East-west variations in age, chemical and isotopic composition of the Laramide batholith in southern Sonora, Mexico

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ABSTRACT

We examined an east-west transect from the Gulf of California to the volcanic province of the Sierra Madre Occidental (28°30'N). The transect is divided into three geologic regions: 1) The coastal region (COR) is characterized by scattered exposures of Laramide plutons lying beneath the modern and late Tertiary sediments. No outcrops of the volcanic component (Tarahumara Formation) were found there; 2) The central region (CER) is dominated by widespread outcrops of both the Laramide batholith (LB) and coeval volcanic and volcaniclastic rocks. Exposures of intrusive contacts confirm the close relationship of the plutonic and volcanic rocks there; 3) The eastern segment (SMOc) with exposures of the Laramide arc (LA) that are mostly concealed by the Tertiary Sierra Madre Occidental volcanic rocks. The plutonic rocks in the COR are granodiorite and tonalite and, further inland, they change to granodiorite and granite. Extensive hydrothermal alteration largely obscures textures in the volcanic rocks, but fresh samples range from andesite, dacite and less rhyolite. Chemically, the plutons are medium-K to high-K calc-alkaline, LREE-enriched and with relatively minor europium anomalies. K-Ar and U/Pb dating shows that plutons are older (79–83 Ma) to the west and younger to the east, where age ranges between 55 and 65 Ma throughout the remainder of the transect. The coeval volcanic facies yielded zircon U/Pb ages of 60 Ma, and 70 to 90 Ma within the CER. A younger pulse at ~50 Ma is present in the west of the SMOc region. Radiogenic Sr and Nd isotope values range from initial $^{87}Sr/^{86}Sr$ 0.70547 to 0.70715 and ε_{Nd} varies from -3.3 to -6.3. All of these results are consistent with development of a subduction-related magmatic arc that was emplaced within mature continental crust. The present-day width of the arc is >300 km, which suggests development of a low-angle subduction configuration that produced a significant volume of magmatism. Although the age decreases with the distance to the plate margin, the trend is not regular, and the activity between 55 and 65 Ma is at least 200 km in width. The results also support a configuration in which the Laramide arc of the mainland of southern Sonora is a continuation of the Peninsular Ranges batholith of Baja California. However, the LA shows significant contrasts with the batholith of southern Sinaloa, which is narrower and has a larger age range. The southern Sinaloa batholith also has compositional and isotopic characteristics consistent with emplacement within a younger and less mature crustal domain (Guerrero terrane).

Key words: volcanic arc, geochronology, Laramide batholith, southern Sonora, Mexico.

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RESUMEN

Se estudió un transecto este-oeste desde el Golfo de California hasta la provincia volcánica de la Sierra Madre Occidental (28°30'N). El transecto está dividido en tres regiones geológicas: 1) La región costera (COR) caracterizada por afloramientos aislados de plutones del arco Laramide subyaciendo a sedimentos del Terciario tardío y actuales. No se encontraron afloramientos del componente volcánico del arco Laramide (Formación Tarahumara); 2) la región central (CER) está dominada por afloramientos ampliamente distribuidos, tanto de rocas del batolito Laramide como de rocas volcánicas y volcaniclásticas contemporáneas; 3) en la Sierra Madre Occidental (SMOc), los afloramientos del arco Laramide (LA) están cubiertos por rocas volcánicas de la Sierra Madre Occidental. Las rocas plutónicas de la COR son granodiorita y tonalita. Más al oriente, los plutones son granodiorita y granito. Una extensa alteración hidrotermal obscurece la composición en las rocas volcánicas, pero en muestras frescas varían de andesita, dacita y escasa riolita. Químicamente, los plutones son calcialcalinos, con K moderado a alto, están enriquecidos en LREE, y presentan anomalías de europio relativamente menores. Fechamientos K-Ar y U/Pb muestran que los plutones son más viejos (79–83 Ma) hacia el oeste y más jóvenes hacia el este, donde sus edades varían entre 55 y 65 Ma. Las facies volcánicas cogenéticas proporcionaron edades U/Pb en zircón de 60 y de 70 a 90 Ma en la región central. Un pulso más joven, de ~50 Ma, está presente en la porción occidental de la SMOc. Valores isotópicos de Sr y Nd incluyen relaciones iniciales de $^{87}Sr/^{86}Sr$ de 0.70547 a 0.70715 y valores de ε_{Nd} de -3.3 a -6.3. Estos resultados son consistentes con el desarrollo de un arco magmático relacionado a subducción que fue emplazado en una corteza continental madura. La anchura actual del arco es >300 km y sugiere el desarrollo de una subducción de bajo ángulo, que produjo un volumen significativo de magmatismo. Aunque la edad de este magmatismo decrece con la distancia al límite de placa, la tendencia no es regular y la actividad entre 55 y 65 Ma fue emplazada sobre una franja amplia de al menos 200 km. Los resultados también apoyan una configuración en la cual el arco Laramide en el sur de Sonora es la continuación del batolito de las Cordilleras Peninsulares de Baja California. Sin embargo, el LA muestra contrastes importantes con el batolito del sur de Sinaloa, el cual es más angosto, con un rango amplio de edades y tiene características geoquímicas e isotópicas consistentes con el emplazamiento en una corteza más joven y menos madura (terreno Guerrero).

Palabras clave: arco volcánico, geocronologíaBatolito Laramide, sur de Sonora, México.

INTRODUCTION

A large belt of Cretaceous-early Tertiary batholiths is exposed continuously along the western Cordillera of North America from western Canada, through the western United States, into northwestern Mexico. In the latter region, the belt was disrupted by Neogene extension and opening of the Gulf of California, so the batholithic rocks exposed in Baja California have a clear continuation into Sonora, and farther to the south in Sinaloa, Nayarit and Jalisco (Silver and Chappell, 1988; Henry *et al.*, 2003; Ortega-Gutiérrez *et al.*, 1992). This belt has been particularly well studied in southern California (*e.g.*, Bateman and Clark, 1974; Silver and Chappell, 1988) and northern Baja California, (*e.g.*, Gastil *et al.*, 1975; Ortega-Rivera, 2003; Wetmore *et al.*, 2003). This batholith belt is part of the magmatic arc that developed during subduction of the Farallon plate under the North American plate (Atwater, 1989).

In western United States, Coney and Reynolds (1977) related the younger portion of this arc to the Laramide orogeny, which they placed between 80 and 40 Ma, mainly on the basis of K-Ar dates. Published K-Ar ages for these magmatic rocks in northwestern Mexico largely correspond to this time interval. Damon *et al.* (1983) extended this study into Sonora and dated several plutons.

The exposures of these intrusive rocks in Sonora are widely distributed and encompass an area of about 17,000 km^2, extending eastward to the edge of the mid-Tertiary Sierra Madre Occidental (SMOc) volcanic province. However, the original area was extended by Basin and Range tectonics during the Late Miocene.

In addition to the plutonic rocks, coeval volcanic rocks are exposed in Sonora. In this paper we will use the prefixes LA to refer to the entire Laramide arc and LB when referring to the Laramide batholithic component alone. In Sonora, the batholiths are composed of various magmatic pulses (Roldán-Quintana, 2002). The volcanic facies of the Laramide magmatism, although widespread in central-eastern Sonora, are less well studied because of their strong hydrothermal alteration (silicification, and propylitic alteration). To the east, exposures of the LA are limited to erosional windows through the Oligocene volcanic cover of the SMOc. In this study we will present new data to understand the magmatic evolution of the LA, including both its volcanic and the plutonic components.

The published geochronology for the Late Cretaceous and Tertiary magmatism in Sonora was summarized in McDowell *et al.* (2001). In one of his most important works, Damon *et al.* (1983) presented a regional investigation of the Laramide plutonic rocks in Mexico, focused on their relationships with the emplacement of porphyry cooper mineralization. The intrusive rocks were dated by the K-Ar method, using hornblende, biotite, muscovite, and sericite, in a few cases to date hydrothermal alteration. Similarly, Mead *et al.* (1988) published ages for intrusive rocks associated with tungsten mineralization in Sonora. Finally, McDowell *et al.* (2001) provided the first U/Pb zircon ages for the volcanic facies of the LA in Sonora. Four ages of *ca.* 70 Ma and two ages of *ca.* 90 Ma, are the oldest ages known for the LA in east-central Sonora.

Valencia-Moreno *et al.* (2001) examined variations in initial Nd and Sr isotopic values for Laramide granitoids in N-S direction in Sonora and northern Sinaloa, as an indirect way to estimate the influence of regional variations in the composition of the assimilated crust. Their results showed that the isotopic ratios of $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ are more evolved in the north, where the LB intruded proterozoic rocks of North American affinity, with a Proterozoic basement, whereas these ratios are more primitive to the south representing accreted terranes no older than Mesozoic. Recently, Valencia-Moreno *et al.* (2006) published new $^{40}Ar/^{39}Ar$ ages for granitic rocks of central Sonora, which vary from 80 Ma in the area of Bahia Kino to 59 Ma in Maycoba, near the border with the State of Chihuahua. In a more regional study of the Sr, Nd, and Pb isotope geochemistry of Laramide age and younger igneous rocks, Housh and McDowell (2005) identified five distinct crustal provinces in northwestern Mexico. Province "B" coincides with the studied transect and is shown in Figure 1.

In this study, we integrate and interpret the age and chemistry for the Late Cretaceous and early Tertiary granitic intrusives along a transect perpendicular to the main NW-

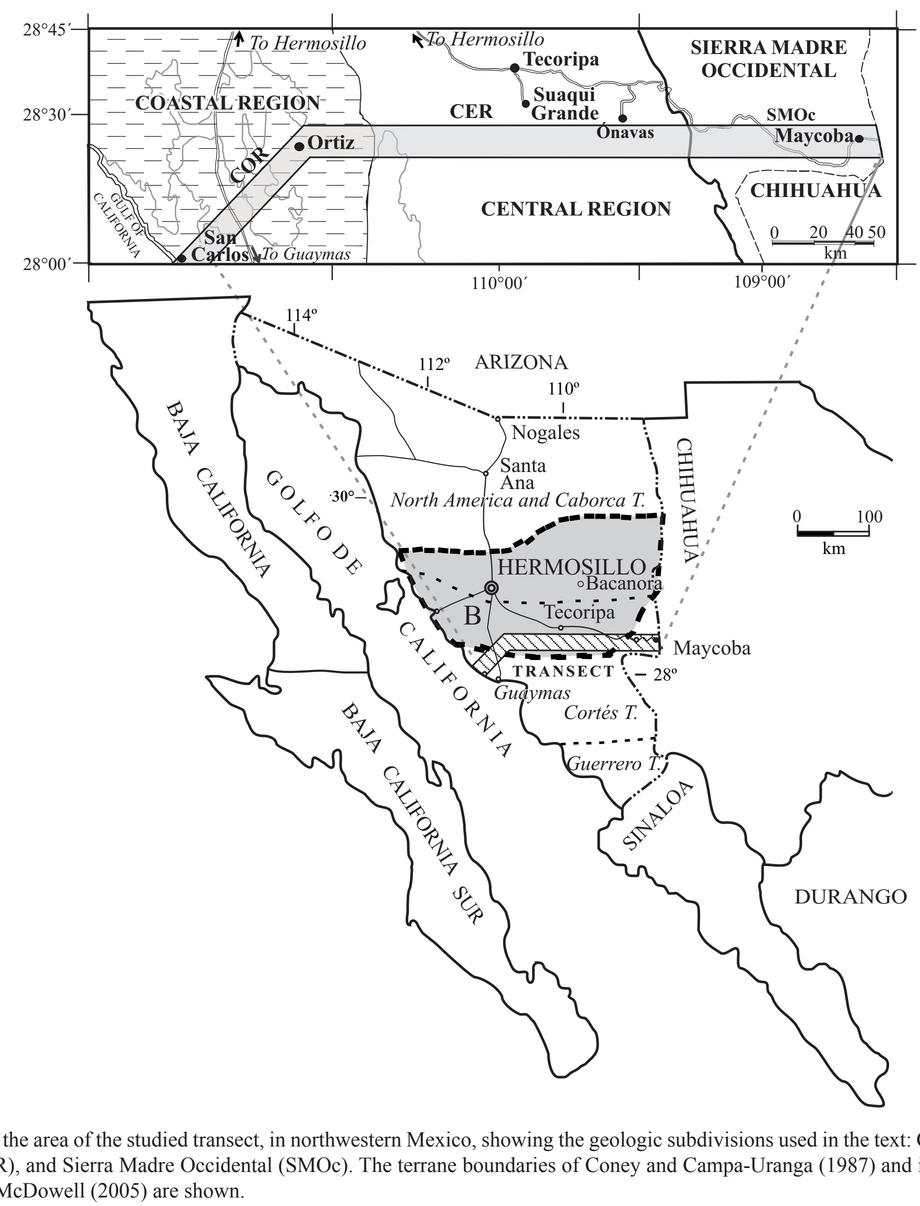

Figure1. Location of the area of the studied transect, in northwestern Mexico, showing the geologic subdivisions used in the text: Coastal Region (COR), Central Region (CER), and Sierra Madre Occidental (SMOc). The terrane boundaries of Coney and Campa-Uranga (1987) and isotopic province B (in gray) of Housh and McDowell (2005) are shown.

