Protolith age of the Altar and Carnero complexes and Late Cretaceous–Miocene deformation in the Caborca–Altar region of northwestern Sonora, Mexico

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ABSTRACT

In the Caborca–Altar area of northwest Sonora, variably deformed and metamorphosed sedimentary and volcanic rocks crop out in a northwest-southeast–trending belt (El Batamote belt) at least 70 km long. We obtained detrital zircon U-Pb ages from two distinctive components of the belt near Altar, here termed the Altar complex and Carnero complex. Zircon ages for metasandstone and metaconglomerate matrix from the Altar complex indicate a Late Cretaceous maximum age of sedimentation, with at least part of the complex no older than 77.5 ± 2.5 (2σ). Pre-Cretaceous detrital zircons in the complex were derived largely from local sources, including Proterozoic basement, the Neoproterozoic–Cambrian miogeocline and the Jurassic arc. The detrital zircon ages and lithologic character of the Altar complex suggest correlation with the Escalante Formation, the uppermost unit of the Upper Cretaceous El Chanate Group. In contrast, one sample from the Carnero complex yielded a Middle Jurassic maximum depositional age and a detrital zircon age distribution like that of the Jurassic eolianites of the North American Cordillera. The Carnero complex may correlate with the Middle Jurassic Rancho San Martín Formation but could also be a metamorphosed equivalent of the Upper Jurassic Cucurpe Formation, Upper Jurassic to Lower Cretaceous Bisbee Group, or El Chanate Group derived by recycling of Jurassic erg sandstones. The Late Cretaceous age for the Altar complex protolith contradicts models that relate deposition of the entire El Batamote protolith to a basin formed by oblique slip along the Late Jurassic Mojave-Sonora megashear. Instead, the belt is best explained as an assemblage of Middle Jurassic to Upper Cretaceous formations deformed and locally metamorphosed beneath a northeast-directed Laramide thrust complex. Potassium-argon and $^{40}Ar/^{39}Ar$ ages confirm previous inferences that deformation of El Batamote belt occurred between the Late Cretaceous and late Eocene. A second phase of deformation, involving low-angle normal faults, occurred during and/or after intrusion of the ~22-21 Ma Rancho Herradura granodiorite.

Key words: Altar complex; Carnero complex; El Batamote belt; El Chanate Group; Mojave-Sonora megashear; Laramide orogeny.

RESUMEN

En el área de Caborca-Altar, noroeste de Sonora, aflora una franja orientada noroeste-sureste de, cuando menos, 70 km de longitud, a la que se ha denominado franja El Batamote; esta franja está constituida por rocas sedimentarias e ígneas deformadas y metamorfizadas en grados muy variables. Obtuvimos edades de U-Pb de circones detríticos de dos componentes distintivos de la franja cercana a Altar que denominaremos complejo Altar y complejo Carnero. Edades obtenidas de circones de metareniscas y de la matriz de metaconglomerados del complejo Altar indican una edad máxima de sedimentación del Cretácico Tardío; al menos una parte del complejo no es mayor que 77.5 ± 2.5 (2σ). Circones pre-cretácicos del complejo se derivaron de fuentes locales, incluyendo el basamento proterozoico, el miogeoclinal neoproterozoico-cámbrico y el arco jurásico. Las edades de los circones detríticos y el carácter litológico del complejo Altar sugieren una correlación con la Formación Escalante, la unidad superior del Grupo El Chanate del Cretácico Tardío. En contraste, una muestra del complejo Carnero aportó circones que indican una edad máxima de depósito del Jurásico Medio y una distribución de edades semejante a las de las eolianitas jurásicas de la provincia Cordillerana de Norteamérica. El complejo Carnero puede correlacionarse con la Formación Rancho San Martín del Jurásico Tardío, pero podría ser también un equivalente metamórfico del Grupo Bisbee del Jurásico Tardío-Cretácico Temprano, o del Grupo El Chanate, derivados del reciclado de las areniscas de ergs jurásicos. La edad Cretácico Tardío del protolito del complejo Altar contradice los modelos que relacionan

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el depósito de todo el protolito de la franja El Batamote en una cuenca formada por deslizamiento oblicuo a lo largo de la megacizalla Mojave-Sonora del Jurásico Tardío. En su lugar, la franja se explica mejor como un conjunto de formaciones del Jurásico Medio al Cretácico Superior deformadas y localmente metamorfoseadas debajo de un complejo cabalgante laramídico dirigido hacia el noreste. Edades de potasio-argón y de ^{40}Ar/^{39}Ar confirman inferencias previas de que la deformación de la franja El Batamote ocurrió entre el Cretácico Tardío y el Eoceno tardío. Una segunda fase de deformación, que implicó fallas normales de bajo ángulo, ocurrió durante o después de la intrusión de la granodiorita del Rancho Herradura de ~22–21 Ma.

Palabras clave: complejo Altar; complejo Carnero; franja El Batamote; Grupo El Chanate; megacizalla Mojave-Sonora; orogenia laramídica.

INTRODUCTION

The ranges north and east of Caborca and Altar in northern Sonora expose a narrow, northwest-southeast–trending belt of deformed and locally metamorphosed rocks at least 70 km long, and possibly over 100 km in length, here termed "El Batamote belt" (Figure 1; Damon *et al.*, 1962; Hayama *et al.*, 1984; Jacques-Ayala *et al.*, 1990, 2009; García y Barragán, 1992; Nourse, 1995, 2001; García y Barragán *et al.*, 1998; Jacques-Ayala, 1999; García y Barragán and Jacques-Ayala, 2010). These rocks have also been referred to as "El Batamote Structural Complex" and "Altar Formation"; however, "El Batamote belt" provides better consistency with other terminology that we introduce below. El Batamote belt was derived from a protolith rich in sandstone and conglomerate with minor shale, limestone and volcanic rocks. Distinctive attributes of the belt include southwest-dipping axial-plane cleavage, stretched pebbles in the conglomerates, northeast-verging folds and local greenschist-facies metamorphism. Rocks assigned to El Batamote belt crop out from the Altar area in the southeast to Cerro Basura and Sierra La Gloria in the northwest. Potentially equivalent rocks have been mapped in ranges even farther northwest. The belt is flanked on the southwest by Proterozoic crystalline rocks and the Neoproterozoic–Cambrian miogeoclinal assemblages of the Caborca block (Jacques-Ayala *et al.*, 1990; Anderson and Silver, 2005; Molina-Garza and Iriondo, 2007). Dominant rocks exposed directly

