New age constraints on magmatism and metamorphism of the Western Sonobari Complex and their implications for an earliest Late Cretaceous orogeny on northwestern Mexico

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ABSTRACT

The Western Sonobari Complex in northwestern Mexico is composed of orogenic metamorphic rocks intruded by a variety of unmetamorphosed plutons and dikes. Petrologic studies and U-Pb geochronology allow dividing the protolith of orthogneisses in the next groups: a) Lower Triassic granodiorite and quartz monzodiorite (249.6–241.3 Ma); b) Upper Triassic granodiorite (213.7–203.5 Ma); c) Upper Jurassic tonalite and granodiorite (162.9–159.1 Ma); and d) Lower Cretaceous diorite (99.9–98.8 Ma). Most of these rocks display amphibolite facies metamorphism, pervasive foliation and several stages of folding. Recrystallized zircon rims yield U-Pb ages of 92.3±4.1 and 90.1±1.3 Ma, which are interpreted to date the orogenic metamorphism. Metamorphic rocks are intruded by numerous post-orogenic granitic dikes dated at 83.9±0.5 to 80.6±1.7 Ma. Geochronology of igneous rocks indicates that the Cordilleran magmatic belts including Triassic and Jurassic plutons continue through northwestern-central Mexico apparently without displacement by the Mojave-Sonora megashear. Correlation based on the age, lithology of protoliths and metamorphic imprint suggests that the earliest Late Cretaceous orogen extends at least from southern California up to Nayarit in west-central Mexico. On the basis of its age and contractional character, the orogenic metamorphism event is related to the collision of the Alisitos arc against the western margin of Pangea but occurring inland the continent not at the contact between these blocks.

Key words: U-Pb geochronology; Mesozoic magmatism; orogenic metamorphism; Sonobari Complex; NW Mexico.

RESUMEN

El Complejo Sonobari Occidental en el noroeste de México está compuesto por rocas con metamorfismo orogénico con protolitos ígneos y sedimentarios, que son intrusionadas por diques y plutones no metamorfoseados. Estudios petrológicos y geocronología U-Pb permiten dividir el protolito de los ortogneises en los siguientes grupos: a) cuarzo monzodiorita y granodiorita del Triásico Inferior (249.6–241.3 Ma); b) granodiorita del Triásico Superior (213.7–203.5 Ma); c) granodiorita y tonalita del Jurásico Superior (162.9–159.1 Ma); y d) diorita del Cretácico Inferior (99.9–98.8 Ma). La mayoría de esas rocas muestran un metamorfismo de facies de anfibolita, foliación penetrativa y algunas etapas de plegamiento. Bordes de recristalización en zircón produjeron edades de 92.3±4.1 y 90.1±1.3 Ma, las cuales se interpreta que fechan el metamorfismo orogénico. Las rocas metamórficas son cortadas por numerosos diques graníticos post-orogénicos fechados entre 89.6±1.7 y 83.9±0.5 Ma. La geocronología de las rocas ígneas indica que los cinturones magmáticos cordilleranos incluidos los del Triásico y Jurásico continúan a través de la parte noroccidental-central de México aparentemente sin desplazamiento por la megacizalla Mojave-Sonora. Correlaciones basadas en la edad, litología de los protolitos y el carácter metamórfico, sugieren que el orógeno del Cretácico Tardío más temprano se extiende al menos desde el sur de California hasta Nayarit en México centro-oriental. Con base en su edad y su carácter compresivo, el evento de metamorfismo orogénico se atribuye a la colisión del arco Alisitos contra el margen occidental de Pangea, pero ocurriendo hacia el interior del continente, no en el contacto entre esos bloques.

Palabras clave: Geocronología U-Pb; magmatismo mesozoico; metamorfismo orogénico; Complejo Sonobari; NW de México.

INTRODUCTION

In spite of their complexity, orogenic metamorphic rocks play a crucial role on deciphering the tectonic evolution of mountain belts. The Sonobari Complex of northwestern Mexico is an assemblage of metamorphic rocks regarded either as an extension of the Paleoproterozoic basement of northern Sonora (Mullan, 1978) or as the internal zones of a Paleozoic orogen related to the collision of Gondwanaland against

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southern Laurentia during the Pangea assembly (Peiffer-Rangin, 1979; Poole *et al*., 2005). On the basis of provenance data, protolith ages, lithology, and metamorphic imprint, Vega-Granillo *et al*. (2013) divided the Sonobari Complex into the Eastern Sonobari Complex dominated by Middle-Upper Ordovician, low-grade metasedimentary sequences of Gondwanan provenance (Poole *et al*., 2005; Vega-Granillo, *et al*., 2008); and, the Western Sonobari Complex made of lower Mesozoic (248–206 Ma), medium-grade metaigneous rocks (Anderson and Schmidt, 1983; Keppie *et al*., 2006; Vega-Granillo *et al*., 2013), whose evolution seems rather be related to the geologic evolution of the Cordilleran chain. In this context, the Western Sonobari Complex seems to represent locally-exhumed Mesozoic igneous suites previously preserved in the mid-lower crust, which may be a link between the Baja California and Sonora batholiths to the north, and the Sinaloa and Nayarit batholiths to the south. Parts of these igneous belts remain buried under younger sequences, or they were fragmented during opening of the Gulf of California. Continuity of the Cordilleran igneous and metamorphic belts is important for the tectonic reconstruction of Mexico, whose assemblage was mostly completed during the Mesozoic (*e.g.* Dickinson and Lawton, 2001).

Our field studies indicate the Western Sonobari Complex is made of a variety of protoliths, which underwent orogenic metamorphism, and were subsequently intruded by diverse igneous rocks. Considering the lithological diversity, current geochronological data are insufficient, and for that reason a detailed geochronologic study was carried out in this work, in order to constrain the ages of metamorphism and magmatic events. The obtained data allowed us to refine the geological evolution of the Western Sonobari Complex, to establish lithostratigraphic and to gain a more precise understanding of its role in the construction of the southern Cordilleran orogenic belt.

GEOLOGICAL SETTING

The Sonobari Complex is a low- to medium-grade metamorphic assemblage outcropping in southern Sonora and northern Sinaloa, northwestern Mexico (Figure 1), which was preliminarily mapped by de Cserna and Kent (1961). Mullan (1978) enhanced the cartography separating the western Francisco Gneiss from the eastern Río Fuerte, Corral Falso, and Topaco formations. The Río Fuerte Formation is a thick siliciclastic sequence with very scarce calcareous layers containing Middle-Late Ordovician conodonts (Poole *et al*., 2005; Poole *et al*., 2010), which underwent low-P greenschist facies metamorphism (Vega-Granillo *et al*., 2011). U-Pb geochronology in quartzite indicates a Gondwanan provenance (Vega-Granillo *et al*., 2008). The Corral Falso Formation was described as a metasedimentary sequence very similar to the Río Fuerte Formation, but the original criteria for separating these formations are no longer sustained (Vega-Granillo *et al*., 2008). Metamorphic rocks are intruded by Upper Jurassic (~155–151 Ma) granite stock and sills, and covered in nonconformity by the Upper Jurassic volcanosedimentary Topaco Formation. All previous units are deformed and metamorphosed by a second event tentatively ascribed to the Late Jurassic (Mullan, 1978; Vega-Granillo *et al*., 2008; 2011), and grouped into the Eastern Sonobari Complex by Vega-Granillo *et al*. (2013).

