Laramide to Miocene syn-extensional plutonism in the Puerta del Sol area, central Sonora, Mexico

Elizard González-Becuar¹, Efrén Pérez-Segura¹, Ricardo Vega-Granillo⁶, Luigi Solari², Carlos M. González-León³, Jesús Solé⁴, and Margarita López Martínez²

¹ Departamento de Geología, Universidad de Sonora, Blvd. Encinas y Rosales, 83000, Hermosillo, Sonora, Mexico, Present address, Grupo México, Centro de Investigaciones, Centenario y Turquesa s/n, Colonia La Prieta, 33800, Hidalgo del Parral, Chihuahua, Mexico.
² Universidad Nacional Autónoma de México, Centro de Geociencias, Campus Juriquilla, 76230, Querétaro, Qro., Mexico.
³ Universidad Nacional Autónoma de México, Instituto de Geología, Estación Regional del Noroeste, 83000, Hermosillo, Sonora, Mexico.
⁴ Universidad Nacional Autónoma de México, Instituto de Geología, Ciudad Universitaria, 04510, Cd. de México, Mexico.
⁵ Departamento de Geología, Centro de Investigación Científica y de Educación Superior de Ensenada (CICESE), Carretera Ensenada-Tijuana No. 3918, 22860, Ensenada, Baja California, Mexico.
⁶ Present address, Grupo México, Centro de Investigaciones, Centenario y Turquesa s/n, Colonia La Prieta, 33800, Hidalgo del Parral, Chihuahua, Mexico.

*elizard.gonzalez@mm.gmexico.com

ABSTRACT

Plutonic rocks of the Puerta del Sol area, in central Sonora, represent the extension to the south of the El Jaralito batholith, and are part of the footwall of the Sierra Mazatán metamorphic core complex, whose low-angle detachment fault bounds the outcrops of plutonic rocks to the west. Plutons in the area record the magmatic evolution of the Laramide arc and the Oligo-Miocene syn-extensional plutonism in Sonora. The basement of the area is composed by the ca. 1.68 Ga El Palofierral orthogneiss that is part of the Caborca block. The Laramide plutons include the El Gato diorite (71.29 ± 0.45 Ma, U-Pb), the El Pajarito granite (67.9 ± 0.43 Ma, U-Pb), and the Puerta del Sol granodiorite (49.1 ± 0.46 Ma, U-Pb). The younger El Oquimonis granite (41.78 ± 0.32 Ma, U-Pb) is considered part of the scarce magmatism in Sonora that records a transition to the Sierra Madre Occidental magmatic event. The syn-extensional plutons are the El Garambullo gabbro (19.83 ± 0.18 Ma, U-Pb) and the Las Mayitas granodiorite (19.2 ± 1.2 Ma, K-Ar). A migmatitic event that affected the El Palofierral orthogneiss, El Gato diorite, and El Pajarito granite between ca. 68 and 59 Ma might be related to the emplacement of the El Pajarito granite. The plutons are metaluminous to slightly peraluminous, with the exception of El Oquimonis granite, which is a peraluminous two-mica, garnet-bearing granite. They are mostly high-K calc-alkaline with nearly uniform chondrite-normalized REE and primitive-mantle normalized multielemental patterns that are characteristic of continental margin arcs and resemble patterns reported for other Laramide granites of Sonora. The Laramide and syn-extensional plutons also have Sr, Nd and Pb isotopic ratios that plot within the fields reported for Laramide granites emplaced in the Caborca terrane in northwestern and central Sonora. Nevertheless, and despite their geochemical affinity to continental magmatic arcs, the El Garambullo gabbro and Las Mayitas granodiorite are syn-extensional plutons that were emplaced at ca. 20 Ma during development of the Sierra Mazatán metamorphic core complex. The $^{40}Ar/^{39}Ar$ and K-Ar ages obtained for the El Palofierral orthogneiss, the Puerta del Sol granodiorite, the El Oquimonis granite, and the El Garambullo gabbro range from 26.3 ± 0.6 to 17.4 ± 1.0 Ma and are considered cooling ages associated with the exhumation of the metamorphic core complex.

Key words: Laramide magmatism; syn-extensional plutonism; geochronology; geochemistry; Sr-Nd-Pb isotopes; Sonora; Mexico.

RESUMEN

El área de Puerta del Sol, en el centro de Sonora, se encuentra en la parte sur del batolito El Jaralito y es parte de la placa inferior del complejo de núcleo metamórfico de la Sierra Mazatán, cuya falla de despegue limita sus afloramientos en su parte occidental. La geología la forman varios plutones que registran la evolución magmática del arco Laramide hasta el plutonismo sinextensional del Oligo-Mioceno-Mioceno de Sonora. El basamento del área lo forma el ortogneis El Palofierral cuya edad de ca. 1.68 Ga (U-Pb) lo hace pertenecer al basamento del bloque Caborca. Los plutones laramídicos incluyen a la diorita El Gato (71.29 ± 0.45 Ma, U-Pb), el granito El Pajarito (67.9 ± 0.43 Ma, U-Pb) y la granodiorita Puerta del Sol (49.1 ± 0.46 Ma, U-Pb). El granito El Oquimonis (41.78 ± 0.32 Ma, U-Pb) es un plutón más joven considerado parte del escaso magmatismo regional transicional al de la Sierra Madre Occidental. Los plutones sinextensionales están representados por el gabbro El Garambullo (19.83 ± 0.18 Ma, U-Pb) y la granodiorita Las Mayitas (19.2 ± 1.2 Ma, K-Ar). Un evento migmatítico que ocurrió entre ca. 68 y 59 Ma afectó al ortogneis El Palofierral, a la diorita El Gato y al granito El Pajarito y pudiera estar relacionado a la intrusión de este último. Los plutones del área son metaluminosos a ligeramente peraluminosos, con excepción del granito El Oquimonis que es peraluminoso, de dos micas y con granate. Estas rocas son principalmente calcialcalinas, altas en $K$.

con patrones muy similares en diagramas de tierras raras normalizados a condrita y diagramas multielementales normalizados a manto primitivo, los cuales indican firmas características del magmatismo de arco en zonas de subducción asociadas a márgenes continentales. Tienen además relaciones isotópicas de Nd, Sr y Pb similares a valores reportados para los granitos laramídicos emplazados en rocas del terreno Caborca en el noroeste y centro de Sonora. Sin embargo, a pesar de su afinidad geoaquímicamente con magmatismo de arco, el gabro El Garambullo y la granodiorita Las Mayitas son plutones emplazados durante la extensión asociada al complejo de núcleo metamórfico de la Sierra Mazatán, tal como lo indican sus edades de ca. 20 Ma. Las edades 40Ar/39Ar y K-Ar obtenidos para el ortogneís El Palofierral, la granodiorita Puerta del Sol, el granito El Oquimonis y el gabro El Garambullo tienen un rango de 26.3 ± 0.6 a 17.4 ± 1.0 Ma y se consideran edades de enfriamiento asociadas a la exhumación del complejo de núcleo metamórfico de la Sierra de Mazatán.

