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Genetic implications of new Sr and Nd isotopic data of the intrusive rocks from the Laramide Arc in Northern Sonora, Mexico

Implicaciones genéticas de nuevos datos de Sr y Nd de rocas intrusivas del Arco Laramide en el Norte de Sonora, México

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Abstract

The Laramide Intrusive Arc constitutes a wide intrusive belt broadly parallel to the actual Sonora coastline. It was formed by the subduction of the Farallon Plate beneath the North-American Plate during the Late Cretaceous-Early Tertiary period. New isotopic data on rocks of this arc show initial $^{87}Sr/^{86}Sr$ and εNd isotopic values of 0.7066 to 0.7070 and -5 to -6, respectively, for two samples from Bacanora area; as well as 0.7074 to 0.7081 and -3 to -5.5 respectively, for five samples from Cananea, Mariquita and La Caridad areas. Isotopic ages were determined by U/Pb in zircons (95 Ma) and Ar/Ar in potassic feldspar (56 to 71 Ma) from a quartz monzonite porphyry, and by Ar/Ar in potassic feldspar (56 Ma) from another plutonic granodiorite, both from Bacanora. Initial $^{87}Sr/^{86}Sr$ and εNd values for samples reported in this study suggest that the Laramidic magmas had a large influence from the Proterozoic basement in northeastern Sonora. Four different isotopic zones are proposed for Sonora, according with Sr-Nd data of laramidic rocks and the substratum intruded.

Key words: Sonora, Mexico, Laramide intrusive arc, Sr-Nd isotopes, geochronology.

Resumen

El Arco Intrusivo Laramide constituye un amplio cinturón de rocas intrusivas orientado burdamente paralelo a la costa actual de Sonora. Este cinturón se originó por la subducción de la Placa Farallón bajo la Placa de Norteamérica durante el período Cretácico Tardío – Terciario Temprano. Nuevos datos isotópicos en rocas de este arco indican valores iniciales de $^{87}Sr/^{86}Sr$ y de εNd de 0.7066 a 0.7070 y -5 a -6, respectivamente, para dos muestras del área de Bacanora; así como de 0.7074 a 0.7081 y -3 a -5.5, respectivamente, para cinco muestras de las áreas de Cananea, Mariquita y La Caridad. Se determinaron también edades isotópicas por U/Pb en zircones (95 Ma) y Ar/Ar en feldespato potásico (56 a 71 Ma) para un pórfido de monzonita de cuarzo, y por Ar/Ar en feldespato potásico (56 Ma) para otra granodiorita plutónica, ambas de Bacanora. Los valores iniciales de $^{87}Sr/^{86}Sr$ y εNd para las muestras reportadas en este estudio, sugieren que los magmas laramídicos tuvieron gran influencia del basamento proterozoico en el noreste de Sonora. Cuatro diferentes zonas isotópicas son propuestas para Sonora, de acuerdo con los datos de Sr-Nd de las rocas laramídicas y el sustrato intrusionado.

Palabras clave: Sonora, México, arco intrusivo Laramide, isótopos Sr-Nd, geocronología.

1. Introduction

The Sr, Nd, and Pb radiogenic isotopes have been used to understand magma petrogenesis and also to define the composition of basement rocks through which the magmas raised to the upper crust (Kistler and Peterman, 1973; DePaolo, 1981; Farmer and DePaolo, 1983; Faure, 2001). In northwest Mexico (Fig. 1), Sonora is an important region to understand the paleotectonics of North America since Precambrian, because of the presence of remnants of hypothetical Rodinia continent suggested by Stewart *et al*. (2002), and also due to the probable connection between Laurentia and Gondwana during Paleozoic (Poole *et al.*, 2005). The effect of the Basin and Range tectonics on this region is an inconvenience for the study of the intrusive bodies (Stewart and Roldán-Quintana, 1994), and also the presence of the voluminous Tertiary magmatism which covers the batholiths, mainly on the border between Sonora and Chihuahua (Lanphere *et al.*, 1980; Ferrari *et al.*, 2007). However, it is possible to identify a broad magmatic arc of cordilleran type that was active during the Late Cretaceous-Early Tertiary (Coney and Reynolds, 1977; Atwater, 1989), which produced abundant volcanic and intrusive rocks.

There are very few isotopic data from Sonora to understand the relationship between the basement and the Laramide magmas (Roldán-Quintana *et al.*, 2000; Valencia *et al.*, 2001; Housh and Mc Dowell, 2005). The origin of Tertiary magmatism in the Sierra Madre Occidental has been considered as mantle derived (McDowell *et al.*, 1999; Lanphere *et al.*, 1980) despite an important contribution from the upper crust has been also proposed (Verma, 1984). The aim of this study is to present new Sr and Nd isotopic data from some intrusive rocks of Laramide Arc to discuss their geochemistry, age, different magmas relationship, and the role and type of basement involved.

2. The pre-Laramide substratum

The pre-Laramide substratum is present in the northern Sonora area since the Precambrian. Paleoproterozoic metamorphic and intrusive rocks of 1.8 to 1.7 and 1.7 to 1.6 Ga have been identified at Caborca and Cananea regions, respectively (Anderson and Silver, 1977, 1979; Iriondo *et al.*, 2005). Both assemblages had been juxtaposed during Jurassic probably due to displacements caused by the Mojave-Sonora Megashear (Anderson and Silver, 1979).

Sandstones and dolomites (miogeoclinal series) were deposited in the Neoproterozoic (760-700 Ma) in the Caborca terrane (Campa and Coney, 1983), in the Cambrian to Lower Permian in the Caborca and Cananea regions (Cooper and Arellano, 1946; Mulchay and Velasco, 1954) and all over central Sonora (Stewart *et al.*, 1997, 2002). Eugeoclinal deep basin rocks, consisting of siliceous sediments, sandstones, carbonaceous shales and barite layers, ranging from the Ordovician to Lower Permian, are present in central Sonora (Poole *et al.*, 1991, 2005), between the 28º 00’ N and 28º 30’ N. These eugeoclinal sequences are considered as allochthonous and overthrusted over the miogeoclinal rocks during the Late Permian-Triassic time (Poole *et al.*, 2005). A Mesozoic sequence (continental or deltaic sandstone and carbonaceous shale including some coal layers) was deposited unconformably (Barranca Formation) over the allochthonous rocks (Wilson and Rocha, 1949; Alencaster-De Cserna, 1961; Stewart *et al.*, 1991). In the Caborca region (at El Antimonio area), the Triassic-Jurassic sedimentary rocks exhibit marine signature and were deposited over paleozoic platform rocks (White and Guiza, 1949; González-León, 1997; González-León *et al.*, 2005). A Jurassic volcanic arc composed of andesites, tuffs and rhyolites, occasionally metamorphosed to greenschist facies, is well documented in the Sonoran desert between Santa Ana and Sonoyta (Anderson and Silver, 1979; Corona, 1979), as well as in Cananea (Valentine, 1936; Wodzicki, 1995). Sedimentary rocks of Lower Cretaceous age are well developed in Sahuaripa, Cerro de Oro, Arizpe and Cananea (Rangin, 1982; Pubellier *et al.*, 1995; Jacques-Ayala, 1995; González-León *et al.*, 2000). The continental volcanic and volcanosedimentary arc of Upper Cretaceous age is exposed all over Sonoran region, which is also known as Tarahumara Formation in the Yaqui river area (McDowell *et al.*, 2001; Roldán-Quintana, 2002). Rock units equivalent to the Tarahumara Formation are also exposed along the Sonora coast (Gastil *et al.*, 1977), Caborca (Jacques-Ayala, 1999), Sierra Manzanal (González-León *et al.*, 2000), and Cananea (Valentine, 1936; Meinert, 1982; Wodzicki, 1995). The Laramide Intrusive Arc was emplaced in several parts of the described substratum.

3. The Laramide Intrusive Arc

The Laramide Intrusive Arc (LIA) constitutes a broad discontinuous belt of intrusive rocks (Fig. 1), 300 km wide in a section from Bahía Kino to Moctezuma, without correcting for the tertiary distensive tectonics. The LIA represents the intrusive component of the Laramide Magmatic Arc (Roldán-Quintana, 2002; Roldán-Quintana *et al.*, 2009), which is the product of subduction of the Farallon Plate underneath the North America Plate, from the Late Cretaceous to Early Tertiary (Coney and Reynolds, 1977; Atwater, 1989). At surface, these rocks

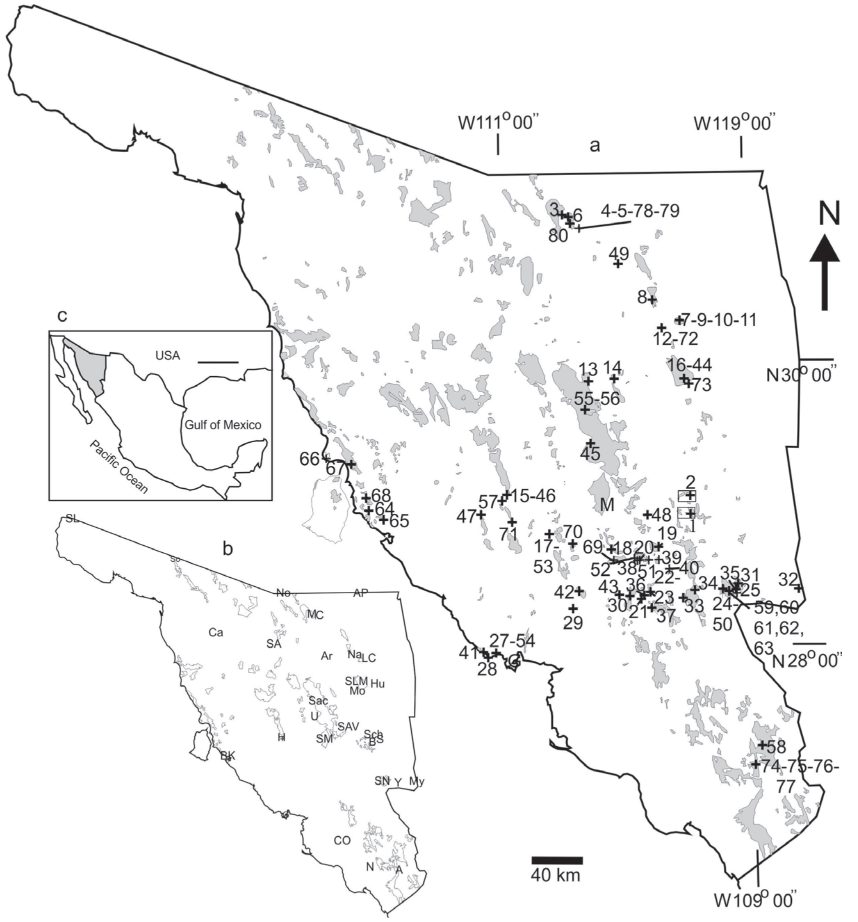

Fig. 1.- a) Location of samples of Table 1. Samples 1 to 7 are reported for the first time in this work. Shaded areas indicate the distribution of intrusive rocks of Laramide age in Sonora. Small rectangles around samples 1 and 2 correspond to areas in Figures 2 and 3. b) Main localities mentioned in the text: A-Alamos, AP-Agua Prieta, Ar-Arizpe, B-Bacanora, BK-Bahía Kino, C-Cananea, Ca-Caborca, CO-Ciudad Obregón, H-Hermosillo, Hu-Huásabas, LC-La Caridad, M-María, Mo-Moctezuma, My-Maycoba, N-Navojoa, Na-Nacozari, No-Nogales, S-Sahuaripa, Sac-Sierra de Aconchi, SA-Santa Ana, SAV-Sierra de Agua Verde, Sch-Sierra Chiltepín, SL-San Luis Río Colorado, SM-Sierra Mazatán, SN-San Nicolás, So-Sonoyta, U-Ures, Y-Yécora. c) Location of Sonora State in Mexico.

Fig. 1.- a) Localización de las muestras de la Tabla 1. Las muestras 1 a 7 son publicadas por primera vez en este trabajo. Las áreas sombreadas indican la distribución de rocas intrusivas de edad Laramide en Sonora. Los pequeños rectángulos alrededor de las muestras 1 y 2 corresponden a las áreas de las Figuras 2 y 3. b) Principales localidades mencionadas en el texto. c) Localización del Estado de Sonora en México.

are expressed by several NNW-SSE oriented sierras, which represent lifted blocks during the Upper Tertiary Basin and Range tectonics. To the south of the 28º 30' N, their outcrops are more dispersed, always following a NNW-SSE trend, even if the sierras are less conspicuous.

Most of the LIA batholiths have not been studied in detail, except few of them exposed along the coast (Valencia-Moreno *et al.*, 2003; Ramos-Velázquez *et al.*, 2008), Mazatán (Richard, 1991), Aconchi and La Madera sierras (Roldán-Quintana, 1991, 1994), Cananea (Wodzicki, 1995) and along the San Carlos-Maycoba transect (Roldán-Quintana, 2002).

