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LATE JURASSIC AND MID-TERTIARY BRITTLE-DUCTILE DEFORMATION IN THE OPODEPE REGION, SONORA, MEXICO

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ABSTRACT

In central Sonora, in the Opodepe region, regional strike-slip foliation in Proterozoic rocks is the result of Middle to Late Jurassic shearing, whereas extensional structures in Paleogene plutons correspond to the evolution of mid-crustal extension during Middle Tertiary. The geologic basement framework is composed of four Proterozoic crystalline units: (1) a granodiorite, locally metamorphosed; (2) a granitic feldspathic gneiss; (3) an anorogenic granite with abundant large feldspar porphyroclasts; and (4) a distinctive red micrographic granite. The unconformably Paleozoic section is composed of a pinkish-red orthoquartzite considered to be Cambrian (?) in age. Mesozoic rocks consist mainly of Middle (?) Jurassic volcanic rocks, tuff and andesite. Paleogene intrusions include a 51.8 to 69.9 Ma granitic to granodiorite pluton, and a 36 Ma peraluminous granite.

Detailed geological mapping and structural analysis reveal the presence of mylonitic fabric in the crystalline basement associated to the evolution of a right-lateral conjugate fault that strikes northeast-southwest. Asymmetric feldspar augen, asymmetric pressure shadows, composite planar fabrics (C- and S-surfaces) and displaced broken grains were used to determine shear sense. Lineation seems to be parallel to and lie within foliation. In addition Precambrian and Tertiary crystalline rocks record kinematic indicators related to a metamorphic core complex deformation. Moderately to weakly foliated Paleogene granodiorite to granitic rocks form the core, while rocks that typically show boudins and recumbent to overturned tight ptygmatic folds, mylonitic foliation, and faults at high angles to foliation correspond to the metamorphic carapace. The detachment zone (The La Ramada-Agua Caliente Detachment Fault) is a steeply dipping fault zone with a resistant brecciated or microbrecciated expression where locally mylonite and gouge occur. Unmetamorphosed but intensely fractured and faulted Proterozoic, Paleozoic, and Mesozoic rocks constitute the hanging wall of the detachment fault.

Key words: Structure, Opodepe, Sonora, Mexico.

RESUMEN

En la región de Opodepe, en Sonora central, las rocas proterozoicas registran una foliación de carácter regional resultado de un cizallamiento ocurrido durante el Jurásico Medio-Tardío, mientras que estructuras de extensión que afectan a plutones terciarios corresponden a la evolución de la corteza media durante el Paleógeno. El basamento cristalino Proterozoico en el área de estudio está formado por cuatro unidades: (1) una granodiorita localmente metamorfizada; (2) un gneis feldespático de origen granítico; (3) un granito tipo anorogénico con abundantes porfidoclastos de feldespato potásico; y (4) un granito micrográfico. Discordante, la secuencia paleozoica está compuesta por una ortocuarcita de posible edad cámbrica (?). Las rocas mesozoicas consisten en tobas y andesitas de posible edad del Jurásico Medio (?); mientras que las rocas del Paleógeno corresponden a intrusivos de composición granítica a granodiorítica cuya edad varía de 51.8 a 69.9 Ma, más un granito peralcalino de 36 Ma.

La cartografía y el análisis estructural indican la presencia de milonitas en la secuencia proterozoica que pueden asociarse a la evolución de una falla a rumbo-derecha con orientación noreste. Ojos de feldespato, sombras de presión, superficies C y S, y granos rotos y desplazados fueron usados para determinar la dirección de cizallamiento. La lineación parece ser paralela a la foliación. Las rocas intrusivas proterozoicas y terciarias contienen indicadores cinemáticos que sugieren una deformación tipo *core complex*. Los plutones graníticos y granodioríticos que se encuentran de moderada a débilmente foliados forman el núcleo, mientras que las rocas que muestran *boudins*, pliegues ptigmáticos, foliación y fallas verticales corresponden al caparazón metamórfico. La zona de despegue (Falla La Ramada-Agua Caliente) presenta una zona de falla de pendiente acentuada con presencia de brechas y salbanda. Rocas proterozoicas, mesozoicas, paleozoicas y terciarias constituyen el bloque de techo de la falla de despegue.

Palabras clave: Estructura, Opodepe, Sonora, México.

NTRODUCTION

Geologic mapping and structural analysis in central So-.iora (Figure 1) has revealed the structure/tectonic signatures of two major regional tectonic events: the formation of the Mojave-Sonora megashear, and the development of metamorphic core complexes. The Mojave-Sonora megashear (Anderson and Silver, 1979) extends northwest-trending from the Sonoyta region into the present study area (Rodríguez-Castañeda, 1984) (Figure 2). Thrusting and foliation are part of the structures associated to the Mojave-Sonora megashear (Corona, 1980; Rodríguez-Castañeda, 1984, 1990; Connors *et al.*, 1989; Connors, 1990). The Mojave-Sonora megashear, within which was concentrated intense mylonitic deformation records the effects of Mesozoic sinistral faulting.

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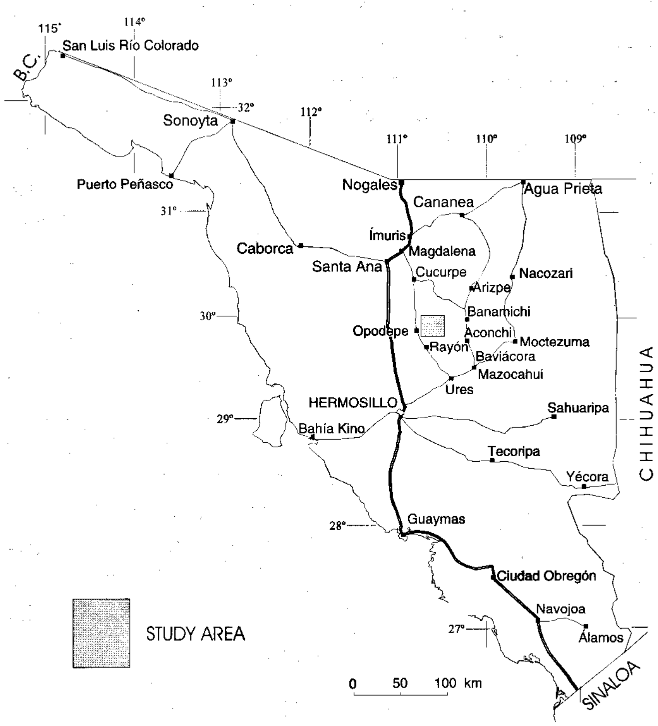


Figure 1. Location map of the study area. B.C.: Baja California.

