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GRAVITY-SLIDING STRUCTURES IN CRETACEOUS-EARLY TERTIARY ROCKS IN NORTH-CENTRAL SONORA, MEXICO—REGIONAL SIGNIFICANCE

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ABSTRACT

The Late Cretaceous to early Tertiary tectonic setting in north-central Sonora has been characterized by compressional structures. This study proposes a northeast extensional deformation event typified by thermal uplift, differential vertical movements and associated gravity sliding. Three deformational events are postulated: (a) a late Early Cretaceous vertical uplift causing gravity block sliding and intraformational folding structures in the Mural Limestone; (b) an extensional back-arc tectonic setting recorded in rocks of the Upper Cretaceous El Tuli formation; the basal conglomerate of the El Tuli formation represents continued Late Cretaceous extensional tectonism which was accompanied by penecontemporaneous denudation and magmatism; this extensional tectonic setting is very different from the proposed compressional environment reported in eastern and northern Sonora; and (c) middle Tertiary extensional low-angle and high-angle normal faulting and perhaps block-mass sliding affecting the Cretaceous and Tertiary rocks; vergence of folds and displacement of faults suggest that movement took place along a surface of detachment.

Lower Cretaceous rocks were deposited in the margin of a shallow sea basin that existed in northern Sonora. Block masses in the study area could be part of or be located in the margin of a structural block. Upper Cretaceous rocks include detrital sediments and mass-debris flows deposited in alluvial fan environment.

Key words: Tectonics, gravity-sliding structures, Cretaceous, Sonora, Mexico.

RESUMEN

La deformación que ocurrió durante el Cretácico Tardío-Terciario temprano en Sonora se caracterizó por la presencia de estructuras originadas por compresión. Se sugiere que esa deformación se deba a un evento distensivo caracterizado por una extensión orientada hacia el noreste, levantamientos térmicos y deslizamientos por gravedad. Se propone tres eventos de deformación: (a) deslizamiento de grandes masas de roca, con pliegues intraformacionales en la Caliza Mural, que manifiestan una deformación por resbalamiento por gravedad o derrumbamiento, producto de un fallamiento vertical que ocurrió a fines del Cretácico Temprano; (b) las rocas de la formación El Tuli registran un evento de extensión en la parte de transárco, donde depósitos sinorogénicos como el conglomerado basal de la formación mencionada indican las primeras manifestaciones de un período temprano de extensión durante el Cretácico Tardío, que fue acompañado por erosión y volcanismo. Este ambiente tectónico extensional es muy diferente del que tradicionalmente se ha propuesto para este tiempo y para esta región del estado; y (c) durante el Terciario medio al tardío la tectónica se caracterizó por fallamiento normal de bajo ángulo y normal, así como posible deslizamiento de grandes masas de roca. La vergencia de pliegues y el desplazamiento de fallas sugieren que el movimiento se haya realizado a lo largo de superficies de despegue.

Las rocas del Cretácico Superior fueron depositadas en la margen de una cuenca marina con aguas someras. Los bloques en el área de estudio indican que pudieran ser parte o localizarse en las márgenes de un bloque estructural. Se interpreta las rocas del Cretácico Superior como abanicos aluviales compuestos parcialmente por flujos de detritos.

Palabras clave: Tectónica, estructuras de deslizamiento por gravedad, Cretácico, Sonora, México.

INTRODUCTION

In Sonora, the Cretaceous structural evolution of the region is considered to be a Late Cretaceous-early Tertiary period of compressional deformation, mainly recorded in Lower Cretaceous rocks that are widely exposed.

Lower Cretaceous rocks that record thrust faulting, folding, cleavage and fracturing crop out in several localities: Agua Prieta region (Sierra Anibácachi [Taliaferro, 1933; Rangin, 1977], Sierra San José, Sierra Cabullona, and Sierra Caloso [Rangin, 1977], rancho San Antonio [Bennet, 1993], Arizpe [González-León, 1978], Santa Ana [Navarro-Fuentes, 1988; Jacques-Ayala, 1993], Sierra El Chanate [Jacques-Ayala, 1983, 1993), Tuape [Rodríguez-Castañeda, 1984], Cerro de Oro [González-León, 1989], Lampazos [Herrera-Urbina and Bartolini, 1983; González-León, 1988], Sierra El Chiltepín [Himanga, 1977], Sierra Los Chinos [Pubellier, 1987], Cerro Las Conchas [Almazán-Vázquez and Fernández-A., 1988]) (Figure 1). Except the rocks of Sierra El Chanate, that constitute marginal deposits (Jacques-Ayala and Potter, 1987) all sequences are predominantly marine beds. Pioneering

