northeastern Mexico is imperfectly preserved in the detrital zircons record, no matter how exhaustively sampled. With this caveat in mind, the agreement between Figure 5 and 6 supports an interpretation that: (1) the East Mexico arc was active ca. 280–235 Ma; (2) the Nazas arc and its extensions to the northwest in Arizona became active ca. 235 Ma and continued until Late Jurassic time; and (3) the Nazas arc system shut down ca. 150 Ma. This arc system was active when the GoM began to open, although it appears to have shut down before GoM opening was complete.

BORDER RIFT SYSTEM

The GoM = BAB hypothesis sheds light on a related interarc basin that developed with the GoM. The Border rift system can be traced from the GoM >2000 km west-northwest into the Independence Dike Swarm of east-central California. From east to west, the Border rift system axis can be traced discontinuously (because of younger cover and deformation) through the Sabinas Basin, Chihuahua Trough, Bisbee Basin, McCoy Basin, and Independence Dike Swarm (Fig. 2; Bilodeau, 1982; Dickinson and Lawton, 2001b; Garrison and McMillan, 1999; Lawton and McMillan, 1999). The Border rift system is intimately associated with the Nazas magmatic arc (and equivalents to the north) and thus should be regarded as an IAB. The Border rift system acted as a "swinging door" that opened in southwestern North America during Jurassic time, from a hinge in California through a chasm that widened progressively eastward into the GoM. Subsequent Border rift system thermotectonic subsidence created an extensive depositional domain along the U.S.–Mexico border region. Subsidence analysis of the Sabinas Basin implies a stretching factor (β) of 1.6–1.8 (Cuevas Lee, 1985, quoted *in* Dickinson and Lawton, 2001b). Late Jurassic marine transgression advanced northwest up the Sabinas Basin from the GoM during Oxfordian time (161–156 Ma) and up the Chihuahua Trough during Kimmeridgian time (156–151 Ma; Dickinson and Lawton 2001b).

The Border rift system joins with the GoM where the Tehuantepec transform and the postulated volcanic rifted margin offshore Texas (Mickus et al., 2009) meet, making a ridge-ridge-transform triple junction. These three elements meet near the mouth of the Rio Grande at archetypal ~120° angles (Fig. 2), in what we call the Rio Grande triple junction. We note that the junction is structurally complex, much more so than depicted in Figure 2. Jurassic paleogeography included uplifts, shoals, and islands along the Border rift system northward from the Tamaulipas arch (Dickinson and Lawton, 2001a). There was an interbasinal sill also between the Sabinas Basin and the Chihuahua Trough, as well as the Aldama platform between the Chihuahua Trough and the Bisbee Basin. The Rio Grande embayment, Sabinas Basin, Chihuahua Trough, and Bisbee Basin may have been en echelon segments of the evolving Border rift system, but there is clearly stratal consanguinity along the Border rift system trend.

There is no evidence that seafloor spreading occurred in the Border rift system, which acted as an aulacogen, but the presence of Oxfordian salt indicates that Late Jurassic extension in its eastern part was large enough to subside below sea level and allow seawater to fill and refill the basin. Salt in the Sabinas Basin seems to be early Kimmeridgian, slightly younger than the Louann Salt (Vega and Lawton, 2011). Nevertheless, Border rift system extension was related in space and time to the GoM opening (Bilodeau, 1982; Dickinson et al., 1986). Tangentially, great rivers like the Rio Grande tend to flow down rifts like the Border rift system (Potter, 1978).

Previously workers have related Border rift system extension to the GoM opening (Bilodeau, 1982; Dickinson et al., 1986), and the two features reflect a strongly extensional convergent margin of Late Jurassic age. Border rift system extension, and thus partly also GoM opening, is related to changing tectonic regimes associated with the Nazas arc, perhaps due to rollback of the eastward-subducting Mezcalera plate (Lawton and McMillan, 1999). In Arizona, Early Jurassic–Middle Jurassic arc volcanism (pre–170 Ma; Riggs et al., 1993) was succeeded by the eruption of silicic Middle Jurassic–Late Jurassic ignimbrites (170–150 Ma; Lawton and McMillan, 1999). Felsic calderas are common in IABs but missing in BABs (Hughes and Mahood, 2008), such as in the modern Taupo Volcanic Zone of northern New Zealand (Wilson et al., 1995) or the rifted Izu arc (Fiske et al., 2001).