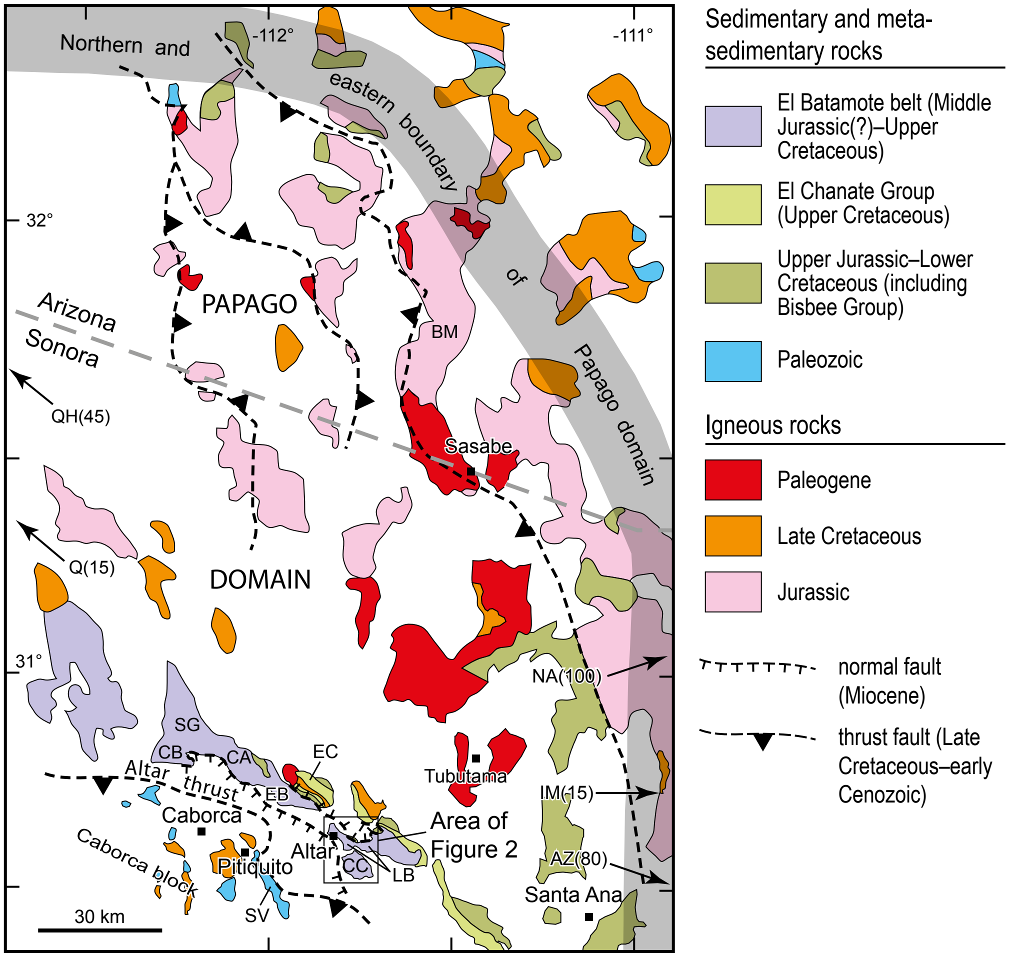

Figure 1. Generalized geologic map of north-central Sonora and south-central Arizona after Haxel *et al.* (2008) with modifications based on Jacques-Ayala (1999), Terán-Martínez (1999), Nourse (2001), Castro-Escárcega (2002a, 2002b) and García-Cortez (2002). Labeled areas denote regions of sedimentary rocks deformed, and in many cases also metamorphosed, during the Late Cretaceous–early Cenozoic Laramide orogeny, including the Baboquivari Mountains (BM), Cerro Basura (CB), Cerro Carnero (CC), Cerro El Alamo (CA), Cerros La Batellera (LB), Sierra El Batamote (EB); Sierra El Chanate (EC), Sierra La Gloria (SG), Sierra La Víbora (SV). Arrows show approximate distances in kilometers (from the tip of the arrow) to additional locations of Laramide tectonism outside the map area: Arizpe (AZ), Imuris (IM), Naco (NA), Quitovac (Q), Quitobaquito Hills (QH).

northeast of the belt include the Upper Jurassic–Lower Cretaceous Bisbee Group and Upper Cretaceous El Chanate Group (Jacques-Ayala *et al*., 1990; García y Barragán, 1992; Jacques-Ayala, 1993, 1995, 1999; García y Barragán *et al.* 1998; Nourse, 2001) (we use the geologic time scale of Walker *et al*., 2018). El Batamote belt lies at the southern end of the Papago domain, a region characterized by almost complete absence of exposures of Precambrian basement (Figure 1; Haxel *et al*., 1980, 1984). Proterozoic rocks, however, are inferred to be present at depth within the Papago domain and to be part of the Mazatzal basement province (Iriondo *et al*., 2004; Anderson *et al*., 2005; Haxel *et al*., 2008).

Most workers consider that deformation and metamorphism of El Batamote belt occurred during northeast-southwest–directed compression associated with the Late Cretaceous to Paleogene Laramide orogeny (Damon *et al*., 1962; Hayama *et al*., 1984; Jacques-Ayala *et al*., 1990, 2009; Jacques-Ayala and DeJong, 1996; García y Barragán *et al*., 1998; Nourse, 2001; Nourse *et al*., 2007). The structural style resembles that observed in areas of Laramide tectonism throughout northern Sonora, southern Arizona and southwestern New Mexico (Haxel *et al*., 1984, 2008; Nourse, 1995; González-León *et al*., 2000, 2017; Iriondo *et al*., 2005; Clinkscales and Lawton, 2015). The timing of the event in El Batamote belt is only loosely constrained. At least part of the deformation postdates the 72 Ma El Charro volcanic complex, which is folded within the center of the range-scale El Chanate syncline (Jacques-Ayala 1993, 1999; Nourse, 2001). The event was probably largely over by the late Paleocene or early Eocene, as indicated by a biotite K-Ar cooling age of 58 ± 3 Ma from the Altar complex east of Altar (Damon *et al*., 1962) and extrusion of the postkinematic San Jacinto volcanics at 51 ± 2 Ma (Jacques-Ayala, 1999, 2000). Laramide contraction was followed in the early Miocene by intrusion of granitoid igneous bodies and exhumation along low-angle normal faults (Nourse, 1995, 2001; Jacques-Ayala, 1999).

In contrast to the broad consensus regarding Laramide and younger history, the protolith age of El Batamote belt has long been a matter of debate. Jacques-Ayala *et al.* (1990, 2009), García y Barragán *et al.* (1998) and Jacques-Ayala (1999, 2000) concluded that a significant fraction of the protolith was Upper Cretaceous; *i.e.* younger than the Bisbee Group and either correlative with or younger than El Chanate Group. In their view, the Upper Cretaceous component of the protolith represents, at least in part, a synorogenic succession deposited in front of, and eventually overridden by, a Laramide thrust complex. The proposed thrust faults, however, have not been definitively identified; they may be buried beneath younger deposits and/or have been excised by middle Cenozoic extensional faults. Alternatively, Nourse (1995; 2001) and Anderson and Nourse (2005) considered that the protolith of El Batamote belt was entirely Upper Jurassic to Lower Cretaceous and correlative with the Glance Conglomerate, the lowest formation of the Bisbee Group. Nourse (1995; 2001) and Anderson and Nourse (2005) further argued that the elongate geometry of El Batamote belt was inherited from deposition in a narrow transtensional (pull-apart) basin adjacent to the inferred Late Jurassic Mojave-Sonora megashear. As such, their proposed Late Jurassic–Early Cretaceous protolith age for the complex represents a primary line of evidence for the megashear in the Caborca–Altar area.

The debate regarding the protolith age of El Batamote belt has added significant uncertainty to both local and regional tectonic syntheses. Recent studies, however, shed new light on this controversy and suggest that the belt was assembled from multiple supracrustal units of various ages (García y Barragán and Jacques-Ayala, 2010). For example, detrital zircon U-Pb ages from El Batamote belt east of Altar, described in preliminary form by Barth *et al.* (2008), confirm that part of the protolith is Upper Cretaceous. On the other hand, Mauel (2008) obtained a latest Middle Jurassic zircon U-Pb age (164 ± 1 Ma) from a siliceous tuff (?) within the belt northwest of Altar, between Sierra El Batamote and Sierra El Chanate. In addition, Mauel *et al.* (2011) noted strong lithologic similarity between a phyllite near Altar and the Upper Jurassic Cucurpe Formation located ~100 km southeast of Altar. Here, we investigate the origin of El Batamote belt based on detailed examination of the detrital zircon results of Barth *et al.* (2008). This dataset includes samples from two components of El Batamote belt (Altar complex and Carnero complex, defined below). In addition to detrital zircon ages, we present several new ^{40}Ar/^{39}Ar ages for the Altar complex, as well as a U-Pb zircon crystallization age for a Miocene granodiorite that intruded the Carnero complex. The ^{40}Ar/^{39}Ar ages and granodiorite age help to constrain the Cenozoic history of the area, including the timing of Miocene low-angle normal faulting.

GEOLOGIC SETTING AND PREVIOUS WORK

We collected samples from Cerro San Judas northeast of Altar; Cerros La Batellera, southeast of Altar and northeast of Highway 2; and Cerro El Amol and Cerro Carnero, southeast of Altar and southwest of Highway 2 (Figure 2). The rocks underlying these areas have commonly been referred to collectively as the Altar Schist, Altar Massif or Altar Formation (Cooper and Arellano, 1946; Damon *et al*., 1962; Hayama *et al*., 1984; García y Barragán *et al*., 1998). However, lithologic differences between the rocks northeast and southwest of Highway 2 have led others to propose that they are separate units (Jacques-Ayala *et al*., 1990), a conclusion reinforced by our detrital zircon results. Specifically, the rocks of Cerros La Batellera and Cerro San Judas were derived at least partly from an Upper Cretaceous protolith likely correlative with El Chanate Group. In contrast, the protolith of the rocks at Cerro Carnero and Cerro El Amol is likely, although not unequivocally, Jurassic. Based on these differences, we divided the rocks of these two areas into the (informal) Altar complex and Carnero complex, which we tentatively infer to be separated by a buried thrust fault (Figure 2). Both are subunits of El Batamote belt (previously known as "El Batamote structural complex" but here renamed to avoid using "complex" at two different hierarchical levels).

Altar complex at Cerros La Batellera

The Altar complex at Cerros La Batellera and Cerro San Judas (to be referred to collectively as "Cerros La Batellera") is part of a ~2–3-km-thick sequence derived from sandstone, conglomerate and rare limestone (García y Barragán, 1992; Jacques-Ayala *et al*., 1990; García y Barragán *et al*., 1998). The rocks exhibit southwest-dipping foliation (generally bedding-parallel) and southwest-plunging lineation. Clasts in the conglomerate are stretched to varying degrees dependent on strength relative to the matrix (Figure 3a). Metamorphic grade decreases from greenschist facies in the west to incipiently recrystallized in the east. Intensity of deformation also decreases from west to east. The boundary between the more- and less-highly-deformed and metamorphosed parts of the complex is gradational, but, for simplicity, is depicted as a discrete contact in Figure 2.