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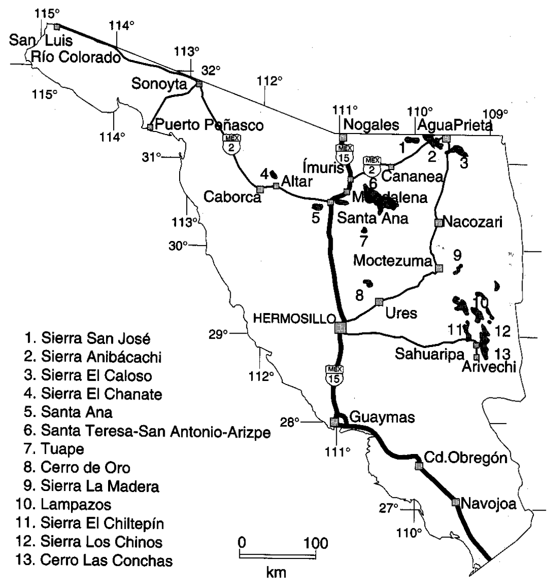


Figure 1. Distribution of Lower Cretaceous rocks in Sonora, northwestern Mexico.

work by Taliaferro (1933) in the Cabullona basin, and more recent works of Rangin (1977), González-León (1978), Herrera-Urbina and Bartolini (1983), Minjares-Sosa and collaborators (1985), Pubellier (1987), González-León (1988), González-León and Jacques-Ayala (1988), Castro-R. and Morfín-V. (1988), González-León (1989), González-León and Jacques-Ayala (1990), Jacques-Ayala (1993), and González-León (1994) support the idea that the deformation recorded in the Lower Cretaceous rocks is a regional compressional event named Mesocretaceous orogeny (Rangin, 1977), or related to the Laramide orogeny of western North America.

Rodríguez-Castañeda (1984, 1986, 1990, 1994) observed in central Sonora a heterogeneous deformation style in Lower Cretaceous rocks and speculated that deformation during the Early Cretaceous could be the result of gravity sliding, associated with vertical uplift that occurred from the Late Jurassic (?) to the late Early Cretaceous time. Afterwards erosion and volcanism did occur in Late Cretaceous-early Tertiary time. Three deformational events are proposed to explain structural evolution. The first one, vertical faulting event of late Early Cretaceous age, seems to be responsible for detached block-slide masses and disharmonic folding recorded by the Mural Limestone. The second event is characterized by thermal uplift, synorogenic deposits and gravity sliding olistholiths in the El Tuli formation. The third middle Tertiary event is recorded by detachment faulting, detached blocks, folding, and high-angle normal faulting that affect Lower Cretaceous, Upper Cretaceous, and Tertiary rocks.

The study area is located in north-central Sonora (Figure 2), approximately 60 km northeast of Cucurpe. The area is characterized by excellent outcrops of clastic, carbonate, and volcanic rocks of Early Cretaceous, Late Cretaceous, and Tertiary ages.

Previous work in the area was carried out by González-León (1978) in the southeast; McKee (1991) in the northwest, and Bennett (1993) whose work covers the study area. González-León (1978) described an Early Cretaceous stratigraphy similar to the study area and suggested that deformation is related to three events: compression, doming, and extension. McKee (1991) described the stratigraphic relationships and postulated that deformation of the Lower Cretaceous rocks is the result of uplift and subsequent gravity-sliding. Bennett (1993) conducted a remote sensing study applied to exploration of mineral resources. He discriminated lithologies and alterations based upon interpretation of TM Landsat images.

In this study, collection of structural data together with analysis of the structural geometry of the exposed rocks proposed evidence of an extensional event and associated gravity sliding.

STRATIGRAPHY

LOWER CRETACEOUS ROCKS

The Lower Cretaceous rocks in the area comprise three formations: the Morita Formation, the Mural Limestone, and the Cintura Formation.

Morita Formation

The Morita Formation (Ransome, 1904) is mainly composed of interbedded sandstone, siltstone, and few conglomerate beds. The unit is widely distributed in the study area (Plate 1).

Sandstone is reddish brown, yellowish brown, greenish gray, fine grained, well sorted, and thin to thick bedded. Locally, some beds contain parallel laminae. Siltstone is mainly red purple, although in the southern portion of the area it is olive green. Beds vary from a few centimeters to 3 m in thickness. Conglomerate is red, medium bedded, and matrix supported. Clasts are composed mainly of volcanic-rock fragments (tuff, andesite) and chert. They vary from 0.5 to 3 cm and are subangular to subrounded.

South of the El Batamote ranch, rocks of the Morita Formation are intensely altered and silicified. Sandstone and siltstone are cut by numerous quartz veins. This alteration is restricted to the Morita Formation and does not extend to the adjacent rocks to the north.

Mural Limestone

The Mural Limestone (Ransome, 1904) is composed of

Figure 2. Location of the study area in north-central Sonora.

limestone, shale, and rare sandstone. It crops out mainly in the central portion of the study area (Plate 1). Limestone is fossil rich (oysters, echinoderms, pelecypods, turritella, gastropods, ichnofossils), gray to light gray, thin to thick bedded and locally this unit is laminated. Shale is olive green, and dark gray, thick-bedded. Sandstone is greenish gray, fine-grained, medium-bedded, and well sorted.