The Border rift system extensional regime evolved quickly. The rifted-arc volcanic assemblage in Arizona is overlain by thick conglomerates interbedded with silicic tuffs and subaqueously erupted pillow basalts (Bilodeau et al., 1987; Lawton and McMillan, 1999). Although the Border rift system across northern Mexico is geographically in a BAB setting (Fig. 2), it nearly parallels the Nazas arc, joining it in southwestern Arizona, where it clearly is an IAB (Fig. 2). The coeval and cogenetic relationship of the Border rift system and GoM required by the Rio Grande triple junction is evidence that the GoM also formed as a result of arc rifting.

The great thickness of sediments, especially in the eastern Border rift system (Fig. 7), makes it difficult to investigate the early volcanically active part of its development. Nevertheless, there are four Border rift system segments where Late Jurassic igneous rocks have been studied: the Sabinas Basin, Bisbee Basin, McCoy Basin, and Independence Dike Swarm. Garrison and McMillan (1999) studied a suite of meta-igneous xenoliths brought to the surface by the

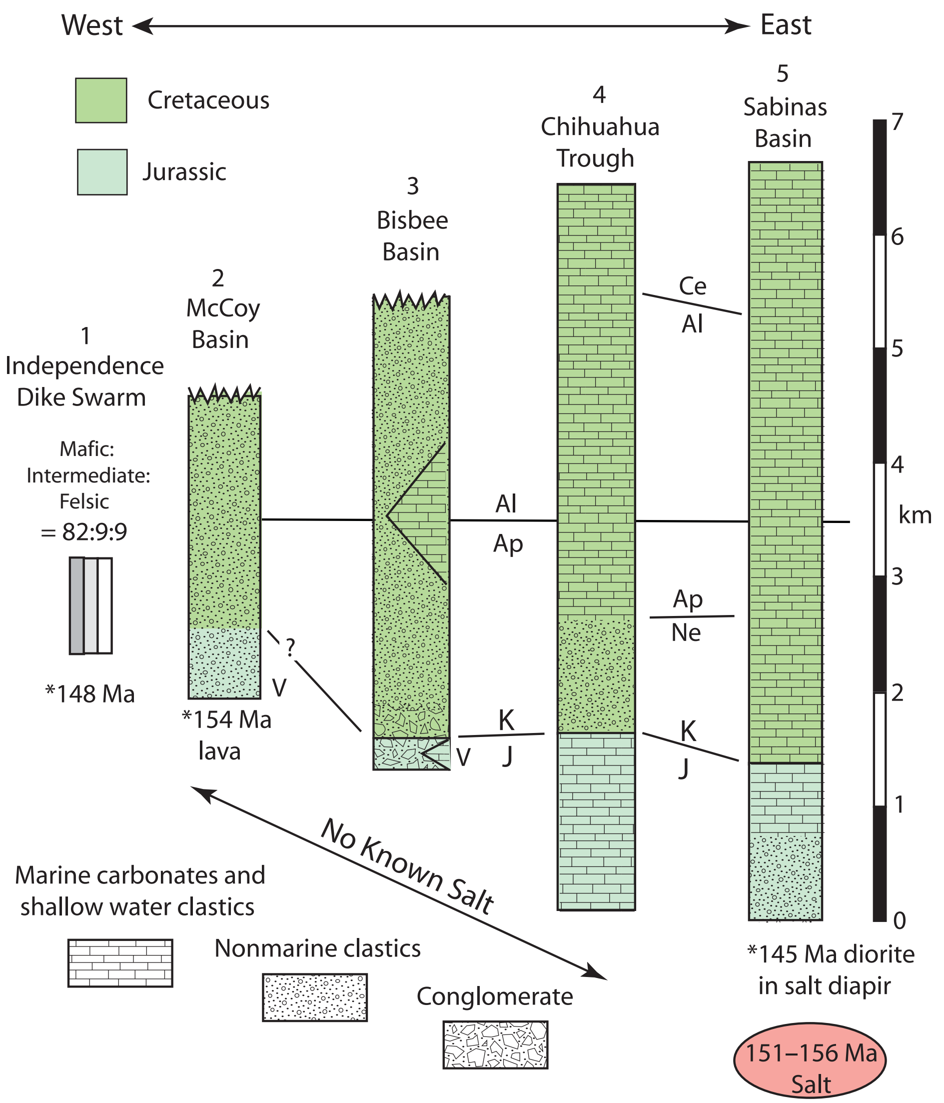

Figure 7. Representative stratigraphic columns (central datum at Aptian-Albian boundary) showing regional gradient of thickness and marine versus nonmarine facies within Jurassic–Cretaceous strata of the Border rift system (see Fig. 2 for locations), modified after Dickinson and Lawton (2001b). Radiometric ages for igneous rocks are shown with asterisk (in Ma). Locations 1–5 are shown in Figure 2. 1—Independence dike swarm (Glazner et al., 2008); 2—McCoy Basin (U-Pb zircon age from Spencer et al., 2011); 3—Bisbee Basin (which grades from nonmarine in the west to mixed marine-nonmarine in the east); 4—Chihuahua Trough; 5—Sabinas Basin (ages for two diorite blocks, interpreted as metamorphic ages, from Garrison and McMillan, 1999). Volcanic rocks denoted with v. Key biostratigraphic intervals: K/J = Cretaceous–Jurassic; Ap/Ne = Aptian–Neocomian; Al/Ap = Albian–Aptian; Ce/Al = Cenomanian–Albian.

El Papalote salt diapir near the southeastern terminus of the Border rift system in Nuevo Leon. Both salt and xenoliths originate deep in the Sabinas Basin, below ~7 km of sediments (Fig. 7). The metaigneous rocks consist of greenschist facies metabasalt, monzonite, and biotite diorite. Biotites separated from two plutonic samples yield $^{40}Ar/^{39}Ar$ ages of 146.5 ± 1.6 Ma and 145.6 ± 1.0 Ma (Late Jurassic), ~20 m.y. younger than the salt. Garrison and McMillan (1999) interpreted these as metamorphic ages.