The batholiths along the coast are composed of tonalite to granodiorite (Valencia-Moreno *et al.*, 2001, 2003), whereas inland they are composed of tonalite-granodiorite-granite (Roldán-Quintana, 1991, 2002). Two magmatic suites are often recognized in the Mazatán, Aconchi and Magdalena sierras: calc-alkaline series and per-aluminous series (Nourse, 1990; Richard, 1991; Roldán-Quintana, 1991). The key minerals present in the first case are hornblende and biotite, whereas the second one is defined by the presence of muscovite with or without biotite (Damon *et al.*, 1983). There is evidence of multiple intrusions, which have been identified by the presence of basic xenoliths in the calc-alkaline granitoids (*i.e.* El Jaralito and Sierra La Madera batholiths), and by the intrusion of per-aluminous granitoids into the calc-alkaline cortege. The temporal definition for the LIA is generally accepted for the 90-40 Ma period, as it has been defined by Damon *et al.* (1983), but the magmatic period overlaps the Late Cretaceous, since the volcanic component of this arc, *i.e.* Tarahumara Formation, has been dated up to 100 Ma (McDowell *et al.*, 2001). One temporal-spatial evolution has been frequently postulated, with a diminish in age from the coast to inland (Damon *et al.*, 1981; Clark *et al.*, 1982; Damon, 1986; Valencia-Moreno *et al.*, 2006). But new ages on the intrusive rocks from Central-East Sonora, as old as 90 Ma (Pérez-Segura *et al.*, 2009 and this work), suggest that space-time evolution of the LIA is more complicate than the simplistic schematic model.

4. Isotope Data

Sr and/or Nd isotopes data for 73 samples of laramide intrusive rocks were compiled (Fig. 1 and Table 1) from previous works (Damon *et al.*, 1983, Mead *et al.*, 1988; Wodzicki, 1995; Espinosa-Perea, 1999; Schaaf *et al.*, 1999; Valencia-Moreno *et al.*, 2001, 2003; Housh and McDowell, 2005; Roldán-Quintana, 2002 and Roldán-Quintana *et al.,* 2009).

Locality	Number	Coordinates	Age	^{87}Sr/^{86}Sr Measured	^{87}Sr/^{86}Sri	^{143}Nd/^{144}Ndac	^{143}Nd/^{144}Ndi	εNd	T_{DM} Ga	Ref(*)
1	03-102	3203423N; 649209E	56	0.7067	0.7066	0.512355	0.512311	-5.0	1.11	TW
2	03-116	3217317N; 646483E	95	0.7074	0.7070	0.51227	0.512208	-6.0	1.04	TW
3	Lucy	3438.6N; 548.9E	64	0.7082	0.7081	0.512317	0.512275	-5.5	0.98	TW
4	Can-12	3430.0N; 552.5E	64	0.7081	0.7077	0.512454	0.512407	-3.0	0.98	TW
5	IntrCan	3427.8N; 560.5E	59	0.7073	0.7074	0.512324	0.512284	-5.3	0.93	TW
6	IntMaria	3436.0N; 554.4E	60	0.7082	0.7080	0.51232	0.512279	-5.5	1.01	TW
7	Car-5	3357.8N; 642.5E	54	0.7082	0.7080	0.512375	0.512337	-4.5	0.96	TW
8	19 Batamote	30-26-48N; 109-26-47W	56.8 biotite	0.7080	0.7070					1
9	20La Caridad	30-20N; 109-32W	52.5 biotite	0.7088	0.7064					1
10	21La Caridad	30-19N; 109-31W	54.3 biotite	0.7075	0.7067					1
11	22La Caridad	30-19N; 109-31W	50.0 biotite	0.7077	0.7064					1
12	25Bella Esperanza	30-16-17N; 109-42-22W	55.5 sericite	0.7075	0.7062					1
13	35San Felipe	29-53N; 110-18W	51.1 orthoclase	0.7141	0.7103					1
14	39Washington	29-54-29N; 110-05-26	56.4 biotite	0.7079	0.7067					1
15	41Cerro Mariachi	29-05-20N; 110-56-08W	64.1hn 49.6biotite	0.7071	0.7066					1
16	44Sierra Oposura	29-52N; 109-27W	62.7 biotite	0.7109	0.7071					1
17	46Granito Hermita	28-52-18N; 110-45W	62.9hn 55.5 biotite	0.7092	0.7072					1
18	48Cobachi	28-50-32N; 110-12-20W	66.7, 65.9 biotite	0.7076	0.7070					1
19	49Rebeico	28-53-06N; 109-48-54W	61.2 matrix	0.7053	0.7051					1
20	50San Javier	28-37N; 109-53-18W	62.0hn 61.2 biotite	0.7076	0.7064					1
21	54Lucia	28-25-32N; 109-51-53W	56.9 sericite	0.7112	0.7064					1
22	55Suaqui La Verde	28-24-41N; 109-48-11W	56.7 sericite	0.7074	0.7074					1
23	56Suaqui La Verde	28-25-12N; 109-49-01W	58.8hn 56.4 biotite	0.7065	0.7065					1
24	57San Nicolas	28-24-36N; 109-14-12W	49.6 biotite	0.7080	0.7080					1
25	58Santa Rosa	28-24-30N; 109-10-54W	49.5hn 49.3 biotite	0.7060	0.7060					1
26	58-96	3142.50N; 560.87E	60	0.7073	0.7064	0.512370	0.51232	-4.6	1.27	2, 3
27	101-97	3093.62N; 498.69E	83	0.7061	0.7055	0.512423	0.51236	-3.3	1.12	2, 3
28	102-97	3090.31N; 490.31E;	83	0.7066	0.7060	0.512421	0.51236	-3.4	1.21	2, 3
29	127-97	3142.29N; 578.85E	44	0.7076	0.7069	0.512388	0.512357	-4.4	1.08	2, 3
30	1-98	3137.74N; 602.75E	60	0.7075	0.7065	0.512379	0.512337	-4.4	1.12	2,3
31	9-98	3147.46N; 685.17E	49.9	0.7073	0.7064	0.512405	0.512369	-4.0	1.10	2, 3
32	11-98	3143.14N; 732.22E	63.6	0.7075	0.7065	0.512391	0.512343	-4.1	1.17	2, 3
33	13-98	3135.66N; 644.10E	55.3	0.7077	0.7061	0.512396	0.512349	-4.1	1.25	2, 3
34	TC9822	3140.57N; 651.81E	60	0.7102	0.7066	0.512414	0.512375	-3.6	1.00	2, 3
35	TC9825	3147.74N; 683.51E	62	0.7071	0.7062	0.512401	0.512358	-3.9	1.10	2, 3
36	1-99	3137.22N; 619.05E	70	0.7078	0.7072	0.512277	0.512226	-6.3	1.32	2, 3
37	SO-80	3128.70N; 623.10E	63	0.7073	0.7063	0.512414	0.512366	-3.7	1.16	2, 3
38	SO-2	3165.55N; 606.65E	65	0.7079	0.7068	0.512315	0.512255	-5.9		2, 4
39	SO-3	3164.65N; 624.10E	67	0.7072	0.7069	0.512217	0.512156	-7.7		2, 4
40	SO-5	3160.20N; 631.60E	59	0.7063	0.7062	0.512411	0.512357	-4		2, 4
41	SO-25	3094.65N; 487.55E	81	0.7063	0.7057	0.512434	0.512360	-3.4		2,4
42	SO-63	3140.45N; 563.05E	44	0.7076	0.7069	0.512301	0.512357	-6.2	1.08	2,4
43	SO-64	3140.45N; 591.25E	63	0.7074	0.7067					2, 4
44	MV-6 R. El Encino	29-52-54N; 109-26-54W	60	0.7109	0.7073	0.512381	0.512343	-4.2	1.03	5
45	MV-7 NE Puerta del Sol	29-34-05N; 110-01-05W	57	-	-	0.512362	0.512336	-4.5	1.11	5
46	MV-12 Hermosillo	29-06-49N; 110-56-19W	64	0.7092	0.7088	0.512331	0.512318	-5.3	0.98	5
47	MV-17 Cruz Galvez	28-53-51N; 111-07-43W	64	0.7076	0.7070	0.512322	0.512283	-5.3	1.12	5
48	MV-19 Barita de Sonora	28-53-51N; 109-54-16W	62	0.7097	0.7089	0.512345	0.512281	-5.4	0.98	5
49	A-163 Bacanuchi	30-39-30N; 110-10-30W	68	0.7099	0.7075	0.512420	0.512295	-5.0	1.05	5
50	MV-1 San Nicolás	28-26-10N; 109-10-21W	57	0.7085	0.7074	-	0.512375	-3.7	1.03	5
51	MV-4 Tecoripa	28-36-49N; 109-54-07W	62	0.7076	0.7064	0.512342	-	-	-	5
52	MV-9 Cerro Bola	28-36-16N; 110-0114W	62	0.7091	0.7079	-	0.512298	-5.1	1.0	5
53	MV-11Gran. Hermita	28-48-49N; 110-37-43W	63	0.7092	0.7072	0.512423	-	-	-	5
54	MV-21 San Carlos	27-56-29N; 111-04-23W	83	0.7066	0.7059		0.512358	-3.4	1.01	5
55	Ant-1 Jaralito	29-40-37N; 110-17-00W	47	0.7100	0.7091					6
56	Ant-1 Jaralito	29-40-37N; 110-17-00W	47	0.7099	0.7089					6
57	He-4 Palo Verde	29-02-34N; 110-59-00W	42	0.7072	0.7068					6
58	SA-8 San Alberto	27-21N; 108-57W	53	0.7059	0.7055					6
59	77-2044 Los Verdes	28-25N; 109-11W	59	0.7084	0.7059					6
60	77-2046 Los Verdes	28-25N; 109-11W	59	0.7107	0.7058					6
61	77-2047 Los Verdes	28-25N; 109-11W	59	0.7068	0.7061					6
62	77-2048 Los Verdes	28-25N; 109-11W	59	0.7101	0.7059					6
63	77-2050 Los Verdes	28-25N; 109-11W	59	0.7064	0.7054					6
64	BC25	28-56.1N*; 112-1.1W	82	0.7068	0.7060	0.512470	0.512407	-2.5	0.91	7
65	BC26	28-54.1N*; 112-55.9W	82	0.7067	0.7059	0.512360	0.512293	-4.7	1.17	7
66	BC70	29-20.1N*; 112-24.1W	82	0.7076	0.7068	0.512479	0.512416	-2.3	0.90	7
67	BC76	29-17.1*; 112-11.6W	82	0.7076	0.7062	0.512417	0.512360	-3.4	0.90	7
68	BC99	29-2.2N*; 112-3.8W	82	0.7067	0.7063	0.512368	0.512308	-4.4	1.02	7
69	SO7	3166.3N; 588.0E	66	0.7080	0.7067	0.512310	0.51225	-6.1		4
70	SO8	3179.5N; 557.8E	55	0.7128	0.7080	0.512110	0.51206	-9.8		4
71	SO26	3173.0N; 513.3E	60	0.7074	0.7070					4
72	CH98-11	3348.3N; 625.5E	56.9	0.7074	0.7070					4
73	CH98-17	3306.6N; 652.0E	63.6	0.7076	0.7070	0.512406	0.51235	-4.1		4
74	Tgdpx	27-10N; 109-1.2W	62			0.512531	0.512466	-1.8	1.43	8
75	Tqfp	27-10N; 109-1.2W	62			0.512442	0.512390	-3.3	1.08	8
76	Tgdp(tb)	27-10N; 109-1.2W	62.2			0.512491	0.512445	-2.2	0.85	8
77	Tqd	27-10N; 109-1.2W	61.7			0.512505	0.512457	-2.0	0.87	8
78	BD2397-489 Por Q-Feld	3427.8N; 560.5E	64	0.7100	0.7081	0.512307	0.512265	-5.7	0.99	9
79	38.3 Porf 8-110	3427.8N; 560.5E	64	0.7158	0.7086	0.512322	0.512275	-5.5	1.10	9
80	224 Gdi Cuitaca	3429.2N; 551.0E	64	0.7089	0.7069	0.512333	0.512285	-5.3	1.10	9

(*) TW. This work. 1. Damon *et al*. (1983); ^{87}Sr/^{86}Sr calculated by us. 2. Roldán-Quintana (2006). 3. Roldán-Quintana *et al*. (2009). 4. McDowell and Housh (2005). 5. Valencia-Moreno *et al*. (2001). 6. Mead *et al*. (1988); ^{87}Sr/^{86}Sr calculated by us using the ages of Mead *et al*. (1988) and Sansores-Bolivar and Wine (1977). 7. Valencia-Moreno *et al*. (2003); 8. Espinosa-Perea (1999); ^{143}Nd/^{144}Nd*i* and εNd recalculated by us. 9. Woodzicki (1995).

Table 1. Compilation isotopic data for ^{87}Sr/^{86}Sr and εNd according with references indicated. Data 1 to 7 are reported by the first time in this work.
Tabla 1. Recopilación de datos isotópicos para ^{87}Sr/^{86}Sr y εNd según las referencias. Los datos 1 a 7 son publicados por primera vez en este trabajo.