The Western Sonobari Complex is mainly exposed in the Sonobari and San Francisco ranges (Figure 1), which are limited by ~N-S Oligocene-Miocene normal faults bordering wide alluvial valleys. The main unit of this complex is the Francisco Gneiss, which consists of orthogneisses (Figure 2a, 2d, 2e), minor tabular bodies of amphibolite (Figure 2b, 2c), scarce paragneisses and schists, which underwent amphibolite facies metamorphism (Mullan, 1978; Keppie *et al*., 2006; Vega-Granillo *et al*., 2013). Facies assigment was based on the presence of amphibolite (*sensu stricto*, according to definition in Fettes and Desmons, 2007) and the mineral assemblage in orthogneisses (Best, 2003), which consists of plagioclase (andesine-oligoclase) + K feldspar + quartz + biotite ± muscovite ± hornblende. Metamorphic rocks display widespread migmatization developing stromatic leucosome bands, net-like veinlets, and disperse patchs of leucosome (Figure 2a, 2c, 2d, 2e). Detrital zircon data in paragneisses suggest a Laurentian provenance (Vega-Granillo *et al*., 2013) contrasting with the Gondwanan provenance of the Eastern Sonobari Complex. Orthogneisses yielded U-Pb ages of ~220 Ma (Anderson and Schmidt, 1983), ~206 Ma (Keppie *et al*., 2006), and an upper intercept age of 248±28 interpreted as a crystallization age (Vega-Granillo *et al*., 2013). At least one ENE-WSW oriented pervasive foliation overprints the metamorphic rocks, although some metasediments display two foliations. Some phases of north-verging isoclinal to open folds bend the foliation causing fold superposition structures (Figure 2e). These rocks are intruded by unmetamorphosed coarse-grained diorite to gabbro bodies, which in turn are cut by ultramafic and dioritic dikes (Figure 2f). Numerous pegmatite to aplite dikes, intrude previous lithologies (Figure 2d). Metamorphic rocks are also intruded by the lowermost Paleocene Los Parajes Granodiorite (64 Ma; U-Pb zircon) and by the Eocene Macochin Gabbro (54 Ma, ^{40}Ar-^{39}Ar hornblende) (Vega-Granillo *et al*., 2013), both exposed in the southern Sonobari range.

METHODS

Rock modal classification was performed through detailed petrography of selected samples. Samples include a variety of orthogneisses, and different types of non-foliated felsic rocks, which intrude the tectonites. Details of the procedures for sampling and analyzing are described in the supplemental file S1. Low-resolution cathodolumiscence images were obtained in the Arizona LaserChron Center, while high-resolution images were obtained in the Facultad de Ciencias de la Tierra de la Universidad Autónoma de Guerrero. The U-Pb analyses were performed by LA-ICPMS at the Arizona LaserChron Center (Tucson, Arizona). Data were collected during several analytical sessions from 2013 and 2015, utilizing a Nu Plasma ICPMS connected to a Photon Machines Analyte G2 excimer laser. A complete Excel dataset is included in the supplemental file S2.

RESULTS OF U-PB GEOCHRONOLOGY

Metamorphic rocks

The oldest orthogneisses in the area derive from medium-grained mesocratic granodiorite and quartz monzodiorite corresponding to the samples SFO-159 and SFO-56 (Figures 2a, 2b). Location and mineralogical composition of each sample are included in Table 1. These rocks yielded Early Triassic weighted average ages of 249.6±2.1 Ma and 241.3±2.4 Ma, respectively (Figure 3a, 3b). Scarce lower Paleozoic ages in the sample SFO-56 were obtained from inherited zircons, although most of the dated cores yielded similar or slightly older ages than the rims.

A second group of ages is given by five Upper Triassic rocks. Orthogneiss SFO-155 is a medium-grained leucocratic granodiorite that yielded a weighted mean age of 213.7±1.6 Ma (Figure 3c). Zircons in this sample do not display inherited cores but several have irregular recrystallized rims. The next three dated orthogneisses are medium-grained leucocratic granodiorites very similar in mineralogy

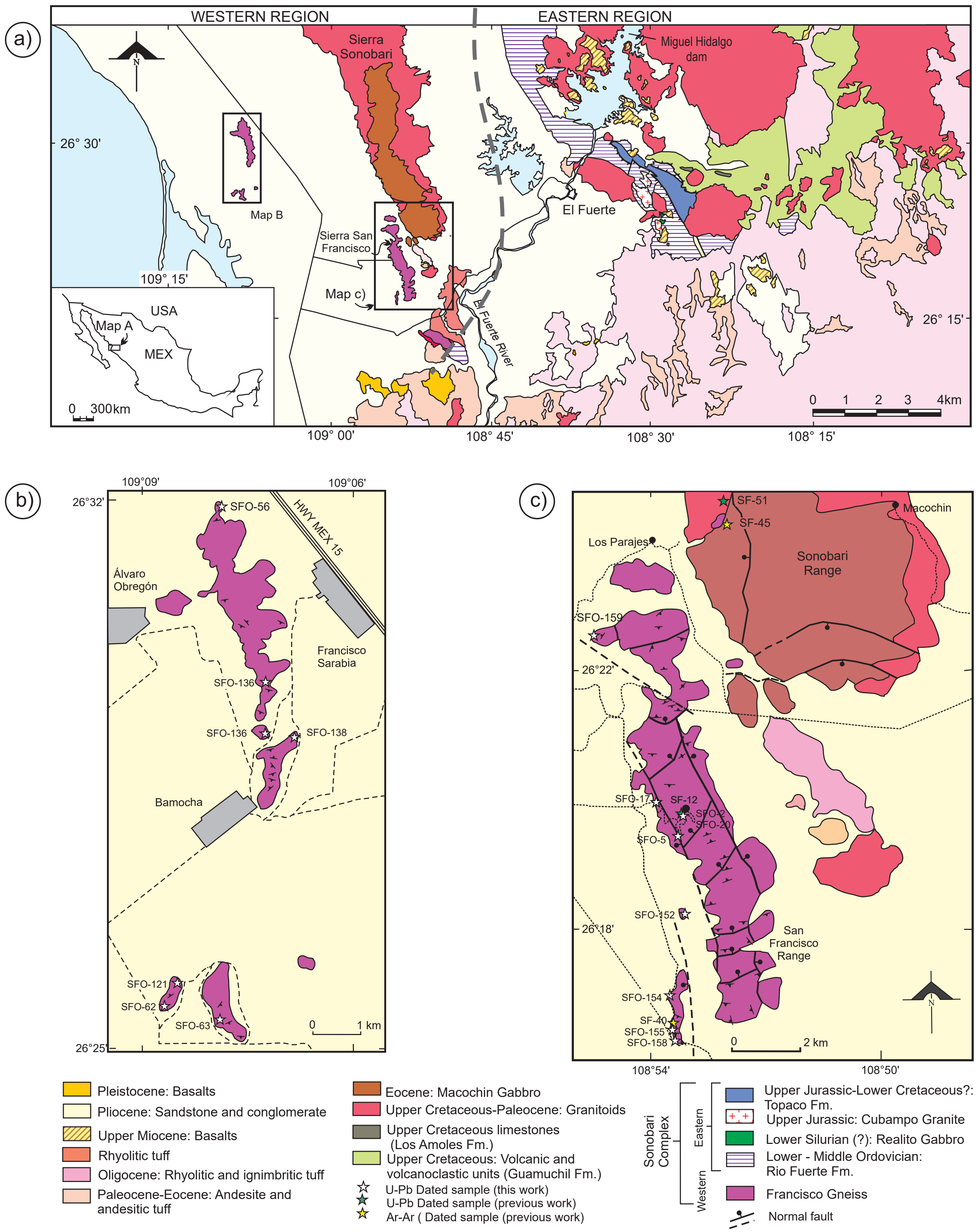

Figure 1. a) Geological map of the Sonobari Complex (modified from Escamilla-Torres *et al*., 2000); b) Geological map of the western exposures; c) Geological map of the eastern exposures.

