Mazatan metamorphic core complex (Sonora, Mexico): structures along the detachment fault and its exhumation evolution

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Abstract

The Mazatán Sierra is the southernmost metamorphic core complex (MCC) of the Tertiary extensional belt of the western Cordillera. Its structural and lithological features are similar to those found in other MCC in Sonora and Arizona. The lower plate is composed of Proterozoic igneous and metamorphic rocks intruded by Tertiary plutons, both of which are overprinted by mylonitic foliation and N70°E-trending stretching lineation. Ductile and brittle--ductile deformations were produced by Tertiary extension along a normal shear zone or detachment fault. Shear sense is consistent across the Sierra and indicates a top to the WSW motion. The lithology and fabric reflect variations in temperature and pressure conditions during extensional deformation. The upper plate consists mainly of Cambrian–Mississippian limestone and minor quartzite, covered by upper Cretaceous volcanic rocks, and then by Tertiary syntectonic sedimentary deposits with interbedded volcanic flows. Doming caused uplift and denudation of the detachment, as well as successive low-angle and high-angle normal faulting across the western slope of Mazatán Sierra. An 18\textsuperscript{3} Ma apatite fission-track age was obtained for a sample of Proterozoic monzogranite from the lower plate. The mean fission-track length indicates rapid cooling and consequent rapid uplift of this sample during the last stage of crustal extension.

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1. Introduction

During the Cretaceous and Tertiary, the tectonic evolution of northwestern Mexico was controlled by the interaction between the Farallon and Pacific oceanic plates and the western margin of the North American craton. A large increase in the convergence rate between the Farallon and North America plates at 75 Ma (Engebretson et al., 1985) may have caused the Late Cretaceous–Early Tertiary Laramide orogeny, which was characterized by intense magmatism and compressional tectonics that involved cortical thickening (Coney and Harms, 1984; Dickinson, 1989). During the Tertiary, the western margin of the North American plate was the locus of complex subduction, mainly due to the fragmentation of the Kula and Farallon oceanic plates. Through Eocene–Oligocene time, continuous subduction generated voluminous inland magmatism that formed the Sierra Madre Occidental ignimbritic belt (Clark et al., 1982). By the Late Oligocene–Early Miocene, the volcanic front migrated to the west. In Sonora, between 26 and 12 Ma, magmatism was contemporaneous with late orogenic collapse throughout northwestern Mexico (Gans, 1987; Nourse et al., 1994), which produced metamorphic core complexes (MCC) and the Basin and Range morphotectonic province.

Tertiary extension in Sonora occurred on previously deformed continental crust, including four tectonostatigraphic terranes (Fig. 1): (1) To the north and northeast, the Pinal schist and younger rocks of the southwestern margin of the North American craton consist of Proterozoic metamorphic rocks intruded by 1.68 Ga and mid-Proterozoic plutons, overlain by upper Proterozoic and Paleozoic strata. (2) To the northwest, in the Altar desert region, the Papago terrane (Haxel et al., 1980) is characterized by a thick sequence of Early–Late Jurassic low-grade metamorphic volcanic rocks, which represents supracrustal rocks...
of the magmatic arc accreted on the southwestern margin of the craton (Busby-Spera, 1988). Proterozoic and Paleozoic rocks are scarce and locally thrust on Jurassic units (Calmus and Sosson, 1995; Caudillo-Sosa et al., 1996), similar to the pattern of structures described in the Quitobaquito Hills area of southwestern Arizona (Haxel et al., 1984). (c) South of the Papago terrane, the Caborca terrane consists of a high-grade metamorphic lower Proterozoic basement intruded by the 1100 Ma Aibo granite (Anderson and Silver, 1981) and unconformably overlain by more than 3000 m of upper Proterozoic–Cambrian shallow-water sequences (Stewart et al., 1984). Triassic–Upper Jurassic marine fossiliferous deposits unconformably overlie older rocks. (d) South of the Caborca terrane, the Cortés terrane is made up of lower Paleozoic deep marine sequences deposited along the margin of the North American craton; these rocks were thrust on coeval shelf deposits of the craton at the end of the Paleozoic. Although Basin and Range tectonics extend to the south into the Trans-Mexican volcanic belt and probably into Oaxaca (Henry and Aranda-Gómez, 1992, 2000), MCC are not known south of the limit between the Caborca and Cortés terranes, which suggests that the Tertiary crustal extension is partly controlled by inherited structures and an overthickened crust (Coney and Harms, 1984), as in the North American Cordillera, where MCC are located only west of the Overthrust belt.