Between Oxfordian and Kimmeridgian the effects of this translation is further illustrated by the existence of barely preserved mylonitic rocks such as those exposed in Sonoyta (Connors *et al.*, 1989), Quitovac (Connors *et al.*, 1989; Caudillo-Sosa and Oviedo-Lucero, 1990; Caudillo-Sosa *et al.*, in press; Connors, 1990), Estación Llano (Calmus *et al.*, 1992a), and Tuape (Rodríguez-Castañeda, 1984).

The trace of the Mojave-Sonora megashear is postulated north of the study area. However, perhaps the area is inside on the Mojave-Sonora shear zone. In northwestern Mexico, the Mojave-Sonora megashear marks the boundary between the Caborca block and the Pápago terrane (Rodríguez-Castañeda and Anderson, in preparation). Highly deformed Proterozoic and Paleozoic rocks of the Caborca block representing remnants of the North American craton crop out in the study area.

Metamorphic core complex type rocks are distributed along a belt that extends from Canada to northwestern Mexico (Davis and Coney, 1979). In northern Sonora examples of metamorphic core complexes occur in the Magdalena region, sierras Las Jarillas-Potrero, sierra La Tortuga, sierra El Mezquital, Sásabe (sierra Pozo Verde), Tubutama, Cerro Carnero, Puerta del Sol, and sierra de Mazatán (Anderson *et al.*, 1980; Davis *et al.*, 1981; Nourse, 1989, 1990; and Nourse *et al.*, 1994). To this list will now be added this new locality, the "Opodepe" core complex, in central Sonora, (Figure 2). The core complexes nearest to the study area are Magdalena and Mazatán. The Magdalena core complex zone crops out tens of kilometers northwest where lineated greenschist and amphibolite grade schist and orthogneiss are characteristic. Mylonite zones are exposed in sierra Magdalena and sierra La Madera (Nourse, 1990). The Mazatán core complex lies one hundred kilometers to the south of Opodepe where metamorphic rocks are composed of mylonitic gneiss and schist (Davis *et al.*, 1981).

Precambrian, Paleozoic, Mesozoic, and Tertiary rocks in central Sonora constrain structural kinematic indicators that suggest brittle-ductile Late Jurassic and Tertiary core complex deformation. Proterozoic rocks preserve distinctive Jurassic mylonitic fabric that does not extend into the adjacent Tertiary plutons. Ductile and brittle deformation attributable to Tertiary crustal extension is also recorded in Precambrian as well as in Paleogene granites.

Opodepe is different in that structural denudation that accompanied the evolution of the core complex and subsequent uplift and erosion did not result in metamorphic exposures of the same geometric configuration as those at Magdalena and Mazatán. This paper stresses the effects of structural denudation at Opodepe.

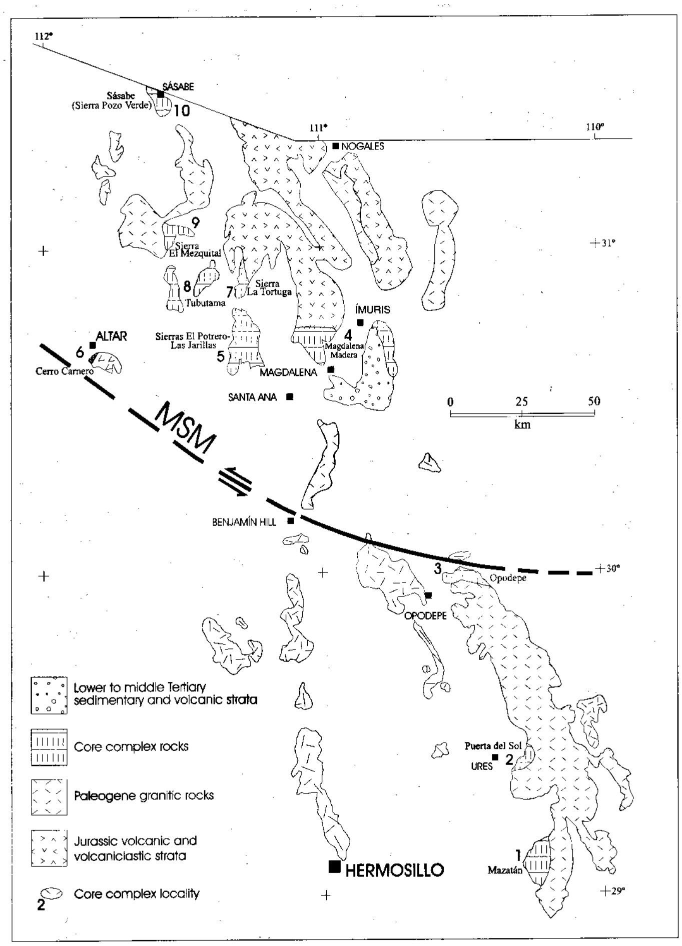


Figure 2. Schematic geologic map that shows distribution of outcrops of metamorphic core complexes areas in northern Sonora and the trace of the Mojave-Sonora megashear (MSM)(Anderson and Silver, 1979). *1*, Mazatán; *2*, Puerta del Sol; *3*. Opodepe; *4*, Magdalena; *5*, sierras El Potrero-Las Jarillas; *6*, Cerro Carnero; *7*, sierra La Tortuga; *8*, Tubutama; *9*, sierra El Mezquital; *10*, Sásabe (sierra Pozo Verde). Compiled from various sources, see text.

PRINCIPAL GEOLOGIC UNITS

The Opodepe region is in north-central Sonora, about 150 km northeast of Hermosillo (Figure 1). The study area lies at the northern end of the sierra Los Locos, where exposures of Proterozoic, Paleozoic, Mesozoic, and Tertiary rocks occur (Plate 1). These exposures were initially studied by Castillo-Mendoza (1988), who mapped and described them at the scale 1:50,000. Later, Figueroa-V. and Grijalva-H. (1989) and Roldán-Quintana (1989, 1991) expanded the mapped area and subsequently studied the plutonic rocks.