SE trend of the Laramide arc. The transect is 15 km wide, and 300 km long, and is located approximately at latitude 28°15′ N (Figure 1). This corridor was selected because it contains good exposures of the LA and also because it is located within a single basement terrane which minimizes the effects of basement variations on our interpretations.

The Cortés terrane consists of Mesozoic intrusions and deep water Late Paleozoic rocks that underlain most of southern Sonora (Coney and Campa-Uranga, 1987). Our objective is to outline the variations in composition, age, geochemistry and isotopic composition of the intrusive rocks along the selected transect, using both new and published analytical data. For convenience, we have divided the transect into three geologic regions**:** (1) Coastal Region (COR); (2) Central Region (CER); (3) and Sierra Madre Occidental Region (SMOc) (Figure 1). The limits of these regions were based on stratigraphy, structural style, and the age of the igneous rocks.

The Coastal Region (COR) begins near the Gulf of California, and continues northeast to Estación Ortiz (Figure 1), then it continues eastward for another 30 km, with a total length of about 110 km (Figure 2). Elevation ranges from sea level to about 300 meters m a.s.l. The stratigraphy of the COR is summarized in Figure 3. The Central Region (CER) of the transect has a length of 120 km, from east of the town of Estación Ortiz, to the east of Río Yaqui (Figure 4). The CER lies entirely within the Sonoran Basin and Range province (mid to late Miocene) and it displays a moderate elevation ranging from 600 to 800 m a.s.l. The Sierra Madre Occidental transect (SMOc) is ~70 km long from the western edge of the SMOc province to the Sonora-Chihuahua state limit, to the east of the town of Maycoba at an elevation of 2300 m a.s.l. (Figures 1 and 5). The stratigraphy for the CER and the SMOc portions of the transect is shown on Figure 3.

METHODOLOGY

Forty five samples of LA rocks were collected from selected outcrops of the intrusives and four samples from the volcanic component for petrographic and geochemical analysis (Appendix). Thirteen of these samples were used for age determinations and REE analysis (Appendix). Samples selected for geochemical analyses were prepared at the *Estación Regional del Noroeste* of the *Instituto de Geología*, UNAM in Hermosillo, Sonora. The fragments were first washed with distilled water, dried, hand picked and crushed in a steel jaw crusher. The crushed samples were reduced to approximately 1 cm in diameter, and a representative portion was taken and powdered in a Herzog mill with an alumina shatter box. Five additional samples were prepared at the University of Texas at Austin in a similar manner. Thirty-three samples were analyzed for major and some trace elements by X-Ray Fluorescence (XRF) at the *Laboratorio Universitario de Geoquímica Isotópica* (LUGIS) of the UNAM in México City. The instrumental conditions and analytical techniques were described in Lozano-Santacruz *et al.* (1995). Most of the samples studied are intrusives, but four are from the Late Cretaceous volcanic rocks, which we include into the Laramide arc. To investigate the petrogenesis of the Laramide magmatism along the studied transect, 14 plutonic and three volcanic rocks were analyzed for rare earth elements (REE) concentrations. Analyses were performed by inductively coupled plasma mass spectrometry (ICP-MS), using a Quadrion Thermo Jarrel instrument installed in the *Instituto de Geofísica* of the UNAM. Approximately 50-100 mg of each powered sample was totally dissolved using high-pressure digestion vessels and open digestion acid treatments. The evaluated instrumental precision was less than 1% for all the lanthanides, except for gadolinium. A complete description of the analytical techniques is provided in Morton *et al.* (1997). For the samples analyzed at the University of Texas at Austin major element concentrations were obtained by wet chemical techniques and trace elements by ICP-MS.

Twelve samples of intrusive rocks were analyzed for Rb-Sr, Sm-Nd and isotope concentrations at LUGIS in Mexico City. In the LUGIS lab, analyzes were performed using a thermal ionization mass spectrometer FINNIGAN MAT-262 equipped with nine collectors. The Rb, Sr, Sm and Nd elemental concentrations were determined by isotope dilution (Schaaf *et al.*, 2000). At the time when the analyses were done, the SRM987 Sr standard yielded a mean $^{87}Sr/^{86}Sr$ ratio of 0.710233 ± 16, and the La Jolla, Nd standard yielded a mean $^{143}Nd/^{144}Nd$ ratio of 0.511881 ± 21.

Nine intrusive samples and four volcanic rocks were dated by the K-Ar method at the University of Texas at Austin. Procedures for the K-Ar at the University of Texas were published in McDowell and Mauger (1994) and in Henry *et al.* (2003).

GEOLOGICAL DESCRIPTION

The transect is located within the Cortés terrane, which underlies most of southern Sonora State (Figure 1). The Cortés terrane is characterized by deep-water marine deposits of Ordovician to Permian age, which were tectonically thrust over the North American platform (Stewart *et al.*, 1990). The Late Triassic deltaic sediments of the Barranca Group unconformably overlie the suture zone and limit the time of accretion to between middle Permian to Late Triassic (Poole *et al.*, 1991).

Pre- and post-Laramide arc rocks

In the COR, the pre-batholithic rocks comprise limited exposures of contact metamorphosed sediments including silicified conglomerate, sandstone and some marble with

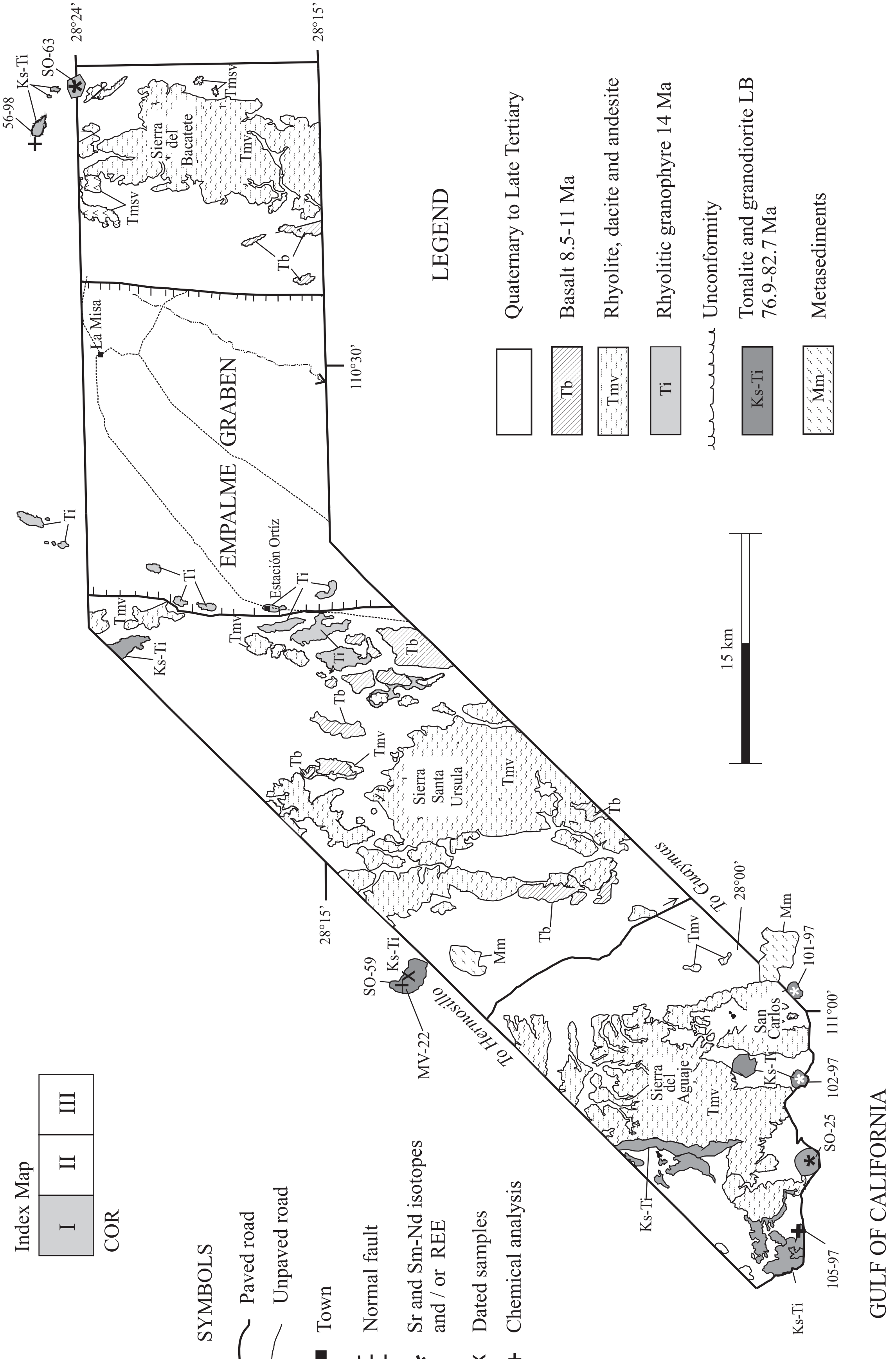

Figure 2. Generalized geologic map of the Coastal Region (COR). Samples used for analysis are indicated.

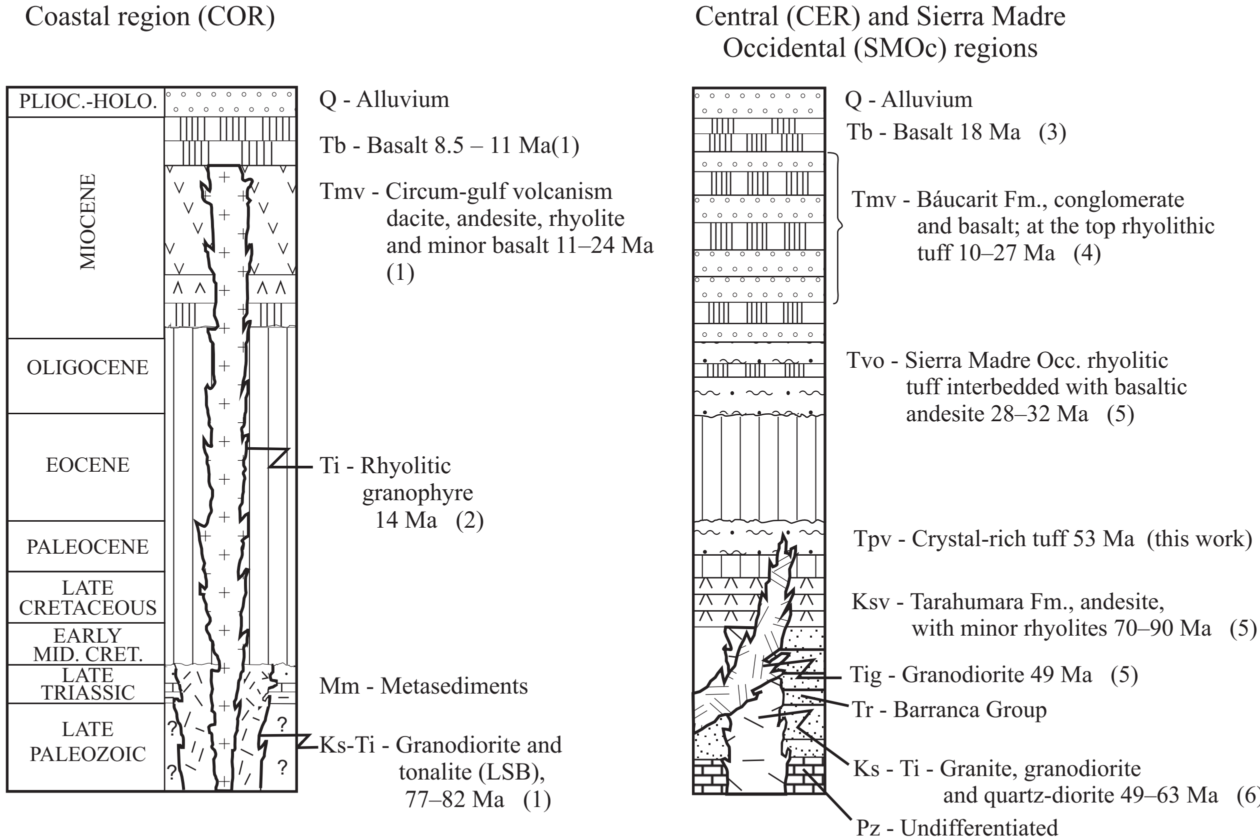

Figure 3. Simplified stratigraphic columns, one for the COR and other for the CER and SMOc regions of the transect. Sources of data are: (1) Mora-Alvarez y McDowell (2000); (2) Mora-Klepeis *et al.* (1997); (3) Bellon, (2001); (4) McDowell *et al.* (1997); (5) McDowell *et al.* (2001); (6) Damon *et al.* (1983).

wollastonite and garnet. This sequence is assumed to be of probable Triassic age, on the basis of similarities with the unmetamorphosed Triassic Barranca Group (Alencaster-de Cserna, 1961), which is exposed in the CER (Roldán-Quintana, 2002). It is noteworthy that outcrops of the Tarahumara Formation are not known in the COR.