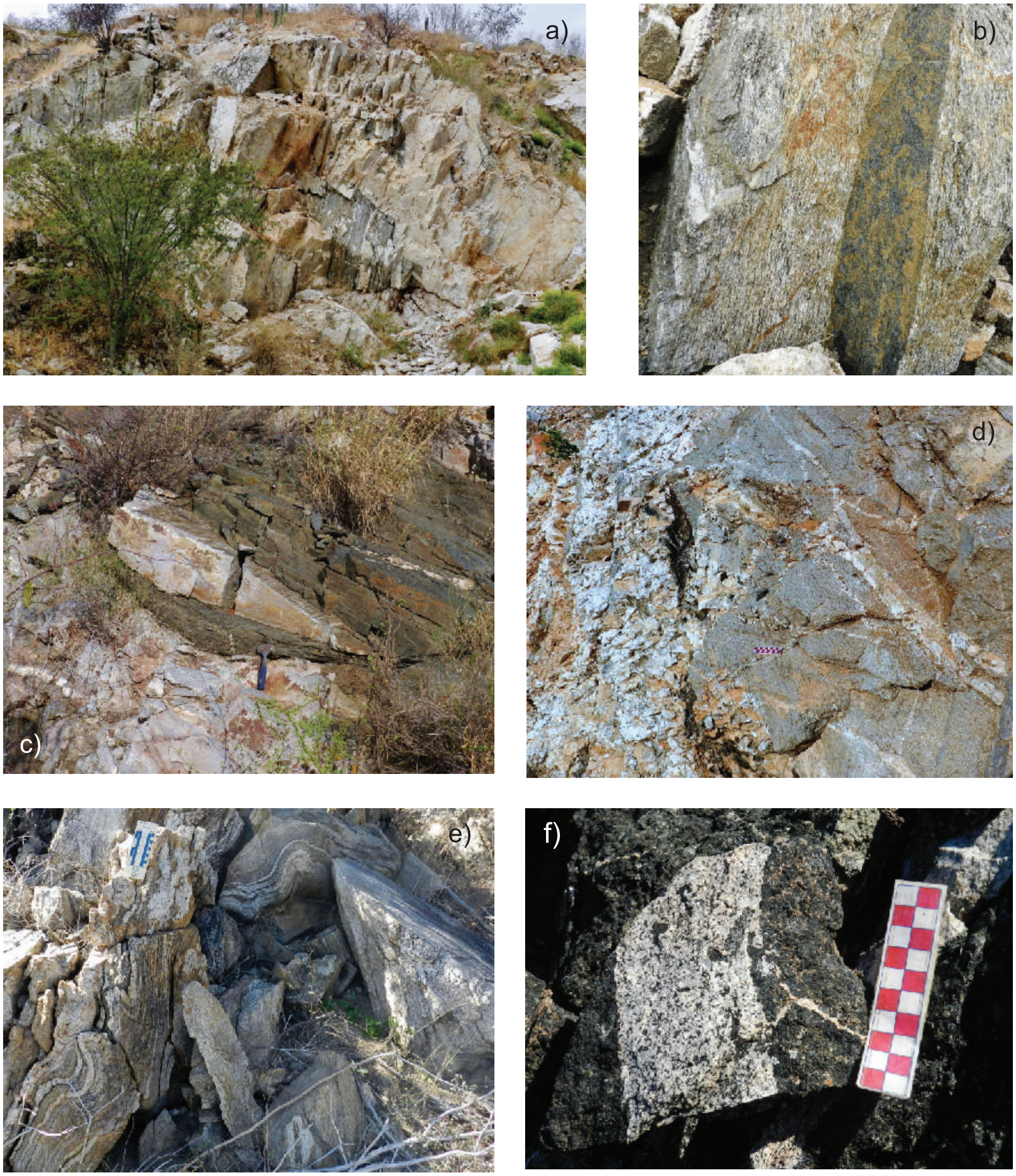

Figure 2. Outcrop images of the Western Sonobari Complex: a) Xenoliths of Lower Triassic quartz monzodiorite gneiss surrounded by Upper Cretaceous leucocratic aplite and pegmatite; b) Detail of the Lower Triassic quartz monzodiorite gneiss transected by amphibolite, foliation is parallel to the amphibolite-gneiss contact; c) Amphibolite dikes crosscutting Upper Triassic granodiorite gneiss, leucosome bands follow the foliation in both types of rocks, which is parallel to the amphibolite-gneiss contact; d) Upper Jurassic granodiorite gneiss transected by leucocratic pegmatite; e) Upper Jurassic tonalite gneiss with stromatic leucosome layers; f) Upper Cretaceous leucocratic diorite traversing melanocratic gabbro.

(Figure 2c, 2d; Table 1). Samples SFO-20, SFO-5, and SFO-158 yielded weighted mean ages of 207.4±1.7 Ma, 205.9±2.9 Ma, and 205.5±2.6 Ma, respectively (Figure 3d, 3e). Several zircons of the SFO-5 and SFO-20 samples indicate a trend to younger ages culminating at ~90 Ma. Sample SFO-154 is a granodioritic orthogneiss that yielded a weighted average age of 203.5±1.4 Ma (Figure 3f). Ten younger ages of this sample are considered to reflect Pb-loss caused by the metamorphic imprint and were not included in the age calculation. Zircons of the sample SFO-20 display recrystallized rims with irregular shape (Figure 4). Some of these rims were dated with a 15 µm diameter beam yielding an age of 92.3±4.1 Ma (Figure 5a).

The third group of ages comprises four Middle-Upper Jurassic rocks. Samples SFO-62 and SFO-121 are medium-grained leucocratic granodiorites that yielded weighted mean ages of 162.9±2.5 Ma and 159.1±1.1 Ma, respectively (Figure 3g, 3j). In both samples, some zircons yield dispersed Middle Ordovician to Middle Triassic ages derived of inherited zircons. The sample SFO-63 is a medium-grained melanocratic rock of tonalitic composition (Figure 2e) that yielded a mean age of 161.0±1.5 Ma (Figure 3h). Although this sample has a similar age than the previous two samples, the rock is more mafic, schistose, commonly with stromatic leucosome bands. The sample SFO-152 is a medium-grained mesocratic rock of granodioritic composition that yielded a weighted mean age of 160.3±0.6 Ma (Figure 3i). The four oldest zircons yielded Middle Permian to Early Triassic ages. A trend to younger ages is found in all the samples of this group, probably indicating mixing between igneous zircon and recrystallized zircon rims. In sample SFO-152 the six younger data obtained from the rims yielded a weighted mean age of 90.1±1.3 Ma (Figure 5b).

A fourth group of orthogneisses is represented by one lowermost Upper Cretaceous rock, sample SFO-138, which is a foliated diorite yielding an average age of 98.8±1.3 Ma (Figure 3k). Foliation in this rock is subparallel to the overall tectonic foliation and is made by preferred orientation of amphibole, elongation of plagioclase, and minor grain boundary recrystallization. Deposition of minerals in low-strain sites perpendicular to the foliation low-strain sites also occurs.