Palabras clave: magmatismo Laramide; plutonismo sinextensional; geocronología; geoquímica; isótopos de Sr-Nd-Pb; Sonora, México.

INTRODUCCIÓN

The geology of the Puerta del Sol area, located in central Sonora, has been poorly reported despite its location at an intermediate position between the well-studied El Jaralito batholith (Roldán-Quintana, 1989, 1991) to the north and the Sierra Mazatán core complex to the south (Figure 1). In this regard, this area records the southern extension of the batholithic magmatism related to the Laramide arc, and given its position in the footwall of the Sierra de Mazatán core complex (Anderson et al., 1980; Wong and Gans, 2008), it also records the Miocene syn-extensional plutonic evolution.

Late Cretaceous to Eocene volcanic sequences and associated plutons comprise an important fraction of the outcropping rocks of Sonora and are part of the Laramide magmatic arc constrained between 90 and 40 Ma by Damon et al. (1983). Development and eastward migration of the arc in southwestern North America during Late Cretaceous time was postulated to be related to progressive shallowing of the subducting Farallon plate (Coney and Reynolds, 1977; Dickinson and Snyder, 1978; Cuéllar-Cárdenas et al., 2012). Subsequent slab steepening of the Farallon plate that started in Eocene-Oligocene time produced westward regression of magmatism toward the continental-margin (Clark et al., 1982), which was accompanied by upper crustal extension and core complex exhumation related to Basin and Range tectonism (Calmus et al., 2011).

The volcanic succession of the Laramide magmatic arc was assigned to the Tarahumara Formation (Wilson and Rocha, 1949, McDowell et al., 2001), while plutons and batholiths were assigned to the Sonoran batholith (Damon et al., 1983). Outcrops of these rocks are widespread in Sonora, and recent contributions have improved the knowledge of their regional stratigraphy, geochronology, geochemical and radiogenic isotopic composition, to better constrain the timing, nature and implication of basement variations, associated mineralization, and petrogenesis (Rockland-Quintana, 1991, McDowell et al., 2001, Valencia-Moreno et al., 2001, Valencia-Moreno et al., 2003, Iriondo et al., 2004, Barra et al., 2005, Housh and McDowell, 2005, Nourse et al., 2005, Valencia et al., 2005, Noguez-Alcántara et al., 2007, Rockland-Quintana et al., 2009, Pérez-Segura et al., 2009, González-León et al., 2011, Pérez-Segura et al., 2013, Del Río Salas et al., 2013).

In central Sonora, the Laramide magmatism is best represented by the El Jaralito batholith (Rockland-Quintana, 1989, 1991) (Figure 1). Although this batholith was originally studied in sierra Aconchi and in the northern part of sierra El Jaralito (Rockland-Quintana, 1989, 1991; González-León et al., 2011), it extends to the south in a 100 km-long and up to 30 km-wide belt of plutons that end in Sierra Mazatán (Figure 1). Furthermore, the El Jaralito batholith not only holds a nearly complete history of Laramide plutonism but it also records the late Cenozoic magmatic events associated with the extensional phase that exhumed the Sierra Mazatán metamorphic core complex and the batholith itself.

Within El Jaralito batholith, Laramide magmatism is represented by dioritic to granitic plutons, including two-mica peraluminous granites, that range in age from ~70 to ~50 Ma (González-León et al., 2011), whereas in its flanks there are Oligocene-Miocene metamorphic core complexes of Sierra Mazatán, Sierra El Jaralito and Sierra Aconchi (Coney, 1980; Anderson et al., 1980; Nourse et al., 1994; Vega-Granillo...
and Calmus, 2003; Wong and Gans, 2003, 2008; Lugo Zazueta, 2006; Wong et al., 2010, Calmus et al., 2011) (Figure 1).

The El Jaralito batholith intrudes a Proterozoic basement composed of ~1.7 Ga and ~1.1 Ga granites of the Caborca terrane, a Neoproterozoic, Paleozoic and Mesozoic sedimentary succession that reaches an estimated thickness of 12 km, as well as the contemporaneous ~4 km thick volcanic succession of the Tarahumara Formation (González-León et al., 2011).

The purpose of this work is to detail the geology of the Puerta del Sol quadrangle located just south of the El Jaralito batholith, and 15 km to the north of the Sierra Mazatán core complex (Figure 1) (González-Becuar, 2013). The rocks of this area comprise an almost continuous record of plutonism that illustrates the transition from the Laramide magmatic arc event to the Oligo-Miocene core complex extension in central Sonora. Our work is based on field cartography at the 1:50,000 scale, U-Pb, K-Ar and 40Ar/39Ar geochronology that helps to constrain the age of the magmatic events, while major, trace and Sr-Nd-Pb isotope geochemistry helps to infer the petrogenesis of the different igneous events.

**GEOLOGY OF THE STUDY AREA**

The Puerta del Sol area is located 70 km E-NE of the city of Hermosillo, within coordinates 110° 00' to 110° 20' W and 29° 15' to 29° 30' N. It covers almost the complete 1:50,000 topographic chart H12D33 edited by INEGI (2004) and includes the El Pajarito and El Batamote sierras in its eastern and southern parts, respectively (Figure 2).

The geology of the area was first reported by Radelli (1986) in a general map where he recognized and named some of the plutons that are herein described in detail. Radelli (1986) named the El Pajarito, El Oquimonis, Garambullo, and Las Mayitas plutons, and his nomenclature is followed in this paper. Anderson et al. (1980) named the Puerta del Sol granodiorite and reported a U-Pb age of 57 ± 2 Ma for this pluton. In addition to these plutons, we recognized the El Palofierral orthogneiss, El Gato diorite and the occurrence of widespread zones of migmatization. Damon et al. (1983) reported a zircon U-Pb age of 57 ± 3 Ma (originally reported by Damon and Mauger, 1966) for a “granitic porphyry” sample from the Puerta del Sol pluton.

Anderson et al. (1980) suggested that the Puerta del Sol area was part of the lower plate of a metamorphic core complex, which Nourse et al. (1994) later referred to as the Puerta del Sol domain. Vega-Granillo and Calmus (2003) considered the Puerta del Sol area as a continuation of the Sierra Mazatán metamorphic core complex shear zone, which was mainly active from ~25 and 16 Ma (Wong and Gans, 2008). The denudation of this core complex was mostly driven along a major detachment fault that crops out in its western part and that we informally refer herein as the Sierra Mazatán detachment fault (Figure 2).

