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Geochronology, Geochemistry, and Tectonic Setting of the Mesozoic Nazas Arc in North-Central Mexico, and its Continuation to Northern South America

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ABSTRACT

Volcanic, sedimentary, and granitic plutonic rocks that are part of the early Mesozoic Cordilleran continental magmatic arc are exposed in a belt from the southwestern United States to Guatemala. In the Mexican states of Chihuahua, Coahuila, Durango, Zacatecas, and San Luis Potosí, these rocks form a discontinuous southeast-trending belt across north-central Mexico. Whole-rock geochemical analyses of volcanic and intrusive rocks in north-central Mexico indicate a calc-alkaline suite formed in this continental volcanic arc along the convergent margin of western North America. Paleomagnetism, field relations, and isotopic ages ($^{40}Ar/^{39}Ar$, K-Ar, Rb-Sr, and U-Pb) of 73 volcanic and intrusive rocks document the Late Triassic–Middle Jurassic age of the arc. In the region, isotopic ages commonly are reset, apparently because of thermotectonic events during the ''Laramide'' orogeny that led to the development of the Sierra Madre Oriental fold and thrust belt and to deep burial of the arc rocks. Available evidence suggests that the arc underwent two main phases of subsidence. One phase of extensional subsidence created intra-arc basins and a peak of volcanism throughout the arc in the Early–Middle Jurassic. A second phase began in the Oxfordian, with subsidence and initial deposition of the Zuloaga and La Gloria Formations. Continued sedimentation during this phase led to accumulation of 5–7 km of strata above the arc, as Cretaceous seas transgressed westward over inland Mexico.

The similarities in age, depositional environment, clastic composition, magma types, and geochemical affinity and, more importantly, the tectonic settings that gave rise to the Nazas Formation in Mexico and La Quinta and Girón Formations in Venezuela and Colombia suggest that these two volcanic-sedimentary sequences, now hundred of kilometers apart, were once part of the Late Triassic–Jurassic continental magmatic arc. This arc extended from Alaska to South America and evolved during simultaneous subduction along the western margin of Pangea, rifting in the Caribbean–Gulf of Mexico region, and associated large-scale transpressive activity.

INTRODUCTION

A discontinuous, northwest-southeast-trending belt of volcanic rocks, volcanic-sedimentary sequences, and granitic plutons that range in age from Middle Triassic to Middle Jurassic constitute the Nazas magmatic arc across Mexico (Figure 1). This arc, which extends from Sonora and Baja California into Chiapas and Guatemala, is the southward continuation of a Jurassic continental magmatic arc in the western United States (Damon et al., 1981). In this study, delineating the Nazas magmatic arc in northern and central Mexico was based essentially on surface stratigraphy and geochronology (Appendix 1 and Tables 1–6) of volcanic and volcanic-sedimentary sequences in Durango, Chihuahua, Zacatecas, Coahuila, and San Luis Potosí states (Figure 1). A limited number of Triassic and Jurassic isotopic ages on granitic plutons and volcanic rocks encountered by Pemex wells also were utilized.

We also integrate available published geochemical results with our geochemical analysis and interpretation of magma genesis and tectonic setting. In this study, we use the name Nazas magmatic arc for the intra-arc volcanic-sedimentary strata and volcanic rocks that constitute the upper volcanic part of the arc, as well as the granitic plutons that represent the roots of this continental arc in Mexico.

Although numerous field observations about the Nazas arc have been reported, only a few regionally integrated studies on the arc exist (de Cserna, 1956, 1970; Damon et al., 1975; López-Infanzón, 1986; Grajales et al., 1992; Jones et al., 1995; Bartolini, 1998). In an effort to understand the nature and evolution of the Mesozoic magmatic arc, and to attempt to constrain its age and configuration, we mapped 1000 km^2 (Appendix 2) of the largest arc exposures in Sierra de San Julian, Zacatecas; integrated more than 30 measured stratigraphic sections (key sections in Appendix 3); and incorporated and evaluated all the dates from plutonic and volcanic rocks within the Nazas magmatic arc that have been published during the past 35 years (Tables 1–6).

The main goals of this investigation are: (1) to discuss the validity of the geochronologic data obtained from the Nazas magmatic arc, (2) to identify the volcanic suites and to interpret magma genesis based on whole-rock geochemistry, (3) to constrain the tectonic and magmatic framework for the Triassic-Jurassic, and (4) to discuss the development of extensional intra-arc basins and subsidence mechanisms in the arc.

THE AGE OF THE MESOZOIC MAGMATIC ARC IN WESTERN NORTH AMERICA

A major reorganization of tectonic plates in the Early Mesozoic led to the development of a convergent margin along western North America. The subduction of oceanic lithosphere beneath the North American plate in the Late Triassic gave rise to continental arc magmatism from Alaska to Mexico (Coney, 1979). The existence of the Mesozoic Cordilleran volcanic arc has been documented for more than 25 years by hundreds of geoscientists. Remnants of this arc have been studied along North America and northernmost South America as discussed in next paragraphs.

The Aishihik batholith in Alaska is exposed in an area of more than 40,000 km^2, and is one of the larger batholiths in the North American Cordillera. It developed in response to subduction during the development of Jurassic magmatic arcs (Johnston and Erdmer, 1995). One Early Jurassic U-Pb age of 186.0 ± 7.8 Ma is reported from this batholith (Johnston and Erdmer, 1995).

In southwest British Columbia, Canada, Early and Middle Jurassic shale and siltstone, volcaniclastic and volcanic rocks, monzonite, syenite, and minor granite yield Nd-Sr isotope values that support continental arc environments (Ghosh and Lambert, 1995). U-Pb and K-Ar ages of granitic and volcanic rocks from

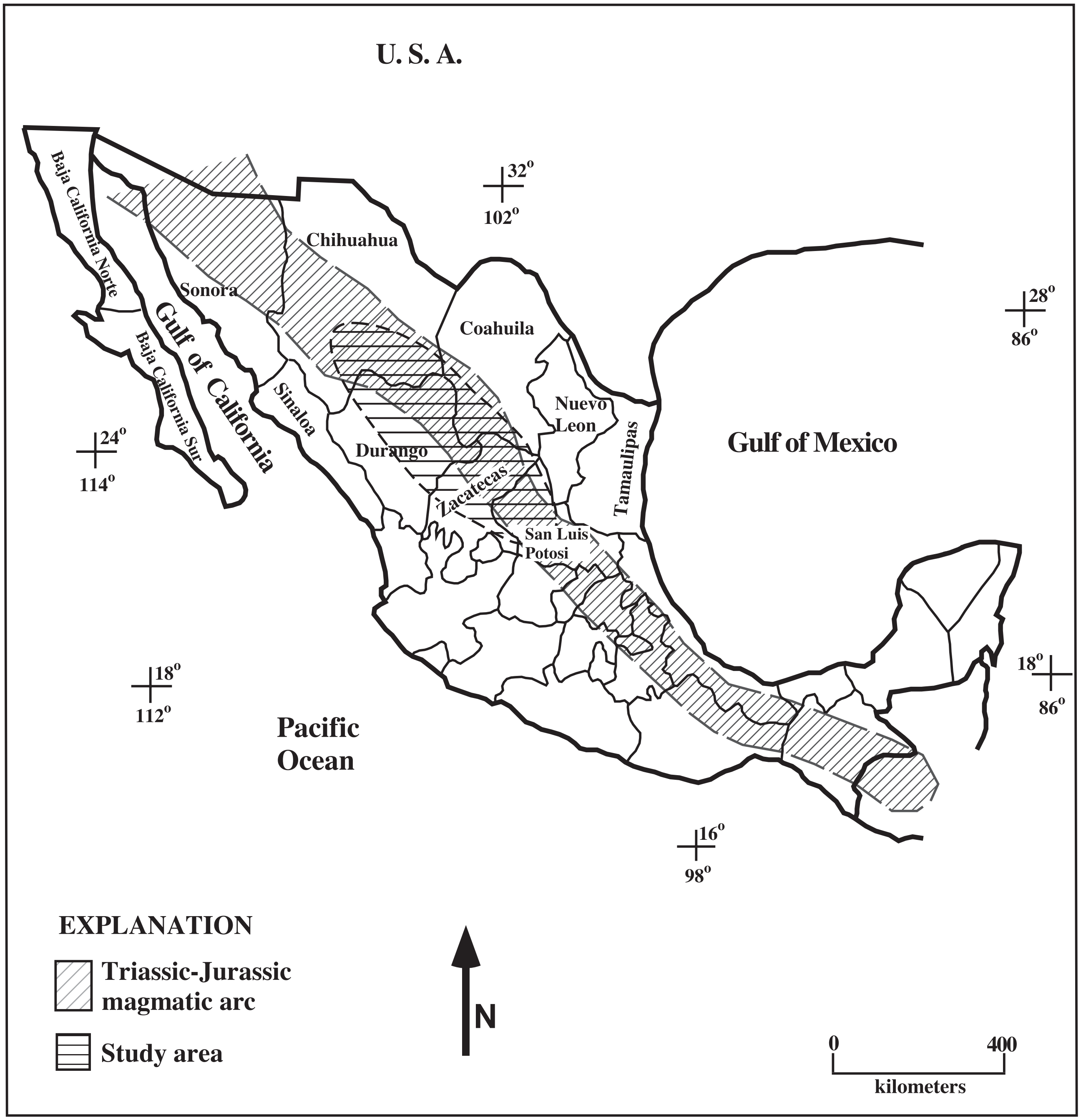

Figure 1. Approximate trend and configuration of the Mesozoic Nazas arc in Mexico and location of the study area.

the southern Coast Belt of British Columbia range from 145 to 187 Ma (Friedman and Armstrong, 1995). Late Triassic plutonic and volcanic suites in western Canada and western United States are high-potassium and shoshonitic rocks (Mortimer, 1986). Thorkelson et al. (1995) documented Early Jurassic volcanism along the northern margin of the Hazelton trough, northern British Columbia.

Early Mesozoic igneous rocks of the western United States are widely accepted to be the products of subduction along the western margin of the North American plate. Arc volcanism was nearly continuous during the Late Triassic to Jurassic, with magmas becoming more alkalic eastward (Lipman, 1992). K-Ar ages of granitic rocks in Nevada and Utah range from Late Triassic to Early Jurassic. Jurassic igneous activity reached a peak before 150 Ma ago (Armstrong and Suppe, 1973).

Palmer (1983) reported the widespread distribution of Late Triassic and Early Jurassic–age (~190–230 Ma) igneous rocks along the western Cordillera. Middle to Late Jurassic plutonism in the central Mojave desert (Miller and Glazner, 1995) consists of

Table 1. $^{40}Ar/^{39}Ar$ **ages from selected volcanic rocks of the Nazas magmatic arc (Bartolini, 1998; Appendix 1).**

Sample	*Material*	*Unit*	*Locality*	*Age (Ma)*
Rhyolite (CC-R)	Plagioclase	Nazas Formation	Cerritos Colorados, Durango	98.6 ± 4.1 (I)
Rhyolite dike (CC-D)	Plagioclase	Nazas Formation	Cerritos Colorados, Durango	93.0 ± 9.0 (W)
Rhyolite (VJ-1)	Sanidine and plagioclase	Nazas Formation	Cerritos Colorados, Durango	59.3 ± 1.6 (W)
Rhyolite (SMO-R)	Sanidine	Nazas Formation	Santa Maria del Oro, Durango	33.8 ± 0.2 (W)
Basalt (LB-B1)	Whole rock	Nazas Formation	Sierra de Salinas, Zacatecas	82.9 ± 0.6 (S)
Rhyolite (SR-R1)	Sanidine	Nazas Formation	Sierra de Ramírez, Durango	93.9 ± 0.6 (W)
Rhyolite (CR-C1)	Plagioclase	Caopas Formation	Sierra de San Julian, Zacatecas	109.7 ± 1.1 (S)
Rhyolite (CR-C2)	Hornblende	Caopas Formation	Sierra de San Julian, Zacatecas	99.4 ± 0.7 (W)
Rhyolite (CR-C3)	Sanidine	Caopas Formation	Sierra de San Julian, Zacatecas	74.8 ± 0.5 (W)
Andesite (CR-R4)	Plagioclase	Rodeo Formation	Sierra de San Julian, Zacatecas	145.5 ± 2.5 (I)
Rhyolite (CC-V)	Plagioclase	Nazas Formation	Cerritos Colorados, Durango	62.6 ± 5.2 (I)
Rhyolite (ST-C2)	Feldspar concentrate	Nazas Formation	Sierra de Teyra, Zacatecas	96.0 ± 3.0 (W)
Rhyolite (ST-N16)	Whole rock	Nazas Formation	Sierra de Teyra, Zacatecas	75.4 ± 0.5 (S)
Rhyolite (VJ-R1)	Plagioclase	Nazas Formation	Villa Juárez, Durango	195.3 ± 5.5 (I)
Andesite (CR-N1)	Plagioclase	Nazas Formation	Sierra de San Julian, Zacatecas	72.7 ± 0.6 (W)

W = Weighted mean I = Isochron S = Age spectrum.

calc-alkaline gabbro to quartz monzonite; granite is rare. Jurassic continental magmatism in the central Mojave Desert, California (Schermer and Busby, 1994), is represented by a Middle Jurassic batholith and coeval andesite, rhyolitic ignimbrite, silicic tuff, sedimentary rocks, and caldera-forming rhyolitic and dacitic ignimbrite. The Late Jurassic is characterized by vent-proximal rhyolite lavas, felsic and mafic vent complexes, mafic dikes, and felsic intrusions. In the western Mojave Desert, Gerber et al. (1995) report a 160 Ma U-Pb date for a pluton and a 145 Ma U-Pb age for dikes that intrude the pluton.

A Middle Triassic to Middle Jurassic volcanic-plutonic belt (Kistler, 1978) extends from California through Baja California and Sonora, Mexico, and a belt of alkalic plutons in California is known to be restricted to the early Mesozoic between 170 and 230 Ma (Miller, 1978). The extensional nature of the arc

Table 2. **K-Ar ages of volcanic and intrusive rocks from the Nazas magmatic arc (or equivalent).**

Sample	*Material*	*Unit*	*Reference*	*Locality*	*Age (Ma)*
Rhyolite	Whole Rock	Aserradero Rhyolite	Bartolini (1998)	Caballeros Canyon, Tamaulipas	50 ± 1.3
Rhyolite	Whole Rock	Nazas Formation	Bartolini (1998)	Sierra de Candelaria, Zacatecas	75.3 ± 1.9
Rhyolite	Whole Rock	Und. Red Beds	Bartolini (1998)	Aramberri, Nuevo León	70.7 ± 1.8
Rhyolite	Whole Rock	La Boca Formation	Bartolini (1998)	Huizachal Valley, Tamaulipas	52.1 ± 1.4
Rhyolite	Whole Rock	Und. Red Beds	Bartolini (1998)	Miquihuana, Tamaulipas	57.8 ± 1.5
Andesite dike	Whole Rock	La Boca Formation	Bartolini (1998)	San Marcos, Nuevo León	104 ± 3.0
Rhyolite	Whole Rock	Nazas Formation	Bartolini (1998)	Sierra de San Julian, Zacatecas	72.7 ± 0.6
Basalt	Whole Rock	Nazas Formation	Bartolini (1998)	Sierra de Jimulco, Coahuila	69.9 ± 2.4
Rhyolite	Whole Rock	Nazas Formation	Bartolini (1998)	Sierra de Candelaria, Zacatecas	59.2 ± 1.6
Rhyolite	Whole Rock	Nazas Formation	Bartolini (1998)	Sierra de Ramírez, Durango	99.3 ± 2.6
Rhyolite	Whole Rock	Nazas Formation	Damon (written comm.,1997)	Gómez Palacio, Durango	69 ± 1.0
Rhyolite	Whole Rock	Caopas Formation	Damon (written comm.,1997)	Sierra de San Julian, Zacatecas	56.4 ± 1.2
Rhyolite	Whole Rock	Caopas Formation	Damon (written comm.,1997)	Sierra de San Julian, Zacatecas	69.9 ± 2.4
Monzonite	Hornblende	Unnamed	Damon (written comm.,1997)	Hidalgo del Parral, Chihuahua	197 ± 6.93

Table 3. Rb-Sr ages of volcanic rocks from the Nazas magmatic arc (Geochron Laboratory).