Undeformed igneous rocks

In several places of the westernmost exposures, coarse-grained melanocratic plutons lacking pervasive foliation intrude the deformed metamorphic rocks. In turn, these rocks are intruded by coarse-grained holomelanocratic pyroxenite, and by irregular coarse-grained leucocratic diorite dikes consisting of plagioclase-hornblende-clinopyroxene-biotite (Figure 2f, Table 1). A melanocratic gabbro is made of amphibole with minor plagioclase-clinopyroxene-titanite-rutile, with epidote-zoisite partially replacing plagioclase. A leucocratic dioritic dike (sample SFO-136) that crosscut the gabbro, yielded a mean age of 99.9±1.1 Ma (Figure 3l).

Numerous leucocratic granite dikes with thickness varying from several meters to centimeters crosscut the foliation of the metamorphic rocks (Figure 2a, 2d). Sample SFO-142 is a pegmatite dike from the western exposures (Figure 1) that yielded a weighted mean age of 83.9±0.5 Ma (Figure 6a). Sample SFO-17 is a pegmatite dike crosscuting the paragneisses in the western foothills of the Francisco range, which yields a mean age of 82.9±1.0 Ma (Figure 6b). The sample SFO-02 obtained uphill in the same range (Figure 1) is a medium-grained rock that yielded a weighted mean age of 80.6±1.7 (Figure 6c) coincident with that obtained from the pegmatite dike.

DISCUSSION

Chronology of magmatic events

The oldest metasedimentary rocks in the Western Sonobari Complex are paragneisses and micaschists that crop out in the lower western hillside of the San Francisco Range (Vega-Granillo *et al.*, 2013). These rocks were intruded by several magmatic pulses dated in this work, most of them preceding an orogenic metamorphism event. The first magmatic pulse is indicated by Lower and Middle Triassic

Table 1. U-Pb geochronology of the Western Sonobari Complex.

Event	Sample	UTM Zone 12 R E	UTM Zone 12 R N	Rock type	Petrography	Mineralogy	Age (Ma)
1st Pulse	SFO-159	707,809	2'918,858	Orthogneiss	Medium-grained mesocratic granodioritic rock	Pl + Qtz + Bt + Amp + Ep + Zr	249.6 ± 2.1
	SFO-56	686,235	2'935,748	Orthogneiss	Medium-grained mesocratic quartz monzodiorite, migmatized with stromatic bands	Pl + Qtz + Bt + Amp + Ep + Sph + Zr	241.3 ± 2.4
2nd Pulse	SFO-155	710,474	2'907,659	Orthogneiss	Medium-grained leucocratic granodiorite rock	Pl + Qtz + Bt + Ms + Zr	213.7 ± 1.6
	SFO-20	710,652	2'913,886	Orthogneiss	Medium-grained and foliated leucocratic granodiorite	Pl + Qtz + Bt + Kfs + Sph + Zr	207.4 ± 1.7
	SFO-5	710,515	2'913,490	Orthogneiss	Medium-grained leucocratic granodiorite with penetrative foliation	Pl + Qtz + Bt + Ep + Zr	205.9 ± 2.9
	SFO-158	710,536	2'907,194	Orthogneiss	Medium-grained leucocratic granodiorite	Pl + Qtz + Bt + Pl + Zr	205.5 ± 2.6
	SFO-154	710,382	2'908,478	Orthogneiss	Medium-grained leucocratic granite	Pl + B t+ Qtz + Ep + Zr	203.5 ± 1.4
3rd Pulse	SFO-62	685,013	2'923,976	Orthogneiss	Medium-grained leucocratic granodiorite with patch migmatites estructures	Qtz + Pl + Bt + Kfs + Sph + Zr	162.9 ± 2.5
	SFO-63	686,202	2'923,555	Orthogneiss	Medium-grained melanocratic rock of tonalitic composition, schistose, and migmatized, with common stromatic leucosome bands	Bt + Amp + Pl + Qtz + Ep + Zr	161.0 ± 1.5
	SFO-152	710,928	2'910,966	Orthogneiss	Medium-grained mesocratic granodiorite	Pl + Qtz + Bt + Ep + Zr	160.3 ± 0.62
	SFO-121	685,220	2'924,370	Orthogneiss	Medium-grained leucocratic granodiorite	Pl + Qtz + Bt + Ep + Zr	159.1 ± 1.1
4th Pulse	SFO-136	687,358	2'930,299	Diorite dike	Coarse-grained leucocratic and undeformed diorite	Pl + Amp + Qtz + Sph + Px + Z r + Rt	99.9 ± 1.1
	SFO-138	687,942	2'930,260	Diorite	Medium-grained diorite with penetrative foliation	Pl + Amp + Qtz + Kfs + Bi + Ep + Zr	98.8 ± 1.3
5th Pulse	SFO-142	687,267	2'931,609	Pegmatite dike	Coarse-grained muscovite pegmatite	Kfs + Qtz + Pl + Ms + Grt + Zr	83.9 ± 0.5
	SFO-17	709,909	2'913,987	Pegmatite dike	Coarse-grained muscovite pegmatite with dynamic recrystallization	Kfs + Qtz + Pl + Ms + Grt + Zr	82.9 ± 0.7
	SFO-02	710,652	2'913,886	Aplite dike	Medium grained granitic rock with magmatic foliation	Qtz + Pl + Bt + Grt+ Zr	80.6 ± 1.7

Note: Qtz=Quartz, Pl=Plagioclase, Bt-=Biotite, Ms=Muscovite, Amp=Amphibole, Grt=Garnet, Ep=Epidote, Kfs=K-feldspar, Sph=Sphene, Zr=Zircon.