Precambrian crystalline rocks include four units: (1) the oldest (1,700 Ma) is a white-yellowish granodiorite which weathers yellowish light-gray and is locally metamorphosed into a gneiss; (2) a yellowish to gray gneiss, locally an augen-gneiss, that presents dark layers constituted by biotite and felsic layers of quartz, K-feldspar, and plagioclase with porphyroblasts of quartz and feldspar, 1 to 2 cm in size. The age of this gneiss is unknown but could be assigned to the Precambrian rocks that were metamorphosed 1,650 Ma ago (Anderson and Silver, 1971, 1981); (3) a dark-gray reddish granite (quartz-monzonite) 1,400 Ma old; and (4) a distinctive red micrographic granite (1,100 Ma). Three of the granites locally show mylonitic fabric, disrupted by several generations of faults, and intruded by two Tertiary plutons. Stratigraphic assemblages represent a portion of the North American craton.

The Paleozoic section consists of a pinkish-red mature orthoquartzite that is Cambrian(?) in age (Rodríguez-Castañeda, 1984). It overlies the crystalline basement and may be equivalent to the Proveedora Quartzite of the Caborca region.

Mesozoic volcanic rocks, composed of rhyolitic tuff, and andesitic flows, are part of the Jurassic magmatic arc widely distributed in northern Sonora (Anderson and Silver, 1979; Corona, 1980; Rodríguez-Castañeda and Anderson, in preparation).

Mylonitic rocks are common and exceptionally well exposed at Cerro Los Chinos (Plate 1). Mylonite has been formed from basement Precambrian granodiorite, porphyritic feldspathic granite, and micrographic granite. A Jurassic age is assigned to this phase of deformation based upon stratigraphic relationships (Tertiary plutons cut these rocks) and field evidence.

The Tertiary granitic suite is composed of two plutons: The coarse-grained porphyritic granite (K-Ar, 51.8 to 70 Ma El Jaralito batholith) and the two-mica granite (K-Ar, 36 Ma Aconchi batholith) (Roldán-Quintana, 1991).

Neogene rocks consist of conglomerate, breccias, and basalt similar to the Báucarit Formation. One basalt has been dated (K-Ar) at 21.7 ± 0.4 Ma, Miocene (Roldán-Quintana, 1979).

CONTACT-RELATIONS

Where exposed, the contacts among Precambrian granites are mainly strike-slip faults. Steep NE striking shear-zone contacts are exposed along the road to the Rancho El Carrizo (Plate 1). Nearly 20 km to the north, near Rancho El Tuli (located off the study area), the micrographic granite intrudes the 1,700 Ma granodiorite (Castillo-Mendoza, 1988; Rodríguez-Castañeda, 1994). The 1,400 Ma porphyritic granite commonly is in fault contact with the other Precambrian rocks.

The Paleozoic orthoquartzite commonly lies structurally above the Mesozoic volcanic rocks and Precambrian granodiorite and micrographic granites, at Cerro El Carrizo and around it. Also, for example, the orthoquartzite overlies mylonitic rocks, forming a brecciated sheet that extends southward of the Arroyo El Carrizo. The contact of the orthoquartzite with the underlying Precambrian granites, exposed in the confluence of the Arroyo El Carrizo and Cañada Los Chinos, is characterized by intense fracturing and brecciation.

Similar features have been observed north of the study area in sierra El Jucaral, where the orthoquartzite is overthrusting volcanic Jurassic rocks. In the fault zone are large breccia boulders (Rodríguez-Castañeda, 1994) similar to those in the study area.

North of Rancho El Carrizo, Jurassic volcanic rocks rest normally above micrographic granite and these volcanic rocks are overlain by allochthonous Paleozoic rocks.

The Tertiary porphyritic granite intrudes the Precambrian gneiss and locally it is cut by the fine-grained granite that also cuts the Precambrian gneiss, granodiorite, and mylonites.

A proposed detachment zone, the La Ramada-Las Jarillas Fault (Plate 1), occurs near the contact between metamorphosed Precambrian granodiorite from weakly deformed Tertiary plutonic rock. This detachment zone is characterized by migmatitic gneiss whose extent is restricted largely to Cañada Las Jarillas. However, rocks north and northwest of Cañada Las Jarillas contain the evidences of the strong Tertiary overprint.

STRUCTURAL GEOLOGY

MAP-SCALE STRUCTURAL FEATURES

A. Fault zones within the study area

The dominant structural features of the Opodepe region, include a zone of brittle-ductile deformation near Rancho El Carrizo and a zone of ductile and brecciated rocks in Cañada Las Jarillas (Plate 1).

Proterozoic foliated granites occur along a strike-slip shear zone (Plate 1) as seen in Cañada El Carrizo. Mylonites derived from these three Precambrian granite bodies occur along this brittle-ductile deformation zone. However, the most important mylonitic zone (Cerro Los Chinos; Plate 1) extends for almost 6 km westward.

The contacts between Precambrian rocks in the west-central part of the study area are strike-slip faults. These faults have developed a mylonitic fabric with systematically oriented

(NE-SW) high-dipping (>56° SE) foliation that has been imposed above Precambrian lithologies (Figure 3). If lineation exists, it is parallel to and lies within foliation and would be represented by elongate minerals such as the grain minerals of the porphyritic granite.

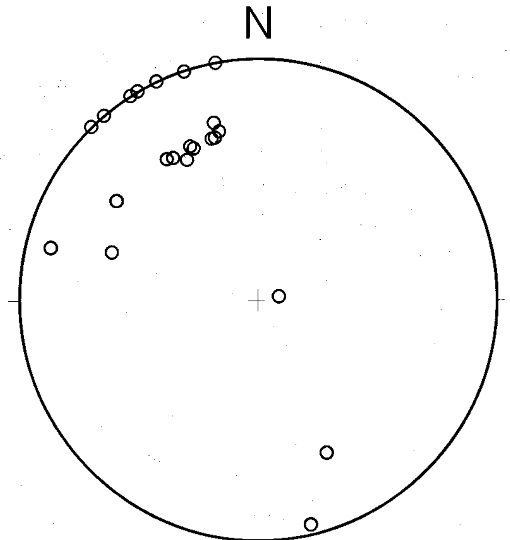


Figure 3. Lower hemisphere equal-area projection. Foliation data from mylonitic Proterozoic rocks in Arroyo El Carrizo and Cerro Los Chinos.