Sample	*Locality*	*Material*	*Rb (ppm)*	*Sr (ppm)*	$^{87}Rb/^{86}Sr$ *(atomic)*	$^{87}Sr/^{86}Sr$ *(+/- 2 S.D.)*	*Age (Ma)*
Rhyolite	Sierra de Candelaria,	Whole rock	17.6	44.12	1.1519	0.717250	~880
SC-R7	Zacatecas	Feldspar	5.2	32.7	0.4562	0.708437	
Rhyolite	Sierra de Jimulco,	Whole rock	29.9	329.09	0.2628	0.707535	~400
SJC-B	Coahuila	Feldspar	10.3	135.32	0.2206	0.707781	
Rhyolite	Sierra de Ramírez,	Whole rock	40.9	459.2	0.2574	0.707670	~350
SR-R2	Durango	Feldspar	8.1	105.32	0.2222	0.707849	
Rhyolite	Sierra de Candelaria,	Whole rock	96.3	66.9	4.1666	0.713797	~16
SC-R1	Zacatecas	Feldspar	11.2	73.04	0.4431	0.714675	

The Sr isotope analyses are normalized to $^{86}Sr/^{88}Sr$ = 0.11940.
Analyses of NBS 987 averaged 0.710240 (10) during this period.
Errors on $^{87}Sr/^{86}Sr$ are given as 2 sigma in the last two digits.
Errors on Rb and Sr concentrations are approximately +/− 0.5%.
Sub-specimens approximately 3 × 3 × 3 cm were selected from each field sample. They were crushed and homogenized to −80 mesh whole-rock powders prior to analysis.
Feldspar concentrates were prepared for each sample and analyzed to provide a second point and allow an isochron to be defined for each rock.

in western Nevada, California, and Arizona was documented by Busby-Spera (1988) and Burchfiel et al. (1992) and is described as constituted of granite-granodiorite, alkaline and calc-alkaline, and volcaniclastic rocks. In 1992, Saleeby and Busby-Spera suggested that this continental arc was well-established by the Late Triassic (230–208 Ma). Late Triassic to Early Jurassic (208–187 Ma) volcanism, intra-arc sedimentation, and plutonism are recorded along the entire continental arc. In the Middle Jurassic (187–163 Ma), there was a decrease in volcanic activity, and Late Jurassic (162–144 Ma) magmatism was characterized by local activity rather than a regionally coherent belt along the plate edge. In west-central Nevada, Dilles and Wright (1988) recognized two periods of magmatic activity in the Yerington district. The first magmatic pulse was in the Late Triassic (U-Pb 232 Ma date) and included diorite and possibly comagmatic andesite to rhyolite. The second pulse occurred in the Middle Jurassic (165–169 Ma) and produced as much as 4 km of volcanic and volcaniclastic strata and coeval batholiths. To the south, in Arizona, Krebs and Ruiz (1987) presented major and trace-element geochemistry of welded rhyolite ash-flow tuffs, basalts, trachyandesite flows, and quartz monzonite plutons, which are part of the Jurassic magmatic arc. Also, U-Th-Pb ages of zircons from volcanic and plutonic rocks of the volcanic arc in southeastern Arizona yield ages that range from Late Triassic to Middle Jurassic (Asmeron et al., 1990), whereas Jurassic caldera systems in southern Arizona consist of bimodal volcanic suites (Lipman and Hagstrum, 1992). Seemingly, Riggs and Busby-Spera (1990) describe a 4.5-km-thick sequence of Early Jurassic volcanic, subvolcanic, and subordinate sedimentary rocks that were formed in a multivent volcanic complex within a subsiding arc graben depression in the volcanic arc in southern Arizona. Regionally, the volcanic arc in southern California and Arizona and northern Sonora is characterized by pyroclastic rocks, volcanic flows, and local sedimentary rocks of Early to Late Jurassic age intruded by calc-alkaline granitoids of the late Middle to early Late Jurassic (Tosdal et al., 1989).

THE AGE OF THE VOLCANIC ARC IN NORTHWEST MEXICO

K-Ar ages of intrusive and volcanic rocks (Damon et al., 1991) in northwestern Mexico, particularly in the states of Chihuahua and Sonora, range from Late Triassic to Late Jurassic. In Baja California, Mexico, Gastil et al. (1978) documented the distribution of an andesite volcanic-plutonic belt of early Middle Jurassic age that is part of this continental arc. The existence of a Jurassic arc in northwestern Sonora and Baja California also has been documented through the study of volcanogenic and granitic plutonic rocks (Anderson and Silver, 1978; Anderson and Roldán-Quintana, 1979; Silver and Anderson, 1974; Corona, 1979; Corona and Anderson, 1981; Silver and Anderson, 1983; Leveille and Frost, 1984; Tosdal et al., 1989).

The age of the Mesozoic Nazas magmatic arc in north-central Mexico has been established by direct and indirect methods. Methods used include paleomagnetism, field geology, and isotope age studies. These results are summarized in the following sections.

Table 4. Published isotopic ages from volcanic rocks of the Nazas magmatic arc.

Sample	*Method*	*Reference*	*Unit*	*Locality*	*Age (Ma)*
Andesite	K-Ar	Araujo and Arenas (1986)	Nazas Formation	Santa María del Oro, Durango	118 ± 9
Tuff	K-Ar	López-Infanzón (1986)	Nazas Formation	Villa Juárez, Durango	112 ± 6.0
Tuff	K-Ar	López-Infanzón (1986)	Nazas Formation	Villa Juárez, Durango	110 ± 6.0
Tuff	K-Ar	López-Infanzón (1986)	Nazas Formation	Villa Juárez, Durango	80 ± 4.0
Latite	K-Ar	López-Infanzón (1986)	Nazas Formation	Villa Juárez, Durango	72 ± 4.0
Latite	K-Ar	López-Infanzón (1986)	Nazas Formation	Villa Juárez, Durango	64 ± 3.2
Rhyolite	Rb-Sr	Fries and Rincon-Orta (1965)	Caopas Formation	Sierra de San Julian, Zacatecas	156 ± 40
Rhyolite	Rb-Sr	Fries and Rincon-Orta (1965)	Caopas Formation	Sierra de San Julian, Zacatecas	195 ± 20
Rhyolite	Rb-Sr	Fries and Rincon-Orta (1965)	Caopas Formation	Sierra de San Julian, Zacatecas	200 ± 60
Rhyolite	Rb-Sr	Fries and Rincon-Orta (1965)	Caopas Formation	Sierra de San Julian, Zacatecas	220 ± 30
Rhyolite	Pb-α	Pantoja-Alor (1972)	Nazas Formation	Cerritos Colorados, Durango	230 ± 20
Schist	K-Ar	Denison et al. (1971)	Rodeo Formation	Sierra de San Julian, Zacatecas	55 ± 5.0
Andesite	K-Ar	López-Infanzón (1986)	Rodeo Formation	Sierra de San Julian, Zacatecas	183 ± 8.0
Rhyolite	K-Ar	López-Infanzón (1986)	Nazas Formation	Sierra de Jimulco, Coahuila	107 ± 5.0
Diabase	K-Ar	López-Infanzón (1986)	Nazas Formation	Sierra de Jimulco, Coahuila	103 ± 5.0
Basalt	K-Ar	López-Infanzón (1986)	Nazas Formation	Sierra de Jimulco, Coahuila	32 ± 20
Rhyolite	Rb-Sr	Denison et al. (1969)	Caopas Formation	Sierra de San Julian, Zacatecas	141 ± 40
Rhyolite	Rb-Sr	Halpern et al. (1974)	Caopas Formation	Sierra de San Julian, Zacatecas	225 ± 0
Rhyolite	Rb-Sr	Halpern et al. (1974)	Caopas Formation	Sierra de San Julian, Zacatecas	125 ± 0
Rhyolite	U-Pb	Jones et al. (1995)	Caopas Formation	Sierra de San Julian, Zacatecas	158 ± 4.0
Rhyolite	K-Ar	López-Infanzón (1986)	Caopas Formation	Sierra de San Julian, Zacatecas	78 ± 4.0
Rhyolite	K-Ar	López-Infanzón (1986)	Nazas Formation	Sierra de Candelaria, Zacatecas	73 ± 4.0
Andesite	K-Ar	Grajales et al. (1992)	Nazas Formation	Santa María del Oro, Durango	65 ± 3.0
Basaltic dike	K-Ar	Grajales et al. (1992)	Nazas Formation	Santa María del Oro, Durango	132 ± 3.0

PALEOMAGNETISM

Nairn (1976) carried out paleomagnetic studies of the Nazas Formation at the Cerritos Colorados, Durango, in northern Mexico. He determined North American pole positions that provided indirect evidence of possibly Late Triassic but probably Jurassic ages for the Nazas arc rocks in this region.

Field Relationships

In the states of San Luis Potosí and Zacatecas in central Mexico, Nazas arc rocks are underlain by strata of the Zacatecas Formation, which have been dated as Middle–Late Triassic in age (Burckhardt and Scalia, 1905; Burckhardt, 1930; Cantú-Chapa, 1969; Gallo et al., 1993) and are unconformably overlain by Oxfordian marine strata of the Zuloaga Limestone. This

Table 5. Isotopic ages of exposed intrusive rocks from the Nazas magmatic arc.

Sample	*Method*	*Material*	*Reference*	*Locality*	*Age (Ma)*
Granodiorite	K-Ar	Biotite	Denison et al. (1969)	Valle de Acatita–Las Delicias, Coahuila	204 ± 4.0
Granodiorite	K-Ar	Hornblende	Denison et al. (1969)	Potrero La Mula, Coahuila	206 ± 4.0
Granodiorite	K-Ar	Whole rock	Denison et al. (1969)	Valle de Acatita–Las Delicias, Coahuila	203 ± 4.0
Diorite	K-Ar	Hornblende	Grajales et al. (1992)	El Cuarenta, San Bernardo, Durango	154 ± 3.5
Granite	K-Ar	K-feldspar	Grajales et al. (1992)	El Cuarenta, San Bernardo, Durango	115 ± 2.6
Basaltic dike	K-Ar	Whole rock	Grajales et al. (1992)	Santa María del Oro, Durango	132 ± 3.0
Monzonite	K-Ar	Hornblende	Damon et al. (1981)	Santa Barbara Mine, Parral, Chihuahua	198 ± 7.0
Diorite	K-Ar	Hornblende	Damon et al. (1981)	El Cuarenta, San Bernardo, Durango	155 ± 3.0
Diorite	K-Ar	Hornblende	Damon et al. (1981)	El Cuarenta, San Bernardo, Durango	149 ± 3.0
Granodiorite	Rb-Sr	Whole rock	Jones et al. (1984)	Potrero La Mula, Coahuila	207 ± 10
Rhyolite	U-Pb	Zircon	Jones et al. (1995)	Sierra de San Julian, Zacatecas	158 ± 40
Rhyolite	K-Ar	Whole rock	López-Infanzón (1986)	Sierra de San Julian, Zacatecas	78 ± 4.0
Rhyolite	K-Ar	Plagioclase	López-Infanzón (1986)	Sierra de Candelaria, Zacatecas	73 ± 4.0
Andesite	K-Ar	Whole rock	Grajales et al. (1992)	Santa María del Oro, Durango	65 ± 3.0
Basaltic dike	K-Ar	Whole rock	Grajales et al. (1992)	Santa María del Oro, Durango	132 ± 3.0

field relationship brackets the age of the Nazas as latest Triassic–Middle Jurassic in these localities. In northern Durango, the arc rocks are younger than underlying Permian schist (Table 2) but older than overlying Lower Jurassic strata (Aranda et al., 1988). In Coahuila, Nazas volcanic rocks are younger than underlying Permian–Early Triassic granites (López-Infanzón, 1986; Table 4). At Sierra de Catorce, San Luis Potosí, Nazas-equivalent volcanic rocks (Barboza-Gudiño et al., 1997) are younger than underlying Late Mississippian to Permian turbidites (Bacon, 1978; Reaser, 1989; Franco-Rubio, 1997) but older than the overlying Middle Jurassic La Joya Formation. In northern Durango and southwestern Coahuila, the Nazas rocks are unconformably overlain by Oxfordian strata of La Gloria Formation, and in southeastern Coahuila, Zacatecas, and San Luis Potosí, Oxfordian limestones of the Zuloaga Formation rest unconformably on the arc rocks.

ISOTOPIC DATA AND THE AGE OF THE NAZAS ARC SEQUENCES

$^{40}Ar/^{39}Ar$ Method

The ages of fifteen volcanic rock samples from the Nazas arc were dated by the $^{40}Ar/^{39}Ar$ method using both step heating and laser fusion approaches (Table 1). Analytical methods and $^{40}Ar/^{39}Ar$ ages of volcanic rocks are summarized in Appendix 1.

Because the stratigraphic age of Nazas volcanic rocks is Late Triassic to Middle Jurassic, all of the $^{40}Ar/^{39}Ar$ dates obtained in this study, with the exception of sample VJ-R1 (~195 Ma), must have been reset after initial crystallization. Scatter in individual single-crystal analyses may represent the effects of partial resetting of the K/Ar isotopic system. Most of the $^{40}Ar/^{39}Ar$ ages obtained fall into the range of ~70–120 Ma. This could reflect either partial resetting during Laramide uplift, during slow cooling, and/or during burial (as much as 10 km?) beneath the Zuloaga limestone and younger strata deposited during the Cretaceous, when much of Mexico was covered by shallow seas. The cluster of ages in the 90–120 Ma range may indicate that resetting of isotopic systems occurred by this time.

K-Ar Method

The ages of volcanic rocks from the Nazas Formation also were measured, using both mineral separates and whole-rock samples (Geochron Laboratory). Mineral separates included biotite, muscovite/sericite,

Table 6. Isotopic ages of intrusive and volcanic rocks from the Nazas magmatic cut by Pemex wells.

Well/Interval	*Sample*	*Method*	*Reference*	*Locality*	*Age (Ma)*
Parral-1N4 (5000–5007-m interval)	Metarhyolite	K-Ar	Grajales et al. (1992)	State of Durango	60 ± 5.0
Parral-1N6 (5073–5076-m interval)	Metarhyolite	K-Ar	Grajales et al. (1992)	State of Durango	70 ± 5.0
Tepehuanes-1N13 (4685–4687-m interval)	Latite	K-Ar	Grajales et al. (1992)	State of Coahuila	58 ± 5.0
Tarahumara-1N2 (2868–2870-m interval)	Latite	K-Ar	Grajales et al. (1992)	State of Coahuila	83 ± 7.0
Tarahumara-1N3 (2990–2998-m interval)	Latite	K-Ar	Grajales et al. (1992)	State of Coahuila	98 ± 8.0
Mayrán-1 (3039–3041-m interval)	Rhyolite	Rb-Sr	Grajales et al. (1992)	State of Coahuila	222 ± 20*
Paila-1AN9 (2418–2419-m interval)	Ignimbrite	K-Ar	Grajales et al. (1992)	State of Coahuila	80 ± 3.2
Ceballos-1 (5762–5930 m (no detail))	Volcanic Rocks	K-Ar	Eguiluz and Campa (1982)	State of Chihuahua	20 ± 0
Carbón-1 (3365 m)	Schist?	K-Ar	Eguiluz (2001)	State of Coahuila	215 ± 5.0
Concordia-1 (4112–4116-m interval)	Phyllite	K-Ar	Eguiluz (2001)	State of Coahuila	190 ± 7.0
Pecten-1 (2216–2225-m interval)	Granite	K-Ar	Eguiluz (2001)	State of Coahuila	160 ± 6.0
Menchaca-1A (2755–2757-m interval)	Granite	K-Ar	Eguiluz (2001)	State of Coahuila	164 ± 7.0
Linares-1 (2628–2629.5-m interval)	Granodiorite	K-Ar	Eguiluz (2001)	State of Nuevo León	234 ± 8.0
Benemérito-1 (2580–2588-m interval)	Granodiorite	K-Ar	Eguiluz (2001)	State of Nuevo León	138 ± 9.0
Oro-1 (3833–3835-m interval)	Tonalite	K-Ar	Eguiluz (2001)	State of Coahuila	230 ± 11

**Confidential report IMP-Pemex (in Grajales et al., 1992).*

and hornblende (Table 2). If reheating events are suspected, minerals with higher closure temperatures are less likely to be reset. Apparently, all of our plagioclase concentrates or whole-rock ages were reset ages. K-Ar and $^{40}Ar/^{39}Ar$ ages of volcanic rocks from the Nazas Formation all yielded ages that are younger than their stratigraphic age (Tables 2 and 4). In addition, K-Ar and Rb-Sr (Tables 3 and 6) ages of volcanic rocks from borehole samples display a wide range of ages. Selective resetting of minerals with low blocking temperature apparently is quite common in rocks of the Mesozoic arc (M. Grajales, personal communication, 2000).

Published ages obtained using the K-Ar method for granitic samples from Chihuahua, Durango (Damon, et al., 1981; Grajales et al., 1992), and Coahuila (Denison et al., 1969; Jones et al., 1984) are consistently Late Triassic to Jurassic (Table 5); however, our samples that range in age from 90 to 120 Ma may have been partially reset, as these ages are younger than the age of the magmatic arc but older than the commonly accepted date for Laramide orogeny in Mexico.

U-Pb Method

Although U-Pb probably is the most reliable method for determining the crystallization age of igneous rocks affected by subsequent thermal events, it is premature to assess its specific accuracy for dating the Mesozoic continental arc in Mexico. This is because available U-Pb isotopic age determinations are restricted to a single sample (Table 4) from the Caopas Rhyolite in the Sierra de San Julian, northern Zacatecas, that yielded an age of 158 Ma (Jones et al., 1995). This date coincides with the stratigraphic age of the La Casita Formation (Kimmeridgian) (Imlay, 1936), and is clearly younger than the age range of the arc.

