Stratigraphy, geochronology, and geochemistry of the Laramide magmatic arc in north-central Sonora, Mexico

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ABSTRACT

The Laramide magmatic arc in the Arizpe-Mazocahui quadrangle of north-central Sonora, Mexico, is composed of volcanic rocks assigned to the Tarahumara Formation and several granitic plutons that intrude it. The arc was built over juxtaposed crustal basements of the Caborca and Mazatlan provinces. A basal conglomerate of the >4-km-thick Tarahumara Formation overlies deformed Proterozoic igneous rocks and Neoproterozoic to Early Cretaceous strata, thus constraining the age of a contractional tectonic event that occurred between Cenomanian and early Campanian time. The lower part of the Tarahumara Formation is composed of rhyolitic ignimbrite and ash-fall tuffs, andesite flows, and volcaniclastic strata, and its upper part consists of rhyolitic to dacitic ignimbrites, ash-fall tuffs, and volcaniclastic rocks. The Tarahumara Formation shows marked lateral facies change within the study area, and further to the north it grades into the coeval fluvial and lacustrine Cabuilla Group. The age of the Tarahumara Formation is between ca. 79 and 59 Ma; the monzonitic to granitic plutons have ages of ca. 71–50 Ma. The informally named El Babizo and Huépac granites, La Aurora and La Alameda tonalities, and the Puerta del Sol granodiorite compose the El Jaralito batholith in the southwestern part of the area.

Major and trace element composition of the Laramide igneous rocks shows calc-alkaline differentiation trends typical of continental magmatic arcs, and the isotope geochemistry indicates strong contribution from a mature continental crust. Initial 87Sr/86Sr values range from 0.70589 to 0.71369, and εNd values range from –6.2 to –13.6, except for the El Gueriguito quartz monzonite value, –0.5. The Nd, Sr, and Pb isotopic values of the studied Laramide rocks permit comparison with the previously defined Laramide isotopic provinces of Sonora and Arizona. The El Gueriguito pluton and Bella Esperanza granodiorite in the northeastern part of the study area along with plutons and mineralization of neighboring northern Sonora have isotopic values that correspond with those of the southeastern Arizona province formed over the Mazatzal basin (Lang and Titley, 1998; Bouse et al., 1999). Isotopic values of the other Laramide rocks throughout the study area are similar to values of provinces A and B of Sonora (Housh and McDowell, 2005) and to those of the Laramide Pb boundary zone of western Arizona, while the Rancho Vaquería and La Cubana plutons in the northernmost part of the area have the isotopic composition of the Proterozoic Mojave province of the southwestern United States. These data permit us to infer that a covered crustal boundary, between the Caborca block with a basement of the Mojave or boundary zone and the Mazatzal province, crosses through the northeastern part of the area. The boundary may be placed between outcrops of the El Gueriguito and Rancho Vaquería plutons, probably following a reactivated Cretaceous thrust fault located north of the hypothesized Mojave-Sonora megashear, proposed to cross through the central part of the area.

INTRODUCTION

The Late Cretaceous–early Cenozoic Laramide magmatic arc of Sonora, Mexico (Damon et al., 1983a, 1983b; McDowell et al., 2001), is composed of a thick and geographically extensive volcanic succession and nearly contemporaneous, mostly granitic, plutons that are part of the Sonoran batholith (Damon et al., 1983a) (Fig. 1). These rocks formed in a continental, Andean-type magmatic arc related to subduction of the Farallon plate beneath North America during Late Cretaceous and early Cenozoic time (Coney and Reynolds, 1977; Dickinson, 1981, 1989; Damon et al., 1983a; Engebretsen et al., 1985; Stock and Molnar, 1988).

Based mostly on their own data set of predominately K-Ar ages of plutonic rocks, Damon et al. (1983a) proposed that the Laramide arc in Sonora spanned 90–40 Ma, a range mostly accepted by others and broadly supported by subsequent geochronologic studies (Anderson et al., 1980; Valencia-Moreno et al., 2001, 2003, 2006; McDowell et al., 2001; Housh and McDowell, 2005; Pérez-Segura et al., 2009; Roldán-Quintana et al., 2009). In contrast, the study of the arc’s cogenetic volcanic succession has long been neglected despite extensive exposures, although some ages were published from northern and central Sonora (Supplemental Table 1). The name Mesa formation (Valentine,
Figure 1. Map outcrop distribution of plutonic and volcanic rocks of the Laramide magmatic arc in Sonora. The distribution of outcrops of the Late Cretaceous Cabullona Group, localities mentioned in the text, and inset map for location of Figure 2 are shown. The boundary between the Mazatzal province and Caborca blocks is indicated by the trace of the hypothetical Mojave-Sonora megashear as presented by Anderson and Silver (2005, their fig. 4).

1936) was first assigned to outcrops of this succession near the town of Cananea (Fig. 1), where it consists of a basal conglomerate and overlying bedded tuffs, andesite flows, agglomerates, and subordinate rhyolite flows >1600 m thick. Wilson and Rocha (1949) applied the term Tarahumara Formation to the Laramide volcanic succession and it became a commonly used name for extensive volcanic and volcaniclastic outcrops in Sonora; they described it as consisting of highly altered, aphritic intermediate volcanic rocks unconformably overlying Triassic strata in its type section near the town of Tecomipa, in central Sonora (Fig. 1). From that locality, McDowell et al. (2001) reported an age range of 90–70 Ma for an ~2.5-km-thick rhyolitic, dacitic, andesitic, and volcaniclastic succession.

Other studies of partial sections of these rocks in northern Sonora assigned local informal names, including Alcaparros formation and Arroyo Alcaparros andesitic rocks (González-León et al., 2000) and El Tuli formation (Rodríguez-Castañeda, 1994). To avoid confusion and to provide uniformity in the terminology, we follow other authors in applying the formal, more commonly used name Tarahumara Formation to this succession throughout its region of exposure (McDowell et al., 2001).

In this paper we provide new constraints on the stratigraphy and geochronology of the Tarahumara volcanic succession and the petrology and geochronology of associated plutonic bodies that represent the Laramide magmatic arc within the Arizpe-Mazocahui area in north-central Sonora (Fig. 1). The area is located in a position that is transitional between the classic localities of the Tarahumara Formation to the south, and the Mesa formation to the north. It includes the 15° × 20′, 1:50,000 scale topographic quadrangles named Arizpe, Nacoazari (part), Santa Ana (part), Banámichi, Agua Caliente, Aconchi, Cumpas, Baviácora, and El Rodeo (part) (Fig. 2), published by Instituto Nacional de Estadística, Geografía e Informática of the Mexican government. Our work is based on geologic mapping conducted at that scale and illustrated here by a generalized geologic map (Fig. 2). This cartography improves and in many instances corrects some of the previous geologic maps of the Arizpe, Banámichi, Baviácora, and Santa Ana quadrangles (González Gallegos et al., 2003; Quevedo León and Ramírez López, 2008; Servicios Geológicos y Cartográficos del Noroeste, S.A. de C.V., 1999; Corral Gastelum and Hernández Morales, 2008, respectively). Six measured stratigraphic columns and seven accompanying structural sections are included to illustrate the stratigraphic and tectonic relationships of the Laramide rocks with older and younger geologic units. The ages of the Laramide volcanic succession and the plutonic bodies are constrained by 28 U-Pb dates, one 40Ar/39Ar date, and 9 K/Ar dates, none of which have been reported previously. Another new 40Ar/39Ar date reported here helps to constrain the age of the younger unit of the basement over which the Laramide succession was deposited as well as the age of the younger tectonic event that deformed that basement in the region. We also dated detrital zircons from four sandstone units to constrain their maximum deposition ages. Two of these come from the Proterozoic basement and two others are from sandstone beds within the Laramide succession.

The study also incorporates 35 whole rock-geochemical analyses and 12 isotope analyses of Sm/Nd, Rh/Sr, and Pb/Pb of the Laramide plutonic and volcanic rocks, and 2 from the Proterozoic plutons. All of the analyzed samples have age and stratigraphic control. The field and analytical data help to document the stratigraphic, tectonic, and temporal framework of the Laramide magmatic arc for this part of the Cordillera, and the new cartography.
Figure 2. Geologic map of the study area that includes the 15° × 20′ Arizpe, Nacozaí, Banámichi, Santa Ana (part), Aconchi, Agua Caliente, Baviácora and El Rodeo quadrangles. Geology is simplified from our detailed geologic mapping (scale 1:50,000). Location and ages of all the dated samples are indicated. All 40Ar/39Ar and K-Ar ages were done on biotite.
and isotope data place constraints on possible delimitations of the Caborca and Mazatzal crustal blocks.

**ANALYTICAL METHODS**

U-Pb ages by laser ablation–multicollector–inductively coupled plasma–mass spectrometry (LA-MC-ICP-MS) were determined at the Arizona Laser ChronCenter of the Geosciences Department of the University of Arizona (results are reported in Supplemental Table 2) and at Centro de Geociencias, Universidad Nacional Autónoma de México (UNAM) (Supplemental Table 3) (procedures are described in Appendices 1 and 2, respectively). K-Ar analyses on biotites from igneous rocks were conducted at the Instituto de Geología, UNAM. Procedures are described in Appendix 3 and results are in Supplemental Table 4. The ⁴⁰Ar/³⁹Ar dating was performed at the Geochronology Laboratory of the Departamento de Geología, Centro de Investigación Científica y de Educación Superior de Ensenada (CICESE), and procedures were described in González-León et al. (2010). A hornblende separate from sample 04ES-8 was analyzed by the resistance-furnace incremental-heating age spectrum method at the New Mexico Geochronology Research Laboratory. (Details of the method and overall operation of the laboratory are provided at http://www.ees.nmt.edu/Geol/labs/Argon_Lab/Methods/Methods.) Geochemical analyses for major and trace elements were done by X-ray fluorescence and with a SIEMENS SRS 3000 spectrometer in the Laboratorio Universitario de Geocuímica Isotópica, UNAM, and by high resolution ICP-MS at the Department of Geology, University of Wisconsin–Eau Claire, USA. Radiogenic isotopic and select trace element concentrations were determined at the Isotopic Laboratory of the Geosciences Department of the University of Arizona following procedures reported in Appendix 4.

**REGIONAL GEOLOGIC SETTING**

The Proterozoic basement of Sonora was recognized as part of crustal southwestern North America by Damon et al. (1962) on the basis of geochronology data. Silver and Anderson (1974) noted that it could be divided into a northern block with ages between 1.7 and 1.6 Ga and a southern block with ages from 1.8 to 1.7 Ga that were later assigned to the North America (or Mazatzal) and Caborca terranes, respectively (Campa and Coney, 1983) (Fig. 1). However, the nature, age, and location of the crustal boundary are debatable. On one side, the Caborca block is interpreted as a piece of crustal southwestern USA translated to its present position by a major left-lateral fault assigned either to the Jurassic Mojave-Sonora megashear (Silver and Anderson, 1974; Anderson and Silver, 2005) (Fig. 1) or to the Permian–Triassic California-Coahuila transform fault (Dickinson and Lawton, 2001). On the contrary, Poole et al. (2005) argued that the Mojave basement and its Neoproterozoic sedimentary cover wrap around the Laurentian margin in the southwestern USA to continue southeast into the Caborca block, without major structural displacement. Similarly, Arvizu et al. (2009) depicted the Mojave and Mazatzal blocks in Sonora separated by a Nδ isotope Yavapai crustal province.