The metamorphic and plutonic units of the study area include the El Palofierral orthogneiss, which is part of the Proterozoic basement of the region, Laramide plutons and associated migmatite zones, and plutons that were synchronically emplaced with the exhumation of the metamorphic core complex. The Laramide plutons are the El Gato diorite, El Pajarito, Puerta del Sol and El Oquimonis granitoids and syn-extensional plutons are the El Garambullo gabbronorite and the Las Mayitas granodiorite. Two regional swarms of dikes that intrude these rocks are briefly described. Restricted outcrops of metasedimentary rocks of probable Paleozoic age also occur as screens or isolated pendants on younger plutons, while in the eastern and western parts of the area there are outcrops of undifferentiated volcanic rocks, which were tentatively assigned to the Tarahumara Formation (Figure 2). The valley located to the west of the detachment fault is partially occupied by sedimentary and volcanic rocks of Miocene age that represent continental deposits accumulated on the hanging-wall during core-complex formation (Calles-Montijo, 1999; Vega-Granillo and Calmus, 2003; Wong and Gans, 2008).

**El Palofierral orthogneiss**

El Palofierral orthogneiss was originally mapped and referred to as “granite gneiss” by Radelli (1986). This is the oldest unit in the study area, and constitutes small hills along the central part of the area, with the best outcrops found along the El Palofierral and El Bamuco creeks (Figure 2). The orthogneiss is foliated, leucocratic to mesocratic, and coarse-grained, with K-feldspar porphyroclasts up to 5 cm in size (Figure 3a). The main mineral assemblage is K-feldspar (orthoclase and subordinate microcline), quartz, biotite, plagioclase (An$_{20}$-30), opaque minerals and muscovite. Feldspar porphyroclasts show micro-boudinage and quartz-filled pressure shadows. Quartz grains are stretched with strong undulose extinction and biotite occurs as euhedral elongate crystals displaying incipient chloritization. Muscovite is a secondary or metamorphic mineral formed after biotite and plagioclase. This rock shows mineral foliation and banding, as well as large-scale folding indicated by regional dip of the foliation. Dilational-migmatized muscovite (discussed below) consisting of quartz + feldspar + biotite leucosomes are heterogeneously dispersed within this unit.

**El Gato diorite**

This pluton is exposed in a small area in the central part of the Sierra El Pajarito (Figure 2). The pluton consists of hypidiomorphic, holocrystalline, medium- to coarse-grained mesocratic rocks with plagioclase, orthoclase, quartz, biotite and subordinate hornblende and pyroxene (Figure 3b). Plagioclase (An$_{20}$-40) is euhedral, commonly glomeroporphyritic and occasionally myrmekitic, whereas orthoclase is anhedral and is affected by moderate sericitization and secondary muscovite development. Quartz crystals are anhedral with undulose extinction, and mostly fill interspaces between feldspars. This pluton is affected by migmatization in the northern part of its outcrop (Figure 2).

**Migmatites**

A zone of migmatization occurs in the east-central part of the study area (Figure 2), which notably affects the El Gato diorite and the El Palofierral orthogneiss. The migmatites occur as medium- to fine-grained rocks with well-developed banding of melanosome and leucosome (Figure 3d). The melanosome is generally composed of biotite, plagioclase, hornblende and orthopyroxene, and the leucosome includes quartz, plagioclase, K-feldspar, muscovite, biotite, clinopyroxene and titanite. Some of the observed migmatitic structures include patch, veins, stromatic and pytgmatic folds, boudins, schlieren, nebulitic and net-like structures. There are also meter-scale outcrops of foliated to non-foliated amphibolite and diorite that display stromatic, brecciated, and dilatational-type structures characteristic of metatexites (Sawyer, 2008).

**El Pajarito granite**

This is a leucocratic, saccaroid-textured, medium-grained pluton with quartz phenocrysts that crops out in the southern part of the Sierra El Pajarito (Figures 2, 3c). To the north, El Pajarito pluton intrudes the El Gato diorite and is in turn cut by up to 2.5 m thick dikes of pegmatite and aplite, and by less than 1-cm thick veinlets of quartz with muscovite, pyrite and garnet. Petrographically this rock is holocrystalline and hypidiomorphic, mainly composed of quartz, microcline, and plagioclase (An$_{25}$-30), subordinate biotite and opaques; accessory minerals include pyroxene, garnet and zircon. K-feldspar
crystals are subhedral and quartz tends to be subhedral to rounded with parallel extinction. Plagioclase crystals are euhedral and exhibit incipient to moderate alteration to muscovite + sericite, while biotite occurs as euhedral crystals with occasional muscovite and pyrite crystals along cleavage planes.

**Puerta del Sol granodiorite**

Outcrops of the Puerta del Sol granodiorite occupy most of the northern part of the study area (Figure 2). This pluton is mesocratic, medium- to coarse-grained, with well-defined magmatic foliation indicated by the parallel alignment of 2 to 5 cm-long K-feldspar phenocrysts (Figure 3e). Its mineralogy consists of quartz + K-feldspar + plagioclase (An$_{30-50}$) + biotite + titanite + zircon. Quartz crystals are xenomorphic, commonly with undulose extinction, and K-feldspar occurs as orthoclase and less commonly microcline; plagioclase crystals are euhedral to subhedral with common oscillatory zoning. Biotite is anhedral to subhedral with moderate chloritization, and titanite crystals are rhombic, euhedral with skeletal structure. Incipient sericitic alteration is observed in feldspars, and propylitic alteration is observed as veinlets of chlorite and epidote. Proto-mylonitic to mylonitic...
Plutonism in the Puerta del Sol area, central Sonora, Mexico

a) The foliation is restricted to a ~1 km-wide zone along the westernmost part of the Puerta del Sol granodiorite outcrop (Figure 2), recording ductile deformation imprinted by the low-angle detachment fault that exhumed the crystalline rocks in the footwall.

El Oquimonis granite

The medium- to coarse-grained, leucocratic El Oquimonis granite crops out in the southern part of the quadrangle, where it forms the Sierra El Batamote (Figure 2). This pluton intrudes the El Palofierral orthogneiss and the Puerta del Sol granodiorite and is in sharp contact with the El Pajarito granite through a high-angle normal fault. The lithology corresponds to a two-mica granite composed of quartz, feldspar, muscovite, biotite and garnet. Quartz crystals are commonly anhedral, with undulose extinction, and myrmekitic intergrowths with feldspars. K-feldspars are subhedral to euhedral or thoclase and microcline, while plagioclase is albite-oligoclase (An10-20). Subordinate minerals consist of euhedral muscovite and biotite, and the accessory minerals are garnet crystals up to 1 cm long, fine-grained apatite, zircon and opaque minerals. Slight to moderate sericitic alteration is observed in feldspar, while chloritic alteration occurs in biotite.

The western part of this pluton also records the heterogeneous proto-mylonitic foliation caused by shearing along the low-angle Sierra de Mazatán detachment fault, which places El Oquimonis granite in tectonic contact with clastic and volcanic deposits that form the upper plate of the metamorphic core complex.