This unit forms a series of tectonically slided blocks as those that appear northeast of El Grasero corral, near Cerro El Destierro, in Arroyo El Palmillal, between ranchos La Nochebuena and El Parián; and east of Cerro El Tomistón. These blocks rest upon Morita Formation, where contacts show variable deformation (shearing).

Cintura Formation

The Cintura Formation (Ransome, 1904) crops out around rancho San Antonio and northeast of El Grasero corral (Plate 1). This formation is composed of sandstone, siltstone and limestone.

Sandstone is red or light brown, medium to thick bedded, fine grained, well sorted, and beds locally contain parallel laminae. Siltstone is red purple and commonly thick bedded (7 m). Limestone is dark gray, weathered to yellowish ochre, thin to medium bedded, and fossil rich (pelecypods). Fossil wood is characteristic in this unit. Limestone beds form a tabular body oriented northwest to southeast near San Antonio ranch. Low-grade metamorphism is observed in this unit and is represented by oriented mica grains.

Stratigraphic relationships between Morita-Mural and Mural-Cintura units north of San Antonio ranch are conformable, suggesting preservation of original stratigraphic features. However, west of the transfer fault (Plate 1), the sequence has been disrupted by faults, slided masses and duplicated. Fossil content in the Mural Limestone (mainly foraminifer orbitolinid) has been used to indicate an Early Cretaceous age for these three units. Oysters, echinoderms, pelecypods, gastropods (turritella) are some of the fossil content found in the Mural Limestone. No fossil identification was carried out. The Cintura Formation was identified by its stratigraphic position, with respect to the Mural and by fossil wood content. The Morita Formation presents distinctive conglomerate beds which are absent in the Cintura unit, besides its stratigraphic relation with the Mural Limestone.

The depositional environment of the Early Cretaceous rocks has two interpretations. McKee (1991) reports that Lower Cretaceous rocks were deposited in the marine Sonora Basin, below the storm-wave base; differing from the interpretation of Early Cretaceous elsewhere. González-León (1978) considers these rocks be part of transgressive and regressive sequences deposited in coastal plain, delta, and near-shore open marine environments. In the study area, Lower Cretaceous rocks were deposited in a shallow marine basin. Grijalva-Noriega and Rodríguez-Castañeda (1994) indicated that a marine basin extended to the northwest and occupied at least part of northeastern Sonora, and perhaps eastern and southeastern Sonora.

UPPER CRETACEOUS ROCKS

El Tuli Formation

El Tuli formation (Rodríguez-Castañeda, 1994) forms a northwest trending band that crosses the northeastern part of the study area (Plate 1). The rocks form a sequence of conglomerate, sandstone, siltstone, and volcanic rocks.

Conglomerate is mainly composed of limestone, sandstone, quartzite, andesite porphyry, and tuff fragments. Clasts vary from angular to subrounded and from 0.5 to 50 cm in diameter. The conglomerate mainly occurs in the base of the unit, although higher in the unit, conglomerate beds of variable thickness and homogeneous composition are also found. Most of the limestone clasts are derived from Mural limestone, and the rest derives from Paleozoic rocks. Quartzite fragments could have its origin in Precambrian, Paleozoic or Jurassic rocks. Volcanic clasts are derived from the Jurassic volcanic arc. Sandstone fragments seem to be derived from Morita or Cintura formations. In the middle part of the sequence, the conglomerate is composed of limestone, sandstone, tuff, andesite, and quartzite fragments. However, the most important feature in the section is the presence of Mural Limestone blocks (olistoliths) (Figure 3); one of them, several kilometers long and hundred meters wide (Figure 4), constitutes an olistostrome. These blocks are mappable lens-like (shown on Plate 1) stratigraphic units interstratified among normally bedded sequences. Relationship of olistolith with the surrounding sediments is defined in two ways: first, the contact corresponds to a paraconformity; and second, the contact is a fault surface where no deformation occurs nor cuts other structures. Blocks do not show rotation.

Figure 3. Limestone block (olistoliths) of Mural Limestone in the El Tuli formation.

Figure 4. Mural Limestone olistoliths (indicated by arrows) almost 5-km long and 100-m wide.

Sandstone is reddish brown and reddish purple, thick bedded, fine grained, parallel-laminated, and well sorted. Siltstone is reddish brown and reddish purple.

Tuff, andesite, and agglomerate are intercalated in the sequence. The volcanic rocks are part of the sequence and contemporaneous with deposition of clastic rocks. It is possible to see depositional contacts between the sediments and the volcanic rocks.

A fault is the contact between the El Tuli and Morita formations in the area. However, to the south, in the Banámichi and Téhuachi regions, the regular contact is an angular unconformity among El Tuli formation and underlying formations (Rodríguez-Castañeda, 1994). There, El Tuli formation is covering Paleozoic, Jurassic, and Lower Cretaceous rocks.