The Pinal Schist, the basement of the Mazatzal province, crops out in Sierra Los Ajos (Fig. 1) and nearby areas of northern Sonora, where it is dated as 1.69 Ga (Anderson and Silver, 2005) and 1.64 Ga (U-Pb, zircon) (Page et al., 2010). Proterozoic granites with ages near 1.4 Ga intrude the Pinal Schist (Anderson and Silver, 2005), and the nearest outcrop of this granite to the study area is in the town of Bacoachi (Fig. 1; our own observations). Other granites and gabbros that are assigned to the basement of the Caborca block because of their isotopic signatures and ages of ca. 1.7 Ga crop out in near localities of Cerro Prieto (Anderson and Silver, 2005), Rancho La Lámina (Amato et al., 2009), and El Crestón (Valenzuela-Navarro et al., 2005) (Fig. 1). Based on the occurrence of Caborcan Proterozoic granites in Rancho La Lámina, Amato et al. (2009) inferred that if present, the trace of the hypothetical Mojave-Sonora megashear might be located north of that locality (Fig. 1).

Proterozoic, mostly clastic, strata assigned to the Las Viboras and El Aguila Groups by Stewart et al. (2002) crop out within a few kilometers to the west of the study area. These units exceed a combined thickness of 3.5 km and overlie the igneous basement of the Caborca block. Superjacent Paleozoic clastic and carbonate strata (Stewart et al., 1997, 1999) are 2–4 km thick. This Proterozoic–Paleozoic succession of the Caborca block is lithologically different from the Cambrian–Permian sedimentary succession that unconformably overlies the basement of the Mazatzal province and that correlates with and resembles the Paleozoic formations of southeastern Arizona (e.g., Hayes and Landis, 1965). The nearby outcrops of this Paleozoic succession occur in the town of Bacoachi (Stewart and Poole, 2002) and in the vicinity of Cananea, where the succession is 1.2 km thick (González-León, 1986; Page et al., 2010).

Mesozoic rocks of the neighboring region to the north in Sonora include the Lower Jurassic Basomari Formation (Leggett, 2007) and the Middle Jurassic Rancho San Martín (Mauel, 2008), Elentia (Valentine, 1936; Wodzicki, 1994), and Lily (McAnulty, 1970, González-León et al., 2009) Formations, and a few dated Middle Jurassic granites (Anderson et al., 2005). These formations make up a clastic and volcanic succession that was deposited within a continental magmatic arc that developed in northern Sonora (Riggs et al., 1993, Anderson et al., 2005). Marine strata of the Upper Jurassic Cucurpe Formation (Villaseñor et al., 2005; Mauel et al., 2011) overlie the Basomari and Rancho San Martín successions near the town of Cucurpe. The combined thickness of the Jurassic formations is at least 3.5 km, and they are unconformably overlain by strata of the Bisbee Group, which in this region is documented to be Early Cretaceous in age and ~3 km thick (Peryam, 2006; Peryam et al., 2011).

A major Middle to Late Jurassic tectonic event of extensional deformation formed a rift basin, termed the Altar-Cucurpe Basin, where the Cucurpe Formation was deposited (Peryam, 2006; Mauel, 2008; Mauel et al., 2011). Alternatively, formation of this basin has been assigned to development of the left-lateral displacement of the Mojave-Sonora megashear (Anderson and Nourse, 2005; Anderson and Silver, 2005). A younger, contractional tectonic event affected the Bisbee Group and older strata during early Late Cretaceous time (Rangin, 1986). The age of the clastic continental succession of the Cocóspera Formation (Gilmont, 1978) deposited during this tectonic event (González-León et al., 2000) is constrained by a ⁴⁰Ar/³⁹Ar age of 93±3 ± 0.7 Ma (Fig. 3) obtained from an interbedded andesite in outcrops ~2 km northwest of the study area (Lawton et al., 2009). Following a period of uplift and erosion, deposition of the Laramide volcanic arc succession commenced.
Regionally, the Laramide magmatic arc of Sonora has been documented mostly through a large geochronology database and geochemical and isotopic studies of the plutonic rocks (Anderson and Silver, 1977; Anderson et al., 1980; Damon et al., 1983a, 1983b; Wodzicki, 1994; McDowell et al., 2001; Valencia-Moreno et al., 2001, 2003, 2006; Valencia et al., 2005; Roldán-Quintana et al., 2009; Pérez-Segura et al., 2009; Pérez-Segura and González-Partida, 2010), but far fewer data are available for the volcanic rocks (McDowell et al., 2001). Some ages are published for the Laramide volcanic rocks north of the study area, in the Cananea-Nacozari region (Wodzicki, 1994; Valencia et al., 2009; Pérez-Segura and González-Partida, 2010), and 6 40Ar/39Ar ages between 73 and 66 Ma are listed in Supplemental Table 1 (see footnote 1). Based on Sr and Nd isotopic variations and trace element compositions, Laramide granites of northern and central Sonora with ages between 57 and 68 Ma were assigned to northern and central granites by Valencia-Moreno et al. (2001). On the basis of Sr, Nd, and Pb isotope geochemistry, other granites with ages between 59 and 67 Ma were considered as belonging to provinces A and B by Housh and McDowell (2005), who also included isotopic characteristics of Oligocene and Miocene volcanic rocks to define their provinces. Geographically, the Laramide granites of provinces A and B roughly occupy the same region as the northern and central granites of Valencia-Moreno et al. (2001), while rocks of the study area are within the geographic domains of the northern granites and province A.

Younger regional events consist of Late Oligocene–Miocene magmatism, core complex formation, and basin-fill continental sedimentation of the Báucarit Formation that occurred associated with Basin and Range extensional deformation. Basin and Range deformation structurally dismembered the Laramide arc and older basement (Nourse et al., 1994; Wong and Gans, 2008; González-León et al., 2010; Wong et al., 2010).

**GOEKOLOGY OF THE STUDY AREA AND PREVIOUS STUDIES**

Within the study area the older rocks are El Jacalón diorite and the Santa Margarita granite (Rodríguez-Castañeda, 1994) that crop out in the Santa Ana quadrangle (Fig. 2). The diorite and granite have U-Pb (zircon) ages of 1702 Ma and 1104 Ma, respectively (Anderson and Silver, 2005). A gneissic zone developed in the El Jacalón diorite is spatially associated with the El Jucaral normal fault of post–Early Cretaceous age (Fig. 2) and is not a separate Proterozoic lithostratigraphic unit, as previously interpreted (the El Alamito unit of Rodríguez-Castañeda, 1994). A thick Proterozoic succession (>1 km thick) of mostly sandstone that locally overlies the igneous basement crops out in the Banámichi and Santa Ana quadrangles. It was named the Los Changos orthoquartzite, of supposed Paleozoic age by Rodríguez-Castañeda (1994) and later reassigned to the Proterozoic Las Viboras Group by Stewart et al. (2002) (Fig. 2). Detrital zircons from a sample of the middle part of this succession in the Banámichi quadrangle yielded U-Pb peak ages at 1.2, 1.47, 1.67, and 1.87 Ga (Figs. 2 and 4A) (Plascencia Corrales, 2008), similar to a sample collected from this succession that unconformably overlies the El Jacalón granodiorite in the Santa Ana quadrangle (Figs. 2 and 4B).

Isolated outcrops of schist, recrystallized limestone, and quartz-rich sandstone that occur as roof pendants in the Laramide plutons in the Sierra El Jaralito may be Proterozoic and/or Paleozoic in age (Peabody, 1979, in Roldán-Quintana, 1989; Mead et al., 1988) (Fig. 2). Cambrian to Permian formations in the Nacozari and Agua Caliente quadrangles (Fig. 2) are typical of Paleozoic strata that overlie the Mazatzal basin in northeastern Sonora.

The Mesozoic rocks in the study area include incomplete sedimentary successions of the Lilly (González-León et al., 2009) and Cucurpe Formations of Jurassic age, the Morita, Mural and Cintura Formations of the Early Cretaceous Bisbee Group, and the previously undated Cocóspera Formation (Fig. 2). Assignment of a Jurassic age by Rodríguez-Castañeda (1994) and Corral Gasteñum and Hernández Morales (2008) to widespread outcrops of the Bisbee Group and the Tarahumara Formation in the Santa Ana quadrangle are herein corrected on the basis of our geochronology. However, most of the area is occupied by outcrops of the volcanic and plutonic rocks of the Laramide magmatic arc; volcanic rocks, sedimentary strata, and a few rhyolitic domes of Oligocene–Miocene age; and by younger alluvial deposits (Fig. 2).

Previously published geochronologic information of the Laramide volcanic rocks in the study area include a U-Pb (zircon) age of 76 Ma from the Santa Ana quadrangle (McDowell et al., 2001), a 40Ar/39Ar (biotite) age of 58.67 ± 0.17 Ma from the Arizpe quadrangle (González-León et al., 2009); a more detailed 40Ar/39Ar study of the Tuapa Formation (Wong et al., 2010).

**Figure 3.** 40Ar/39Ar age spectrum of hornblende separate of sample 04ES-8 from an andesite interbedded with conglomerate of the Cocóspera Formation. This sample was collected near Rancho San Antonio, ~2 km northwest of the study quadrangle (Universal Transverse Mercator locality 12R 562410E 3382580N). MSWD—mean square of weighted deviates.
León et al., 2000), and a K-Ar (whole rock) age of 40.6 ± 1.1 Ma from the El Rodeo quadrangle (Damon et al., 1983a). Freshwater, non-age-diagnostic fossils including plants (Hernández-Castillo and Cevallos-Ferriz, 1999), algae (Beraldi-Campesi et al., 2004), diatoms (Chacón-Baca et al., 2002), and other microfossils (Beraldi-Campesi and Cevallos-Ferriz, 2005) were reported from local, interbedded lacustrine strata of the Tarahumara Formation in the Aconchi quadrangle.

Ages reported for the plutonic rocks include a 40Ar/39Ar (biotite) age of 56.7 Ma for the Rancho Vaquería pluton (pluton names derive from our informal terminology described in the following; Fig. 2) (González-León et al., 2000), a K-Ar (biotite) age of 56.4 Ma (Mead et al., 1988), and a 40Ar/39Ar (biotite) age of 57.3 Ma (Zuñiga Hernández, 2010) for the Las Cabecitas granodiorite (Fig. 2), and K-Ar ages reported by Damon et al. (1983b) of 51 Ma (orthoclase) for the San Felipe porphyry and 55.9 Ma (biotite) for the Bella Esperanza granodiorite (Fig. 2). The Bella Esperanza granodiorite was also dated as 56.9 Ma (K-Ar, whole rock) by Housh and McDowell (2005). Stocks of monzonite and diorite in the Cumobabi Mine (Fig. 2) yielded K-Ar ages between 63 and 56 Ma on biotite (Scherkenbach et al., 1985) and 51 Ma (40Ar/39Ar; Zuñiga Hernández, 2010).

