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AN OVERVIEW OF THE CENOZOIC TECTONIC AND MAGMATIC EVOLUTION OF SONORA, NORTHWESTERN MEXICO

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ABSTRACT

Cenozoic rocks are widely distributed in Sonora, with igneous rocks being the most abundant, followed by clastic rocks. Metamorphic rocks, even though minor, have great significance in the geologic history of this area. The purpose of the stratigraphic nomenclature here proposed is to organize the naming of units, which at present is quite loose and sometimes confusing. For units we summarize information regarding their tectonic setting as well as isotopic dates for the timing of tectonic events. During the Cenozoic important changes occurred in the tectonic regime due to plate interactions, from subduction in the Paleocene-middle Miocene, to transtension in the late Miocene to Quaternary. The tectonic and magmatic evolution of Sonora is divided into three time intervals: (1) The Paleocene-Oligocene, characterized by abundant calc-alkalic magmatism, related to subduction. Two units of igneous rocks are proposed, the El Jaralito intrusive suite, and the Nacozari group. Changes in the subduction motion induced a change in magmatic activity, giving rise to the Sierra Madre Occidental, a widespread felsic volcanism, related to calderas; this sequence is here named the Yécora group. In this same period, there was emplacement of the two mica granite here referred to as the Aconchi granitic suite. (2) The early to middle Miocene represents a period of transition, when the main stress field changed from compression to extension. Igneous rocks exhibit both calc-alkalic and alkalic affinities, and volcanism was bimodal. During this period, the volcanic rocks along the coast include the Empalme group. The metamorphic rocks associated with the core complexes have been included in the Sierra La Madera metamorphic complex. In the syntectonic basins associated with the core complexes was deposited a volcaniclastic unit, the Magdalena group, containing volcanic interbeds. Another volcaniclastic unit is the Río Yaqui group, which includes clastic and volcanic rocks of calc-alkalic and alkalic affinity. These rocks and the elongated basins were formed in a back-arc position during a period here named the Basin and Range-I phase of normal faulting. (3) The middle Miocene to Present was characterized by diminished volcanism, consisting of mafic rocks of alkalic affinity. The formation and subsequent filling of the continental basins by clastic units are here included in the Sonora group; this is one of the most important geologic processes during this time interval. This event is here referred to the Basin and Range-II. The extrusion of Pliocene-Quaternary basaltic lava flows represents the youngest volcanic activity in continental Sonora; these rocks are referred to the Moctezuma group. Finally, rocks and sediments associated with the opening of the Gulf of California, which in some areas produced marginal marine and deltaic deposits, are here designated as the Río Colorado group. These rocks are poorly known; however they consist of marine sandstone and conglomerate, as well as sand and gravel deposits.

Key words: Stratigraphy, subduction, distension, Cenozoic, Sonora, Mexico.

RESUMEN

Las rocas cenozoicas están ampliamente distribuidas en Sonora, dominando en gran parte los afloramientos de rocas ígneas, seguidas por rocas clásticas. Por su parte, los afloramientos de rocas metamórficas, aunque en menor cantidad, tienen un gran significado en la historia geológica regional. El objetivo de la nomenclatura estratigráfica que se propone en este trabajo, es organizar de manera práctica una gran cantidad de unidades nombradas sin un orden establecido, lo que ha provocado confusión al momento de llevar a cabo correlaciones regionales. La información compilada para cada una de las unidades, incluyendo datos isotópicos, permite ubicarlas en tiempo y en espacio respecto al ambiente tectónico de formación. La interacción entre las placas ha producido cambios importantes en el régimen tectónico durante el Cenozoico, desde una subducción del Paleoceno al Mioceno medio, hasta una transtensión del Mioceno tardío al Cuaternario. La evolución tectónica y magmática de Sonora se divide en tres intervalos: (1) Paleoceno-Oligoceno, caracterizado por un magmatismo calcialcalino abundante relacionado a subducción. El ensamble intrusivo El Jaralito y el grupo Nacozari, son las unidades estratigráficas que se proponen como representativas de este evento. Cambios en las características de la subducción producen un cambio en la actividad magmática, desarrollándose un vulcanismo félsico asociado a calderas que está ampliamente distribuido a lo largo de la Sierra Madre Occidental; esta secuencia se nombra como grupo Yécora. Durante este mismo período, se da el emplazamiento de granito de "dos micas", incluido en este trabajo dentro del ensamble granítico Aconchi. (2) Mioceno temprano-Mioceno medio, representa un período de transición tectónica, cuando el ambiente tectónico regional cambia de compresión a distensión. Las rocas ígneas emplazadas presentan afinidades tanto alcalinas

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como calcialcalinas y el vulcanismo es principalmente bimodal. Para este período, se propone el grupo Empalme, el cual incluye rocas volcánicas que afloran a lo largo de la porción costera del estado. Las rocas metamórficas asociadas al desarrollo de los *"core complexes"* en Sonora son incluidas dentro del complejo metamórfico Sierra La Madera; mientras que a las unidades volcaniclásticas que representan el relleno sedimentario de las cuencas sintectónicas de este evento, se les incluye dentro del grupo Magdalena. Otra unidad volcaniclástica para este período es el grupo Río Yaqui, el cual está representado por rocas clásticas y volcánicas de afinidad alcalina y calcialcalina. Estas rocas, y las cuencas elongadas donde fueron depositadas, fueron formadas en un ambiente de tras-arco durante el período de fallamiento normal aquí nombrado como la fase *Basin and Range* I. (3) Mioceno Medio-Cuaternario, fue caracterizado por una disminución en la actividad volcánica, el cual consistió principalmente en rocas máficas de afinidad alcalina. La formación de cuencas sedimentarias y su relleno sedimentario por unidades clásticas, aquí nombrado como grupo Sonora, es uno de los procesos geológicos más importantes durante este período de tiempo, y al cual en este artículo se menciona como la fase *Basin and Range* II. La extrusión de los basaltos pliocénico-cuaternarios del grupo Moctezuma representa la actividad volcánica más reciente en la porción continental de Sonora. Finalmente, los afloramientos de rocas y sedimentos asociados con la apertura del Golfo de California, representados en algunas áreas por depósitos deltaicos y marino-marginales, son mencionados en este artículo como grupo Río Colorado. Aunque son poco conocidas, estas secuencias consisten, de manera general, en areniscas y conglomerados marinos, así como en depósitos de arena y grava.

Palabras clave: Estratigrafía, subducción, distensión, Cenozoico, Sonora, México.