Metabasalt chemical composition can be used to illuminate tectonic setting. Garrison and McMillan (1999) subdivided the metabasalts into high (>55 ppm) and low (25–52 ppm) Nb suites, and noted that the high Ta and Nb contents of both suites suggest that they were formed by decompression melting of asthenosphere in an extensional setting rather than by flux melting over a subduction zone. They concluded (Garrison and McMillan, 1999, p. 327) that these magmas were not products of the Nazas arc but formed in a rift environment and "...that extension was sufficient in Jurassic time in northeastern Mexico to allow decompression melting of the asthenosphere."

Farther west, Late Jurassic Border rift system igneous rocks occur as lavas and sills in a thick (to 7 km) clastic sequence of the McCoy Mountains Formation of southeastern California and southwestern Arizona. An andesitic lava flow near the top of the section yielded a U-Pb zircon age of 154.4 ± 2.1 Ma (18 grains; Spencer et al., 2011). Geochemical data (Gleason et al., 1999) indicate that these are subalkaline to moderately alkaline high-Al basaltic to andesitic rocks that are moderately enriched in light rare earth elements. Nb abundances were not determined, but assuming typical values of Nb/Ta for basalts (17.5; Green 1995), concentrations of Ta = 0.40–1.8 ppm in McCoy Mountains lavas imply Nb concentrations of 7–32 ppm. This is mostly lower than the Sabinas Basin metabasalts, but significantly higher than concentrations (a few ppm Nb) typical of arc basalts (Thirlwall et al., 1994), further suggesting a mantle source that was more influenced by subduction zone processes than that beneath the Sabinas Basin, as expected for IAB lavas. Spencer et al. (2011) also analyzed 12 samples of basaltic sills and flows for Nd isotopic compositions. These yielded initial ε_{Nd} (for ca. 150 Ma) between –6.1 and +5.5, overlapping values of +2 to +5 reported by Lawton and McMillan (1999) for Bisbee Basin lavas, but with several negative values suggesting that the magma underwent crustal contamination or was derived from a mixture of asthenospheric and old lithospheric sources.