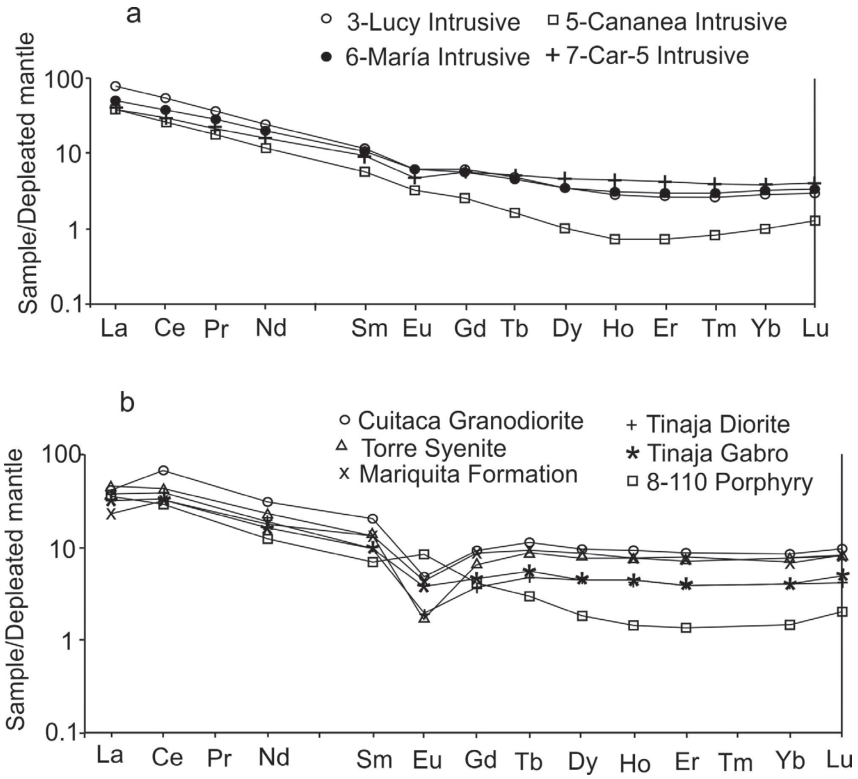

Fig. 2.- Depleated mantle normalizad REE abundances for samples 3, 5, 6 and 7 (a) and other samples from Cananea (b) after Wodzicki data (1995). Depleted mantle values are according to McDonough et al. (1991).

Fig. 2.- Abundancia de REE, normalizadas con relación al manto empobrecido, para las muestras 3, 5, 6 y 7 (a) y para otras muestras de Cananea (b) según los datos de Wodzicki (1995). Los valores para el manto empobrecido son de acuerdo a McDonough et al. (1991).

4.1. Samples of this study

Seven representative samples from Northern Sonora were selected for isotopic analyses (Fig. 1): two samples from the Bacanora area, four samples from the Cananea District and one sample from the La Caridad District. The coordinates of samples are given in Table 1. The initial $^{87}Sr/^{86}Sr$, $^{143}Nd/^{144}Nd$, εSr, εNd values and the model ages for Nd in relation to depleted mantle (DM) were calculated using the equations published by DePaolo (1981) and Farmer and DePaolo (1983). For samples 1 and 2 new isotopic ages determined in this work were used; for samples 3 and 4 (Lucy and Can-12) ages were taken from the Cuitaca Granodiorite published by Anderson and Silver (1977); for samples 5 and 6 (IntrCan and IntrMaria, respectively), the ages are from the Wodzicki (1995) work; and for sample 7 (Car-5) the age used was from the granodiorite reported by Valencia *et al*. (2005) and Barra *et al*., 2005).

Samples 1 and 2 are from the Bacanora area (Fig. 1, 2 and 3). Sample 1 is biotite-hornblende bearing granodiorite with quartz (15%), potassic feldspar (20%), sodic plagioclase (50%), hornblende (7%) and biotite (8%).

Sample 2 is quartz-monzonite porphyry related to skarn mineralization near the San Lucas Ranch (Fig. 3a). This rock intrudes propilitized andesites correlated with Tarahumara Formation (Late Cretaceous). The rock is made of quartz phenocrysts (5%), plagioclase (35%) and biotite

Composition	Sample 3 Lucy Intr.	Sample 5 Can Intr	Sample 6 María Intr	Sample 7 Car-5 Intr
SiO_2	67.11	62.92	66.24	70.63
TiO_2	0.50	0.24	0.52	0.28
Al_2O_3	15.36	17.70	15.51	16.26
Fe_2O_3	3.75	1.01	3.79	0.99
MnO	0.04	-	0.03	-
MgO	1.48	0.64	1.53	0.43
CaO	2.66	-	2.77	0.11
Na_2O	2.78	-	3.80	2.34
K_2O	4.04	4.60	3.86	6.42
P_2O_5	0.15	0.13	0.16	0.19
LOI	2.03	12.72	1.65	2.56
TOTAL	99.9	99.86	99.86	100.21
REE				
La	56.35	27.99	35.77	28.78
Ce	98.47	48.28	69.87	55.0
Pr	10.14	5.006	7.919	6.335
Nd	33.06	16.33	27.43	22.51
Sm	5.172	2.449	4.659	3.985
Eu	1.002	0.526	0.995	0.801
Gd	3.548	1.48	3.395	3.259
Tb	0.501	0.171	0.498	0.528
Dy	2.571	0.723	2.676	3.335
Ho	0.461	0.115	0.501	0.704
Er	1.272	0.34	1.397	1.992
Tm	0.193	0.06	0.217	0.286
Yb	1.372	0.48	1.546	1.872
Lu	0.217	0.094	0.247	0.287
Y	13.97	3.318	15.18	24.73

Table 2. Major and REE by ICP-MS for samples 3, 5, 6 and 7. The analyses were carried out at the *Centre de Recherches Pétrographiques et Géochimiques* (CRPG) of Nancy, France.

Tabla 2. Elementos mayores y REE por ICP-MS para las muestras 3, 5, 6 y 7. Los análisis se realizaron en el *Centre de Recherches Pétrographiques et Géochimiques* (CRPG) en Nancy, Francia.

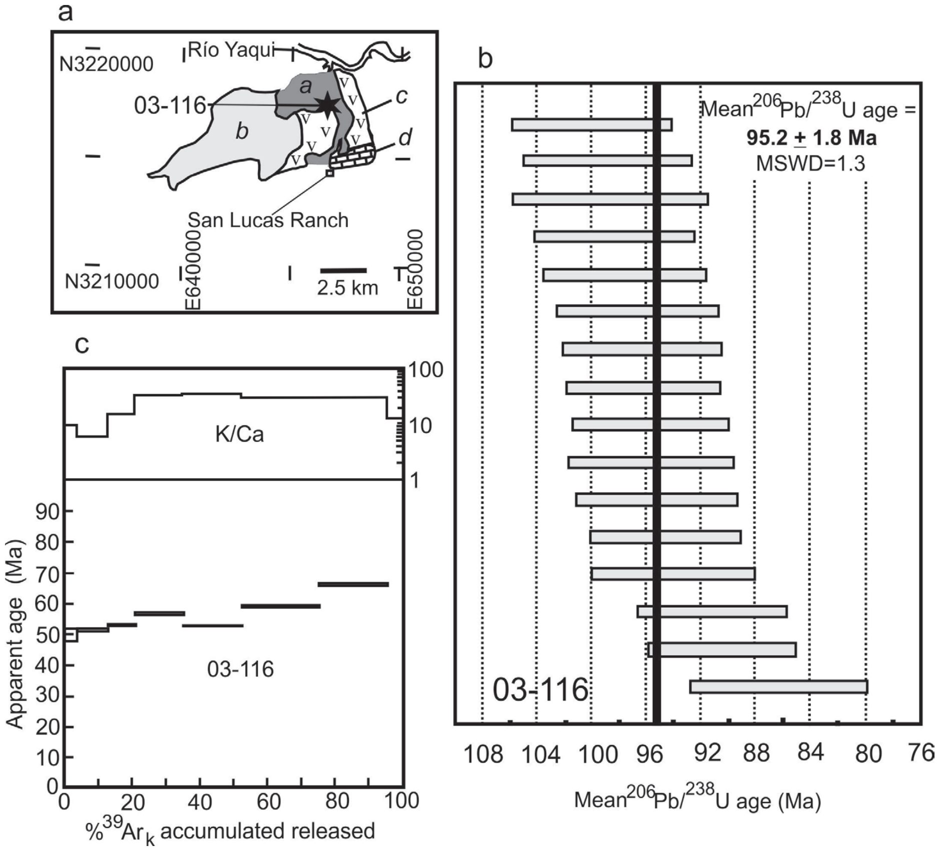

Fig. 3.- a) Location of Sample 2 (03-116) and simplified geology: a-quartz-monzonite porphyry; b-batholith; c-andesitic volcanic rocks; d-Paleozoic carbonated rocks. b) U/Pb individual ages in zircons and Mean age of 95.2 ± 1.8 Ma (see Table 3). c) Apparent ages in potassic feldspar (see Table 4).

Fig. 3.- a) Localización de la muestra 2 (03-116) y geología simplificada: a-pórfido de monzonita de cuarzo; b-batolito; c-rocas volcánicas andesíticas; d-rocas carbonatadas paleozoicas. b) Edades individuales de U/Pb en zircones y edad media de 95.2 ± 1.8 Ma (ver Tabla 3). c) Edades aparentes en feldespato potásico (ver Tabla 4).

Spot Number	Common ^{206}Pb (%)	U (ppm)	Th (ppm)	^{232}Th/^{238}U	^{238}U/^{206}Pb*	^{207}Pb/^{208}Pb	^{238}U/^{206}Pb$^+$	^{207}Pb/^{206}Pb$^+$	^{206}Pb/^{238}U$^\#$	Degree of discordance (%)
03-116										
116-1.1	2.044	112	61	0.57	72.64291 ± 3.68	0.06396 ± 7.18	76.34087 ± 4.55	0.02439 ± 94.35	**86.3 ± 3.2**	-2301
116-2.1	2.456	90	78	0.90	63.35987 ± 3.56	0.06748 ± 7.31	63.35987 ± 3.56	0.06748 ± 7.31	**98.5 ± 3.6**	745
116-3.1	1.348	230	135	0.61	66.06958 ± 3.16	0.05863 ± 5.18	67.98020 ± 3.35	0.03598 ± 27.87	**95.5 ± 3.0**	-772
116-4.1	0.376	284	230	0.84	64.58546 ± 3.11	0.05097 ± 5.07	66.60247 ± 3.30	0.02626 ± 37.51	**98.7 ± 3.1**	-1752
116-5.1	0.551	322	185	0.59	66.86318 ± 3.06	0.05229 ± 4.53	66.86318 ± 3.06	0.05229 ± 4.53	**95.2 ± 2.9**	212
116-6.1	0.522	601	454	0.78	66.59238 ± 2.96	0.05207 ± 3.30	66.59238 ± 2.96	0.05207 ± 3.30	**95.6 ± 2.8**	200
116-7.1	0.686	345	190	0.57	65.19800 ± 3.04	0.05341 ± 4.23	65.19800 ± 3.04	0.05341 ± 4.23	**97.5 ± 3.0**	253
116-8.1	0.078	1485	1439	1.00	67.60167 ± 2.89	0.04852 ± 2.23	67.60167 ± 2.89	0.04852 ± 2.23	**94.6 ± 2.7**	32
116-9.1	0.271	841	408	0.50	66.38932 ± 2.92	0.05009 ± 2.78	66.38932 ± 2.92	0.05009 ± 2.78	**96.1 ± 2.8**	107
116-10.1	0.657	619	310	0.52	70.29456 ± 2.96	0.05304 ± 3.34	70.29456 ± 2.96	0.05304 ± 3.34	**90.5 ± 2.7**	263
116-11.1	0.803	194	103	0.55	67.58890 ± 3.19	0.05426 ± 7.03	70.01618 ± 3.60	0.02599 ± 56.55	**93.9 ± 3.0**	-1877
116-11.2	0.283	1276	1392	1.13	63.92289 ± 2.89	0.05026 ± 2.19	63.92289 ± 2.89	0.05026 ± 2.19	**99.8 ± 2.9**	107
116-12.1	0.401	527	268	0.53	70.47863 ± 2.97	0.04466 ± 3.87	70.47863 ± 2.97	0.04466 ± 3.87	**91.2 ± 2.7**	-182
116-13.1	0.310	616	241	0.40	64.93592 ± 2.95	0.05044 ± 3.50	65.29203 ± 2.96	0.04610 ± 5.92	**98.2 ± 2.9**	-97
116-14.1	0.182	556	208	0.39	66.34091 ± 2.97	0.04938 ± 3.50	66.88931 ± 2.99	0.04283 ± 8.93	**96.3 ± 2.8**	-286
116-15.1	0.422	406	300	0.76	65.99665 ± 3.01	0.05130 ± 4.98	65.99665 ± 3.01	0.05130 ± 4.98	**96.5 ± 2.9**	162

*uncorrected ratios. $^+$ ^{204}Pb corrected for common lead. $^{\#207}$Pb corrected for common lead. All errors are at one sigma level expressed in %, i.e., they are relative standard deviation expressed in % (%RSD, see Verma, 2005). For more details on SHRIMP results, see Nourse *et al.* (2005).