Rb-Sr Method

The least reliable ages that we obtained were those using the Rb-Sr method (Table 3). However, previously reported Rb-Sr ages, which range from 125 to 225 Ma, do appear reliable (Fries and Rincon-Orta, 1965; Denison et al., 1969; Halpern et al., 1974).

The only mineral that was separable from our volcanic rock samples was feldspar, which usually is an appropriate mineral because it normally has a considerably higher Rb/Sr than the total rock. The whole-rock and feldspar concentrates were analyzed separately to provide two points that define the isochron for each rock. Unfortunately, for our samples, the feldspar concentrates had lower Rb content than the whole rocks. This we attribute to feldspar albitization that probably occurred during a tectonic or a hydrothermal event. Albitization can remove original Rb, but not necessarily original Sr, from feldspar crystals. Our calculated "isochrons" all exhibit this problem (Table 3) (Krueger, unpublished report, 1997).

Two subsequent tectonothermal events could have led to albitization: (1) the Late Cretaceous–Tertiary Laramide orogeny severely affected the region where our samples were collected, and (2) the west side of the Nazas arc was affected by the Early–Middle Tertiary development of the Sierra Madre Occidental volcanic arc. Because hydrothermal activity and metasomatism were intimately associated with these events, recrystallization may have occurred after initial crystallization of our volcanic rock samples.

A basic premise of the Rb-Sr method is that the system is closed. That is, for the method to work, neither Rb or Sr can be added or taken away after crystallization. Thus, the low rubidium and potassium values are caused by surface or near-surface alteration, and the resulting apparent ages are too young.

SUMMARY

Most of the Early Mesozoic igneous rocks dated during the course of this investigation yielded apparently reset ages, not crystallization ages. This is in accord with previously published dates, which indicate that isotope systems were reset several times since the Middle Jurassic after crystallization of the arc rocks. Thus, all of these isotopic ages fall into three major groups:

1) Ages that range from 46 to 80 Ma. These may record the thermal effects of the Late Cretaceous–Tertiary Laramide orogeny.
2) Ages that range from 90 to 120 Ma. These are difficult to interpret because they postdate the stratigraphic age of the arc and predate the accepted age for the Laramide orogeny in Mexico. They span the early Cretaceous, a time when most of northern and central Mexico was covered by shallow seas. We interpret these ages as being partially reset.
3) Ages that range from 165 to 230 Ma. These ages date crystallization of the Nazas plutonic and volcanic rocks.
4) Intrusive rocks whose ages range from 145 to 160 Ma can be interpreted as representing partially reset dates.

GEOCHEMISTRY

A total of 45 volcanic rock samples from the Nazas arc were analyzed for major and trace elements (Table 7). With the exception of sample CC-D, which is a dike sample collected at the Cerritos Colorados, Durango, all samples came from volcanic flows.

In Table 7, major elements are listed in weight % and trace elements in ppm. All chemical analyses are included to provide not only ideal results, but also to illustrate the common problems in studying these types of volcanic suites. Several samples have loss-on-ignition values that are greater than 5%. This indicates that the samples were not completely "fresh," as expected.

Based on our data and available geochemical data (Fries and Rincón-Orta, 1965; López-Infanzón, 1986; Grajales et al., 1992; Jones et al., 1995), the volcanic rocks of the Nazas magmatic arc are a typical calc-alkaline suite, with a wide silica range from 35 to 80%. Rhyolites normally range between 70–77% in silica content. Rhyolite samples with silica values higher than 77% probably are silicified. Some of the volcanic samples show a relatively high concentration of potassium, ranging from 7 to 8%. TiO_2 and Al_2O_3 values are quite constant, probably because these major elements are immobile (Winchester and Floyd, 1977). Rb content is consistently low, but it is variable with respect to Sr.

The most abundant volcanic rock types in the Nazas Formation are rhyolite, andesite, and dacite (Figure 2). Some minor alkaline rocks include trachyte, trachyandesite, and rare basalt. The volcanic suites in northern Durango (e.g., Cerritos Colorados and Villa Juarez) consist essentially of silicic volcanics (rhyolite and rhyolitic ignimbrite); the rocks in Zacatecas and

Table 7. Whole rock geochemistry of volcanic rocks within the Nazas magmatic arc in Coahuila, Zacatecas, San Luis Potosí, and Durango.

Sample	*CC-D*	*CC-V*	*CC-V1*	*CC-R*	*CC-R1*	*CC-R2*	*VJ-R1*	*VJ-R2*	*VJ-R3*	*VJ-R4*	*VJ-R5*	*VJ-I*	*SC-R1*	*SC-R2*	*SC-R3*	*SC-R4*	*SC-R5*
(wt. %)																	
SiO_2	75.6	76.4	69.6	75.2	78.6	77.1	79.7	72.4	77.7	73.5	75.0	74.7	76.6	41.9	72.2	68.0	59.2
TiO_2	0.132	0.164	0.362	0.182	0.166	0.159	0.156	0.208	0.127	0.198	0.148	0.162	0.125	0.485	0.374	0.417	0.629
Al_2O_3	12.7	12.1	12.7	12.4	11.5	11.6	9.85	12.8	10.6	12.0	12.4	12.2	11.8	10.5	12.0	11.8	12.3
Fe_2O_3	2.29	2.25	3.37	2.68	1.71	2.54	2.71	2.89	2.54	3.03	2.14	2.09	1.92	3.59	3.41	3.42	4.89
MgO	0.05	0.04	0.37	0.04	0.05	0.04	0.09	0.1	0.05	<.01	<.01	0.04	0.1	1.23	2.1	1.58	1.37
MnO	0.03	<0.01	0.03	<0.01	<0.01	0.03	0.02	0.01	<0.01	<.01	<.01	<0.01	<.01	0.47	0.06	0.08	0.11
CaO	0.5	5.52	1.16	0.27	0.13	0.13	0.22	0.81	0.1	0.63	0.18	0.1	0.32	20.2	1.12	4.7	7.9
Na_2O	4.54	5.52	1.83	5.37	4.08	2.04	2.76	5.04	0.4	4.84	3.91	4.3	3.1	3.0	3.65	2.69	1.76
K_2O	3.74	2.2	7.68	2.76	3.62	6.01	4.1	3.5	7.97	3.44	5.01	4.44	5.06	2.03	1.36	2.21	3.67
P_2O_5	0.02	0.04	0.05	0.03	0.03	0.02	0.03	0.04	0.02	0.03	0.02	0.02	<.01	0.29	0.03	0.06	0.05
Cr_2O_3	<0.01	0.01	<0.01	0.02	0.02	0.02	0.03	0.01	0.03	0.04	0.04	0.01	0.05	<.01	<.01	0.02	<.01
LOI	0.35	0.4	1.5	0.3	0.2	0.3	0.25	1.0	0.2	1.2	0.75	0.15	1.0	16.6	2.35	5.2	8.15
TOTAL	100	99.7	98.9	99.4	100.2	99.4	100.1	98.9	100	99	99.9	98.4	100.2	100.4	98.7	100.3	100.2
(ppm)																	
Rb	80	34	189	43	65	116	66	62	142	57	100	76	78	60	53	85	137
Sr	45	144	72	71	60	70	52	68	51	52	73	67	80	229	122	124	127
Y	28	35	34	31	27	78	22	76	32	34	54	38	37	39	41	41	38
Zr	161	189	254	207	182	406	228	198	355	222	202	155	225	161	161	217	204
Nb	15	12	13	10	12	29	11	16	33	11	14	16	18	9	12	12	11
Ba	477	2330	1680	532	456	711	849	649	2050	773	2080	1180	871	364	276	497	687

Sample	*CR-C1*	*CR-C2*	*CR-C3*	*CR-C4*	*CR-C5*	*CR-R1*	*CR-R2*	*CR-R3*	*CR-R4*	*SJC-R1*	*SJC-B1*	*SJC-B2*	*SJC-B3*	*SJC-B4*
(wt. %)														
SiO_2	73.0	74.8	74.8	78.5	73.1	61.9	62.6	61.0	58.6	72.9	45.6	35.4	41.7	45.6
TiO_2	0.398	0.275	0.387	0.139	0.388	0.697	0.696	0.77	0.723	0.284	3.06	0.637	2.62	0.718
Al_2O_3	12.7	12.1	12.4	11.5	12.4	15.7	16.0	14.9	16.2	12.2	13.9	10.8	13.6	12.7
Fe_2O_3	2.02	1.98	2.6	2.19	2.51	4.66	4.48	5.02	6.32	2.44	13.8	7.47	15.4	8.09
MgO	0.48	0.37	0.63	0.04	0.4	2.97	2.7	3.53	3.07	0.04	6.47	0.34	5.57	0.04
MnO	0.03	0.02	0.05	<0.01	0.03	0.05	0.06	0.06	0.15	0.02	0.15	0.21	0.19	0.2
CaO	1.06	0.58	0.9	0.24	0.84	2.91	2.99	2.96	3.22	1.51	6.28	20	7.63	13.9
Na_2O	2.75	2.37	2.61	5.1	2.74	5.53	5.16	4.35	3.34	3.97	4.42	1.13	4.85	6.99
K_2O	5.68	5.79	4.7	2.02	5.49	0.96	1.75	2.83	3.41	4.51	0.95	7.44	1.45	0.97
P_2O_5	0.08	0.06	0.08	<0.01	0.07	0.2	0.2	0.24	0.16	0.04	0.49	0.11	0.42	0.13

Table 7. Whole rock geochemistry of volcanic rocks within the Nazas magmatic arc in Coahuila, Zacatecas, San Luis Potosí, and Durango (cont.).

Sample	*CR-C1*	*CR-C2*	*CR-C3*	*CR-C4*	*CR-C5*	*CR-R1*	*CR-R2*	*CR-R3*	*CR-R4*	*SJC-R1*	*SJC-B1*	*SJC-B2*	*SJC-B3*	*SJC-B4*
Cr_2O_3	0.01	0.01	0.01	0.02	0.04	<0.01	<0.01	<0.01	<.01	0.05	0.03	0.03	0.02	0.03
LOI	1.0	0.9	0.9	0.35	0.8	4.15	3.35	3.75	3.35	1.55	3.3	16.7	7.1	10.9
TOTAL	99.4	99.4	100.3	100.2	99	99.8	100.2	99.6	98.8	99.7	98.6	100.6	100.6	100.3
(ppm)														
Rb	260	306	203	56	256	38	65	61	102	91	21	178	41	6
Sr	110	62	151	122	82	340	523	318	327	60	226	127	88	66
Y	46	52	44	80	46	15	17	18	24	32	46	20	39	22
Zr	260	194	257	349	280	170	180	208	167	309	218	74	148	99
Nb	11	15	14	29	8	8	8	8	8	15	8	5	5	5
Ba	1220	542	1260	351	767	108	807	734	1230	1190	482	2540	316	202

Sample	*CR-N1*	*CR-N2*	*ST-C2*	*ST-N16*	*CH-T1*	*LB-BI*	*SR-R1*	*SR-R2*	*SR-R3*	*SC-R6*	*SC-R7*	*SC-R8*	*SCJ-B5*
(wt. %)													
SiO_2	77.9	58.5	61.3	69.2	67.9	51.1	75.0	69.3	80.1	62.6	79.7	74.9	61.3
TiO_2	0.114	1.01	0.542	0.606	0.712	1.12	0.158	0.433	0.186	0.544	0.138	0.156	0.672
Al_2O_3	10.8	14.3	14.0	14.8	14.6	17.1	12.4	12.8	12.7	14.7	10.3	12.0	12.7
Fe_2O_3	1.8	8.3	5.47	4.08	4.17	8.54	1.62	3.22	1.32	4.22	1.96	2.11	8.14
MgO	0.16	4.15	0.79	0.91	2.08	6.98	0.35	0.38	1.32	3.24	0.08	0.51	0.16
MnO	<0.01	0.07	0.1	<0.01	0.04	0.15	0.01	0.05	<.01	0.08	<.01	<.01	0.04
CaO	0.09	3.35	5.32	0.32	0.95	3.41	0.54	2.85	0.26	3.23	0.21	0.14	3.25
Na_2O	0.15	3.28	2.81	0.94	3.83	5.55	0.19	2.57	0.06	2.46	0.68	1.21	0.99
K_2O	7.85	1.96	4.8	5.8	1.61	0.91	7.86	4.91	2.67	3.51	6.04	6.87	9.6
P_2O_5	<0.01	0.21	0.23	0.16	0.07	0.25	0.02	0.12	0.02	0.09	<.01	0.02	0.1
Cr_2O_3	0.01	<0.01	0.02	<0.01	0.02	0.04	0.02	0.02	0.03	<.01	0.05	0.04	0.05
LOI	1.0	4.75	4.9	2.1	3.0	4.95	1.3	3.6	2.55	5.0	1.1	1.5	2.85
TOTAL	100	100	100.4	99	99.1	100.2	100	100.4	100.2	99.8	100.5	99.6	100.3
(ppm)													
Rb	154	89	160	159	46	36	162	121	63	154	126	168	198
Sr	34	166	153	43	181	194	89	69	262	90	55	116	67
Y	50	24	23	21	22	24	22	25	18	49	54	20	17
Zr	313	201	184	234	173	191	156	269	220	262	386	253	90
Nb	21	15	11	13	13	29	32	14	27	18	20	15	2
Ba	294	719	705	536	360	285	4420	739	2190	430	1660	826	3880

San Luis Potosí include intermediate and silicic volcanics; and rocks in the Sierra de Jimulco, Coahuila, are basalt. The Coahuila basalt flows are unique and restricted to this area in northern Mexico. Metamorphosed volcanic sequences of similar age (?) and lithology have been reported in the Roca Verde Taxco Viejo Formation in Guerrero, southern Mexico (Lang et al., 1996; Lang, personal communication, 2003).

These data are insufficient to evaluate in detail any specific petrogenetic model; however, they do provide initial constraints on the geochemical characteristics of the Mesozoic Nazas magmatic arc in northern and central Mexico. The total alkali-silica diagram (Figure 2; LeBas et al., 1986) and Rb vs. Nb-Y (Figure 3) and Rb-SiO_2 (Figure 4) paleotectonic discrimination diagrams (Pearce et al., 1984), suggest that, overall, the Nazas arc was calc-alkaline and related to subduction along the western margin of North America. This agrees with results of geochemical analyses of 13 volcanic and intrusive samples from Chihuahua, Durango, and Coahuila reported by Grajales et al. (1992) and with results from volcanic samples from the Caopas-Teyra area, Zacatecas, reported by Fries and Rincon-Orta (1965) and Jones et al. (1995).

These geochemical data support the model that subduction of the paleo-Pacific oceanic plate beneath the North American continental plate gave rise to Late Triassic to Middle Jurassic subaerial volcanism along the continental margin of Mexico. The same tectonic setting had been suggested already by numerous geological studies (Rogers et al., 1961; Fries and Rincon-Orta, 1965; Denison et al., 1969; Denison et al., 1971; Damon, 1975; Belcher, 1979; Blickwede, 1981, 2001; Damon et al., 1984; López-Infanzón, 1986; Jones et al., 1990, 1995; Maher et al., 1991; Grajales et al., 1992; Bartolini and Marsaglia, 1996; Anderson et al., 1991; Bartolini and Spell, 1997; Bartolini, 1998; Lang, personal communication, 2003).