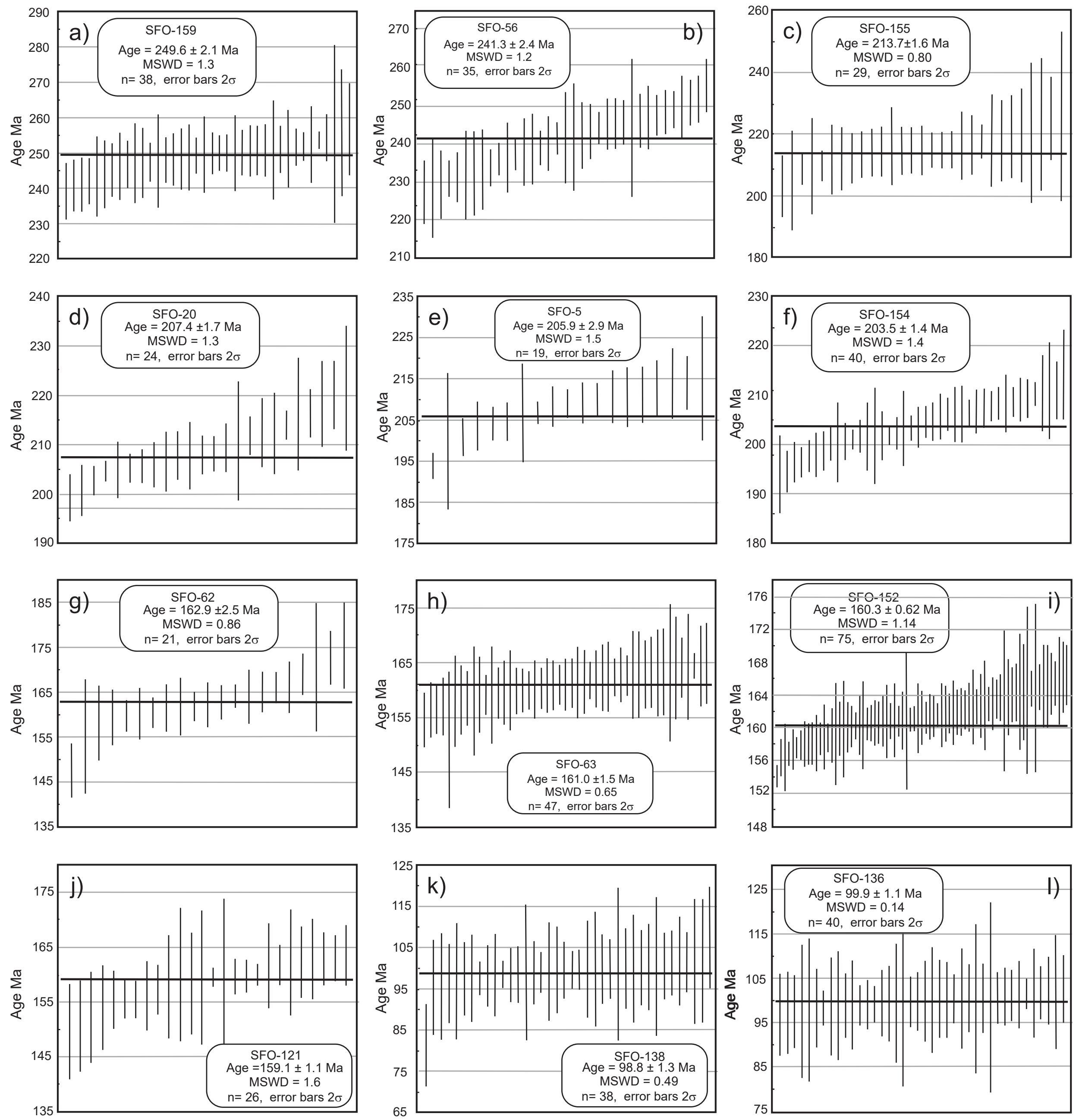

Figure 3. Weighted average ages of the Francisco Gneiss.

(249–241 Ma) granodiorite and quartz monzodiorite plutons. A second magmatic stage occurred in the Late Triassic (Norian-Rhaetian) with intrusion of two-mica granodiorite (213 Ma) followed by leucocratic biotite granodiorite (207–203 Ma). The latter rocks made the larger rock volume in the Francisco range although coeval rocks were not founded in the western exposures. The biotite granodiorite probably corresponds to the ~206 Ma age reported by Keppie *et al.* (2006) and the ~220 Ma age reported by Anderson and Schmidt (1983), considering the radiogenic Pb input of inherited zircons that cannot be avoided in the latter datation. The third magmatic pulse is made up of granodioritic plutons locally with garnet, and melanocratic tonalite, which yield Late Jurassic ages (Oxfordian, 163–159 Ma). All previous rocks are traversed by mafic tabular bodies, currently amphibolites, from which zircons cannot be extracted; therefore the age of their protolith remains unknown. Geochemistry and field relationships of the amphibolites suggest these rocks are tholeiitic basalts emplaced as dikes in a back-arc setting (Keppie *et al*., 2006; Vega-Granillo *et al*., 2013). The fourth group of orthogneisses is represented only for a tonalite dated at 98 Ma, which is coeval to the undeformed diorite dike dated at 99 Ma (Figure 2f). The undeformed diorite dike and its gabbro host are interpreted as segregations of a same parental magma based on mineralogy similarity and field relationships, and hence, they are considered nearly contemporaneous. The lacking of observable deformation of the gabbro and the crosscuting dike, while coeval dioritic rocks display well-developed foliations, can be ascribed to differences in competence caused by the coarser grain-size and predominant mafic mineralogy of the gabbro pluton. Alternatively, diorite foliation may be ascribed to magmatic or sub-magmatic flow caused by forced

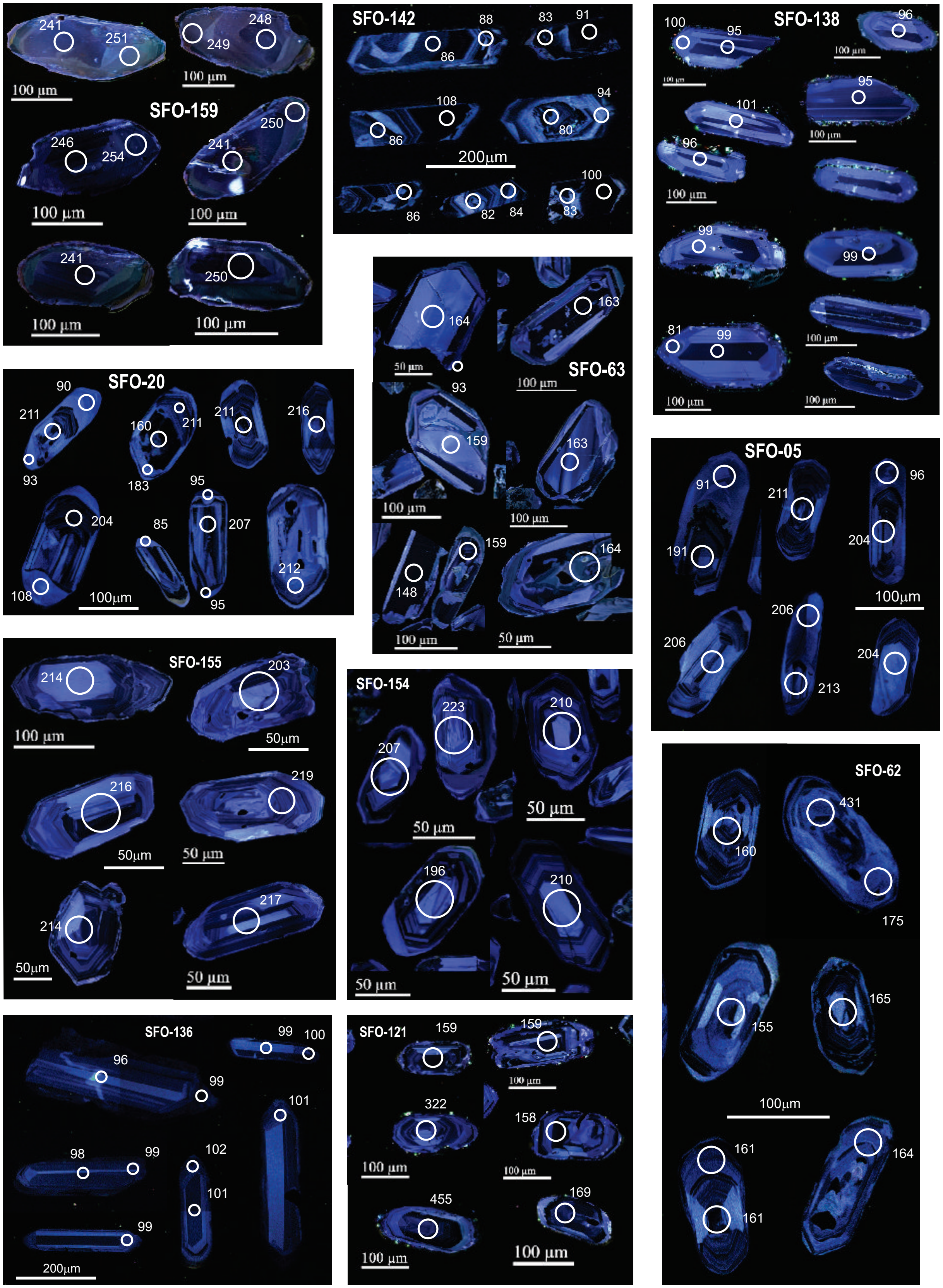

Figure 4. Cathodoluminscence images showing selected laser spots in zircons derived from metamorphosed and unmetamorphosed igneous rocks of the Western Sonobari Complex.