Table 3.- Analytic and individual U/Pb dating data in zircons for sample 03-116 using SHRIMP.

Tabla 3.- Datos analíticos y dataciones individuales por U/Pb en zircones para la muestra 03-116 utilizando SHRIMP.

+ hornblende (10%), disseminated in a felsitic groundmass made of potassic feldspar (50%).

Samples 3 and 6 are from Mariquita mineralized zone, and they were weakly affected by phyllic alteration. Sample 3 corresponds to the Cuitaca Granodiorite, which is mineralized at the Lucy open pit, and the sample 6 is quartz-monzonite porphyry related to mineralization at the María open pit.

Samples 4 and 5 are from the Cananea District. The sample 4 was collected from the Puerto Cananea, which corresponds to the Cuitaca Granodiorite, whereas sample 5 was collected from one of the porphyries related with mineralization at the Cananea mine.

Sample 7 was collected from the La Caridad mine. This sample (Car-5) comes from a core of a diamond drill hole at a deeper level than the lowest bench (1245 m) of current open pit. The rock is granodiorite in a potassic alteration zone with rare anhydrite veinlets.

4.2. Analytical procedures

Sr and Nd isotopes were analyzed by Mihai Ducea at the geochemistry laboratory of the Geosciences Department, University of Arizona, following the methodology and standards described by Ducea *et al*. (2002). The Sr isotopic ratios of standards and samples were normalized to $^{86}Sr/^{88}Sr = 0.1194$, whereas the Nd isotopic ratios were normalized to $^{146}Nd/^{144}Nd = 0.7219$. The estimated analytical $\pm 2\sigma$ uncertainties are similar to those reported in Ducea *et al*. (2002) and Otamendi *et al*. (2009). The measured $^{87}Sr/^{86}Sr$ (Otamendi *et al*., 2009) for the SRM987 Sr standard were 0.710285±7 (n=10) and the measured $^{143}Nd/^{144}Nd$ for the La Jolla Nd standard were 0.511853±2 (n=10). We also note that our results were not adjusted to any accepted values for these standards.

U/Pb and Ar/Ar geochronology were performed by Alexander Iriondo. For U/Pb geochronology a sensitive high-resolution ion microprobe-reverse geometry (SHRIMP-RG) instrument at the Stanford University was used; dating techniques in zircons were those reported by Williams (1998) and Nourse *et al*. (2005). $^{40}Ar/^{39}Ar$ dating was carried out at the USGS in Denver, following the

Step	Temp. °C	%^{39}Ar of total	Radiogenic Yield (%)	$^{39}Ar_k$ (Moles x 10^{-12})	$^{40}Ar^*/^{39}Ar_k$	Apparent K/Ca	Apparent K/Cl	Apparent Age (Ma)	Error (Ma)
03-116 *Arroyo San Lucas monzonite porphyry K-feldspar J=0.004895 ± 0.50% wt=19.2 mg #85KD45*									
A	550	4.1	27.4	0.11576	5.711	9.8	40	49.74	± 0.91
B	650	9.0	75.9	0.25846	5.918	6.1	312	51.52	± 0.17
C	750	8.0	81.1	0.22677	6.091	15.5	385	53.00	± 0.17
D	950	14.1	79.9	0.39869	6.513	33.4	348	56.62	± 0.09
E	1100	17.5	76.9	0.49559	6.037	36.1	369	52.54	± 0.10
F	1200	22.7	64.6	0.64028	6.792	30.6	68	59.00	± 0.15
G	1225	20.0	67.0	0.56584	7.605	30.4	116	65.94	± 0.12
H	1250	4.5	59.3	0.12851	8.192	12.6	90	70.93	± 0.36
	Total Gas	100.0	70.0	2.82630	6.668	26.8	217	57.94	
03-101 *Bacanora-Novillo Granodiorite K-feldspar J=0.004903 ± 0.50% wt=20.7 mg #79KD45*									
A	750	7.3	53.0	0.43299	6.156	5.8	150	53.64	± 0.16
B	950	22.3	95.8	1.33138	6.386	8.9	3087	55.62	± 0.03
C	1000	9.4	97.7	0.56239	6.422	16.2	4301	55.93	± 0.06
D	1100	9.5	96.3	0.56758	6.419	12.9	1335	55.90	± 0.06
E	1175	7.8	88.3	0.46768	6.371	6.8	97	55.49	± 0.08
F	1200	6.9	84.0	0.41043	6.413	6.6	321	55.85	± 0.07
G	1225	10.1	88.1	0.60359	6.453	11.7	394	56.19	± 0.09
H	1250	15.2	91.9	0.90728	6.473	23.2	538	56.37	± 0.04
I	1275	9.2	91.4	0.54909	6.497	22.3	669	56.57	± 0.06
J	1300	2.1	86.7	0.12602	6.498	7.0	526	56.58	± 0.35
	TotalGas	100.0	89.5	5.95843	6.409	13.1	1458	55.82	

Ages calculated assuming an initial $^{40}Ar/^{36}Ar = 295.5 \pm 0$. All precision estimates are at the one sigma level of precision. Ages of individual steps do not include error in the irradiation parameter J. No error is calculated for the total gas age.

Table 4. Analysis for $^{40}Ar/^{39}Ar$ in potassic feldspar at different step-heating for samples 03-116 and 03-101.

Tabla 4. Análisis por $^{40}Ar/^{39}Ar$ en feldespato potásico para diferentes etapas de calentamiento (*step-heating*) para las muestras 03-116 y 03-101.

Sample Number	Sample Name	Rb (ppm)	Sr (ppm)	$^{87}Rb/^{86}Sr$ measured	$^{87}Sr/^{86}Sr$ measured	$^{87}Sr/^{86}Sr_i$	εSr	Sm (ppm)	Nd (ppm)	$^{147}Sm/^{144}Nd$ measured	$^{143}Nd/^{144}Nd$ measured	$^{143}Nd/^{144}Nd$ initial	εNd	t_{DM} Ga
1	03-102	13.84	404.7	0.099	0.70671	0.70663	31	3.47	17.50	0.1200	0.512355	0.512311	-5.0	1.11
2	03-116	27.14	248.8	0.315	0.70741	0.70699	37	3.39	20.29	0.1009	0.512270	0.512208	-6.0	1.04
3	Lucy	20.54	337.2	0.176	0.70821	0.70805	51	4.47	26.89	0.1006	0.512317	0.512275	-5.5	0.98
4	Can-12	71.07	444.5	0.463	0.70813	0.70771	47	3.62	17.92	0.1222	0.512454	0.512407	-3.0	0.98
5	IntrCan	222.65	243.6	2.645	0.70965	0.70740	43	1.80	11.33	0.0961	0.512324	0.512284	-5.3	0.93
6	IntMaria	25.61	394.4	0.188	0.70815	0.70799	51	4.66	26.88	0.1049	0.512320	0.512279	-5.5	1.01
7	Car-5	39.24	435.1	0.261	0.70823	0.70803	51	2.97	16.60	0.1080	0.512375	0.512337	-4.5	0.96

The Sr isotopic ratios of standards and samples were normalized to $^{86}Sr/^{88}Sr = 0.1194$, whereas the Nd isotopic ratios were normalized to $^{146}Nd/^{144}Nd = 0.7219$.
The estimated analytical $\pm 2\sigma$ uncertainties are similar to those reported in Ducea *et al*. (2002) and Otamendi *et al*. (2009).

Table 5.- Isotope and trace element data for samples 1 to 7.

Tabla 5.- Datos isotópicos y de elementos traza para las muestras 1 a 7.

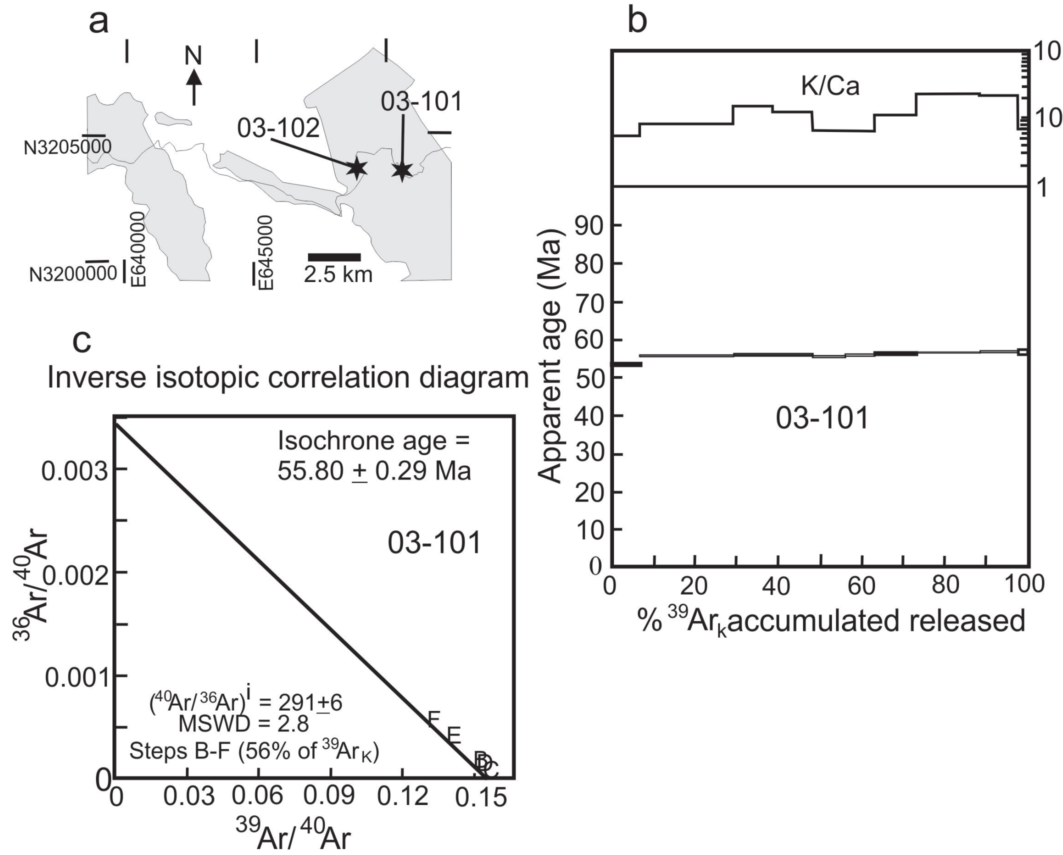

Fig. 4.- a) Location of samples 1 (03-102) and 03-101. Shaded areas indicate laramidic batholith, curve line in gray is the paved road Hermosillo-Bacanora. b) Ar/Ar apparent ages in potassic feldspar (see Table 4). c) Isochrone of 55.8 ± 0.3 Ma for step-heating B to F.

Fig. 4.- a). Localización de las muestras 1 (03-102) y 03-101. Las áreas sombreadas indican el batolito laramídico, la línea curva en gris es el camino pavimentado Hermosillo-Bacanora. b) Edades aparentes de Ar/Ar en feldespato potásico (ver Tabla 4). c) Isocrona de 55.8 ± 0.3 Ma para las etapas de calentamiento B a F.

methodology described by Iriondo *et al*. (2004).

Chemical analyses for major and trace elements (including REE) were carried out at the *Centre de Recherches Pétrographiques et Geochimiques (CRPG)* of Nancy, France.

4.3. Results

Geochemistry

Analytical values in major and trace elements for samples 3, 5, 6 and 7 are presented in Table 2. The rare earth elements (REE) values were normalized using the data proposed by McDonough *et al*. (1991). The REE pattern for the studied rocks is observed on Figure 2a. Normalization to depleted mantle was made just to compare with the spectrum from Wodzicki (1995) for the Cananea rocks (Fig. 2b). The rocks analyzed indicate patterns enriched in LREE and depleated in HREE, which is a characteristic feature of continental arcs. It is important to mention that the sample 3 corresponding to the mineralized plutonic intrusive at Lucy and the number 6, belonging to the mineralized hypabysal porphyry at Maria open pit, show a very similar geochemistry behavior, suggesting a comagmatic origin. Sample 5 coming from a mineralized porphyry stock of Cananea is affected by a strong hydrothermal alteration, as it is evidenced by absence of CaO (Table 2) and a very high value of 12.7 % on Lose on Ignition (LOI). This sample show HREE depleted pattern with a concave curve and an apparent absence of negative Eu anomaly. Similar pattern is in the 8-110 mineralized porphyry reported by Wodzicki (1995), with a significant positive Eu anomaly (Fig. 2b). In general the REE pattern of Cananea fresh rocks suggests a comagmatic origin; depletion in HREE elements for the mineralized porphyries is probably caused by hydrothermal alteration. The behavior of REE pattern for the sample 7 (Car-5), corresponding to the La Caridad Granodiorite, shows a similar pattern to those from Lucy and Maria (3 and 6), but with a slightly impoverishment in LREE and an enrichment in HREE.