Mead et al. (1988) first reported 40Ar/39Ar ages of 46.6 Ma (hornblende) and ca. 37.1 Ma (biotite), and a K-Ar age of ca. 39.5 Ma (biotite) for a granodiorite pluton in the Sierra El Jaralito. The El Jaralito and the Aconchi batholiths are names assigned by Roldán-Quintana (1991) to plutonic rocks that crop out in the Sierra El Jaralito and the Sierra de Aconchi, respectively (Fig. 2). Roldán-Quintana (1991)}
noted that the El Jaralito batholith is composed of granitic, granodioritic, quartz dioritic, and quartz monzonite facies with ages between ca. 69 and ca. 51 Ma, whereas he referred to the Aconchi batholith as a two-mica, alkaline granite with red garnet with an age of 35.96 ± 0.7 Ma. Radelli et al. (1991) and Macías Valdés (1992) later renamed this two-mica pluton the Huépac granite. In this work we follow the subsequent authors to include the Aconchi batholith as part of the El Jaralito batholith and based on our geochronology identify granite outcrops to the south in the Sierra El Jaralito as the Huépac granite. Furthermore, in this work and based mostly on geochronology and geochemistry, we recognize the El Jaralito batholith as a plutonic suite that includes previously unrecognized plu-

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Abundant centimeter- to meter-thick pegmatite dikes composed of K-feldspar, quartz, plagioclase, muscovite, biotite, garnet, and accessory minerals that cut through the El Jaralito batholith were studied in detail by Roldán-Quiñata et al. (1989) and Macías-Valdez (1992). Several published K-Ar and 40Ar/39Ar ages obtained from K-feldspars, hornblende, muscovite, and biotite from the two-mica Huépac granite, from pegmatite dikes, and from skarn rocks range from 41.6 Ma to ca. 18 Ma. The older ages are interpreted as cooling ages of the plutons (Mead et al., 1988), while ages between ca. 28 to ca. 18 Ma were interpreted by Lugo Zazueta (2006) and Wong et al. (2010) as cooling ages of the exhumed footwall of the core complex that forms the Sierra de Aconchi (Fig. 2).

The Laramide and older rocks of the study area are intruded by rhyolitic and dacitic dikes with ages between 23 and 25 Ma (Fig. 2; González-León et al., 2010; our data) and by basaltic dikes with ages near 23 Ma (Wong and Gans, 2008). These rocks are deformed by normal faults of the Basin and Range extensional event that formed the north-south elongated basins of the Sonora and Moctezuma Rivers, where thick, Late Oligocene to Miocene volcanic and terrigenous strata of the Búcarit Formation accumulated (González-León et al., 2010) (Fig. 2).

Stratigraphy and Structural Relationship of the Tarahumara Formation

Structural relationships of the Tarahumara Formation with older and younger units are illustrated along seven cross sections (Figs. 2 and 5). Tarahumara Formation stratigraphy is described by means of six measured columns (Fig. 6) and from its estimated thickness along structural sections F-F’ and G-G’ (Fig. 5). Samples from different stratigraphic levels of the Tarahumara sections were collected during field work for petrographic, geochronologic, and geochemical studies. A summary of the U-Pb, K-Ar, and 40Ar/39Ar geochronology is presented in Table 1. Geochemical and isotope analyses were performed from samples collected at same stratigraphic levels of the dated samples and results are presented in Supplemental Table 5 and Table 2, respectively. The main structural and the stratigraphic characteristics of the Tarahumara Formation along the cross sections are described next.

Cross-section A-A’ located in the Arizpe quadrangle crosses through the Picacho de Arizpe peak (Figs. 2 and 5). On the eastern flank of the Picacho, the Tarahumara Formation unconformably overlies deformed strata of the tectonically juxtaposed Mural and Cocóspora Formations. It dips homoclinally to the northeast and is unconformably overlain by Oligocene volcanic rocks (González-León et al., 2000). In the western flank of the Picacho de Arizpe, the Mural Formation is part of a block of Bisbee Group strata that thrusts over the deformed Cocóspora Formation. The measured thickness of the Tarahumara is 1260 m (Fig. 6A). Its lowermost part consists of crystal-poor rhyodacitic welded tuff and crystal-rich porphyritic dacite. Zircons from the rhyodacite gave a U-Pb age of 75.70 ±0.30/0.70 Ma (Fig. 7A; mean 206Pb/238U age, 97.3% confidence, n = 21). The remainder of the section is composed of well-beded rhyolite ash-fall tuff and brown to reddish volcaniclastic sandstone and siltstone.

Along cross-section B-B’, the Tarahumara Formation unconformably overlies the deformed Late Jurassic Cucurpe Formation, which crops out in an erosional window of an open anticline of the Tarahumara Formation in the El Teguachi ranch area (Figs. 2 and 5). In the southern part of this section the Cintura and Tarahumara Formations are normally faulted against each other across the Los Alisos fault. Between the El Teguachi ranch and the Sierra El Juparo, the Tarahumara Formation dips to the north and its section is offset by the normal fault of Cañada El Potrero. The composite stratigraphic column of the Tarahumara Formation starts north of the El Teguachi ranch and ends in Sierra El Juparo (Fig. 6B). It has an incomplete thickness of 1000 m and its lower part is occupied by a basal, 29-m-thick conglomerate that grades upward to interbedded volcaniclastic strata, rhyolitic to dacitic ignimbrite, ash-fall tuff and lacustrine limestone. The overlying unit consists of andesitic breccia, rhyolitic ash-fall tuff, and ignimbrite. A normal fault at the top of this unit omits part of the stratigraphic column, and its upper part was measured in the southern flank of Sierra Los Juparos. It is composed of bedded ash-fall tuff, rhyolitic breccias, sandstone, and conglomerate, and its upper part is composed of ignimbritic rhyolite and subordinate interbedded rhyolitic ash-fall tuff. Zircons from the upper ignimbritic rhyolite gave a U-Pb age of 71.7 ± 1.7 Ma (Fig. 7B; mean 206Pb/238U age, n = 16).

In cross-section C-C’ (Fig. 5) the Tarahumara Formation unconformably overlies the El Jacalón diorite and the Morita Formation of the Bisbee Group, both of which are juxtaposed across the El Jucaral fault (Fig. 2). Tarahumara rocks dip homoclinally 30°NE and at Cañada La Nopalosa are unconformably overlain by Cenozoic dacite, rhyolite, and conglomerate of the Sierra Las Guijas (Fig. 5). The 880-m-thick Cañada Motepori stratigraphic column (Fig. 6C) was measured between the creek of same name and Cañada La Nopalosa. Its basal unit is a 100-m-thick conglomerate with subordinate coarse-grained sandstone and ash-fall tuff beds that grade upward to volcaniclastic sandstone and ash-fall tuffs. Its middle part is composed of dacite to rhyolite ignimbrite and subordinate ash-fall tuffs and its upper part consists of volcaniclastic sandstone, siltstone, andesite breccia, fiamme-rich rhyolite ignimbrite, and dacite ignimbrite. A tuff bed from the lower part of this column did not yield zircons, but McDowell et al. (2001) reported a U-Pb zircon age of 76 Ma for the “volcanic section near El Tuli” ranch (Fig. 2) that we believe probably belongs to our measured section.

At cross-section D-D’ (Figs. 2 and 5), the Proterozoic Las Viboras Group thrusts over the Early Cretaceous Mural Formation of the Bisbee Group and the Tarahumara Formation overlies both faulted units. Tarahumara beds homoclinally dip to the northeast with angles as steep as 50°. The 1040-m-thick stratigraphic column El Salmón (Fig. 6D) has in its lower part an 80-m-thick conglomerate that is overlain by conglomerate, sandstone, and siltstone beds arranged in upward-fining successions with intercalations of rhyolitic and andesitic ash-fall tuffs. Concordant detrital zircons separated from a tuffaceous sandstone collected 133 m above the base of the formation yielded a younger U-Pb peak age of 76.39 ± 0.67 Ma, interpreted as the maximum age of deposition (Fig. 4C, inset; concordia age, n = 10), and abundant Proterozoic grains.
The middle part of the column is composed of andesite flows and breccia, while the upper part that crops out between Cerros El Cuervo and Cañada El Cuervo (Fig. 5) is composed of rhyolite ignimbrite, ash-fall tuff, and andesitic to dacitic breccia and agglomerate. A rhyolite from this section yielded a 70.02 ± 1.5 Ma age (Fig. 7C; mean 206Pb/238U age, n = 24). The uppermost part of this section between Cañada El Cuervo and Arroyo El Aliso (Fig. 5) has an estimated thickness of 700 m and is composed in its lower part of bedded dacitic ignimbrite, dacitic agglomerate and subordinate volcaniclastic sandstone with an uppermost quartz porphyritic rhyolite ignimbrite.

Cross-section E–E′ preserves the most complete stratigraphic succession of the Tarahumara Formation (Figs. 2 and 5), which unconformably
overlies the Proterozoic Las Viboras Group and dips homoclinal to the east. In the western foothills of the Sierra El Oso, the Tarahumara is offset by the northwest-southeast El Saucito normal fault that dips steeply to the southwest. In the eastern part of the section the Tarahumara is unconformably overlain by conglomerate and rhyolite of the Báucarit Formation. Because of the El Saucito fault offset, we measured the stratigraphy of the Tarahumara in two columns, named Cerro Colorado and Sierra El Oso, located west and east of the El Saucito fault, respectively.

The Cerro Colorado stratigraphic column (Fig. 6E) is 1865 m thick. Its basal unit is a 50-m-thick conglomerate composed of quartz-rich sandstone clasts that grades upward to a volcaniclastic succession with interbedded rhyolite and dacite ignimbrite. Zircons from a 20-m-thick, fiamme-rich rhyolite tuff located 120 m above the base of the formation yielded an age of 74.30 ± 1.3 Ma (Fig. 7D; mean 206Pb/238U age, n = 39). Upward, the succession is composed of rhyolite ignimbrite and ash and lapilli tuff, whereas its middle part consists of andesite flows and breccia, rhyolitic and dacitic ignimbrite, volcaniclastic sandstone, and well-beded ashl-fall tuff. Its upper part is composed of rhyolitic and dacitic ignimbrite, interbedded volcaniclastic sandstone, conglomerate, and andesite ashl-fall tuff. The lower part of this column located between the measured section and the Santa Elena Mine (Fig. 2) is intruded by a quartz phenocryst-bearing rhyolite dome that we dated as 73.56 ± 1.3 Ma (Figs. 6E and 7E; mean 206Pb/238U age, n = 59).

The exposed lower part of the 930-m-thick Sierra El Oso stratigraphic column (Fig. 6F) is a rhyolitic ignimbrite flow that was dated as 74.64 ± 1.5 Ma (Fig. 7F; mean 206Pb/238U age, n = 43). Most of the lower part of this succession is composed of rhyolitic to dacitic ignimbrite and interbedded ash-fall tuffs, whereas its middle part consists of volcaniclastic strata, minor ash-fall tuffs, dacite, and andesitic breccia. Its upper part is andesitic and rhyolitic ash-fall tuff, trachyanandesite flows, and rhyolite. Zircons from a rhyolitic tuff of this upper part yielded a U-Pb age of 75.10 ± 2 Ma (Fig. 7G; mean 206Pb/238U age, n = 41).

Structural cross-sections F-F′ and G-G′ in the southern part of the area traverse thick successions of the upper Tarahumara Formation as its lower part is offset by normal faults and cut by plutonic intrusions (Figs. 2 and 5). Its estimated thickness along section F-F′ is more than 2 km dipping homoclinal to the northeast, except in its upper part where it forms an open syncline, the northwest-southeast axis of which follows the upper part of the Sierra Las Palomas (Fig. 2). Outcrops of its exposed lower part are interbedded andesitic volcaniclastic sandstone, conglomerate, and andesite flows that are overlain by crystal- and lithic-rhyolite ignimbrite and an interbedded porphyritic dacite that was dated as 68.50 ± 2.0 Ma (Fig. 7H; mean 206Pb/238U age, n = 14). The middle part of the Tarahumara Formation is occupied by andesitic flows and its upper part is composed of stratified, crystal-
lithic-rich rhyolite ignimbrite with subordinate rhyolitic and andesitic ash-fall tuff and breccias. A rhyolite from the uppermost part of this succession was dated as 63.5 ± 1.4 Ma (Fig. 7; mean 206Pb/238U age, n = 19).