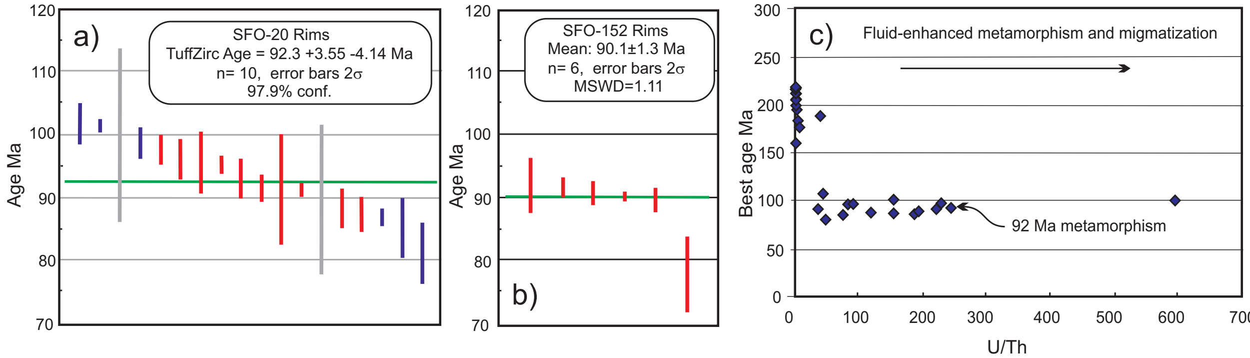

Figure 5. a) TuffZirc ages from recrystallized zircon rims of the Upper Triassic gneiss, sample SFO-20; b) Weighted average age of recrystallized zircon rims of the Upper Jurassic granodiorite gneiss sample SFO-152. c) Best ages versus U/Th content in the zircon Samples SFO-152 and SFO-20. Red bars were data used for age calculation.

emplacement. Anyway, parallelism of the diorite foliation to the overall orogenic foliation suggests that tectonic stresses were active during the diorite emplacement.

On the basis of the lithology and age similarities, the Lower to Upper Triassic magmatism in the Western Sonobari Complex may be related to the Permo-Triassic magmatism in the southwestern Cordillera (Figure 7), which has been classically ascribed to subduction of an oceanic plate under the North American plate (Burchfield and Davis, 1972; Kistler and Peterman, 1973; Dickinson, 1981). The magmatic arc dated from ~260 to 207 Ma in southwestern USA (Miller, 1978; Miller *et al.*, 1995; Barth and Wooden, 2006; Anderson *et al.*, 2010; Barth, 2010; Ehret *et al.*, 2010; Barth *et al.*, 2011; Riggs *et al.*, 2012) was constructed over Proterozoic crust and its Paleozoic metasedimentary cover, and on accreted oceanic terranes or thinned continental crust to the north, and obliquely to the Paleozoic structural trends. Besides, a belt of Permo-Triassic granitoids (287–232 Ma) extends from Sonora along the entire length of Mexico (Figure 7), crossing various terrane boundaries (Damon *et al.*, 1981; Yáñez *et al.*, 1991; Torres *et al.*, 1999; Schaaf *et al.*, 2002; Weber *et al.*, 2005; Arvizu *et al.*, 2009). That belt continues in South America from Venezuela to Peru, yielding ages from 275 to 223 Ma (Cochrane *et al.*, 2013 and references therein), although in this region it is interpreted as emplaced during continental rifting following the Pangea assembly.

Upper Jurassic granodiorite and tonalite intrusions dated in this study are partially coeval to a Lower to Upper Jurassic magmatic belt in the southwestern Cordillera (Figure 7), which includes plutons and a thick volcano-sedimentary sequence (Riggs *et al.*, 1993; Anderson *et al.*, 2005; Haxel *et al.*, 2005). Coeval plutonic rocks occur in the Peninsular Ranges batholith of Baja California (Thompson and Girty, 1994; Schmidt and Paterson, 2002; Shaw *et al.*, 2003; Valencia *et al.*, 2006), the Eastern Sonobari Complex (Vega-Granillo *et al.*, 2008), central Sinaloa (Cuéllar-Cárdenas *et al.*, 2012), the Islas Marías offshore of the Nayarit coast (Pompa-Mera *et al.*, 2013). Dickinson and Lawton (2001) proposed that the Jurassic arc in Mexico was east-facing and entirely exotic to North America prior to its collision in the Cretaceous. However, Schmidt *et al.* (2014) argue that these intrusions are intimately related with Triassic-Jurassic turbidite sequences of North American origin and thus, the Middle Jurassic arc must has formed *in situ* and was not exotic to North America. In eastern Mexico, the Middle-Late Jurassic Nazas Formation yielding ages from ~198 to 158 Ma (López-Infanzón, 1986; Bartolini and Spell, 1997; Barboza-Gudiño *et al.*, 2004; 2008; Fastovsky *et al.*, 2005; Zavala-Monsiváis *et al.*, 2009; Barboza-Gudiño, 2012) has been also proposed as the extension of the northern Sonora Jurassic arc (Figure 7), but displaced by the left-lateral Mojave-Sonora megashear (Jones *et al.*, 1995). That displacement has been challenged based on differences in the basements of each region (Molina-Garza and Iriondo, 2007), as well as on significant discrepancy in detrital zircon plots of sandstones intercalated within the volcanic sequences of each region (Lawton and Molina-Garza, 2014). If the Jurassic magmatism in our area and that of the Nazas arc were not displaced, then a wide magmatic arc must have occurred at that time, because more than 600 km separate both areas (Figure 7). An example of a wider than 600 km continental magmatic arc occurred in the Andean Cordillera from the Oligocene to Holocene times (*e.g.* Trumbull *et al.*, 2006).