The Independence Dike Swarm of eastern California forms the northwest terminus of the Border rift system. It extends >600 km from the Mojave Desert into the eastern Sierra Nevada. The Independence Dike Swarm has not previously been related to the Border rift system, but the ages and trends of the Independence Dike Swarm and Border rift system are similar, and the southern terminus of the swarm is coterminous with the McCoy Basin, the westernmost Border rift system sedimentary basin. Independence Dike Swarm dikes are predominantly mafic (<55 wt% SiO_2), although dikes range in composition from basalt to rhyolite (Fig. 7) and are often composite (Glazner et al., 2008). Independence Dike Swarm mafic rocks have ε_{Nd} (150 Ma) of –2.3 ± 1, lower than expected for asthenospheric melts. It is not clear whether this reflects contamination by continental crust and/or subducted sediments, or reflects melting of Paleoproterozoic mantle lithosphere (Glazner et al., 2008). Independence Dike Swarm mafic samples contain 5–10 ppm Nb and show a strong, arc-like depletion in Nb, as expected for IAB melts.

JURASSIC EVOLUTION OF THE GULF OF MEXICO AS A BACKARC BASIN

The overview presented here shows that the formation of the GoM and Border rift systems were coeval, and that the western Border rift system in particular evolved in a subduction-related tectonic setting. Continental arc magmatism was an important aspect of the Permian–Jurassic evolution of the northeastern Mexico–southwestern U.S. region, trenchward of where the GoM formed. This convergent margin seems to have evolved from a high-standing Andean-type arc to a strongly extensional (low standing) arc when the GoM and Border rift system formed, before arc magmatism stopped ca. 150 Ma. The various tectonic, stratigraphic, and magmatic episodes of Permian–Early Cretaceous time for the region of interest are summarized in Figure 8.

The GoM clearly formed as a backarc basin, an interpretation that is demanded by its position behind a magmatic arc and above a subduction zone. This interpretation helps explain some other aspects of the Jurassic evolution of this region, including the intimate relationship of the GoM with an IAB and the relatively short lifetime (<23 m.y.) of the GoM. The GoM appears to have opened first along with coeval arc volcanism and continued to open after the arc shut down. This is consistent with the behavior of arc and/or BAB systems discussed herein, where arc volcanism may or may not shut down while BAB spreading occurs.

Our preferred scenario is shown in Figure 9. As noted here, BABs form in response to extensional stresses, which can have many causes. Multiple forces may also have contributed to stretching in the GoM–Border rift system region. This is especially likely because the time from the beginning of extension until seafloor spreading began was so long, ~60 m.y., beginning in Late Triassic time well before seafloor spreading started. Through this time, the causes and orientations of extensional stresses varied. For example, Beutel (2009) concluded that Pangea breakup (ca. 230 Ma) reflected northwest motion of North America, followed by the beginning of Central Atlantic Magmatic Province magmatism ca. 200 Ma and south-southeastward motion of South America, followed soon thereafter by resumption of North American northwest motion.