Observations in outcrop and thin section, southwest of Rancho El Carrizo, allow to determine the sense of motion along the shear zone. It corresponds to a dextral-lateral strike-slip faults (see next section). Deformation in mylonites in Cerro Los Chinos (foliation strikes northeast-southwest) (Plate 1) is most pronounced where steeply dipping northeast striking mylonitic rocks of Precambrian (?) granites represent a strike-slip shear zone.

Other structures outside of the strike-slip zones are thrust faults that place Paleozoic rocks above the Mesozoic volcanic rocks (Plate 1). Porphyritic granite overlies the micrographic granite, exposed at Cerro El Carrizo (Plate 1).

Deformation in these rocks may be Late Jurassic in age. Previous regional tectonic considerations (Rodríguez-Castañeda, 1984; Anderson *et al.*, 1984) support the Jurassic age for deformation. Moreover this crystalline basement is intruded by two generations of Tertiary granites that record a youngest period of deformation.

Metamorphic core complex relationships in the Opodepe region are characterized by a major steep normal fault (detachment) that separates ductile hanging-wall rocks (Proterozoic basement) from a ductile deformed footwall (36 Ma granite). The Rancho La Ramada area core complex lies at the northern tip of a large batholithic body (100 km long)—formed, from north to south, by sierra Los Locos, sierra de Aconchi, sierra El Pajarito and sierra Mazatán—which is largely composed of Tertiary plutonic rocks (Roldán-Quintana, 1989, 1991; Roldán-Quintana *et al.*, 1989) (Figure 4).

The detachment fault, here named the La Ramada-Las Jarillas Fault, is a steeply north-northwest fault where an array

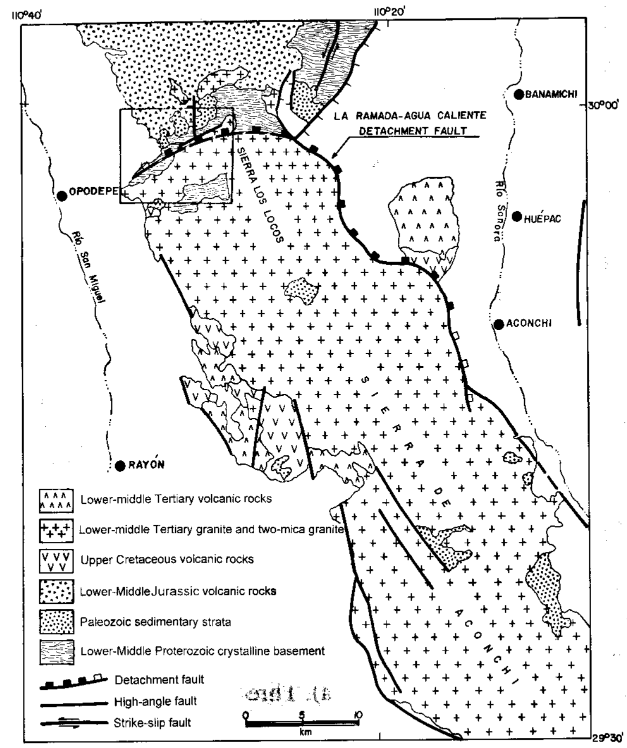
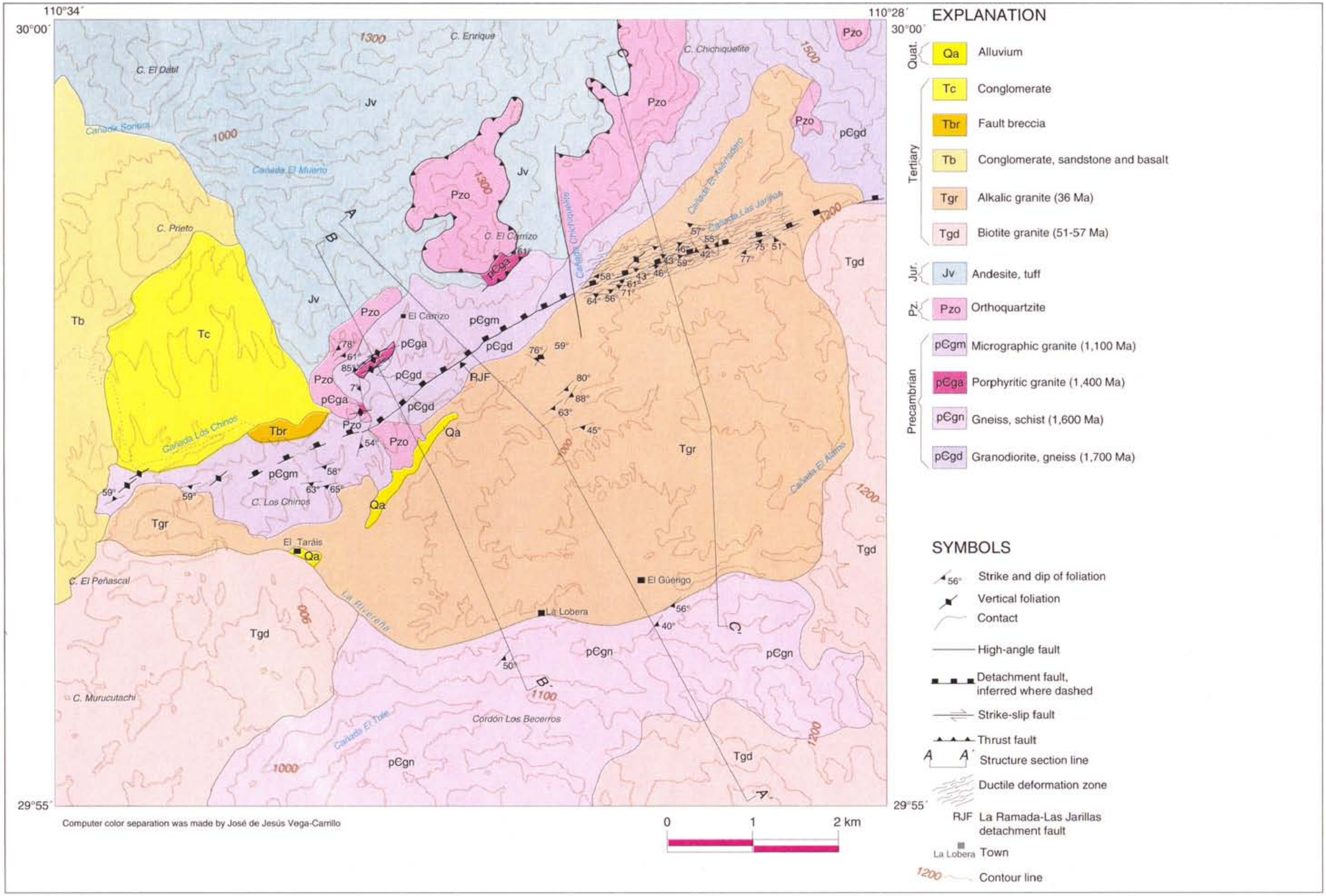