East of the map area, the lesser-deformed/metamorphosed portion of the Altar complex is in contact with rocks interpreted as El Chanate Group, although the stratigraphy does not match in detail with that of the type El Chanate Group of the Sierra El Chanate (García y Barragán *et al*., 1998). This contact has been interpreted as either depositional or a thrust fault (Jacques-Ayala *et al*., 1990; García y Barragán *et al*., 1998; Nourse, 2001). The fault interpretation appears most plausible considering the evidence presented here that the Altar complex is a metamorphosed and deformed equivalent of El Chanate Group (see

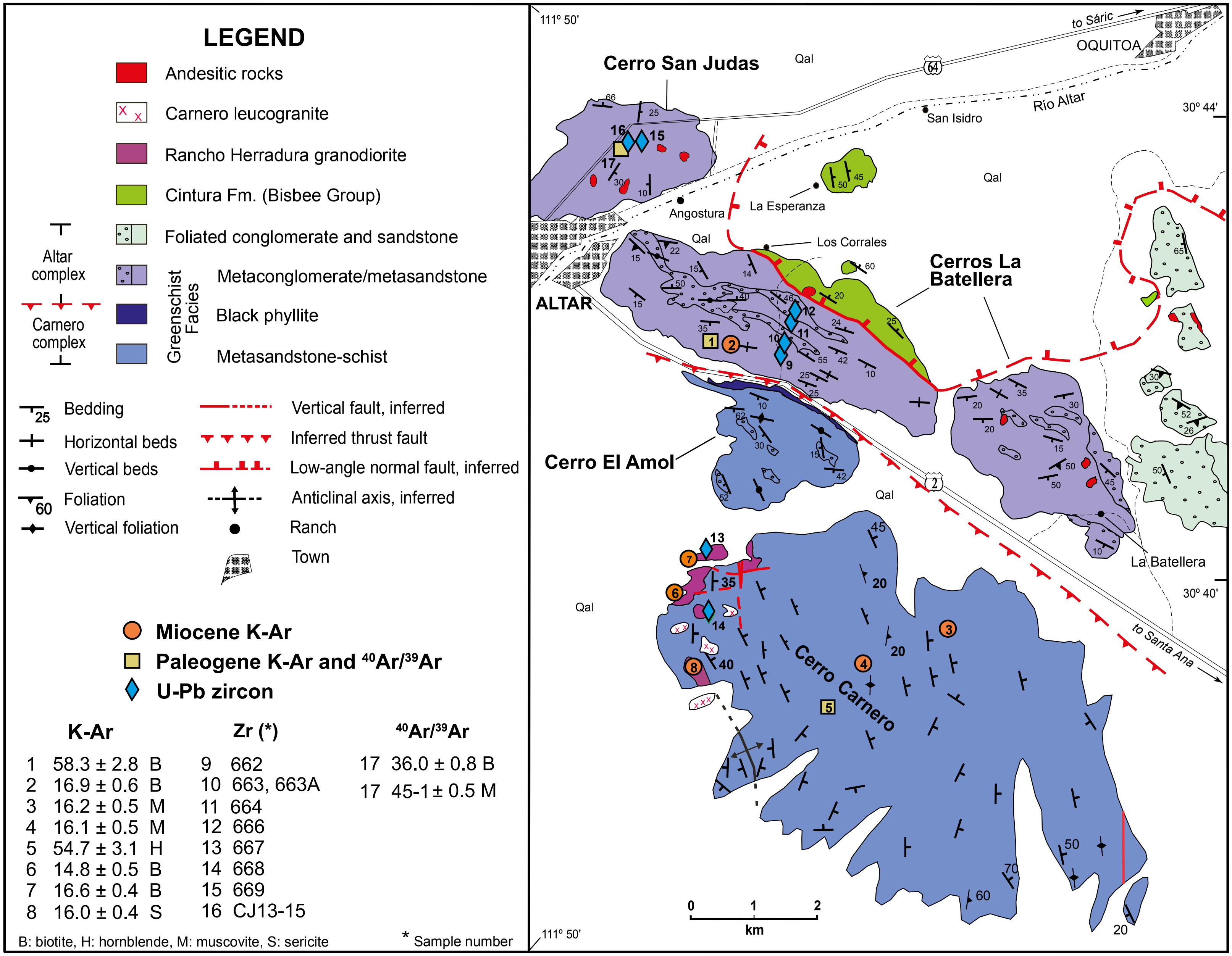

Figure 2. Geologic map of the study area (modified after García y Barragán, 1992). Numbered circles, squares and diamonds on the map show locations of K-Ar samples from Damon *et al.* (1962) and Hayama *et al.* (1984) and $^{40}Ar/^{39}Ar$ and detrital zircon samples from this study. The legend shows the ages and errors (2σ) for the K-Ar and $^{40}Ar/^{39}Ar$ ages and sample numbers for the zircon samples. Note that some previous publications have applied the name "Cerros El Amol" to hills northeast of Highway 2 and east of Cerros La Batellera. In contrast, we follow INEGI (2001) in applying the name "Cerro El Amol" to the small set of hills 3–5 km southeast of Altar.

also Barth *et al*., 2008; Jacques-Ayala *et al*., 2009). Even farther east, El Chanate Group is in depositional contact with the Bisbee Group. Rocks of the Bisbee Group are also exposed to the north of Cerros La Batellera in the upper plate of a low-angle normal fault of inferred Miocene age.

Carnero complex at Cerro Carnero

The Carnero complex of Cerro Carnero and Cerro El Amol (to be referred to collectively as "Cerro Carnero") was derived from sandstone and minor conglomerate, mudstone and limestone. The rocks exhibit a well-developed east- to northeast-dipping foliation and east-trending lineation (Figures 2 and 3b) (Damon *et al*., 1962; Hayama *et al*., 1984; Jacques-Ayala *et al*., 1990; García y Barragán *et al*., 1998). A thin band of black phyllite is present at the north end of the Carnero complex. Mauel *et al*. (2011) suggested that the phyllite was derived from marine deposits correlative with the Upper Jurassic Cucurpe Formation. A Jurassic age for the protolith of the Carnero complex is consistent with the detrital zircon results described below.

The Carnero complex is intruded by the Rancho Herradura granodiorite (Figure 3c) and the Carnero leucogranite. The granodiorite is foliated and exhibits a gently west-plunging lineation parallel to lineation in the metasedimentary rocks. Asymmetric ("S-C") fabrics record top-west extension.

Thermal history

The cooling and exhumation history of the area is constrained by a limited number of K-Ar ages. Damon *et al*. (1962) reported a biotite K-Ar age of 58 ± 3 Ma from the Altar complex of Cerros La Batellera 2 km southeast of Altar, whereas Hayama *et al*. (1984) obtained a significantly younger biotite K-Ar age of 16.9 ± 0.6 Ma nearby (Figure 2). For Cerro Carnero, Hayama *et al*. (1984) reported K-Ar ages for the metasedimentary rocks of 55 ± 3 Ma for hornblende and 16.2 ± 0.5 Ma and 16.1 ± 0.5 Ma for muscovite. These workers also obtained biotite K-Ar ages of 14.8 ± 0.5 Ma and 16.6 ± 0.4 Ma for the Rancho Herradura granodiorite and a K-Ar age for fine-grained white mica (sericite) of 16 ± 0.4 Ma for the Carnero leucogranite. We consider that the Paleogene K-Ar ages reflect cooling following Laramide underthrusting of the protoliths. Thermal resetting during Laramide magmatism is also possible, although we deem this option less likely, as no Laramide plutons are exposed near the dated localities. The ~17–15 Ma ages presumably reflect a second phase of cooling associated with detachment faulting and/or conductive cooling following intrusion of the Rancho Herradura granodiorite and Carnero leucogranite.

ANALYTICAL METHODS

Zircon U-Pb analyses

We analyzed eight samples for detrital zircon, seven from the Altar complex and one from the Carnero complex (Figure 2; see Table A1 of the Electronic Supplement for coordinates of all sample localities). The Altar samples include five of metasandstone (662, 664, 666, 669 and CJ13-15), the (metamorphosed) sand matrix of a metaconglomerate (663) and a quartzite clast from the metaconglomerate (663A). The Carnero sample is a metasandstone (668).

Figure 3. (a) Metaconglomerate within Altar complex at Cerros La Batellera. Site of sample 663. (b) Carnero complex at Cerro Carnero. Site of sample 668. (c) Granodiorite of Ranch Herradura at Cerro Carnero. Site of sample 667.

All detrital samples except CJ13-15 were collected and processed during an early phase of the study. We crushed approximately 1 kg of each sample using a jaw crusher and disc mill. For the metaconglomerate clast, only fragments from the interior were used to avoid matrix material adhering to the outer surface. The crushed material was sieved and ~50 ml volumetrically of the fraction finer than 150 µm was processed in heavy liquids (tetrabromoethane followed by methylene iodide) after removing iron filings with a magnet. The final sink was further cleaned with a Frantz® magnetic separator. We obtained a few hundred or more zircon grains for all samples except sample 669, which yielded relatively few grains, most of which were quite small. As a result, we were able to obtain only five ages from this sample.