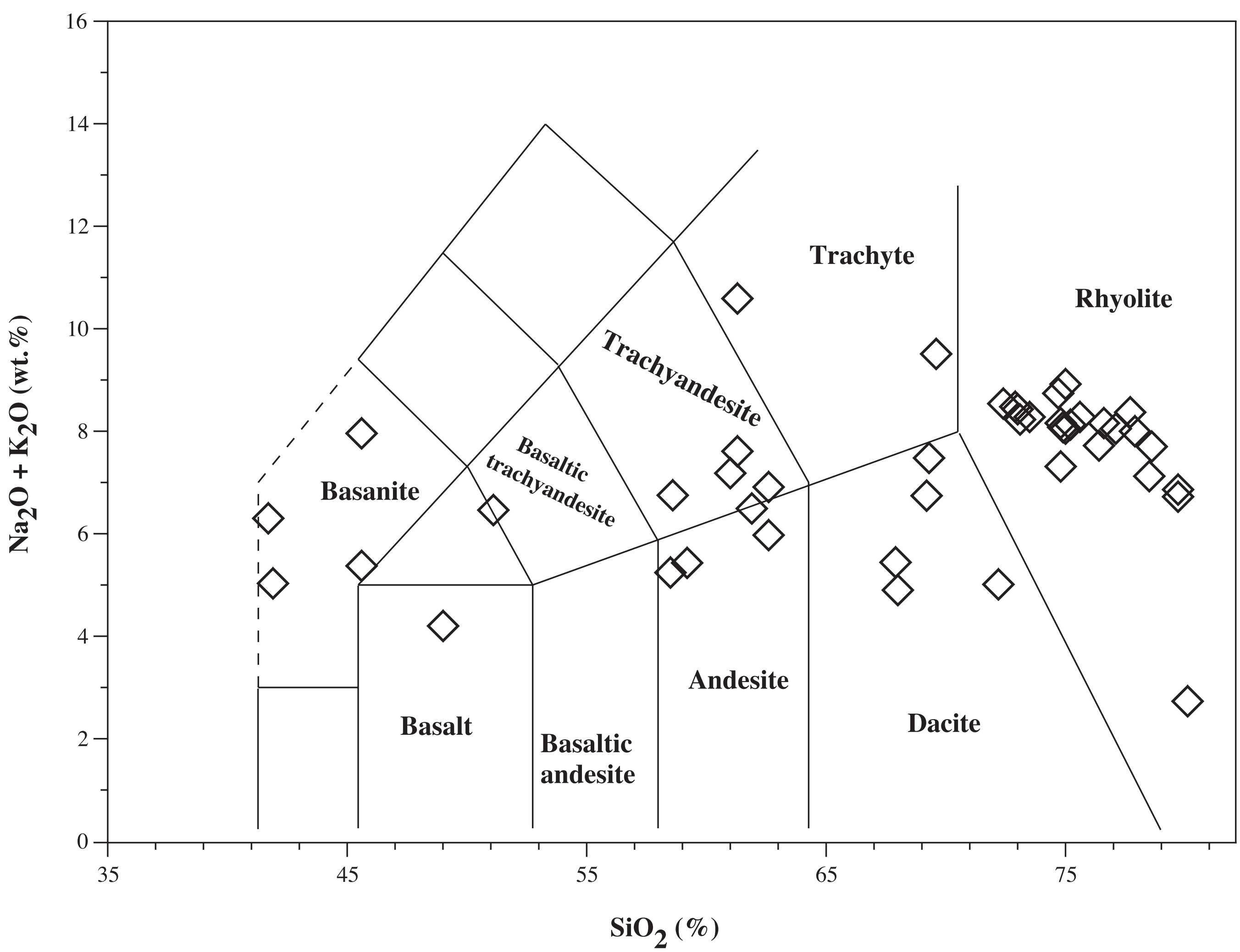

Figure 2. Total alkali-silica diagram (LeBas et al., 1986) showing the compositions of volcanic rocks of the Nazas arc from the study area.

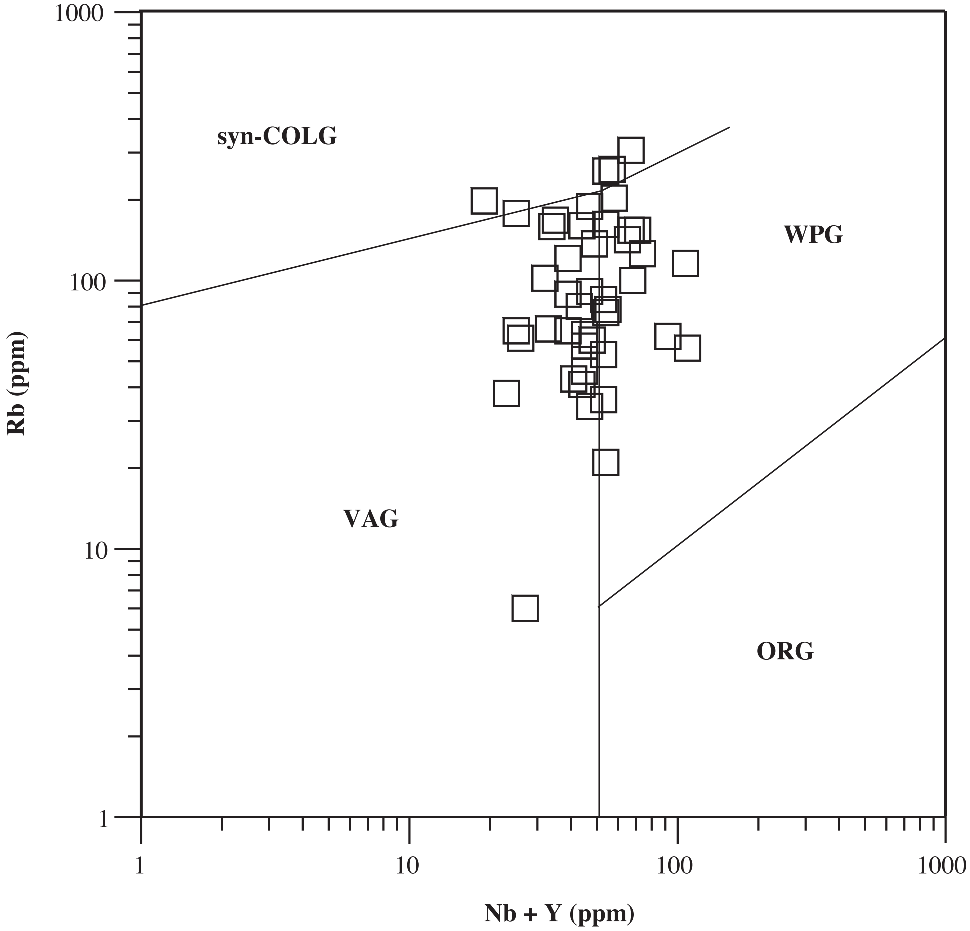

Figure 3. Rb-Nb + Y discriminant diagram (Pearce et al., 1984) for collision granites (Syn-COLG), volcanic arc granites (VAG), within plate granites (WPG), and ocean ridge granites (ORG). All 45 volcanic samples (Table 7) from the study area are plotted.

TECTONO-MAGMATIC EVOLUTION

An Overview of the Characteristics of the Arc

The trend of outcrops from Baja California and Sonora to central Mexico, and from central Mexico to Chiapas in southern Mexico, suggests that the Mesozoic volcanic arc was northwest-oriented and slightly sinuous across Mexico (Figure 1). Taking into account the outcrop scatter and subsurface data, the estimated width of the arc is 150 km.

The magmatic arc was strictly continental; we have found no record of marine sedimentation. In general, clastic sedimentation within the volcanic arc was in immature, ephemeral, fluvial, and alluvial-fan depositional systems that likely developed in intra-arc basins that were contemporaneous with volcanism. The pattern of sedimentary facies within the arc is not known in detail. Resulting lithologic associations, depositional environments, and sediment-body geometries are highly variable. This complexity is manifested locally by the mixed basement/volcanic provenance of clastic sediments where pre-arc rocks are exposed in the terrestrial basins.

We speculate that the Nazas volcanic arc was comprised of a combination of volcanic edifices that probably were medium- to high-standing features characterized by composite volcanoes that experienced significant erosion between periods of volcanic eruptions. Rare basalt may indicate isolated low-lying shield volcanoes or cinder cones. These basalt flows are interbedded with quartz-rich eolian (?) sandstone and fluvial (?) conglomerate that probably were blown or carried by streams into the volcanic arc. Modern analogs of low-standing continental-margin volcanic arcs include the Cascade Range (Smith et al., 1987) and northern Central America (Burkart and Self, 1985). Analogs of topographically high-standing continental volcanic chains include the modern Andean arc in South America and the modern Trans-Mexican volcanic belt and Tertiary Sierra Madre Occidental volcanic arcs in Mexico.

Based on the volcanic and volcanic-sedimentary sequences exposed, volcanic edifices must have been principally rhyolitic and andesitic composite volcanoes. Explosive volcanism also occurred along the Nazas magmatic arc, as shown by the presence of interbedded pyroclastic deposits. Magmas were fundamentally calc-alkaline (Table 7), although the distribution in time and space of specific magma types may have been complex. For example, some regions show rhyolite-andesite associations (Zacatecas and San Luis Potosí), others are primarily rhyolite (Durango and Chihuahua), and basalt predominates locally (Coahuila).

Interbedding of volcanic and sedimentary packages throughout the arc suggests that volcanic activity was intermittent and perhaps short-lived locally,

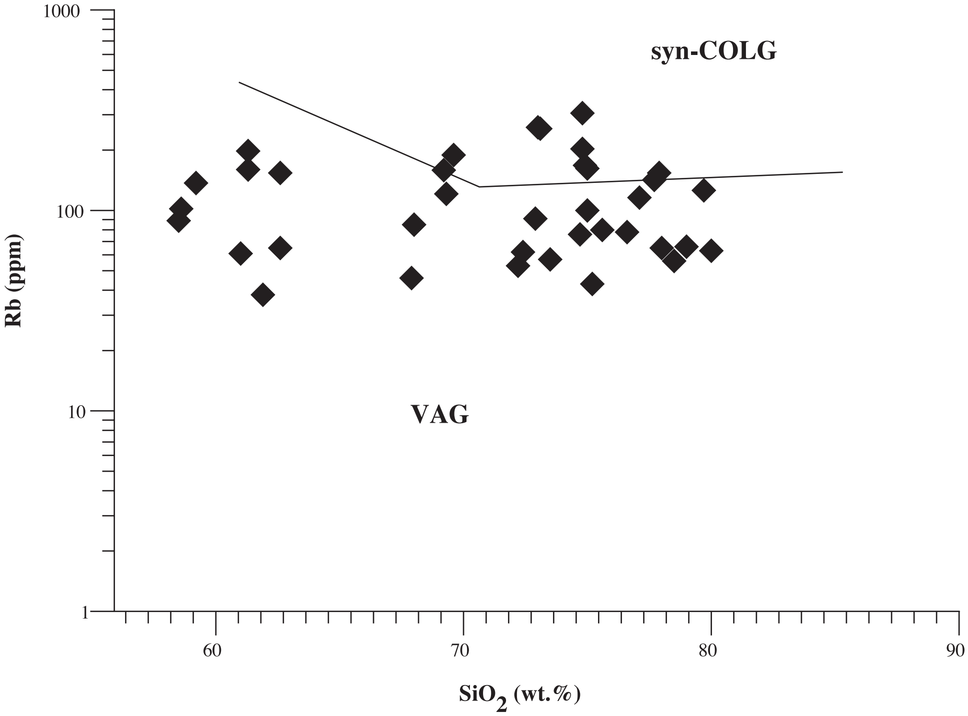

Figure 4. SiO_2-Rb discriminant diagram (Pearce et al., 1984) for volcanic arc granites (VAG) and collision granites (Syn-COLG). Only those volcanic samples from the study area with SiO_2 values higher than 56% (Table 7) are plotted.

as suggested by clastic intervals that typically are thicker than lava flows. Sediment dispersal and supply, as well as sediment composition, texture, structure, and facies architecture, are poorly understood. We can only speculate that proximal coarse- to very coarse–grained, poorly sorted, massive conglomerates composed of assorted volcanic clasts possibly were formed adjacent or very close to eruption centers or in depressions among higher blocks. Interbedded fine-grained strata originally may have been ash-fall pyroclastic particles or reworked particles in incised channels on the flanks of volcanic edifices. Conglomerate and medium-grained, moderately sorted sandstone could have accumulated in basins where either mid-fan facies and/or immature stream channels existed. Fine- and very fine-grained sandstone and shale probably were distal deposits, perhaps a mixture of ash-fall particles and outer alluvial-fan deposits. Locally, true continental red beds formed during long magmatic lulls. Also, low-lying shield volcanoes (Coahuila) were covered by quartzose sands of probable eolian origin (Bartolini et al., 1999).

Regional deformation and metamorphism of the Nazas arc may be related to pre-Laramide Jurassic (?) tectonic deformation. Unlike the arc in the western United States and northwest Mexico, where regional greenschist to granulite facies metamorphism was synchronous with the intrusion of Middle and Late Jurassic age granitoids (Tosdal et al., 1989), the greenschist facies and metamorphism of Nazas arc rocks has not been tied to a documented tectonic event. Mapping the areas affected by the event is hampered by the fragmentary record of data. Nonetheless, we may speculate that metamorphism and structural deformation may be linked to coeval tectonic activity (Anderson and Silver, 1979; Longoria, 1985; Montgomery, 1988).

Unlike the Mesozoic volcanic arc in northwest Mexico and the western United States, where igneous activity extended until the Late Jurassic (Damon et al., 1981; Tosdal et al., 1989), igneous activity along the segment of the arc in north-central Mexico ended sometime in the Middle Jurassic, prior to the westward advance of the Oxfordian seas and subsequent subsidence of the arc. The westward retreat of the subducting slab is one explanation for cessation of arc activity in north-central Mexico. But westward slab retreat also would have terminated igneous activity of the arc in the western United States and northwest Mexico, unless the slab was segmented. Unfortunately, many questions remain unanswered, including: What were the subduction rates and angles of convergence? Was the continental margin volcanic arc a continuous belt across Mexico? Was the arc composed of independent active segments?

Red Color in Rocks of the Magmatic Arc: Oxidation and Weathering or Regional Potassium Metasomatism

Oxidation products (primarily hematite) permeate volcanic, pyroclastic, and clastic sedimentary rocks of the Nazas volcanic arc. Their red color has led some geologists to call these rocks red beds. Formally designating them red beds is inappropriate, because the Nazas Formation includes a substantial component of volcanic flows and pyroclastic rocks. According to the Bates and Jackson (1987) definition, red beds are "strata composed largely of sandstone, siltstone, and shale, with locally thin units of conglomerate, limestone or marl, that are predominantly red in color due to the presence of ferric oxide (hematite) usually coating individual grains. At least 60% of any given succession must be red before the term is appropriate, the interbedded clastic strata being of any color."

Regional episodes of alteration of both volcanic and sedimentary rocks have been documented. For example, potassium metasomatism was described by Chapin and Glazner (1983) and Chapin (1992) for Cenozoic volcanic rocks of the southwestern United States. According to them, the conditions of K-metasomatism are oxidizing, as shown by the reddening of both sedimentary and volcanic rocks caused by increase in the Fe^{+3}/Fe^{+2} ratio. While this alteration can be related to hydrothermal activity, it occurs at low temperature and is not related directly to magmatism (Chapin and Lindley, 1986).

Oxidation of the arc rocks is a regional phenomenon indistinctly affecting the different stratigraphic levels in the upper-arc structure. Because potassium metasomatism of volcanic and sedimentary rocks is a common type of alteration in areas of regional extension (Chapin and Lindley, 1986), it provides a reasonable explanation for the red color of some of the volcanic, pyroclastic, and sedimentary rocks of the Nazas, which also formed in an extensional arc setting. Oxidation by means of diagenetic processes is not ruled out.

Particle Provenance

Based on petrography, the most important sediment sources for the clastic strata of the Nazas Formation are the volcanic and pyroclastic rocks of the arc itself, and reworked intraclasts. Locally, epiclastic particles and crystals derived from peripheral pre-Nazas outcrops also is significant. Epiclastic sediment sources either were exposed at the surface by faults, or were originally topographically high and never covered by volcanic rocks of the arc. These non-arc sources include metamorphosed shale and sandstone of the Middle Late Triassic Zacatecas Formation (Zacatecas and San Luis Potosí), Permian-Triassic granite (Coahuila) metasediments of the Taray Formation (Zacatecas), and Upper Paleozoic metamorphic rock at Santa Maria del Oro, Durango.

Throughout the Nazas volcanic arc, distinguishing the volcanic-derived epiclastic pyroclastic and hydroclastic particles becomes a serious problem. Mixtures of epiclastic and pyroclastic particles are expected to have been deposited along the Nazas arc, but are difficult to identify, especially when the rocks are strongly oxidized, deformed, and altered.

On What is the Nazas Arc Built?

The volcanic edifices of the Nazas magmatic arc in northern and central Mexico rest on Paleozoic crystalline basement, Upper Paleozoic (?) successions, and older Mesozoic sedimentary sequences. In northern Durango, the Nazas sits on metamorphic rocks of Late Paleozoic age (Damon, personal communication, 1998). Nazas outcrops rest unconformably (López-Infanzón, 1986) on granitic plutons of Late Permian–Early Triassic age in southern Coahuila (Denison et al., 1969; Denison et al., 1971). In Zacatecas and San Luis Potosí, the volcanic arc was built on the Middle–Late Triassic clastic turbidites of the Zacatecas Formation (Burckhardt and Scalia, 1905; Burckhardt, 1930; Cantú-Chapa, 1969; Gallo et al., 1993). In the Sierra de Teyra, northern Zacatecas, the Nazas arc rocks rest unconformably on sedimentary rocks of the Taray Formation (Upper Paleozoic–Triassic?) (Córdoba, 1964; López-Infanzón, 1986; Anderson et al., 1990; Bartolini, 1998). At Sierra de Catorce, San Luis Potosí, pyroclastic rocks and volcanic flows presumably belonging to the Nazas volcanic arc rest on turbidite sequences (Barboza-Gudiño et al., 1997), which have yielded Mississippian-Pennsylvanian spores (Bacon, 1978) and Permian fossil plants (Franco-Rubio, personal communication, 2002).