Geochronology

Sample 2 (03-116 in Figure 3a and coordinates indicated in Table 1) was dated by U/Pb and Ar/Ar. U/Pb in zircons yield an age of 95.2 ± 1.8 Ma (Fig. 3b and Table 3); but ages obtained by $^{40}Ar/^{39}Ar$ in potassic feldspar of porphyry groundmass goes from 53-71 Ma, for C-H hot steps (Fig. 3c and Table 4).

For the Sr and Nd isotopic calculation of Sample 1 (03-102) we used the age of sample 03-101 (Mercator coordinates: 3203 487 N and 650 739 E), located 17 km to the west of Sample 1 (Fig. 4a). Sample 03-101 shows apparent ages (Fig. 4b, Table 4) very homogeneous for steps B-J in 56-57 Ma., and it is possible to plot an isochron line with B to F data yielding an age of 55.8 ± 0.29 Ma (Fig. 4c). There is no evidence of older ages.

Sr and Nd isotopic data

Table 5 show the isotopic analysis and calculated data for Sr and Nd of our samples. A summary of the same data is also given in Table 1.

Samples 1 and 2 from the Bacanora area gave initial $^{87}Sr/^{86}Sr$ of 0.7066 and εNd of -5.0 (granodiorite); and of 0.7070 and -6.0 (porphyry), respectively. Samples 3 and 6 (Mariquita mineralized zone) have initial $^{87}Sr/^{86}Sr$ and εNd of 0.7081 and -5.5 for sample 3 (granodiorite) and 0.7080 and -5.5 for sample 4 (porphyry). Samples 4 and 5, from the Cananea District, present an initial $^{87}Sr/^{86}Sr$ and εNd of 0.7077 and -3 for Sample 4 (Cuitaca Granodiorite), and of 0.7074 and -5.5 for sample 5 (porphyry). Finally, Sample 7 (granodiorite) from the La Caridad mine, has initial $^{87}Sr/^{86}Sr$ and εNd of 0.7080 and -4.5, respectively.

5. Interpretation of the results

5.1. Geochronology

The age of 95 Ma for sample 2, is similar to other U-Pb ages from zircons on a dyke correlative with the same porphyry (Mercator coordinates: 3215270 N and 646945 E) which yield 88 Ma (Pérez-Segura *et al.*, 2009). The 95 Ma age is interpreted as a crystallization age, whereas the Ar-Ar ages from 52 to 71 Ma for the same sample are interpreted as cooling ages. Variations in the range of the Ar-Ar ages, indicate that the rock was subjected long time above the blocking temperature of the potassic feldspar, or that the rock was reheated during different periods.

The age of sample 03-101 around 56 Ma is considered as a cooling age. This age is in agreement with the better known ages (50 to 60 Ma) for the LIA in Sonora (Damon *et al.*, 1983). It is also similar to one age reported by Pubellier *et al.* (1995) in Sierra Chiltepin (22 km N30°E from 03-101) dated 64 Ma (K-Ar) in a granitoid rock. However, the U-Pb age obtained from sample 2 (95 Ma) and other ages reported using the same method in the area,

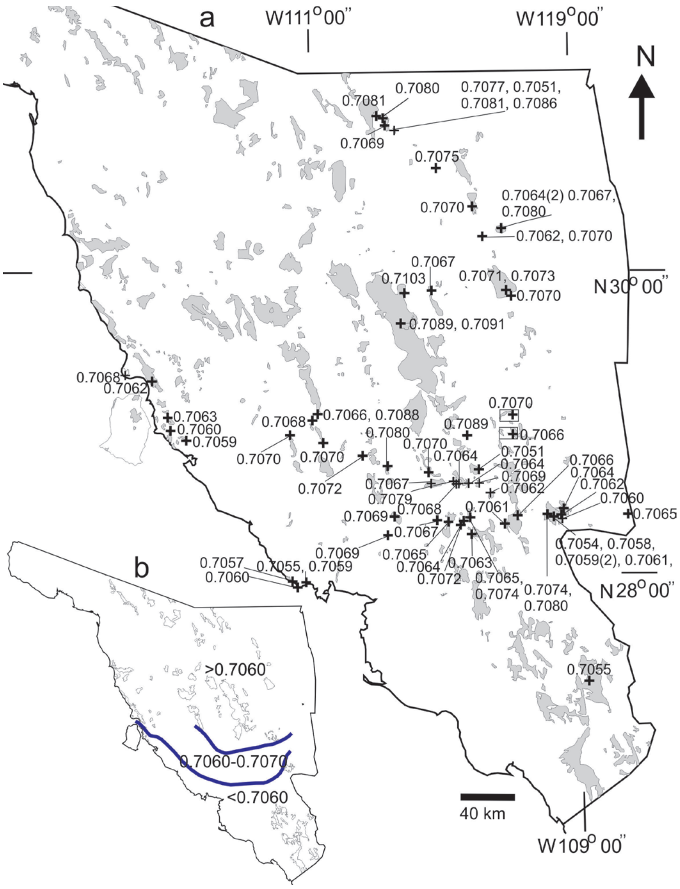

Fig. 5.- Initial $^{87}Sr/^{86}Sr$ isotopic data for all the samples of Table 1 (a), and main range of values by regions (b).

Fig. 5.- Datos de $^{87}Sr/^{86}Sr$ iniciales para todas las muestras de la Tabla 1 (a), y principales rangos de valores por regiones (b).

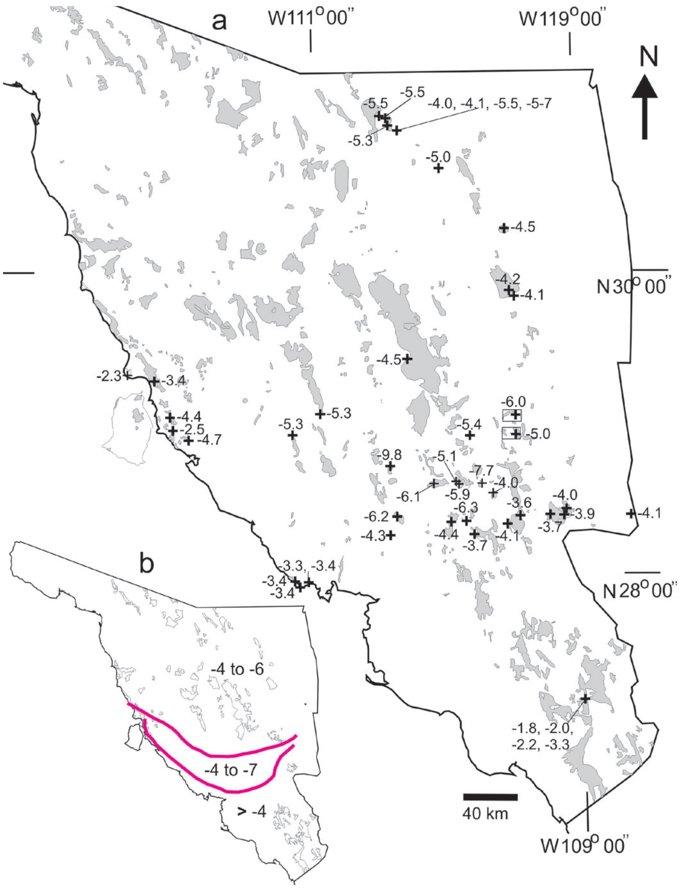

Fig. 6.- εNd data for all the samples of Table 1 (a), and main range of values by regions (b).

Fig. 6.- Datos de εNd (a) para todas las muestras de la Tabla 1, y principales rangos de valores por regiones (b).

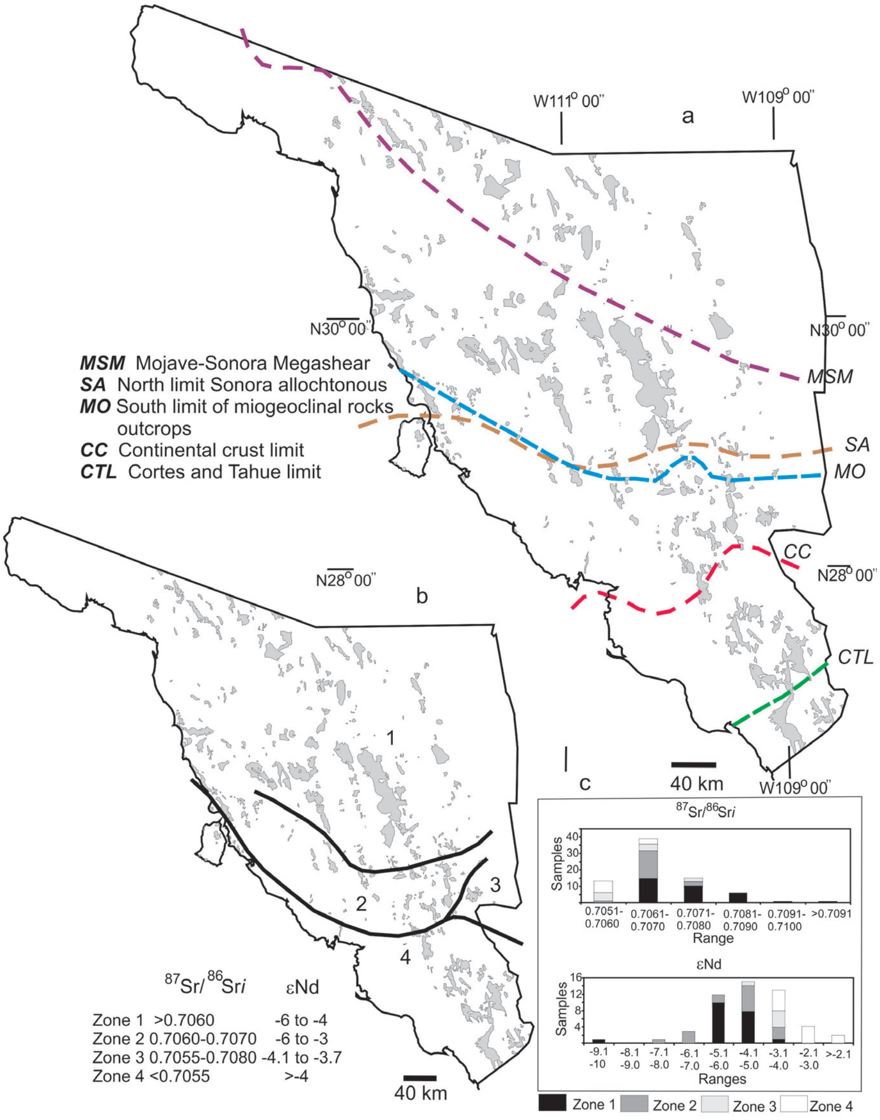

Fig. 7.- Relations between principal tectonic features in Sonora and isotopic ranges for initial $^{87}Sr/^{86}Sr$ and εNd. a) Principal tectonic features: MSM-Mojave-Sonora Megashear (Anderson and Silver, 1979; 2005); SA-North limit Sonora allochtonous (Poole *et al*., 2005); MO-South limit of miogeoclinal rocks outcrops (Stewart *et al*., 1999); CC-Continental crust limit (Poole *et al*., 2005); CTL-Cortes and Tahue terranes limit (Centeno-García *et al*., 2008). b) Isotopic zones proposed in this work. c) Initial 87Sr/86Sr and εNd ranges for different zones.

Fig. 7.- Relaciones entre las principales características tectónicas de Sonora y rangos isotópicos de $^{87}Sr/^{86}Sr$ inicial y εNd. a) Principales características tectónicas: MSM-Megacizalla Mojave-Sonora (Anderson y Silver, 1979; 2005); SA-Límite norte del alóctono de Sonora (Poole *et al*., 2005); MO-Límite sur de afloramientos de rocas de miogeocinal (Stewart *et al*., 1999); CC-Límite de la corteza continental (Poole *et al*., 2005); CTL-Límite de los terrenos Cortés y Tahue (Centeno-García *et al*., 2008). b) Zonas isotópicas propuestas en este trabajo. c) Rangos de $^{87}Sr/^{86}Sr$ inicial y de εNd para las diferentes zonas.