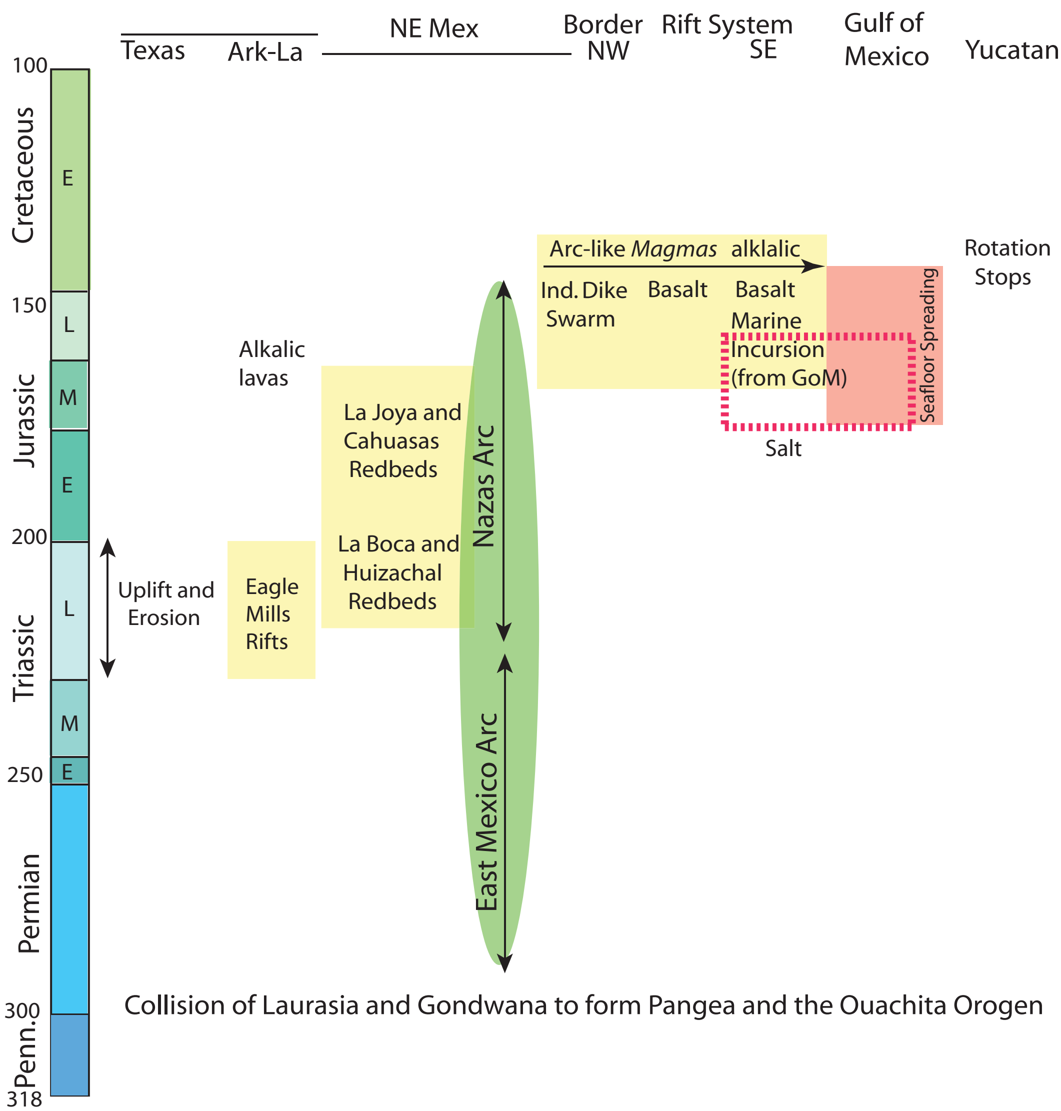

Figure 8. Summary of tectonic events for Gulf of Mexico (GoM), Texas-Arkansas (Ark)-Louisiana (La) region of United States, East Mexico and Nazas arcs, Border rift system, and environs. Ind.—Independence. Color scheme for tectonic features follows that shown in Figure 2. Penn.—Pennsylvanian.