INTRODUCTION

The Cenozoic tectonic evolution of northwestern Mexico, and Sonora in particular, is one of the most complex of the country, since during this period there were important changes in the tectonic environment, from the development of a continental arc in the early Tertiary to intense normal faulting related to extension in middle Tertiary time (Aranda-Gómez *et al.*, 1997). Some of the most important geologic features of this region such as the Sierra Madre Occidental volcanic field (McDowell, 1993), and the Gulf of California (Larson *et al.*, 1968) were produced during this period.

Cenozoic rocks are widely exposed in Sonora and cover a greater area than older rocks. In the Geologic Map of the Republic of Mexico (Ortega-Gutiérrez *et al.*, 1992), and in the Geologic Map of Sonora (Fernández-Aguirre *et al.*, 1993), Tertiary volcanic rocks are the predominant rock type in the eastern portion of Sonora, and the clastic continental deposits of Late Cenozoic age are more abundant to the west on the coastal plains and deltas. In this paper, the area considered is limited to the south by latitude 28ºN and to the north by the border with the United States; to the west from the coast of the Gulf of California, and the border with the State of Chihuahua to the east. Our description also includes Tiburón Island within the Gulf of California (Figure 1).

In northwestern Mexico, the Cenozoic rocks testify the continuation of a very important period of igneous activity, and record a fundamental change in tectonic regime from compressive deformation in the early Paleocene to extension in the late Oligocene. Regionally, during this time, the stress regime is interpreted to be compressive with the maximum principal stress oriented east-northeast, reflecting east-northeast convergence between the North American and the subducting Farallon plate (Aranda *et al.*, 1997). However, to prove the age relations in detail is more complex, although veins and dikes striking north-northwest (perpendicular to the principal stress) are present in mining districts such as Cananea and Mina María in Sonora, and Ocampo in Chihuahua (40 km southeast of Yécora); the Paleocene-late Oligocene age of the dikes and veins is only known by field relations (Clark *et al.*, 1979).

From the geology of northern Sonora, only recently have there been published studies describing in detail the chemistry of intrusive and volcanic rocks, allowing the interpretation of their tectonic setting (Cochemé and Demant, 1991; Richard,

Figure 1. Map of Sonora showing the location of the study area and some localities mentioned in the text

1991). In addition, the studies of deformation in core complexes (CC), and the dating of the intrusives associated with them, have provided good age estimates regarding the earliest Tertiary extension known in this portion of Sonora (Nourse *et al.*, 1994).

Although the early Tertiary is interpreted to have been a period of compression, the rocks of this age have only been affected by wide open folds, which at outcrop scale only present minor tilting. Normal faulting is the main structural characteristic of the Cenozoic deformation; the effect of this deformation consists of at least two directions of faulting outside of that of the CC. More recently there is active tectonics associated with the opening of the Gulf, consisting of strike-slip faults and the development of pull-apart basins within the Gulf of California, which represents a plate boundary.

In the following paragraphs the tectonic evolution of Sonora will be described in more detail, beginning with units associated with subduction, following with the analysis of other units related to extension, and finally a brief description of the active tectonics inland and within the Gulf of California.

The stratigraphic nomenclature of the Cenozoic rocks of Sonora is poorly established, and it is restricted to a few units, including the Báucarit and Lista Blanca Formations (King, 1939). However, enough stratigraphic and cartographic information has been published, which allows us to propose a new informal stratigraphic nomenclature which may be useful for more regional interpretations, and subsequently a better communication among people working in Cenozoic rocks.

With basis on published information and new data, the objectives of this paper are: (1) to describe the tectonic evolution during the Cenozoic era in Sonora on the basis of the characteristics of the magmatism and sedimentation associated with each one of these episodes; and (2) as mentioned before, to propose a series of lithostratigraphic and lithodemic informal units, at level of group, suite and complex. All this effort is directed towards the definition of a lithostratigraphic column of the Cenozoic of Sonora. It is also expected that the information contained in this paper will constitute an updated compilation of the geologic history of the Cenozoic rocks of Sonora.

PRE-CENOZOIC ROCKS

Late Cretaceous to early Paleocene

At the end of the Cretaceous period, an episode of intense igneous activity related to subduction was still active in northwestern Mexico (Damon *et al.*, 1983; McDowell and Clabaugh, 1979). At Late Cretaceous time, a group of large batholiths and some volcanic rocks associated with them, were emplaced in a belt along coastal and central Sonora. The intrusives are of calc-alkalic affinity and their mineralogy includes biotite + hornblende + sphene. At this time, there were also deposited several volcanic and volcaniclastic associations described as the Tarahumara (McDowell *et al.*, 1994), El Tuli (Martínez-García and Soots-López, 1994), and Papigochi (Grijalva-Noriega, 1995) formations. The intrusive bodies and the volcanic rocks represent a magmatic arc constructed on a continental margin that was related to subduction of the Farallon Plate under the North American Plate during Late Cretaceous to the Eocene time (McDowell and Clabaugh, 1979).

CENOZOIC ROCKS ASSOCIATED TO SUBDUCTION

Paleocene-early Eocene

This magmatic activity continued at least to early Eocene as calc-alkalic intrusions, here grouped as the El Jaralito intrusive suite. The main characteristic of the plutons of this suite is a wide range of lithologic composition from granite to diorite (Roldán-Quintana, 1991). In age they cover the interval from 50 to 65 Ma. This suite is the Cenozoic equivalent of the Sonoran Laramide Batholith defined by Damon and collaborators (1983); however, we prefer the use of the term El Jaralito because it better constrains the age and composition than the former. Another important characteristic of the intrusives of this suite is their wide geographic distribution covering a great area of eastern Sonora (Figure 2).

Spatially associated with these intrusive bodies is a series of volcanic and volcaniclastic rocks, here named as the Nacozari group; they are well exposed in eastern Sonora (Figure 2). These volcanic rocks represent the extension of the Late Cretaceous continental arc to the east; in the region of Nacozari they range in age from Paleocene to early Eocene. These volcanic sequences vary in composition from andesitic to dacitic, and to a lesser extent they contain interbeds of rhyolitic rocks that have been dated at 52.1 ± 1.9 Ma (Berchenbriter, 1976) and 43.2 ± 1.1 Ma (Damon *et al.*, 1983). Because of the intense hydrothermal alteration present in these rocks, it is not possible to obtain useful geochemical information from them. This volcanic sequence is commonly intruded by the batholiths of the El Jaralito intrusive suite, and it is lithologically similar to the Upper Cretaceous calc-alkalic volcanic rocks; for this reason we consider that the Late Cretaceous arc along the continental margin was still active at the beginning of the Cenozoic. The Nacozari group is broadly equivalent to the Lower Volcanic Complex in the Sierra Madre Occidental defined by McDowell and Clabaugh (1979).