The first detailed studies of MCC were performed in the Basin and Range province (Coney, 1980), which appear in Arizona and southeastern California (Whipple, Buckskin,
Harquahala, and Catalina Mountains; Davis et al., 1980) and along a belt in the North America Cordillera from southwestern Canada to Sonora. Previous structural studies, radiometric ages, and thermochronologic studies of MCC provide precise constraints on their thermotectonic evolution (Rehrig and Reynolds, 1980; Rehrig et al., 1980; Wernicke, 1992; Foster et al., 1993; Fayon et al., 1996). In Sonora, Coney (1980) identifies four MCC: Magdalena, Madera, Mazatán, and Pozo Verde Sierras. The Aconchi Sierra, located 75 km north of Mazatán Sierra, also exhibits in its northeastern area structural characteristics of MCC (Nourse et al., 1994; Calmus et al., 1996; Rodríguez-Castañeda, 1999). Structural and petrologic studies have focused mainly on the Magdalena MCC (Nourse, 1990) and the Mazatán Sierra MCC (Richard, 1991; Vega-Granillo, 1996a,b). In Arizona, the stretching rate of the mid-Tertiary pre-Basin and Range extension might locally exceed 100% (Hamilton and Myers, 1966; Davis, 1983).

The presence of probable Proterozoic crystalline basement in the footwall of Mazatán Sierra, as in the southeast Arizona Santa Catalina MCC (Precambrian Oracle granite and Pinal schist), may suggest a similar important stretching. Continental deposits related to syntectonic basins located on the hanging wall of MCC are terrigenous and lacustrine with interlayered volcanic rocks, including sparse nonmetallic deposits of gypsum, borates, and zeolites (Miranda-Gasca et al., 1998).

2. Pre-Oligocene geology of the Mazatán Sierra

The Mazatán Sierra is located in central Sonora (Fig. 1), almost 70 km east of Hermosillo. The range is roughly circular, with a diameter of 15 km and an elevation of 1000 m above the surrounding plains. It is classically considered the southern end of the Upper Cretaceous-Paleocene Aconchi batholith, though it is isolated from the main range. The oldest rocks are gneisses, amphibolites, mica schist, and quartzite that form blocks that are included as xenoliths in a monzogranite (Fig. 2a). One xenolith located at an elevation of 1180 m in the Bachán creek displays an unconformity between migmatitic gneisses and metasedimentary rocks. The metamorphic rocks can be correlated with the Lower Proterozoic (~1700 Ma) basement of the Caborca terrane by their lithological character and amphibolite facies metamorphism; metasedimentary rocks can be correlated with Neoproterozoic rocks widespread in northwestern and central Sonora.

The metamorphic rocks are intruded by a porphyritic monzogranite of uncertain age. An Rb/Sr age of...
1475 ± 29 Ma (Damon, pers. comm.), which appears as 1480 ± 30 Ma in an unpublished report, corresponds to a granite collected near the Bachán ranch at the top of the Sierra. A granite body of 1410 Ma was reported (Richard, 1991; after Damon, pers. comm.) northwest of the Sierra in the foothills close to the La Feliciana ranch. These unpublished and poorly located radiometric ages do not conclusively establish the age of the bulk of the Mazatán Sierra. Nevertheless, the presence of xenoliths of Precambrian gneisses and metasedimentary rocks and the lack of Paleozoic sedimentary rocks as roof pendants in the Mazatán Sierra, which are abundant in the Paleocene Aconchi batholith, suggest a Proterozoic age for the porphyritic monzogranite.