El Garambullo gabbro

The El Garambullo gabbro is a melanocratic pluton that crops out in an area of ~20 km² (Figure 2), and intrudes the western part of the Puerta del Sol granodiorite. It is a fine- to medium-grained, equigranular to porphyritic rock consisting of plagioclase (An60-70) + hornblende + opaque minerals + biotite + orthopyroxene, with common glomerophyric association of hornblende + opaque minerals. Plagioclase (labradorite-bytownite) forms a crystalline groundmass of euhedral crystals over which hornblende phenocrysts grow. Hornblende includes disseminated opaque minerals (magnetite-
ilmenite) and is moderately to strongly altered to chlorite, epidote and actinolite. Biotite crystals are euhedral to subhedral with moderate chloritic alteration, and with opaque mineral inclusions along cleavage planes. Orthopyroxene (enstatite) is subrounded and associated with Fe-Mg minerals. Subordinate minerals are fine-grained, euhedral and disseminated rutile, spinel, apatite and zircon.

This pluton has local schlieren-like cumulates of ferromagnesian minerals, and mylonitic xenoliths from the Puerta del Sol granodiorite (Figure 3g) near the contacts. It also contains 2 to 20 cm-long aligned enclaves of gabbro and hornblende that define a magmatic foliation, as well as fragmented syn-plutonic mafic dikes. A few, up to 10 m-long darker gabbro enclaves are also recognized.

Las Mayitas granodiorite

This is a small pluton that forms a ~7 km² outcrop in the north-central part of the study area (Figure 2). It intrudes the Puerta del Sol granodiorite along a sharp contact, while its contact with the El Garambullo gabbro is a mingling zone (Figures 3h). This pluton consists of a fine-grained, mesocratic rock with quartz and plagioclase phenocrysts. The texture is hypidiomorphic and mineralogically consists of quartz, plagioclase (An₃₀₋₃₅) and orthoclase with subordinate biotite and accessory titanite, iron oxide and zircon. Plagioclase crystals are euhedral and occasionally glomeroporphyritic, whereas orthoclase has compositional zonation. Phenocrystic quartz is subhedral to anhedral, and it also fills spaces between feldspar crystals. The contact between the Las Mayitas and El Garambullo plutons is a diffuse zone that includes abundant aligned enclaves derived from both plutons developing flame and schlieren structures. These magmatic structures and fabrics occur in both plutons without evidence of magma mixing.

Dikes

Pegmatitic and aplitic dikes occur in the central and southeastern parts of the area (Figure 2) forming parallel dike swarms with a NW15-30° trend. They are composed of quartz, orthoclase, plagioclase, muscovite, biotite, and garnet, with thicknesses ranging from 5 to 120 cm, and intrude the El Oquimonis and the Puerta del Sol plutons. According to their field relationships they might be genetically related to the El Oquimonis granite, which is the younger rock they intrude.

A second, younger, prominent swarm of basaltic dikes cuts the Puerta del Sol granodiorite and the El Garambullo gabbro forming conspicuous NE- and NW-trending ridges in the northern part of the area (Radelli et al., 1995; Bronner and Radelli, 1996; Wong and Gans, 2008). The mafic dikes dip 50°-70° SW and their thickness varies from 30 cm to 2 m. They are fine-grained rocks composed of plagioclase (An₃₀₋₃₅), hornblende, biotite, and opaque minerals. Scarcer, thinner dikes of rhythmic composition that display parallel trends might be coeval to the mafic dikes forming a bimodal pulse. The rhythmic dikes are porphyritic with crystals of quartz, K-feldspar and plagioclase up to 3 mm in size, along with accessory chloritized biotite in a fine, equigranular groundmass of quartz and feldspar. Wong and Gans (2008) dated one of the mafic dykes from outcrops along the Ures-Mazocahui highway and reported a ⁴⁰Ar/³⁹Ar hornblende age of 22.6 ± 0.4 Ma.

GEOCHEMISTRY

In order to geochemically characterize the different geologic events in the Puerta del Sol area, we analyzed 21 rock samples that were collected from fresh representative rock outcrops. Whole-rock samples were analyzed for major and trace elements (Table 1), while isotopic ratios of Sr, Nd and Pb were obtained in five samples (Table 2). Major elements were determined by X-ray fluorescence at Laboratorio Universitario de Geoquímica Isotópica (LUGIS) of the Universidad Nacional Autónoma de México (UNAM), with a Rigaku Primus II 488 spectrometer, according to procedures described in Lozano-Santa Cruz and Bernal (2005). Trace element data were determined by ICP-MS at Laboratorio de Estudios Isotópicos, Centro de Geociencias, UNAM, using a Thermo ICAP Q-ICPMS, and following the analytical techniques described in Mori et al. (2007). Isotopic ratios of Sr, Nd and Pb were determined at the Isotopic Laboratory of the University of Arizona, Department of Geosciences following procedures reported in appendix 4 of González-León et al. (2011) and at the University of Texas at Austin, according to procedure reported in appendix 1 of González-León et al. (2017).

Major and trace element geochemistry

The analyzed rock samples have loss on ignition (LOI) values ≤2.5 wt.% (Table 1), except for mafic dykes EGB12-38 and EGB12-39 that exceed that value and were only used for trace element interpretations. The concentration of major oxides was recalculated to 100% on an anhydrous basis and the results were plotted on classification diagrams to make geochemical interpretations.

A chemical classification of the rocks of the area based on the R1-R2 diagram of De la Roche et al. (1980) is consistent with the petrographic classification (Figure 4a). Two samples of the El Palofierral orthogneiss classify near the boundary between monzogranite and granodiorite and two samples of the El Gato pluton range from diorite to gabbrodiorite. Two leucosome migmatises classify as granodiorite and monzodiorite and a third sample from a melanosome is a syenogabbro. Two samples from the El Pajarito granite classify as monzogranite and syenogranite, three other from Puerta del Sol plot in the granodiorite field and four samples from the El Oquimonis granite plot closely as syenogranite, monzogranite and granodiorite. Two samples from the El Garambullo pluton plot as olivine gabbro, and a third sample classifies as a syenogabbro, while a single sample from the Las Mayitas plots as granodiorite.

The Laramide plutons have silica contents ranging from 55 to 76 wt. %. Silica variation diagrams of the major oxides show a general negative correlation with SiO₂, with the exception of Na₂O which displays a negligible positive correlation. All samples are subalkaline in a total alkali vs. silica diagram (Irvine and Baragar, 1971; Le Bas et al., 1986). The AFM diagram (Irvine and Baragar, 1971) (Figure 4b) indicates calc-alkaline compositions, but one migmatite sample straddles the boundary to tholeiitic field. The SiO₂–K₂O diagram (Figure 4c) with discriminating fields of Peccerillo and Taylor (1976) indicates that the El Palofierral orthogneiss and the Laramide plutons are mostly high-K in composition except for the Puerta del Sol and El Gato plutons that plot as medium-K, close to the boundary with the high-K field. One of the migmatite samples is shoshonitic and the syn-extensional El Garambullo and Las Mayitas plutons plot also in the high-K and shoshonitic field.