Middle Eocene-Oligocene

A change in direction of Farallon-North America plate convergence occurred sometime between 50 and 42 Ma, which is related to a counter-clockwise rotation of the Pacific Plate (Engebretson, 1982; Engebretson *et al.*, 1985; Stock and Molnar, 1988). During this period a different type of intrusive activity occurred consisting of smaller granitic batholiths, with a mineralogy of biotite + muscovite + garnet. These batholiths

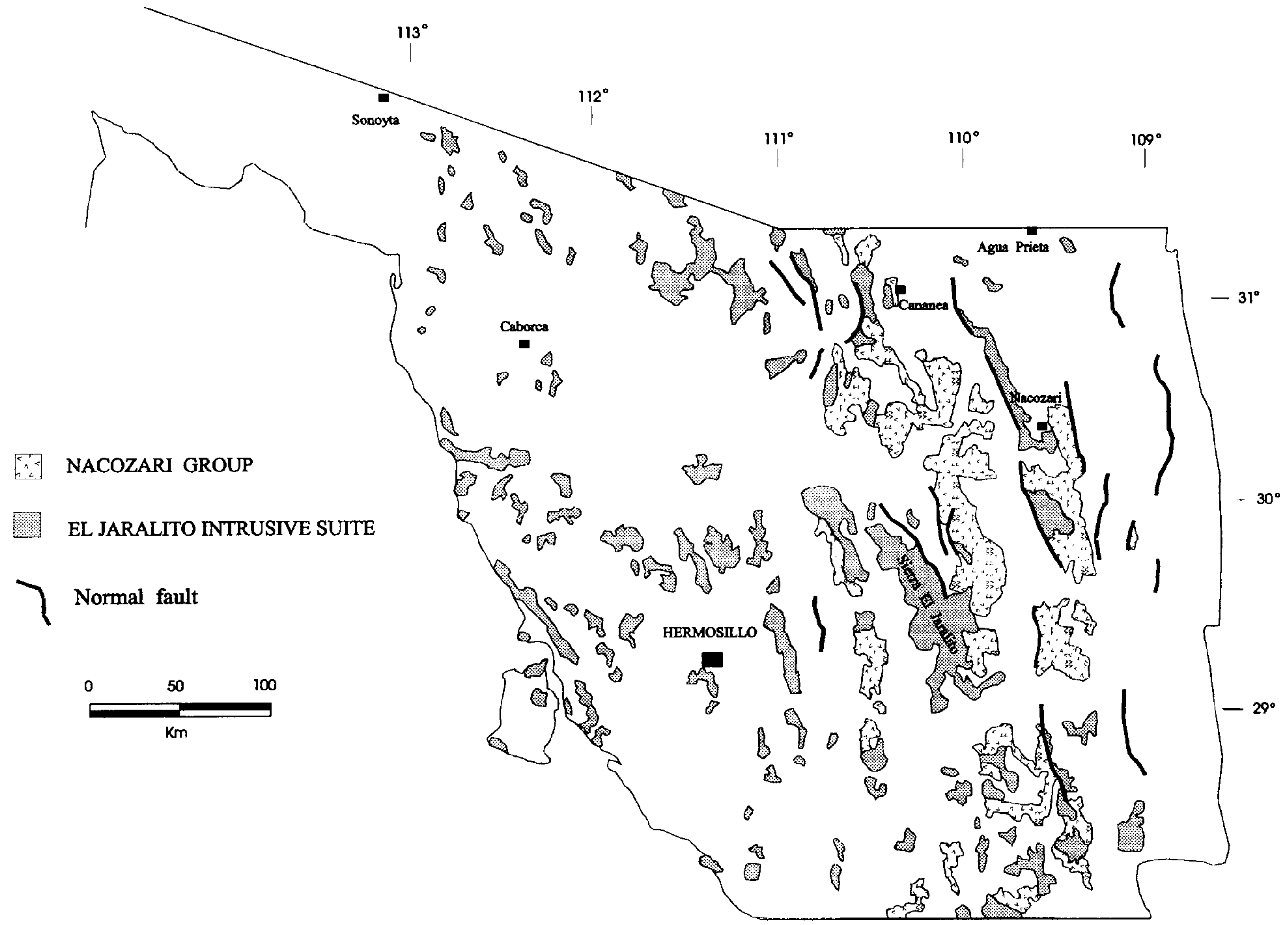

Figure 2. Outcrop distribution of the El Jaralito intrusive suite and the volcanic rocks of the Nacozari group (including rocks of Late Cretaceous age). Modified after Ortega-Gutiérrez and collaborators (1992) and Fernández-Aguirre and collaborators (1993).

correspond to two-mica granite and here are defined as the Aconchi granitic suite. The geographic distribution of these intrusives is restricted in northern Sonora to a narrow belt oriented northwest, from Sierra de Mazatán to El Sásabe on the border with the United States (Figure 3). The isotopic data available for these intrusives is limited, but in the area of Aconchi, K-Ar ages from 35 to 41 Ma have been reported (Damon *et al.*, 1983; Roldán, 1991); and in Estación Llano, a K-Ar age of 41 Ma was reported by Pérez-Segura and Cheilletz (1991). The geochemistry, field relations and the structures associated with these leucogranite rocks, suggest that they were emplaced during a period in which the tectonic environment was changing from subduction to extension within a continental arc (Radelli *et al.*, 1995). Contemporary with these leucogranite rocks, in eastern Sonora, a felsic explosive caldera-related volcanism, characterized by abundant ignimbrites and rhyolitic domes was generated to form the Sierra Madre Occidental (Figure 3). These felsic volcanic rocks are here included in the Yécora group, which also contains andesite and dacite at the bottom. Because of their calc-alkalic affinity, they have been related to subduction (Cochemé and Demant, 1991). The isotopic ages for these rocks suggest an age range for the Yécora group in eastern Sonora from 30 to 35 Ma (McDowell, 1993); however, the entire volcanic province of the Sierra Madre Occidental is considered a broader range, varying from 28 to 45 Ma (Aguirre-Díaz and McDowell, 1991).