In central Sonora, the crystalline basement is covered by Paleozoic miogeoclinal sequences that crop out as isolated hills (Stewart et al., 1990; Richard, 1991). They contain strata of Middle Cambrian–Middle Pernian age (Veiga-Granillo, 1996a,b). Paleozoic rocks are unconformably covered by an intermediate to felsic volcanic unit, which could be correlated with the Tarahumara Formation (Wilson and Rocha, 1946) of Late Cretaceous–Paleocene age (McDowell et al., 1995, 2001). In central Sonora, the Tarahumara Formation is mostly older than the calc-alkaline diorite–granitic intrusive rocks of the Sonoran batholith (McDowell et al., 2001). A porphyritic granodiorite from northwest of the Mazatán Sierra, close to El Garambullo ranch, yields a U–Pb age of 58 ± 3 Ma (Anderson et al., 1980). A mid-Tertiary two-mica peraluminous granite was emplaced over Middle Proterozoic–Lower Paleocene crystalline rocks and under Paleozoic limestone. A leucocratic dike, presumably associated with an intermediate to felsic volcanic unit, which could be correlated with the Tarahumara Formation (Wilson and Rocha, 1946) of Late Cretaceous–Paleocene age (McDowell et al., 1995, 2001). A porphyritic granodiorite from northwest of the Mazatán Sierra, close to El Garambullo ranch, yields a U–Pb age of 58 ± 3 Ma (Anderson et al., 1980). A mid-Tertiary two-mica peraluminous granite was emplaced over Middle Proterozoic–Lower Paleocene crystalline rocks and under Paleozoic limestone. A leucocratic dike, presumably associated with this intrusion, yields 33.0 ± 8 Ma (Damon, pers. comm.).

3. Structures in Mazatán Sierra MCC

Three structural features can be recognized in the Mazatán Sierra MCC: (1) shear zone with dynamic metamorphism, (2) local doming, and (3) brittle normal faulting.

The metamorphic core of the Mazatán Sierra, similar to that of many other western Cordillera MCC, is characterized by igneous and regional metamorphic rocks overprinted by dynamic metamorphism related to a ductile to brittle–ductile shear zone. The core corresponds to the lower plate (footwall) of the MCC (Coney, 1980) and the shear zone to a detachment fault. Due to the movement along the shear zone, mylonitic foliation (S2) and stretching lineation were developed in Proterozoic crystalline rocks, as well as in upper Cretaceous and Tertiary intrusive rocks. The most common rocks in the shear zone are mylonitic to protomylonitic granite derived from Proterozoic two-mica porphyritic granite. The typical fabric in this protomylonitic granite is shear band cleavages (S-C′ and S-C) with schistosity formed by dynamically recrystallized quartz lenses and preferred orientation of biotite, diagonally transected by discontinuous extensional shear bands (C′).

Structures and microstructures of the dynamically metamorphosed rocks give evidence for a shear zone along which deformation and differential displacement were produced by ductile flow. The main deformation mechanism in mylonitic gneiss was quartz deformation by intracrystalline slip with recovery and dynamic recrystallization. Quartz deformation allows the rotation of planar or prismatic minerals, which enhances foliation development. Feldspars are mainly deformed by cataclasis and intracrystalline slip and display dynamic recrystallization. Muscovite and local epidote are neoformed. Dynamic recrystallization in quartz occurs at temperatures higher than 300 °C, whereas in feldspars, this mechanism is important above 400–500 °C (Passchier and Trouw, 1998). Deformation temperatures and the few neoformed metamorphic minerals suggest greenschist facies conditions during the dynamic metamorphism event.