In the alkali index diagram (Shand, 1943) (Figure 4d), the El Pajarito, the Puerta del Sol and Las Mayitas plutons are weakly peraluminous with Al₂O₃/(CaO+K₂O) molar ratios between 1 and 1.1. The El Oquimonis granite is clearly peraluminous, and the El Gato and El Garambullo plutons are metaluminous. Two of the migmatite samples are weakly peraluminous while a third sample is metaluminous. The Rb vs. (Y+Nb) tectonic discrimination diagram of Pearce et al. (1984; Figure 4e) shows that all of studied samples plot in the field of volcanic–arc granites.

Rare earth elements (REE) abundance of the studied samples were normalized to chondrite values (McDonough and Sun, 1995) and the resulting diagrams are shown in Figure 5. The Laramide plutons show an overall enrichment in light REE (LREE) with a negligible depletion in heavy REE (HREE), except for the leucocratic El Oquimonis and El
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Table 1. Major (in wt. % oxide) and trace element (in ppm) data for metamorphic and magmatic rocks from the Puerta del Sol area.
Figure 4. Geochemical discrimination plots for the plutons of the Puerta del Sol area. a) Chemical classification of the rocks based on the R1-R2 diagram of De La Roche et al. (1980). R1 and R2 parameters express equations in millicationic proportions: $R1 = 4Si - 11(Na+K) - 2(Fe+Ti)$; $R2 = 6Ca + 2Mg + Al$. b) AFM ternary diagram including the discrimination line from Kuno (1968). A: Na$_2$O+K$_2$O; F: Total FeO; M: MgO. c) $K_2O$ vs. SiO$_2$ diagram with K fields of Peccerillo and Taylor (1976). d) Discrimination diagram based on the Shand index in molar proportions. Stippled line on the vertical axis marks the boundary between slight to high peraluminous fields from Chappel and White (1974). e) Pearce et al. (1984) tectonic discrimination diagram showing the composition of the studied plutons: VAG (volcanic arc granite), syn-COLG (syn-collisional granites), WPG (within-plate granites), ORG (oceanic ridge granites).
Pajarito plutons that have different REE patterns. Two samples from the El Oquimonis granite show the lowest LREE values (Figures 5a), while two samples from the El Pajarito granite show overall flat REE patterns. The El Oquimonis and El Pajarito intrusives also have pronounced negative Eu anomalies and the Puerta del Sol granodiorite tends to mimic this pattern but with a less negative Eu anomaly. REE diagrams for the El Garambullo gabbro and the mafic dikes show nearly similar patterns with enrichment in LREE and depletion of the HREE, which display nearly flat curves. The Las Mayitas granodiorite follows a nearly similar trend than the mafic rocks but at relatively lower total REE content.

Multielemental diagrams normalized to primitive mantle values (Sun and McDonough, 1989) display nearly similar jagged patterns (Figure 5c, 5d). They show relative enrichment in K, Rb, Ba and Pb compared to Hf, Zr and Y. The El Pajarito granite however has very low values in Ba. They also show negative anomalies for Nb-Ta (Figures 5c), Sr, P and Ti. The syn-extensional plutons and mafic dikes follow the same elemental pattern (Figure 5d).

Isotope geochemistry
Isotope ratios of Sr, Nd and Pb were obtained in samples from El Gato diorite, El Oquimonis granite, Las Mayitas granodiorite and El Garambullo gabbro, and Pb isotope values were obtained for the El Palofierral orthogneiss (Table 2). The initial ⁸⁷Sr/⁸⁶Sr ratios for these plutons range from 0.7069 to 0.7089 and their initial εNd values from -2.6 to -7.7 (Table 2). Their ²⁰⁶Pb/²⁰⁴Pb ratios range from 19.09 to 19.26, the ²⁰⁷Pb/²⁰⁴Pb ratios from 15.65 to 15.68, and the ³⁶Ar/³⁹Ar ratios from 38.69 to 38.89. The ²⁰⁶Pb/²⁰⁴Pb, ²⁰⁷Pb/²⁰⁴Pb and ²⁰⁸Pb/²⁰⁴Pb ratios for the El Palofierral orthogneiss are 19.48, 15.67, and 38.73, respectively. The composition of these rocks is plotted in Figure 6, and compared with similar data reported for Paleoproterozoic and Laramide plutonic rocks from neighboring areas of central Sonora.

GEOCHRONOLOGY
Ages of the magmatic events that occurred in the Puerta del Sol area are constrained by nine U-Pb, five K-Ar and two ⁴⁰Ar/³⁹Ar ages (Table 3). U-Pb zircon ages were obtained by laser ablation inductively-coupled plasma mass spectrometry (LA-ICPMS) in the Centro de Geociencias, UNAM following procedures described in Solari et al. (2010, 2015) [results are reported in Supplemental Table A], and by laser ablation–multicollector–inductively coupled plasma–mass spectrometry (LA-MC-ICP-MS) at the Arizona LaserChron Center of the Department of Geosciences, University of Arizona, using the procedures described by Gehrels et al. (2006) [results are reported in...
Supplemental Table B]. K-Ar analyses were conducted at Instituto de Geología, UNAM, with the procedures described in appendix 3 of González-León et al. (2011). The $^{40}$Ar/$^{39}$Ar dating was performed at Laboratorio de Geocronología of the Departamento de Geología, Centro de Investigación Científica y de Educación Superior de Ensenada (CICESE), with procedures described in González-León et al. (2010).

U-Pb ages were determined in zircon separates for samples of the El Palofíerial orthogneiss, El Gato diorite, El Pajarito granite, Puerta del Sol granodiorite, El Oquimonis granite, two different samples of migmatites, and the Garambullo gabbro (see sample locations in Figure 2). One sample of the El Palofíerial orthogneiss was collected from the El Bamuco creek (sample EGB12-24) and a second one from near rancho El Palofíerial (sample EGB13-7). Zircons of these samples are euhedral to anhedral, with concentric zoning, and some display irregular metamorphic overgrowths. From sample EGB12-24 we measured 26 individual zircons in their rims and cores. The concordia diagram of Figure 7a indicates that the analyzed zircons describe a discordia line, with a Paleoproterozoic upper intercept and a Late Cretaceous lower intercept. The mean age of the zircons defining the

Table 3. Summary of U-Pb, K-Ar and Ar/Ar ages obtained for Puerta del Sol units.