Figure 4. Schematic geologic map of Opodepe region, modified from Roldán-Quintana (1991), showing the La Ramada-Agua Caliente Detachment Fault, a middle Tertiary structure in central Sonora. Location of fault inferred where squares are hollow. Large square shows location of Plate 1.

of mylonitic gneisses and schists is associated to it. The La Ramada-Las Jarillas fault strikes east-northeast and is mapped for a distance of 8 km. Along the Cañada Las Jarillas the detachment fault is characterized by migmatitic gneiss where typical ductile structures, such as boudins, recumbent tight ptygmatic folds, cleavage, and faults have been developed. From the Cañada Chichiquelite to Cerro Los Chinos the detachment fault is defined by intense brecciation, microbrecciation with local occurrence of gouge. The breccia (Tbr, Plate 1) seems to be related to the evolution of this fault.

Foliation in the detachment zone exhibits a consistent orientation, generally east-west with dips >40° southward and southeast (Figure 5). South of the detachment zone, the Tertiary pluton exhibits a northeast-striking steep dipping (>70° to the southeast; Figure 5) non-penetrative foliation.

The Davis and Coney's (1979) subdivision: core, metamorphic carapace, décollement zone, and cover applies in the study area. The core consists of syntectonic granitic intrusions weakly foliated. The geometry of this granitic surface into the characteristic dome-shaped (Davis and Coney, 1979) gives the distinctive physiographic expression of the core complex terrane. Metamorphic carapace shows typical ductile structures. Metamorphism of the granitic Proterozoic rocks that show foliation and schistosity, intruded by Tertiary pegmatitic and aplitic dikes can be part of this metamorphic carapace. The



GEOLOGIC MAP OF RANCHO LA RAMADA AREA IN OPODEPE REGION, CENTRAL SONORA, MEXICO

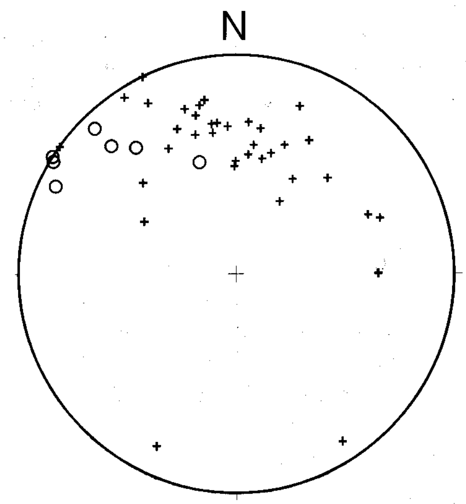


Figure 5. Lower hemisphere equal-area projection of foliation data from the detachment zone. Precambrian and fine-grained Tertiary granites are involved. Cross: foliation in Cañadas Las Jarillas and Aserradero; hollow circle: foliation in Tertiary fine-grained pluton, from Rancho La Ramada to Rancho El Güérigo.

décollement zone is represented by a high-dipping fault (the La Ramada-Las Jarillas Fault) (Plate 2) with a resistant brecciated or microbrecciated fault zone. The unmetamorphosed but intensely fractured and faulted Precambrian, Paleozoic, and Mesozoic rocks represent the cover which commonly is marked by tectonic slices.

Other structures present in the study area are two post-mylonitic main fault systems. One of the groups has a predominant northwest-southeast strike with dips >40° southwest and northeast (Figure 6). Another fault system has a NE-SW orientation dipping >40° toward northwest and southeast (Figure 6).

B. The Agua Caliente Detachment Fault

East of the study area in the Aconchi batholith of Roldán-Quintana (1989, 1991), the La Ramada-Las Jarillas fault becomes a listric normal fault (Calmus *et al.*, 1992b) named the Agua Caliente fault. This structure, the Agua Caliente fault, that marks the boundary of the sierra Los Locos or Aconchi Batholith is part of evolved normal faulting as result of the arched décollement zone (Figure 4). Nourse and others (1994) referred to this fault as Aconchi detachment fault.

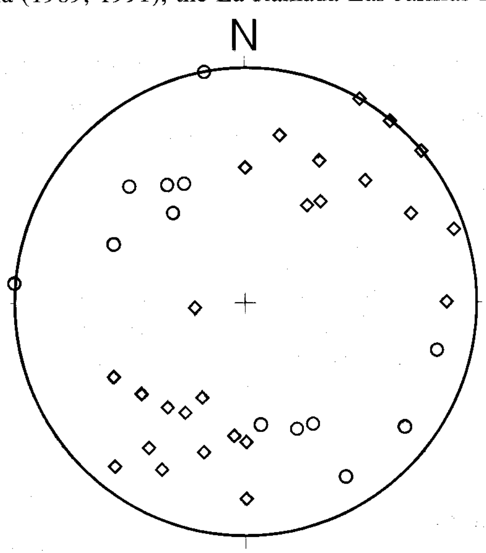


Figure 6. Lower hemisphere equal-area projection. Fault poles of Basin and Range fault systems. NE and NW oriented normal faults. Hollow circles: NE faults; diamonds: NW faults.

For purposes of this paper, the Agua Caliente fault will be called the Agua Caliente detachment fault, because it appears to be formed by processes along a preferred zone of detachment. The Agua Caliente detachment fault does not appear to be controlled by any major pre-existing structure. The detachment fault formed as response to the regional Tertiary extensional event that occurred in late Oligocene-Early Miocene (Rodríguez-Castañeda and Anderson, in preparation; Nourse *et al.*, 1994). Mylonites and lineation in the northeast flank of the sierra Los Locos are geometrically and kinematically associated with this major structure. Direction of extension suggested by the mylonitic foliation and lineation is top to the northeast, based upon characteristics of the lower plate where the Aconchi batholith has developed a cataclastic deformation zone (Calmus *et al.*, 1992b). In contrast, most Cordilleran core complexes in Sonora exhibit a direction and vergence of extension top to the southwest (Nourse *et al.*, 1994). However, this detachment zone is more typical of Sonora core complex because (1) detachment fault is localized between lower plate composed of Tertiary granite with an upper plate of lower Miocene sedimentary and volcanic rocks that belongs to Báucarit Formation; and (2) foliation in lower plate is concordant with shallow dipping detachment.