Late Oligocene-Miocene

Along the coast in central Sonora, in the Sierra Santa Úrsula, a volcanic sequence of intermediate to felsic composition and of calc-alkalic affinity was described by Mora-Álvarez (1992). These rocks have been included as the lower part of the Empalme group, and their age range reported varies from 23.5 to 11.4 Ma (Figure 4). The geochemical characteristics of these rocks suggest their association with subduction processes. This late Oligocene-Miocene magmatic arc occupied the area of what is now the Gulf of California (Mora-Álvarez, 1992; McDowell *et al.*, 1997; Umhoefer *et al.*, 1996).

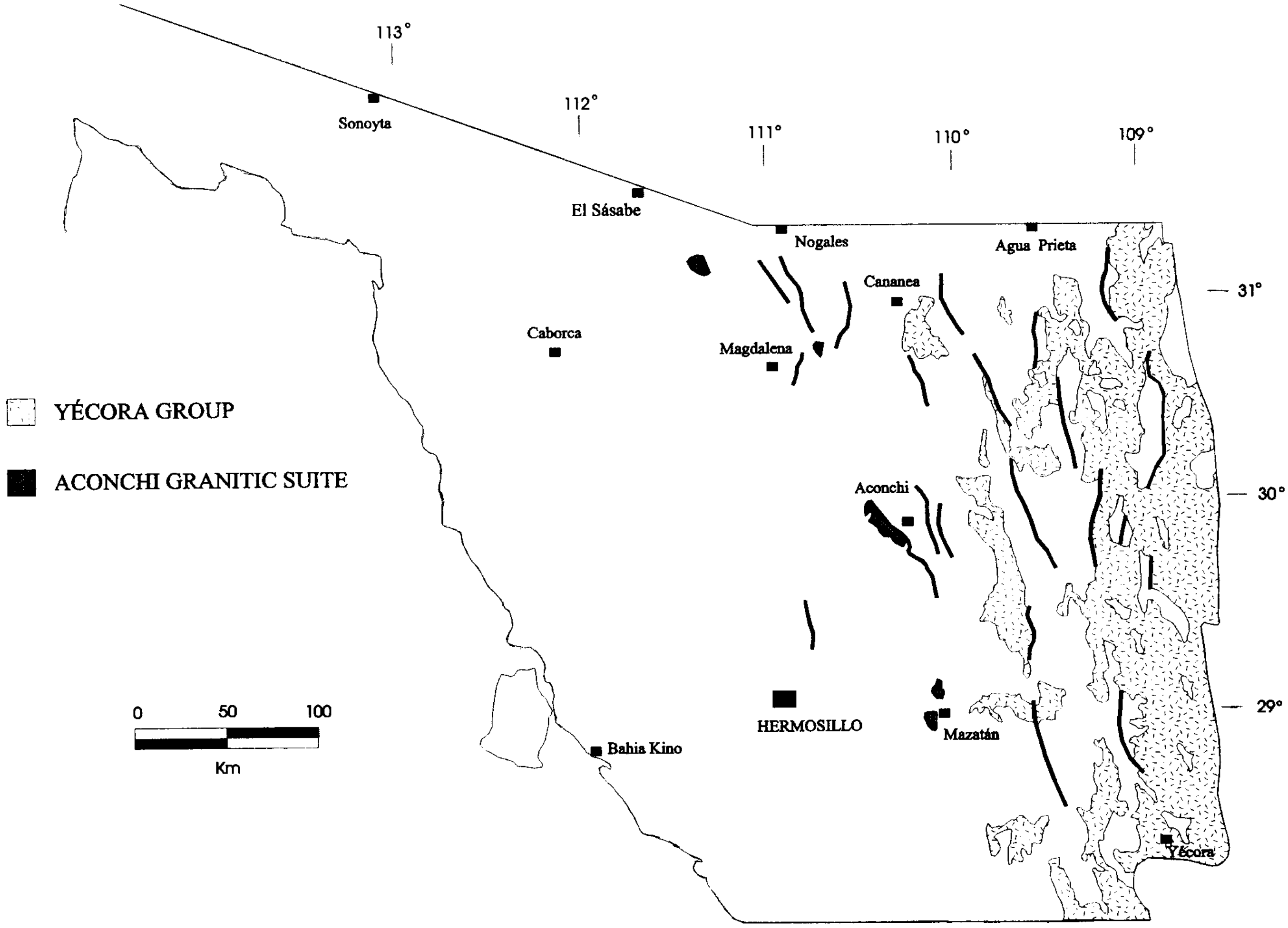

Figure 3. Outcrop distribution of the intrusive rocks of the Aconchi granitic suite and the volcanic rocks of the Yécora group. Modified after Ortega-Gutiérrez and collaborators (1992) and Fernández-Aguirre and collaborators (1993).

Within this region, on Isla Tiburón, this group is represented by a volcaniclastic sequence in which are intercalated marine conglomerates of middle Miocene age (Neuhaus *et al.*, 1988; Cassidy, 1990). The upper part of the Empalme group consists of a sequence of felsic ignimbrites intercalated with tholeiitic basalts, dated by K-Ar at 10.3 to 8.5 Ma (Mora-Álvarez, 1992). These two episodes of magmatic activity present in the lithology of the entire Empalme group, have been interpreted as indicators of a change from subduction to rifting along the western margin of North America in late Cenozoic time. However, the timing of the end of the arc volcanism is not clearly constrained with data on rocks of this unit.

CENOZOIC UNITS ASSOCIATED WITH EXTENSION

It is not well known exactly when the main stress field changed from compression to extension; however it seems that the formation of the metamorphic core complexes (CC) was the first evidence of extensional deformation in northern Sonora. Extension in Sonora is evidenced by various structural, geochemical and sedimentological characteristics in rocks ranging in age from late Oligocene to the present. In the Neogene, extension environment is responsible for the construction of the morphology present in continental Sonora today, and for the formation of the Gulf of California.