Polished epoxy mounts of the above samples were analyzed at the Arizona Laserchron Center, University of Arizona, using a 193-nm excimer laser and a GVI Isoprobe multicollector-inductively coupled plasma-mass spectrometer (MC-ICP-MS) following the procedures of Gehrels *et al.* (2008). The ions ^{206}Pb, ^{207}Pb, ^{208}Pb, ^{232}Th and ^{238}U were measured with Faraday collectors. A channeltron multiplier was used for ^{204}Pb. Sri Lanka zircon (SL2; 563.5 Ma ± 3.2 Ma 2σ) was used as the primary standard (Gehrels *et al.*, 2008). Common lead was corrected using the ^{204}Pb method. For unknowns, we targeted grain interiors to minimize the effects of lead loss during metamorphism. We avoided visible inclusions and fractures, but otherwise selected grains randomly, without using cathodoluminescence (CL) imagery. Analytical results are presented in Table A2 of the Electronic Supplement.

We use the ^{206}Pb/^{238}U age for grains younger than 800 Ma and the ^{207}Pb/^{206}Pb age for grains with ^{206}Pb/^{238}U ages >800 Ma. Discordance is relatively minor among the analyses with ^{206}Pb/^{238}U ages > 800 Ma. For this age group, maximum normal discordance is 25%, with a median of 3%; the maximum reverse discordance is 3%, with a median of 1%. None of these ages were excluded. For ages <800 Ma, particularly Mesozoic ages, evaluation of discordance can be problematic owing to potential large errors associated with ^{207}Pb/^{235}U ages obtained by ICP-MS analysis. For these analyses, we evaluated discordance individually for each result in the context of its analytical errors.

Because of the low yield from sample 669, we later collected and processed a second sample (CJ13-15) from the same location (Cerro San Judas, near the shrine to Saint Jude; Figure 2). The sample was crushed in the laboratory and heavy minerals were separated using a Wilfley table and a Frantz® magnetic separator. Zircon grains were extracted from the residual non-magnetic fraction, randomly selected under a binocular microscope, mounted in epoxy resin and polished. Intra-grain compositional zoning was identified by CL. Twenty-two zircons were analyzed using a Resonetics Resolution M050 excimer laser workstation coupled to a Thermo ICapQc ICP-MS at the Laboratorio de Estudios Isotópicos (LEI), Centro de Geociencias, Universidad Nacional Autónoma de México, following the methodology reported in Solari *et al.* (2010). Analytical results are presented in Table A3 of the Electronic Supplement.

Zircon from the Rancho Herradura granodiorite from Cerro Carnero was extracted during processing of the initial set of detrital samples. Grains were mounted in epoxy and polished prior to examination using CL. The CL images were used to guide selection of analysis points in zoned zircon grains. Uranium and Pb concentrations and isotopic ratios were measured on the SHRIMP-RG ion microprobe at Stanford University using analytical and data analysis procedures described in Barth and Wooden (2006). Isotopic ratios were standardized against Braintree Complex zircon R33 (419 Ma; Black *et al.*, 2004). Analytical results are presented in Table A4 of the Electronic Supplement.

^{40}Ar/^{39}Ar analyses

Material generated during crushing of sample CJ13-15 for zircon was used to obtain separates of muscovite, biotite and plagioclase for ^{40}Ar/^{39}Ar analysis. The separates were irradiated at the University of McMaster reactor. Analyses were performed at Queen's University, Canada. Step heating was conducted using a Merchantek MIR 10-30 CO_2 laser. A facetted lens was used to diffuse the beam over 3 mm pits. Ions were measured using an MAP-216 mass spectrometer. The J values and errors for samples were determined by polynomial fit to replicate analyses of a flux monitor (biotite GA1550, 98.5 Ma) at measured positions along the length of the irradiation capsule. Analytical results results are presented in Tables A5-A7 of the Electronic Supplement.

We report sample ages as total gas ages. In our view, these provide the best estimate for the time of bulk closure of argon diffusion (Jacobson *et al.*, 2002).

RESULTS

Detrital zircon ages

Cerros La Batellera

Probability density plots and cumulative probability plots for the individual samples of the Altar complex from Cerros La Batellera are shown in Figure 4. A plot of the combined age results for the metasandstone and metaconglomerate matrix samples is presented in Figure 5a.

Detrital zircon ages for the metasandstone and metaconglomerate matrix samples from Cerros La Batellera range from Archean (2708 Ma) to latest Cretaceous (72 Ma) (Figures 4a–4f and 5a). Five of the six samples include zircon of latest Early Cretaceous and/or Late Cretaceous age. Two samples include zircon as young as Campanian, five grains with ages of 81–72 Ma in sample 662 and one grain with an age of 77 Ma in sample 663. A weighted mean calculation using Isoplot (Ludwig, 2003) suggests that the six latest Cretaceous grains could all be part of a single population with an average age of 77.5 ± 2.5 Ma (Figure 6). Alternatively, averaging only the three youngest grains (*e.g.*, Dickinson and Gehrels, 2009a) yields a statistically-equivalent weighted mean age of 76.5 ± 4.4 Ma. We take the average of the six grains as the more conservative estimate of the maximum depositional age for the Cerros La Batellera samples.

Grains younger than 285 Ma comprise 72% of the total for the metasandstone and conglomerate matrix samples and are inferred to be derived from Cordilleran magmatic arcs (*cf.* Dickinson and Gehrels, 2009b; González-León *et al.*, 2009, 2017; Mauel *et al.*, 2011; Peryam *et al.*, 2012; Lawton and Molina Garza, 2014):

(1) The latest Cretaceous zircon could have been derived from multiple sources in Sonora, including ranges near Cerros La Batellera (McDowell *et al.*, 2001; Iriondo *et al.*, 2005; Jacques-Ayala *et al.*, 2009; Roldán-Quintana *et al.*, 2009; González-León *et al.*, 2011, 2017; Ortega-Gutiérrez *et al.*, 2014).

(2) Grains of late Early and early Late Cretaceous age (~120–90 Ma) comprise ~10% of the total zircon population. Igneous rocks of this age are not abundant in Sonora, although the oldest zircons in this group are compatible with a derivation from volcanic rocks within the Aptian–Albian Arroyo Sásabe Formation (Jacques-Ayala *et al.*, 1990; Jacques-Ayala, 1995). Alternatively, late Early and early Late Cretaceous igneous rocks are widespread within the Alisitos and Peninsular Ranges arcs of Baja California, which would have been adjacent to western Sonora prior to opening of the Gulf of California (Wetmore *et al.*, 2003; Busby *et al.*, 2006; Jacques-Ayala *et al.*, 2009; Peryam *et al.*, 2012; Kimbrough *et al.*, 2015). Peryam *et al.* (2012) presented evidence for a fluvial connection between the Late Jurassic–Early Cretaceous Guerrero and Alisitos arcs of Baja California and the Cucurpe area of Sonora during deposition of the Bisbee Group. This drainage system could have remained active into the Late Cretaceous.

(3) Jurassic grains are the most abundant of the arc-derived grains, consistent with the widespread presence of Jurassic igneous rocks in northwest and northcentral Sonora (Figure 1; Nourse, 2001; Anderson *et al.*, 2005; Leggett, 2009).

(4) Four of the six samples include minor Permian–Triassic peaks. Permian–Triassic plutons have been described from northwest Sonora and may be more common than previously recognized (Arvizu *et al.*, 2009; González-León *et al.*, 2009; Arvizu and Iriondo, 2015; Riggs *et al.*, 2016).

Most pre-Permian ("pre-arc") zircon ages in the above samples fall within three age peaks centered near 1.7, 1.4 and 1.1 Ga, the first being the most prominent (Figures 4a–4f and 5a). Igneous and metamorphic complexes with ages of ~1.7 and ~1.4 Ga are widespread in the southwestern United States (U.S.) and Sonora (Barth *et al.*,