The age of the Agua Caliente detachment fault is well constrained by relations of the detachment fault and plutonic rocks. Deformation must postdate 36 Ma, because the 36 Ma Aconchi granite displays the tectonic fabric (Calmus *et al.*, 1992b). It may also postdate the 21 Ma basalt (Roldán-Quintana, 1979) in the upper plate Báucarit Formation.

The name La Ramada-Agua Caliente detachment fault is proposed here to identify this structure in central Sonora (Figure 4).

MESOSCOPIC AND MICROSCOPIC DEFORMATION FABRICS

Two kinds of deformation fabrics occur along Cañada Los Chinos and Cañada Las Jarillas. The first one along Cañada Los Chinos appears to be related to the evolution of a dextral strike-slip conjugate fault, spatially associated with the Mojave-Sonora megashear. This right-lateral fault is probably continuation of the strike-slip fault reported by Rodríguez-Castañeda (1994) 10 km to the northeast. The second deformation appears to be related to core complex deformation.

The ages of both mylonitic fabrics are constrained by relations with two Tertiary plutons. Steep mylonitic foliation in basement granitoids must be older than the Tertiary granites; this is inferred to be Late Jurassic in age. On the other hand the age of the deformation fabric in the detachment zone is constrained to be younger than the 36 Ma pluton because the granite of that age displays the tectonic fabric.

Strike-slip mylonitic foliation is well developed in the Precambrian basement and strikes northeast and dips steeply >55° southeast. The orientation is very consistent. Stretched and flattened minerals, and quartz in pressure shadows define the foliation. Asymmetric augen structures within foliation were used to determine sense of shear. Lineation seems to be parallel to and lie within foliation. These mylonites define a mappable unit that indicates a zone of ductile shearing.

Mylonitic porphyritic granitic gneiss is characterized by elongate porphyroclasts of K-feldspar that vary from 1 to 6 cm in length and 6 to 15 mm in width within a matrix of fine-grained quartz and plagioclase. The nature of the K-feldspar porphyritic clasts in the mylonite suggests that they are pre-tectonic and persist as relicts of primary igneous texture. The foliation is defined by bands comprised of smaller grains of quartz and plagioclase which form the matrix around larger asymmetric feldspar augen. Foliation planes are asymmetrically distributed around the porphyroclasts with tails of fine grains of the same composition as the coarser porphyroclast. The tails extend along the foliation in the sense of shearing. Pressure shadows at the end of the porphyroclasts indicate dextral shear.

Granodiorite mylonite (augen-mylonite) is characterized by bands of microcrystalline quartz and feldspar porphyroclasts. Quartz grains are undulose and partially to completely recrystallized. Mylonite (proto-mylonite) derived from micrographic granite presents irregular grains of quartz, some quartz bands. Plagioclase is altered to sericite and abundant microcline occurs. Porphyritic granite mylonite (augen-mylonite) is distinguished by quartz bands and K-feldspar porphyroblasts. Mylonitic rocks in the Cerro Los Chinos vary from augen-mylonite to ultra-mylonite. Mineralogy is composed of microcrystalline quartz, microcline porphyroclasts, biotite, actinolite, epidote, and sphene. Tails of the feldspar porphyroclasts together with C- and S-surfaces indicate a dextral shear.

The general mineralogic characteristics of the basement mylonites are: quartz is flattened and defines fluxion texture around feldspar porphyroclasts which have remained rigid giving to the rock an augen-mylonitic texture. Plagioclase is oriented. Twining is bent and diffuse. Microstructures such as pressure-shadow (NE oriented) at the end of the porphyroclasts in the mylonites, C-S structures, and displaced hard grains of K-feldspar clearly reveal that the fabric evolved through dextral strike-slip shear zones. Porphyroclasts are more elongate in the horizontal direction than in the vertical direction without lineation.

The orthoquartzite is brecciated in the vicinity of faults. Aligned quartz grains are flattened parallel to boundary faults. Recrystallized grains of quartz form polyhedral grains with triple-grain junctions. In thin section quartz grains show undulose extinction. Both, original and recrystallized grains, are deformed. Incipient lineation and foliation are present.

The core complex related deformation fabric is a schistosity and gneissic foliation that developed near the margins of the fine-grained Tertiary intrusive. The Tertiary biotite porphyritic granite is unfoliated. Mineralogy of porphyritic granite in thin sections is quartz, microcline, orthoclase, albite, oligoclase, and accessory biotite, hornblende, zircon. Locally the granite has coarse-grained K-feldspar 2 to 3 cm in size. However, a late fine-grained phase of this granite is weakly foliated. In thin section, foliation occurs as bands bounding domains 1 mm wide. The quartz grains do not show features typical of ductile deformation.

Migmatitic gneissic rocks occur in Arroyo Las Jarillas and Cañada El Aserradero, in the northern part of sierra Los Locos (Figure 5) around the margin of fine-grained Tertiary pluton. In the contact aureole migmatitic amphibolitic gneiss composed of quartzo-feldspathic layers is mingled with foliated biotite and hornblende amphibolite. The amphibolitic gneiss varies from black to dark-green color. It contains few-millimeter-thick white layers of plagioclase and scarce quartz. Under the microscope a granoblastic texture is recognized by porphyroblasts of quartz and feldspar. Besides this quartz-feldspathic gneiss also occurs a dark-green to black color mafic rock of hornblende composition. The composition of this hornblendite is hornblende, tremolite, actinolite, and an unidentified pyroxene. Locally the texture resembles a schist. It is not present dip-slip lineation. Epidote and chlorite are present. Some of the chlorite is alteration of hornblende and the remainder could be hydrothermal.