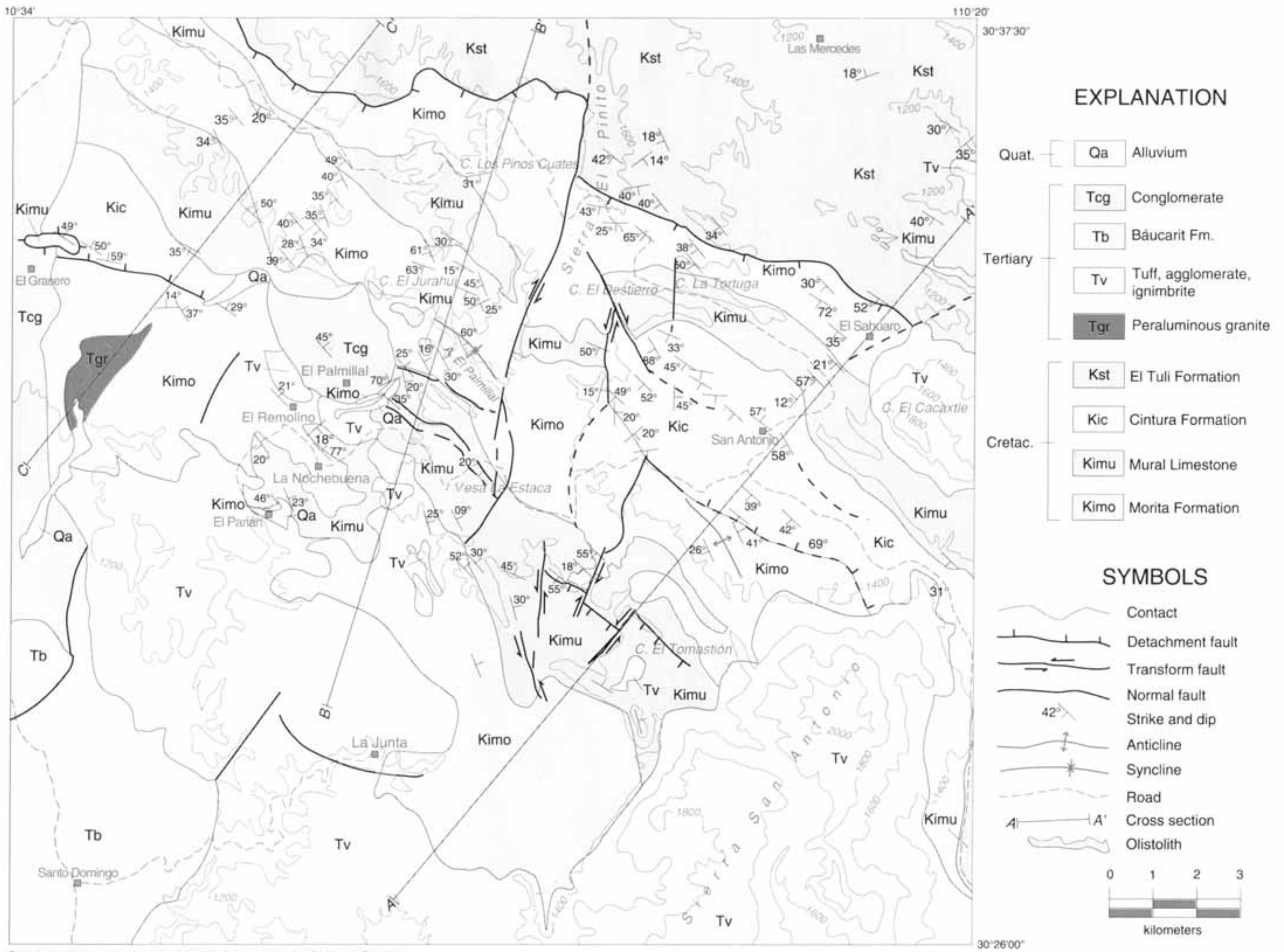
Rodríguez-Castañeda (1994) suggested a Late Cretaceous age for this formation, based upon field relationships and correlation with the Fort Crittenden Formation of southern Arizona.

Upper Cretaceous rocks correspond to detritic and mass-debris flows deposited in an alluvial fan environment.

TERTIARY ROCKS

Tertiary rocks in the field area include peraluminous granite, diorite, tuff, agglomerate, ignimbrite, and conglomerate. They are found throughout the area. They include dikes, sills, and flows. Most of the outcrops are not scale mappable. Tuff conforms the main body of Sierra San Antonio and those in the southern portion of the area. Tuff and ignimbrite are part of the Cerro El Cacaxtle, while agglomerate appears north of Cerro El Cacaxtle.