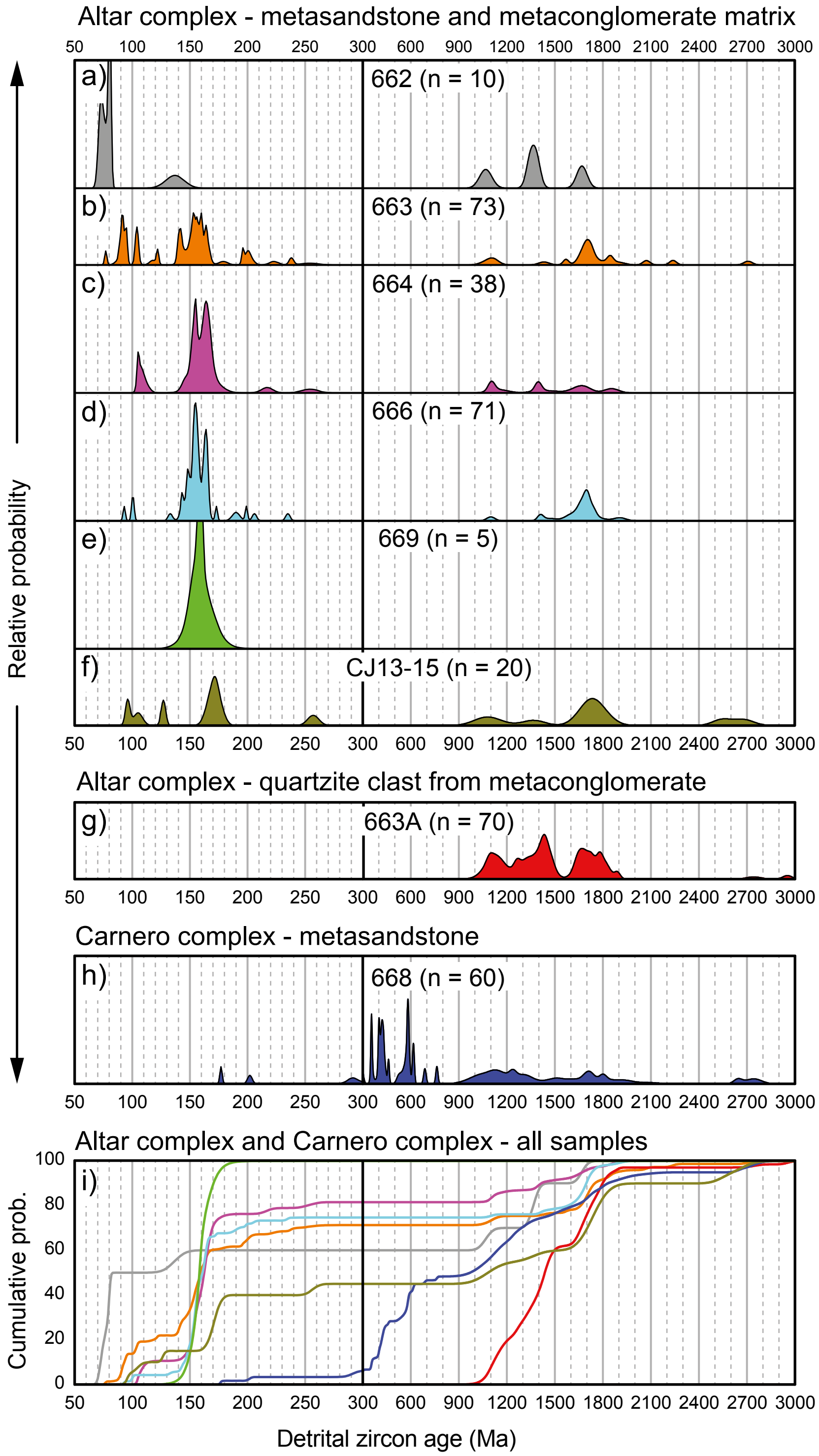

Figure 4. Relative and cumulative probability plots of detrital zircon ages from the Altar complex at Cerros La Batellera and the Carnero complex at Cerro Carnero. All samples are metasandstone, except sample 663, which is from the sand matrix of a metaconglomerate, and sample 663A, which is a single quartzite clast from that conglomerate. Note age-axis scale break at 300 Ma. For relative probability plots, vertical scales differ to left and right of the age-axis scale break such that equal area represents equal probability throughout the graph. Line color in the cumulative probability plot corresponds to the fill color in relative probability plots. Location of samples shown in Figure 2. n: number of analyses.

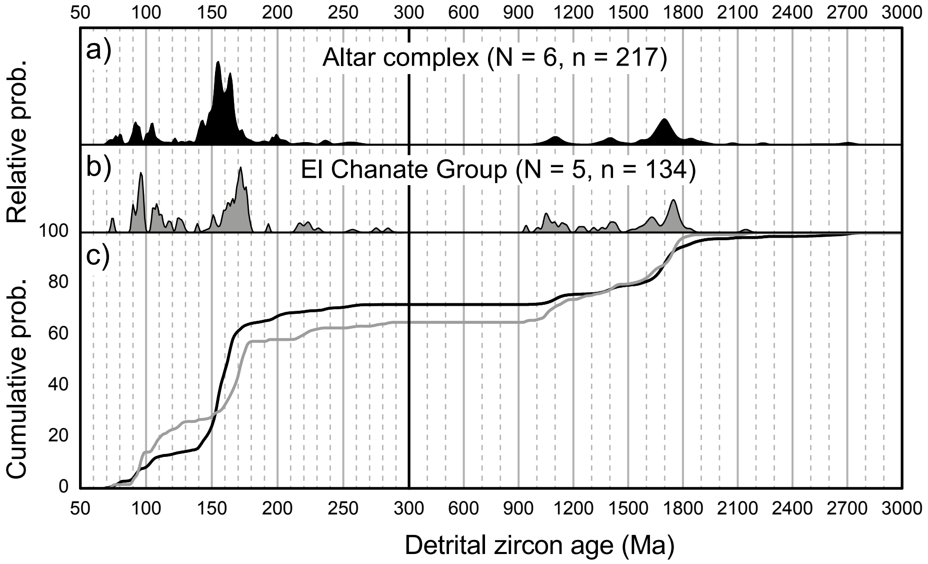

Figure 5. Composite detrital zircon age distributions for metasandstone and conglomerate matrix from the Altar complex at Cerros La Batellera (samples 662, 663, 664, 666, 669, CJ13-15) and sandstone from El Chanate Group of Sierra El Chanate (Jacques-Ayala *et al.*, 2009). Scale break and color-coding of relative versus cumulative probability plots as in Figure 4. N: number of samples, n: number of analyses.

2000, 2001a, 2001b; Anderson and Silver, 2005; Farmer *et al.*, 2005; Iriondo *et al.*, 2004; Nourse *et al.*, 2005). Those with ages of ~1.7 Ga dominate over ~1.4 Ga units, consistent with the relative sizes of these two peaks in the Altar samples. In contrast, basement rocks with ages of ~1.1 Ga are not common in the southwestern U.S. and Sonora (Iriondo *et al.*, 2004; Anderson and Silver, 2005). On the other hand, ~1.1 Ga detrital zircon is a significant component of Neoproterozoic and Cambrian cratonal and miogeoclinal quartz arenites from this part of the Cordillera (Gehrels *et al.*, 1995, 2011; Gehrels and Stewart, 1998; Stewart *et al.*, 2001; Gehrels and Pecha, 2014). Hence, we suspect that much, if not most, of the ~1.1 Ga zircon in the Altar complex of Cerros La Batellera is recycled from local miogeoclinal sequences (Figure 1). Accordingly, some of the ~1.7 and ~1.4 Ga zircon in La Batellera samples may also be recycled. However, the ratio of ~1.7 Ga to ~1.1 Ga zircon in our samples exceeds that typically found in Neoproterozoic–Cambrian sedimentary rocks. This suggests that ~1.7 Ga bedrock contributed directly to the protolith of the Altar complex. Potential source areas are present in the Caborca block immediately south of the map area of Figure 1.

Some uncertainty in the interpretation of the Cerros La Batellera section is introduced by the results from sample 669, collected from Cerro San Judas near the shrine to St. Jude. This sample differs from all the others from Cerros La Batellera in that it yielded only Jurassic ages. The dataset, however, is small—only five analyses. As noted in the analytical methods section, zircons obtained from sample 669 were smaller on average than those from the other samples. Only the larger grains could be analyzed, which may have biased the results. In addition, Cretaceous zircon is not abundant in any of the samples of Altar complex from Cerros La Batellera (Figures 4 and 5a) and could have been missed in sample 669 owing to the small number of analyses. Furthermore, Cretaceous zircon is present in sample CJ13-15 from the same locality (Figure 4f). Considering these factors, we conclude that sample 669 likely has the same Late Cretaceous depositional age as the other Cerros La Batellera samples, despite the failure to yield any zircon younger than Jurassic.

In contrast to the dominant arc sources for the sand component of the Altar complex, the 70 ages from the quartzite clast (sample 663A) are all Precambrian—68 Proterozoic (minimum age of 1060 ± 37 Ma) and two Archean (Figure 4g). The Proterozoic ages define the same three age peaks (~1.7, ~1.4 and ~1.1 Ga) as in the sands, although in more nearly equal proportions than in the latter (Figure 4g *versus* Figure 5a). The age distribution for sample 663A is typical of that for the Neoproterozoic and Cambrian sedimentary sequences from Sonora and adjacent areas (Gehrels and Stewart, 1998; Stewart *et al.*, 2001; Gehrels and Pecha, 2014). Miogeoclinal rocks of this age crop out in ranges west and south of Caborca and comprise a potential source for the quartzite clasts in the Altar complex (Figure 1). The original clasts may have been quartz arenite that was converted to quartzite during Laramide deformation and metamorphism.