Late Oligocene-middle Miocene

The volcanic rocks of this age are represented by a sequence consisting mainly of basalt and basaltic andesite flows of alkalic affinity (Cochemé and Demant, 1991), that are intercalated with clastic rocks. However, as mentioned before, the first evidence of a tectonic regime in extension is expressed in the metamorphic core complexes (Nourse *et al.*, 1994). These structures are characterized by the development of detachment faults and an associated ductile deformation which produced metamorphic rocks (mainly mylonitic) of Tertiary age (Figure 5), which are unique in all northwestern Mexico. These metamorphic rocks are here referred as the Sierra La Madera metamorphic complex. Ar/Ar ages reported by

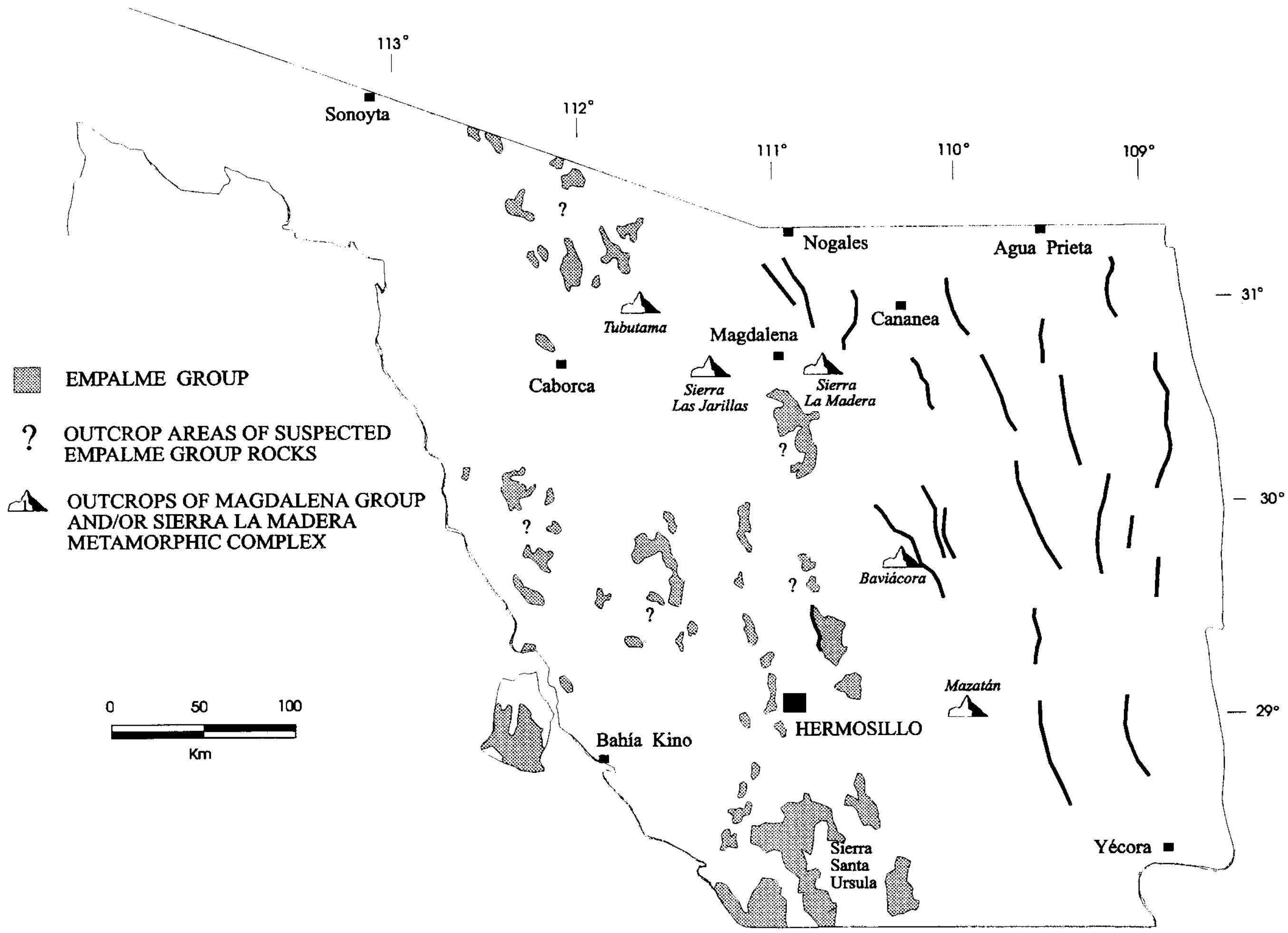

Figure 4. Outcrop distribution of the volcanic rocks of the Empalme group. North of Hermosillo, the inclusion of the outcrops of Tertiary volcanic rocks within the Empalme group is tentative. Modified after Ortega-Gutiérrez and collaborators (1992) and Fernández-Aguirre and collaborators (1993).

Herrera-Urbina and collaborators (1995) from rocks of this complex in localities near Magdalena (Sierras La Jojoba and Las Jarillas), suggest that the ductile deformation was active at 28 Ma.

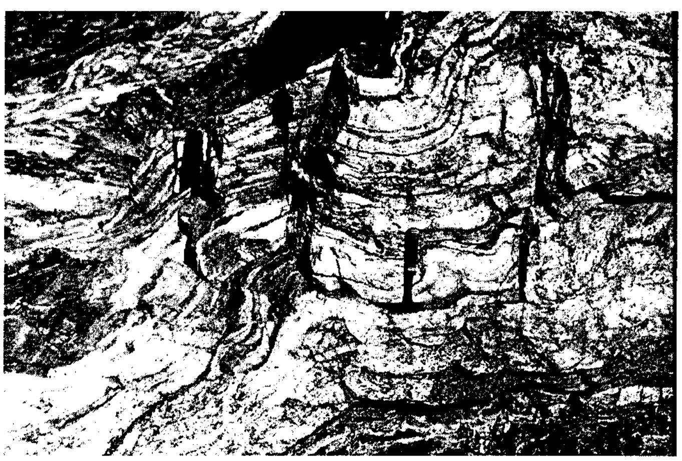

Figure 5. Mylonitic gneisses of the Sierra La Madera metamorphic complex. Arroyo El Bachán in Sierra Mazatán, 72 km east of Hermosillo.

Also, this extensive tectonic event produced a series of syntectonic basins, in which the associated volcanism presents alkalic affinity. The volcanic rocks consist of andesitic flows interbedded with lake deposits filling the basins and which are defined here as the Magdalena group. Sequences of this type have been described in basins associated with other CC such as Tubutama-Magdalena (Gómez-Caballero *et al.*, 1980), Baviácora (Roldán-Quintana, 1989), and Mazatán (Vega-Granillo, 1996). It is important to mention that the outcrops of the Sierra La Madera metamorphic complex and the Magdalena group are not included in the figures because at the scale used in this compilation, they cannot be shown. However, the outcrops are indicated in Figure 4.