Diorite is found in small outcrops that are not mappable; it forms dikes and sills. Although the age of the diorite in the area is unknown, south of Mesa La Estaca, a diorite was dated as 40 Ma (K-Ar whole rock) (UNAM-USGS, 1995 map compilation). Both rocks could be part of the same intrusion event. The peraluminous granite outcrops south of El



Computer color separation was made by José de Jesús Vega-Carrillo

GRAVITY-SLIDING STRUCTURES IN NORTH-CENTRAL SONORA, MEXICO

Batamote. A radiometric age date (K-Ar) of 36 Ma was obtained from muscovite (Bennett, 1993).

Tuff, agglomerate, and ignimbrite are part of the regional igneous event of the Sierra Madre Occidental. Although no radiometric dates have been obtained from these rocks, a late Oligocene age is estimated (Rodríguez-Castañeda, 1994).

Tertiary sediments unconformably overlie Cretaceous rocks and Tertiary volcanic rocks. Báucarit Formation (Tb, Plate 1) is composed by conglomerate and sandstone. The younger unit (Tcg, Plate 1) consists of low dipping poorly indurated conglomerate, that fills a small intermontane basin north of El Palmillal ranch. Another outcrops of this unit occur west of the area. It is also a poorly indurated conglomerate that was deposited in a northern basin.

STRUCTURE

In the study area, essential components of compressional folding and thrust faulting do not exist; the absence of these elements contrasts with those regions where the Lower Cretaceous rocks are assumed to record these structures. The sedimentary rocks of Early Cretaceous age are widely distributed through the study region. Folding and faulting in northeast, east-central, central, and northwestern Sonora during Late Cretaceous have been interpreted as the result of compression-induced regional thrusting. Lower and Upper Cretaceous rocks in the area serve as important guides to understanding the style and kinematics of late Mesozoic deformation. Structural analysis was based on orientation and distribution of beds, folds, faults (tectonic movement and transport), and striated surfaces.

BEDDING

The strike and dip of the Lower Cretaceous beds define a series of tilted blocks and folds (Plate 1). In general the blocks strike northwest and dip to the northeast or southwest. There, the change of dip direction is controlled by faults (Plate 1).

From the Cerro El Centinela and El Grasero corral, to as far as Cerro Los Pinos Cuates and Cerro El Jirahui, the beds form a half-graben dipping south-southwest. Another block is located in the eastern part of the area, where the Sierra El Pinito is the western limit. Locally, some parts of these blocks show intense deformation. Other blocks are those south of the El Batamote and south of Mesa La Estaca-Cerro El Tomistón. The limit among blocks runs approximately along El Palmillal-La Nochebuena-El Parián line (Plate 1).

In the Arroyo Pozo Nuevo, south of San Antonio, the beds form an anticline; and in Arroyo El Cable, northwest of San Antonio, the beds are intensely deformed, showing variation in dip, from vertical to horizontal, in short distances. Similar relationships occur in Arroyo El Sahuaro, west of Cerro El Cacaxtle, where beds of the Cintura Formation pass from 12 to 90° in a distance of tens of meters. West of Cerro El Cacaxtle, the limestones from the Mural unit are vertical, but at the top they are horizontal (Figure 5).

Figure 5. Dragging or inflection of strata of the Mural Limestone west of Cerro El Cacaxtle, along Arroyo El Sahuaro. In the foreground plane the beds are vertical, while at the top, they are horizontal.

FOLDS

The folds that occur in the study area are disharmonic and intraformational. Folds were identified at least in three localities: Cerro El Destierro, west of Cerro La Tortuga, and south of Cerro Los Pinos Cuates. They only occur in the Mural Limestone (Figure 6). These disordered folds have a synsedimentary origin, because the over-and underlying strata are not disturbed. The presence of such structures within undeformed beds lead to consider these structures associated with block gravity sliding (slumping), along the flank of a basin or in the border of a structural block. It is suggested that folding occur before the blocks of strata drifted, maybe at the beginning of downslope sliding. West of Cerro El Cacaxtle, the Mural beds record inflection or dragging that is associated to gravity deformation (Figure 5).

Figure 6. Intraformational disharmonic folds within the Mural Limestone at Cerro El Destierro. These structures formed by gravity sliding. The same structures occur to the north, around Cerro La Tortuga.

Along the Arroyo Pozo Nuevo, located south of Rancho San Antonio, appears a northwest-trending anticline (Plate 1). This anticline may be the result of a crust upwelling due to the presence of magmatic chambers. It might also be interpreted as a rollover anticline associated to a low-angle normal fault. The magmatic chambers in the area can be related to the hypabyssal intrusives and the peraluminous granite. On the other hand, these magmatic chambers, when cooling, produced granitic masses that are widespread in all Sonora. The area lies inside the region most influenced by early and middle Tertiary thermal dynamic events that affected most of eastern Sonora.

Southeast from Cerro Jirahui, a northwest-oriented fault-ramp syncline (Plates 1 and 2) is interpreted to be related to the evolution of the listric and detachment faults.

There are also some mesoscopic folds along Arroyo El Cable, in the Cintura Formation, where an intense deformation is present (Figure 7). These folds are interpreted to be the result of a collision of two blocks. The main movement seems to occur from north to south, as indicated by structures along Arroyo El Cable (Plate 2 and Figure 7). Pencil structure is recorded in rocks of the Mural Limestone west of El Palmillal.