Within the shear zone, deformation is relatively homogeneous, with the exception of a few meters of thick discrete zones, where mylonitic granite is gradually transformed into stripped gneisses with isoclinal microfolding. Dynamically metamorphosed rocks form the bulk of Mazatán Sierra; however, highly strained rocks are best exposed along the western slope and foothills. On the basis of the relationships between the topography and outcrops, we estimate that the shear zone thickness exceeds 200 m.

Thin bands of mylonite and ultramylo nite occur within the mylonitic granite, typical of highly strained zones described in other MCC. The rocks are black, coherent, and very fine grained (chert-like), sometimes with feldspar bands and porphyroclasts, as well as neoformed muscovite in foliation planes. The matrix is formed by fine (<0.1 mm), dynamically recrystallized grains of quartz, feldspar, and mica. Ultramylo nite bands have straight contacts with the mylonitic granite host and wedge out laterally (Fig. 2b).

The regional metamorphic foliation (S1) in Proterozoic rocks tends to be parallel to the shear plane. Consequently, a shear cleavage develops in those rocks. However, in some places, a mylonitic foliation overprints S1 and F1 folds. The F2 folds, which are generated by the shear movement, are well represented in amphibolite and schist that display two phases of isoclin al to tight decimetric folds, the latter with recumbent folds whose axial planes are subparallel to the shear plane. In some places, pytgmatic folding is associated with shear deformation of the heterogeneous mix of xenoliths and host rocks (Fig. 2a). Proterozoic xenoliths, some of tens meters along, outcrop like boudins in the mylonitic granite host. Quartzite, amphibolite, schist, and gneiss show dynamic recrystallization in the shear zone, but in areas outside the dome, the quartzite has a laminated fabric with polygonal grains. In the bulk of Mazatán Sierra, stretching lineation defines
a shear direction between 60 and 90°NE with an average of 70°NE (Fig. 3a and b). This shear direction coincides with those defined in other MCC in Sonora (Nourse, 1990; Nourse et al., 1994) and Arizona (Keith et al., 1980) and thus suggests a coherent extension trend through the south Basin and Range provinces. Mylonitic granites have parallel quartz-feldspar bands, centimeters to decimeters thick, which could be formed by isoclinal to subisoclinal folding of leucocratic dikes. Mylonitic to ultramylonitic bands, some thicker than 10 m, are highly strained in the shear zone. In these zones, centimeter-scale ultramylonite bands are intercalated with mylonitic gneisses and granites (Fig. 2). Common structures inside them are sheath, oblique, and rootless folds; boudinage; folded boudins; and superposed folds. Tubular morphology of sheath folds was observed in a few exposures (Fig. 4). Decimetric oblique folds vary from isoclinal to open. Isoclinal and subisoclinal fold axes in mylonitic and ultramylonitic rocks trend between N60 and 90°E and N70 and 90°W (Fig. 3c), partially coincident with the stretching lineation trend or the maximum elongation direction, typical in sheath or oblique folds. A pattern of fold interference exists in some ultramylonitic rocks and corresponds to a combination of a domed, crescent mushroom pattern and a convergent–divergent pattern (Ramsay, 1967; Ramsay and Huber, 1987). The coexistence of both fold types in the same rock can be attributed to the bending of sheath folds.

Ultramylonitic zones in the lower part of the Bachán creek enclose some folded boudins, which indicates a progressive rotation of the strain ellipse during simple shear deformation that induces folding of the mylonitic bands at the same time. Rotation is required to produce the observed change in the deformation process from extension (boudinage) to shortening (folding) domains.

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**Fig. 3.** Equal area lower hemisphere projections of stretching lineation in (a) mylonitic granite and (b) mylonite and ultramylonite bands. (c) Equal area lower hemisphere projections of fold axes in mylonitic granite, mylonite, and ultramylonite. (d) Equal area lower hemisphere projections of mylonitic foliation poles in mylonitic rocks, measured within the entire dome. $n = 30$ in (a)–(c) and 55 in (d).