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Note: bt: biotite; kf: k-Feldspar; pg: plagioclase; mc: muscovite; z: zircon
Figure 7. U-Pb ages for the rocks of the study quadrangle. a-c) Ages of sample EGB12-24 from the El Palofierral orthogneiss obtained in cores (b) and in rim (c) of the dated zircons. d-f) Sample EGB13-7 from the El Palofierral orthogneiss collected in rancho El Palofierral: e) age of zircon cores and f) in rims. g-h) Sample EGB12-44 from the El Gato diorite: h) mean-age diagram. i-j) Sample EGB12-42 from the El Pajarito granite: j) mean-age diagram. k-m) Sample EGB12-37 from a migmatite: l) in zircon cores and m) in rims. n-o) Sample EGB12-40 from a migmatite: o) mean-age diagram. p-q) Sample 112083 from the Puerta del Sol granodiorite: q) mean-age diagram. r-s) Sample 202082 from El Oquimonis granite: s) mean-age diagram. t-u) Sample 1121093 from the El Garambullo gabbro: u) mean-age diagram.
upper intercept is of 1.685 ± 1.5 Ma (Figure 7b) and a younger population obtained from zircon rims yielded a mean age of 66 ± 2.1 Ma in a group of five zircons (Figure 7c). Sample EGB13-7 has a similar behavior, with a discordia (Figure 7d) that joins an upper intercept with a mean age of 1.672 ± 12 Ma (Figure 7e) in 52 measured zircons, and a lower intercept at a mean age of 61.7 ± 4.1 Ma (Figure 7f) obtained by analysis of zircon rims.

Sample EGB12-44 from the El Gato diorite yielded euhedral to subhedral, slender zircons with concentric zoning. All of them are concordant to slightly discordant (Figure 7g), with a mean age of 71.29 ± 0.45 Ma defined by a coherent group of 44 analyses (Figure 7h). The El Pajarito granite sample EGB12-42 yielded euhedral to subhedral, slender concordant zircons with concentric zoning and a mean age of 67.9 ± 0.43 Ma obtained from a coherent group of 19 zircons (Figures 7i and 7j).

Dated samples EGB12-37 and EGB12-40 were collected from migmatites that crop out along the El Batmuco creek. Sample EGB12-37 belongs to a foliated migmatitic amphibolite with stromatic leucosome bands that crop out within the El Palofierral orthogneiss. It yielded euhedral to subhedral zircons with concentric zoning. The concordia diagram evidences upper and lower intercepts (Figure 7k). Six ages obtained from the zircon cores yielded a mean age of 1.683 ± 0.96 Ma (Figure 7l), while six ages from zircon rims yielded a mean age of 64.3 ± 1.1 Ma (Figure 7m). Sample EGB12-40 collected from a migmatite exposed near the El Gato pluton and near El Pajarito ranch yields concordant ages (Figure 7n) with a mean age of 58.91 ± 0.41 Ma in a group of 40 zircon rim analyses (Figure 7o).

Sample 112083 from the Puerta del Sol granodiorite yields concordant analyses (Figure 7p) with a mean age of 49.1 ± 0.46 Ma in a coherent group of 24 measured zircons (Figure 7q), while sample 202082 from the El Oquimonis granite also yielded concordant ages (Figure 7r) with a mean age of 41.78 ± 0.32 Ma in a group of ten zircons (Figure 7s). The youngest U-Pb age obtained was for sample 1121093 collected from El Garambullo gabbro that yielded concordant results (Figure 7t) with a mean age of 19.83 ± 0.18 Ma (Figure 7u) in a coherent group of nine out of 17 measured zircons.

We also obtained K-Ar ages for El Palofierral orthogneiss, El Oquimonis granite, and Puerta del Sol and Las Mayitas granodiorites (Table 4). A biotite separated from sample GPF-01 from El Palofierral orthogneiss gave an age of 23.2 ± 0.8 Ma and two ages obtained from sample CGO-01 from the El Oquimonis granite yielded ages at 26.3 ± 0.6 Ma in muscovite and at 21.8 ± 0.5 Ma in biotite. Also, sample PSO2-01 from the Puerta del Sol granodiorite was dated at 20.2 ± 0.6 Ma in biotite, while sample 927092 from the Las Mayitas granodiorite was dated at 19.2 ± 1.2 Ma.

Two other samples, one collected from the El Palofierral orthogneiss (19091F) and another one collected from the El Garambullo gabbro (1026081) were dated by the 40Ar/39Ar method. Sample 19091F1 reveals excess argon as suggested by the “U” shaped age spectrum (Figure 8a), the best age was obtained at the intercept with an isochron age of 23.0 ± 1.3 Ma in K-feldspar. Sample 1026081 yielded an acceptable plateau age of 17.4 ± 1.0 Ma in plagioclase (Figure 8b) for the El Garambullo gabbro.

**DISCUSSION**

The study area lies within the Proterozoic crustal Caborca block, far south of the boundary with the Mazatzal block (see inset map in Figure 1). This boundary, that juxtaposes both blocks, corresponds to the Jurassic Mojave-Sonora megashear as postulated by Anderson and Silver (2005). Arvizu et al. (2009) however suggested that a parallel strip of the Yavapai province (Bennet and DePaolo, 1987) separates the crustal Mazatzal and Caborca blocks in Sonora. They also assigned the Caborca block to the Paleoproterozoic Mojave province of southwestern North America, with U-Pb ages for the crystalline basement in Sonora of ca. 1.76 to 1.64 Ga (summarized in Iriondo and Premo, 2011). The age of ca. 1.68 Ga that we obtained for the El Palofierral orthogneiss is within the age range assumed for the basement of the Caborca block and the obtained Pb isotope ratios plot close to the field of the Paleoproterozoic rocks of the Mojave province (Wooden et al., 1988; Wooden and DeWitt, 1991) (Figure 6b), similarly to other Paleoproterozoic granitoids reported from the Caborca block in Sonora (Farmer et al., 2005; González-León et al., 2011). In Figure 6b, the El Palofierral orthogneiss also plots within the field of values for Laramide granites emplaced in the Caborca block of central and southern Sonora (as compiled in González-León et al., 2011), as observed for other plutonic rocks of the study quadrangle.

**Laramide plutonism**

The oldest Laramide plutonic event in the area is recorded by the intrusion of the El Gato diorite that occurred at 71.29 ± 0.45 Ma. The restricted outcrop of this pluton in the east-central part of the study area is separated from the El Palofierral orthogneiss by a zone of migmatization that affects both units. In its eastern part, El Gato diorite intrudes undated rocks of the Tarahumara Formation. Volcanic rocks of the Tarahumara Formation from nearby areas of central Sonora have been dated between ca. 80 and 59 Ma (González-León et al., 2011). The El Pajarito granite is a leucocratic, slightly peraluminous granite that intruded the El Gato diorite at ~68 Ma.

The migmatization event in the central part of the area affects rocks of El Gato diorite and El Palofierral orthogneiss along the intrusive contact between both units. Far from this contact, local patches of migmatization also occur within the El Palofierral orthogneiss (Figure 2). The migmatization event also affects the El Pajarito granite along its contact with the southern part of the El Gato diorite. The zone of migmatization occurring to the north of the El Pajarito granite and northeast of the El Palofierral orthogneiss might be affecting these three plutonic bodies. Nevertheless, the migmatization event in the area is a complex event and should be better clarified by subsequent studies.