Figure 7. Vergence of folding and faulting in Cintura Formation suggesting north to south displacement. Outcrop is located in Arroyo El Cable. View to the north.

FAULTS

In San Antonio, several generations of intense faulting are recorded. Low-angle normal faults, strike-slip faults, and basin and range faults occur in the Cretaceous sedimentary rocks. Also, the high-angle normal basin and range faults are cutting Tertiary volcanic and sedimentary rocks. Linear features recognized on a TM Landsat image and aerial photographs were identified and mapped.

Two groups of steeply dipping faults were identified: a NE and a NW striking group (Figure 8). The NE group of faults accommodates mainly strike-slip movement and less oblique-slip movement (Figure 9). The second group, the NW-striking faults, are dominated by high-angle normal faulting (dips >50°) as well as oblique listric-normal faulting with dips that range between 30 and 50° (Figures 8 and 9). Major NW striking faults also accommodate detachment movement, like those near El Batamote (Plate 1) and north-northwest Cerro El Tomistón. These low-angle normal faults seem to mark the major boundaries among tilted blocks.

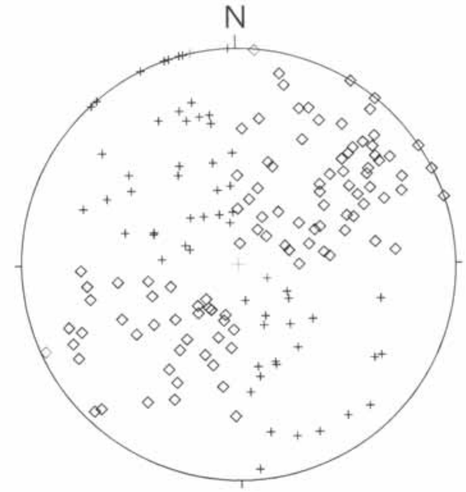


Figure 8. Lower hemisphere stereonet plot. Poles of two Tertiary normal fault sets: a NE group (cross) and NW group (diamond). The NE set is associated with metamorphic core complex deformation and the NW set is part of basin and range extensional deformation.

The detachment fault near El Batamote shows an intense brecciation along its trace. This fault zone and others, like that south of rancho San Antonio, show displacement and rotation of beds that indicate a listric or detachment movement. Frequently, fault zones are brecciated. Along Arroyo El Cable, it is possible to see that an older fault zone, identified by the development of calcite, considered as a Lower Cretaceous detachment fault involved in sliding, has been deformed by younger Tertiary detachment. The fault zones of NW set do not show brecciation.

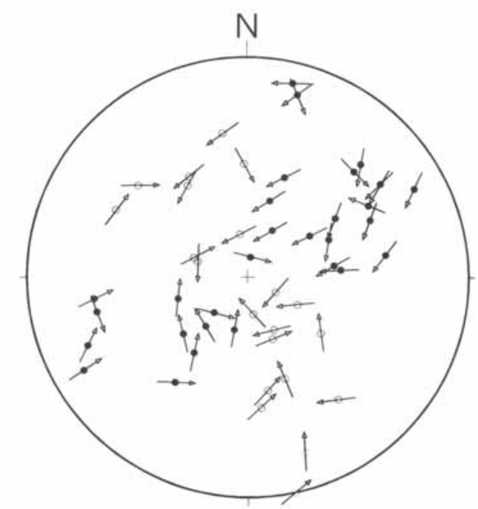
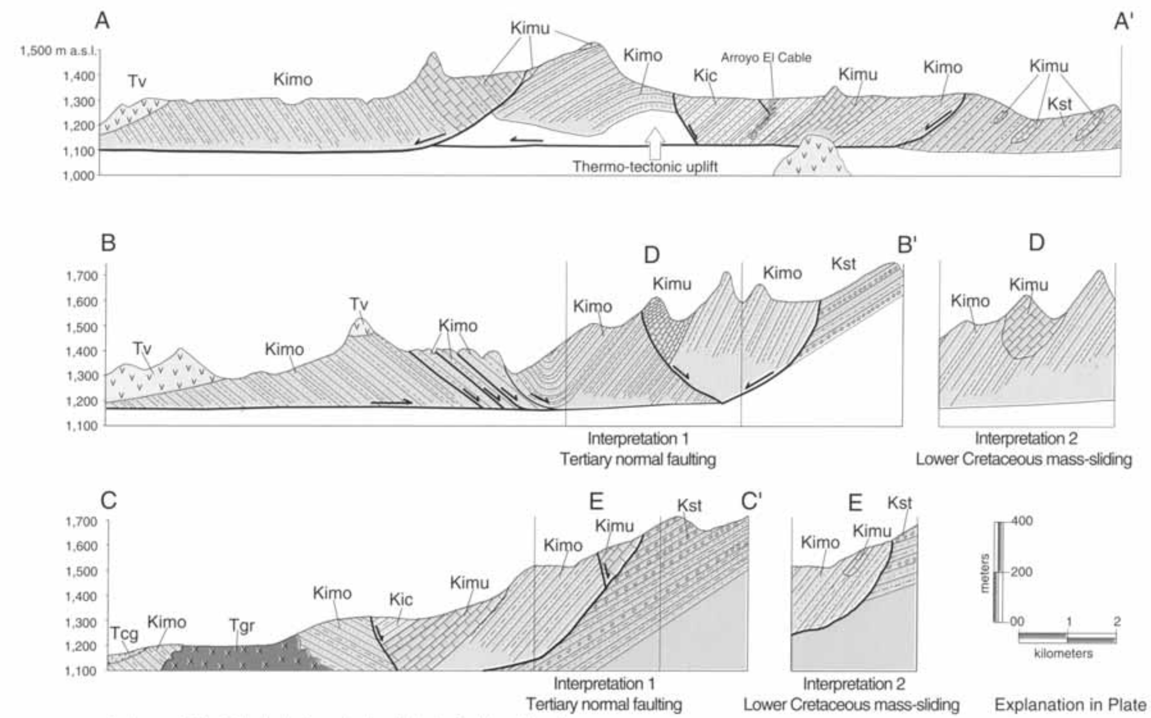