Along eastern Mexico, the relationship between the Nazas arc and the Upper Permian–Lower Triassic volcanic arc remains unknown. Nonetheless, Bartolini (1998) suggested the existence of a partial spatial overlap. For the most part, however, the Upper Permian–Lower Triassic arc lies east of the Upper Triassic–Middle Jurassic Nazas volcanic arc. The older arc has been delineated and dated using granitic samples from Pemex boreholes (López-Ramos, 1972; Damon, 1975; Jacobo, 1986; Grajales et al., 1992; Tórres-Vargas et al., 1993; Tórres et al., 1999). Volcanic rocks of unknown age that underlie Late Triassic or early Middle Jurassic red beds in the states of Tamaulipas, Nuevo León, and San Luis Potosí provisionally are considered part of the Permian–Early Triassic arc (Bartolini et al., 1999).

Where is the Root of the Mesozoic Magmatic Arc in North-Central Mexico?

Large subduction-related granitic batholiths are major components of continental-margin magmatic

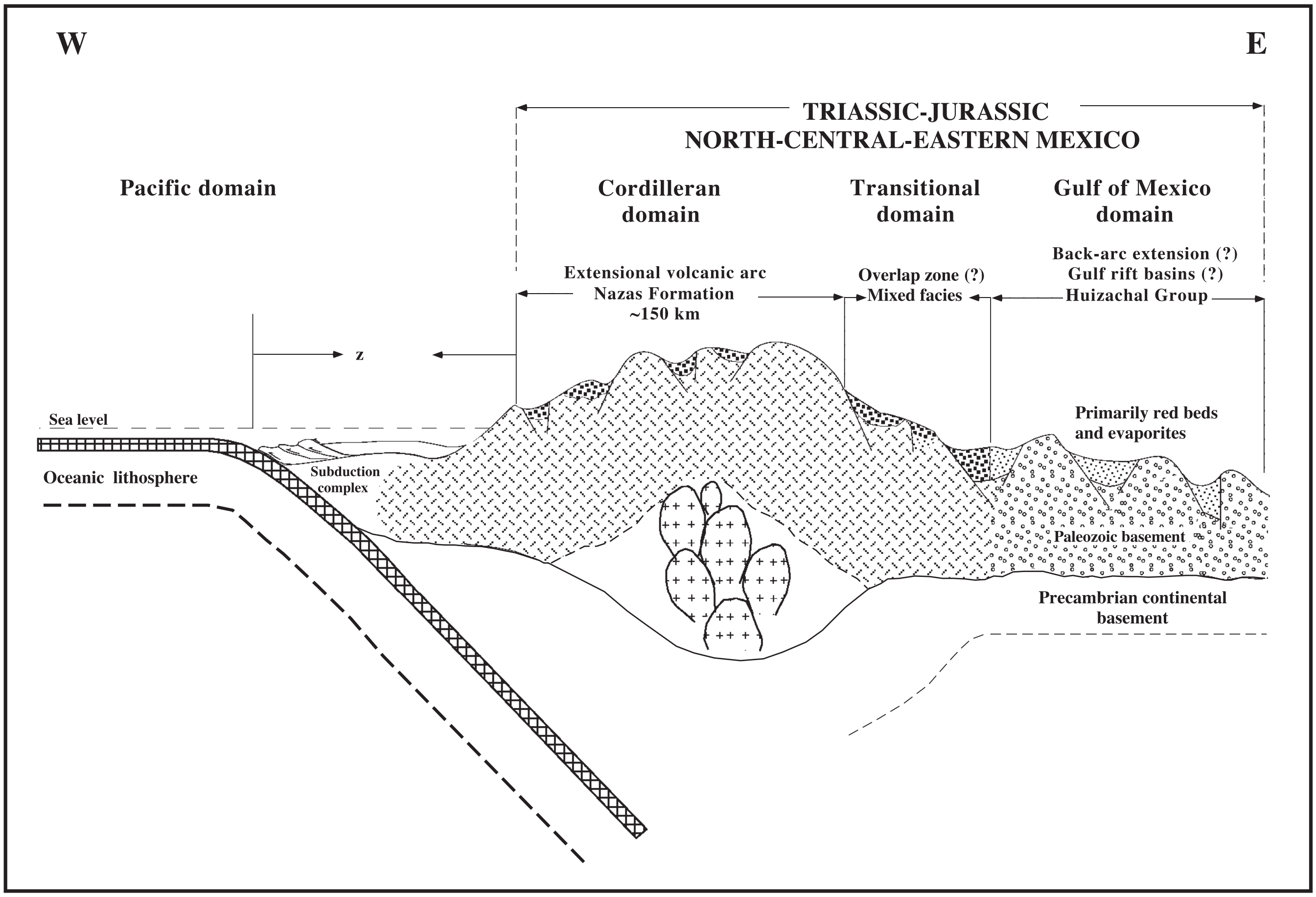

Figure 5. Idealized Nazas continental margin extensional magmatic arc showing the proposed depositional framework for the Nazas Formation and Huizachal Group and possible zone of overlap between both settings.

arcs and represent the roots of the arc structure (Figure 5). Hamilton (1969) first illustrated the relationship between Benioff zones and the formation of a batholith and its capping volcanic component. He proposed that the great Mesozoic batholiths of North America were formed in three episodes of magmatism in the Late Triassic, the Middle Jurassic, and the Late Jurassic. Volcanic covers mostly have been removed from Mesozoic plutons, but presumably these plutons also typically reached into volcanic superstructures. The Cordilleran volcanic arcs in Mexico constituted a vast granitic batholith and associated dominantly andesitic and rhyolitic volcanic flows (Damon et al., 1984). Granitic plutons represent the deeply eroded roots of the Mesozoic magmatic arc system of western North America (Hamilton, 1969). Volcanoes and associated volcanic rocks in the western United States are linked directly with subvolcanic granitic batholiths. Unroofed granitic plutons record the late stages of emplacement and crystallization of silicic magmas (Lipman, 1984). The vast batholiths of Sonora and Sinaloa are the exposed roots of a Mesozoic volcanic arc (Damon, 1986). These granitic batholiths are associated with dominantly andesitic volcanism. Typical American continental-margin batholiths include those of the Sierra Nevada, the Coast Range in Canada, the Peninsular Ranges of California and Baja California, and the Coastal Andes (Hess, 1989).

In the northern and central Mexico states of Durango, Coahuila, San Luis Potosí, Zacatecas, Chihuahua, and Sonora, the discontinuous outcrops of the Nazas Formation (or equivalent) represent the continental-margin volcanic arc of western North America. These rocks, which range in age from Late Triassic to Middle Jurassic, are mainly volcanic flow, pyroclastic, volcaniclastics, and continental clastic sedimentary rocks that correspond to parts of a magmatic arc edifice (Damon et al., 1991; López-Infanzón, 1986; Grajales et al., 1992; Jones et al., 1995; Bartolini, 1997, 1998). However, a few exposures of the granitic roots of this arc have been found in northern Mexico. For instance, in El Cuarenta and La Parrita, northern Durango, relatively small granitic plutons have K-Ar ages of 155 ± 3 Ma and 149 ± 3 Ma (Damon et al., 1984). In the Santa Barbara, Parral area, Chihuahua, a quartz monzonite pluton yielded a K-Ar age of 198 ± 7 Ma (Damon et al., 1981).

The existence of Nazas volcanic and volcanic-sedimentary rocks representing chiefly the upper part of a chain of volcanic edifices leads to the following questions and uncertainties: Was the arc too small to develop a large batholith as a root? Was the arc a short-lived volcanic structure? The presence of granitic and granodioritic plutons in Chihuahua and Coahuila states, on the other hand, suggests that this segment of the volcanic arc was uplifted, and its upper volcanic part was eroded, exposing the roots of the arc structure. Borehole data (Table 6) indicate that intrusive rocks of the magmatic arc in central Mexico occur beneath 5–7 km of Jurassic, Cretaceous, and Tertiary cover. Alternatively, erosional level to the south was probably not deep enough; thus, the roots of the arc were not exposed to any extent.

The Position of Mexico in the Early Mesozoic

Tectonic reconstructions for the early Mesozoic (Coney, 1983; Pindell, 1985, 1993; Marton and Buffler, 1994) depict a poorly defined Mexico surrounded by major tectonic plates. The uncertain position of Mexico was the key factor controlling the complex tectono-structural, magmatic, and stratigraphic settings that prevailed at that time. Attempts to disentangle the early Mesozoic geologic evolution of this region are hindered by coexistence of the following events: (a) existence of a convergent margin along western Mexico; (b) emplacement of allochthonous sequences along the Pacific margin; (c) separation of North and South America; (d) development of the Nazas terrestrial magmatic arc, formation of intra-arc basins, and regional arc extension; (e) low-grade regional metamorphism; (f) possible large-scale, active transpressive structures; (g) salt tectonics; and (h) crustal extension, formation of rift-basins, and deposition of red beds and evaporites.

Arc-Related Extension (Intra-Arc) versus Gulf of Mexico-Related Extension (Rift): Where is the Boundary?

East of the arc, along the Gulf of Mexico, extensional processes related to rifting in the Gulf were responsible for the extensional deformation of Precambrian and Paleozoic basement. Upper Triassic rift-basin deposits are represented by red beds of La Boca Formation (Mixon et al., 1959; Belcher, 1979), whereas Early to Middle Jurassic transitional sequences include red beds of La Joya Formation (Mixon et al., 1959; Carrillo-Bravo, 1961; Rueda-Gaxiola et al., 1993; Salvador, 1991; Favstosky et al., 1997) and Upper Jurassic evaporite deposits of the Minas Viejas Formation (Michalzik, 1991; Gotte and Michalzik, 1992).

The presence of volcanic and pyroclastic rocks interbedded with the red beds in Tamaulipas and San Luis Potosí (López-Infanzón, 1986; Strater, 1993; Barboza et al., 1997; McKee et al., 1997; Favstosky et al., 1997) suggests the possibility of an overlap in time and space of crustal extensional deformation, where both arc products and basin-rift strata may have mixed (Figure 5). Volcanic rocks reported from this overlap zone are characteristic of a continental arc setting. The only igneous rocks whose trace composition element suggests a continental rift magmatism are the 145 and 146 Ma metaplutonic and metavolcanic suites exposed in La Popa basin in Nuevo León (Garrison, 1998). These igneous rocks apparently were associated with the opening of the Gulf of Mexico in the Jurassic (Garrison and McMillan, 1999).

Thus, it is reasonable to assume that arc-related extension may have extended east toward the Gulf of Mexico region (Figure 6), and at the same time, Gulf of Mexico rift-related extension may have reached west toward inland Mexico. Finally, disregarding the different tectonic origin for extensional processes, both intra-arc sequences and rift-basin red bed strata are overlain by the same marine sequences deposited during a marine transgression over the highly extended Mexican crust in the Late Jurassic. Triassic–Jurassic red beds along the Gulf coast also are overlain by Late Jurassic evaporite deposits.

The Arc and Coeval Transpressive Activity

It has been speculated that the general northwest-southeast trend of the Mesozoic volcanic arc across Mexico has been truncated by the Mojave-Sonora megashear, which is considered to be a transpressive left-lateral fault, active in the Middle–Late Jurassic (Silver and Anderson, 1974; Anderson and Silver, 1979; Jones et al., 1995; Anderson and Silver, 1997). Oblique subduction has been linked to the development of several other major strike-slip faults in Mexico during the Mesozoic (McKee et al., 1984; Longoria, 1985; Montgomery, 1988).

Given the left-lateral sense of displacement proposed for these faults, the Mesozoic volcanic arc should

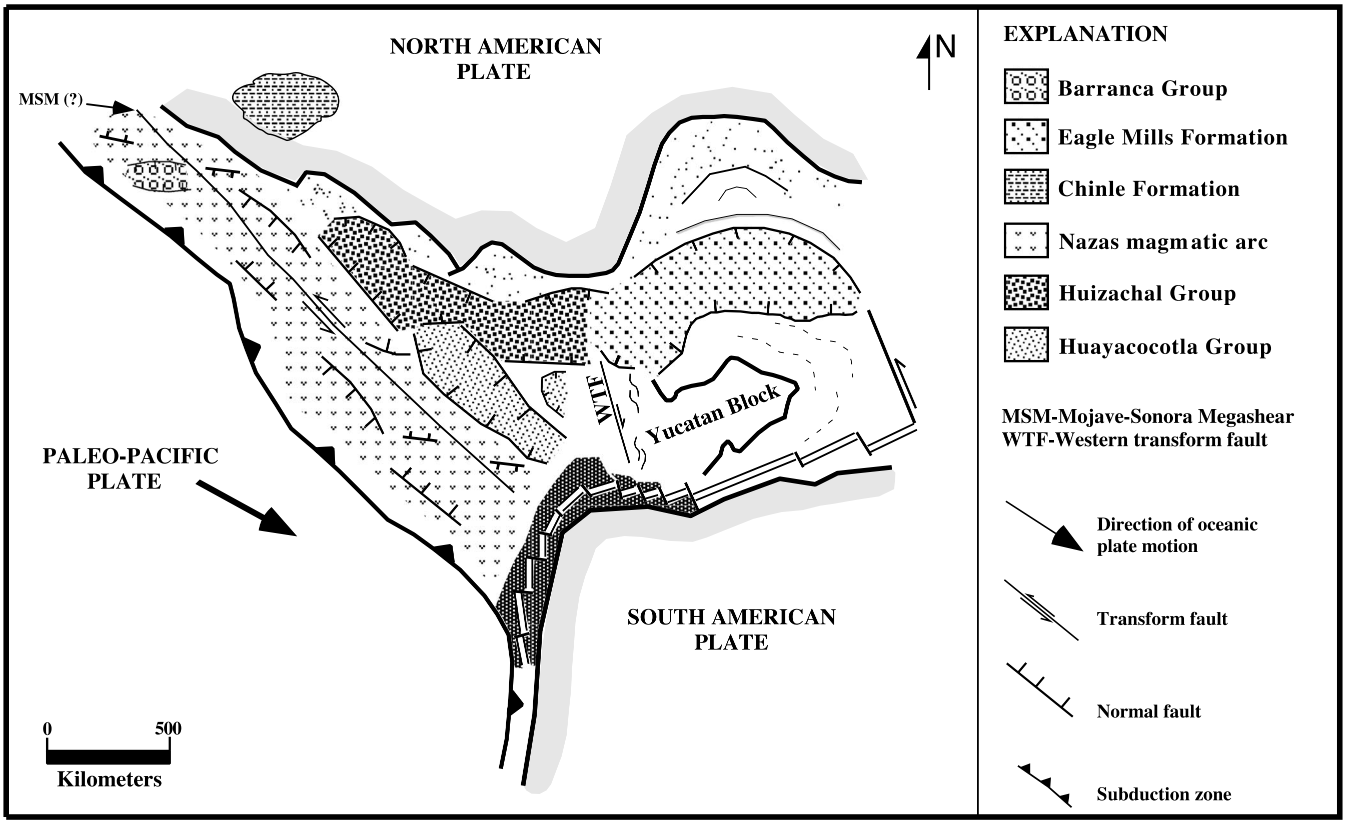

Figure 6. Diagrammatic plate tectonic map showing the Nazas magmatic arc, the possible trace of the Mojave-Sonora megashear, and equivalent Upper Triassic and Jurassic continental strata. Tectonic and paleogeographic elements in part are after Silver and Anderson (1974), Salvador (1991), Pindell (1985), and Marton and Buffler (1994).

have been displaced to the southeast and dismembered. It would have lost continuity with equivalent arc rocks in Sonora and Baja California. But it is clear that arc rocks in Chihuahua, Coahuila, Durango, Zacatecas, and San Luis Potosí correlate in age and lithology and link spatially with rocks of the arc in Sonora (Corona, 1979; Stewart et al., 1986; Damon et al., 1984; Damon et al., 1991) and Baja California (Gastil et al., 1978). Furthermore, Nazas volcanic rocks have been encountered in Pemex boreholes in northern Mexico (Grajales et al., 1992). The arc also extends south from central Mexico into southern Mexico and Guatemala (Damon, 1975; Damon et al., 1991).

If the Mojave-Sonora megashear exists as a major left-lateral fault, it must be within and parallel to the Nazas arc (Figure 6). This interpretation is consistent with results from a detailed paleomagnetic investigation by Molina-Garza and Geissman (1999) of Neoproterozoic to Cretaceous rocks on both sides of the proposed trace of the Mojave-Sonora megashear in Sonora. They report that paleomagnetic data do not support the 800–1000 km of left-lateral displacement and/or substantial counterclockwise rotation of the Caborca block suggested by proponents of the Mojave-Sonora megashear.

NAZAS VOLCANIC ARC: POSSIBLE SUBSIDENCE MECHANISMS

To our knowledge, an assessment of extension and subsidence of the Mesozoic Nazas volcanic arc in north-central Mexico has not been published, nor have tectonic models been proposed to explain the arc within a tectonic framework. In this section, we address these topics based on our regional study of arc rocks in five states of north-central Mexico.