West of Sierra Santa Úrsula, the metamorphic rocks are intruded by the LB (Mora-Álvarez and McDowell, 2000). In the Sierra del Aguaje and Sierra Santa Úrsula (Figure 2), the LA is overlain unconformably by early to middle Miocene volcanic rocks of dacitic to rhyolitic composition (Mora-Álvarez, 1992). These rocks belong to the Early to Middle Miocene circum-Gulf volcanic arc (Mora-Álvarez and McDowell, 2000). They are exposed throughout the COR, including the easternmost Sierra del Bacatete (Figure 2). Late Miocene basaltic flows, in part of tholeiitic affinity (Mora-Álvarez, 1992), represent the youngest volcanic rocks known in the entire transect. These appear to be related to the initial stages of rifting of the Gulf of California. The prominent Empalme Graben (Figure 2) has been described by Roldán-Quintana *et al.* (2004). It is a large N-S structure, 25 km wide and 100 km long, that contains sediments at least 700 m thick in the southern part of the graben, located approximately 30 km northeast of Empalme (Campos-Coy *et al.*, 1984). This structure is considered to be related to the early formation of the Gulf.

In the CER, the oldest rocks are exposed only a few kilometers north and east of Tecoripa (Figures 1 and 6). They consist of early to late Paleozoic marine limestone, sandstone and shale intruded by the LB. These rocks are unconformably overlain by the Late Triassic quartz sandstone, conglomerate and black shale deltaic deposits of the Barranca Group (Stewart and Roldán-Quintana, 1991).

An erosional unconformity, exposed throughout the CER and the western part of the SMOc, was developed on batholithic rocks and Tarahumara Formation during Paleocene-Eocene time. In the eastern part of the CER, post-LA volcanic rocks belonging to the Sierra Madre Occidental volcanic province are exposed. The sediments of the Báucarit Formation (King, 1939) are widespread in the CER, and consist of thick clastic deposits that filled Miocene basins developed during the Basin and Range extensional episode (McDowell *et al.*, 1997). In some of these basins, felsic tuffs and mafic lavas interbedded with the Báucarit sediments have been dated to establish the timing of the basin formation at ~27 Ma at the bottom and 12 Ma near the top (McDowell *et al.*, 1997).

No pre-LB rocks are exposed within the SMOc transect, and Cenozoic volcanic rocks, mostly Oligocene

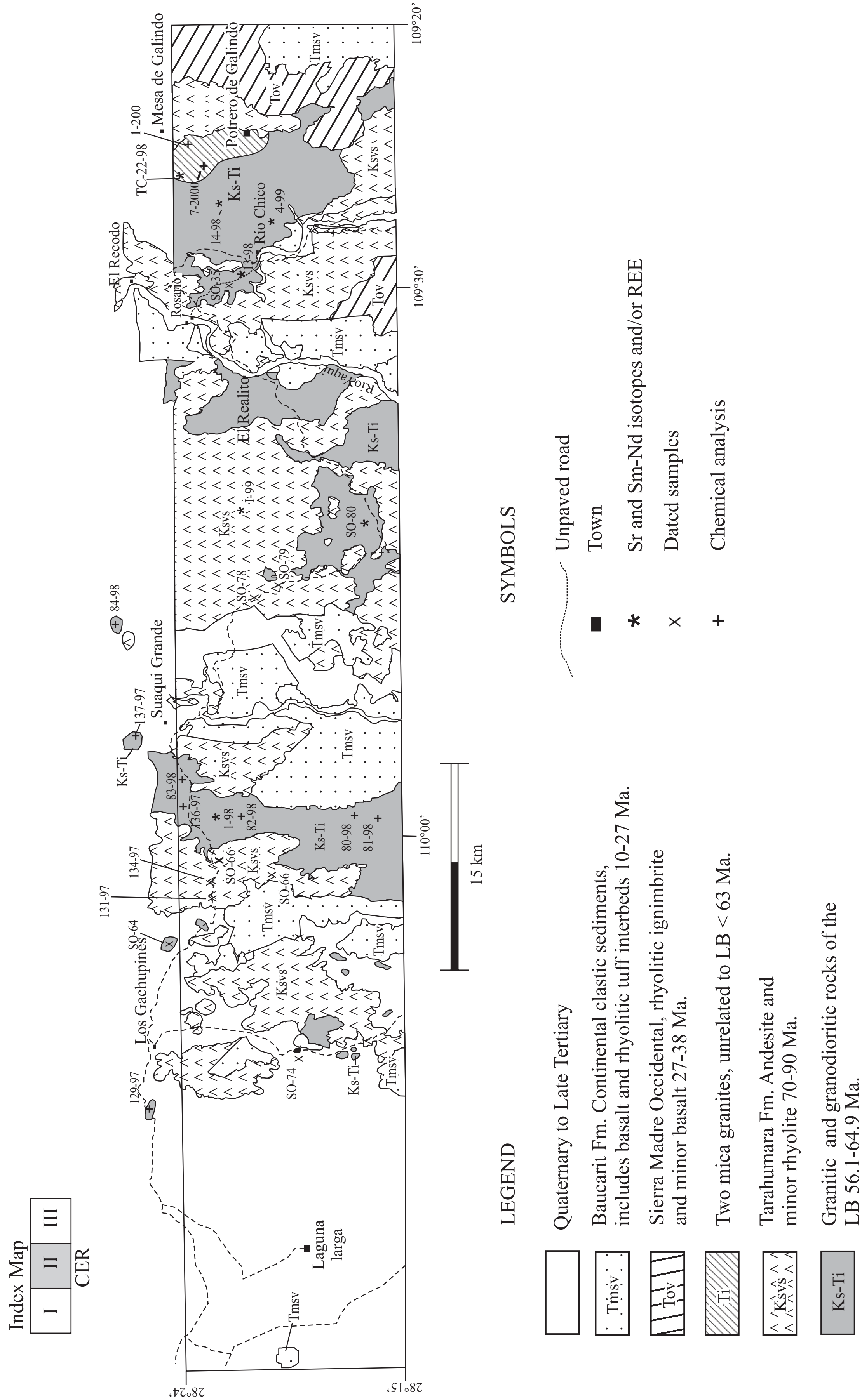

Figure 4. Generalized geologic map of the Central Region (CER). Samples used for analysis are indicated.

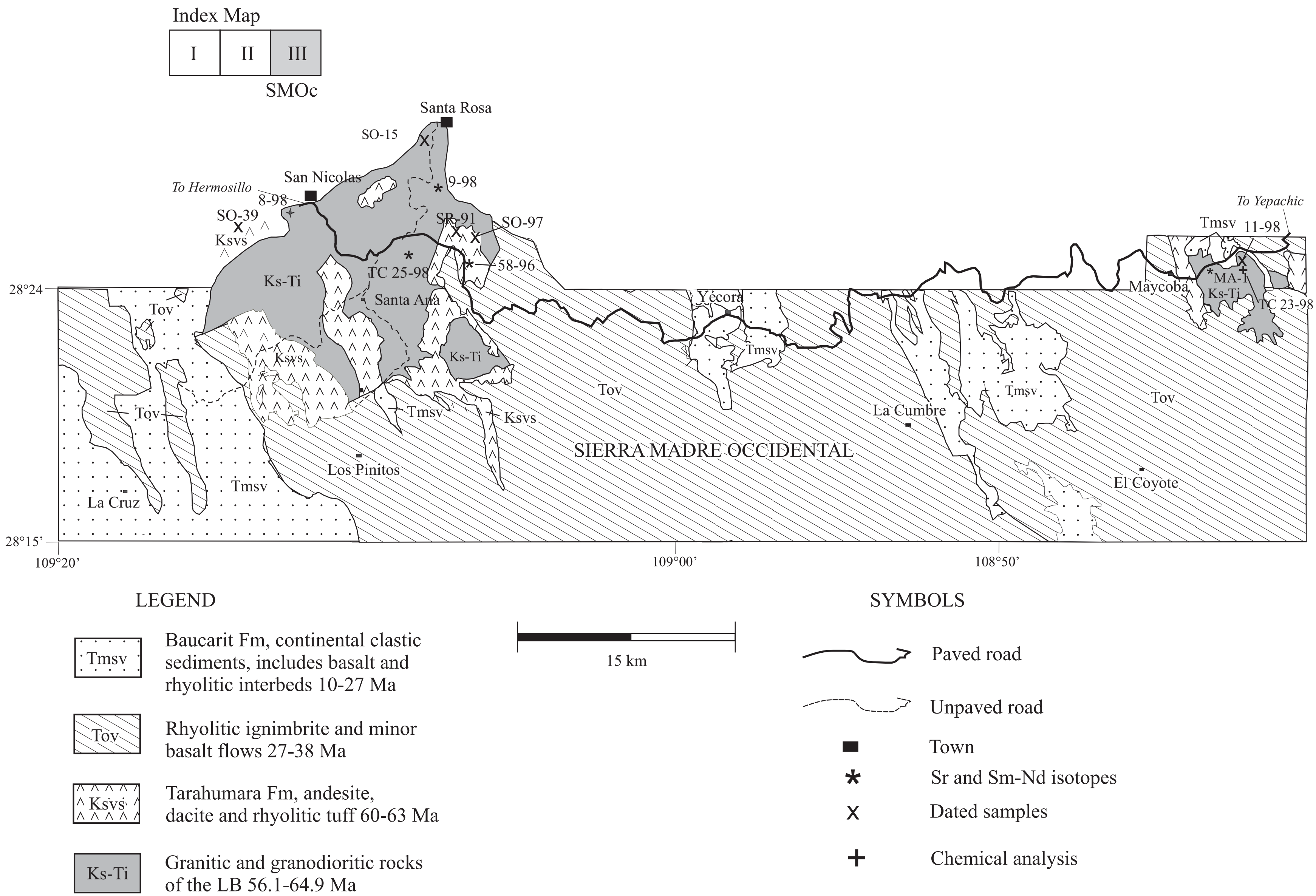

Figure 5. Generalized geologic map of the Sierra Madre Occidental Region (SMOc). Samples used for analysis are indicated.

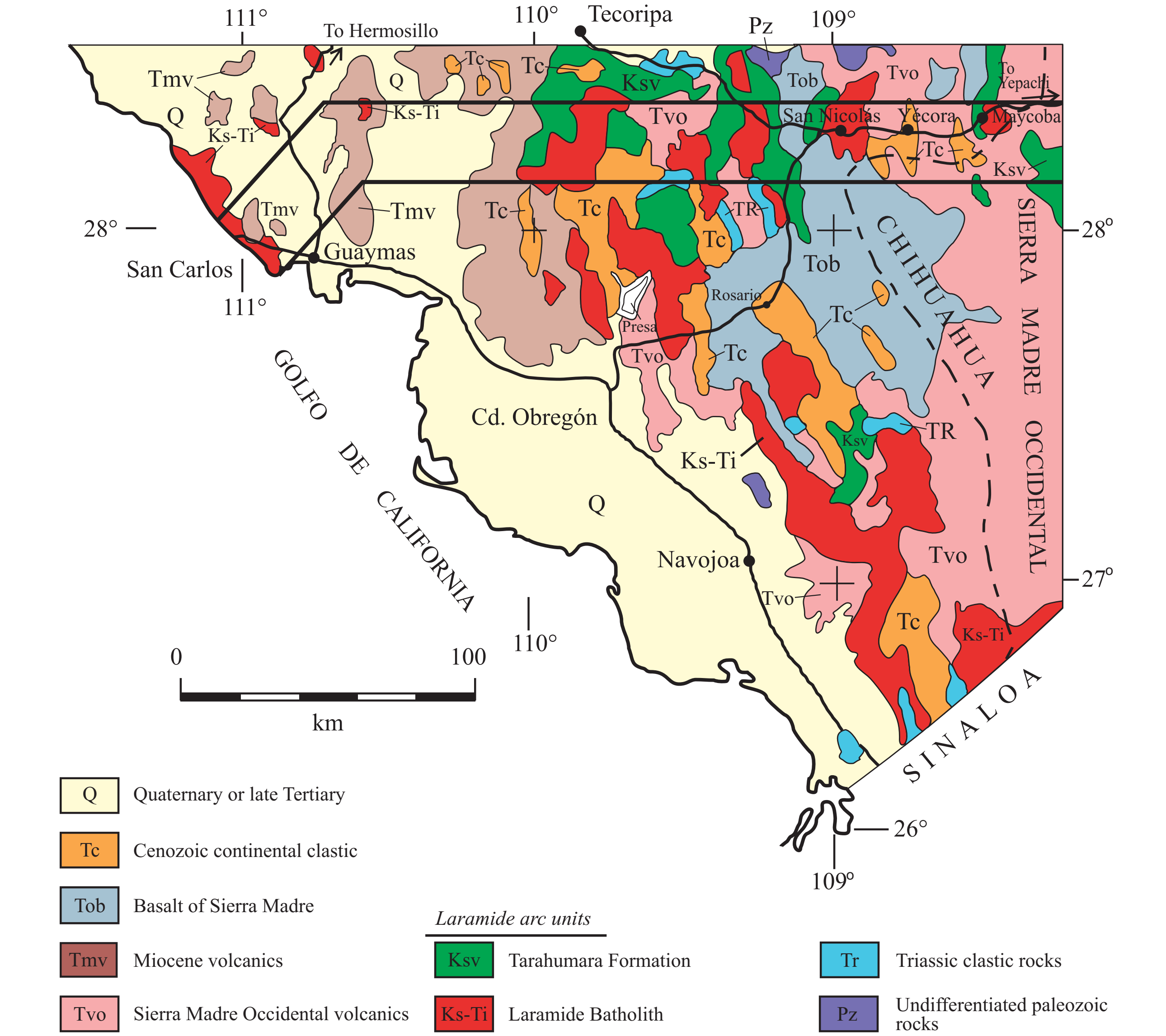

Figure 6. Generalized geologic map of southern Sonora; the location of the transect is indicated. The map shows the geographic association of the Laramide Arc units: LB intrusive (Ks-Ti) and volcanic rocks of the Late Cretaceous Tarahumara Formation (Ksv). The Sierra Madre Occidental is located to the east.

ignimbrites, are widespread. The volcanic sequence of the SMOc consists of predominantly felsic ignimbrites with minor rhyolitic lava flows and domes, and minor basaltic andesite flows (Figure 5). Their formation is related to the continental margin arc (McDowell and Roldán, 1993; Damon *et al.*, 1983), formed between 35 and 23 Ma (Roldán-Quintana *et al.*, 2003).