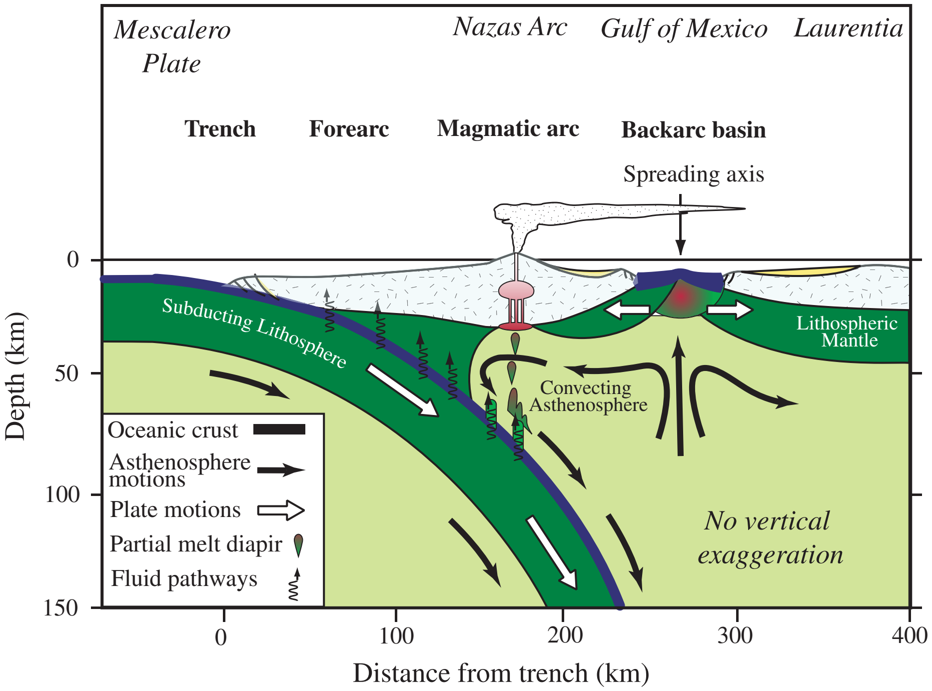

Figure 9. Schematic section through the upper 150 km of a subduction zone, showing the principal crustal and upper mantle components and their interactions; modified from Stern (2002) to show a section through Mexico to the Gulf of Mexico. Note that the location of the mantle wedge (unlabeled) is that part of the mantle beneath the overriding plate and between the trench and the most distal part of the arc where subduction-related igneous or fluid activity is found. Not all convergent plate margins have backarc basins.

The inference that the Gulf of Mexico formed as a Jurassic BAB also explains the observed variations in initial extension style, from an apparent volcanic rifted margin in the west (Texas; Mickus et al., 2009) to rifted margin (Louisiana-Mississippi; Marton and Buffler, 1994; Harry and Londono, 2004) farther east. The mantle beneath magmatic arcs is hot (>1200 °C) and rich in water derived from the underlying subducted lithosphere (Stern, 2002), and we have noted that BAB mantle is likely to be drier with distance from the trench. The relationship seen in the northern GoM of volcanic rifted margin near the arc and non–volcanic rifted margin at a greater distance is similar to that inferred for the Black Sea, which has recently been interpreted as an extinct BAB. The eastern Black Sea (a volcanic rifted margin) was ~175 km closer to the paleosubduction zone than was the non–volcanic rifted margin northwest Black Sea. Shillington et al. (2008) argued that lateral temperature and water variations in the mantle reflected greater distance of the Black Sea from the associated arc to the south. Seaward-dipping reflectors have been imaged in the extreme east of the GoM, beneath the Florida escarpment (Imbert, 2005); these manifest the presence of a volcanic rifted margin in the far east of the basin, perhaps related to the ca. 200 Ma Central Atlantic Magmatic Province, which extends north from Florida (Marzoli et al., 1999).

A final point is that the inferred GoM spreading ridge was oriented at a high angle (~90°) to the associated magmatic arc (Fig. 2). Although the Border rift system follows the arc trend, the inferred GoM spreading axis does not. This orientation is problematic, because most intraoceanic BABs have spreading axes that approximately parallel the associated trench. For these systems, BAB orientation manifests extensional stresses oriented approximately perpendicular to the plate margin and parallel to the arc. This reflects the importance of slab density and trench rollback in controlling BAB opening. Certainly the high-angle intersection of the inferred GoM spreading ridge with the Nazas arc suggests that forces other than trench rollback alone contributed to the extension; this is not surprising, given that the GoM opened during Pangea breakup. The GoM spreading axis is thus likely to have responded to this global stress field to become oriented approximately parallel to the evolving east-west–oriented Tethys. Nevertheless, we stress that the relative orientation of the BAB spreading axis is not part of the definition of BAB that we or any other workers have adopted.