Phase 1: Arc Extension and Subsidence

The maximum thickness of Nazas volcanogenic sequences is unknown because only partial sections are exposed as a result of subsequent erosion of basin-fill during uplift and burial of much of the arc. The thickest sections are exposed in Sierras de San Julian, Teyra, and Candelaria in northern Zacatecas (Rogers et al., 1961; Cordoba, 1964; Belcher, 1979; Blickwede, 1981, 2001; López-Infanzón, 1986; Anderson et al., 1991; Jones et al., 1995; Bartolini, 1998). These sections show that basin-fill must be more than 3-km thick.

In similar arcs, quiescent periods commonly are marked by aggradation of epiclastic sediment or by widespread stream incision and paleosol development (Francis, 1983). The accumulation of thick columns of alluvial and fluvial clastic sediment normally is facilitated by an increase of local subsidence of the receiving area, and although rates of subsidence along the Mesozoic Nazas arc are not known, subsidence probably was strongly controlled by active extensional faulting and by the weight of the volcanic-sedimentary load. The association of syneruption (volcanic and pyroclastic) and intereruption (alluvial and fluvial sediments) facies has been interpreted to indicate subsidence rapid enough to accommodate both volcanic and alluvial-fan debris (Smith and Vincent, 1987). Thus, deposition and preservation of the Nazas arc basin-fill in north-central Mexico result from subsidence accommodated by extensional faulting. Nevertheless, some segments of this 2000-km-long arc may have experienced different magmatic, structural, and tectonic processes.

Smith et al. (1989) studied the Deschutes basin in the Cascade Range, Oregon, and found that basin subsidence is controlled primarily by flexural loading of elastic lithosphere by the growing volcanic chain. They explain development of intra-arc basins as a response to extension of a thermally weak crust, where subsidence is not only controlled by thinning associated with extension, but also by changes in the isostatic compensation of the arc.

Studies of the central High Cascade Range, Oregon, led Taylor (1990) to propose that interaction between Cascade crust and a dynamic mantle caused uplift of the western Cascades and associated extensional tectonic processes and subsidence of the High Cascades. He suggested that circulating mantle currents during decreasing rates of convergence reached higher levels in the lithosphere and generated east-west extension and graben subsidence in the arc platform.

Analysis of Miocene subsidence along the Cascade Range indicates that uplift related to isostatic rebound contributes to dissection of the arc basin-fills deposited earlier (Smith et al., 1987). The reworking of Nazas clasts in the basin-fill is strong evidence for uplift and erosion of the arc and the basin-fill that formed first. This phenomenon could explain, at least in part, the episodic nature of graben development in the Nazas arc structure. The duration of these episodes of extension is unknown.

A compilation of seismic strain field for 16 volcanic arc regions around the world indicate that extension perpendicular to the arc is a large-scale phenomenon and cannot be explained simply by emplacement of magma bodies (Apperson, 1991). Extension along the arc invariably is normal to the arc, regardless of the obliquity of convergence. Apperson (1991) suggests that intra-arc extension is controlled by asthenospheric corner flow induced by subduction, a model modified after Taylor (1990). According to this model, if the rate of convergence is low, mantle circulating cells are wide and elliptical and produce melting in a wide area of the asthenosphere, creating a wide arc. If the rate of convergence is high, circulating mantle cells are more circular and impinge upon the base of the overriding lithosphere to create tensional stresses that induce graben subsidence.

Contrary to the Early Jurassic continental magmatic arc in eastern California and southern Arizona, where low-lying volcanoes were localized in a central graben system that received eolian sands primarily (Busby-Spera, 1988), we envision the Nazas arc as an intricate system of intra-arc basins of unknown size and geometry, both parallel and traverse to the arc, and whose basin-fill is highly variable in lithology, composition, thickness, and facies (Figure 7), and where most basin-fill is red in color because of potassium-metasomatism associated with coeval arc extension. Our interpretation is preliminary because key data, such as the structural styles along the arc, the timing and size of eruptions, the rates of subsidence and durations of periods of syneruption sedimentation, and the timing of faulting, are not available. However, the extensional nature of the Nazas volcanic arc in north-central Mexico is certain based on the following evidence: (a) the existence of ubiquitous, thick, volcanic-sedimentary sequences that fill intra-arc basins; (b) the oxidation of intra-arc basin-fill produced by potassium-metasomatism; (c) the eruption of ignimbritic and rhyolitic lavas, suggesting local caldera activity and collapse; and (d) the uplift and reworking of basin-fill formed during earlier extension throughout the arc.

Subsidence caused by downfaulting of calderas also should be invoked locally as a mechanism contributing to subsidence of the Nazas arc. The common occurrence of ignimbrites along the arc can be linked to caldera-forming eruptions. Commonly, depressions formed during the eruption of ignimbrites

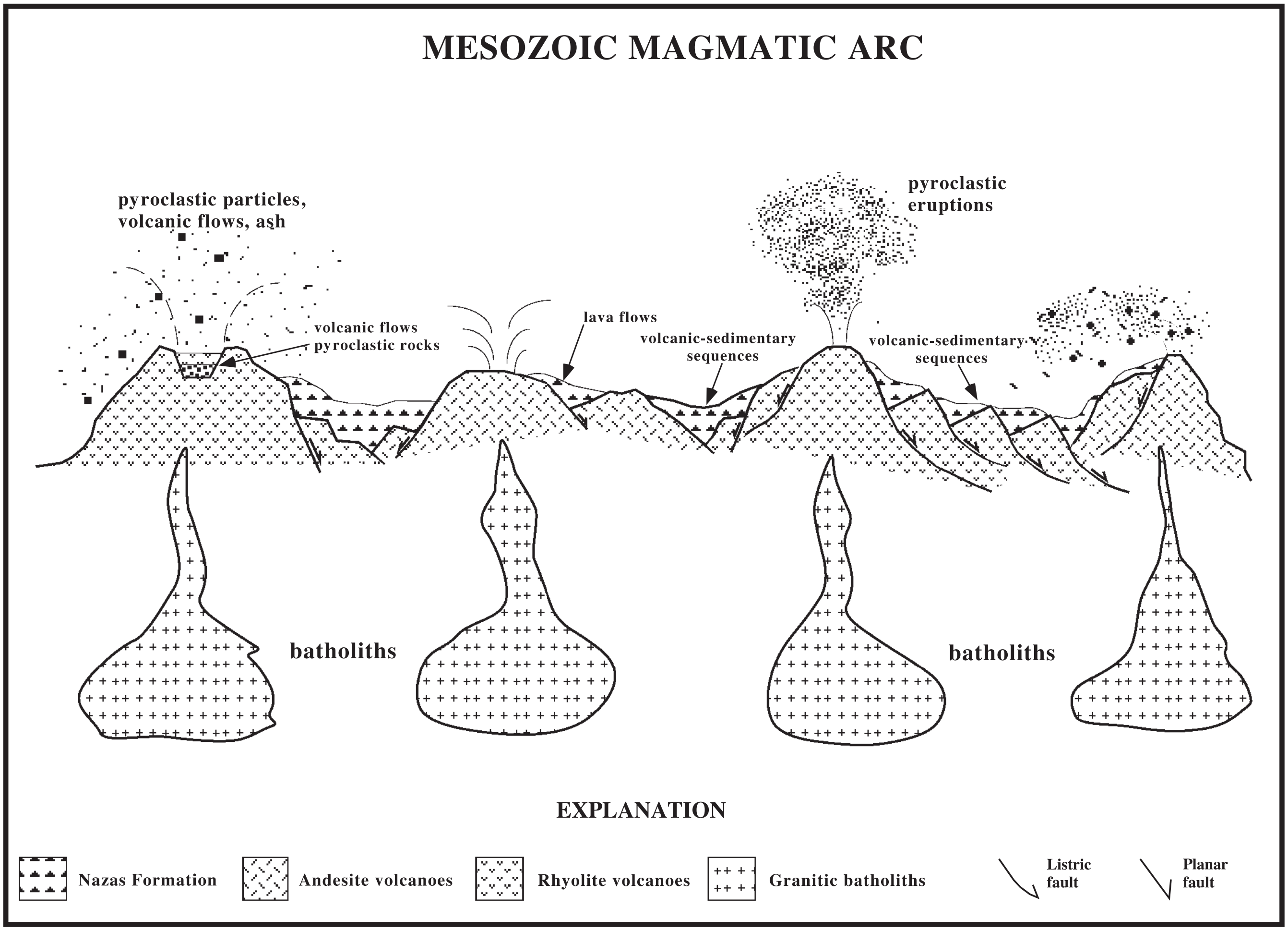

Figure 7. Hypothetical traverse section across the extensional Nazas arc domain, northern and central Mexico. Volcanic flows are very close to or on eruption centers. Volcanic-sedimentary sequences include pyroclastic, volcanic flows, and arc-derived epiclastic sediments and are near eruptive centers, particularly in grabens and intermontane areas in the arc.

and subsequent collapse of calderas are caused by partial evacuation of the magma chamber and are known to cause normal-faulted downsags in continental volcanic arcs (Walker, 1984).

Based on their study of the early Proterozoic Great Bear magmatic zone in Canada, Hildebrand and Bowring (1984) proposed that long, linear, continental intra-arc depressions are not extensional in origin but rather are regions of broad subsidence caused by downwarping of the crust during periods of ash-flow eruptions. Because intra-arc basins remained close to sea level for millions of years, they suggested that the mass of dense mafic magmas added to the lower crust is equal to the mass of vitric ash removed during eruptions. Presumably, this process leads to long-term subsidence in nonextensional intra-arc basins. This nonextensional model is relevant where eruption of siliceous ash is voluminous locally, but it cannot explain the overall extensional nature of volcanic arcs.

Phase 2: Lithostatic Subsidence

After a period of intra-arc basin development, volcanism, and continental sedimentation in the Late Triassic–Middle Jurassic (Figure 8A), in the Oxfordian, the volcanic arc, a subaerial, topographically low and eroded structure, was covered by shallow-marine seas that transgressed westward onto Mexico. The Zuloaga Formation records a major marine inundation of the pre-Oxfordian Mexican continent. Continental rocks of the arc are unconformably covered by marine limestone of Zuloaga Formation in Coahuila, Zacatecas, and San Luis Potosí states. Contemporaneous with the deposition of the Zuloaga, but around the Coahuila Peninsula, a positive landmass remained emergent from Late Jurassic to Early Cretaceous (Böse, 1923; Imlay, 1936). During the Oxfordian, in northern Durango and Coahuila states, littoral quartz-feldspathic sands derived from the peninsula were transported west and southwest and were deposited

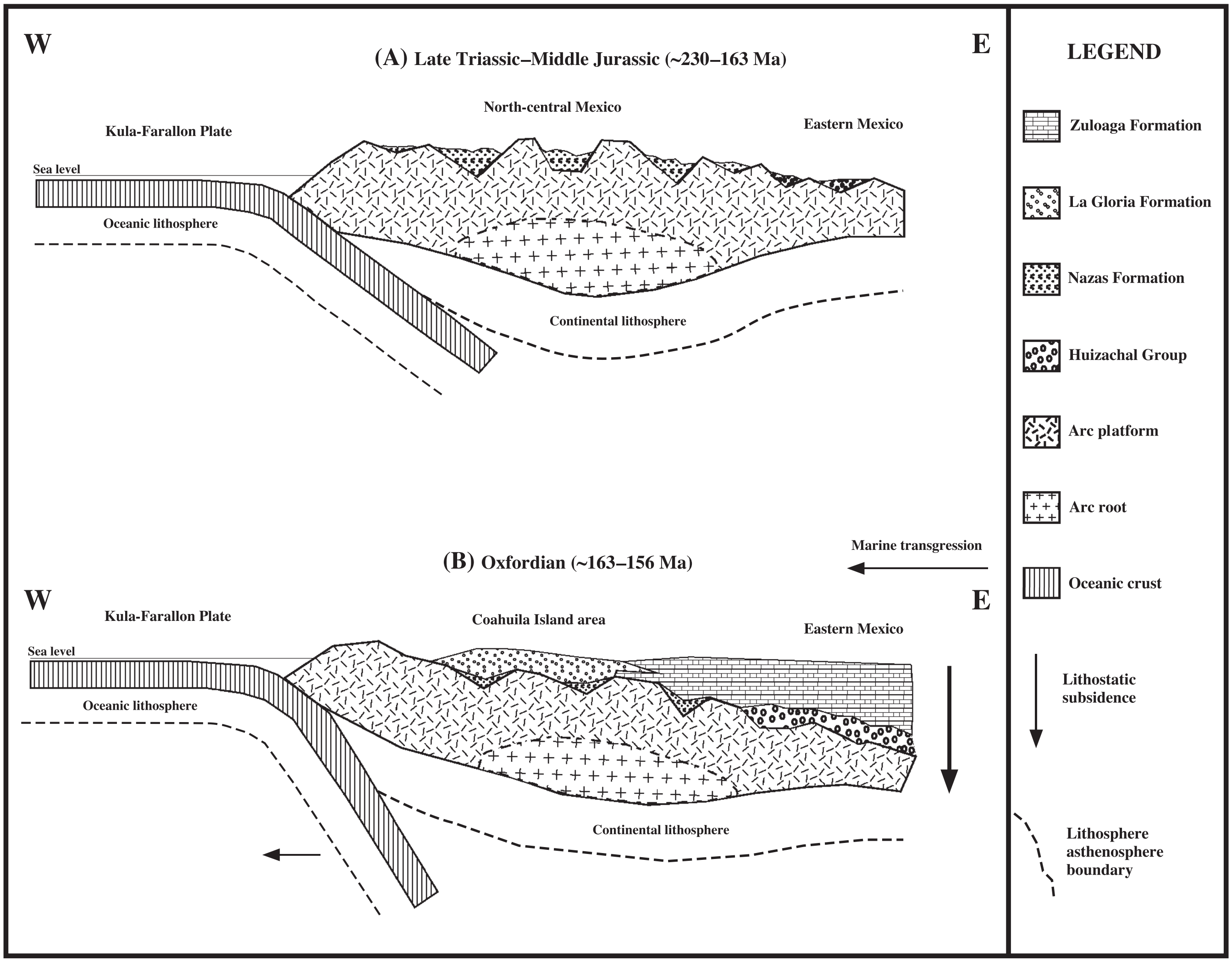

Figure 8. Stages of subsidence and possible subsidence mechanisms for the Nazas arc in north-central Mexico.

directly on arc rocks (López-Infanzón, 1986; Grajales et al., 1992; Bartolini, 1998). Accumulation of these deposits along the Mexican geosyncline is the earliest evidence for lithostatic subsidence along the arc (Figure 8B). Sedimentation of La Casita during Kimmeridgian and Tithonian time (Imlay, 1936) and subsequent continuous deposition of thousands of meters of marine sediments along the geosyncline during the Cretaceous record increasing rates of lithostatic subsidence that led to burial of the volcanic arc under 5–7 km of strata (Figure 8B).

CORRELATION

Two stratigraphic correlations are intended to facilitate the visualization of different groups of red beds and Nazas arc terrestrial sequences. The generalized correlation suggested by Bartolini (1998) of Triassic red beds, Nazas Formation and younger Mesozoic strata in north-central and northeastern Mexico, and the Gulf Coast region of the United States (Figure 9) depicts a broad distribution and age range of Mesozoic strata.

The chronostratigraphic correlation of different Mesozoic red bed units in northeastern and central Mexico and the Mexican Gulf Coast region (Figure 10) is a valuable factor in constraining Mesozoic rifting stages in Mexico. This correlation is particularly important because it is based on biostratigraphic studies using fossil flora (Silva-Pineda, 1963, 1979), invertebrate fossils (Clark and Hopson, 1985; Favstosky et al., 1987), and pollen and spores (Rueda-Gaxiola, 1972, 1975; Rueda et al., 1993) in several localities of the country.

Geographic locations			Gulf coastal plain	Huizachal-Peregrina anticlinorium	Nuevo León	North-central Mexico
MESOZOIC	JURASSIC	Late	Smackover Formation Norphlet Formation	Zuloaga Formation	Zuloaga Formation Minas Viejas Formation	Zuloaga Formation / La Gloria Formation
		Middle	Louann Salt	La Joya Formation	La Joya Formation	Nazas Formation
		Early	Werner Formation	La Boca alloformation		
	TRIASSIC	Late	Eagle Mills Formation	Huizachal alloformation	Huizachal Formation	
References			Newkirk (1971)	Rueda-Gaxiola et al. (1993)	Michalzik (1988)	Bartolini (1998)

Figure 9. **Generalized correlation of Triassic red beds, Nazas Formation, and younger Mesozoic strata in north-central and northeastern Mexico and the Gulf Coast region of the United States (Bartolini, 1998).**

No reliable stratigraphic correlation can be established between Nazas measured sections in Mexico because of the lack of age controls and pre-Oxfordian erosional level, which determines what is exposed in the field.

THE NORTH-SOUTH AMERICA CONNECTION (?)