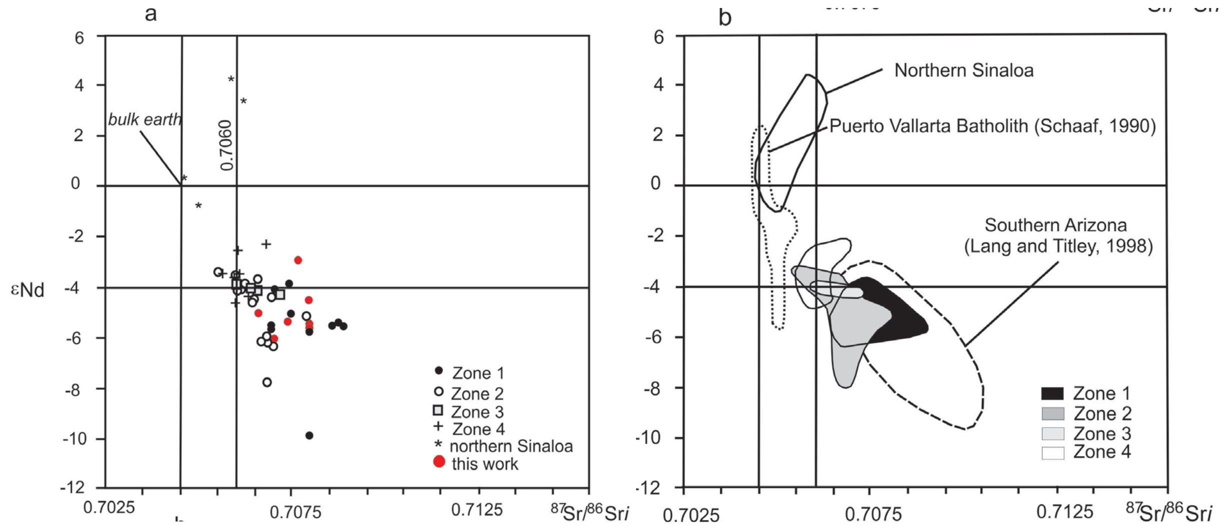

Fig. 8.- Initial values of $^{87}Sr/^{86}Sr$ versus εNd for samples grouped by zones according to isotopic values and geological features (a), and comparison with other provinces in Mexico and Southern Arizona (b). Province of Northern Sinaloa defined by Valencia-Moreno *et al*. (2001). Values for bulk earth and for important values of $^{87}Sr/^{86}Sr$ and εNd indicated in figures 5 and 6 are shown.

Fig. 8.- Valores iniciales de $^{87}Sr/^{86}Sr$ versus εNd para muestras agrupadas por zonas de acuerdo a los valores isotópicos y a características geológicas (a), y comparación con otras provincias en México y Sureste de Arizona (b). También se muestran los valores para bulk earth y valores importantes de $^{87}Sr/^{86}Sr$ y εNd indicados en las figuras 5 y 6.

ranging from 88 to 91 Ma (Pérez-Segura *et al.*, 2009) do not allow to discard the possibility that ages older than 56 Ma have been probably erased.

5.2. Sr and Nd isotopic data

Bacanora area

The isotopic values of 0.7066 to 0.7070 for initial $^{87}Sr/^{86}Sr$ and -5.0 to -6.0 for εNd, as well as the model ages for Nd in relation to the depleted mantle of 1.11 to 1.04 Ga, are very similar to previous isotopic values reported in northern Sonora, which indicates the probable presence of a Proterozoic basement in the area; in fact, other geological evidences indicate the presence of Neoproterozoic rocks between Bacanora and Sahuaripa (Stewart *et al.*, 1999, 2001, 2002). Also the relative uniformity of the isotopic data for samples 1 and 2 could be interpreted as that the source of the magma in the area of Bacanora remained constant at least during the period between 95 and 56 Ma, if the last age was close to the age of crystallization of the plutonic rocks.

Cananea District

Seven samples have been reported from the Cananea District (3, 4, 5, 6, 78, 79 and 80; Fig. 1). The first four samples refer to the data reported here, and the other samples were from Woodzicki (1995). All the initial $^{87}Sr/^{86}$ values range for the Cuitaca Granodiorite goes from 0.7069 to 0.7081 and εNd from -3.0 to -5.5, whereas for the porphyries the initial $^{87}Sr/^{86}Sr$ varies from 0.7074 to 0.7086 and εNd from -5.3 to -5.7. The very similar values in Sr and Nd for the Cuitaca Granodiorite and the mineralized porphyry in Maria mine indicate a co-magmatic origin for both units and that hydrothermal alteration did not have any influence on the isotopic behavior; but in the case of Cananea mine there are small differences in initial $^{87}Sr/^{86}Sr$ probably due to differences in the rock composition as it has been demonstrated for other igneous rock series (Verma, 2001). The co-magmatic origin for Cuitaca Granodiorite and mineralized porphyries is also supported by the REE behavior. It is possible to suppose that the magmas that gave origin to the intrusives in the area of Cananea and María were derived from the same source at depth. The origin of both could be due to melting of the Proterozoic lower crust, as it is suggested by the Sr and Nd data in xenoliths from Arizona and Northern México (Ruiz *et al.*, 1988). However, considering the lower Sr and less negative Nd values in Sonora compared with the values reported in southern Arizona (Wodzicki, 1995; Lang and Titley, 1998; Valencia-Moreno *et al.*, 2001), we do not exclude some mantle contribution.

La Caridad District

Four samples have been compiled for Sr isotopic data from this region which range from 0.7064 to 0.7080 (Damon *et al.*, 1983, and this study). Other data from Sr in Bella Esperanza (localities 12 and 72 in figure 1) indicates 0.7062 and 0.7070, respectively. The only available Nd data from this region indicates a value of -4.5 (sample 4). In this regard, we have analyzed a granodiorite with potassic hydrothermal alteration (Sample 7 in Table 2). The sample shows very low CaO (0.11%) and high K_2O (6.4%) with relatively high loss on ignition (LOI-2.6%). The value of initial $^{87}Sr/^{86}Sr$ in sample 7 as well as of sample 3 are somewhat higher compared to other samples reported from the area (Damon *et al.*, 1983; Housh and McDowell, 2005; see also Table 2), differences could be caused by hydrothermal alteration as it has been observed in oceanic basalts and in the volcanic geothermal field of Los Azufres (Verma, 1992; Verma *et al.*, 2005). The isotopic values of Sr and Nd from La Caridad and Cananea are very similar suggesting the same origin for the magmas in both districts.

6. Correlation with other areas of Sonora and with the pre-Laramide substratum

Values for initial $^{87}Sr/^{86}Sr$ and εNd grouped by different ranges are represented on Figures 5 and 6, trying to relate the distribution with geography. One problem for interpretation is that most of data are located in central and northern Sonora. In any event it is evident that initial $^{87}Sr/^{86}Sr$ upper than 0.7060 and εNd more negatives than -4 are located broadly north to the 28° parallel and to the east of coastline from Kino Bay. South and west of the same line, values for initial $^{87}Sr/^{86}Sr$ are lower than 0.7060 and εNd less negatives than -4; as well as in central-eastern Sonora on the San Nicolás batholith (Roldán-Quintana, 2002). Some of the most important tectonic features are shown on the Figure 7, trying to relate different geological terranes with the isotopic values. Following this logic and using isotopic data published up to date, four isotopic regions can be proposed for Sonora:Zone 1. To the north of the limit of the Sonora Allochthonous (Poole *et al.*, 2005) and with values of initial $^{87}Sr/^{86}Sr$ >0.7060 and εNd <-4.

Zone 2. Corresponding to the zone where the Sonora Allochthonous overlaps the inferred continental crust. In terms of isotopic values it is characterized by $^{87}Sr/^{86}Sr$ between 0.7060-0.7070 and εNd from -6 to -3.

The south isotopic limits follows a line trough the north of Tiburon Island.

Zone 3. This zone corresponds to the San Nicolas Batholith with variable $^{87}Sr/^{86}Sr$ but with a very constant εNd between -4.1 to -3.7.

Zone 4. Located to the south of the supposed as the limit of continental crust (Poole *et al*., 2005). Typical values for this zone are $^{87}Sr/^{86}Sr$ <0.7055 and εNd>-4.

Initial $^{87}Sr/^{86}Sr$ and εNd data are plotted in Fig. 8. For comparison, the fields for intrusive rocks in southern Arizona and other parts of Mexico are also included.

The data discussed in this paper are located in here called zone and most of the known analytical data are located in the zones 1 and 2. These zones are characterized by initial $^{87}Sr/^{86}Sr$ greater than 0.7060 and initial εNd < -4 and they roughly coincide to the south with the limit of the continental crust proposed by Poole *et al.* (2005); however, the limit to the west is parallel to the coast of Sonora and continues obliquely to north of Tiburón Island (Fig. 7). In both zones 1 and 2, the isotopic data allow us to presume the presence of Proterozoic basement at depth.

The zone 4, south and west of the previous one, shows few data, where we only have information along the coast between San Carlos and Punta Tepopa. The isotopic values although punctual, indicate initial $^{87}Sr/^{86}Sr$ < 0.7060 and εNd > -4. These data plus the model ages for Nd of 1.43 and 0.85 Ga allow us to interpret that the intrusive rocks were emplaced at the external border of the Proterozoic basement. The prelaramide geology in southern Sonora is very little known, this region belongs partially to the Cortés and Guerrero Terranes (Campa and Coney, 1983) or the Tahue Terrane (Centeno-García *et al*., 2008). It is known that metavolcanic rocks, and metasediments of lower Paleozoic are exposed in northern Sinaloa (Mullan, 1978; Centeno-García *et al*., 2008). Similar series are correlated by other authors with the eugeoclinal rocks from central Sonora related to Gondwana (Poole *et al*., 2005). In southern Sonora, there are many exposed rocks of the Late Triassic Sonobari Complex (Mullan, 1978; Centeno-García *et al*., 2008), these protoliths have been proposed as tholeiitic volcanic rocks originated in an oceanic rift (Keppie *et al*., 2006; Vega-Granillo *et al*., 2012). According to the data mentioned previously, the magmas which originated the granitoids south of the parallel 28° were not derived from a Proterozoic basement related to the North American Craton, instead of that it is derived from a source with an important mantle contribution, including contamination from the lower crust of the Tahue Terrane (Centeno-García *et al*., 2008). This could be valid also for the granitoids exposed along the coast of Sonora between San Carlos and Punta Tepopa. The wide range of the model ages for Nd may indicate the heterogeneity in the composition of the Lower Crust.

Finally, in zone 3, the values of initial $^{87}Sr/^{86}Sr$ are in a wide range (0.7054 to 0.7080) and εNd are relatively constant (-4.1 to -3.7), similar to values in the area of Tómochic, Chihuahua (Mcdowell *et al*., 1999). This, allow us to speculate on the absence of Sonoran proterozoic basement in this zone and relate the isotopic data to a pre-Laramidic geologic history similar to that of central Chihuahua (Housh and Mcdowell, 2005).

7. Conclusions

New isotopic data on hydrothermally mineralized rocks as for the Maria and La Caridad mines indicate that the isotopic compositions may change with respect to the fresh rock values, as it has been documented by other authors (Verma, 1992; Verma *et al*., 2005). This is important for future interpretations taking into account that many of the published isotopic data come from mineralized areas (Damon *et al*., 1983; Sansores-Bolivar and Wayne, 1977; Mead *et al.*, 1988). Another important aspect in the Bacanora and Cananea regions is that the isotopic signature of the magmatic source did not change during the Early to Late Cretaceous (95-55 Ma).

According with new isotopic data and those published so far, various isotopic zones can be delineated in Sonora related to the major pre-Laramide tectonic features. Two of these zones have also been suggested by other authors. The isotopic characteristics and relation with substratum for the different regions proposed by us are:

Zones 1 and 2 located at North and Central Sonora (Fig. 7) are characterized by > 0.7060 initial $^{87}Sr/^{86}Sr$ and < - 4 εNd values. They plot into the range values field of laramidic intrusions in Southern Arizona (Fig. 8). Proterozoic and Neoproterozoic rocks have been recognized in the region of zones 1 and 2 at Cananea, Caborca, Bacanora and Sahuaripa and the limit to the south coincide with the continental crust limit proposed by Poole *et al*. (2005). It means that the Proterozoic basement of North America underlies zones 1 and 2, as it has been suggested by other authors (Valencia-Moreno *et al*., 1999, 2001, 2006; Poole *et al.* 2005). We assume that the Sr and Nd isotopic data of the laramidic intrusions in zones 1 and 2 could have a large influence of the underlying Proterozoic crust, that does not crop out continuously due to the Tertiary tectonics of the Basin and Range province. We also emphasize that the Mojave-Sonora Megashear (Anderson and Silver, 1979) had no influence on the isotopic signatures in these areas.

The zone 4 with isotopic data of < 0.7060 initial $^{87}Sr/^{86}Sr$ and > - 4 εNd is clearly separated from zones 1 and 2 (Fig. 8). We interpret that Laramide age intrusive rocks are related to magmas with a probable mantle contribution, or due to contamination from the Tahue Terrane in which tholeiitic volcanic rocks of Paleozoic and Mesozoic age are present (Vega-Granillo *et al*., 2012).