Along section G-G' the Tarahumara Formation dips homoclinal to the east and is offset by normal faults that bound north-trending Cenozoic basins (Fig. 5). At the southwestern end of this section, the Tarahumara Formation is intruded by the La Aurora tonalite (discussed in the following). The faulted section of the Tarahumara Formation in this section may be >1.5 km thick.

Other U-Pb ages of the Tarahumara succession in the study area come from samples that are not located on a measured section. From the Santa Ana quadrangle (Fig. 2) we dated detrital zircons from a volcaniclastic sandstone (Fig. 4D, n = 8) that yielded a dominant age peak of 152 Ma and subordinate peaks of 78, 192, 1060, and 1700 Ma, and two other rhyolites that yielded ages of 76.0 ± 2.7 Ma (Fig. 8C; mean 206Pb/238U age, n = 23). A reworked, tuffaceous rhyolite from the Aconchi quadrangle (Fig. 2) yielded an age of 69.1 ± 2.4 Ma (Fig. 8E; mean 206Pb/238U age, n = 17).

**Laramide Plutonic Rocks**

Laramide plutons in the northern part of the study area crop out as small exposures of a few square kilometers, but they form larger outcrops in Sierra El Jaralito batholith in the southern part (Roldán-Quintana, 1989). Based on field observation of well-exposed outcrops, most of the plutons are apparently fresh and homogeneous in texture and mineralogy, although detailed examination could reveal subtle variations in these characteristics. As also observed by other authors from the Laramide plutons of Sonora (Richard et al., 1989; Roldán-Quintana, 1991), mineralogy of the study plutons is simple with varying proportions of plagioclase, alkalii feldspar, quartz, biotite, scarce amphibole and pyroxene, and accessory minerals including titanite, opaque minerals, and zircon. Feldspar, biotite, and hornblende may present slight to moderate...
### TABLE 1. SUMMARY OF U-Pb, K-Ar AND 39Ar/40Ar GEOCHRONOLOGY FOR THE LARAMIDE ROCKS IN THE STUDY AREA

<table>
<thead>
<tr>
<th>Sample</th>
<th>Age (Ma) U-Pb (zr)</th>
<th>Age (Ma) K-Ar (bi)</th>
<th>Age (Ma) Ar/Ar (bi)</th>
<th>UTM location, altitude</th>
<th>Observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>4-23-09-9</td>
<td>63.9 ± 1.4</td>
<td></td>
<td></td>
<td></td>
<td>Porphyritic rhyolite with quartz, sodic plagioclase, and chloritized grains of biotite in a eutaxitic vitric mesostasis moderately altered to sercite.</td>
</tr>
<tr>
<td>4-23-09-12</td>
<td>68.5 ± 2</td>
<td></td>
<td></td>
<td></td>
<td>Crystal-rich, porphyritic dacite with plagioclase, biotite, and hornblende strongly altered to chlorite. Hyalopillic mesostasis recrystallized to microcrystalline quartz, chlorite, and iron oxides.</td>
</tr>
<tr>
<td>3-5-08-2</td>
<td>70.02 ± 1.5</td>
<td></td>
<td></td>
<td></td>
<td>Porphyritic rhyolite with resorbed and fragmented quartz crystals to 3 mm long, broken plagioclase crystals, biotite altered to chlorite and scarce volcanic rock fragments. Hyalopillic mesostasis and glass shards.</td>
</tr>
<tr>
<td>1-28-09-2</td>
<td>71.7 ± 1.7</td>
<td></td>
<td></td>
<td></td>
<td>Crystal-rich rhyolitic ignimbrite with corroded and fragmented quartz crystals to 3 mm long, K-feldspar and sodic plagioclase and subordinate biotite in a hyalopillic mesostasis with glass shards.</td>
</tr>
<tr>
<td>11-25-09-6</td>
<td>72.20 ± 1.60/–1.20</td>
<td></td>
<td></td>
<td></td>
<td>Rhyodacite with altered crystals of feldspar up to 2 mm long, quartz and subordinate latths of biotite altered to chlorite. Groundmass is vitric and fluidal with fragments of fiamme recrystallized to quartz and calcite.</td>
</tr>
<tr>
<td>11-16-07-4</td>
<td>73.56 ± 1.3</td>
<td></td>
<td></td>
<td></td>
<td>Porphyritic rhyolite with resorbed quartz grains to 2 mm long, sodic plagioclase and orthoclase and subordinate chloritized biotite. Vitric mesostasis with incipient recrystallization.</td>
</tr>
<tr>
<td>12-5-08-2</td>
<td>73.8 ± 1.6</td>
<td></td>
<td></td>
<td></td>
<td>Rhyolitic tuff with crystals of quartz, plagioclase, subordinate lithic fragments, and biotite. Crystals are broken and angular. Quartz is locally resorbed and plagioclase is altered to calcite. Matrix recrystallized to microcrystalline quartz.</td>
</tr>
<tr>
<td>9-18-07-2</td>
<td>74.30 ± 1.3</td>
<td></td>
<td></td>
<td></td>
<td>Crystal-poor (&lt;20 vol% crystals), ignimbrite rhyolite with resorbed quartz crystals, broken feldspar altered to sercite and calcite, scarce volcanic rock fragments in a vitric matrix with glass shards.</td>
</tr>
<tr>
<td>3-30-09-13</td>
<td>69.1 ± 2.4</td>
<td></td>
<td></td>
<td></td>
<td>Rhyolitic tuff with reassembled and angular quartz crystals to 3 mm long in a vitric matrix with abundant glass shards and pumice fragments.</td>
</tr>
<tr>
<td>11-19-07-1</td>
<td>74.64 ± 1.5</td>
<td></td>
<td></td>
<td></td>
<td>Igmbrinitic rhyolite with feldspar, albite, and sanidine, biotite and fragments of volcanic rocks altered to iron oxide. Hyalopillic matrix.</td>
</tr>
<tr>
<td>2-27-08-4</td>
<td>75.10 ± 1.2</td>
<td></td>
<td></td>
<td></td>
<td>Rhyodacite with broken crystals of albite to 3 mm long, sanidine and biotite in a hyalopillic mesostasis. Fiamme fragments are chloritized.</td>
</tr>
<tr>
<td>4-7-08-1</td>
<td>75.70 ±0.30/–0.70</td>
<td></td>
<td></td>
<td></td>
<td>Crystal-poor (20 vol% crystals) rhyodacite with quartz, biotite altered to iron oxide, volcanic rock fragments and fiamme. Vitric mesostasis with moderate recrystallization and some alteration to clay and iron oxide.</td>
</tr>
<tr>
<td>11-26-09-3</td>
<td>75.75 ±0.55/–0.85</td>
<td></td>
<td></td>
<td></td>
<td>Crystal-rich dacite with plagioclase altered to calcite. Quartz is resorbed. Biotite altered to chlorite. Crystals are broken and angular, plagioclase is fractured. Vitric matrix with glass shards.</td>
</tr>
<tr>
<td>3-3-09-7</td>
<td>76.0 ± 2.7</td>
<td></td>
<td></td>
<td></td>
<td>Crystal-rich, porphyritic rhyodacite-dacite with crystals of feldspar to 3 mm long. Feldspar locally in glomeroporphyritic texture. Hyalopillic groundmass with microclasts of feldspar altered to calcite.</td>
</tr>
<tr>
<td>11-26-09-4</td>
<td>78.7 ± 1.3</td>
<td></td>
<td></td>
<td></td>
<td>Igmbrinitic rhyolite with broken and resorbed orthoclase, sanidine, plagioclase, quartz, and biotite crystals in a fluidal banded vitric matrix with fragments.</td>
</tr>
</tbody>
</table>

Note: UTM—Universal Transverse Mercator; zr—zircon; bi—biotite.
Table 2. Summary of isotopic analyses for the Laramide and Proterozoic igneous rocks of the study area.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Unit</th>
<th>Sm</th>
<th>Nd</th>
<th>Sm/Nd</th>
<th>εNd(Ga)</th>
<th>147Sm/144Nd</th>
<th>143Nd/144Nd(0)</th>
<th>Standard error (%)</th>
<th>εNd(i)</th>
<th>TDM (Ga)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4-23-09-5</td>
<td>Tarahumara volcanic rock</td>
<td>63</td>
<td>5.69</td>
<td>32.96</td>
<td>0.1727</td>
<td>0.14419</td>
<td>0.51236</td>
<td>0.0009</td>
<td>-7.84</td>
<td>-7.10</td>
</tr>
<tr>
<td>10-24-07-3</td>
<td>Tarahumara volcanic rock</td>
<td>74</td>
<td>3.74</td>
<td>23.69</td>
<td>0.1577</td>
<td>0.095431</td>
<td>0.512189</td>
<td>0.0014</td>
<td>-8.76</td>
<td>-8.00</td>
</tr>
<tr>
<td>11-25-09-6</td>
<td>Tarahumara volcanic rock</td>
<td>72</td>
<td>8.48</td>
<td>43.55</td>
<td>0.1948</td>
<td>0.117728</td>
<td>0.512123</td>
<td>0.0012</td>
<td>-10.05</td>
<td>-9.32</td>
</tr>
<tr>
<td>9-29-09-3</td>
<td>Huelpac granite</td>
<td>55</td>
<td>1.51</td>
<td>8.42</td>
<td>0.1908</td>
<td>0.115309</td>
<td>0.511907</td>
<td>0.0000</td>
<td>-11.56</td>
<td>-10.90</td>
</tr>
<tr>
<td>9-30-04-4</td>
<td>La Aurora tonalite</td>
<td>70</td>
<td>6.40</td>
<td>32.39</td>
<td>0.1923</td>
<td>0.116235</td>
<td>0.512284</td>
<td>0.0010</td>
<td>-8.91</td>
<td>-8.19</td>
</tr>
<tr>
<td>10-1-09-2</td>
<td>La Alamedita</td>
<td>70</td>
<td>6.04</td>
<td>32.86</td>
<td>0.1837</td>
<td>0.111116</td>
<td>0.512175</td>
<td>0.0016</td>
<td>-9.03</td>
<td>-8.27</td>
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<tr>
<td>11-27-09-5</td>
<td>Puerta del Sol granodiorite</td>
<td>49</td>
<td>5.33</td>
<td>33.30</td>
<td>0.1914</td>
<td>0.097579</td>
<td>0.512228</td>
<td>0.0011</td>
<td>-12.32</td>
<td>1.50</td>
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<tr>
<td>2-27-09-8</td>
<td>El Babizo granite</td>
<td>58</td>
<td>0.62</td>
<td>3.10</td>
<td>0.1976</td>
<td>0.119521</td>
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<td>0.0014</td>
<td>-10.48</td>
<td>-9.89</td>
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<tr>
<td>9-29-09-3</td>
<td>Huelpac granite</td>
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<td>4.68</td>
<td>25.13</td>
<td>0.1864</td>
<td>0.116284</td>
<td>0.512208</td>
<td>0.0022</td>
<td>-8.39</td>
<td>-7.78</td>
</tr>
<tr>
<td>11-25-09-6</td>
<td>Tarahumara volcanic rock</td>
<td>72</td>
<td>8.48</td>
<td>43.55</td>
<td>0.1948</td>
<td>0.117728</td>
<td>0.512123</td>
<td>0.0012</td>
<td>-10.05</td>
<td>-9.32</td>
</tr>
<tr>
<td>9-29-09-3</td>
<td>Huelpac granite</td>
<td>55</td>
<td>1.51</td>
<td>8.42</td>
<td>0.1908</td>
<td>0.115309</td>
<td>0.511907</td>
<td>0.0000</td>
<td>-11.56</td>
<td>-10.90</td>
</tr>
<tr>
<td>10-24-07-3</td>
<td>Tarahumara volcanic rock</td>
<td>74</td>
<td>3.74</td>
<td>23.69</td>
<td>0.1577</td>
<td>0.095431</td>
<td>0.512189</td>
<td>0.0014</td>
<td>-8.76</td>
<td>-8.00</td>
</tr>
<tr>
<td>11-25-09-6</td>
<td>Tarahumara volcanic rock</td>
<td>72</td>
<td>8.48</td>
<td>43.55</td>
<td>0.1948</td>
<td>0.117728</td>
<td>0.512123</td>
<td>0.0012</td>
<td>-10.05</td>
<td>-9.32</td>
</tr>
</tbody>
</table>