In Colombia and Venezuela, Jurassic volcanic, intrusive, and sedimentary rocks of La Quinta and Girón Formations share many of the characteristics of the Nazas Formation in Mexico, such as age, lithologies, geochemical affinity, environments of deposition, and tectonic setting. These similarities, along with the configuration of Pangea in the early Mesozoic, suggest that La Quinta, Girón and Nazas Formations were an integral part of a once-continuous Triassic-Jurassic continental-margin magmatic arc that may have existed along the western margin of Pangea supercontinent.

The name La Quinta Formation was originally proposed by Kundig (1938) for a sequence of red sediments of Mesozoic age that underlie Cretaceous marine strata in the Venezuelan Andes.

In Colombia, the same successions are exposed near Bucaramanga (Maze, 1984) and are known as the Girón Formation. In the Santander massif, volcanic and sedimentary rocks of the Jordán and overlying Girón Formation apparently are correlative with La Quinta Formation of Venezuela (Cediel, 1969).

Multiple lines of evidence suggest an Early to Late Jurassic age for volcanic, granitic, and sedimentary rocks of La Quinta Formation at the Sierra de Perijá and the Mérida Andes, Venezuela (Burkley, 1976; Odreman and Benedetto, 1977; Benedetto and Odreman, 1977; Espejo et al., 1978; Dasch, 1982; Maze, 1984; Steinitz and Maze, 1984). Supporting data include the following:

U-Pb: Zircon from granitic and volcanic rocks defines a discordia with a lower intercept of 167 ± 3 Ma; one hornblende andesite yielded 163 ± 5 Ma; and a rhyolitic welded tuff-breccia from the upper part of La Quinta Formation gives an age range of 140–160 Ma (Dasch, 1982).

Rb-Sr: Whole-rock geochemistry determined for 13 volcanic rocks and one granite sample gives a 174 Ma isochron. An isochron determined for six volcanic rocks is 156 Ma (Maze, 1983, 1984).

K-Ar: Amphiboles from one diorite dike yielded a 168 ± 5 Ma (Espejo et al., 1978). Whole-rock age dating of two hornblende andesites gave 155 ± 5 and 146 ± 7 Ma (Steinitz and Maze, 1984).

Paleontology: Odreman and Benedetto (1977) and Benedetto and Odreman (1977) determined Middle to Late Jurassic ages for strata of the Macoita and La Quinta Formations. Maze (1983, 1984) collected fossils from La Quinta Formation of the Sierra de Perijá that were assigned a Late Triassic to Early Jurassic age.

In the Mérida Andes, the age of a basal volcanic tuff in La Quinta Formation was dated at 229 ± 15 Ma (Burkley, 1976). Fossil plants identified by Odreman and Benedetto (1977) indicate an Early Jurassic age for the lower part of La Quinta Formation.

Whole-rock X-ray fluorescence analysis for major and trace elements of more than 50 rocks from the La Quinta Formation indicate a calc-alkaline suite (Maze, 1984), similar to the whole-rock geochemistry of volcanic rocks in the Nazas Formation (Fries and Rincón-Orta, 1965; Grajales et al., 1992; Jones et al., 1995;

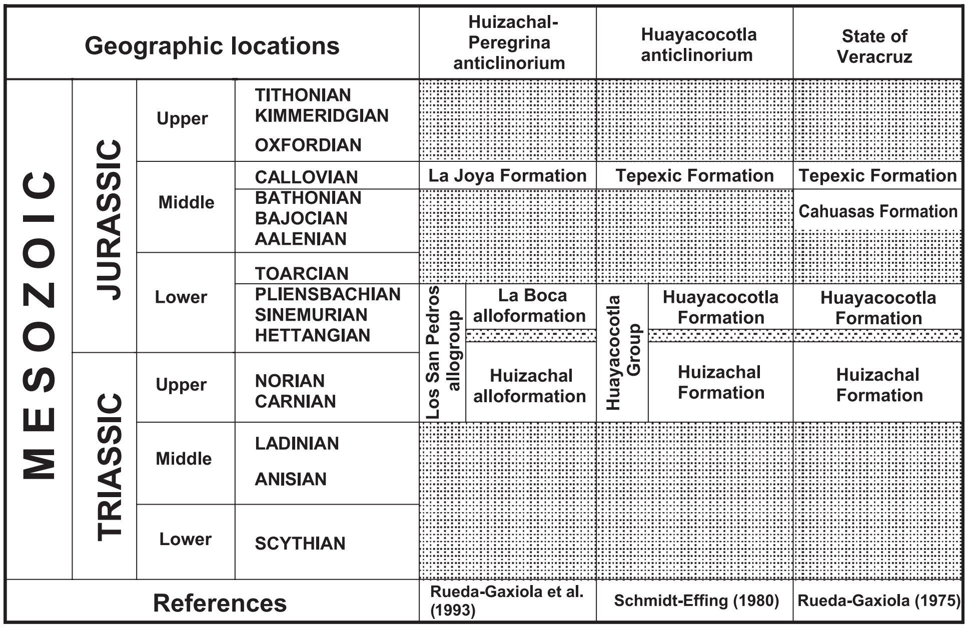

Figure 10. **Chronostratigraphic correlation of different Mesozoic red bed units in northeastern and central Mexico and the Mexican Gulf Coast region. This correlation is based on biostratigraphic results using fossil flora (Silva-Pineda, 1963, 1979), invertebrate fossils (Clark and Hopson, 1985; Favstosky et al., 1987), and pollen and spores (Rueda-Gaxiola, 1972, 1975; Rueda-Gaxiola et al., 1993).**

Bartolini, 1998). It is apparent that volcanic rocks in both the Nazas and La Quinta Formations share the same geochemical affinity and record-convergent continental-margin magmatism.

Maze (1983, 1984) first attempted to correlate the Jurassic rocks of the magmatic arc in Venezuela and Colombia with similar sequences in Central America and Mexico. Unfortunately, given the limited information available at that time on the Nazas arc rocks, Maze's correlations were done essentially with continental red beds of the La Joya and La Boca Formations (Mixon et al., 1959; Carrillo-Bravo, 1965) and red beds of the Todos Santos Formation (Richards, 1963; Blair, 1981, 1987). More recently, Bartok (1993) indicated the close relationship between red beds strata and rifting processes related to the evolution of the Caribbean and the opening of the Gulf of Mexico. He remarked on the importance of lithologic similarity and tectonic framework between red beds of La Quinta and Girón Formations in Venezuela and Colombia and Triassic and Jurassic continental red beds of the Eagle Mills, Huizachal, La Joya, and Todos Santos Formations in the United States, Mexico, and Central America.

Proposed reconstructions of the western margin of Pangea in the Late Triassic–Jurassic (Mann, 1999) are hindered by the poorly understood geology and tectonic processes that took place at the Mexico–South America boundary. One significant problem is the splitting of the magmatic arc into two segments in the Sierra de Perijá and Mérida Andes, Venezuela, which has been interpreted to represent tectonic escape of northwestern South America by strike-slip faulting in response to Romeral arc collision (Burke, 1988). Maze (1984), using paleomagnetic data, suggested a possible allochthony of the arc rocks in this region, but he stated that paleomagnetic measurements were not conclusive to establish a coherent tectonic hypothesis. On the other hand, Gose et al. (1993) made 115 paleomagnetic analyses of Mesozoic sedimentary rocks from the Perijá Mountains and determined that magnetization of the Jurassic La Quinta Formation is pre-Middle Cretaceous in age. Paleomagnetic data indicate that 45° clockwise rotations are the result of fault-bounded blocks in a left-lateral strike-slip zone in the Late Oligocene.

Maze (1983, 1984) and Bartolini (1998) agree that rifting in the Gulf of Mexico–Caribbean region and subduction of the Pacific margin are distinct tectonic processes that occurred simultaneously and are difficult to separate. The emplacement of subduction-related magmas contemporaneous with sedimentation of clastic sedimentary piles in continental grabens records the coeval existence of a compressive continental-margin setting and an extensional regime, possibly accompanied by large-scale transpressive structures.

Palinspastic paleogeographic maps were constructed for western and northern South America (Pindell and Tabbutt, 1995). One of these maps, for the Triassic–Early Jurassic (about 190 Ma), shows the southward continuation to southern South America of the magmatic arc and associated continental red beds in Colombia and Venezuela.

The correlation of Nazas, La Quinta, and Girón Formations with similar rocks in the Chortís Block is not possible because no arc-related rocks of Triassic–Jurassic age have been documented in that region.

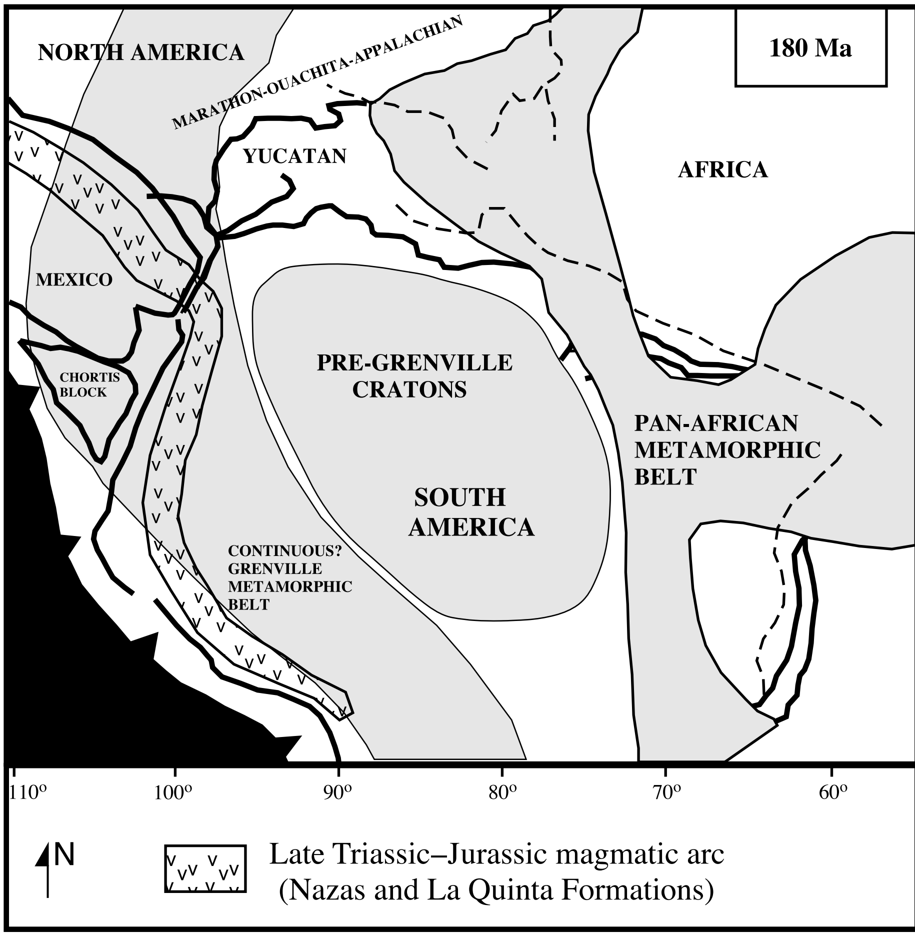

Figure 11. Reconstruction of the Caribbean region at 180 Ma. Modified after Mann (1999).

The oldest rocks in Honduras are metamorphic sequences of Precambrian and Paleozoic age that constitute the basement (Fakundiny, 1970; Horne et al., 1976). Metamorphic basement rocks are overlain either by the Upper Jurassic Todos Santos Formation (Mills et al., 1967) or by the Agua Fría Formation (Gordon, 1993), which consists of more than 200 m of continental and marine shale and sandstone that contain fossil floras of Middle Jurassic age (Delevoryas and Srivastava, 1981) and ammonites of Bathonian age (Gordon and Young, 1993). On the other hand, Neocomian strata of the Yojoa Group (Gordon, 1993) that overlie the Agua Fría Formation can be partially correlated with the San Ricardo and Todos Santos Formations in Guatemala and southern Mexico (Richards, 1963; Blair, 1987).

The palinspastic paleogeographic map constructed for the Triassic–Early Jurassic (190 Ma) (Pindell and Tabbutt, 1995) depicts only continental rocks in the Chortis Block, and no explanation is provided for the apparent lack of contemporaneous igneous rocks.

The scarcity or absence of early Mesozoic magmatic arc rocks in the Chortís block cannot be explained with certainty. The lack of a terrestrial volcanic arc may possibly be related to a poorly known original geographic position of the Chortis block west of Mexico and northwestern North America (Mann, 1999; Figure 11) or to the existence of a complex Late Triassic–Early Jurassic transpressive setting (Gordon, 1993) that did not permit a significant accumulation of volcanogenic sequences in the early Mesozoic (Gordon, 1989).

CONCLUSIONS

The structural, stratigraphic, and magmatic evolution of Mexico during the early Mesozoic is the result of the combination of geologic settings that developed during complex plate interactions. The uncertain position of Mexico, at a time when North and South America were separating, the Gulf of Mexico was evolving, and a convergent margin developed along western Mexico, determined to a great extent the geologic processes that prevailed in the interior of Mexico's landmass. To date, these processes and their timing are understood only partially.

The Nazas volcanic arc in north-central Mexico is part of the Mesozoic Cordilleran arc of the western North America Plate. Nazas volcanic and volcanic-sedimentary rocks record volcanic activity, crustal extension, and erosion of volcanic edifices in a subaerial volcanic arc that developed from the Late Triassic to the Middle Jurassic on the western continental margin of Mexico. The Nazas arc consists of more than 3 km of volcanic flows, pyroclastic rocks, and clastic sedimentary strata that were formed in extensional in tra-arc basins in the upper arc structure. The stratigraphy, depositional environments, geochronology, sediment composition, geochemistry, and deformation of the Nazas arc in the states of Durango, Coahuila, Chihuahua, San Luis Potosí, and Zacatecas, north-central Mexico, document the tectono-magmatic and depositional setting of this major convergent plate-tectonic feature. Drastic facies changes over short distances, highly variable thicknesses of basin-fill, mixed sediment composition, heterogeneous lithologic associations, and poorly known fluvial and alluvial facies distribution reflect the complexity of any arc environment. The size, original orientation, and geometry of individual basins in the arc are unknown in detail because of younger tectonic events and erosion.

Magmatic activity along the Nazas arc was intermittent, and although it is not feasible to precisely document the regional pulses of magmatic activity, it is at least possible to recognize the existence of broad magmatic pulses, such as an intrusive event in the Late Triassic and regional volcanic episodes in the Early and Middle Jurassic.

Jurassic extension along the arc was contemporaneous with rifting along the western Gulf of Mexico to the east. Rift basins along the Gulf were filled with red beds and evaporite deposits. In the Nazas arc, two distinct extensional provinces overlapped, with volcanic and pyroclastic rocks dominant in the west and true red beds, containing few intercalations of volcanic and pyroclastic rocks, in the east. Volcanic materials erupted from the arc and probably traveled east, reaching the zone of rifting that created the Gulf of Mexico. The complex interaction of geologic processes related to two distinct but coeval tectonic settings (subduction beneath the arc and rifting along the Gulf of Mexico rim) rule out previously proposed, simple rift-system models. Whether extension along the Nazas magmatic arc is the result of westward propagation of Gulf-related rifting or extension along the Gulf of Mexico coastal region related to back-arc crustal extension is an issue to be resolved.

The geochronology of rocks of the Nazas Formation was measured using $^{40}Ar/^{39}Ar$ (feldspars, hornblende, and whole rock), and K-Ar (whole rock, mineral separates) methods. Results show a wide range of ages, from Jurassic to Tertiary, most of which reflect resetting. Published isotopic data, paleomagnetic studies, and our stratigraphic constraints all show the Nazas volcanic arc to be as old as Late Triassic, but it is no younger than the Oxfordian Zuloaga and La Gloria Formations that cover it unconformably. Field relationships indicate that the volcanic arc in north-central Mexico ceased activity earlier than the arc in northwest Mexico and the western United States, where the arc was active until the Late Jurassic. The exact time of cessation (sometime between the Middle Jurassic and the Oxfordian) is unknown.

Whole-rock geochemistry of 45 volcanic rock samples collected at Nazas arc outcrops in northern and central Mexico agree with earlier interpretations of magma genesis, which indicate that volcanism was predominantly calc-alkaline and included rhyolite, rhyodacite, dacite, andesite, trachyte, trachyandesite, and rare basalt. Pyroclastic rocks include breccia and tuff, which are mostly felsic to intermediate. The total alkali-silica diagram and Rb vs. Nb-Y and Rb-SiO_2 paleotectonic discrimination diagrams show that the overall composition of the Nazas arc was calc-alkaline and related to a convergent subduction margin. Plutonic and volcanic rocks of the arc in northern and central Mexico both show the same chemical affinity, typical of subduction settings.