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**Fig. 4.** Sketch of a sheath fold: (a) black ultramylonite with quartz-feldspar and quartz bands. $L$ is the stretching lineation; (b) lateral view; (c)–(d) fold reconstruction before erosion. $X$ indicates the maximum elongation direction.
Domains of extension are followed by shortening, only in the case of polyphase deformation (Passchier and Trouw, 1998).

Shear sense is defined by microstructures created by noncoaxial deformation, such as oblique foliations, shear-band cleavages (S-C', S-C), mantled porphyroclasts, mica fish, and microfolding (Fig. 5). Shear sense is consistent in the analyzed sites around the dome and indicates a top to the SW sense of shear. In thin, highly strained horizons, inversions in shear sense were detected. We theorize that shear sense inversions could be produced during sheath fold formation (Fig. 6).

The most accepted model to explain Cordilleran MCC proposes that shear zone deformation corresponds to a low-angle normal fault (Wernicke, 1981, 1985; Spencer and Reynolds, 1989) that extends through the crust or even

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Fig. 5. Kinematic indicators used to define the shear sense in Mazatán Sierra mylonites: (a) oblique foliation (fs-C) in quartzite mylonite; stair-stepping of C bands can be observed. (b) Shear band cleavage (S-C') in porphyroclastic mylonite; intracrystalline sliding occurs in potassic feldspar porphyroclasts with antithetic (at) and synthetic (st) slides. (c) Muscovite mica fish and oblique foliation (fs-C) in quartzite mylonite. (d) Delta-type feldspar porphyroclast in laminate ultramylonite. (e) Sigma-type opaque minerals and biotite in laminated mylonite. Dark bands are dynamic recrystallized biotite; white bands are dynamic recrystallized quartz. (f) Ultramylonite with microfolding of recrystallized feldspar bands; folding is interpreted as due to the rotation of porphyroclasts. Rounded feldspar porphyroclasts are in a very fine recrystallized matrix. Shear sense is indicated by arrows. All thin sections are parallel to stretching lineation and normal to mylonitic foliation. Plane light except photos (e) and (f). Scale as in (e).
the lithosphere. Along those major faults, a spatial variation of deformation mechanisms exists, from cataclasis in the upper crust to intracrystalline deformation with recovery and dynamic recrystallization in the deepest zones. A temporal variation, other than the spatial variation previously discussed, exists in the deformational style. In the Mazatán Sierra shear zone, the deepest zone underwent ductile deformation with a low strain rate in the first stages to produce mylonitic granites from granular rocks. This strain affects a great volume of rock, because at higher temperatures, strain is more disperse (Williams et al., 1991). When the lower plate is uplifted to shallower depths with lower temperatures and confining pressures, strain is concentrated in narrow zones with high strain, which cut previously formed mylonitic granites and produced zones of mylonite and ultramylonite. This strain concentration phenomenon (tectonic softening) has been noted by Williams et al. (1991). In Mazatán Sierra, mylonitic horizons thicker than ten meters mainly occur along lithological discontinuities, due to differences in the rheological behavior of rocks. When the ductile shear zone cooled due to tectonic exhumation, brittle deformation overprinted mylonitic zones, which was expressed as brecciated zones with thicknesses from centimeters to tens of meters.

In the Mazatán Sierra, no radiometric ages have been obtained for minerals formed during dynamic metamorphism (e.g. muscovite). However, K–Ar 33 Ma pegmatitic leucocratic dikes are strained, whereas andesitic dikes with 21.1 ± 5 Ma K–Ar age (Damon, pers. comm.) are undeformed and cross through the mylonitic foliation. This strain concentration phenomenon (tectonic softening) has been noted by Williams et al. (1991). In Mazatán Sierra, mylonitic horizons thicker than ten meters mainly occur along lithological discontinuities, due to differences in the rheological behavior of rocks. When the ductile shear zone cooled due to tectonic exhumation, brittle deformation overprinted mylonitic zones, which was expressed as brecciated zones with thicknesses from centimeters to tens of meters.