K-Ar ages suggest that the lower plate cooling and the tectonic unroofing during extension in the CC occurred between 25–18 Ma (Nourse *et al.*, 1994). The andesites within the Magdalena group gave K-Ar ages of 21.6–22.7 Ma

(Miranda-Gasca and DeJong, 1992), and the alkalic volcanic rocks in the El Torreón Formation, considered as part of this group, were dated as 19 ± 0.9 Ma (Miranda-Gasca and Quiroz-Luna, 1988). The continental extension which produced the Cordilleran CC including the ones in Sonora, was developed in a tectonic environment of intra- or back-arc position, because the subduction in Western North America was still active in the west during this time interval (Dickinson, 1991; Stock and Lee, 1994).

Contemporary with the deep extensional event of the CC, high angle normal faulting product of a N70°E-S70°W extension direction (Stewart and Roldán-Quintana, 1994) was developed at the upper crustal levels in central and eastern Sonora. This event is defined here as the early phase of the Basin and Range deformation (BR-1). As in the case of the CC, the sedimentary basins generated by the extension in the BR-1 phase were filled by the clastic and volcanic interbeds, here defined as the Río Yaqui group (Figure 6). In this unit are included a series of volcanic rocks defining a range of age for this event between 27–10.4 Ma. The Río Yaqui group includes the clastic sequence (mainly conglomeratic) with mafic volcanic-rock interbeds of the Báucarit Formation, and in some localities as Onavas and Sierra del Bacatete, a volcanic sequence of felsic flows, including ignimbrites and tuffaceous sandstones, of the Lista Blanca Formation (Morales-Montaño *et al.*, 1990). The Lista Blanca Formation in some localities conformably overlies the Báucarit Formation and has been dated by K-Ar between 12.8–10.4 Ma (Bartolini *et al.*, 1994; McDowell *et al.*, 1997).

Middle Miocene-Holocene

Beginning in the middle Miocene, a late extensional phase (BR-II) is present in northern Sonora, that has different characteristics of orientation and distribution of the structures than the early Basin and Range deformation. The faults produced by this phase present a 10° clockwise rotation presenting a N80°E-S80°W extension direction (Stewart and Roldán-Quintana, 1994). The BR-II tectonic phase is responsible for present day morphology consisting of parallel ranges and val-

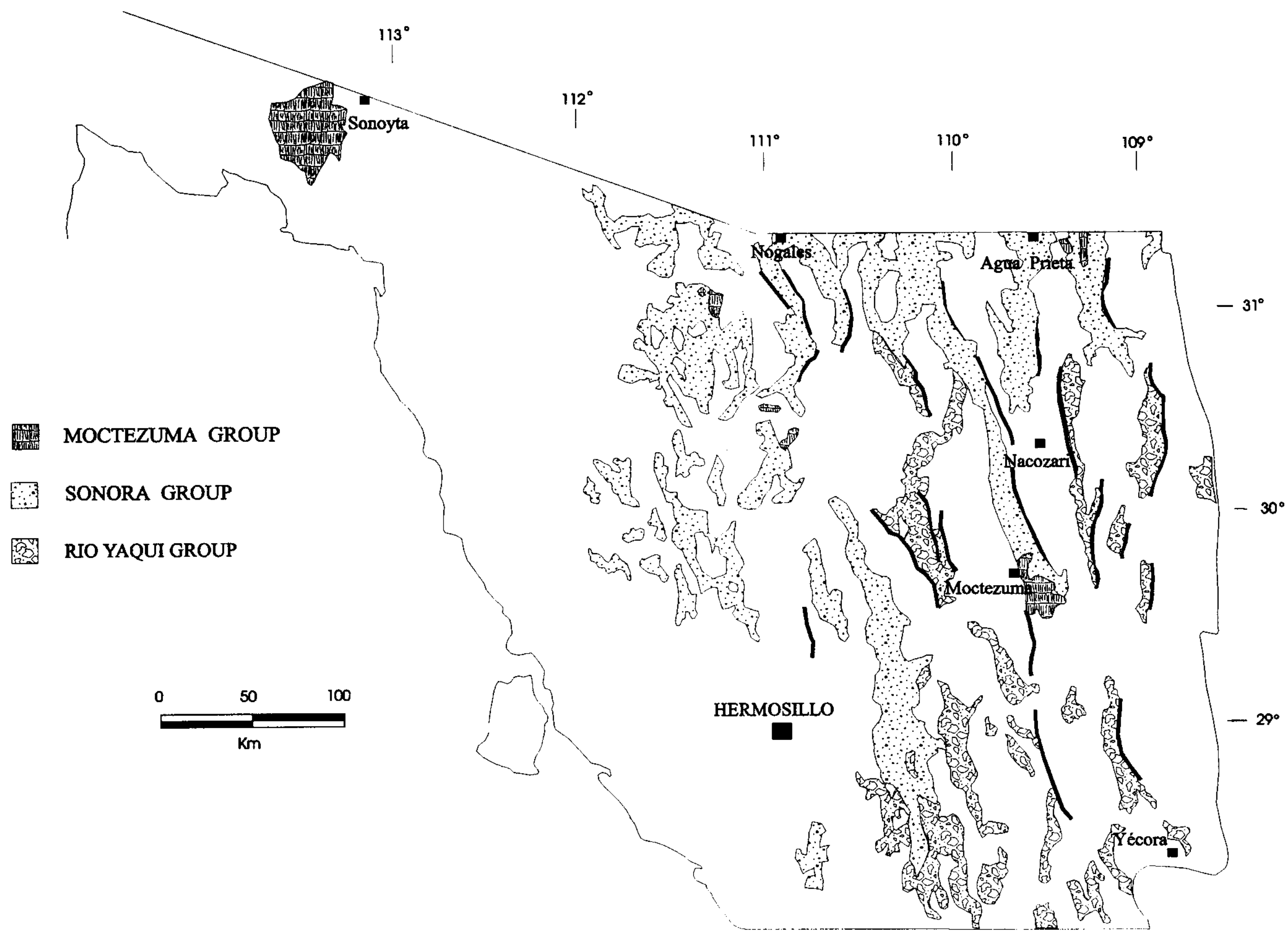

Figure 6. Outcrop distribution of the volcaniclastic sequences of Río Yaqui and Sonora groups. The mafic volcanic rocks of the Moctezuma group are also shown in this figure. Modified after Ortega-Gutiérrez and collaborators (1992) and Fernández-Aguirre and collaborators (1993).