Clastic and interbedded volcanic rocks of the Báucarit Formation overlie the Sierra Madre Occidental volcanic section in the Arroyo Los Pilares, 10 km east of Yécora (Figure 5). The graben of Yécora-Los Pilares was filled up with rocks of the Báucarit Formation. Basaltic andesite lavas intercalated within the lower part of these clastic deposits have been dated at 22 Ma (Bellon, 2001, personal communication).

The Laramide arc

Volcanic component

The Laramide arc in Sonora includes a coeval volcanic sequence, first described as the Tarahumara Formation by Wilson and Rocha (1949). The Tarahumara Formation is the most widely exposed unit in the CER (Figure 4) and in the western portion of the SMOc, where it unconformably overlies the Late Triassic rocks of the Barranca Group. These rocks are commonly intruded by plutons of the LB along the transect, particularly along the road from El Recodo to Río Chico, and 5 km east from San Nicolás along the road to Yécora (Figure 4).

About 5 km southeast of Suaqui Grande, the Tarahumara volcanic section varies, from 20 m to more than 1000 m in thickness. This change in thickness may be due to the position near the volcanic source, or to differential erosion. The Tarahumara Formation is unconformably covered by Oligocene volcanic rocks in the SMOc region.

The Tarahumara Formation is divided in to three units. Its lower part consists of propylitically altered andesitic to dacitic lavas, agglomerates, and tuff interbeds. The middle part of the section contains volcaniclastic intervals, andesitic tuff, with intercalated siltstone and sandstone, and limestones with lenses of black chert. In the Arroyo El Obispo located 10 km northeast of El Recodo (Figure 4) limestone beds in the section contain fossil remains of Late Cretaceous fossil plants of fresh water environment (Beraldi-Campesi *et al.*, 2004). The upper part of the Tarahumara Formation consists of thin andesitic tuffs, containing crystal-rich tuff interbeds of rhyolitic composition. These rocks yielded U/Pb zircon ages in the range of 70–90 Ma (McDowell *et al.*, 2001). However, the volcanic rocks are hydrothermally altered, and only a few geochemical analyses (major and trace elements) were obtained.

Intrusive component (LB)

Exposures of LB are found at sea level, north of San Carlos (Figure 2), and at elevations of 1,700 m a.s.l., near Maycoba, in easternmost Sonora (Figure 5). Although the exposed area of the intrusives in Sonora may be only a few hundred square kilometers, because of the younger cover of volcanic rocks of Tertiary age and alluvium, the actual subsurface area may be comparable to that of the Sierra Nevada batholith or the Peninsular Ranges batholith of Baja California (Bateman and Clark, 1974), or the Coastal batholith of Peru (Cobbing and Pitcher, 1972). The most widespread exposures of both the volcanic and plutonic rocks of the LA are found in the CER (Figure 4). Contiguous areas with exposures of more than 150 km^2 of the intrusive rocks represent true batholiths (Best, 1982). One such area is located southeast of Suaqui Grande, and the other in the area east of Río Chico (Figure 4).

Within the COR, intrusive rocks are exposed in isolated areas in the vicinity of San Carlos and west and south of Sierra el Aguaje. These outcrops are small due to extensive cover of Miocene volcanic rocks and alluvium (Figure 2). The host rocks of these intrusions are Triassic(?) metasediments exposed north of Guaymas. Other host rocks are Paleozoic marine sediments, which crop out just north of the transect.

In the CER, the plutonic rocks locally intrude the lower portion of the Tarahumara Formation (Wilson and Rocha, 1949). This intrusive relationship is well exposed along the road from Rancho El Recodo to Río Chico, and 5 km south east of San Nicolás along the road to Yécora, (Figures 4 and 5). In both localities porphyritic andesites of the Tarahumara Formation are in contact with granodiorite. The contact is a silicified zone with sericite, tourmaline and occasionally sulfide mineralization. These field relations are interpreted to represent the less eroded part of the arc, because the volcanic component has not been deeply eroded.

In the SMOc, a batholithic exposure occurs in the San Nicolás-Santa Rosa area (Figure 5), and continues to the north of the transect (Gans, 1997). In Maycoba, batholitic rocks intrude the volcanic sequence of the Tarahumara Formation, which lies in erosional contact beneath the Oligocene Sierra Madre Occidental volcanic cover. Along the road to Yécora, a conspicuous unconformity is exposed between the intrusives and the Tarahumara Formation, which generally shows propylitic alteration, contrasting with the unaltered Oligocene volcanic rocks of the SMOc. In this region, Oligocene volcaniclastic red beds probably formed on an unconformity. Ignimbrite deposits and lithic tuffs of rhyolitic composition are covered by 18 Ma old basalt (Bellon, personal communication, 2001). Near Maycoba (Figure 5), a 63 Ma granodiorite stock intrudes Tarahumara volcanics, which are in turn unconformably covered by SMOc volcanic rocks.

PETROGRAPHY OF THE INTRUSIVES ALONG THE TRANSECT

Twenty-eight thin sections from intrusive rocks were studied, including five from the COR, 14 from the CER, and nine from SMOc. The granitic samples show a phaneritic holocrystalline texture, with equigranular crystals from 3 mm to more than 5 mm in size. The mineralogy consists of quartz, plagioclase, and K-feldspar (mainly as microcline) in variable proportions, along with hornblende, biotite and locally muscovite. Sphene, zircon and opaque minerals are the most common accessory minerals.

The intrusives present some mineralogical and textural differences in the three regions. Although the number of samples counted for each region was not the same, some differences are evident in the modal classification of Streckeisen (1976) (Figure 7). Rocks from the COR have the lowest quartz content (18 to 30%) and they are also richer in plagioclase and are classified as granodiorite, tonalite and quartz-monzodiorite. An important characteristic is the presence of large, 1 to 2 cm long, hornblende phenocrysts. Also, the plagioclase is selectively altered to epidote and sericite, which are present in most of the outcrops in this region.

In the CER and SMOc regions, the plutonic rocks are mainly granodiorite and granite, (Figure 7), and both have very similar mineralogy. Rocks from the CER have a wider range of quartz content from 20 to 59%. Textural differences were also observed in the CER and SMOc regions. Porphyritic rocks and myrmekitic textures are more common, and the rocks exposed in these regions are less altered. In the modal classification diagramm (Figure 7), it is possible to see a progression from more mafic rocks in the COR to a more felsic compositions to the east. However, there is not a clear distinction between the CER and the SMOc regions.

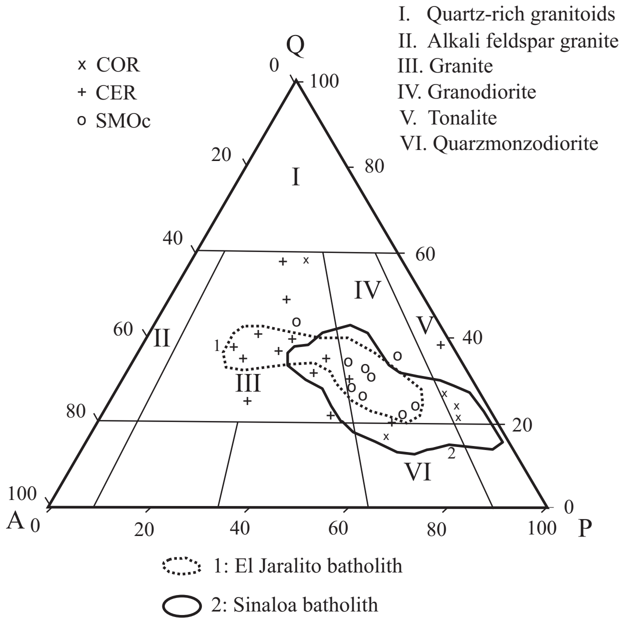

Figure 7. Modal composition of Laramide Batholith (LB) rocks along the transect. Samples are indicated by region. A: Alkali feldspar; P: Plagioclase; Q: Quartz. Classification is according to Strekeisen (1976). The LB rocks are compared with those of southern Sinaloa (Henry *et al.*, 2003) and with the El Jaralito batholith in central Sonora (Roldan-Quintana, 1991).

Also, a small stock of two-mica granite was found in the CER (in the batholith east of Río Chico, Figure 4) with primary muscovite and biotite. This variability in lithology is probably due to a better exposure of the batholiths in this region. It is well established that two-mica granites are related to extension (Chappell, and White, 1974), and are post LA, generally as dikes or small stocks.

GEOCHEMISTRY OF THE LARAMIDE ARC

The silica content varies from 52 to 76 wt.% and that of K_2O from 0.7 to 5.1 wt.% (Table 1). In a diagram of SiO_2 *vs.* K_2O, most of the samples correspond to high-K or medium-K rocks, with two samples from the Tarahumara Formation falling in the low-K field of the diagram (Figure 8). These samples have silica contents near 60 wt.%, and K_2O contents near 0.75 wt.%. From Figure 8, it seems that the compositions of the rocks from the CER and the SMOc region overlap. Three samples from the COR are located near the coast, and have relatively low values of SiO_2 and K_2O of 62–67 wt.% and 2.5–2.8 wt.%, respectively.

A muscovite-bearing granite sample from the COR is located 82 km from the coast (sample SO-63 in Figure 2). This two-mica granite yielded SiO_2 and K_2O values of 74 wt.% and 5.1 wt.%, respectively, being quite different from three other samples collected in the coastal region. The major element analysis of the two-mica granites are shown in Table 1.

The volcanic rocks of the Tarahumara Formation are generally altered by hydrothermal processes, and good chemical analyses were difficult to obtain. Four samples of the less altered rocks were selected for XRF analysis. The analyses indicate andesitic compositions, but show anomalous results, including relatively high total Fe content, and lower contents of $Na_2O + K_2O$ which are probably the result of hydrothermal alteration. Alteration is also reflected in the presence of iron oxides, sulphides and minerals such as sericite, chlorite and epidote.

In the AFM diagram (Figure 9), intrusive and volcanic rocks of the Tarahumara Formation almost all fall in the calc-alkaline field. In Figure 9, two samples of the Tarahumara Formation (triangles) show very similar compositions to the intrusives. Two of the volcanic samples plot within the tholeiitic field, but this may be due to secondary enrichment of Fe possibly related to hydrothermal alteration.

Because of the common pervasive alteration, only three samples of the Tarahumara Formation were analyzed for rare earth elements (REE); the La value were not reported (Table 2). Their REE values appear slightly more enriched than granitoids, although the chondrite normalized slopes are generally similar in both rock types (Figures 10 and 11).

A larger number of LB granite samples were analyzed for REE (Table 3). The normalized values show relatively steep slopes with La_N/Lu_N ratios from 6.61 to 34.03, whereas La abundance is of 108 ppm in average.

Most of the studied samples of granitoids and volcanic rocks display weak to moderate negative Eu anomalies (Figures 10 and 11). Typical values for total REE contents in plutons with similar SiO_2, increase from about 330 ppm in the COR to about 500 ppm in the CER and SMOc.

Although based upon limited values, this observation may reflect that the continental crust is thicker in eastern Sonora. The REE diagrams for the Laramide granites (Figures 10 and 11) show enrichment in LREE, which is characteristic of areas involving continental crust in their genesis. The enrichment of LREE is interpreted here as result of higher assimilation due to a thicker continental crust toward the east.