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4. Syntectonic clastic deposition

Tectonic unroofing of the MCC core through displacement of the upper plate along a low-angle normal fault created a syntectonic basin, which was filled with clastic deposits produced by the erosion of uplifted blocks. A thick clastic series, informally named the Belleza Formation (Richard, 1991; Vega-Granillo, 1996a), crops out west of Mazatán Sierra along more than 12 km perpendicular to strike, though in great part, these strata are concealed by younger sediments. Bedding dips vary from vertical far from the main fault to 30°NE closest to the fault, which suggests a syntectonic tilting. These strata are overlain by alluvial deposits. We distinguish three units in the Belleza Formation. The lowest is composed of intercalations of conglomerate, siltstone, and sandstone with thin volcanic flows and tuffs. Clasts in conglomerate vary from mainly volcanic in the lower beds to limestone and granitic rocks in the upper part. The middle unit is formed of intercalations of sandstone and siltstone with scarce thin limestone and gypsum beds. The upper unit consists primarily of sedimentary breccias with andesite clasts. The Belleza Formation rocks have sedimentological characteristics of alluvial fans and lakes, with both fluvial and lacustrine facies and minor volcanic and volcanoclastic contributions. The formation was displaced over a Tertiary (?) garnet-bearing two-mica granite along a low-angle normal fault subsidiary to the detachment fault of the Mazatán MCC. Both granite and sedimentary rocks are very brecciated along the fault, but there is no evidence of ductile penetrative strain in the granite. In some places, siltstones and sandstones are deformed by subisoclinal to isoclinal drag folds generally less than 1 m in scale. Large open folds with large interlimb angles and NE-trending axes have been mapped in the Belleza Formation between the Mazatán and Puerta del Sol Sierras (Fig. 8). The intercalated andesite is very similar to andesitic dikes crossing the lower plate; one dike has a 22 Myr K–Ar date (Damon, pers. comm.).
The Belleza Formation can be correlated with continental sequences with minor volcanic contributions, which have been associated with exhumation of MCC. These regions in Sonora include the Tubutama, Magdalena, and Aconchi areas (Frye, 1975; Roldán-Quintana, 1979; Paz, 1988; Nourse, 1989; Miranda-Gasca and De Jong, 1992). Palynological studies in Tubutama and Magdalena indicate Oligocene–Miocene and Miocene–Pliocene ages, respectively (Richard, 1991). Volcanic rocks beneath the clastic sequence in Magdalena yield a K–Ar age of 27 Ma; intercalated basaltic andesite indicates a K–Ar age of 22 Ma (Miranda-Gasca and Gómez-Caballero, 1993).

The lithological character of the Belleza Formation, the basal low angle normal fault, the presence of syngenetic conjugate faults, slumps folds, drag folds and the systematic dip variation toward the main fault, indicate that sedimentation and extensional deformation were contemporaneous, at least during the later stages of MCC formation.