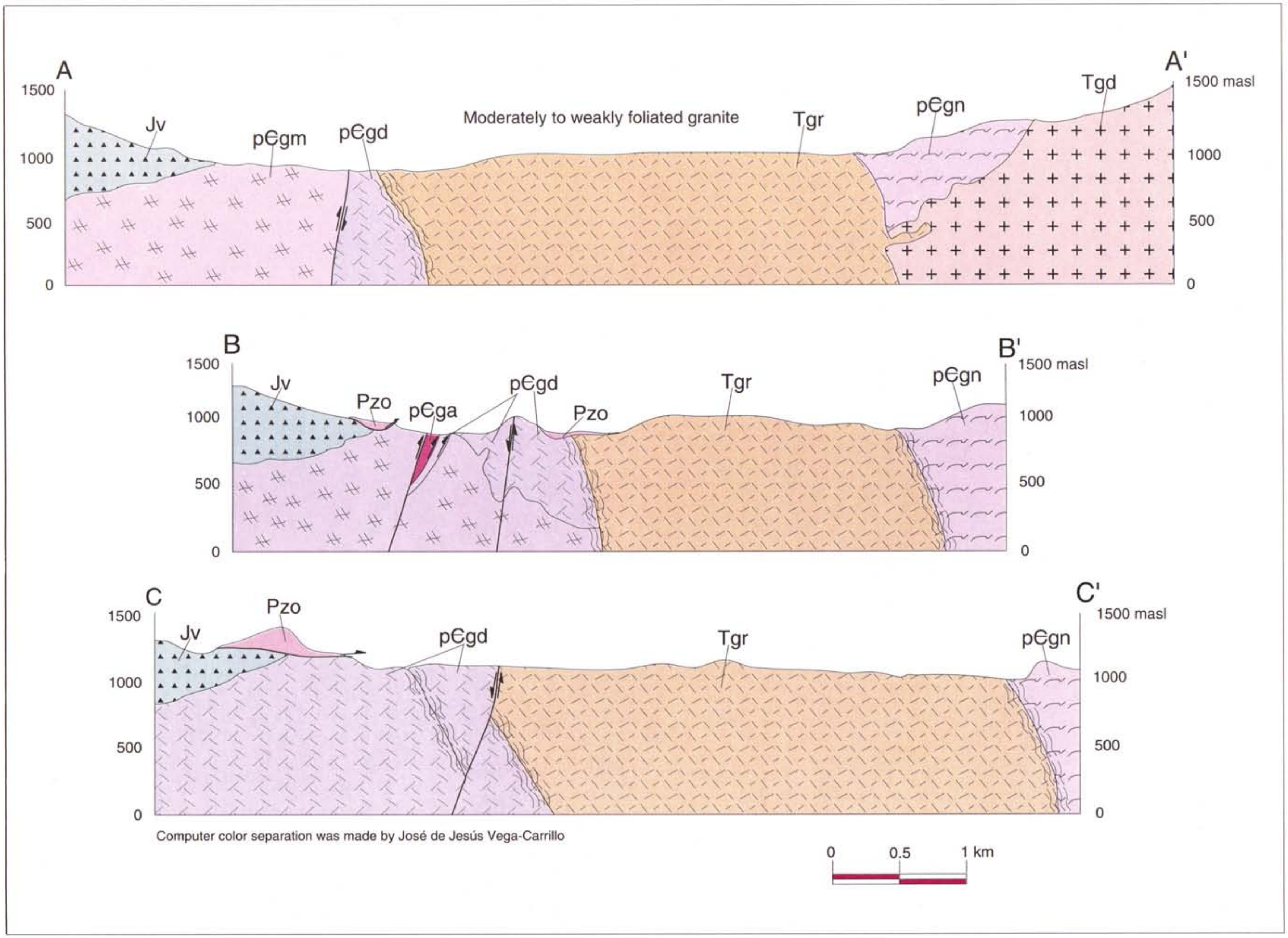
Mirmekitic relict texture suggests that protoliths of some components of the migmatitic gneiss could be plutonic rock (Figueroa-V. and Grijalva-H., 1989). This plutonic rock may be derived from Precambrian granodiorite. In Cañada Las Jarillas the layers of mafic and quartzo-feldspathic material are so mixed that the rocks were very ductile or even experienced partially melted conditions.

Folded layers and boudins are common. The migmatite could be the result of pluton emplacement in the mesozone. The country rock is probably Precambrian granodiorite that has been deformed by the emplacement of the younger granite which is part of a series of multiple intrusions.

Differences in petrographic characteristics of the evolved metamorphic rocks in the studied area suggest that rocks with mylonitic texture are derived from a strike-slip shearing event while gneiss from the detachment zone is part of the evolution of extensional deformation during Tertiary intrusion. Presence of ptygmatic structures is very characteristic of deformed aplite and pegmatite veins in core-complex terrains.

INTERPRETATION

Outcrops of granitic mylonite in the study area (Cerro Los Chinos and Arroyo El Carrizo) represent a brittle-ductile shear zone, that could be associated with a shear zone of regional dimension: the Mojave-Sonora megashear. Only a



STRUCTURAL CROSS SECTIONS IN THE LA RAMADA AREA IN OPODEPE REGION, CENTRAL SONORA small part of this zone has been exposed in the study area. The mylonite is the result of regional tectonic movements which compressed and translated the upper-crustal rocks in northern Sonora (Rodríguez-Castañeda and Anderson, in preparation). Mylonites are exposed due to uplift and erosion, and therefore it is recognized that a deep-seated fault zone has been exhumed.

Outcrops of Proterozoic rocks north of the area described by Rodríguez-Castañeda (1984) initially as San Isidro gneiss is a mylonite similar to that of this area. Both mylonitic fabrics—in the study area and north of it—may be related to the megashear that is generally believed to have been active during Late Jurassic time. Other structures like thrust faults that juxtapose Paleozoic orthoquartzite above Jurassic volcanics are part of the contractional stresses associated to the Mojave-Sonora megashear (Rodríguez-Castañeda, 1984, 1990).

The deformed youngest Tertiary granite and its relationship with the Proterozoic granodiorite (1,700 Ma), reveal a middle Tertiary tectonism as a response of a regional extension, thermal inclusion, and tectonic denudation.