Another part of the reason that the GoM may not have previously been considered as a BAB (although Fillon [2007] first interpreted the GoM as a BAB, his model is flawed, both in geometry [west-dipping Atlantic subduction zone] and timing of opening [Early Cretaceous]) may be that the behavior of continental BABs is poorly understood. Behind-the-arc zones of extension and igneous activity on continents have variable manifestations and they show tectonic and magmatic styles that are distinct from those of intraoceanic BABs. Sometimes voluminous continental backarc igneous activity does not even produce a basin, as in the case of the Columbia River Flood Basalt province, where backarc extension–related igneous activity produced thick basalt flows but no basin (Smith, 1992).

A useful perspective comes from comparing the GoM–Border rift system to three other continental BABs: the modern Andaman Sea, the Miocene Sea of Japan, and the Cretaceous Black Sea (Fig. 10). The first two represent transtensional BAB systems, associated with a strong strike-slip component, similar to the tectonic setting in which the Jurassic GoM formed. All three analogues evolved with extension axes oriented at a high angle to the associated arc and convergent plate boundary. The Andaman Sea has spreading axes that are oriented approximately perpendicular to its convergent margin, a response to the increasing distance between the northward advancing Himalayan collision zone and the Indonesian arc. The Sea of Japan opened during Middle Miocene time by spreading along ridges that were oriented approximately parallel to the southwest Japan arc but perpendicular to the northeast Japan arc. It is not clear why intraoceanic BABs invariably have arc-parallel spreading axes whereas continental BABs do not, but the weaker nature of continental crust and more complex stress regimes may be responsible. Regardless, the orientations of the Andaman Sea, Sea of Japan, and Black Sea spreading axes do not preclude these from being considered as excellent examples of BAB, nor should the orientation of the GoM spreading axis.

CONCLUSIONS

The most compelling part of the GoM = BAB hypothesis is geometrical, i.e., that the GoM opened above an active subduction zone and was associated with an active magmatic arc. We follow long-accepted definitions of backarc and interarc basins as being extensional basins