Note: TDM—depleted mantle model age.
Mean $^{206}\text{Pb}/^{238}\text{U}$ age at 75.70 ± 0.30/-0.70 Ma

MSWD = 2.0

(97.3% confidence, from coherent group of 21)
medium grained with plagioclase, quartz, biotite, K-feldspar, hornblende, titanite, apatite, zircon, and iron oxides. Plagioclase is euhedral oligoclase in crystals as large as 7 mm and quartz is anhedral. Biotite occurs as euhedral phenocrysts as large as 8 mm, and K-feldspar is euhedral orthoclase and microcline as large as 3 mm. Zircons from this pluton yielded a U-Pb age of 61.10 +0.90/–0.50 Ma (Fig. 8H; mean 206Pb/238U age, 95.1% confidence, n = 17). La Aurora is the largest pluton of the study area and varies in composition from diorite in its western outcrops to tonalite in its eastern outcrops. It is medium grained, holocrystalline, and hypidiomorphic with anhedral quartz, euhedral plagioclase (oligoclase), biotite, orthoclase, and microcline. Accessory minerals are titanite, apatite, zircon, and iron oxides. La Aurora yielded a zircon U-Pb age of 69.65 +1.05/–0.45 Ma (Fig. 8I; mean 206Pb/238U age, 95% confidence, n = 26), and three other samples of different localities of the pluton gave K-Ar ages (biotite) of 60.4 ± 1.2, 57.2 ± 1.4, and 49.5 ± 1.1 Ma (Table 1).

Granodioritic plutons include the Rancho Vaquería, Los Alisos, San Antonio, Las Cabezas, Puerta del Sol, and Bella Esperanza (Figs. 2 and 9A). The Rancho Vaquería is a medium-grained, phaneritic, hypidiomorphic rock with plagioclase, quartz, K-feldspar, and biotite and equal or lesser amounts of hornblende, titanite, augite, and iron oxide. This pluton gave a U-Pb age of 55.8 ± 0.9 Ma (Fig. 10A; mean 206Pb/238U age, n = 27). The Los Alisos granodiorite (Fig. 2) is medium grained, holocrystalline, and porphyritic with euhedral plagioclase (albite-oligoclase), subhedral quartz, and euhedral orthoclase. Secondary minerals are biotite and magneteite in a plagioclase porphyry texture, and accessory minerals are titanite, apatite, and zircon. This pluton yielded a 40Ar/39Ar plateau age of 61.76 ± 0.81 Ma in biotite (Fig. 11; Table 1). The San Antonio granodiorite is medium grained, holocrystalline, and hypidiomorphic with euhedral plagioclase (oligoclase-anorthoclase), anhedral quartz, K-feldspar, biotite and lesser amounts of hornblende, titanite, magnetite, apatite and zircon. It yielded a U-Pb age of 67.7 ± 1.6 Ma (Fig. 10B; mean 206Pb/238U age, n = 22). Las Cabecitas granodiorite is medium grained, hypidiomorphic, and granular with commonly zoned plagioclase, quartz, K-feldspar, biotite, and lesser amounts of hornblende, titanite, and magnetite. Two samples collected at different localities in this pluton yielded ages of 59.1 ± 1.6 (Fig. 10C; mean 206Pb/238U age, n = 12) and 56.3 ± 1.2 Ma (Fig. 10D; mean 206Pb/238U age, n = 18).

The Puerta del Sol pluton intrudes La Alamedita tonalite and the Huépac granite in its outcrop in the eastern part of the Sierra de Aconchi, but its more extensive outcrop is in the southwestern part of the study area (Fig. 2). We assume that these outcrops belong to the same pluton based on their similar composition and age. The Puerta del Sol was named by Anderson et al. (1980) for its outcrops that extend south of the study area, where U-Pb zircon ages of 57 ± 3 Ma and 49.1 Ma were reported by Anderson et al. (1980) and González Becuvar (2011), respectively. It is medium to coarse grained and holocrystalline, with quartz, plagioclase, K-feldspar, biotite, titanite, muscovite, zircon, and iron oxide. Quartz is anhedral, as long as 1.3 cm, and K-feldspar is euhedral orthoclase and microcline as long as 1.2 cm; plagioclase is albite-oligoclase. Biotite crystals are euhedral and muscovite is secondary. Samples from the two different outcrops of the Puerta del Sol within the study area yielded U-Pb ages of 51.26 ± 1.0 (Fig. 10E; mean 206Pb/238U age, n = 17) and 49.95 ±1.05/–0.45 Ma (Fig. 10F; mean 206Pb/238U age, 95% confidence, n = 26), but a biotite K-Ar age was 23.6 ± 1.1 Ma (Table 1). We did not study the Bella Esperanza granodiorite that was dated by Housh and McDowell (2005), but their isotopic data are referred in the Discussion.

Granites are part of the El Jaralito batholith and include the leucocratic El Babizo and Huépac granites (Fig. 2). These plutons have 23.6 ± 1.1 Ma (Table 1). We did not study the Bella Esperanza granodiorite that was dated by Housh and McDowell (2005), but their isotopic data are referred in the Discussion.

The analyzed volcanic rocks range in composition between 63 and 78 wt% SiO2. They are mostly high-K calc-alkaline andesites to rhyolites, and half of the samples are high-silica rhyolites in the (K2O/SiO2) vs. SiO2 relation trends with SiO2, except for K2O (Fig. 9B). Major elements such as Al2O3, Fe2O3, and CaO show negative correlation trends with SiO2, except for K2O (Fig. 9B), typical calc-alkaline differentiation trends.

The Huépac granite is fine to medium grained, allotriomorphic-granular to hypidiomorphic-granular, and composed of quartz, K-feldspar, plagioclase, muscovite, biotite, garnet, zircon, and magnetite. Quartz is subhedral to euhedral with undulose extinction. K-feldspar is euhedral to subhedral orthoclase and microcline with late-stage inclusions of quartz, plagioclase, and muscovite. Plagioclase is mostly euhedral oligoclase and minor albite. Muscovite is euhedral and biotite is anhedral. Myrmekite and perthitic intergrowths are present. Two samples from different localities yielded ages of 58 +0.60/–0.90 Ma (Fig. 10I; mean 206Pb/238U age, 93.5% confidence, n = 11) and 54.95 ± 1.6 Ma (mean 206Pb/238U age, n = 36); two other samples yielded K-Ar biotite ages of 29.5 ± 0.9 and 28.7 ± 1.0 Ma (Table 1).

Other intrusive rocks that crop out in the area and were not studied are the Rancho Viejo diorite, the San Felipe porphyry, local stocks of diorite and granodiorite in the Cumobabi Mine (Scherkenbach et al., 1985), a rhyolitic dome near Rancho Agua Caliente (Fig. 2), and dikes of pegmatite, microgranite, diorite, and basalt that occur throughout the area.

**GEOCHEMISTRY**

**Elemental Geochemistry**

The analyzed volcanic rocks range in composition between 63 and 78 wt% SiO2. They are mostly high-K calc-alkaline andesites to rhyolites, and half of the samples are high-silica rhyolites in the (K2O/SiO2) vs. SiO2 relation trends with SiO2, except for K2O (Fig. 9B), typical calc-alkaline differentiation trends.
Mean $^{206}\text{Pb}/^{238}\text{U}$ age at 58.1 ± 1.7 Ma

MSWD (concordance) = 0.26

3-3-09-8

El Gueriguito

Mean $^{206}\text{Pb}/^{238}\text{U}$ age at 52.76 ± 0.9 Ma

MSWD (concordance) = 0.73

3-3-08-1

La Cubana

Mean $^{206}\text{Pb}/^{238}\text{U}$ age at 69.1 ± 2.4 Ma

MSWD (concordance) = 0.79

3-30-09-13

La Cubana

Intercepts at 73.0 ± 4.1 & 1443 ± 33 Ma

MSWD = 2.0

60 64 68 72 76 80

Mean = 73.8 ± 1.6 Ma

MSWD = 0.45 (95% confidence)

(error bars are 2σ)

Figure 8.
Figure 9. Geochemical discrimination plots for the geochronologically dated Laramide volcanic and plutonic rocks of the study area. (A) Chemical classification of the dated Laramide plutons according to the R1-R2 diagram of De la Roche et al. (1980). Rock grouping used in this paper is derived from this plot. (B) Al₂O₃ versus SiO₂, Fe₂O₃ versus SiO₂, and CaO versus SiO₂ Harker diagrams, as well as (K₂O vs. SiO₂) diagram with fields of Peccerillo and Taylor (1976). (C) Rare earth element diagram normalized to chondrite (McDonough and Sun, 1995) for the volcanic and plutonic rocks of the study area compared with the northern and central granites of Sonora reported by Valencia-Moreno et al. (2001). (D) Shand’s index diagram A/(NK) versus A/(CNK) from Maniar and Piccoli (1989) to characterize geochemical and tectonic environments of the studied plutons, including the Proterozoic El Jacalón diorite and the Santa Margarita granite. Fields for island arc (IAG), continental collision (CCG), and continental arc (CAG) granites are indicated. (E) Rb versus (Y+Nb) diagram (Pearce et al., 1984) characterizing tectonic environment.
Chondrite-normalized rare earth element (REE) patterns are primarily enriched in the light (L) REEs and have unfractionated heavy (H) REE patterns. $\text{La}_\text{N}/\text{La}_\text{H}$ ratios are moderately fractionated, ranging from 6.7 to 21, and all samples have moderate negative Eu anomalies ($\text{Eu}/\text{Eu}^* \approx 0.45$ and 0.94) (Fig. 9C).

Plutonic rocks range in composition between 57 and 76 wt% SiO$_2$ and, based on the major element classification scheme of Frost et al. (2001), are mostly calc-alkaline and magnesium rocks that plot within the field of Cordilleran granites. Harker diagrams of their major element show correlations similar to those for the volcanic rocks (Fig. 9B). This behavior reflects the fractionation effect of feldspar, titanite, and oxides during the crystallization of the plutonic rocks. Similarly, the plutonic rocks are enriched in LREEs and depressed in middle and HREEs oxides during the crystallization of the plutonic rocks. The measured Pb isotopic values for the Tara–Humera volcanic rocks range from 19.06 to 19.28 for $^{207}\text{Pb}/^{204}\text{Pb,}$ and 38.65–39.34 for $^{208}\text{Pb}/^{204}\text{Pb}$.

The $^{87}\text{Sr}/^{86}\text{Sr}$ initial ratios for the Tarahumara volcanic rocks are in the range of 0.70589–0.70863 and the plutonic rock range is 0.70650–0.71369 (Fig. 12). Initial (i) $\varepsilon_{\text{Nd}}$ values for the Laramide magmatic arc are negative, ranging between −7.1 and −9.3 and between −6.2 and −13.6 for the plutonic rocks, apart from the El Gueriguito, which has an $\varepsilon_{\text{Nd}}$ of −0.5. The measured Pb isotopic values for the volcanic rocks range from 19.06 to 19.28 for $^{206}\text{Pb}/^{204}\text{Pb}$, from 15.65 to 15.67 for $^{207}\text{Pb}/^{204}\text{Pb}$, and from 38.72 to 38.91 for $^{208}\text{Pb}/^{204}\text{Pb}$.