The earliest Late Cretaceous magmatic pulse dated in this study also occurred in the Sierra Nevada batholith (*e.g.* Sams and Saleeby, 1988; Saleeby *et al.*, 2008); the Peninsular Ranges batholith (Schmidt and Paterson, 2002; Johnson *et al.*, 2003; Wetmore *et al.*, 2005; Peña-Alonso *et al.*, 2012; Kimbrough *et al.*, 2015), and central Sinaloa (Henry

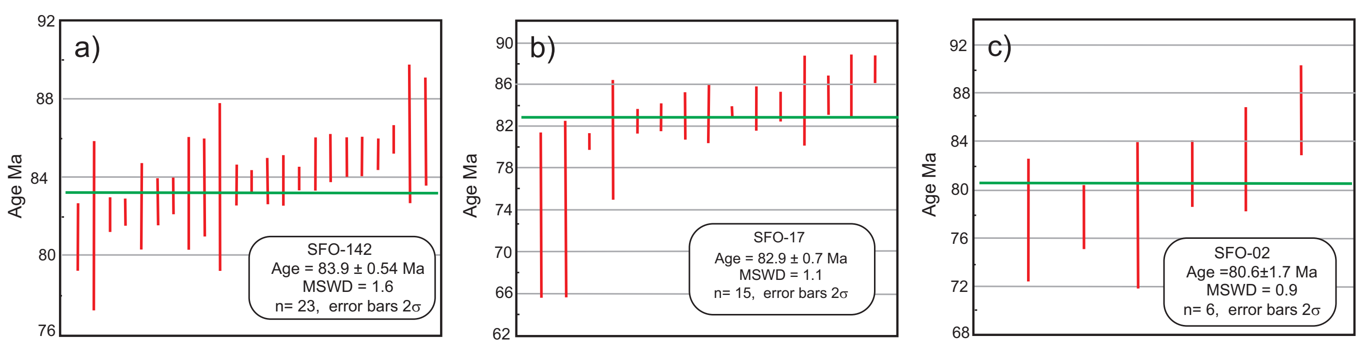

Figure 6. Weighted average ages of leucocratic pegmatite and aplite dikes that crosscut the metamorphosed rocks of the Francisco gneiss.

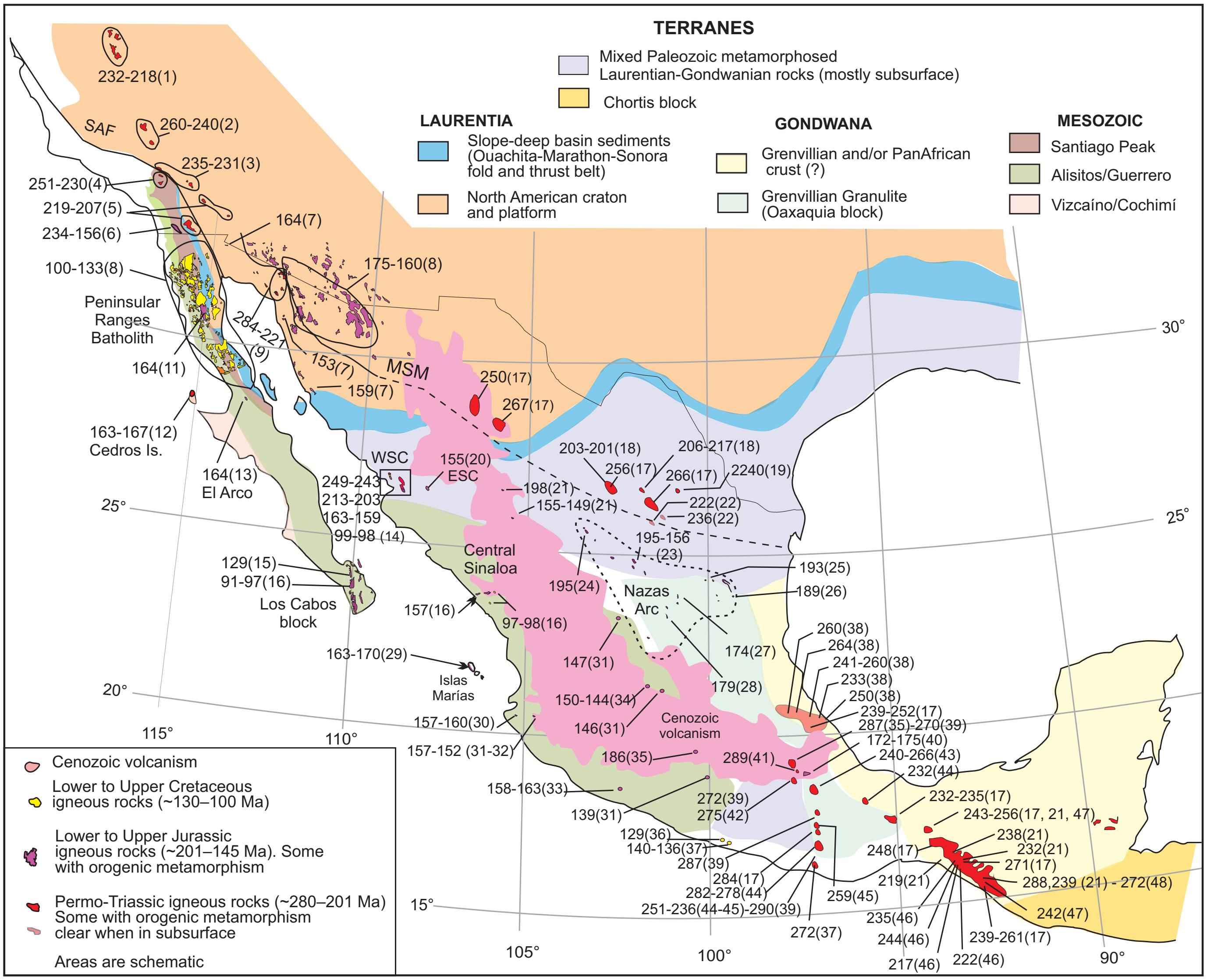

Figure 7. Map of terranes of Mexico and adjacent regions, mainly based on Poole *et al.* (2005); Campa and Coney (1983); Ortega-Gutiérrez *et al.* (1995); and Sedlock *et al.* (1993). Numbered references: 1: Anderson *et al.*, 2010; Ehret *et al.* (2010); Barth *et al.* (2010, 2011); 2: Miller *et al.* (1995); 3: Miller (1978); Barth and Wooden (2006); 4: Barth and Wooden (2006); 5: Barth *et al.* (1990); Barth and Wooden (2006); 6: Thompson and Girty (1994); 7: Anderson *et al.* (2005); 8: Anderson *et al.* (2005); Haxel *et al.* (2005); 9: Arvizu *et al.* (2009); Riggs *et al.* (2009; 2010); 10: Schmidt *et al.* (2014); 11: Schmidt and Paterson (2002); 12: Kimbrough and Moore (2003); 13: Valencia *et al.* (2006); 14: this work; 15: Schaaf *et al.* (2000); 16: Cuéllar-Cárdenas *et al.* (2012); 17: Murillo and Torres (1987, *in* Torres *et al.*, 1999); 18: Denison *et al.* (1969); Molina-Garza (2005); 19: McKee *et al.* (1990); 20: Vega-Granillo *et al.* (2008); 21: Damon *et al.* (1981); 22: Denison *et al.* (1975, *in* Grajales-Nishimura *et al.*, 1992); 23: Fries and Rincón-Orta (1965); López-Infanzón (1986); Jones *et al.* (1995); 24: Bartolini and Spell (1997); 25: Barboza-Gudiño *et al.* (2008); Zavala-Monsiváis *et al.* (2009); 26: Fastovsky *et al.* (2005); Zavala-Monsiváis *et al.* (2009); 27: Barboza-Gudiño *et al.* (2004); 28: Zavala-Monsiváis *et al.* (2012); 29: Pompa-Mera *et al.* (2013); 30: Schaaf *et al.* (2003); Valencia *et al.* (2013); 31: Mortensen *et al.* (2008); 32: Bissig *et al.* (2008); 33: López-Infanzón and Grajales-Nishimura (1984); Centeno-García *et al.* (2003); 34: Martini *et al.* (2011); 35: Elías-Herrera *et al.* (2000); 36: Solari *et al.* (2007); 37: Ducea *et al.* (2004); 38: Jacobo (1986); 39: Ortega-Obregón *et al.* (2013); 40: Yáñez *et al.* (1991); 41: Kirsch *et al.* (2012); 42: Solari *et al.* (2001); 43: Torres *et al.* (1986); 44: Grajales-Nishimura (1988); 45: Grajales-Nishimura *et al.* (1985, in Torres et al. 1999); 46: Schaaf *et al.* (2002); 47: Damon (1975); 48: Weber *et al.* (2007).

et al., 2003) (Figure 7). This magmatic belt can have resulted from the subduction resuming after collision of the Alisitos arc.