Figure 9. Lower hemisphere slip-linear stereonet plot of the fault pole and the direction of the slip that shows kinematics of fault array. The NE fault system (open dot) accommodates oblique-slip and lesser strike-slip movements. Striae of the NW faults indicate mainly oblique-and dip-slip movements.



Redrawn in Macintosh platform by José de Jesús Vega-Carrillo

STRUCTURAL SECTIONS OF THE NORTH-CENTRAL SONORA AREA, MEXICO

The NE group is older and is related to the evolution of the metamorphic core complex deformation (36 Ma) (Rodríguez-Castañeda and Anderson, in preparation). The younger NW faults are part of the basin and range normal faulting that extended in northwestern Mexico. Southward, around Rancho Santo Domingo and Rancho El Babiso (the latter out of the study area, Rodríguez-Castañeda, 1994), the Báucarit Formation is cut by a NW striking fault, indicating that NW-oriented faults are the youngest. The NE faults are not recorded in these sediments.

There is a north-strike fault that occurs in the central part of the area (Plate 1) and that has a transfer fault nature. This fault separates two tilted blocks, with different morphological characteristics, different predominant directions of tilting—northern blocks are dipping southward, while southern blocks dip towards the north—and different amounts of extension.

CHARACTERISTICS AND INTERPRETATION OF THE SUPERFICIAL STRUCTURES

The deformation of the Lower Cretaceous rocks in the study area corresponds to a particular structural level, characterized by superficial deformation with a different set of disordered structures.

Superficial deformation can occur in subaerial and subaqueous conditions; the first are distinguished for having little or no lithostatic load. It is brittle and results in intense fracturing and has suffered weathering. These features are continuous along with deformation and suggest that faults can use preexisting structures for their emplacement. Breccias and clastic deposits as a result of faulting can be associated.

In case of subaqueous conditions—applicable to the study area—deformation has particular characteristics. Folds occur, rocks or sediments are hydroplastic and respond easily to deformation. Deformation in this kind of rocks has a particular style, because folds are constrained above and below by unfolded more consolidated (?) sediments (Figure 6).

The folds are very ductile, disharmonic and are never accompanied by faults, although the entire sequence is cut by younger faults; the strata are plastic without fractures. Folds can be the result of thrusting or when olistoliths or mass-gravity deposits advance to the sea.

When a sufficient gradient exists, the rocks can be deformed by gravity without influence of tectonic forces of deep crustal levels. Gravity results can be different: it is possible to find areas where deformation caused by gravity sliding can result in a chaotic deformation or areas with undisturbed sequences.

To the northwest of the area, slide-blocks and slide-masses gravity occur (McKee, 1991); while to the east, around Cerro El Cacaxtle, deformation is represented by dragging or inflection of strata (Figure 5).

Late Early Cretaceous intraformational folds in the Mural Limestone (Cerro El Destierro, Cerro La Tortuga; Figure 6 and Plate 2) are the result of gravity sliding that occurs in the margin or flank of a basin (McKee, 1991) and they resemble the characteristics previously observed where strata in the above and below deformed sediments are unconformable and undeformed (Figure 6).

This type of structures can form in deeper levels of the crust, where the rocks are partially melted; they are also frequent in sediments that have been compressed by tectonic forces, but the context in the study area is evidently very different. The superficial character of the intraformational folds in the Mural Limestone and blocks of the same unit is evident and sufficient to recognize this special kind of deformation, associated with submarine sliding and slumping. In this case, slumping is associated with uplift and subsequent sliding.