DISCUSSION

Basement and Structural Relationships

The Laramide magmatic arc in the study area was built upon two different crustal basement types, which are discriminated on the basis of their contrasting ages and lithologies. The Caborca block basement in the western part of the area is represented by the 1.7 Ga El Jacalón diorite and its overlying succession, the Neo-protozoic Las Viboras Group, and the Cambrian–Permian succession that crops out in the northeastern part of the area represents formations that overlie the Pinal Schist, the basement of the Mazatzal block in northeastern Sonora. Anderson and Silver (2005, their Fig. 4) interpreted the boundary between the two blocks in the study quadrangle as the Jurassic Mojave-Sonora megashear, transecting northwest-southeast through its central part (Figs. 1 and 2).

The Neoprotozoic to early Late Cretaceous sedimentary succession of the area is at least 12 km thick, considering better-preserved successions in the neighbor areas. Although tectonic events that affected these strata remain poorly constrained, during Jurassic time the region was affected by arc magmatism (Busby-Spera, 1988; Riggs et al., 1993; González-León et al., 2009; Dickinson et al., 2010; Lawton et al., 2010) and subsequent extensional deformation (Peryam, 2006; Mauel, 2008; Mauel et al., 2011; Peryam et al., 2011). Contractual deformation, which created reverse faults and folds in strata as young as late Albian (La Juana Formation; Mauel et al., 2011) and generated syntectonic conglomerate of the Cocóspora Formation (Fig. 2), took place between the Cenomanian and early Campanian on the basis of our age of ca. 93 Ma for the Cocóspora, and overlap by the Tarahumara Formation, which has a maximum age of ca. 78 Ma.

Our timing data are consistent with shortening related to accretion in western Mexico of outboard arc terranes followed by the establishment of a voluminous continental margin arc. Accretion of either the offshore (Johnson et al., 1999) or fringing (Bushy, 2004) Alisitos arc was likely completed along western Baja California by ca. 93 Ma (Alsleben et al., 2008), while the following subduction of the Farallon plate established a continental margin with Cordilleran magmatism extending along western Mexico southward from California (Dickinson and Lawton, 2001). Assuming that the Baja Peninsula was part of the continent before Neogene rifting of the Gulf of California, La Posta-type magmatism began at 105 Ma in Baja and by ca. 90 Ma had migrated eastward to the vicinity of coastal Sonora (Silver and Chappell, 1988; Gastil et al., 1990; Valencia-Moreno et al., 2006; Ramos-Velázquez et al., 2008) to form the Laramide arc. A similar scenario of fringing arc amalgamation, i.e., Cenomanian–Turonian (ca. 93–84 Ma) shortening followed by Santonian–Maastrichtian arc establishment along the Pacific coast of southern Mexico, was reported by Centeno-García et al. (2011).

The Laramide magmatic arc that migrated eastward into Sonora likely encountered and developed on already tectonically thickened crust, indicated by the unconformable relationship of the Tarahumara Formation on the older deformed rocks and its local overlapping relationship with thrust faults. Although the structural attitude of the Tarahumara varies mostly from homoclinal to kilometer-scale open folding, similar to deformation recorded by Basin and Range fill deposits of the study area (Fig. 2), crustal shortening and associated basement- cored uplift is recorded in the Cabullona basin (González-León and Lawton, 1995) (Fig. 1). Middle Cenozoic detachment faulting events that disrupted the Tarahumara Formation and older rocks are not clearly constrained, but the north-south Basin and Range faulting is evident (González-León et al., 2010).

Nature and Timing of the Laramide Magmatism

The thickness of the lower Tarahumara Formation is at least 1.8 km at Cerro Colorado, but considering the estimated >2 km for its younger, upper part at cross-section F-F’, we infer that the volcanic pile might exceed 4 km in the study area. The Tarahumara succession is mostly ryholitic, volcanioclastic, and andesitic, with subordinate lacustrine limestone in its lowermost 2 km, and rhyolitic to dacitic in its upper...
part, with subordinate andesite and volcanic clastic strata. The most conspicuous stratigraphic characteristic of the formation is its regionally extensive basalt conglomerate. Overlying lithologies in the succession show marked lateral facies changes, mainly a gradation from mostly volcanic in the Banamichi quadrangle to more volcaniclastic and tuffaceous lithologies toward the northern part of the Arizpe quadrangle.

Further to the north, between the study area and the city of Cananea, several \(^{40}\)Ar/\(^{39}\)Ar dates indicate that the Tarahumara succession has ages as old as ca. 73 Ma and as young as ca. 64 Ma (Cox et al., 2006; Supplemental Table 1 [see footnote 1]). Northward and east of Cananea, the Tarahumara Formation grades laterally into the Cabullona Group, a mostly fluviolacustrine sedimentary succession that was deposited in the Laramide Cabullona basin (Talíaferro, 1933; González-León and Lawton, 1995). Ashfall tuffs in the lower strata of the Cabullona Group yielded late Campanian U-Pb ages (López-Higuera et al., 2008) that corroborate its equivalence with the Tarahumara Formation. At Sierra Los Ajos, an intermediate area between the main outcrops of the Cabullona Group to the north and the Tarahumara Formation to the south, there is an incomplete basal succession of detrital and volcanic rocks that is correlative with the Cabullona Group (Page et al., 2010).

The \(^{40}\)Ar/\(^{39}\)Ar ages between ca. 80 and 74 Ma obtained by Page et al. (2010) from volcanic rocks of this succession are similar to the ages we report here, supporting the inference of a transitional facies relationship between the mostly volcanic Tarahumara Formation to the south and the mostly sedimentary Cabullona Group to the north.

In southern Sonora, strata assigned to the Tarahumara Formation are >2.5 km thick and composed of dacite and andesite flows, volcaniclastic strata, and felsic tuffs (McDowell et al., 2001); the 1.4-km-thick lower member of the formation here has U-Pb ages from 89 to 70 Ma (McDowell et al., 2001) and ages as old as ca. 90 Ma have also been reported for plutonic rocks of the region (Pérez-Segura et al., 2009).

The geochronological results indicate that the Tarahumara Formation ranges from 80 to 59 Ma in the study area. The older age is based on a dated rhyolite (sample 11–26–09–4) from the El Rodeo quadrangle and from young detrital grains in a volcaniclastic sandstone (sample 12–5–08–3, Fig. 4D) of the Santa Ana quadrangle. Although the base of the formation is not exposed at these places, the ages of the basal Tarahumara where it unconformably overlies basement are consistently ca. 76 Ma (Fig. 5). The proposed maximum age for the Tarahumara is also supported by ages reported by Page et al. (2010) from Sierra Los Ajos. The younger U-Pb age that we obtained for the Tarahumara is ca. 63 Ma from a rhyolite in the upper part of section F-F, but a \(^{40}\)Ar/\(^{39}\)Ar age of ca. 59 Ma was previously reported for a Tarahumara dacite from the Arizpe quadrangle (González-León et al., 2000). Similarly, according to our U-Pb ages, pluton emplacement in the study area occurred ca. 70–50 Ma. This indicates that Tarahumara volcanism is ~10 m.y. older than plutonism and it continued after volcanic activity ended.

On the basis of these data, we infer that Laramide magmatism in the study area took place between 80 and 50 Ma (Fig. 13). Damon et al. (1983a, 1983b), taking into consideration that plutons as old as 90 Ma are present in coastal Sonora, proposed that Laramide arc development in Sonora occurred between 90 and 40 Ma; McDowell et al. (2001) and Valencia-Moreno et al. (2006) noted that eastward migration of the arc plutonism resulted in ages arranged in approximately north-south isochronous belts (Fig. 14). Our study area is within the 70 Ma isochron of McDowell et al. (2001) and the 60 Ma isochron of Valencia-Moreno et al. (2006, their Fig. 6), but we modify this eastern isochron line to a 50 Ma age based on a regional age compilation and our new ages (Figs. 13 and 14; Supplemental Table 1 [see footnote 1]), although relatively minor magmatic activity reached central Chihuahua to the east ca. 68 Ma (McDowell and Mauger, 1994). Compilation of somewhat varied and limited Laramide volcanic and plutonic ages within the 70–50 Ma isochronous belt (Fig. 13) confirms that regional Laramide volcanism began near 80 Ma, ended ca. 55 Ma, and had a peak age of activity near 73 Ma, apparently predating local plutonism. The compilation is also consistent with U-Pb ages in our study area suggesting that Laramide plutonism occupied central Sonora for at least 20 m.y., from the Maastrichtian to early Eocene, with an apparent peak of activity ca. 56 Ma.

Protracted magmatic activity may have contributed to the evident resetting of ages of the plutonic bodies, as indicated by discordant U-Pb and K-Ar ages. For example, La Aurora tonalite (ca. 70 Ma U-Pb) yielded K-Ar ages of ca. 60, 57, and 49 Ma in three different parts of its regionally extensive outcrop and a ca. 49 Ma K-Ar age was obtained from an El Babizo granite sample dated as ca. 70 Ma (U-Pb). We consider the K-Ar age of the Mazocahui monzodiorite, ca. 48 Ma, as a result of the ca. 49 Ma resetting event that coincided with ending of important plutonic activity.

Two other apparently separate pulses of magmatism in the age compilation of central Sonora (Fig. 13) are supported by scarce data. These episodes include an older one centered near...
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90 Ma and a younger one near 43 Ma. Based on their age compilation for a quadrangle in southwestern Sonora, McDowell et al. (2001) considered that arc development occurred between 90 and 55 Ma, although they noted a gap of magmatism between 90 and 74 Ma (their Fig. 5) and the long duration of the Laramide event. Because the same gap of magmatism is indicated in the study quadrangle between 93 Ma, the age of the Cocospera Formation, and the 80 Ma maximum age of the Tarahumara Formation, we regard the ca. 90 Ma magmatic event as syndeformational with earliest Late Cretaceous shortening, an idea that might be tested by future work. The younger magmatism with ages near 43 Ma is rare in Sonora. For example, a 42 Ma (U-Pb) two-mica granite (González Becuvar, 2011) and upper Eocene volcanic rocks (Supplemental Table 1 [see footnote 1]) with poor stratigraphic control are present in this region. This event corresponds to sporadic igneous activity that, according to Damon et al. (1983a), postdates the Laramide arc, which by 46 Ma had migrated, with abundant magmatism, to central Chihuahua (McDowell and Mauger, 1994).

Younger K-Ar ages of ca. 30 and 24 Ma that we obtained from the Huépac granite and that the Puerta del Sol granodiorite are similar to 40Ar/39Ar ages obtained from these same plutons by Lugo Zazueta (2006), Wong and Gans (2008), and Wong et al. (2010), that they interpreted as cooling ages related to metamorphic core complex denudation of this region.