The migmatitic gneiss formed within the extensional shear zone at levels of 10 km depth or more. The intense denudation that accompanied progressive strain raised early-formed, deep-level migmatitic gneiss through higher structural levels (Plate 2). The mylonitic and brittle-deformed rocks that formed at shallow levels probably were eroded. The original shapes of the core complex shear zones which commonly are spoon-shaped or mullion-like curviplanar form are controversial (Davis, 1987). However, in contrast to the inclination of the shear zone that commonly is shallow dipping in other core complexes, in the study area this ductile-brittle shear zone is steep dipping at angles >60°. This orientation is postulated to be the initial dip as a response to continental crustal extension. However, rotation of the ductile shear zone during uplift/exhumation of the metamorphic core complex can not be ruled out. The shear zone angles with an average less than 30° that is observed in most of the core complex in northern Sonora and southern Arizona may reflect significant rotations associated with large magnitude extension in these areas.

Gravity sliding of Tertiary volcanic rocks east of the study area (Calmus *et al.*, 1992b) could support the idea of core complex related denudation. Alternatively, southwest of the present area, González-León and Jacques-Ayala (1988) and Castro and Morfín-V. (1988) indicate that structures in the Cerro de Oro area are part of a Mesozoic Laramide disruption that is widespread in Sonora. Another interpretation is that tectonic slices in that area could be a result of listric normal faulting due to gravity sliding. This deformational style seems to be common in Tertiary extensional terranes.

A remarkable feature is the distribution of the metamorphic complex in this part of Sonora. Both the Mazatán core complex and the La Ramada core complex crop out in the southern and northern tips of a large Tertiary batholith. A similar distribution is present in the Coyote mountains and Pozo Verde core complex which crop out in the northern and southern tips of the Baboquivari mountains in southern Arizona (Davis *et al.*, 1981; Haxel *et al.*, 1984) (Figure 7).

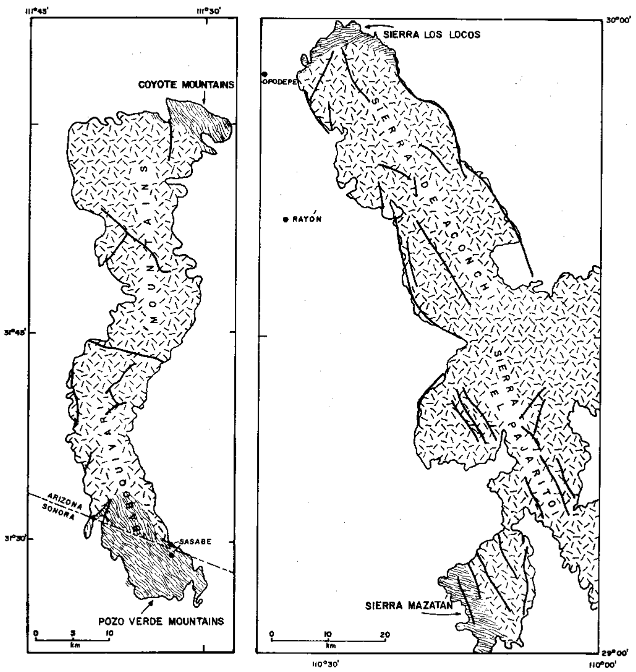


Figure 7. Comparison of outcrops-distribution of metamorphic core complex type rocks in the Baboquivari mountains (Coyote mountains and Pozo Verde mountains, from Haxel *et al.*, 1984) in southern Arizona and sierra de Aconchi-sierra El Pajarito in central Sonora.

It has been suggested that there is a genetic relationship among the Jurassic Mojave-Sonora megashear (forming a thrust slice along NW-SE belt in northern Sonora) and the Tertiary low-angle normal faulting (Nourse, 1993) and formation of the Basin and Range. Particulary in Sonora there is a direct relationship between the origin of core complex and denudation that exhume the widespread Tertiary plutonic rocks along Sonora. Recent studies in central Sonora (Rodríguez-Castañeda, 1994) show a thick sequence of volcano-sedimentary rocks of possible Late Cretaceous age that seems to be have been deposited in a large north-south (?) oriented basin as result of uplift in Late Cretaceous. This concept is related to the model of overthickened crust that had been created by previous episodes of compression (Coney and Harms, 1984), although in Sonora are present perhaps extension with associated uplift. This model predicts the spatial association of Tertiary extensional fabrics and upper Mesozoic-lower Tertiary structures.

NW-SE and NE-SW fault systems are the result of σ_3 oriented NE and NW respectively (Rodríguez-Castañeda and Anderson, in preparation), associated to the evolution of the normal faulting of the Basin and Range province of southwest United States and northern Mexico.

CONCLUSIONS

The structural geometry and lithologic characteristics of the mylonitic gneissic zone along the Cañada Las Jarillas and

Cañada El Aserradero constitute evidence of a metamorphic core complex. The location of migmatites represents the site of intrusion of the 36 Ma granite into a shear zone developed in Precambrian rocks. The thermal input of 36 Ma granite must have softened the country rock and made the site vulnerable to ductile flow.

The main body of the Tertiary granite that intruded Proterozoic rocks remained almost rigid during deformation, compared with other core complex bodies in northern Sonora. The Tertiary pluton actually shows a non-penetrative foliation (moderately to weakly foliated) without lineation. The main deformation as was noticed occurs in the margins of the granite.

The effect of mid-Tertiary extension was a metamorphic fabric formed around 36 Ma in plutonic rocks. The tectonic fabric is most obvious along the detachment ductile zone, which constitutes the La Ramada-Agua Caliente fault, north and northeast of the sierra Los Locos.

The characteristics of deformation are similar to other mid-Tertiary ductile deformation zones described by Nourse (1989) in the Magdalena region, northern Sonora, and in the sierra de Mazatán, south of the study area (Davis *et al.*, 1981). Related green-schist to amphibolite facies metamorphism and intrusion of syntectonic mid-Tertiary peraluminous granites are similar in age, metamorphic grade, and fabric to the core complexes present in northern Sonora and southern Arizona.

Jurassic metamorphic fabric in the Proterozoic rocks records northeast directed shear while in the mid-Tertiary extensional fabric records east-west and northeast directed shear. These differences in age, distribution, characteristics, and sense of shear between the two fabrics indicate a difference in strain and association with two different models, the Mojave-Sonora megashear and metamorphic core complex deformations, respectively.

Geologic relationships in Opodepe region record a history of compression associated with dextral shear, followed by extension and denudation. Structural terranes similar to the present in the study area have been recognized in several places in Sonora.

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