The integration of available surface and subsurface geologic data suggests that subsidence of the volcanic arc must have occurred in two stages. The first stage was sometime in the Early–Middle Jurassic, during the main stage of arc igneous activity, and involved extension, thinning, erosion of the arc, development of intra-arc basins, and deposition of continental volcanic-sedimentary sequences. The second stage was in the Oxfordian, when subsidence was lithostatic under the weight of sedimentary deposits of the La Gloria and Zuloaga Formations along the Mexican geosyncline; the subducting slab migrated west, and the arc structure cooled. Starting at the end of the Cretaceous and extending into the Tertiary, continuous subsidence along the Mexican geosyncline allowed for accumulation of more than 5 km of strata that buried the arc.

The Nazas Formation in Mexico and La Quinta and Girón Formations in Venezuela and Colombia have many similarities, such as age, depositional facies, composition of clastic rocks, magma types, geochemical affinity (with all the limitations), and, more importantly, tectonic settings in which these volcanic-sedimentary sequences were formed. These two suites, now hundred of kilometers apart, record simultaneous subduction along the Pacific margin of western Pangea, rifting events in the Gulf of Mexico and the Caribbean region, and possibly large-scale transpressive activity.

A correlation between the Nazas, La Quinta, and Girón Formations with similar rocks in Central America is less clear, because Triassic–Jurassic arc-related igneous rocks in the latter region have not yet been documented. One alternative for the absence of early Mesozoic igneous rocks in this region may the geographic position, to the west, of the Chortís Block with respect to Mexico and South America in the Triassic-Jurassic.

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APPENDIX 1
ANALYTICAL METHODS: ^{40}AR/^{39}AR

Samples analyzed by the $^{40}Ar/^{39}Ar$ method at the University of Houston were wrapped in Al foil and stacked in 6-mm (inside diameter) pyrex tubes. Neutron fluence monitors (ANU 92-176, Fish Canyon Tuff sanidine) were placed every 5–10 mm along the tube. Loaded tubes were packed in an Al container for irradiation. Synthetic K-glass (B. Turrin, U.S. Geological Survey) and CaF2 were included to monitor neutron-induced argon interferences from K and Ca. Samples were irradiated in the D3 position of the 1MW TRIGA type reactor at the Nuclear Science Center of Texas A&M University. Irradiations were performed in a dry tube device, shielded against thermal neutrons by a 5-mm-thick jacket of B4C powder, which rotates about its axis at a rate of 0.7 revolutions per minute to mitigate horizontal flux gradients. Correction factors for interfering neutron reactions on K and Ca were determined by repeated analysis of K-glass and CaF2 fragments. Measured ($^{40}Ar/^{39}Ar$) K values were 1.298 (±0.32) × 10^{-2}. Ca correction factors were ($^{36}Ar/^{37}Ar$)Ca = 2.85 (±0.03) × 10^{-4} and ($^{39}Ar/^{37}Ar$)Ca = 7.76 (±0.22) × 10^{-4}. J factors were determined by fusion of 3–5 individual crystals of 92–176 sanidine, which gave reproducibilities of 0.15 to 0.20%. Variation in neutron flux along the 80-mm length of the irradiation tube was <7%. An error in J of 0.5% was used in age calculations.

Irradiated crystals, together with CaF2 and K-glass fragments, were placed in a Cu sample tray in a high-vacuum extraction line and were fused using a 10 W CO2 laser. Sample viewing during fusion was by a video camera system and positioning was by a motorized sample stage. Reactive gases were removed by a 50-L sec-1 SAES getter prior to being admitted to a MAP 215-50 mass spectrometer by expansion. Some samples were step heated in a double-vacuum resistance furnace. The relative volumes of the extraction line and mass spectrometer allow ~80% of the gas to be admitted to the mass spectrometer. Peak intensities were measured using a Johnston electron multiplier by peak hopping through seven cycles; initial peak heights were determined by linear regression to the time of gas admission. Mass spectrometer discrimination and sensitivity was monitored by repeated analysis of atmospheric argon aliquots from an on-line pipette system. Measured atmospheric $^{40}Ar/^{36}Ar$ ratios yielded discrimination corrections of 1.00095 to 1.00198 (1 AMU), which were applied to measured sample isotope ratios. The sensitivity of the mass spectrometer was ~1.6 × 10^{-17} mol mV-1. Line blanks averaged 1.2 × 10^{-16} mol for mass 40 and 2.4 × 10^{-18} mol for mass 36. Computer-automated operation of the sample stage, laser, extraction line, and mass spectrometer, as well as final data reduction and age calculations, were done using Macintosh based software written by A. Deino (University of California at Berkeley). An age of 27.9 Ma (Steven et al., 1967; Cebula et al., 1986) was used for the Fish Canyon Tuff sanidine flux monitor in calculating ages for samples.

^{40}AR/^{39}AR DATING OF VOLCANIC ROCKS

Rhyolite CC-R: The age of this sample was measured by laser fusion analysis of individual plagioclase phenocrysts. The individual ages obtained range from ~27–176 Ma with a mode at ~120 Ma comprising the majority of the analysis. The age of this sample comes from an isochron plot that yields 98.6 ± 4.1 Ma with an initial $^{40}Ar/^{36}Ar$ of 306 ± 2, indicating a small amount of excess argon.

Rhyolite dike CC-D: Laser fusion analysis of plagioclase phenocrysts gave apparent ages ranging from ~85–323 Ma. Of the seven analyses, five define a mode at ~100 Ma , and a weighted mean of these analyses was 93.0 ± 9.0 Ma.

Rhyolite VJ-1: Sanidine and plagioclase phenocrysts were separated and analyzed by the laser fusion method. The majority of these analyses gave ages of ~60 Ma, with older ages ranging to ~500 Ma. The mode at ~60 Ma is dominated by sanidine ages and yields a weighted mean of 59.3 ± 1.7 Ma.

Rhyolite SMO-R: Sanidine phenocrysts separated from this sample were analyzed by the laser fusion method and yielded extremely consistent ages of ~34 Ma, with high radiogenic yields. A weighted mean of all analyses is 33.8 ± 0.2 Ma.

Basalt LB-B1: Furnace step-heating analysis of a whole-rock sample yielded a fairly flat age spectrum, with high ages in the initial ~2% gas released followed by a plateau-like segment, and then high ages in the final ~2% gas released. Steps comprising ~10–95% gas ^{39}Ar released give a weighted mean of 82.9 ± 0.6 Ma.

Rhyolite SR-R1: Individual sanidine phenocrysts from this sample were analyzed by the laser fusion method, which yielded consistent apparent ages ranging from 91–95 Ma. A weighted mean of these analyses is 93.9 ± 0.6 Ma.

Rhyolite CR-C1: A plagioclase separate from this sample was analyzed by the furnace step-heating approach, which gave a fairly flat age spectrum, with initial ages falling from ~376 Ma to a plateau-like segment giving apparent ages of ~110 Ma, which comprises ~95% of the ^{39}Ar released. This plateau segment yields an age of 109.7 ± 1.1 Ma.

Rhyolite CR-C2: Laser fusion of hornblende phenocrysts gave apparent ages ranging from ~85–106 Ma, with mode at ~100 Ma comprising four of the seven crystals analyzed. These analyses define a weighted mean of 99.4 ± 0.7 Ma.

Rhyolite CR-C3: Sanidine phenocrysts gave individual laser fusion ages that scatter from ~56 to 101 Ma, with no distinct mode defined. Thus, the best estimate of this sample's age comes from an average of all analyses — 74.8 ± 0.5 Ma.

Andesite CR-R4: Individual plagioclase phenocrysts yielded laser fusion ages ranging from 131–238 Ma, with most analyses at 150–160 Ma. The average is 156 Ma; however, isochron analysis gives an age of 145.5 ± 2.5 Ma and indicates an excess argon component with a $^{40}Ar/^{39}Ar$ of 333 ± 6 Ma.

Rhyolite CC-V: Plagioclase phenocrysts separated from this sample gave scattered apparent ages, determined by laser fusion analysis, which ranged from 72–347 Ma. Several modes are apparent at 70, 110, and 170 Ma. However, isochron analysis reveals a common excess argon component with a $^{40}Ar/^{39}Ar$ of 332 ± 4, which is shared by all phenocrysts analyzed. The isochron gives an age of 62.6 ± 5.2 Ma.

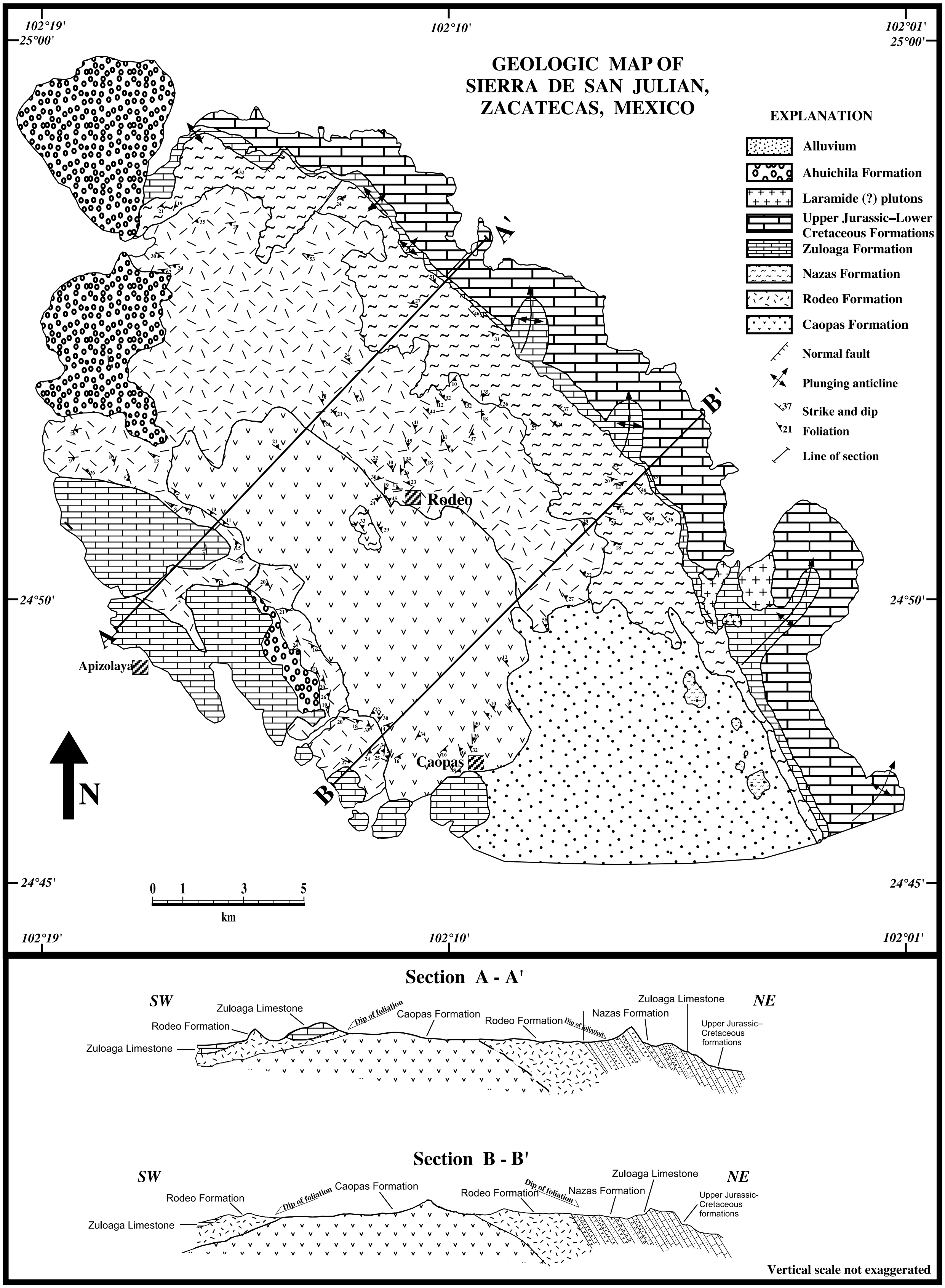
Rhyolite ST-C2: Individual plagioclase phenocrysts gave laser fusion ages ranging from ~89–225 Ma, with a strong mode at ~100 Ma comprising 11 of the 27 crystals analyzed. The analyses defining this mode yield a weighted mean of 96.0 ± 3.0 Ma.

Rhyolite ST-N16: A whole-rock sample yielded a step-heating age spectrum that exhibits slightly high initial and final step ages, with intermediate steps that comprise ~95% of the gas released and giving apparent ages of 70–75 Ma. These intermediate steps have a weighted mean of 75.4 ± 0.5 Ma.

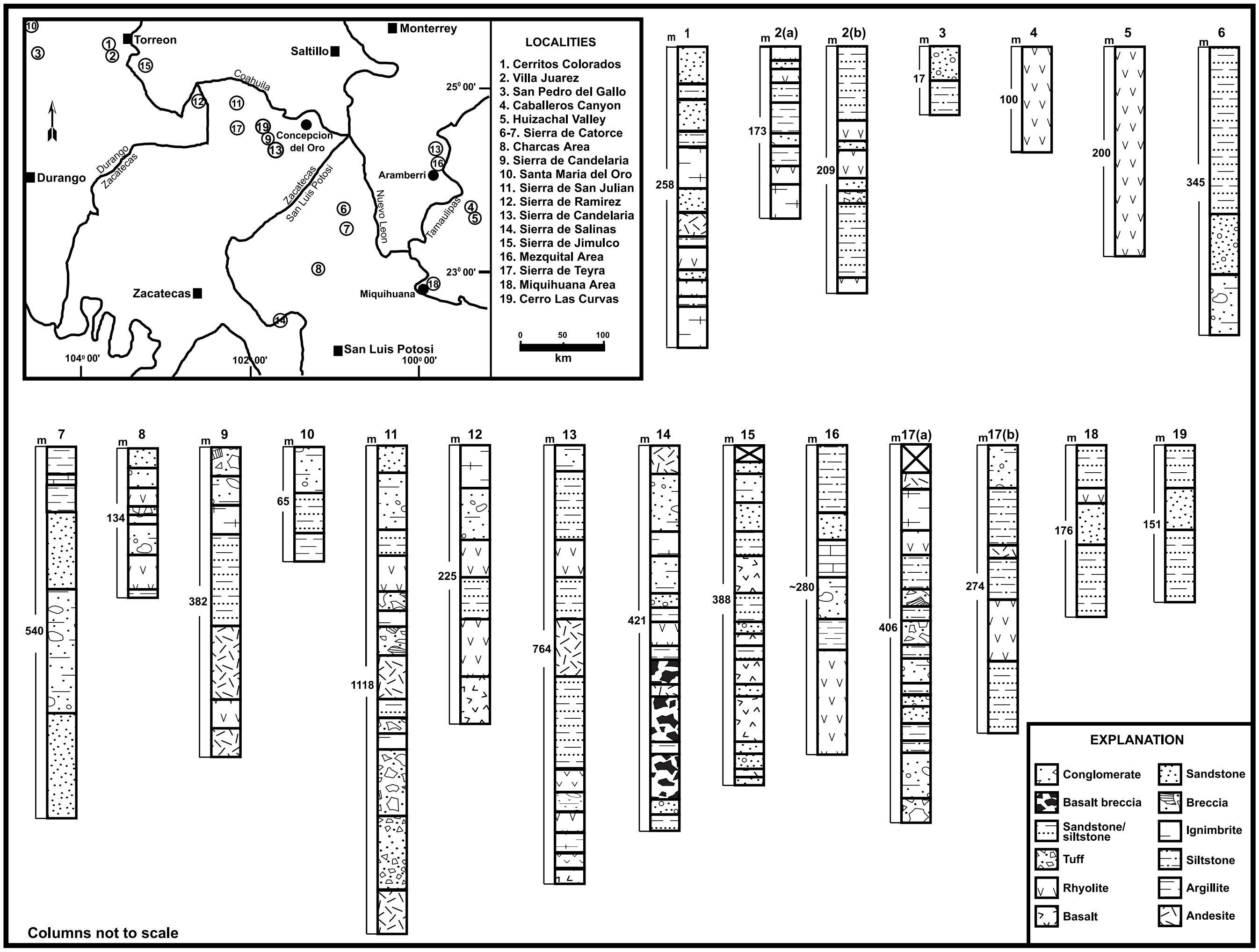
Rhyolite VJ-R1: Laser fusion analysis of individual plagioclase phenocrysts gave very scattered ages ranging from ~100–543 Ma, with the most significant mode at ~200 Ma. The analyses that define this mode fall on an isochron that yields an age of 195.3 ± 5.5 Ma and a trapped argon $^{40}Ar/^{39}Ar$ ratio of 310 ± 3 Ma, suggesting the presence of a small amount of excess argon.

Andesite CR-N1: Plagioclase phenocrysts were analyzed by the laser fusion method and yielded fairly consistent ages, which, with the exception of two older analyses, define a mode at ~72 Ma. The weighted mean of these data is 72.7 ± 0.6 Ma.

APPENDIX 2
GEOLOGIC MAP OF SIERRA DE SAN JULIAN, ZACATECAS



APPENDIX 3
MEASURED STRATIGRAPHIC COLUMNS OF THE NAZAS FORMATION IN CENTRAL MEXICO



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