Geochemistry and Isotope Interpretation

The Laramide volcanic and plutonic rocks of the study quadrangle show LREE enrichment relative to HREE, a typical distinctive character of arc-related magmas, and they plot within that field in the diagram Rb versus Y + Nb of Pearce et al. (1984) (Fig. 9E). Notable differences in the
REE characteristics of the Laramide rocks are associated with variations in rock types within the study area. The intermediate plutonic rocks (diorite to granodiorite) have a similar, consistent steep-sloped fractionation pattern with enrichment of LREE, lower HREE, and minor to negligible negative Eu anomalies. The volcanic rocks have patterns similar to those of these plutons, but show a more notable negative Eu anomaly. The REE pattern of El Babizo granite is similar to that of the volcanic rocks and intermediate plutonic rocks, but REEs of the Huépac granite are fractionated, depleted with respect to the other rocks, and have an important negative Eu anomaly. The REE pattern of the Laramide rocks of the study area is similar to the REE patterns reported by Valencia-Moreno et al. (2001) for granites of central and northern Sonora, except for the Huépac granite (Fig. 3C).

The Nd and Sr isotope data of these rocks have consistent narrow ranges, except for the El Gueriguito, Rancho Vaquería, Huépac, and El Babizo granites (Fig. 12A). The εNdi value of −0.5 for the El Gueriguito granite is the least negative, while the Huépac and the Rancho Vaquería granites have the most negative values. All the other rocks have εNdi values that range from −6.2 to −9.3. The El Babizo granite has the most radiogenic initial Sr value (0.71369); an initial Sr value of 0.70900 reported by Mead et al. (1988) for the Huépac granite is more radiogenic than the two values we obtained for this pluton. The Huépac and probably El Babizo granites have characteristics of S-type granites; they are both peraluminous, two-mica leucocratic granites with low εNdi values and meter-sized enclaves of metasedimentary rocks. The Huépac granite contains garnet and El Babizo has the higher initial Sr value. As a whole, the isotope geochemistry is indicative of a strong crustal contribution to an arc built over mature continental crust; this is supported by highly radiogenic 87Sr/86Sr initial ratios, negative εNdi ratios, and highly radiogenic common Pb.

In Figure 12 we compare our isotope data with others few published from Sonora, although those of Pb isotopes are scarcer. The data are also compared with provinces of Arizona recognized from Laramide magmatic complexes to try to find isotopic affinities within the neighboring regions. Lang and Titley (1998) defined the northwest, southeast, and south provinces according to Nd and Sr isotope variations, and Bouse et al. (1999) defined the Mojave, boundary zone, central, and southeast Arizona provinces (Fig. 14) according to Pb isotope compositions of Laramide plutons and sulfide mineralization. Bouse et al. (1999) further divided the southeast province into northern and southern subprovinces (Fig. 14) and suggested that the lead isotope compositions of the Laramide rocks of these provinces reflect the Pb isotope compositions of their Paleoproterozoic basement rocks.

Our initial Nd versus Sr values are more similar to the values of provinces A and B of Sonora defined by Housh and McDowell (2005) and south and southeast provinces of Arizona, but the Huépac, Rancho Vaquería, and one Tarahumara rhyolite from near Mocetzuma plot within the northwest province (Fig. 12A). Nevertheless, the El Gueriguito granite and granites of the Cananea-Nacozi region (Figs. 12B and 14) plot apart, with values that are clearly restricted to the geographically neighboring south province of Arizona (Fig. 12A), as are the northern and central granites of Valencia-Moreno et al. (2001). Two data from ca. 73 Ma Laramide granites were reported by Nourse et al. (2005) from northwesternmost Sonora. One of them, interpreted by Nourse et al. (2005) to be in the Mazatzal block, plots within the southeastern province of Arizona, and the other, assigned to the Yavapai province, plots within the northwestern province of Lang and Titley (1998) (Fig. 12A).

In the western part of the study area, the Proterozoic El Jacalón diorite (1.7 Ga) and the Santa Margarita granite (1.1 Ga) have εNdi values of 0.56 and 4.58 and depleted mantle model ages (TDM) of 2.23 Ga and 1.34 Ga, respectively (Table 2). The initial Nd and TDM values of the El Jacalón correspond to values of the Proterozoic Mojave isotopic province of southwestern North America (Bennett and DePaolo, 1987) and are similar to values of Proterozoic granites from La Lámina (Amato et al., 2009), El Crestón (Valenzuela-Narvarro, 2005), and other granite and metamorphic rocks of the Caborca block (Farmer et al., 2005) (Fig. 1). Iriondo et al. (2004) reported other Proterozoic granites of the Caborca block with εNdi values between 0.6 and 2.6 and Nd model ages between 2.07 and 1.8 Ga, and considered them to have affinity either to the Yavapai or the Mojave-Yavapai boundary zone provinces. Pb isotope data indicate that the El Jacalón pluton plots within the trend of the 1.7 Ga Mojave basement in the uranogenic diagrams of Wooden et al. (1988) and Wooden and DeWitt (1991), and the Santa Margarita granite plots in the 1.7 Ga central Arizona trend (Fig. 12B). These data plots are similar to those reported by Farmer et al. (2005) for the 1.7 and 1.1 Ga metamorphic and plutonic basement rocks of the Caborca region (Fig. 12B). The Laramide rocks of the study area and the Oposura granodiorite located east of the study area (Fig. 14) show transitional 207Pb/206Pb versus 206Pb/204Pb isotope compositions between the Mojave and Arizona trends and have values that overlap with Sonoran provinces A and B and with the Laramide Pb boundary zone of Arizona (Bouse et al., 1999). However, the El Gueriguito, the Bella Esperanza granodiorite, and sulfur mineralization of the Cananea district (Fig. 12B) are within the south-southeastern subprovince of Arizona (Bouse et al., 1999). Bouse et al. (1999) recognized that sulfur mineralization of the Cananea Mine district belongs to that subprovince. La Cubana and Vaquería plutons have the higher 206Pb/204Pb isotope values and plot in the Mojave province (Fig. 12B).

In a thorogenic diagram, the Pb values of the El Jacalón and Santa Margarita plutons plot intermediate between the Mojave and central Arizona Pb isotope provinces (Wooden and Miller, 1990; Wooden and DeWitt, 1991), similar to most of the scattered field of the Proterozoic...
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granites and so-called Grenvillian granites reported by Iriondo et al. (2004) and Farmer et al. (2005) from the Caborca block (Fig. 12C). As noted by Bouse et al. (1999) for Arizona, the Pb isotope compositions of the Laramide granites of Sonora show a restricted range of values compared with the wider values of the Proterozoic rocks. In this diagram, our Laramide rocks overlap with the Sonoran provinces A and B and partially overlap with the Pb boundary zone of Bouse et al. (1999). Nevertheless, the El Gueriguito, Bella Esperanza granodiorite, Laramide mineralization of the Cananea district, and probably the Oposura granodiorite cluster within the south-southeastern Arizona subprovince.

Although the database is limited, isotope data of the El Gueriguito and Bella Esperanza granodiorite of the northeastern part of the study quadrangle, along with granite and mineralization of the Cananea-Nacozari region (Fig. 14), indicate isotopic affinity with the Nd, Sr, and Pb Laramide isotope province of south-southeastern Arizona located within the Mazatzal province. In contrast, data from the other Laramide rocks (including the northernmost La Cubana and Rancho Vaquería plutons; Fig. 14) of the study area, which are similar to isotope data from Laramide provinces A and B, show isotopic affinity with the Laramide Pb boundary zone of Arizona that is located with the Proterozoic boundary zone of Arizona. These isotopic affinities support the hypothesis that a crustal boundary between the Caborca block with an affinity either to Proterozoic Mojave or boundary zone provinces, and the Mazatzal province, may cross through the area.
This boundary may occur between outcrops of the El Gueriguito and Rancho Vaquería plutons (Fig. 14), probably coincident with the thrust fault at Picacho de Arizpe that places the Bisbee Group over the Cocóspera Formation. To the northwest, this boundary may extend and continue as the San Antonio fault (Rodríguez-Castañeda, 2000), which also emplaces Bisbee Group strata over the Cocóspera Formation, interpreted as having formed during the early Late Cretaceous deformation. Nevertheless, the crustal boundary is not observable and its precise age is not herein constrained because the San Antonio fault may be a reactivated transtensional fault of Jurassic age (Anderson and Nourse, 2005). In any case, our inferred crustal boundary is north of the proposed trace of the Mojave-Sonora megashear suggested by Anderson and Silver (2005) within the study quadrangle, and also north of the Proterozoic granites of Rancho La Lámina as previously proposed by Amato et al. (2009) (Fig. 14).

CONCLUSIONS

Rocks of the Laramide magmatic arc of Sonora are well exposed in north-central Sonora, where the Tarahumara Formation unconformably overlaps basement rocks of Paleo-protrozoic to Cenomanian age. This basement records several deformational events, the youngest of which is an early Late Cretaceous shortening that led to deposition of the clastic Cocóspera Formation, thus indicating that the volcanic arc may have been deposited over a tectonically thickened basement. The ca. 93 Ma age of the Cocóspera Formation and the ca. 80 Ma maximum age of the Tarahumara Formation constrain the duration of the shortening event from Cenomanian to early Campanian, and its inception may be related to accretion of the Alisitos arc to adjacent Baja California.

The >4-km-thick Tarahumara Formation consists of a basal conglomerate overlain by dominant riftic andesitic to dacitic ignimbrite, riftic to andesitic ash-fall tuffs, andesite flows and breccia, interbedded volcaniclastic fluvial strata, and lacustrine limestone. The upper part of the formation consists of basaltic to riftic pyroclastic ignimbrite and tuffs with subordinate volcaniclastic strata. Lateral facies changes are present within the study area, and further into northern Sonora it grades to the contemporaneous fluvial and lacustrine Cabullona basin. Widespread outcrops of the Tarahumara Formation extend into southern Sonora, where they are also composed of riftic, dacitic, and andesitic tuffs (McDowell et al., 2001). Laramide plutons that intrude the Tarahumara Formation comprise dioritic, monzonitic, and granodioritic to granitic plutons that are given informal names. The Proterozoic El Jacalón diorite (1.7 Ga) and the Santa Margarita granite (1.1 Ga) that crop out in the western part of the study area have implications for identification of a Proterozoic crustal boundary in this part of Sonora.

Geochemical data of the Laramide arc indicate that both volcanic and plutonic rocks are calc-alkaline, pertaining to Cordilleran magmatism. The age of the Tarahumara Formation in the study area ranges from ca. 80 to ca. 59 Ma, while the ages of the plutons range from 71 Ma to ca. 50 Ma. The study area was thus within isochrons 70–50 Ma, defined by the eastward-migrating plutonism of the Laramide arc in Sonora (Valencia-Moreno et al., 2006), and a compilation of available published ages between them indicates that volcanism started near 80 Ma and ended ca. 54 Ma. Similarly, regional plutonism started ca. 72 Ma and ended at 50 Ma. These ages agree with our data obtained from the study quadrangle and indicate that regionally, magmatism lasted nearly 30 m.y., ages of volcanism are nearly 10 m.y. older than plutonism, and there were apparent major peak ages of volcanism ca. 73 Ma and a peak age of plutonism ca. 56 Ma. Magmatism as old as ca. 90 Ma in southern Sonora might be syntectonic with the early Late Cretaceous deformation event, while scarcer magmatism as young as 40 Ma corresponds to waning activity of the Laramide arc.