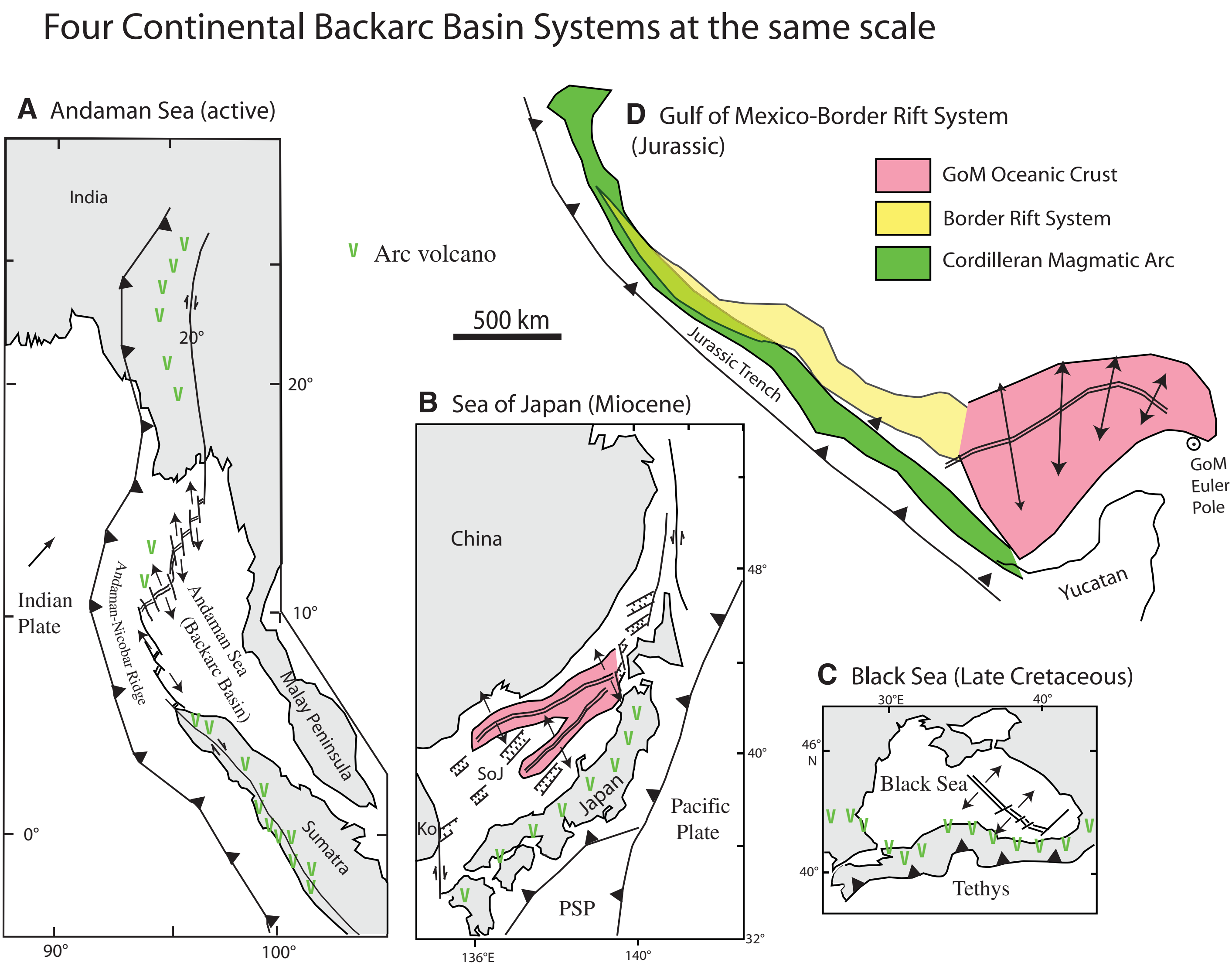

Figure 10. Comparison of the Gulf of Mexico (GoM) backarc basin (BAB) system (A) with two other examples of transtensional BABs, Andaman Sea (B) and Middle Miocene (ca. 20–15 Ma) Sea of Japan (C). Andaman Sea BAB system is simplified after Curray (2005) and Pal et al. (2007). Sea of Japan BAB system is modified after Jolivet et al. (1994). PSP—Philippine Sea Plate; Ko—Korea; SoJ—Sea of Japan.

above an active subduction zone and behind a magmatic arc, distinguished in that BABs have seafloor spreading whereas IABs are rifts without seafloor spreading. It is clear that the GoM began to form at the same time that Nazas arc igneous activity associated with an east-dipping subduction zone occurred in what is now Mexico, although this arc shut down ca. 150 Ma as the GoM continued to open. This is consistent with the behavior of BABs, for which associated magmatic arcs sometimes remain active and sometimes are extinguished. A BAB interpretation for the GoM explains why the GoM opened around a pole of rotation distinct from that of the central Atlantic. It helps us understand the intimate relationship between formation of the GoM and the Border rift system. The distribution of volcanic-rifted margins in the western part of the basin and nonvolcanic rifted margins is easily explained by the interpretation that the GoM is a backarc basin. The "GoM = BAB" hypothesis is useful because it explains why seafloor spreading was so short lived, 23 m.y. at most. Certainly there are important details to be resolved, including the extensional forces that were responsible. We stress that BAB formation can be a response to many different causes of upper plate extensional stress, so the likelihood that the GoM BAB opening was at least partly a response to Pangean sundering does not detract from the hypothesis. The GoM = BAB hypothesis focuses attention on the GoM as the juncture between evolving tectonic regimes of Cordilleran subduction and Tethyan extension during Jurassic time.

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