Chronology of the orogenic metamorphism

The recrystallized zircon rims of samples SFO-20 and SFO-152 render well defined ages of 92.3±4.1 Ma and 90.1±1.3 Ma, respectively (Figures 5a, b). Concordance and coincidence of ages from some zircon rims in these samples suggest that metamorphism caused either complete radiogenic Pb-loss in the recrystallized sectors of the original zircons or formed new zircon overgrowths. The U/Th ratios of the zircon rims in both samples are higher than 23.5 (Figure 5c). High U/Th values have been regarded as indicative of metamorphic imprint (Mezger and Krogstad, 1997; Rubatto 2002; Gehrels *et al.*, 2009). Also, several samples display a trend to younger ages culminating at ~90 Ma. The 92–90 Ma age of the metamorphic event is consistent with the 83 to 80 Ma ages of the leucocratic granitic dikes that clearly crosscut and postdate the orogenic foliation (Figures 6a - 6c). The ages of recrystallized zircon postdate concordant U-Pb titanite ages ranging from 112 to 98 Ma, and coincide with the oldest U-Pb xenotime ages varying from 91 to 51 Ma (Keppie *et al.*, 2006). A 67 ± 5 Ma $^{40}Ar/^{39}Ar$

hornblende age reported for the amphibolite of the Francisco range was interpreted as a cooling age after an orogenic event or after intrusion of the Los Parajes Granodiorite 64 Ma ago (Vega-Granillo *et al.*, 2013), which could produce an overprinting contact metamorphism on the Francisco Gneiss.

On the basis of metamorphic facies, anatexis, folation development, and isoclinal folding, it is inferred that the orogenic metamorphism must require crustal shortening and thickening, and thus was originated in a contractional regime. Orogenic metamorphic rocks coeval to those in the study area have been reported from California to central Mexico. In the southernmost Sierra Nevada, Lower Cretaceous orthogneisses are intruded by lowermost Upper Cretaceous plutons (Sams and Saleeby, 1988), and ductile deformation is constrained to take place about 90 Ma (Saleeby *et al.*, 2008). In the central zone of the southern Peninsular Ranges batholith, peak metamorphism reaching upper-amphibolite facies was achieved at ~100 Ma (Schmidt *et al.*, 2014). The orogenic metamorphism and deformation in the Los Cabos block supposedly occured between 129 and 94 Ma (Pérez-Venzor, 2013). Two mylonitic gneisses of the same region yield $^{40}Ar/^{39}Ar$ ages of 91.5 and 97.1 Ma, obtained from biotite and muscovite respectively, which are considered as indicating the age of metamorphism (Cuéllar-Cárdenas *et al.*, 2012). Deformed plutons in the Los Cabos block yield K-Ar ages older than 98 Ma, while post-tectonic intrusives yield K-Ar ages between 98 and 65 Ma (Aranda-Gómez and Pérez-Venzor, 1989). In central Sinaloa, syntectonic intrusions yield K-Ar hornblende ages ranging from 98 to 90 Ma; which are interpreted as cooling after regional metamorphism (Henry *et al.*, 2003). In the same area, tonalites regarded as syntectonic were dated at 98.0 and 97.1 Ma (U-Pb zircon), while schist yielded a $^{40}Ar/^{39}Ar$ muscovite age of 94.47 Ma (Cuéllar-Cárdenas *et al.*, 2012), while post-tectonic intrusions were emplaced nearly continuously between 90 and 45 Ma (Henry *et al.*, 2003). In the Islas Marías, two dated rims from a latest Middle Jurassic orthogneiss yielded 87 and 83 Ma ages that are interpreted as indicating the metamorphic event (Pompa-Mera *et al.*, 2013). Metamorphic rocks in these islands are intruded by 80.8-83.4 Ma (U-Pb, zircon) granites and overlain by Upper Cretaceous volcanic rocks dated at -80.6–71.6 Ma (Ar-Ar, sanidine; Pompa-Mera *et al.*, 2013).

On the basis of its age and contractional character, the earliest Late Cretaceous orogenic event in the study area can be ascribed to the collision of the Late Jurassic-Early Cretaceous Alisitos arc against western North America. Most of the authors agree that the above mentioned arc was separated from the continent by a Cretaceous ocean basin of uncertain width (*e.g.*, Busby *et al.*, 1998; Johnson *et al.*, 1999; Wetmore *et al.*, 2003). The closure of this ocean basin began between by ~115 and 110 Ma and was completed between 108 and 105 Ma (Wetmore *et al.*, 2002; 2003; Alsleben *et al.*, 2008; Peña-Alonso *et al.*, 2015). The impingement of the Alisitos arc against the North American margin caused greenschist to lower-amphibolite facies metamorphism in the marginal rocks of both blocks (Wetmore *et al.*, 2002; Schmidt *et al.*, 2012). Such tectonic event could have spread inland the continent causing metamorphism and deformation in the study area several millions of years after collision.

Although Campa and Coney (1983) trace the limit of the Guerrero terrane through southern Sonora, in our view, irrefutable evidence of volcanic sequences similar to those of the Alisitos arc does not exist in the study area. Instead, the Triassic and Jurassic Cordilleran magmatic belts seem to extend from southern California until northern Sinaloa and possibly farther south. As a consequence of this continuity, the Mojave-Sonora Megashear may not cause the mentioned ~800 km of left-lateral displacement in Late Jurassic time as originally proposed (Campbell and Anderson, 2003; Anderson and Silver, 2005).

CONCLUSIONS

The Western Sonobari Complex is made of sedimentary rocks intruded by granitic plutons and dikes that underwent orogenic metamorphism. An extended history of magmatism is revealed by U-Pb geochronology, with five pulses encompassing from Early Triassic to Late Cretaceous, which continued until the Eocene according to previous works (Vega-Granillo *et al.*, 2013). That plutonic suite indicates that Permo-Triassic to Late Cretaceous magmatic belts of the southwestern Cordillera extend along the Peninsular Ranges batholith and northwestern Sonora at least as far as the studied region and probably farther south, offshore of the Nayarit coast (*e.g.* Ortega-Gutiérrez *et al.*, 2014. From California until Nayarit, the Permian to Lower Cretaceous plutons and their host rocks underwent a medium-grade orogenic metamorphism and deformation, which is well-constrained in the study area at ~92–90 Ma on the basis of U-Pb geochronology of zircon rims. Continued high-thermal gradients are indicated by the intrusion of numerous post-orogenic leucocratic pegmatite and aplite dikes between 83 and 80 Ma. The orogenic event occurred in a tectonic setting defined by collision-accretion of the Alisitos arc against the margin of the North America craton. In consequence, the Western Sonobari Complex is mostly related to the Mesozoic evolution of the North America Cordillera and evidence of the role of its oldest rocks in the Pangea assembly has not been found.

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SUPPLEMENTARY MATERIAL

Supplemental files S1 "Methods" and S2 "U-Pb geochronological data" can be found at the journal web site <http: //rmcg. unarm. mx/>, in the table of contents of this issue.

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