The zone 3 with a wide range in initial $^{87}Sr/^{86}Sr$ values from 0.7054 to 0.7080 and a very restricted εNd values of - 4.1 to - 3.7. The position in the Sr/Nd diagram (Fig. 8) between zones 3 and 4 suggests a different type of substratum. In this case the underlying basement must be the same of central Chihuahua, consisting of a Paleozoic arc accreted to the Proterozoic North American craton during Late Paleozoic. The variation in Sr isotopic data of laramidic intrusions can reflect a more complex petrology of this substratum.

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References

Alencaster-De Cserna, G. (1961): Estratigrafía del Triásico Superior de la parte central del Estado de Sonora, Parte I. In: Alencaster de Cserna, G. (ed.), Paleontología del Triásico Superior de Sonora, Universidad Nacional Autónoma de México, Instituto de Geología, Paleontología Mexicana 11, 18 p.

Anderson, T.H., Silver, L.T. (1977): U-Pb isotope ages of granitic plutons near Cananea, Sonora. *Economic Geology* 72, 827-836. doi: 10.2113/gsecongeo.72.5.827

Anderson, T.H., Silver, L.T. (1979): The role of the Mojave-Sonora megashear in the tectonic evolution of northern Sonora. In: Anderson, T.H., and Roldán-Quintana, J. (eds.), Geology of Northern Sonora, Geological Society of America Field Trip Guidebook, Field trip no. 27, 59-68.

Atwater, T. (1989): Plate tectonic history of the Northeastern Pacific and western North America. In: Winterer, E.L., Hussong, D.M., Decker, R.W. (eds.), *The Eastern Pacific Ocean and Hawaii*, Geological Society of America, The Geology of North America N, 21-72.

Barra, F., Ruiz, J., Valencia, V. A., Ochoa-Landín, L., Chesley, J.T., Zurcher, L. (2005): Laramide porphyry Cu-Mo mineralization in northern México: Age constraints from Re-Os geochronology in molybdenites. *Economic Geology* 100, 1605-1616. doi:10.2113/gsecongeo.100.8.1605

Clark, K.F. Foster, C.T., Damon, P.E. (1982): Cenozoic mineral deposits and subduction-related magmatic arcs in Mexico. *Geological Society of America Bulletin* 93, 533-544. doi: 10.1130/0016-7606(1982)93<533:CMDASM>2.0.CO;2

Campa, M.F., Coney, P.J. (1983): Tectono-stratigraphic terranes and mineral resource distributions in Mexico. *Canadian Journal of Earth Sciences* 20, 1040-1051. doi: 10.1139/e83-094

Centeno-García, E., Guerrero-Suastegui, M., Talavera-Mendoza, O. (2008): The Guerrero Composite Terrane of western Mexico: Collision and subsequent rifting in a supra-subduction zone. In: Draut, A., Clift, P.D., Scholl, D.W., (eds.), *Formation and Applications of the Sedimentary Record in Arc Collision Zones*, Geological Society of America Special Paper 436, 279–308. doi: 10.1130/2008.2436(13)

Coney, P., Reynolds, S.J. (1977): Cordilleran Benioff zones. *Nature* 270, 403-406. doi: 10.1038/270403a0

Cooper.G.A., Arellano, A.R.V. (1946): Stratigraphy near Caborca, northwest Sonora, Mexico. American Association of Petroleum Geologists Bulletin 30, 4, 606-611.

Corona, F.V. (1979): Preliminary reconnaissance geology of Sierra La Gloria and Cerro Basura, northwestern Sonora, Mexico. In: Anderson, T.H., and Roldán-Quintana, J. (eds.), Geology of Northern Sonora: Geological Society of America Field Trip Guidebook, Field trip no. 27, 32-48.

Damon, P.E., Shafiqullah, M., Clark, K.F. (1981): Age trends of igneous activity in relation to metallogenesis in the Southern Cordillera. In: Dickinson, W.R., Payne, W.D. (eds.), *Relations of tectonics to ore deposits in Southern Cordillera: Arizona Geological Society Digest* 14, 137-154.

Damon, P.E., Shafiqullah, M., Roldán-Quintana, J. Cocheme, J.J. (1983): El batolito Laramide (90-40 Ma) de Sonora. *Memorias Técnicas XV Convención Nacional de la Asociación de Ingenieros de Minas, Metalurgistas y Geólogos de México*, Guadalajara, Jalisco, 63-95.

Damon, P.E. (1986): Batholith-volcano coupling in the metallogeny of porphyry copper

Deposits. In: Friedrich, G.H. *et al*. (eds.), *Geology and Metallogeny of Copper*

Deposits. Springer-Verlag, Berlin, Heildeberg, 215-234. doi: 10.1007/978-3-642-70902-9_5

DePaolo, D.J. (1981): A neodymium and strontium isotopic study of the mesozoic calc-alkaline granitic batholiths of the Sierra Nevada and Peninsular Ranges, California. *Journal of Geophysical Research* 86, B11, 10470-10488. doi: 10.1029/JB086iB11p10470

Ducea, M., Sen, G., Eiler, J., Fimbres, J. (2002): Melt depletion and subsequent metasomatism in the shallow mantle beneath Koolau volcano, Oahu (Hawaii). *Geochemistry, Geophysics, Geosystems* 3, 2: 1-17. doi: 10.1029/2001GC000184

Espinosa-Perea, V. (1999): *Magmatic evolution and geochemistry of the Piedras Verdes deposit, Sonora, Mexico*. Tucson, Arizona, MS Thesis, The University of Arizona, 114 p.

Farmer, G.L., DePaolo, D.J. (1983): Origin of Mesozoic and Tertiary granite in the Western United States and implications for pre-Mesozoic crustal structure 1. Nd and Sr isotopic studies in the Geocline of the Northern Great Basin. *Journal of Geophysical Research* 88, 84, 3379-3401. doi: 10.1029/JB088iB04p03379

Faure, G. (2001): *Origin of igneous rocks. The isotopic evidence*. Springer, Berlin. 496 p.

Ferrari, L., Valencia-Moreno, M., Bryan, S. (2007): Magmatism and tectonics of the Sierra Madre Occidental and its relation with the evolution of the western margin of North America. In: Alaniz-Álvarez, S.A., Nieto-Samaniego, Á.F. (eds.), *Geology of México*: Celebrating the Centenary of the Geological Society of México, Geological Society of America Special Paper 422: 1–39. doi: 10.1130/2007.2422(01)

Gastil, R.G., Krummenacher, D. (1977): Reconnaissance geology of coastal Sonora between Puerto Lobos and Bahía Kino. *Geological Society of America Bulletin* 88, 189-198. doi:

10.1130/0016-7606(1977)<189:RGOC5B>2.0.CO;2

González-León, C. (1997): Sequence stratigraphy and paleogeographic setting of the Antimonio Formation (Late Permian-Early Jurassic), Sonora, Mexico. *Revista Mexicana de Ciencias Geológicas* 14, 136-148.

González-León, C.M., McIntosh, W.C, Lozano-Santacruz, R., Valencia-Moreno, M., Amaya-Martínez, R., Rodríguez-Castañeda, J.L. (2000): Cretaceous and Tertiary sedimentary, magmatic and tectonic evolution of north-central Sonora (Arizpe and Bacanuchi Quadrangles), northwest Mexico. *Geological Society of America Bulletin* 112, 600-610.

González-León, C., Stanley, G.D., Gehrels, G.E., Centeno-García, E. (2005): New data on the lithostratigraphy, detrital zircon and Nd isotope provenance, and paleogeographic setting of the El Antimonio Group, Sonora, Mexico. In: Anderson, T.H., Nourse, J.A., McKee, J.W. Steiner, M.B. (eds.), *The Mojave-Sonora Megashear Hypothesis: development, assessment and alternatives*: Geological Society of America, Special Paper 393, 259-282. doi: 10.1130/0-8137-2393-0.259

Housh, T.B., McDowell, F.W. (2005): Isotope provinces in Laramide and mid-Tertiary igneous rocks of northwestern Mexico (Chihuahua and Sonora) and their relation to basement configuration. In: Anderson, T.H., Nourse, J.A., McKee, J.W., Steiner, M.B. (eds.), The Mojave-Sonora Megashear Hypothesis: Development, assessment, and alternatives, *Geological Society of America Special Paper* 393, Boulder, Colorado, 671-692. doi: 10.1130/0-8137-2393-0.671

Iriondo, A., Kunk, M.J., Winick, J.A., CRM. (2004): ^{40}Ar/^{39}Ar dating studies of minerals and rocks in various areas in Mexico. *USGS/CRM Scientific collaboration (Part II)*, U.S. Geological Survey, Open File Report 04-1444, on line edition, Denver, Co. 46 p.

Iriondo, A., Martínez-Torres, L.M., Kunk, M.J., Atkinson Jr., W.W., Premo, W.R., McIntosh, W.C. (2005): Northward Laramide thrusting in the Quitovac region, northwestern Sonora, Mexico: Implications for the juxtaposition of Paleoproterozoic basement blocks and the Mojave-Sonora, megashear hypothesis. In: Anderson, T.H., Nourse, J.A., McKee, J.W., Steier, M.B. (eds.), The Mojave-Sonora megashear hypothesis: Development, assessment, and alternatives, *Geological Society of America Special Paper* 393, Boulder, Colorado, 631-669. doi: 10.1130/0-8137-2393-0.631

Jacques-Ayala, C. (1999): Stratigraphy of the El Chanate Group (Late Cretaceous) and its implications for the tectonic evolution on northwestern Sonora. Revista Mexicana de Ciencias Geológicas 16, 2, 97-120.

Jacques-Ayala, C. (1995): Paleogeography and provenance of the Early Cretaceous Bisbee Group in the Caborca-Santa Ana region. In: Jacques-Ayala, C., González-León, C.M., Roldán-Quintana, J. (eds.), *Studies on the Mesozoic of Sonora and Adjacent areas: Geological Society of America, Special Paper* 301, 79-98.

Keppie, D., Dostal, J., Miller, B.V., Ortega-Rivera, A., Roldán-Quintana, J., Lee, J.W.K. (2006): Geochronology and geochemistry of the San Francisco gneiss: Triassic continental rift tholeiites on the Mexican Margin of Pangea metamorphosed and exumed in a Tertiary Core Complex. *International Geology Review* 48: 1-16.

Kistler, R.W., Peterman, Z.E. (1973): Variations in Sr, Rb, K, Na, and initial ^{87}Sr/^{86}Sr in mesozoic granitic rocks and intruded wall rocks in central California. Geological Society of America Bulletin 84, 3489-3512.

Lanphere, M.A., Cameron, K.L., Cameron, M. (1980): Sr isotope geochemistry of voluminous rhyolitic ignimbrites and related rocks, western Mexico. Nature 286, 594-596. doi: 10.1038/286594a0

Lang, J.R., Titley, S.R. (1998): Isotopic and geochemical characteristics of Laramide magmatic systems in Arizona and implications for the genesis of porphyry copper deposits. Economic Geology 93, 138-170. doi: 10.2113/gsecongeo.93.2.138

McDonough, W.F., Sun, S, Ringwood, A.E., Jagoutz, E., Hofmann, A.W. (1992): K, Rb and Cs in the Earth and Moon and the evolution of the Earth's mantle. *Geochimica* et *Cosmochimica Acta* 56, 1001-1012.

McDowell, J.W., Housh, T.B., Wark, D.A. (1999): Nature of the crust beneath west-central Chihuahua, Mexico, based upon Sr, Nd and Pb isotopic compositions at the Tomóchic volcanic center. Geological Society of America Bulletin 111, 823-830. doi: 10.1130/0016-7606(1999)111<0823:NOTCBW>2.3.CO;2

McDowell, F.W., Roldán-Quintana, J., Connelly, J. (2001): Duration of Late Cretaceous-early Tertiary magmatism in east-central Sonora, México. Geological Society of America Bulletin 113, 521-531. doi: 10.1130/0016-7606(2001)113<0521:DOLCET> 2.0. CO;2

Mead, R.D., Kesler, S.E., Foland, K.A., Jones, L.M. (1988): Relationship of Sonoran tungsten mineralization to the metallogenic evolution of Mexico. In: Clark, K.F., Salas, G.A. (eds*.), A Special Edition Devoted to the Geology and Mineral Deposits of Mexico*, Economic Geology 83, 1943-1945. doi: 10.2113/gsecongeo.83.8.1943

Meinert, L.D. (1982): Skarn, manto, and breccia pipe formation in sedimentary rocks of the Cananea mining district, Sonora, Mexico. *Economic Geology* 77, 919-949. doi: 10.2113/gsecongeo.77.4.919

Mulchay, R.B., Velasco, J.R. (1954): Sedimentary rocks at Cananea, Sonora, Mexico, and tentative correlation with the sections at Bisbee and the Swisshelm Mountains, Arizona. *Mining Engineering* 6, 628-631.

Mullan, H.S. (1978): Evolution of part of the Nevadan orogen and northwestern Mexico. *Geological Society of America Bulletin* 89, 1175-1188. doi: 10.1130/0016-7606(1978)89<1175:EOPOTN>2.0.CO;2

Nourse, J.A. (1990): Tectonostratigraphic development and strain history of the Magdalena metamorphic core complex, Sonora, Mexico. In: Gehrels, G., Spencer, J. (eds.), *Geologic excursions through the Sonoran desert region, Arizona and Mexico*, Arizona Geological Society Special Paper 7, 155-164.