GEOCHRONOLOGY ALONG THE TRANSECT

Because of the generally strong alteration, the volcanic component of the Laramide arc (Tarahumara Formation) has been relatively poorly dated. Therefore U/Pb dating of zircon grains separated from dacitic and rhyolitic flows and tuffs provided the best age constraint.

Published ages from volcanic rocks within the study transect includes one whole-rock Rb-Sr isochron age of 59 Ma from a porphyritic dacite flow near Santa Rosa (SMOc) (Sansores and Wyne, 1977). Gans (1997) reported an $^{40}Ar/^{39}Ar$ of 60 Ma on plagioclase from an andesite (sample SR-91) northwest of Santa Ana. From an andesite (sample SO-97) located in the area south of Santa Rosa (Figure 5),

Table 1. Major and some trace element analysis of Laramide granitoids (*g*) from the Coastal region (COR), Central region (CER) and Sierra Madre Occidental region (SMOc) along the transect. Volcanic rocks (*v*) of the CER and SMOc, and two-mica granites (*tmg*) from the CER and COR are also included. Volcanic rock samples 106-90 and 109-90 are located 25 km NE of Suaqui Grande in the CER. Locations are shown in Figures 2, 4 and 5.

		Sample	SiO_2	TiO_2	Al_2O_3	$Fe_2O_3^T$	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	LOI	Total	Rb	Sr	Ba	Y	Zr	Nb	V	Cr	Co	Ni	Cu	Zn	Th	Pb
COR	*g*	101-97	62.7	0.64	16.5	5.49	0.10	2.28	5.33	2.92	2.50	0.13	0.61	99.2	77	400	900	21	118	8	120	11	17	5	20	64	6	9
	g	105-97	67.1	0.52	15.8	4.03	0.08	1.42	4.03	3.31	2.83	0.13	0.34	99.6	90	463	1072	19	124	10	61	2	9	3	9	71	2	10
	g	SO-25 [b]	64.5	0.57	16.3	3.90	0.08	1.94	4.22	3.54	2.79	0.18	1.34	99.4	und.	460	704	17	und.	und.	681	70	27	und.	und.	61	und.	und.
	g	SO-59	64.2	0.44	16.4	4.08	0.08	1.50	4.42	3.78	2.09	0.14	2.82	100.0	und.	und.	und.	und.	und.	und.	und.	und.	und.	und.	und.	und.	und.	und.
	g	SO-63	74.5	0.11	12.9	0.45	O.02	0.24	0.28	3.19	5.05	0.04	0.58	97.6	und.	118	324	5	und.	und.	15	35	14	und.	und.	0	und.	und.
	g	MV-22 [a]	68.0	0.34	14.5	5.52	0.05	0.99	2.72	4.18	3.73	0.07	2.55	99.7	124	128	842	21	63	14.3	12.8	und.	und.	und.	und.	und.	20.1	und.
	g	56-98	65.7	0.51	16.1	4.38	0.07	1.96	4.05	3.25	3.24	0.11	1.21	100.6	118	463	840	17	137	10	91	16	13	5	24	68	9	18
	tmg	SO-63 [b]	74.5	0.11	12.9	0.49	0.02	0.24	0.28	3.19	5.05	0.04	0.61	97.6	und.	118	324	17	5	und.	und.	15	3	26	und.	und.	und.	und.
CER	*g*	80-98	52.0	0.86	17.9	8.64	0.14	6.00	8.18	2.59	1.88	0.16	0.78	99.1	70	478	778	23	148	8	206	202	32	44	65	102	<1	7
	g	81-98	55.3	0.91	17.8	8.05	0.13	3.64	6.42	3.27	2.14	0.17	1.37	99.2	86	525	659	22	134	6	182	8	21	8	86	98	4	11
	g	82-98	64.9	0.59	14.8	4.98	0.08	2.81	3.93	2.75	3.71	0.11	0.87	99.5	152	375	868	22	213	10	103	62	17	26	76	62	14	16
	g	83-98	66.6	0.49	15.3	4.36	0.07	1.88	3.69	3.01	3.34	0.09	0.52	99.3	151	372	792	20	133	10	78	2	9	6	30	44	15	11
	g	84-98	64.7	0.59	16.4	4.61	0.06	1.93	4.22	3.42	2.90	0.13	0.37	99.3	119	511	854	13	153	11	90	8	10	8	97	52	15	10
	g	SO-80	61.5	0.74	16.3	6.04	0.09	2.53	5.31	3.07	3.02	0.11	0.49	99.2	151	421	689	22	179	8	126	25	19	16	52	77	21	19
	g	129-97	61.8	0.69	15.9	5.82	0.10	2.44	4.91	2.83	3.11	0.16	1.22	98.9	125	361	838	28	172	9	126	13	18	6	36	65	13	19
	g	131-97	64.8	0.58	16.1	4.66	0.08	1.68	4.21	3.30	3.01	0.13	0.49	99.1	179	467	1042	18	160	7	118	15	15	14	10	92	5	16
	g	136-97	67.8	0.49	16.2	3.82	0.05	1.74	3.55	3.08	3.51	0.09	0.63	100.9	170	361	717	12	116	9	76	4	10	7	15	43	19	10
	g	137-97	67.6	0.51	15.6	3.84	0.05	1.44	3.34	2.94	3.33	0.11	0.99	99.7	137	387	903	17	138	11	77	und.	8	7	76	39	18	13
	g	1-98	66.4	0.52	15.5	4.26	0.08	1.70	4.07	3.12	3.44	0.08	0.97	100.1	148	377	795	15	124	6	90	7	10	10	16	51	20	13
	g	SO-35	64.4	0.61	15.2	5.04	0.08	2.08	4.29	2.91	3.87	0.07	0.74	99.3	204	329	709	24	178	9	108	20	15	12	61	74	29	16
	g	14-98	68.4	0.41	15.6	2.98	0.07	0.80	3.49	3.69	3.16	0.09	0.79	99.5	127	520	1031	12	155	8	44	5	5	6	16	74	10	19
	g	SO-64 [b]	62.6	0.67	16.3	4.88	0.09	2.38	4.58	3.22	3.21	0.19	1.10	99.3	und.	440	661	17	und.	und.	114	3	26	und.	und.	73	und.	und.
	v	1-99	60.9	0.72	17.0	6.13	0.11	2.44	4.94	3.64	2.83	0.17	1.70	100.6	104	451	814	25	225	10	und.	20	16	4	23	108	und.	und.
	v	106-90	60.4	0.92	16.4	7.77	0.12	2.55	2.03	5.80	0.75	0.46	2.99	100.1	30	307	346	27	309	15	80	9	22	6	10	128	und.	und.
	v	109-90	60.5	0.92	16.5	7.68	0.12	2.57	4.00	2.05	0.77	0.46	2.96	100.3	35	304	338	27	310	15	82	8	40	6	12	124	und.	und.
	tmg	TC-22-98	75.6	0.20	12.9	1.49	0.02	0.48	0.80	2.69	5.71	0.03	0.56	100.5	278	190	731	8	133	9	21	<1	<2	2	47	19	55	14
	tmg	1-2000	76.5	0.07	13.6	0.88	0.05	0.22	0.64	4.19	4.14	0.05	0.53	100.9	291	106	265	36	61	23	9	5	<3	2	12	40	10	und.
	tmg	2-2000	74.7	0.08	14.5	0.89	0.05	0.3	0.96	4.37	3.88	0.07	0.51	100.3	233	255	682	28	84	21	9	<2	<3	2	14	29	7	und.
	tmg	7-2000	71.1	0.26	15.6	2.21	0.06	0.68	2.42	3.99	3.73	0.10	0.54	100.7	158	442	1013	22	143	8	29	<2	4	3	6	54	16	und.
SMOc	*g*	9-98	66.6	0.49	15.1	4.09	0.08	1.67	3.82	3.02	3.40	0.06	1.51	99.7	158	371	707	12	114	7	87	4	11	7	14	53	16	8
	g	11-98	63.2	0.62	15.2	5.02	0.08	2.18	4.48	3.01	3.43	0.10	1.18	99.6	153	430	900	24	184	9	107	32	14	17	32	56	9	15
	g	TC23-98	63.9	0.60	16.0	5.33	0.08	2.47	4.36	3.14	3.53	0.11	0.88	100.4	154	433	828	26	190	10	106	24	14	15	46	56	15	11
	g	TC25-98	65.1	0.53	16.0	4.69	0.08	2.15	4.00	3.08	3.44	0.10	0.55	99.7	143	412	738	14	114	7	99	4	11	9	24	45	16	14
	g	MA-1 [b]	57.4	1.01	16.4	3.83	0.11	3.61	5.91	3.16	3.18	0.19	2.36	98.2	und.	440	635	26	und.	und.	165	1	28	und.	und.	78	und.	und.
	g	SO-15 [b]	63.3	0.67	17.0	3.84	0.07	1.44	4.77	4.07	2.29	0.24	2.36	100.1	und.	644	701	8	und.	und.	87	2	28	und.	und.	26	und.	und.
	v	58-96	59.4	0.77	16.1	6.42	0.09	2.75	4.39	3.04	3.21	0.12	4.14	100.4	150	331	659	23	160	8	145	19	24	11	31	96	und.	und.

[a] Samples analyzed at the University of Arizona; [b] samples analyzed at the University of Texas at Austin. All other analysis were performed at the XRF Lab, LUGIS, by Rufino Lozano. Major oxide in weigth %; trace elements in parts per million (ppm). und: undetermied analysis.

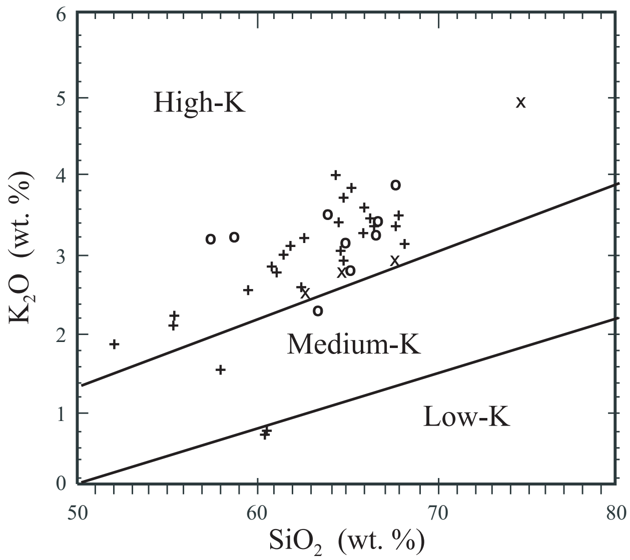

Figure 8. SiO_2 *vs.* K_2O diagram for intrusive rocks of the LB. (×) COR; (+) CER; (○) SMOc. Fields are those proposed by Le Maitre *et al.* (2002).

(McDowell *et al.*, 2001) obtained a plagioclase K-Ar age of 61 Ma (Table 4).

McDowell, *et al.* (2001) analyzed zircons separated from six samples, three of which (SO-66, SO-78 and SO-79) were obtained from south of Suaqui Grande within the CER (Figure 4), and obtained ages of 70.2 ± 0.6, 89.0 ± 0.8, and 90.1 ± 0.7 Ma. The other three samples are from outside the transect (28 km NE of Suaqui Grande) yielded ages between 69.7 and 72.6 Ma. Analytical errors are generally <1Ma. Farther to the east, in the western part of the SMOc (Figure 5), U/Pb ages for volcanic rocks of the Laramide arc appear to be younger and ranges from 70 to 90 Ma (Mc Dowell *et al.*, 2001).

Other dates for granitic rocks were published by Damon *et al.* (1983); they reported five K-Ar ages for hornblende and biotite from LB granodiorite samples from batholithic exposures in the area of Santa Rosa-San Nicolás (Figure 5). The ages range from 49 to 67 Ma for hornblende and 49 to 51 for biotite. One $^{40}Ar/^{39}Ar$ date from a granodiorite in the Santa Rosa area provided an age of 57 Ma on hornblende, and 51 Ma on biotite (Gans, 1997). In eastern Sonora, within the area of the transect, Valencia *et al.* (2006) reported three ages obtained by the ^{40}Ar-^{39}Ar method in hornblende concentrates; one sample from the CER, 7 km southwest of Suaqui Grande dated at 56 Ma, and two samples from the SMOc, one near San Nicolás with an age of 60 Ma, and the other in Maycoba in the easternmost part of the transect with an age of 59 Ma. These ages are in general agreement with the K-Ar dates reported in this paper for the same regions.

In this work, 12 samples of intrusive rocks of the LB were dated by K-Ar at the University of Texas at Austin, and two by the Rb-Sr method in the LUGIS, UNAM in México City. All the dated samples are plotted on the geologic maps (Figures 2, 4 and 5), and the analytical results are provided in Tables 4 and 5.