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**Table 4. Analytical data of K-Ar ages obtained for plutons of the Puerta del Sol area.**

<table>
<thead>
<tr>
<th>Sample</th>
<th>Rock Unit</th>
<th>Mineral</th>
<th>%K</th>
<th>40Ar* (moles/g) × 10^-10</th>
<th>%40Ar*</th>
<th>Age (Ma)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GPF-01</td>
<td>El Palofierral orthogneiss</td>
<td>Biotite</td>
<td>7.49</td>
<td>3.03</td>
<td>49.1</td>
<td>23.2 ± 0.8</td>
</tr>
<tr>
<td>CGO-01</td>
<td>El Oquimonis granite</td>
<td>Biotite</td>
<td>7.65</td>
<td>2.906</td>
<td>89.1</td>
<td>21.8 ± 0.5</td>
</tr>
<tr>
<td>CGO-01</td>
<td>El Oquimonis granite</td>
<td>Muscovite</td>
<td>8.35</td>
<td>3.839</td>
<td>85</td>
<td>26.3 ± 0.6</td>
</tr>
<tr>
<td>PSO2-01</td>
<td>Puerta del Sol granodiorite</td>
<td>Biotite</td>
<td>7.42</td>
<td>2.611</td>
<td>91.2</td>
<td>20.2 ± 0.6</td>
</tr>
<tr>
<td>927092</td>
<td>Las Mayitas granodiorite</td>
<td>Biotite</td>
<td>7.38</td>
<td>2.465</td>
<td>75.2</td>
<td>19.2 ± 1.2</td>
</tr>
</tbody>
</table>
Zircon cores from a migmatitic amphibolite (sample EGB12-37) within the El Palofierral orthogneiss yielded inherited ages accordingly to the host rock, but ages of 64.3 ± 1.1 Ma were obtained for the zircon rims (Figure 7f). Another age obtained for a migmatite that affects the El Gato diorite (sample EGB12-40) was of 58.91 ± 0.41 Ma (Figure 7o). Furthermore, zircon rims dated from sample EGB12-24 and EGB13-7 of the El Palofierral orthogneiss yielded mean ages of 66 ± 2.1 Ma (Figure 7c) and 61.7 ± 4.1 Ma (Figure 7f), respectively. If the ages obtained from zircon rims of the El Palofierral orthogneiss are considered to be part of this event, and considering the error margins, they apparently indicate that migmatization occurred between ~68 and ~59 Ma, in a time slightly younger than emplacement of the El Pajarito granite (ca. 68 Ma). Consequently, the migmatization in the area might be tentatively assigned to partial melting related to thermal metamorphism resulting from a contemporaneous deep-seated plutonic intrusion in the area. This pluton might be the El Pajarito granite as it is the magmatic pulse occurring close to the migmatization age, or possibly another unexposed contemporaneous pluton.

A Paleocene migmatization event has not been reported in Sonora, but a Laramide tectonic event is assumed by many authors to have synchronously occurred with the Laramide magmatic arc (Haxel et al., 1984; Goodwin and Haxel, 1990). Tectonic structures recording the Laramide orogeny are more clearly dated from northwestern Sonora, where Iriondo et al. (2005) dated white micas developed in thrust faults affecting plutons of Late Cretaceous age. Similarly, in south-central Arizona, ductile thrusting started in Late Cretaceous time and culminated about 60 to 58 Ma ago (Haxel et al., 1984). According to Haxel et al. (1984), latest Cretaceous to early Tertiary metamorphic rocks in that region share common features of an orogenic event characterized by thin-skinned faulting and thickening in the upper crust, while the middle crust was traversed by deep-seated upthrust faults reaching amphibolite facies conditions with associated migmatization.

The El Gato diorite and the El Pajarito granite are part of the several nested plutons that compose the El Jaralito batholith and they have similar U-Pb ages to the El Babizo granite and the La Aurora granodiorite, which crop out further north within the batholith (González-León et al., 2011). Similarly, the Puerta del Sol granodiorite, which occupies a large outcrop in the study area, extends to the north forming an important part of the El Jaralito batholith. The U-Pb zircon age of 49.1 ± 0.46 Ma obtained for the Puerta del Sol pluton is closely similar to U-Pb ages of 49.95 ± 1.05 and 51.26 ± 1.0 Ma reported by González-León et al. (2011) for this pluton to the north, in Sierra El Jaralito.

Considering that Laramide magmatism in central Sonora mostly ended at ~50 Ma (Gans, 1997; González-León et al., 2011), the emplacement of the Puerta del Sol granodiorite occurred near the end of that event. El Oquimonis granite, emplaced at ca. 42 Ma, well-after crystalization of the Puerta del Sol pluton, might be part of the regionally scarce, transitional magmatism between the Laramide event and the volcanism of the Sierra Madre Occidental (Ferrari et al., 2007). The only other dated rocks with ages near 40 Ma include an andesite and a rhyolite reported by Damon et al. (1983) (K-Ar ages) and a dacite dome dated by Gans (1997) at 43.8 ± 0.2 Ma (40Ar/39Ar). The latter author considered that the dacite dome was formed during a phase of minor exhumation, slow cooling and erosion that occurred at the end of the Laramide event and just before the onset of magmatism of the Sierra Madre Occidental event and metamorphic core complex formation (Wong et al., 2010).

The Laramide plutons herein reported are mostly high-K calc-alkaline, metaluminous to slightly peraluminous (except for the peraluminous El Oquimonis granite) (Figure 4). The REE patterns

Figure 8. 40Ar/39Ar dating for (a) Sample 19091F from the El Palofierral orthogneiss and (b) sample 1026081 from the El Garambullo gabbro.
characterized by LREE enrichments suggest an important degree of crystal fractionation. The peraluminous leucogranites however have different REE patterns. The El Oquimonis granite is relatively depleted in LREE and has a pronounced negative Eu anomaly, which resembles the pattern shown by the ca. 57 Ma Huépac granite, a two-mica, garnet-bearing granite that crops out to the north within the El Jaralito batholith (González-León et al., 2011). Similarly, the samples of the garnet-bearing El Pajarito granite have a large negative Eu anomaly and a nearly flat REE pattern with clearly higher REE enrichments compared to the rest of the samples (Figure 5a). Peraluminous leucogranites are generally interpreted to be formed by partial melting of mature continental crust or to be derived from metasedimentary rocks (Pitcher, 1993). That may be the case for the El Pajarito and El Oquimonis granites since roof pendants of metasedimentary rocks are observed in several places within these plutons (Figure 2).

In the primitive mantle normalized multi-element diagrams of the Laramide granites, all of them show consistent patterns with negative anomalies of Nb-Ta, Sr, P and Ti that are also consistent with a continental magmatic arc origin, while the negative initial epsilon Nd values support important crustal assimilation by the mantle-derived magmas. The REE-pattern of these plutons are similar to the REE-patterns reported for other Laramide plutons of central Sonora (e.g. Valencia-Moreno et al., 2001; Boldán-Quintana et al., 2009; González León et al., 2011), and their Sr, Nd and Pb isotope compositions are also within the range of values reported for Laramide plutons of central Sonora (summarized in González León et al., 2011) (Figure 6).