leys. Within the basins sedimentary sequences constituted by gravel, sand and clay, poorly consolidated or unconsolidated were deposited, which are here defined as the Sonora group (Figure 6). The beginning of this sedimentation is not well constrained; however, in the Tubutama basin Gómez-Caballero and collaborators (1981) reported K-Ar ages of 7.01–5.46 Ma for some interbedded intermediate volcanic rocks. From these ages we interpret that the BR-II phase must have begun between 10 and 7 Ma. In the Western United States the early BR-I was developed in a back arc position (Eaton, 1984; Dickinson, 1991). The late phase coincides with a change in tectonic environment from subduction to rifting and transform faulting associated with the opening of the Gulf of California. The most recent igneous activity in northern Sonora is contemporary with the late phase of Basin and Range (BR-II). These rocks include two Pliocene-Quaternary basaltic fields (Paz-Moreno, 1993) in eastern Sonora and the alkalic basalts dated as Quaternary (Lynch, 1981) in the El Pinacate region. In the same way, these mafic rocks have been included in the Moctezuma group (Figure 6).

Neotectonic activity related to continental extension in northern Sonora is limited to the northeastern portion of the State. In 1887 an earthquake of estimated magnitude of 7.25 produced a 75-km-long scarp, known as the Pitáycachi fault (Natali and Sbar, 1982), along which the vertical displacement varied from 1 to 5 m (Pearthree *et al.*, 1990). In a more recent geophysical study, Montaño-Rey and collaborators (1993) collected seismic information during 10 days within the area of influence of the Pitáycachi fault, detecting microseisms (<1.0) and only one event of magnitude larger than 3.9 with an intensity of IV on the Mercalli scale.

OPENING OF THE GULF OF CALIFORNIA

Information from the Sonoran side

The Gulf of California is a young marine basin that was produced by a transtensional motion between the North America and the Pacific plates. Motion occurred in two consecutive extensional events: "protogulf extension" in the late Miocene, and the present day opening, which began in the Pliocene (Stock and Hodges, 1989). Lee and collaborators (1996) support the hypothesis that the transcurrent movement had an extensional component in the northern portion of the Peninsula of California during late Miocene. This extensional component has a direction perpendicular to the plate boundary, that is E-NE, producing normal faulting with similar characteristics to those seen in the continental portion of Sonora during phase BR-II. These normal faults affect calc-alkalic rocks (23.5–11.4 Ma) of the lower Empalme group in the Sierra Santa Úrsula in central Sonora. These volcanic rocks are tilted, with dips varying between 20° and 35° E, while the upper Empalme group sequence of ignimbrites and tholeiitic basalt flows (10.3–8.5 Ma) is only tilted 5° E. Likewise, the first marine invasion associated with the opening of the gulf is represented by marine conglomerates on the Isla del Tiburón, where marine and continental conglomerates are interbedded with felsic rocks dated using K-Ar between 13 and 11 Ma (Neuhaus *et al.*, 1988).

The opening of the Gulf of California also produced areas with marginal marine environments, mainly deltaic, which have been described in a very general manner because they are poorly exposed, since in most cases they are covered by Quaternary sediments. However, in the paleodelta of the Colorado River in northwestern Sonora, clastic and marine sequences up to 6,000 m thick have been reported by Colletta and Ortlieb (1984). The Miocene age of the beginning of deposition of these deltaic sediments is contemporaneous with the beginning of the opening of the gulf ("protogulf"). All deltaic sediments along the coastal Sonora are included in this article under the Río Colorado group. This group must include those deposits formed in the paleo deltas of the main rivers in northern Sonora, such as the Mátape, Sonora, Asunción and the Colorado rivers. Also, included within the Río Colorado group are deposits that form the Pleistocene marine terraces along the coastal portion of Sonora described by Ortlieb (1991). Unfortunately, there are not enough cartographic works to show the spatial distribution of this group. These rocks could be considered as equivalent to those in Baja California Sur (Loreto basin), where there are nonmarine to marine sedimentary rocks and interbedded tuffs of Pliocene age that coincide with the beginning of the modern stage of the Gulf of California at 3.5 Ma (Umhoefer *et al.*, 1994).

DISCUSSION AND CONCLUSIONS

The information compiled in this paper constitutes a first approach towards the understanding of the complex Cenozoic tectonic history of this portion of northwestern Mexico. Certainly, many of the tectonic and stratigraphic details required to understand completely these complex processes are still lacking. This is true when trying to define the tectonic position of the metamorphic core complexes (CC) within the early Cenozoic volcanic arc, or when relating the CC to the volcanism of the Yécora group. There are still large areas with no geological information, which may be of crucial importance.

The geologic evolution of Sonora may be divided in three time intervals (Figure 7): (1) Paleocene-Oligocene, characterized by abundant calc-alkalic magmatism, and with a predominantly compresional stress field related to subduction; (2) early to middle Miocene, is considered a transition period during which the stress field changed from compression to extension into continental Sonora. Normal faulting develops graben and half-graben basin that were filled by clastic sediments deposited into fluvial and lacustrine environments. Some of the igneous rocks have alkalic affinities, even though some of the volcanic rocks are still calc-alkalic; in some cases, volcanism