Nourse, J.A., Premo, W.R., Iriondo, A., Stahl, E.R. (2005): Contrasting Proterozoic basement complexes near the truncated margin of Laurentia, northwestern Sonora–Arizona international border region. In: Anderson, T.H., Nourse, J.A., McKee, J.W., Steiner, M.B. (eds.), The Mojave-Sonora megashear hypothesis: Development, assessment, and alternatives: *Geological Society of America Special Paper* 393, 123–182. doi: 10.1130/0-8137-2393-0.123

Otamendi, J.E., Ducea, M.N., Tibaldi, A.M., Bergantz, G.W., De la Rosa, J.D., Vujovich, G.I. (2009): Generation of tonalitic and dioritic magmas by coupled partial melting of gabbroic and metasedimentary rocks within the deep crust of the Famantinian Magmatic Arc, Argentina. *Journal of Petrology* 50, 841-873. doi: 10.1093/petrology/egp022

Pérez-Segura, E. (2006): *Estudio metalogenético de los yacimientos de Ni, Co (Cu-Zn) de la Esperanza, Sonora central: Caracterización de los depósitos y relaciones con el magmatismo laramídico*. México, D. F., PhD Thesis, Universidad Nacional Autónoma de México, 214 p.

Pérez-Segura, E., González-Partida, E., Valencia, V.A. (2009): Late Cretaceous adakitic magmatism in East-central Sonora, Mexico, and its relation to Cu-Zn-Ni-Co skarns. *Revista Mexicana de Ciencias Geológicas* 26, 411-427.

Poole, F.G., Madrid, R.J., Oliva-Becerril, F. (1991): Geological setting and origin of the stratiform barite in central Sonora, México. In: Raines, G.L. *et al*. (eds.), *Geology and ore deposits of the Great Basin*, Geological Society of Nevada, Reno, NV. 1, 517-522.

Poole, F.G., Perry, W.J.Jr., Madrid, R.J., Amaya-Martínez, R. (2005): Tectonic synthesis of the Ouachita-Marathon-Sonora orogenic margin of the southern Laurentia: Stratigraphic and implications for timing of deformational events and plate-tectonic model. In: Anderson, T.H., Nourse, J.A., McKee, J.W., Steier, M.B. (eds.), The Mojave-Sonora megashear hypothesis: Development, assessment, and alternatives, *Geological Society of America Special Paper* 393, 543-596. doi: 10.1130/0-8137-2393-0.543

Pubellier, M., Rangin, C., Rascón, B., Chorowicz, J., Bellon, H. (1995): Cenomanian thrust tectonics in the Sahuaripa region, Sonora : implications about northwestern megashears. In: Jacques-Ayala, C., González-León, C.M., Roldán-Quintana, J. (eds.), *Studies in the Mesozoic of Sonora and adjacent areas*, Geological Society of America Special Paper 301, 111-120. doi: 10.1130/0-8137-2301-9.111

Rangin, C. (1982) : *Contribution a l'etude géologique du systeme cordillerain du N.O. Mexique.* Paris, France, These Doctorat d'Etat, Université Pierre et Marie Curie, No. 82-12.

Ramos-Velázquez, E., Calmus, T., Valencia, V., Iriondo, A., Valencia-Moreno, M., Bellon, H. (2008): U-Pb and ^{40}Ar/^{39}Ar geochronology of the coastal Sonora batholith: New insights on Laramide continental arc magmatism. *Revista Mexicana de Ciencias Geológicas* 25, 314-333**.**

Richard, D. (1991) : *De la subduction a l'extension intra-continentale: plutonisme et gisements de tungstène de l'Etat de Sonora (Mexique)*. Orsay, These de doctorat. Université de Paris-Sud, 745 p.

Roldán-Quintana, J. (1991): Geology and chemical composition of the Jaralito and Aconchi batholiths in east-central Sonora, México. In: Pérez-Segura, E., Jacques-Ayala, C. (eds.), *Studies in Sonoran geology*, Geological Society of America Special Paper 254, 69-80.

Roldán-Quintana, J. (1994): Geología del Sur de la Sierra de Oposura, Moctezuma, Estado de Sonora, México. *Revista Mexicana de Ciencias Geológicas* 11, 1-10.

Roldán-Quintana, J. (2002): *Caracterización geológico-geoquímica y evolución del arco magmático Mesozoico-Terciario entre San Carlos y Maycoba, sur de Sonora, México*, México, D.F., Universidad Nacional Autónoma de México, PhD Thesis, 185 p.

Roldán-Quintana, J., Calmus, T., Schaaf, P. (2000): Evidencias isotópicas de las diversas fuentes para el Batolito de Sonora, México. Universidad Nacional Autónoma de México, Publicaciones Ocasionales 2, 109-110.

Roldán-Quintana, J., McDowell, F.W., Delgado-Granados, H., Valencia-Moreno, M. (2009): East-west variations in age, chemical and isotopic composition of the Laramide batholith in southern Sonora, Mexico**.** *Revista Mexicana de Ciencias Geológicas 26, 543-563.*

Ruiz, J., Patchett, P.J., Arculus, R.J. (1988): Nd-Sr isotope composition of lower crustal xenoliths-Evidence for the origin of mid-Tertiary felsic volcanics in Mexico: Contributions to Mineralogy and Petrology 99, 36-43. doi: 10.1007/BF00399363

Sansores-Bolívar, O., Wyne, L.F. (1977): Geología, mineralización y origen de las brechas de cuarzo-turmalina del Distrito Minero de Santa Ana de Yécora, Sonora, México. Memoria Técnica 12 Asociación de Ingenieros de Minas, Metalurgistas y Geólogos de México: 501-549.

Schaaf, P., Roldán-Quintana, J., Calmus, T. (1999): Terrane reconnaissance in NE Sonora, Mexico, in light of Sr-Nd-Pb isotopic data from coastal belt granitoids. *EOS (Transactions, American Geophysical Union)* 80, F1079–F1080.

Stewart, J.H., Roldán-Quintana, J. (1991): Upper Triassic Barranca Group; nonmarine and shallow marine rift-basin deposits of northwestern Mexico. Geological Society of America, Special Paper 254, 19-36.

Stewart, J.H., Roldán-Quintana, J. (1994): Map showing Late Cenozoic extensional tilt patterns and associated structures in Sonora and adjacent areas, Mexico. U.S.Geological Survey, *Miscelaneous Field Studies Map*, MF-2238.

Stewart, J.H., Amaya-Martínez, R., Stamm, R.G., Wardlaw, B.R., Stanley, G.D., Stevens, C.H. (1997): Stratigraphy and regional significance of Mississippian to Jurassic rocks in Sierra Santa Teresa, Sonora, Mexico. Revista Mexicana de Ciencias Geológicas 14, 115-135.

Stewart, J.H., Poole, F.G., Harris, A.G., Repetski, J.E., Wardlaw, B.R., Mamet, B.L., Morales-Ramírez, J.M. (1999): Neoproterozoic (?) to Pensylvanian innershelf, miogeoclinal strata in Sierra Agua Verde, Sonora, Mexico. *Revista Mexicana de Ciencias Geológicas* 16, 35-62.

Stewart J.H., Gehrels, G.E., Barth, A.P., Link, P.K., Christie-Blick, N., Wrucke, C.T. (2001): Detrital zircon provenance of Mesoproterozoic to Cambrian arenites in the western United States and northwestern Mexico. Geological Society of America Bulletin 113, 1343–1356. doi: 10.1130/0016-7606(2001)113<1343:DZPOMT>2.0. CO;2

Stewart J.H., Amaya-Martínez, R., Palmer, A.R. (2002): Neoproterozoic and Cambrian strata of Sonora, Mexico: Rodinian supercontinent to Laurentian Cordilleran margin. In: Barth, A. (ed.), Contributions to crustal evolution of the southwestern United States, Geological Society of America, Special Paper 365, 5-48. doi: org/10.1130/0-8137-2365-5.5

Valencia-Gómez, V. (2005): *Evolution of La Caridad porphyry copper deposit, Sonora and geochronology of porphyry copper deposits in northwest Mexico*. Tucson, Arizona, U.S.A., Ph D thesis, The University of Arizona, 197 p.

Valencia-Moreno, M., Ruiz, J., Roldán-Quintana, J. (1999): Geochemistry of Laramide granitic rocks across the southern margin of the Paleozoic North American continent, Central Sonora, Mexico. *International Geology Review*, 41: 1409-1422. http://dx.doi.org/10.1080%2F00206819909465174

Valencia-Moreno, M., Ruiz, J., Barton, M.D. , Patchett, P.J., Zürcher, L., Hodkinson, D.G., Roldán-Quintana, J. (2001): A chemical and isotopic study of the Laramide granitic belt of northwestern México: Identification of the southern edge of the North American Precambrian basement. *Geological Society of America Bulletin* 113, 1409-1422. doi: 10.1130/0016-7606(2001)113<1409:ACAISO>2.0.CO;2

Valencia-Moreno, M., Ruiz, J., Ochoa-Landín, L., Martínez-Serrano, R., Vargas- Navarro, P. (2003): Geochemistry of the Coastal Sonora batholith, Northwestern México. *Canadian Journal of Earth Sciences* 40, 819-831. doi: 10.1139/e03-908

Valencia, V. A., Ruiz, J., Barra, F., Gehrels, G.E., Ducea, M.N., Titley, S., Ochoa-Landín, L. (2005): U-Pb zircon and Re-Os molybdenite geochronology from La Caridad porphyry copper deposit; Insights from the duration of magmatism and mineralization in the Nacozari district, Sonora, Mexico. *Mineralium Deposita* 40, 175-191. doi: 10.1007/s00126-005-0480-1

Valencia-Moreno, M., Iriondo, A., González-León, C. (2006): Temporal constrains on the eastward migration of the Late Cretaceous-early Tertiary magmatic arc of NW Mexico based on new ^{40}Ar/^{39}Ar hornblende geochronology of granitic rocks. Journal of South American Earth Sciences 22, 22-38. doi: 10.1016/j.jsames.2006.08.006

Valentine, W.G. (1936): Geology of the Cananea Mountains, Sonora, Mexico. Geological Society of America Bulletin 47, 53–86.

Vega-Granillo, R., Vidal-Solano, J.R., Herrera-Urbina, S. (2012): Island arc tholeiites of Early Silurian, Late Jurassic and Late Cretaceous ages in the El Fuerte region, northwestern Mexico. Revista Mexicana de Ciencias Geológicas 29, 492-513.

Verma, S.P. (1984): Sr and Nd isotopic evidence for petrogenesis of Mid-Tertiary felsic volcanism in the mineral district of Zacatecas, Zac. (Sierra Madre occidental), Mexico. Isotope Geoscience 2, 37-53. doi: 10.1016/0009-2541(84)90164-5

Verma, S.P. (1992): Seawater alteration effects on REE, K, Rb, Cs, Sr, U, Th, Pb, and Sr-Nd-Pb isotope systematics of mid-ocean ridge basalt. Geochemical Journal 26, 159-177. doi: 10.2343/geochemj.26.159

Verma, S.P., (2001): Geochemical and Sr-Nd-Pb isotopic evidence for a combined assimilation and fractional crystallisation process for volcanic rocks from the Huichapan caldera, Hidalgo, Mexico. Lithos 56, 141-164. doi: 10.1016/S0024-4937(00)00062-1

Verma, S.P. (2005): Estadística básica para el manejo de datos experimentales: aplicación en la Geoquímica (Geoquimiometría). Universidad Nacional Autónoma de México, México, D.F., 186 p.

Verma, S.P., Torres-Alvarado, I.S., Satir, M., Dobson, P.F. (2005): Hydrothermal alteration effects in geochemistry and Sr, Nd, Pb, and O isotopes of magmas from the Los Azufres geothermal field (Mexico): a statistical approach. Geochemical Journal 39, 141-163. doi: 10.2343/geochemj.39.141

White, D.E., Guiza, R. (1949). Los depósitos minerales del distrito El Antimonio, Sonora, México. *Boletín Comité Directivo para la Investigación de los Recursos Minerales de México* 23, 48 p.

Williams, I.S., (1998): U-Th-Pb geochronology by ion microprobe. In: McKibben, M.A., Shanks, W.C. (eds.), *Applications of microanalytical techniques to understanding mineralizing processes*. Reviews in Economic Geology 7, 1-35.

Wilson, F.I., Rocha, S.V. (1949): Coal deposits of the Santa Clara district near Tónichi, Sonora, México. United States Geological Survey Bulletin 962A, 80 p.

Wodzicki, W.A. (1995): *The evolution of the Laramide igneous rocks and porphyry copper mineralization in the Cananea District, Sonora, Mexico*: Tucson, Arizona, U.S.A., PhD thesis, The University of Arizona, 181 p.