Lithologic and map relations led Jacques-Ayala *et al.* (1990), García y Barragán *et al.* (1998) and Jacques-Ayala (1999) to conclude that the protolith of the Altar complex at Cerros La Batellera was either correlative with El Chanate Group or deposited above it. Comparison of composite age distributions for the Altar complex at Cerros La Batellera (this study) and El Chanate Group of the Sierra El Chanate (Jacques-Ayala *et al.*, 2009) favors the former (Figure 5). This conclusion is somewhat speculative, because application of the Kolmogorov-Smirnoff (K-S) test to the two groups yields a P value of 0.005, which implies that the two groups were not derived from the same source

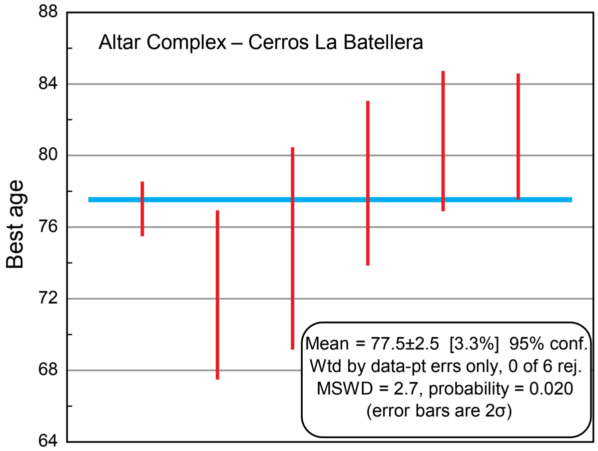

Figure 6. Weighted mean plot of six youngest zircon ages from the Altar complex of Cerros La Batellera. Diagram constructed using Isoplot Version 3.75 (Ludwig, 2003).

(*cf*. Dickinson and Gehrels, 2009b). Nonetheless, we note multiple similarities between the two datasets: (1) Dominance of Jurassic zircon in each, albeit skewed to older ages in El Chanate Group. (2) Similar proportions of ~1.7, ~1.4 and ~1.1 Ga populations. (3) Comparable small numbers of Permian–Triassic zircons. (4) Similar distribution of Cretaceous ages, including similar youngest ages (~75 Ma in both groups). These relations lead us to conclude that the protoliths of the Altar complex of Cerros La Batellera and El Chanate Group are correlatives, despite the negative K-S result. We suggest that the low P value derives from the small sample sizes, minor local variation in source area and/or systematic analytical differences between the Altar complex ages, which were obtained by ICP-MS methods, and El Chanate results, which were determined by ion microprobe. Further work is needed to resolve this issue.

Based on the high abundance of quartzite clasts, Jacques-Ayala (1999) and Jacques-Ayala *et al*. (2009) proposed that the Altar complex at Cerros La Batellera correlates with the Pozo Duro Formation, the oldest unit of El Chanate Group. Alternatively, the 77.5 ± 2.5 Ma maximum depositional age of the Cerros La Batellera samples may indicate a correlation with the Escalante Formation, the youngest part of El Chanate Group. The Escalante Formation has a maximum depositional age of 75 ± 2 Ma based on two zircon ages derived from the upper part of the formation (Jacques-Ayala *et al*. (2009). Correlation of the Altar complex of Cerros La Batellera with the Escalante Formation has also been proposed by González-León *et al*. (2017). Nonetheless, the maximum depositional ages of both the Altar and El Chanate samples are not well constrained, as most of the detrital zircon ages are pre-Late Cretaceous (Figure 5). In other words, even those samples that have so far failed to yield zircon younger than late Early or early Late Cretaceous could, in fact, have Campanian depositional ages. This ambiguity reinforces the need for additional analyses.

Cerro Carnero

We determined detrital zircon ages for one sample of metasandstone from the Carnero complex (sample 668; Figure 4h). In contrast to the samples from the Altar complex, the Carnero sample includes little arc-derived zircon. Another distinctive aspect of the Carnero sample is the high fraction of Grenville-age zircon (1310–912 age group of Dickinson *et al*., 2012) relative to the ~1.7 and ~1.4 Ga peaks. In addition, the Carnero sample includes abundant Neoproterozoic (~600 Ma) and Paleozoic (~400 Ma) zircon, age groups not observed in the samples of Altar complex.

The strong Grenville, Neoproterozoic and Paleozoic components of the Carnero sample suggest affinities with the Jurassic eolian (erg) sandstones of the Colorado Plateau, U.S. (Figure 7b; Dickinson and Gehrels, 2009b). Erg-type sands have been documented in Sonora; *e.g*. in the Middle Jurassic Rancho San Martín Formation near Cucurpe (Leggett, 2009; Mauel *et al*., 2011). The Rancho San Martín Formation and our sample of Carnero complex exhibit similar detrital zircon age spectra, including similar maximum depositional ages (~180–170 Ma) (Figures 7a and 7c; Leggett, 2009; Mauel *et al*., 2011). In detail, the Carnero complex and Rancho San Martín Formation display some con-

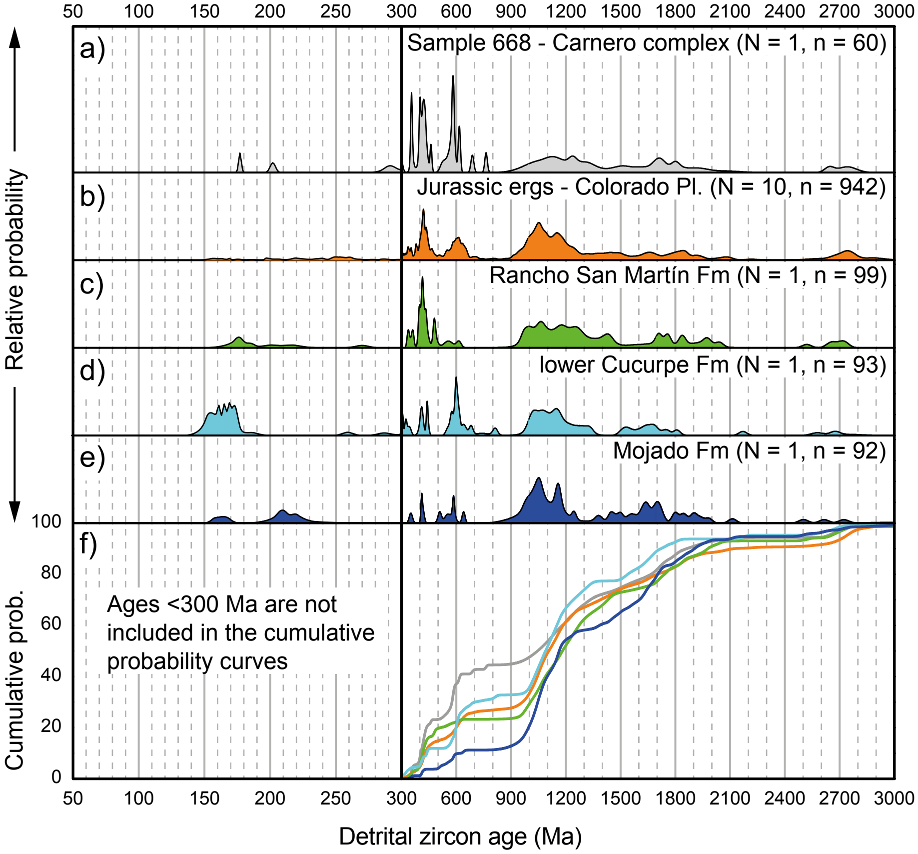

Figure 7. Comparison of detrital zircon age results from the Carnero complex of Cerro Carnero (sample 668 of Figure 4) with selected Jurassic and Cretaceous formations in Sonora and the southwestern U.S. exhibiting an erg-type detrital zircon signature (*cf.* Dickinson and Gehrels, 2009b). Data sources: (a) this study; (b) Dickinson and Gehrels (2009b); (c) Leggett (2009); (d) Mauel *et al.* (2011); (e) Clinkscales and Lawton (2015). Scale break and color-coding of relative versus cumulative probability plots as in Figure 4. N: number of samples, n: number of zircon ages.

trasts, such as fewer Neoproterozoic grains in the latter. However, variability of this scale is typical within the Jurassic eolianites (Dickinson and Gehrels, 2009b).

The zircon age results for the Carnero sample are consistent with a Middle Jurassic protolith age, but do not rule out a younger age. For example, the basal part of the Upper Jurassic Cucurpe Formation of the Cucurpe area exhibits a strong erg signature, attributed to reworking of eolianite layers in the underlying Rancho San Martín Formation (Figure 7d; Mauel *et al.*, 2011). The basal Cucurpe Formation also includes Late Jurassic zircon, confirming its young age relative to the Rancho San Martín Formation. However, the Late Jurassic zircon is thought to be locally derived (Mauel *et al.*, 2011), and need not be present in all parts of the Cucurpe Formation derived by recycling of eolianites sands.

A strong erg signature has also been observed in the Cintura Formation of the Bisbee Group in southern Arizona, U.S. (Dickinson *et al.*, 2009) and in the Mojado Formation, a correlative of the Cintura Formation in southwestern New Mexico, U.S., (Clinkscales and Lawton, 2015). The Mojado example is particularly instructive. Clinkscales and Lawton (2015) obtained 92 zircon ages for one sample of the Mojado Formation. The pre-Permian grains exhibit an age distribution remarkably like that of the Colorado Plateau Jurassic ergs (Figures 7b and 7e). The Mojado sample also includes a modest number of Triassic and Jurassic arc-derived grains. However, none of the ages are younger than early Late Jurassic, despite the well-constrained Albian depositional age.