In the COR, near San Carlos, two pluton samples yielded K/Ar ages of 76 and 82 Ma, respectively; these ages represent the oldest intrusives within the transect. To the east, in the CER, the age of the batholiths varies from 56 to 64 Ma (K/Ar, hornblende; Figure 4, Table 4). In the batholith of Tecoripa, 25 km north of the transect, we obtained six ages varying from 55 to 64 Ma. For the SMOc, four ages of the batholiths vary from 53 to 63 Ma. Intrusive rocks as young as 49 Ma (Damon *et al.*, 1983) crop out in the area of Santa Rosa (SMOc), this intrusive pulse is also present in other parts in Sonora, including one quartz-diorite from Cerro Mariachi in Hermosillo with one K/Ar hornblende age of 48 Ma (Roldán-Quintana, *et al.*, 2000).

ISOTOPIC DATA ALONG THE TRANSECT

Isotopic ratios of Rb-Sr and Sm-Nd were obtained in samples of ten intrusive rocks and two volcanic rocks. The results are shown in Table 6. The initial $^{87}Sr/^{86}Sr$ ratios vary from 0.70547 to 0.70715. The three lower values (0.7055-0.7059) are from tonalites located in the COR, north of San Carlos (samples 101-97, 102-97), which also correspond to the oldest rocks along the transect. The highest $^{87}Sr/^{86}Sr$ value (0.70715) is from a porphyritic andesite in the CER, located in the area of La Dura (sample 1-99, Figure 4).

The εNd values obtained for the intrusive rocks within the transect are all negative and vary from -3.3 to -4.1 (Figure 2). The least negative value of -3.3 (sample 101-97) is from a tonalite near San Carlos in the COR (Figure

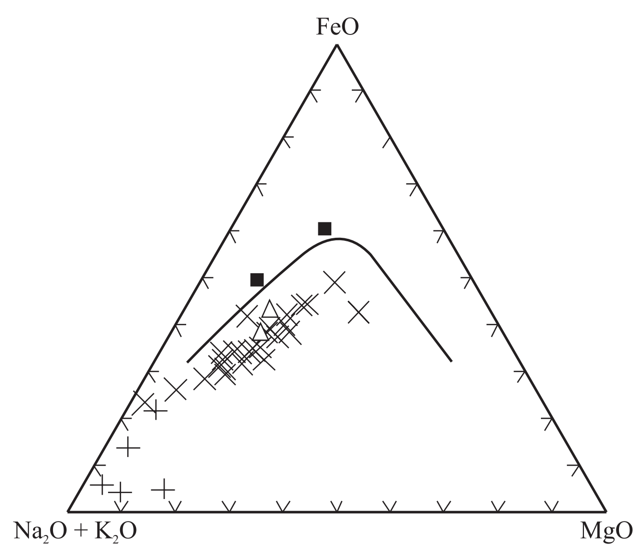

Figure 9. AFM diagram for samples of the LB, and four volcanic rocks. The limit between the calc-alkaline and tholeiitic series is after Irvine and Baragar (1971). A: $Na_2O + K_2O$; F: FeO; M: MgO. (×) Granitoids from COR, CER and SMOc regions; (■) Andesite; and (Δ) Porphyritic dacite of the Tarahumara Formation in the CER; (+) Two-mica granites in the CER.

Table 2. REE analysis of andesites of the Tarahumara Formation.

	106-90	109-90	58-96
Ce	118.17	119.93	67.58
Pr	13.79	13.84	7.60
Nd	53.19	52.40	27.48
Sm	8.58	8.05	5.04
Eu	2.00	4.57	1.12
Gd	6.69	6.45	4.44
Tb	0.94	0.91	0.63
Dy	4.97	4.82	0.39
Ho	1.02	1.00	0.71
Er	2.73	2.72	1.97
Tm	0.37	0.37	0.26
Yb	0.38	0.39	0.27
Total	212.83	215.45	120.56

2), whereas the most negative εNd value (-4.1) is from a granodiorite intrusive exposed in the area of Maycoba in the SMOc region.

The two samples analyzed from the volcanic facies of the Laramide arc, yielded initial εNd values of -6.3 (sample 1-99 in the CER) and -4.6 (sample 58-96 in the SMOc), which are the most negative values of the dataset (Figures 4 and 5).

The isotopic values from the studied intrusive and the volcanic rocks of the LA are in general similar to those obtained by Valencia-Moreno (1998) for the intrusive rocks of the Cortés terrane in southern Sonora. All fall within the lower right quadrant of the $^{87}Sr/^{86}Sr$ *vs.* εNd diagram (Figure 12).

In a simplified profile of the intrusive rocks from San Carlos to Maycoba (Figure 13), based on the available isotopic and age data, the only major change in age, $^{87}Sr/^{86}Sr$ ratios, and εNd values is between the sample in the San Carlos area (SO-25) in the COR and the sample in Maycoba (Ma-1) in the SMOc region.

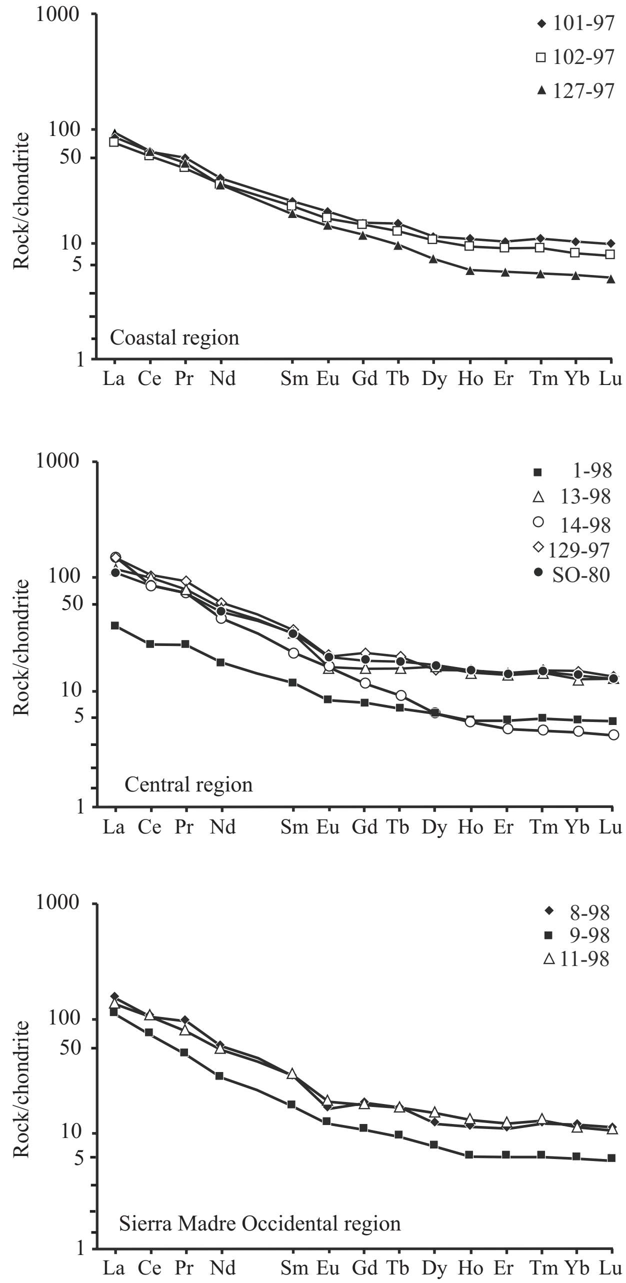

Figure 10. Chondrite-normalized REE patterns for 11 samples from the LB drafted for each region. Normalization values are from Anders and Grevesse (1989).

DISCUSSION

The studied corridor stretches for 300 km mostly along latitude 28°30'N (Figure 1), from the coast of Sonora into the Tertiary Sierra Madre Occidental volcanic province. Near coastal Sonora, the Laramide rocks are mostly covered by late Tertiary continental deposits related to Basin and Range extension, and by modern alluvial deposits. In the SMOc, the LA is exposed in a few places beneath the Oligocene-Miocene volcanic cover. However, within the central portion of the transect (easternmost COR, CER, and western part of the SMOc; Figures 2, 4 and 5), exposures of both the batholithic (LB) and volcanic (Tarahumara Formation) rocks of the LA are found together. How far the LA extends eastward of the transect is still unknown. East of the SMOc volcanic field, in central Chihuahua, scattered plutons equivalent in age to the LA are present (McDowell and Mauger, 1994), however arc volcanism is well known in this region.

Along the entire transect, no pre-Basin and Range deformation was observed in the batholiths, the Late Cretaceous Tarahumara Formation or other clastic sequences with volcanic rocks interbeds in Late Cretaceous basins are not deformed. Major exposures of the LB are composite, reflecting separate magmatic pulses, although internal contacts between separate plutons are rarely observed. Within the CER, local field relationships show that plutons intruded the coeval volcanic rocks. This contact relation is

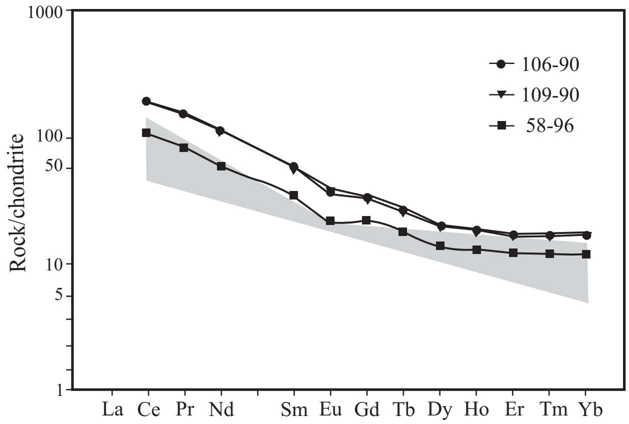

Figure 11. Chondrite-normalized REE patterns for three samples from the Tarahumara Formation (Central region). Values for the LB are shown in the gray area. Normalization values are from Anders and Grevesse (1989).

well exposed southwest of Ónavas in the batholith of Río Chico, and to the east in San Nicolás-Santa Rosa batholith (Figure 4), where altered andesites are intruded by diorites or granodiorites. The prominence of both plutons and volcanic rocks outcrops indicate a relatively minor erosion of the LA in the CER.

Lithology of the plutons varies eastward from the coast, from tonalite and quartz-monzodiorite in the COR, to granite and granodiorite in the CER and the SMOc (Figure 7). Excluding five samples (TC-22-98, 1-2000, 2-2000, 7-200 and SO-63 in Table 1), which are two-mica granitoids and unrelated to the arc, the SiO_2 contents vary from 52 to 76 wt.% and K_2O from 1.9 to 4.2 wt.% (Tables 3). They are thus medium- to high-K calc alkaline rocks (Figure 8). All studied granitoids are chemically and petrographically of I type, as defined by Chappell and White (1974). The calc-alkaline affinity is characteristic of continental margin arcs (Wilson, 1989), which is consistent with the tectonic setting for the LA in Sonora. Normalized REE values for both the granitoids and the volcanics of the Laramide arc, also indicates the affinity to a continental-margin arc, in which the LREE are enriched relative to the values of HREE by approximately 10 times. The enrichment in LREE elements, with relatively minor negative Eu anomalies, and the Nd and Sr isotopic values, reflect the influence of both the oceanic and a thicker continental crust in the genesis of the LB. The plutonic rocks are as old as 83 Ma near the coast in the COR but they become younger to the east, where their ages are between 65 and 53 Ma. The younger intrusions are generally small stocks or dikes of fine-grained diorite, intruding older batholithic rocks.

Three U/Pb dates for the Tarahumara volcanic rocks exposed in the eastern portion of the CER yielded 70 to 90 Ma (SO-66, SO-78 and SO-79) (McDowell *et al.*, 2001) in Figure 4. Three other samples from north of the transect (about 20 km north of Suaqui Grande) have U/Pb ages of 69–72 Ma (McDowell *et al.*, 2001). Other Ar-Ar and K-Ar ages for andesite lava of the Tarahumara Formation, range from 60 to 62 Ma (this study; Gans, 1997). Some of these ages in volcanic rocks are older than the dates obtained for the LB in the CER, where ages of plutons vary from 56 to 64 Ma (Table 4). These results indicate that the Tarahumara Formation in central Sonora are slightly older than the LB plutons in this region or overlap. However, in the area of Bacanora (85 km NE of the CER, Figure 1), Pérez-Segura

Table 3. REE content (ppm) for the LB granitoids along the transect, normalized to values of the Orgueil chondrite (Anders and Grevesse, 1989) . Their location is indicated on Figures 2, 4 and 5.