Although structural attitudes of the Tarahumara Formation in the study area range from homoclinal to open folds apparently related to strong dissection of Cenozoic normal faulting, compressive deformation by basement- cored uplift thrusting is recorded for the origin of the Cabullona basin in northeastern Sonora (González-León and Lawton, 1995). Nd and Sr isotope data of the studied Laramide rocks compare more with values of Laramide provinces A and B of Sonora (Housh and McDowell, 2005) and with those of the northwest and southeast isotopic provinces of Arizona (Lang and Titley, 1998). However, the El Gueriguito pluton in the northern part of the area has the less negative εNd value and, along with granites of the Cananea-Nacozari region, can be compared with the neighboring southern Laramide province of Arizona (Lang and Titley, 1998) (Figs. 12 and 14) that is in the Proterozoic Mazatzal province. Similarly, when Pb isotope data of the El Gueriguito quartz monzonite, Bella Esperanza granodiorite, and ore minerals from the Cananea Mine district are plotted in a uranogenic diagram (Wooden et al., 1988; Wooden and DeWitt, 1991), they show values similar to the south-southeastern province of Arizona (Bouse et al., 1999), while the other Laramide rocks plot within the field of the Pb boundary zone of Arizona (Bouse et al., 1999), but the northernmost La Cubana and Rancho Vaquería plutons plot within values of the Mojave province.

The isotope affinities of the Laramide rocks indicate that a crustal boundary between the Caborca block that has an affinity to the Mojave or boundary provinces and the Mazatzal province is present in the area. This inference is supported by outcrops of the Proterozoic El Jacalón diorite, which has Mojave isotopic affinity, in the western part of the quadrangle and outcrops of Paleozoic strata belonging to the Mazatzal province in the northeastern part of the quadrangle. The boundary may be south and west of the Paleozoic outcrops and between the El Gueriguito and the Rancho Vaquería plutons, most probably following the early Late Cretaceous thrust fault at Picacho de Arizpe. The nature and age of this boundary, however, cannot be precisely determined because outcrops are covered, although it is located well to the north of the proposed trace of the Mojave-Sonora megashear in the area (Anderson and Silver, 2005).

APPENDIX 1. U-Pb AGE DETERMINATION PROCEDURES AT ARIZONA LASERCHRON CENTER, GEOSCIENCES DEPARTMENT, UNIVERSITY OF ARIZONA, TUCSON

Zircon crystals were extracted from samples by traditional methods of crushing and grinding, followed by separation with a Wilfley table, heavy liquids, and a Frantz magnetic separator. Samples were processed such that all zircons were retained in the final heavy mineral fraction. A large split of these grains (generally 1000–2000 grains) was incorporated into an epoxy mount together with fragments of our Sri Lanka standard zircon. The mounts were sanded down to a depth of ~20 μm, polished, imaged, and cleaned prior to isotopic analysis.

U-Pb geochronology of zircons was conducted by laser ablation–multicollector–inductively coupled plasma–mass spectrometry (LA-MC-ICP-MS) at the Arizona LaserChron Center (Gehrels et al., 2006, 2008). The analyses involved ablation of zircon with a New Wave UP193HE Excimer laser (operating at a wavelength of 193 nm) using a spot diameter of 30 μm. The ablated material is carried in helium into the plasma source of a Nu Plasma high-resolution MC-ICP-MS, which is equipped with a flight tube of sufficient width that U, Th, and Pb isotopes are measured simultaneously. All measurements were made in static mode, using Faraday detector with 10-E11 ohm resistors for 204U, 232Th, 208Pb–204Pb, and discrete dynode ion counters for 206Pb and 202Hg. Ion yields are ~0.8 mV/ppm. Each analysis consisted of one 15 s integration on peaks with the laser off (for backgrounds), 15 s integrations with the laser firing, and a 30 s delay to purge the previous sample and prepare for the next analysis. The ablation pit is ~15 μm deep. For each analysis, the errors in determining 206Pb/238U and 208Pb/204Pb resulted in a measurement error of ~1%–2% (at 2σ level) in the 206Pb/238U age. The errors in measurement of 206Pb/204Pb and 208Pb/204Pb also result in ~1%–2% (at 2σ level) uncertainty in age for grains that are older than 1.0 Ga, but are substantially larger for younger grains due to low intensity of the 208Pb.
signal. For most analyses, the crossover in precision of $^{206}\text{Pb}/^{204}\text{U}$ and $^{208}\text{Pb}/^{204}\text{U}$ ages occurs at ~1.0 Ga.

The $^{206}\text{Hg}$ interference with $^{206}\text{Pb}$ was accounted for in measurement of $^{206}\text{Hg}$ during laser ablation and subtraction of the natural $^{206}\text{Pb}/^{204}\text{Hg}$ of 4.35. This $^{206}\text{Hg}$ correction is not significant for most analyses because our $^{206}\text{Hg}$ backgrounds were low (generally ~150cps at mass 204).

Common Pb correction was accomplished by using the Hg-corrected $^{206}\text{Pb}$ and assuming an initial Pb composition of Stacey and Kramers (1975). Uncertainties of 1.5 for $^{206}\text{Pb}/^{204}\text{Pb}$ and 0.3 for $^{206}\text{Pb}/^{207}\text{Pb}$ were applied to these compositional values based on the variation in Pb isotopic composition in modern crustal rocks.

Interelement fractionation of Pb is generally ~5%, whereas apparent fractionation of Pb isotopes is generally <0.2%. In-run analysis of fragments of a large zircon crystal (generally every fifth measurement) with known age of 563 ± 3.2 Ma (2σ error) was used to correct for this fractionation. The uncertainty resulting from the calibration correction is generally 1–2% for both $^{206}\text{Pb}/^{204}\text{Pb}$ and $^{206}\text{Pb}/^{207}\text{Pb}$ ages. Concentrations of U and Th were calibrated relative to a large zircon, which contains ~518 ppm of U and 68 ppm Th.

The analytical data are reported in Supplemental Table 2 (see footnote 2). Uncertainties shown in these tables are at the 1σ level, and include only measurement errors. Analyses that are >2σ discordant (by comparison of $^{206}\text{Pb}/^{207}\text{Pb}$ and $^{206}\text{Pb}/^{208}\text{Pb}$ ages) or >5% reverse discordant were not considered further.

The resulting interpreted ages are shown on Pb/$^{204}\text{Pb}$ concordia diagrams (Figs. 3, 7B–7I, 8C–G, and 10A–F) and relative age-probability diagrams using the routines in Isoplot (Ludwig, 2008). The age-probability diagrams show each age and its uncertainty (for measurement error only) as a normal distribution, and sum all ages from a sample into a single curve. Composite age probability plots were made from an in-house Excel program (available from www.geo.arizona.edu/alc) that normalizes each curve according to the number of constituent analyses, such that each curve contains the same area, and then stacks the probability curves.

**APPENDIX 2. U-Pb AGE METHODOLOGY EMPLOYED AT CENTRO DE GEOCIENCIAS, UNIVERSIDAD NACIONAL AUTÓNOMA DE MÉXICO**

U-Pb ages on separate zircons were dated by laser ablation–inductively coupled plasma–mass spectrometry (LA-ICP-MS) at the Laboratorio de Estudios Isotópicos, Centro de Geociencias, Universidad Nacional Autónoma de México, according to the procedures in Solari et al. (2010). The analytical data are reported in Supplemental Table 3 (see footnote 3). The Pélovicé reference zircon (ca. 337 Ma; Sláma et al., 2008) was used in combination with NIST 610 standard glass to correct for instrumental drift and down-hole fractionation and to recalculate elemental concentrations, using U-Pb Age software (Solari and Tanner, 2011). Precision on the measured $^{206}\text{Pb}/^{204}\text{Pb}$, $^{206}\text{Pb}/^{207}\text{Pb}$, and $^{208}\text{Pb}/^{204}\text{Hg}$ ratios was typically ~0.3% for $^{206}\text{Hg}$, 0.7%, and 0.9% for relative standard deviation, respectively.

Replicate analyses of the Pélovicé zircon indicate an external reproducibility of 0.75%, 0.6%, and 1.6% on the measured $^{206}\text{Pb}/^{204}\text{Pb}$, $^{206}\text{Pb}/^{207}\text{Pb}$, and $^{208}\text{Pb}/^{204}\text{Hg}$ ratios, respectively. These errors are quadratically included in the quoted uncertainties for individual analyses of the analyzed zircons. Because its signal is swamped by the $^{206}\text{Hg}$ contained in the carrier gases, $^{206}\text{Pb}$ was not analyzed during this study.

Common Pb correction was thus performed employing the algebraic method of Andersen (2002). A filter was then applied to ensure the quality of selected analyses, consisting in evaluation of the concordance. For grains with ages younger than 1000 Ma, the analysis was considered concordant if the $^{206}\text{Pb}/^{204}\text{Pb}$ and $^{206}\text{Pb}/^{207}\text{Pb}$ ages differed by <10%. The concordia, probability density distribution, and histogram plots, as well as age-error calculations, were performed using Isoplot (v. 3.70) (Ludwig, 2008). The Tuff-Zirc algorithm (Ludwig and Mundil, 2002) was used to calculate the mean $^{206}\text{Pb}/^{207}\text{Pb}$ age and their errors, as well as to filter for outliers. The $^{206}\text{Pb}/^{207}\text{Pb}$ ages are preferred for grains younger than 1000 Ma because of the uncertainty involved in determining the $^{206}\text{Pb}$ isotope in young crystals.

**APPENDIX 3. K-Ar ANALYSIS PROCEDURES**

K-Ar analyses on biotites from igneous rocks were conducted at the Instituto de Geología, Universidad Nacional Autónoma de México. The analytical data are reported in Supplemental Table 4 (see footnote 4). Samples were cleaned by crushing with steel jaws, sieving, selection of the best fraction (300–400 μm), washing, separation of biotite by magnetic methods (Isodynamic Frantz separator), and slight manual grinding with mortar and pestle under acetone to remove chlorine. The K content of each sample was measured by X-ray fluorescence on 50 mg aliquots using a specific regression for measuring K in K-Ar sample (Solé and Enrique, 2001). Analytical precision was >2%. Samples weighing between 1 and 2 mg were degassed under high vacuum at ~150 °C for 12 h before analysis in order to reduce atmospheric contamination. Argon was extracted by total sample fusion using a 50W CO2 laser defocused to 1–3 mm diameter. The evolved gases were mixed with a known amount of $^{40}\text{Ar}$ and purified with a cold finger immersed in liquid nitrogen and two SAES getters in a stainless steel extraction line. Measurements were done in static mode with an MIM1200B mass spectrometer using electromagnetic peak switching controlled by a Hall probe. Analytical precision for $^{40}\text{Ar}$ and $^{39}\text{Ar}$ peak heights was >0.2%, and >0.6% on $^{40}\text{Ar}$. The data were calibrated with internal standards and the international reference materials LP-6 and HD-B1 biotites. All ages were calculated using the constants recommended by Steiger and Jäger (1977). A detailed description of the procedure and calculations was given in Solé (2009).

**APPENDIX 4. ISOTOPIC AND SELECT TRACER ELEMENT PROCEDURES**

The isotopic ratios of $^{87}\text{Sr}/^{86}\text{Sr}$, $^{143}\text{Nd}/^{144}\text{Nd}$, and the trace element concentrations of Rb, Sr, Sm, and Nd were measured by thermal ionization mass spectrometry on whole-rock samples. Rock samples were crushed to about one-third of their grain size. Rock powders were put in large Savillex vials and dissolved in mixtures of hot concentrated HF-HNO3, or alternatively, mixtures of cold concentrated HF-HClO4. The dissolved samples were spiked with the Caltech NBS-981 standard to ensure the quality of selected analyses, whereas external errors are derived from long-term reproducibility of the NBS-981 Pb standard and result in part from the mass bias effects within the instrument. In all cases, external error exceeded the internal errors: external errors associated with each Pb isotopic ratio were $^{208}\text{Pb}/^{206}\text{Pb} = 0.028\%$, $^{207}\text{Pb}/^{206}\text{Pb} = 0.028\%$, $^{206}\text{Pb}/^{204}\text{Pb} = 0.031\%$.
Laramide magmatic arc in northern Sonora


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