Erg-style detrital zircon age patterns have also been found locally in Upper Cretaceous strata in Sonora (Jacques-Ayala and Garcia y Barragán, 2018). Nonetheless, most Upper Cretaceous sandstones from Sonora that have been analyzed for detrital zircon include only minor numbers of erg-derived grains (Jacques-Ayala *et al.*, 2009; González-León *et al.*, 2017; this study).

In summary, correlation of the Carnero sample with the Middle Jurassic Rancho San Martín Formation is the most straightforward interpretation, although correlation with the Cucurpe Formation, Bisbee Group or even El Chanate Group is also permissible, with the last option least likely.

Rancho Herradura Granodiorite

Zircon grains extracted from the Rancho Herradura granodiorite (Sample 667) are euhedral to subhedral prismatic and up to 200 microns long. About half the grains contain recognizable cores. We analyzed nine grains. Seven yielded Miocene ages, which we interpret as synmagmatic. Two older ages (56 and 946 Ma) are considered premagmatic. The ^{206}Pb/^{238}U ages for the synmagmatic zircons range from 23 to 19 Ma and form an array along concordia on a Tera-Wasserburg diagram (Figure 8). We interpret this age range to indicate varying degrees of lead loss, perhaps associated with extensional deformation of the granodiorite. The four oldest grains, which presumably underwent the least lead loss, yield a mean age of 21 ± 1 Ma (95% confidence level). However, even these grains may have lost some Pb, so the true age of the granodiorite could be closer to the upper end of the range of analyses; *i.e.*, ~22 Ma. On the other hand, Nourse *et al.* (2007) inferred a zircon U-Pb age of 21.2 ± 0.2 (95% confidence level) for this same intrusion, also using the SHRIMP-RG ion microprobe at Stanford University. Considering the two datasets together, we conclude that the age of the granodiorite is ~22–21 Ma.

^{40}Ar/^{39}Ar Results

The ^{40}Ar/^{39}Ar results vary in degree of interpretability (Figure 9). The muscovite spectrum for sample CJ13-15 is the least complicated, with a profile indicative of Ar loss in the low-temperature steps leading to a moderately well-developed plateau for the high-temperature steps. The total gas age is 45.1 ± 0.5 Ma.

The biotite age spectrum is less regular. Nonetheless, even the oldest steps are younger than those on the plateau of the muscovite spectrum, consistent with the lower inferred closure temperature for biotite than muscovite (~350 ± 50 °C and ~400 ± 50 °C, respectively; McDougall and Harrison, 1999). The total gas age is 36.0 ± 0.8 Ma.

The plagioclase sample exhibits a U-shaped spectrum indicative of excess radiogenic argon (McDougall and Harrison, 1999). The youngest steps yield ages >50 Ma; *i.e.* older than the oldest steps for muscovite and biotite. This confirms that all steps have been impacted by excess radiogenic argon, as the closure temperature for plagioclase (and thus age) is expected to be equal to or less than those for muscovite and biotite (McDougall and Harrison, 1999). We do not believe that a geologically meaningful age can be determined for this sample and do not consider it further.

The muscovite and biotite ^{40}Ar/^{39}Ar ages fall in a gap between clusters at 58–55 Ma and 17–15 Ma defined by the K-Ar analyses of Damon *et al.* (1962) and Hayama *et al.* (1984) (Figure 2). It is difficult to compare ^{40}Ar/^{39}Ar and K-Ar ages directly. Nonetheless, our results are consistent with the evidence from the K-Ar ages for an extended period of cooling from early to mid-Cenozoic time.

DISCUSSION

Protolith age of El Batamote belt and tectonic implications

Our detrital zircon analyses confirm the view that much, or all, of the Altar complex at Cerros La Batellera was derived from an Upper Cretaceous protolith likely correlative with El Chanate Group (*e.g.*, Jacques-Ayala *et al.*, 1990, 2009; García y Barragán *et al.*, 1998; Jacques-Ayala, 1999, 2000) and contradict the interpretation that the entire protolith of El Batamote belt is correlative with the Glance Conglomerate (*e.g.*, Nourse, 2001). Some parts of La Batellera section are no older than 77.5 ± 2.5 Ma, which may indicate correlation with the Escalante Formation, the uppermost unit of El Chanate Group (González-León et al., 2017).

Some fraction of El Batamote belt, however, must be derived from units older than Late Cretaceous. The most direct line of evidence is provided by the latest Middle Jurassic (164 Ma) tuff (?) located northwest of Altar (Mauel, 2008; Mauel *et al.*, 2011). An age as old as Middle Jurassic is also suggested by the erg-style detrital zircon

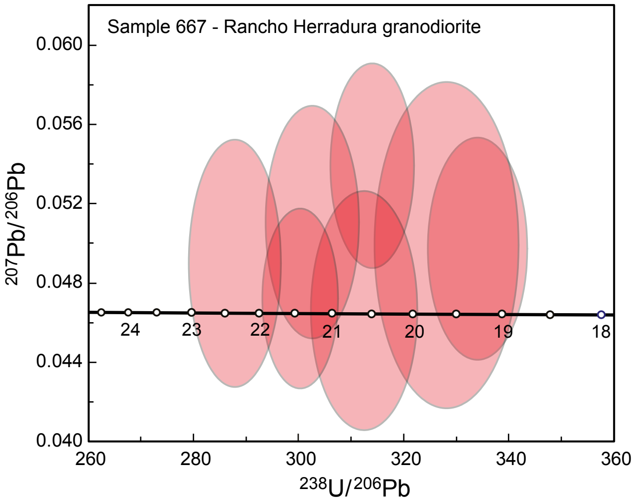

Figure 8. Tera–Wasserburg concordia plot of zircon ages from the Rancho Herradura granodiorite (sample 667).

age spectrum of the sample from the Carnero complex. Alternatively, the Carnero sample could be younger than Middle Jurassic (above), although the most-plausible options nonetheless require that the protolith be pre-Late Cretaceous and thus older than the Altar complex. Similarly, the distinctive lithologic composition of the black phyllite at the north end of the Carnero complex body is consistent with, but not proof of, correlation with the Middle Jurassic Cucurpe Formation (Mauel *et al.*, 2011).

It is apparent from various issues discussed herein that further work is needed to more fully characterize the protolith of El Batamote belt, including additional mapping, petrography, whole-rock geochemical analysis and detrital zircon studies throughout its geographic extent. Nonetheless, based on the available data, we hypothesize that El Batamote belt was derived from a range of Middle Jurassic to Upper Cretaceous supracrustal sequences that were present in the Caborca–Altar area at the time of the Laramide orogeny (see also García y Barragán and Jacques-Ayala, 2010). We envision that the various units were deformed and metamorphosed together beneath a now-hidden Laramide thrust sheet (or sheets). The youngest strata involved in this thrusting (Escalante Formation and parts of the Altar complex) may have been synorogenic deposits shed from the thrust belt as it advanced northeastward toward the Caborca–Altar area (Jacques-Ayala *et al.*, 1990, 2009; García y Barragán *et al.*, 1998; Jacques-Ayala, 1999, 2000). This style of tectonism is analogous to that proposed for much of the Cretaceous–Paleogene Mexican orogen (Fitz-Díaz *et al.*, 2018). Application to the Caborca–Altar area, however, is more speculative, because of the lack of definitive evidence for major thrust faults, either bounding or within El Batamote belt. The inferred thrust fault(s) could be (1) buried beneath basin fill southwest of the exposures of El Batamote belt (Jacques-Ayala and Garcia y Barragán, 2015, 2018); (2) present within the complex, but difficult to recognize because of the lack of good stratigraphic control; and/or (3) overprinted by Miocene detachment faults (Nourse, 2001). Late Cretaceous thrust faults have been recognized within the Sierra La Vibora of the Caborca block southwest of Altar (De Jong *et al.*, 1988; Jacques-Ayala *et al.*, 1990) and could be part of the proposed thrust system.

According to Nourse (1995; 2001) and Anderson and Nourse (2005), the protolith of El Batamote belt was deposited in a northwest-southeast–elongated transtensional basin along the Late Jurassic Mojave-Sonora megashear. Our results, however, indicate that much of the protolith is too young to be related to the megashear. Instead, we propose that the northwest-southeast trend of the belt is the consequence of Late Cretaceous northeast-southwest shortening followed by Miocene extension along approximately the same azimuth. We cannot rule out that some components of the protolith of El Batamote belt were deposited in northwest-southeast–trending basins (*e.g.* The Altar-Cucurpe basin of Mauel *et al.*, 2011). Nonetheless, we consider it unlikely that the present linear outcrop geometry of El Batamote belt is a fundamental signature of Late Jurassic transtension. This conclusion does not by itself disprove the megashear concept, but it greatly diminishes the importance of El Batamote belt as an argument in favor of the megashear.