Sample num.	COR			CER									SMOc	
	101-97	102-97	SO-63	1-98	TC22-98	13-98	129-97	14-98	SO-80	4--99	80-98	11-98	9-98	8-98
La	84.38	75.30	91.30	36.46	90.69	113.70	144.44	142.23	106.61	131.14	106.47	130.24	105.57	150.11
Ce	64.67	58.16	64.95	25.16	65.14	96.96	98.49	83.00	84.78	92.95	81.00	102.02	70.81	105.02
Pr	55.21	45.91	50.46	25.66	46.36	76.12	90.70	70.52	70.48	87.29	83.00	77.21	48.30	94.57
Nd	37.42	32.99	33.11	17.66	28.25	52.25	58.48	42.94	50.23	55.40	57.63	53.26	30.15	57.44
Sm	23.53	21.03	18.66	11.69	14.84	32.37	34.10	21.69	32.03	32.64	34.97	32.08	16.80	31.08
Eu	18.84	16.91	14.39	8.54	7.37	15.90	20.52	16.61	20.18	16.98	24.53	18.66	12.04	16.46
Gd	15.37	14.84	12.08	7.84	7.54	16.06	21.24	11.68	19.15	20.48	22.00	17.45	10.62	18.20
Tb	14.88	12.78	9.78	7.14	7.72	16.22	20.36	9.23	18.12	19.41	20.36	16.24	9.20	16.56
Dy	11.45	10.72	7.48	6.45	7.90	16.39	15.58	6.40	17.10	14.66	14.96	15.04	7.78	12.16
Ho	11.18	9.33	5.86	5.61	7.19	14.25	15.41	5.42	15.19	14.12	14.48	12.86	6.33	11.61
Er	10.47	9.10	5.78	5.74	7.65	13.97	14.55	4.86	14.61	13.20	13.24	12.37	6.26	11.03
Tm	11.19	9.27	5.48	5.90	8.76	14.37	15.67	4.69	15.13	14.15	13.74	12.96	6.26	12.15
Yb	10.57	8.38	5.37	5.70	8.00	12.57	14.68	4.43	14.12	13.20	12.57	11.01	6.13	11.69
Lu	9.95	8.11	4.94	5.51	8.05	12.92	13.69	4.18	13.12	12.25	11.40	10.82	5.85	11.23
Total	379.11	332.83	329.64	175.06	315.46	504.05	577.91	427.88	490.85	537.87	510.35	522.22	342.10	559.31
La_N/Lu_N	8.48	9.28	18.48	6.61	11.27	8.80	10.55	34.03	8.13	10.71	9.34	12.03	18.05	13.36
Eu*/Eu	0.97	0.94	0.94	0.87	0.66	0.66	0.74	0.99	0.79	0.64	0.86	0.75	0.88	0.67

* Analyses were performed at the ICP-MS laboratory of the *Instituto de Geofísica*, UNAM, by Ofelia Morton and Elena Lunejeva.

Table 4. New K/Ar ages for Laramide intrusive and volcanic rocks along the transect. Sample location is shown on Figures 2, 4 and 5; UTM coordinates are included in Appendix I.

Sample No.	Geographic coordinates	Rock type	Mineral	%K	$\%^{40*}Ar$	$^{40*}Ar\times10^{-6}$ (scc/gm) [a]	Age [b] ± Ma	Lithologic unit
Samples from the coastal Region (COR), located in Figure 2								
SO-25	27° 57’ 15” N	Granodiorite	bt	6.414	89	19.80	81.1 ± 2.8	Ks-Ti
	111° 07’ 32” E			6.362	92	21.09		
			hbl	0.4161	75	1.362	82.7 ± 1.7	
					74	1.372		
SO-59	28° 13’ 01” N	Granodiorite	bt	6.732	94	19.72	76.9 ± 2.8	Ks-Ti
	110° 58’ 30” E			6.704	94	21.12		
SO-63	28° 24’ 13” N	Granodiorite	bt	7.106	76	12.63	44.7 ± 0.7	Ks-Ti
	110° 14’ 30” E			7.193	74	12.53		
			ms	8.658	90	19.63	57.6 ± 0.9	
					83	19.77		
Samples from the Central Region (CER), located in Figure 4								
SO-13	28° 27’ 28” N	Rhyolitic tuff	bt	7.562	79	15.75	55.3 ± 2.1	Ksvs
	109° 21’ 32” E			7.517	85	15.63		
	(Out of the transect, 15 km NE of Mesa de Galindo)							
SO-35	28° 20’ 32” N	Granodiorite	bt	6.789	91	14.44	56.1 ± 1.9	Ks-Ti
	109° 32’ 12” E			6.762	91	15.40		
			hbl	0.4054	68	0.89	58.2 ± 3.3	
				0.3864	66	0.93		
SO-64	28° 24’ 20” N	Granodiorite	bt	7.402	85	18.65	63.4 ± 1.0	Ks-Ti
	110° 04’ 10” E				90	18.45		
			hbl	0.4731	11	0.99	56.7 ± 5.1	
				0.4712	31	1.12		
SO-74	28° 18’ 15” N	Cuarzodiorite	bt	6.322	80	16.60	64.9 ± 1.7	Ks-Ti
	110° 08’ 00” E			6.387	71	16.02		
SO-80	28° 17’ 10”	Granodiorite	bt	7.372	83	18	62.0 ± 1.0	Ks-Ti
	109°47’ 00” E		hbl	1.021	77	2.61	62.0 ± 3.0	
				1.063	81	2.6		
				1.104				
Samples from the Sierra Madre Occidental Region (SMOc), located in Figure 5								
SO-15	28° 28’ 03” N	Granodiorite	bt	6,944	86	14.51	53 ± 0.8	Ks-Ti
	109° 06’ 30” E			7.007	60	14.62		
			hbl	0.304	19	0.68	54.3 ± 2.9	
				0.3081	29	0.63		
SO-39	28° 24’ 15” N	Rhyolitic tuff	bt	7.185	82	16.39	56.8 ± 0.9	Ksvs
	109° 14’ 13” E			7.290	88	16.07		
SO-97	28° 24’ 45” N	Andesite	pl	0.5126	42	1.24	61.2 ± 3.4	Ksvs
	109° 05’ 10” E			0.5269	48	1.32		
				0.5446				
MA-1	28° 29’ 14” N	Granodiorite	bt	7.218	82	17.56	62.7 ± 1.0	Ks-Ti
	108° 46’ 08” E			7.111	90	17.99		

Ages obtained at the University of Texas at Austin by F. W. McDowell. [a] Radiogenic argon (scc/gm = cm^3/gr of sample), [b] Decay constant: $\lambda\beta= 4.963\times10^{-10}$ years^{-1}; $\lambda c+c' =0.581\times10^{-10}$ years^{-1}; $^{40}K/K = 1.167\times10^{-4}$. bt: Biotite, hbl: hornblende, pl: plagioclase, ms: muscovite. Errors are 1σ.

(2006) reported U/Pb zircon ages of 88 and 90 Ma for granitoids intruding andesite lavas similar to those of the Tarahumara Formation. Older plutons and/or younger Tarahumara may underlie the Tertiary cover.

Housh and McDowell (2005) measured radiogenic Sr, Nd, and Pb isotopes of samples from Sonora, including three samples of intrusives collected along the study transect. They obtained for a COR sample (SO-25, Figure 2) values of $^{87}Sr/^{86}Sr_i$ of 0.70571 and εNd of -3.4. For two CER samples (Figure 4), they reported εNd and $^{206}Pb/^{204}Pb$ values of -6.2 and 19.076 (SO-63), repectively; no $^{87}Sr/^{86}Sr_i$ were reported. For sample SO-64, they obtained values and $^{206}Pb/^{204}Pb$ of 0.70669 and 15.705, respectively; they did not reported values for εNd (Housh and McDowell, 2005). These results are similar to the data obtained by Valencia-Moreno *et al.* (2001), particularly for their central granites (Cortés terrane), an area that roughly coincides with the transect described in this paper. Their $^{87}Sr/^{86}Sr$ initial values range from 0.7064 to 0.7073 and the εNd initial values from -5.1 to -3.4. These closely resemble the values obtained

Table 5. New Rb-Sr ages of whole rocks of the LSB intrusive rocks along the transect or in their vecinity. Sample location in Figures 4 and 5.

Sample No.	Geographic coordinates	Rock type	Mineral	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$	1s	Concentration (ppm) Rb	Sr	Age ± Ma
Sierra Madre Occidental (SMOc)									
9-98	28°26'30'' N 109°06'37'' E	Granodiorite	bt	752.545	0.707	39	152.48	355.21	
9-98			hbl	1.242	1.239881	60	881.17	3.57	49.9 ± 2.0
Central Region (CER)									
SO-80	28°16'38'' N 109°44'19'' E	Tonalite	bt	583.419	0.707	42	154.87	392.76	
			hbl	1.141	1.23153	66	934.64	4.87	63.4 ± 2.5

Ages obtained in the *Laboratorio de Geoquímica Isotópica* (LUGIS), UNAM, in Mexico City. The analysis were performed with a Mass Spectrometer Finnigan MAT262. Value of the lab standard SRM987: 0.71033±17 (in the last two figures, number of analysis performed (*n*)=195). Ages calculated by ISOPLOT. The analytical work was done by: M.S. Hernández-Bernal, G. Solís Pichardo, J. Morales Contreras and T. Hernández-Treviño. bt: biotite; hbl: hornblende. Rb and Sr concentrations determined by isotopic dilution.

along the transect ($^{87}Sr/^{86}Sr$: 0.7054 to 0.7071 and εNd: -3.3 to -6.29; Table 6). These values are very similar to those obtained for the southern part of the North American craton, in the Cortés Terrane by Valencia-Moreno (1998) and by Housh and McDowell (2005) in northwestern Mexico, including their Pb isotopic values.

Recent publications have provided ample information on major batholith belts in Sinaloa (Henry *et al.*, 2003), and in the Peninsular Ranges of Baja California (Ortega-Rivera, 2003). The three areas are part of the same arc, but each one has unique particularities and differences (Table 7).

In the Peninsular Ranges batholith (PRB) of Baja California, there are two contrasting belts of batholithic rocks. The western belt has been related to an island arc that was tectonically accreted to the continental margin (Wetmore *et al.*, 2003). The eastern belt has a more continental affinity (Silver and Chappell, 1988). The western portion of the Peninsular Ranges batholith is calcic in composition, with U/Pb ages ranging from 101 to 124 Ma. Isotopic ages (U/Pb and $^{40}Ar/^{39}Ar$) within the eastern belt of the PRB show a clear decrease in age toward 80 Ma at the east coast of Baja California (Ortega-Rivera, 2003). If the Gulf of California is closed using restoration by Oskin *et al.* (2001) and Oskin and Stock (2003), which translate the Baja Peninsula about 250 km southeast, the isotopic ages from the PRB, continue progressively into Sonora. At the match area in Sonora, ages are as old as 83 Ma and decrease to ~63 Ma in central and eastern Sonora.

Table 6. Isotopic ratios of Sm/Nd and Rb/Sr for LB granitoids along the transect. Data for two volcanic rocks (I-99, 58-96) are also included.

Sample	Age Ma ±	Concentration (ppm) Rb	Sr	Sm	Nd	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$ ± σ	$^{87}Sr/^{86}Sr$ initial	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$ ± σ	$^{143}Nd/^{144}Nd$ initial	εNd initial	Nd model ages (Ma) (DM)
Costal region (COR)													
101-97	83	75.90	404.57	3.79	20.08	0.543	0.706101 ± 33	0.705470	0.114	0.512423 ± 34	0.512361	-3.3	1123
102-97	83 ± 2	75.24	411.29	3.56	17.81	0.529	0.706587 ± 45	0.705971	0.121	0.512421 ± 29	0.512356	-3.4	1210
SO-63	44 ± 7	151.19	389.94	3.44	19.71	1.122	0.707647 ± 43	0.706930	0.105	0.512388 ± 17	0.512357	-4.4	1079
Central region (CER)													
58-96	60	144.87	399.36	4.93	25.11	1.050	0.707285 ± 49	0.706405	0.119	0.512370 ± 20	0.512324	-4.6	1266
1-98	60	140.01	359.68	3.67	20.43	1.127	0.707470 ± 43	0.706509	0.108	0.512379 ± 15	0.512337	-4.4	1122
13-98	55.3 ± 2	203.85	306.94	5.57	27.73	1.922	0.707730 ± 47	0.706092	0.121	0.512396 ± 94	0.512349	-4.1	1251
TC-22-98	60	239.62	164.33	2.48	15.00	4.221	0.710197 ± 43	0.706591	0.100	0.512414 ± 23	0.512375	-3.6	997
1-99	70	102.82	432.20	5.03	27.16	0.688	0.707837 ± 40	0.707153	0.112	0.512277 ± 16	0.512226	-6.3	1318
SO-80	63.4 ± 2	154.87	392.76	4.83	25.18	1.141	0.707317 ± 42	0.706296	0.116	0.512414 ± 18	0.512366	-3.7	1160
Sierra Madre Occidental Region (SMOc)													
9-98	49.9 ± 2	152.48	355.21	3.06	16.94	1.242	0.707302 ± 39	0.706420	0.109	0.512405 ± 17	0.512369	-4.0	1096
11-98	63.6 ± 1	147.37	414.08	5.48	29.02	1.030	0.707457 ± 40	0.706521	0.114	0.512391 ± 20	0.512343	-4.1	1171
TC-25-98	62	141.34	385.58	3.37	18.60	1.061	0.707097 ± 54	0.706193	0.109	0.512401 ± 21	0.512358	-4.0	1101

Analysis performed using a Finnigan MAT 262; laboratory value for the standard SRM987: 0.710233 ± 16**, and for the Nd La Jolla standard: 0.511881± 21**.(**) In the two last figures. DM values from Goldstein *et al.* (1984). The analytical work performed by: M.S. Hernández Bernal, T. Hernández Treviño, J. Morales Contreras and G. Solis Pichardo. Rb, Sr, Sm and Nd concentrations were determined by isotopic dilution.