**Miocene syn-extensional plutonism**

The current understanding on the initiation and evolution of the Sierra Mazatán core complex (Figure 1) was refined by structural, geochronological and thermochronological studies by Vega-Granillo and Calmus (2003) and Wong and Gans (2003, 2008). Wong and Gans (2008) considered the Puerta del Sol area as part of the lower plate of the Sierra Mazatán metamorphic core complex and concluded that the low-angle normal fault that unroofed the complex had two major tectonic slip events: the first from 25 to 23 Ma, and the second from 21 to 16 Ma. The mylonitization of the footwall rocks in the western part of the complex formed synchronously with the early fault slip, also the total amount of slip along the fault was estimated to be of 15 km at 21 Ma, prior to exhumation.

For the study area, Wong and Gans (2008) reported three “Ar/39Ar ages from the Puerta del Sol granodiorite (Figure 2). Biotites from their PS3 and PS2 samples yielded plateau ages of 24.4 ± 0.1 Ma and 22.0 ± 0.1 Ma, respectively, while K-feldspars from sample PS1 yielded a complex age spectrum that qualitative indicate rapid cooling from 21 to 17.5 Ma (Wong and Gans, 2008).

According to the U-Pb zircon age for the El Garambullo gabbro, it was emplaced at 19.83 ± 0.18 Ma, while “Ar/39Ar dating indicates a cooling age for plagioclase of 17.4 ± 1.0 Ma (Figures 7u and 8b), which coincides with the second phase of tectonic denudation in the Mazatán metamorphic core complex (Wong and Gans, 2008). The El Garambullo gabbro was emplaced well after the phase of mylonitization, which did not affect it, although it contains mylonitized xenoliths of the Puerta del Sol granodiorite. The other K-Ar and “Ar/39Ar cooling ages obtained for the El Palaíferal, Puerta del Sol and El Oquimonis plutons range from ~26 and ~20 Ma and are within the range of ages reported for the Sierra Mazatán metamorphic core complex denudation (Vega-Granillo and Calmus, 2003; Wong and Gans, 2008). The K-Ar age of 19.2 ± 1.2 Ma obtained for the Las Mayitas granodiorite however may be close to its age of emplacement, as that age is similar to the age of crystallization of the El Garambullo gabbro with which it shares mingling and other related structures.

Geochemically, the El Garambullo and Las Mayitas plutons display features fitting the ca. 25 to 16 Ma crustal “condensed” orogenic rocks reported from Sonora (Gómez-Valencia et al., 2015). They show relatively negative Nb-Ta anomalies and negative initial epsilon Nd values suggesting a continental magmatic arc origin and important crustal assimilation by the mantle-derived magmas. They however are clearly related to tectonic extension and are emplaced in the western sector of the Sierra Mazatán core complex, where the highest exhumation rates occurred (Wong and Gans, 2008). The coeval nature of these mafic and felsic plutons also suggest that they may be part of the magmatic systems that generated the Miocene bimodal volcanism that is interbedded with the clastic sediments of the Bácara Formation, which was extruded along high-angle normal faults during the regional extensional event that exhumed the metamorphic core complex systems in Sonora. Three samples of mafic rocks dated by Wong and Gans (2008) from the adjacent basin-fill of the Sierra Mazatán metamorphic core complex have ages from ca. 18 to 15 Ma (samples MV-2, MV-3 and MV-4 in their figures 3 and 5), which constrain the younger time of denudation and sedimentation for this complex.

**CONCLUSIONS**

The Puerta del Sol area, located in central Sonora, Mexico, holds a record of Laramide arc to Miocene syn-extensional magmatism that is represented by plutons that range in age from ca. 71 to 20 Ma. The area is part of the El Jaralito batholith and is the northern prolongation of the Sierra Mazatán metamorphic core complex lower plate. The basement is represented by the El Palofierral orthogneiss whose ca. 1.7 Ga age and isotopic signature is characteristic of the Paleoproterozoic basement of the Caborca block. Metamorphosed carbonate rocks of this terrane occur as pendants on the Laramide plutons.

The Laramide plutons are the El Gato diorite, El Pajarito and El Oquimonis granites and the Puerta del Sol granodiorite. The oldest is El Gato diorite with an emplacement age of 71.29 ± 0.45 Ma and the youngest is the 41.78 ± 0.32 Ma El Oquimonis granite. The younger age of the El Oquimonis pluton however might indicate a relation to the regionally scarce, transitional magmatism occurring between the Laramide event and the magmatism of the Sierra Madre Occidental. A ca. 68 – 59 Ma migmatization event affecting the El Palaíferal orthogneiss and the El Gato and El Pajarito plutons might be related to partial melting associated with deep-seated emplacement of the 67.9 ± 0.43 Ma El Pajarito granite. The age of the Laramide plutons in the Puerta del Sol area are within the age range reported for plutons of the El Jaralito batholith to the north, and the extensive outcrops of the Puerta del Sol granodiorite extend further to the north into the Sierra El Jaralito.

The El Garambullo gabbro and the Las Mayitas granodiorite are two small plutons that were emplaced at ca. 20 Ma in the western part of the metamorphic core complex footwall; mingling structures and textures are found at the contact between these Miocene plutons. An “Ar/39Ar age of 17.4 ± 1.0 Ma, in plagioclase for the El Garambullo gabbro is interpreted as a cooling age for this pluton. U-Pb, “Ar/39Ar and K-Ar ages for both plutons also suggest that they were emplaced synchronous with the second phase of tectonic denudation of the Sierra Mazatán metamorphic core complex, which took place from 21 to 16 Ma (Wong and Gans, 2008). Accordingly, these plutons are not affected by mylonitization that occurred during the first phase
Plutonism in the Puerta del Sol area, central Sonora, Mexico


ACKNOWLEDGMENTS

The main author acknowledges and thanks the Consejo Nacional de Ciencia y Tecnología (CONACyT) for scholarship 376860 granted to support his graduate studies at the Departamento de Geología, Universidad de Sonora. Geochronologic and geochemical analysis for this work were supported by Project 24893 granted by CONACyT to one of the authors (González-León, C.M.). Victor Valencia of the LaserChron Center of the Department of Geosciences of the University of Arizona, Carlos Ortega-Obregón at Centro de Geociencias, UNAM, and Paty Girón, Instituto de Geología, UNAM are also acknowledged for analytical support. Our thanks are also expressed to Pablo Peñaflor Escárciga and Aimeé Orci, Estación Regional del Noroeste, Instituto de Geología, UNAM for their help in sample preparation and thin sections elaboration. Reviews by Dr. Martín A. Valencia Moreno and one of the Editors greatly improved this manuscript and are greatly appreciated.

SUPPLEMENTARY MATERIAL

Supplementary Tables S1 “U-Pb geochronology data. Laboratorio de Estudios Isotópicos, Centro de Geociencias, UNAM.” and S2 “U-Pb geochronology data. LaserChron Center, University of Arizona.” can be found at the journal web site <http://rmcg.unam.mx/>, in the table of contents of this issue.

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