5. Local doming

Mazatán Sierra morphology is an isolated asymmetric dome with a more abrupt eastern slope (Fig. 7). This morphology is characteristic of some MCC, though some display an elongation parallel to the maximum stretching direction (Coney, 1979; Davis, 1980, 1983; Wernicke, 1985; Spencer and Reynolds, 1991). North of Mazatán Sierra, another dome, Puerta del Sol Sierra (Fig. 8), is limited along its western slope by mylonitic rocks in a ductile, low-angle fault, which could be related to the detachment fault of Mazatán Sierra. The domical morphology in Mazatán Sierra is reflected by the conic distribution of mylonitic foliation, which dips subparallel to the topography around the range (Fig. 3d) and thus indicates that doming is younger than the formation of mylonite along the detachment fault and is superimposed on a preexisting ductile zone. Both domes are separated by a lower, relatively flat area, which corresponds to the syntectonic basin, where the Miocene Belleza Formation was deposited. Large open folds with NE–SW axes in this Formation could be explained by local shortening due to opposite sliding of the sediments of the hanging wall, top to SW for the Puerta del Sol dome and top to NW for the Mazatán Sierra dome (Fig. 8).
Several hypotheses have been postulated to explain the dome shape of the MCC; discussions can be found elsewhere (e.g. Lister and Davis, 1989; Dickinson, 1991). Spencer (1984) and Spencer and Reynolds (1989) propose that dome morphology is an isostatic response to the tectonic removal of upper crust. The lithospheric model of Wernicke (1985) has a similar consequence, but the MCC axis does not coincide with the thinnest part of the crust. Thinning depends mainly on the amount of extension and results in the uplift of isotherms associated with warping of the lower plate. The isostatic rise, which would warp the lithosphere, must have occurred at a larger scale to include the whole range of MCC in Sonora, from Magdalena MCC to Mazatán Sierra. However, another cause is necessary to explain the small area doming (~12 km diameter), which we call 'local doming'. Buck (1988) proposes that domical morphology could arise from flexural deformation along a brittle normal fault that displaces the ductile shear zone (like a large drag fold). In this case, the range must have an elongated shape parallel to the fault (perpendicular to extension direction), but the morphology of the Mazatán and Sierra del Sol Sierras is quite circular (Fig. 8). Some MCC in Arizona even have elongated shapes perpendicular to the postulated normal faults (e.g. Harcuvar, Harquahala, South Mountain). An alternative model to explain elongated domes parallel to the extension has been developed by Spencer and Reynolds (1991).

Concentric granitic dikes in Puerta del Sol Sierra are similar to cone sheets, and many granitic dikes in Mazatán Sierra, perpendicular to the extension direction, are similar to those dated 33 Ma (Damon, pers. comm.). These dikes suggest the existence at depth of magmatic bodies (with laccolithic shape) that could heat and uplift the lower plate of the MCC, warping the ductile shear zone (Lister and Baldwin, 1993). The dome deforms the syntectonic basin created by upper plate displacement along the shear zone and creates the conspicuous distribution of clastic deposits presented by the Belleza Formation, which encircle the west flanks of both domes (Fig. 8). Unfortunately, we have not had geophysical evidence for the proposed magmatism at depth.

Domical uplift increased the dip of the detachment fault, and upper plate fragments were raised and then slid catastrophically over younger rocks previously displaced along normal faults subsidiary to the detachment fault (note the distribution of Paleozoic limestone in Fig. 1). An example of these slides is showed in Fig. 9, where Paleozoic limestone slid over volcanic rocks ascribed to the upper Cretaceous–Paleocene Tarahumara Formation, which in turn had slid over Tertiary two-mica granite. The directions of the blocks' movement are indicated by striations on the mylonitic foliation planes and have a radial pattern in the western half of the Sierra. Doming was followed by high-angle normal faulting, which transected the dome, as might have occurred along the eastern slope of Mazatán Sierra.

An 18 Ma apatite fission-track (AFT) apparent age was obtained for sample SM 16 (Table 1), located on the lower plate west of Bachán ranch at 1210 m a.b.s.l. (Calmus et al., 1998). The mean confined track length of 15.68 ± 1.15 μm