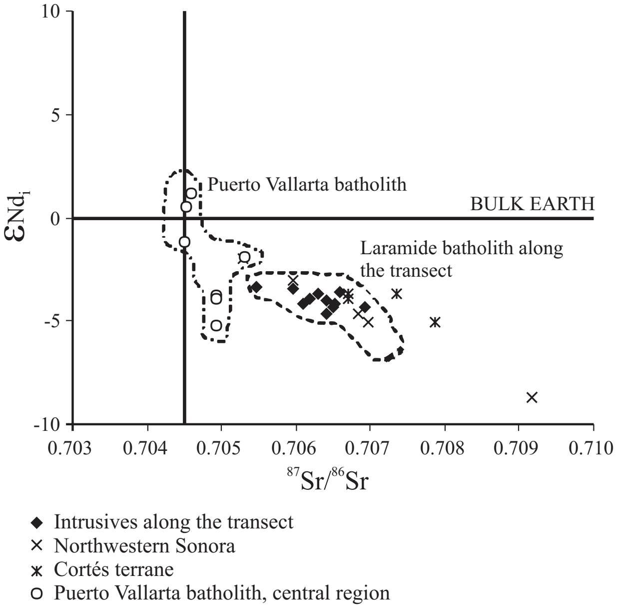

Figure 12. εNd *vs.* $^{87}Sr/^{86}Sr$ for intrusive rocks along the transect. Data for northwestern Sonora (Schaaf *et al.*, in prep.), the Cortés terrane (Valencia-Moreno, 1998); and the Puerto Vallarta batholith, central region (Schaaf and Martínez-Serrano, 1997) are shown for comparison.

The Sinaloa batholith (SB) represents the continuation of the LB of Sonora to the south (Henry *et al.*, 2003). However, there are some important differences between southern Sonora and Sinaloa regions. The SB is exposed in a much narrower belt than the LB. Nevertheless, the age range of the post-tectonic SB granites is much larger (82 to 45 Ma; U/Pb and K/Ar), with one intrusion at 20 Ma. This age range includes intervals with no data and possibly quiescence of plutonism. In Sonora, syntectonic intrusions are not present, the batholiths are undeformed and include tonalite to granodiorite near the coast. These have hornblende K-Ar ages of 86 to 102 Ma. For the Sinaloa batholith, Henry *et al.* (2003) reported that the postectonic rocks dated by both U/Pb and K-Ar range in age from 82 to 45 Ma. The oldest rocks in the Sinaloa batholith include gabbros, which are not present in the LB in Sonora. In southern Sonora, the time span covered by undeformed intrusive rocks varies from 82 to 49 Ma.

CONCLUSIONS

The geological, geochemical and isotopic data indicate that the LA was formed by subduction of the Farallon oceanic plate beneath the North American plate during Late Cretaceous to early Tertiary time, with the participation of both continental and oceanic crust. Genesis of the Laramide batholith (LB) is related to an Andean type subduction, with a moderate inclination (~30–40°) of the subducted plate. Although the arc is mostly concealed by the Cenozoic rocks of the Sierra Madre Occidental volcanic province, it may extend farther to the east in Chihuahua. Volcanic and intrusive rocks of the Laramide arc have been described in central and northern Chihuahua (McDowell and Mauger, 1994). Including these exposures, the arc is more than 500 km wide, not taking into account the effect of late Tertiary extension.

This arc is especially well exposed in the central portion of the studied transect in southern Sonora, where both the plutonic and volcanic (Tarahumara Formation) facies may be readily examined. In some exposures, the contact re-

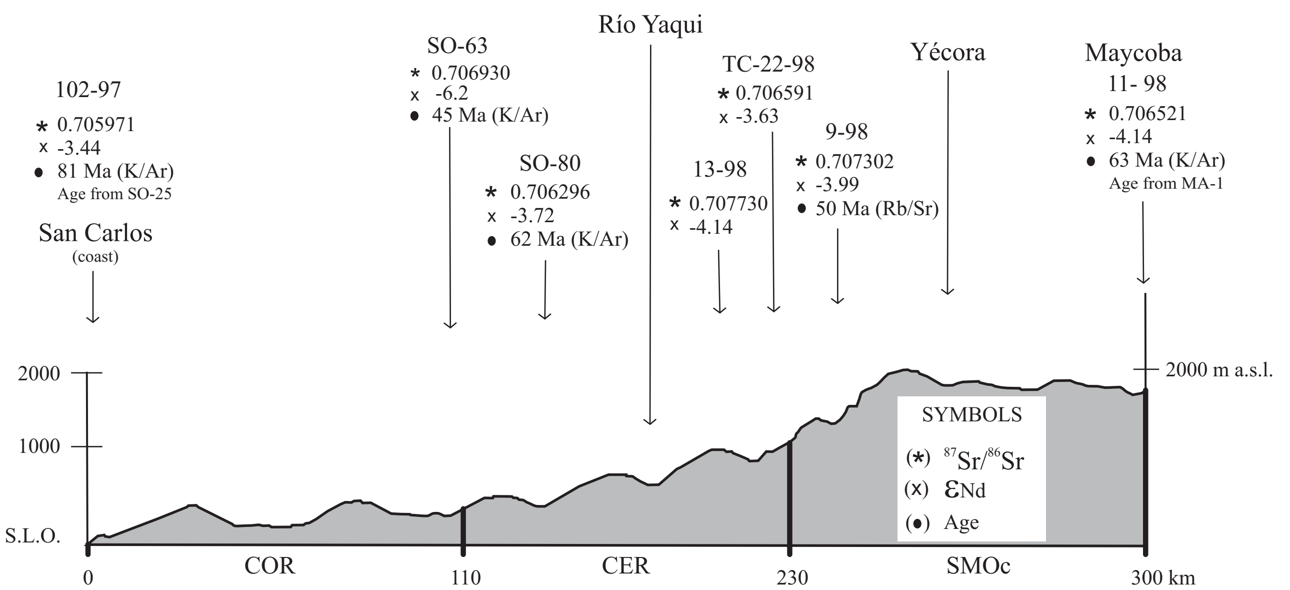

Figure 13. Generalized cross section along the transect displaying the topographic profile of the LB. Some of the isotopic values (*) $^{87}Sr/^{86}Sr$, (×) εNd and ages (●) are indicated. Data for samples SO-25, SO-63 and MA-1 are from McDowell *in* Roldán-Quintana (2002). Other samples are from this paper.

Table 7. Comparison of the Laramide batholith of Sonora with the batholiths of Sinaloa and the Peninsular Range.

	Sinaloa (1)	Laramide Sonoran Batholith along the transect (2)	Peninsular Range Batholith (1), (3) and (4)
Rock type	Early gabbro, quartzdiorite, granodiorite and monzogranite	Early, granodiorite and less granite	Early gabbro, tonalite to granodiorite
Period of intrusion in Ma	82–45 post-tectonic granites	82–62	140–80
K-Ar ages distribution	134, 139, mostly in the west	82–57 in the coast 65–55 in the center 53–62 in eastern most Sonora	129 in the west
Syn-tectonic rocks	Mafic quartzdiorite	Not found	Tonalite and quartzdiorite
Post-tectonic rocks	Granodiorite and granite	Gabbro, granodiorite and granite	Tonalite and granodiorite
Initial $^{87}Sr/^{86}Sr$	Nine samples: 0.7026 to 0.7062	17 samples: 0.7054 to 0.7071	0.7030 in the west 0.7080 in the east

*Data from 1: Henry *et al.* (2003); 2: this paper; 3: Gromet and Silver (1987); 4: Ortega-Rivera (2003).

lationships show that the plutons intrude the volcanic rocks, an observation that is well supported by the geochronology. However, regionally it is clear that the two components are geographically and genetically linked.

With the peninsula of Baja California restored to its pre-Late Miocene position, the chemical and radiogenic isotope compositions and age patterns across the transect are continuous with those of the eastern portion of the Peninsular Ranges batholith. The contrasts with the batholith of southern Sinaloa may reflect an apparent deeper subduction angle, and a longer period of arc magmatism in Sinaloa, where the magmatic arc developed within the younger and less evolved Guerrero terrane.

Although predictable, eastward younger and more evolved rock trend is not regular. Rather, the age ranges, chemistry and radiogenic isotope compositions are quite similar, and certainly do not change in a systematic way. Even the relatively minor plutons exposed far to the east in central Chihuahua, which might be related to the same subduction regime as the LA, have very similar ages (McDowell and Mauger, 1994).

Within the CER, significant exposures of both the intrusive and volcanic components of the LA are present, indicating that the present-day exposure level represents less Tertiary exhumation. The area thus offers a rare opportunity to examine in detail both of these arc components and gain a better understanding of the history and evolution of subduction-related magmatic arc at considerable distance away from the convergent margin.

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APPENDIX. SAMPLE LOCATION

Sample	Coordinates	Analysis	Rock unit
Coastal Region (COR)			
101-97	3093.62 N; 498.69 E	ME, REE, ISO, Rb/Sr	Ks-Ti
102-97	3090.31 N; 490.31 E	REE, ISO	Ks-Ti
105-97	3096.84 N; 484.99 E	ME	Ks-Ti
SO-25	3094.65 N; 487.55 E	ME, K/Ar	Ks-Ti
SO-59	3121.30 N; 502.50 E	ME, K/Ar	Ks-Ti
MV-22	3120.80 N; 500.20 E	ME	Ks-Ti
SO-63	3140.45 N; 563.05 E	ME, REE, ISO, K/Ar	Ks-Ti
56-98	3142.50 N; 560.87 E	ME	Ks-Ti
Central Region (CER)			
106-90	3162.10 N; 618.3 E	ME, REE	
	5 km NE of Suaqui G.		Ksvs
109- 90	3158.40 N; 624.80 E	ME, REE	
	5.3 NE of Suaqui G.		Ksvs
129-97	3142.29 N; 578.85 E	ME, REE	
131-97	3138.30 N; 594.70 E	ME	Ksvs
136-97	3139.73 N; 603.28 E	ME	Ksvs
137-97	3143.18 N; 607.14 E	ME	Ks-Ti
1--98	3137.74 N; 602.75 E	ME, REE, ISO, Rb/Sr	Ks-Ti
13-98	3135.66 N; 644.10 E	ME, REE, ISO, Rb/Sr	Ks-Ti
14-98	3138.80 N; 649:20 E	ME, REE	Ks-Ti
80-98	3128.38 N; 601.48 E	ME, REE	Ks-Ti
81-98	3127.38 N; 601.63 E	ME	Ks-Ti
82-98	3135.37 N; 602.22 E	ME	Ks-Ti
83-98	3141.14 N; 605.73 E	ME	Ks-Ti
4-99	3132.10 N; 649.20 E	REE	Ks-Ti
2-2000	3139.21 N; 653.64 E	ME	Ti
7-2000	3139.57 N; 652.64 E	ME	Ks-Ti
1-99	3137.22 N; 619.05 E	ME, ISO	Ksvs

Appendix (cont.)

Sample	Coordinates	Analysis	Rock unit
Central Region (CER)			
TC-22-98	3140.57 N; 651.81 E	ME, REE, ISO	Ks-Ti
SO-13	3152.60 N; 661.35 E 13 km NE of Mesa de Galindo	K/Ar	Ksvs
SO-35	3136.10 N; 643.60 E	K/Ar, ISO	Ks-Ti
SO-64	3140.45 N; 591.25 E	ME, K/Ar	Ks-Ti
SO-66	3138.35 N; 598.70 E	U/Pb	Ksvs
SO-74	3131.95 N; 583.25 E	K/Ar	Ks-Ti
SO-80	3128.70 N; 623.10 E	ME, REE, K/Ar, ISO	Ks-Ti
Sierra Madre Occidental (SMOc)			
TC-23-98	3143.20 N; 732.37 E	ME	Ks-Ti
TC-25-98	3141.74 N; 683.51 E	ME, ISO	Ks-Ti
58-96	3142.50 N; 683.50 E	ME, ISO	Ksvs
8--98	3145.96 N; 677.04 E	REE	Ks-Ti
9--98	3147.46 N; 685.17 E	REE, ISO, Rb/Sr	Ks-Ti
11--98	3143.14 N; 732.22 E	REE, ISO	Ks-Ti
SO-15	3150.90 N; 685.30 E	ME, ISO, K/Ar	Ks-Ti
SO-39	3143.10 N; 672.80 E	K/Ar	Ksvs
SO-97	3142.44 N; 686.97 E	K/Ar	Ksvs
MA-1	3143.40 N; 733.70 E	ME, K/Ar, Rb/Sr	Ks-Ti
SR-91	3143.90 N; 687.80 E	K/Ar	Ks-Ti

ME: Major elements; REE: Rare earth elements; ISO: Isotopic analysis; Ages: K/Ar and Rb/Sr.

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