Timing and regional correlations

The contractional event that caused deformation and metamorphism of El Batamote belt and folding of the Bisbee and El Chanate Groups in the Caborca–Altar area must be at least partly younger than the ~78–75 Ma maximum depositional ages of the Altar complex and El Chanate Group, as well as the 72 ± 1 Ma El Charro volcanic complex, which was folded along with El Chanate Group (Jacques-Ayala, 1999). The end of Laramide deformation in this region is constrained by eruption of the post-tectonic San Jacinto volcanics rocks at 51 ± 2 Ma (Jacques-Ayala, 1999, 2000). In addition, deformation was likely over, or at least waning, by the early Eocene based on the biotite K-Ar age of 58 ± 3 Ma (Damon *et al.*, 1962) for Altar complex at Cerros La Batellera. However, our ^{40}Ar/^{39}Ar ages of 45.1 ± 0.5 and 36.0 ± 0.8 Ma for muscovite and biotite, respectively, indicate that at least some parts of the section remained at temperatures of 400–350 °C through most of the Eocene.

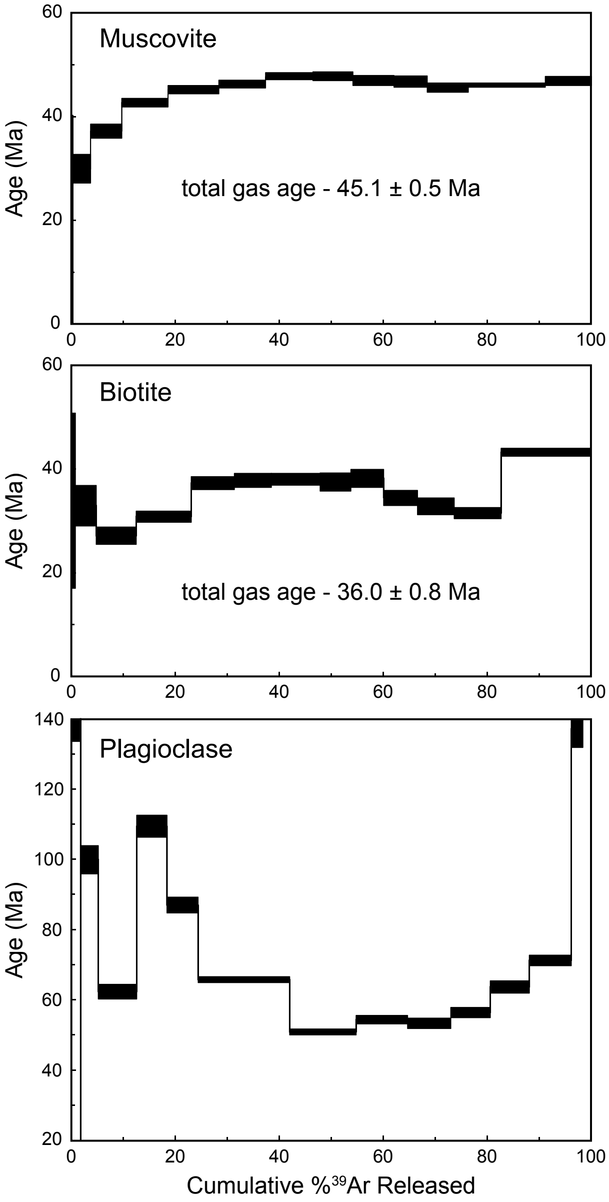

Figure 9. ^{40}Ar/^{39}Ar release spectra for Altar complex sample CJ13-15.

Deformation similar in style and age to that of the Caborca–Altar area is widespread through northern Sonora and adjoining areas; *e.g.*, near Quitovac, Imuris, Arizpe and Naco in Sonora (Iriondo *et al.*, 2005; González-León *et al.*, 2017) and in the Quitobaquito Hills to Baboquivari Mountains of south-central Arizona (Haxel *et al.*, 1984; Goodwin and Haxel, 1990; Calmus and Sosson, 1995). Common attributes of these areas include: (1) deformation involved the full thickness of Mesozoic sedimentary and volcanic rocks; (2) Upper Cretaceous strata (Cabullona Group, Cocóspera Formation, Fort Crittenden

Formation) were deposited in basins bounded by Laramide thrust and high-angle reverse faults; (3) greenschist facies metamorphism, southwest-dipping cleavage and stretched-pebble conglomerates are locally well developed; (4) magmatism generally outlasted deformation; and (5) both magmatism and deformation appear to have migrated northeastward with time. Among these areas, González-León *et al.* (2017) highlighted similarities between the stratigraphic, structural and age relations for the Cocóspera basin near Imuris and Arizpe with those for the Altar complex and El Chanate Group. The Cocóspera Formation was thrust beneath the Bisbee Group along the Late Cretaceous San Antonio fault. González-León *et al.* (2017) interpreted the San Antonio fault as a regional Laramide tectonic front that extended westward to the Caborca–Altar area. The San Antonio fault would thus be equivalent to the Altar thrust of Figure 1 (the "Altar sole fault" of Jacques-Ayala and García y Barragán, 2015).

The orogenic system represented by El Batamote belt may have an analog in the McCoy Mountains Formation of southwesternmost Arizona and southeasternmost California, 400 km northwest of the Caborca–Altar area (Harding and Coney, 1985; Barth *et al.*, 2004; Spencer *et al.*, 2011). The McCoy Mountains Formation includes sandstone, siltstone and conglomerate that, like the inferred protoliths of El Batamote belt, range from Middle or Upper Jurassic to Upper Cretaceous. The lower to middle parts of the McCoy Mountains Formation have been linked to the Bisbee Group, including the Upper Jurassic-Lower Cretaceous Glance Conglomerate (Dickinson and Lawton, 2001). The upper part of the McCoy Mountains Formation, in turn, resembles the upper part of the Altar complex, both in terms of its Late Cretaceous depositional age and the abundance of conglomerate. All parts of the McCoy Mountains Formation were affected by Late Cretaceous deformation. These similarities further highlight the extent and continuity of the Laramide orogen in the southwestern U.S. and northwestern Mexico.

Miocene extension

Laramide deformation probably accounts for the main structures and fabrics in El Batamote belt and the Bisbee and El Chanate Groups of the Caborca–Altar area (see also Nourse, 2001). Nonetheless, top-west extensional fabrics (Jacques-Ayala *et al.*, 1990) in the ~22–21 Ma Rancho Herradura granodiorite at Cerro Carnero provide evidence of an important overprint during Miocene detachment faulting. Biotite and white mica K-Ar ages clustered at 17–15 Ma may indicate that the main phase of extension postdated intrusion of the granodiorite by several million years. In any case, middle Cenozoic extension in the Caborca–Altar is likely part of a much broader metamorphic core-complex event (Nourse, *et al.*, 1994; Wong *et al.*, 2010). The difficulty in recognizing Laramide thrust faults is probably due in large measure to overprinting by middle Cenozoic extensional structures.

CONCLUSIONS

Detrital zircon from the Altar complex of Cerros La Batellera indicates a Late Cretaceous maximum depositional age with at least part of the protolith no older than 77.5 ± 2.5 (2σ). The zircon age spectra are consistent with local to somewhat distant Sonoran sources including Proterozoic bedrock, Neoproterozoic to Cambrian miogeoclinal quartz arenites and Permian–Triassic, Jurassic and Cretaceous arcs. The zircon age results and lithology support correlation with the Upper Cretaceous El Chanate Group.

One sample of the Carnero complex from the Cerro Carnero yielded a Middle Jurassic maximum depositional age and an overall age signature characteristic of the Jurassic eolian (erg) sands of the Colorado Plateau, U.S. This result may indicate a Jurassic depositional age and correlation with the Rancho San Martín Formation. Alternatively, the Cerro Carnero sample could be an equivalent of the Upper Jurassic Cucurpe Formation, Upper Jurassic to Lower Cretaceous Bisbee Group, or even Upper Cretaceous El Chanate Group produced by reworking of Middle Jurassic erg sands.

We infer that the various stratigraphic units incorporated within the Altar and Carnero complexes, specifically, and El Batamote belt, more broadly, were buried beneath a Laramide thrust complex during the Late Cretaceous–Paleogene Laramide orogeny. Initial cooling of the complexes occurred in the late Paleocene to Eocene. A second phase of cooling associated with detachment faulting occurred at ~17–15 Ma following intrusion of the ~22 Ma Rancho Herradura granodiorite.

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SUPPLEMENTARY MATERIAL

The Tables "A1. Sample information and coordinates.", "A2. Results for detrital zircon samples 662, 663, 663A, 664, 666, 668, 669 analyzed by LA-ICP-MS at the Arizona Laserchron Center, University of Arizona.", "A3. Results for detrital zircon sample CJ13-15 analyzed by LA-ICP-MS at the Laboratorio de Estudios Isotópicos (LEI), Centro de Geociencias, UNAM.", "A4. SHRIMP-RG analyses - Rancho Herradura granodiorite.", "A5. ^{40}Ar/^{39}Ar results for biotite sample CJ13-15.", "A6. ^{40}Ar/^{39}Ar results for muscovite sample CJ13-15.", and "A7. ^{40}Ar/^{39}Ar results for plagioclase sample CJ13-15." of the electronic supplement can be found at the journal web site <http://rmcg.unam.mx/>, in the table of contents of this issue.

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