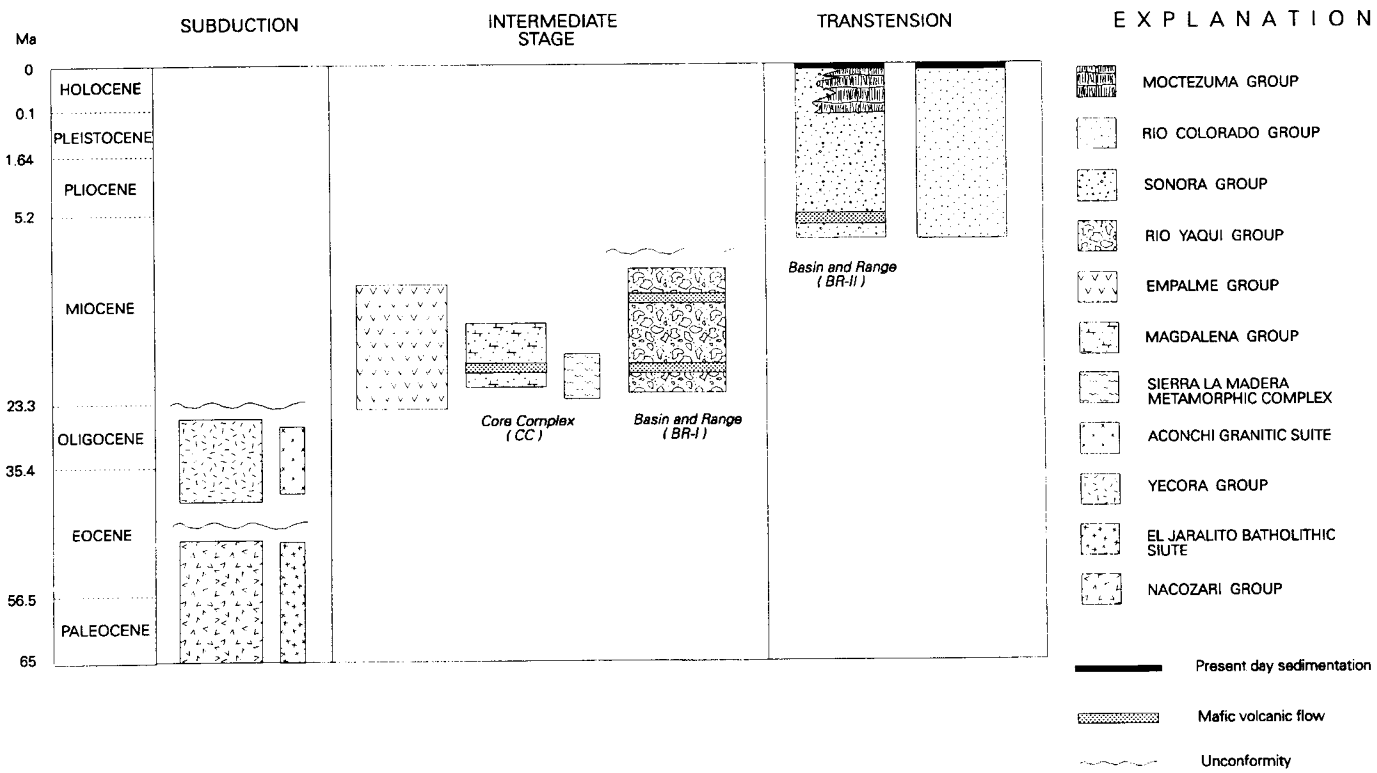

Figure 7. Correlation chart of the different stratigraphic units here proposed. The subdivision of the Cenozoic is according to the geologic time scale, by Harland and collaborators (1989).

is bimodal. During this interval were formed the Tertiary metamorphic rocks, unique in this region of northern Mexico; and (3) late Miocene to Holocene, in this period volcanism clearly of alkalic affinity decreased, and the filling of the continental basins by clastic sedimentation is probably the most important process. The beginning of this last period coincides with the completion of the change in crustal plate boundaries from subduction to strike-slip faulting and rifting.

From the stratigraphic units informally proposed in this paper, the Nacozari group, and El Jaralito intrusive suite, likewise the Yécora group and Aconchi granitic suite are clearly related to subduction processes, and are Paleocene to Oligocene in age. There is a clear spatial relationship between the outcrops of the Nacozari group and El Jaralito intrusive suite. However, in the later evolution of the arc, the Aconchi granitic suite and the Yécora group do not coincide geographically and just barely in time. This is probably due to the thick volcanic cover of the Yécora group, which has not been eroded sufficiently to expose its intrusive equivalents. Many of the granitic rocks of the Aconchi suite are exposed in localities where the CC are present; in fact, in some areas such as Magdalena and Mazatán, these intrusives are deformed by the ductile deformation (Nourse *et al.*, 1994; Vega-Granillo, 1996).

The Sierra La Madera metamorphic complex, the volcanic rocks of alkalic and calc-alkalic affinity within the Magdalena, Empalme and Río Yaqui groups, were emplaced during a transitional environment.

The main change from subduction to a transform environment, which was reflected as extension within continental Sonora, has been documented at ~10 Ma (Mora-Álvarez, 1992). Three stratigraphic units have been considered to correspond to this last tectonic environment, the Sonora, Río Colorado and Moctezuma groups.

Based on stratigraphic characteristics of the sediments within the extensional basins, and isotopic dating of interbedded volcanic rocks, it is possible to constrain the timing of the extensional events of the CC and Basin and Range (BR). The CC and the BR-I are constrained in northern Sonora to late Oligocene-middle Miocene time, and were formed in a back-arc region. The percentage of extension has been estimated for the BR-I, in two areas of northern Sonora. In the Tubutama basin, about 30 km west of Magdalena, Colletta and collaborators (1984) estimated a 30% of extension. In the area of San Nicolás, located in east-central Sonora, a 50-100% extension was proposed by Gans (1997). In the case of the extension within the CC in northern Sonora, no published data were found; however, the percent of extension must be greater. One problem in computing the magnitude of the extension is the influence of the event BR-II, which occurred in the late Neogene. The oblique faulting after 10 Ma must have fragmented the basins, obliterating many of the previous structures formed by the BR-I deformation.

The BR-II consists of normal faults, some of which were active in coastal Sonora between 7–10 Ma (table 3 *in* Lee *et al.*, 1996). In continental Sonora, the tilted rocks of Río Yaqui and Magdalena groups are unconformably overlain by horizontal sediments of the Sonora group. The former includes volcanic rocks dated at 7 Ma. The beginning of the BR-II extension in northern Sonora apparently coincides with the formation of the "protogulf", and was before the opening of the present day Gulf of California (4 to 5 Ma). In some localities, such as the region between Bahía de Kino and Puerto Libertad, dextral NW-SE strike-slip faults have been reported (Gastil and Krummenacher, 1977). A big problem in coastal Sonora is the thick Quaternary cover, which prevents direct observations of older structures. Geophysical studies are required to define the structure and the stratigraphy of the subsurface in this region.

Future studies on the tectonic and stratigraphic evolution of the Cenozoic rocks in northern Sonora should be oriented towards the understanding of the sedimentary fill of the present day continental basins (Sonora group), and to the characterization of the tectonic features of the BR-II, including studies of neotectonics in the areas with basaltic rocks of the Moctezuma group.

Regarding the stratigraphic nomenclature, it is evident that in order to establish it formally more geologic cartography is necessary. This is the reason why in this paper the stratigraphic units are proposed only informally. However it is also clear that the informal units proposed here are useful, since they put together a series of formations genetically, and lithologically related. These new groups will constitute important tools in the interpretation of the geologic evolution of the Cenozoic in Sonora. These informal units may become formal once the requirements established by the North American Stratigraphic Code are fulfilled.

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