Table 1
Fission-track data from sample SM 16

<table>
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<tr>
<th>Location</th>
<th>Latitude (north)</th>
<th>Longitude (west)</th>
<th>ξ</th>
<th>$f(N_f)$ ($\times 10^5$ cm$^2$)</th>
<th>$f(N_d)$ ($\times 10^5$ cm$^2$)</th>
<th>Number of counted grains ($N$)</th>
<th>$P(X^2)$ (%)</th>
<th>$p_d(N_d)$ ($\times 10^5$ cm$^2$)</th>
<th>Age (Ma) ± 1σ</th>
<th>Mean track length μm ± 1σ</th>
<th>SD</th>
<th>Number of tracks measured</th>
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<td>Cañada Bachán</td>
<td>3,219,650</td>
<td>576,875</td>
<td>339</td>
<td>7.45 (255)</td>
<td>14.8 (505)</td>
<td>16</td>
<td>90.87</td>
<td>2.18 (14379)</td>
<td>18.6 ± 1.4</td>
<td>15.68 ± 406</td>
<td>1.15</td>
<td>8</td>
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</tbody>
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indicates a rapid cooling across the apatite partial annealing zone (Fig. 10). Although this result is not very reliable, because of the small number of measured tracks, the age is consistent with many other AFT ages previously obtained in the Basin and Range provinces. For example, the weighted mean AFT age for the Catalina Mountain forerange is $20.1 \pm 1.0 \text{ Ma}$ (Fayon et al., 1996), and AFT ages fall between 21 and 14 Ma in the Harcuvar Mountains and between 16 and 13 Ma in the Buckskin and Rawhide Mountains (Foster et al., 1993). Assuming a slip rate of $4–8 \text{ mm yr}^{-1}$ along the detachment fault (consistent with average slip rates calculated for various detachment faults of MCC of southwestern Arizona and southeastern California; Foster et al., 1993) and a dip angle of $20^\circ$, the time needed to cool through the apatite partial annealing zone would be between 1.6 and 800 Ka, which corresponds to a cooling rate of $31.25–62.5 \text{ °C Myr}^{-1}$. Rapid cooling related to detachment faulting also has been recognized in other MCC, such as the forerange of the Catalina Mountains (Davy et al., 1989; Fayon et al., 1996).

Dynamic metamorphism occurred along a thick, planar, gently dipping shear zone and produced a mylonitic fabric at depth. In the upper plate, tilting of the faulted blocks allowed for the formation of a basin at the surface, which was filled with fanglomerates, sandstones, lacustrine deposits, and a few interbedded volcanic rocks. The position of the sediments in the hanging wall of the MCC, their lithology, the variation of dip, faulting, and slumping coeval with sedimentation indicate a syntectonic character of the Belleza Formation. Finally, upward warping in response to intrusive bodies and tectonic denudation above the shear zone bent the mylonitic foliation of the lower plate and may have accelerated the unroofing. Brittle deformation was superposed over the mylonitic shear zone. Granitic dikes that cross-cut the Mazatán Sierra suggest that the arching may be partly due to intrusions below the core of the Sierra. Doming caused sliding of blocks composed of Paleozoic sedimentary rocks that belong to the upper plate, particularly along the western flank.

We suggest that the Mazatán Sierra MCC belongs to a larger normal shear zone that includes Puerta del Sol Sierra and the area south of the Aconchi batholith. Nourse et al. (1994) map middle Tertiary mylonitic fabric west of Puerta del Sol Sierra. The mylonitic shear zone is hidden between the Sierras, where the Belleza Formation was deposited. Probably only one shear zone extends along Mazatán Sierra through Magdalena Sierra, which would be discontinuously exposed by local doming.

### 6. Discussion and conclusions

Mazatán Sierra is the southernmost MCC of the western Cordillera and presents very similar geological and structural features to other MCC of northern Sonora and southern Arizona (Keith et al., 1980; Nourse et al., 1994). It was formed during a mid-Tertiary extensional event superposed on a thickened crust resulting from Laramide or pre-Laramide compressional events (Coney and Harms, 1984). Based on structural and geological data, our results document the following evolution for the Mazatán Sierra: During the Early Oligocene, peraluminous granite was emplaced along the interface of the metamorphic–plutonic basement and overlying Paleozoic sedimentary rocks.

Fig. 10. Paleoposition of sample Sm 16 at 18 Ma based on AFT data.
tracks. We are grateful to Pablo Peñaflor-Escarcega at the Estación Regional del Noroeste, Hermosillo, François Senebier and Francis Coeur at the Institut Dolomieu, university Joseph Fourier, Grenoble, who were in charge of sample preparation.

References

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