Northwest of the study area, McKee (1991) reported that large-scale mass sliding produced northwest-trending southwest-vergent folds, indicating that displacement was toward the southwest. This transport direction resulted from the Early Cretaceous gravity sliding event; while olistostrome in the lower part of the El Tuli formation, is associated to a Late Cretaceous gravity process.

The conditions that prevail in the study area suggest a subaqueous environment, in an Early Cretaceous shallow marine basin.

Sliding of these masses is associated with important relief, *e.g.*, the Cananea High of McKee (1991) that presumably evolved until Late Cretaceous. This type of deformation is expected to affect big masses of several km^3, where the horizontal displacement has reached several kilometers. Similar regional structures have not been described in other places of Sonora; however, in some areas where the Lower Cretaceous rocks crop out and where intense folding and thrusting have been reported, perhaps such structures are related to gravity sliding (*e.g.*, southeast of the study area, Lampazos, Santa Ana, Anibácachi, Tuape, Cerro de Oro, Arivechi).

The presence of Mural olistoliths or olistostromes in the Upper Cretaceous El Tuli formation is also observed. These structures are part of Late Cretaceous-early Tertiary mass-gravity displacement. The olistoliths do not disturb the sediments where they are embedded, and occur as exotic blocks intercalated in the sequence; the size is variable, from one decimeter to several kilometers long, and about one hundred meters wide. The olistoliths seem to be part of a scarpment that was displaced on a marine slope by gravity. The direction of displacement of these blocks is believed to be northeast, as suggested by the distribution of small olistoliths in front of the big ones. Nevertheless, it was not possible to distinguish folding in the contact with the substrate, in order to confirm this suggestion.

The presence of conglomerates—some of them as lenses—in the El Tuli formation might indicate that the source of these sediments was at some places above sea level. It is assumed that gravitative phenomena that involve sliding together with conglomerates suggest that both subaerial and subaqueous conditions coexisted in Late Cretaceous—early Tertiary time. Sandstone and siltstone intercalated in the formation indicate the subaqueous conditions.

DEFORMATIONAL EVENTS

Three deformational events, one of late Early Cretaceous age, another of Late Cretaceous-early Tertiary age, and the third one of the Neogene, are recognized through the structures of the study area. Although in this paper deformation is separated into three events, there is evidence that extensional deformation might have been a continuous process, at least in the area, from Late Jurassic through the Neogene, with several stages of quiescence and activity.

Late Early Cretaceous deformation is recorded in the Lower Cretaceous rocks by slide masses of the Mural Limestone like those that crop out south of Cerro Los Pinos Cuates; south of Cerro El Destierro, where intraformational or disharmonic folding, as well as inflection or dragging of Mural beds, occur; and by the transfer fault in the middle part of the study area. This kind of deformation is not recorded in younger rocks, thus constraining their age to the late Early Cretaceous. Northwest, near Cerro Azul, Lower Cretaceous rocks conform slide masses that form southwest vergent folds with associated cleavage, penetrative kink bands, and phyllitic and schistose fabrics. Deformation is not uniformly distributed within the Lower Cretaceous rocks. The discussed structures are related to tectonic uplift and associated gravity sliding.

Rangin (1977) suggested that in northern Sonora, and in late Early Cretaceous time (Albian-Cenomanian), the unconformity that is recorded in the base of the Upper Cretaceous rocks was developed. Structures recorded in Lower Cretaceous rocks in other localities—like folding—could have been produced by sliding, but further work on these places is necessary to confirm this hypothesis.

Late Cretaceous-early Tertiary deformation is characterized by vertical movements, synorogenic deposits, and volcanism. An angular unconformity with a regional extent, that separates Upper Cretaceous rocks from underlying Lower Cretaceous sediments, records the beginning of this event. The El Tuli formation is characterized by the intercalation of synorogenic sediments (conglomerate, sandstone, tuffaceous sandstone) and volcanic rocks; as well as a Mural Limestone olistostrom indicates that extension prevailed at this time. Upper Cretaceous rocks are tilted to the northeast or southwest. Folds and thrust faults that could suggest a compressional period of deformation do not occur in these rocks. However, in northeastern Sonora—Sierra Oposura area—the Upper Cretaceous rocks are folded, and this might be due to sliding, though in this case folding may be associated with Tertiary extension (Metamorphic core complex extensional event) that at least began 40 Ma ago (late Eocene). Upper Cretaceous rocks in the study area are affected by younger Tertiary normal faulting.

The period of deformation that occurred during this time has been called the compressional Laramide orogeny typified mainly by folding, thrusting, and reverse faulting (Rangin, 1977, 1982; Himanga, 1977; González-León, 1978; Jacques-Ayala, 1983; Herrera and Bartolini, 1983; Palafox and Martínez, 1985; Minjarez-Sosa *et al.*, 1985; González-León, 1988; Pubellier, 1987; Almazán and Fernández-A., 1988; González-León and Jacques-Ayala, 1988; Castro-R. and Morfín-V., 1988; González-León, 1988; González-León and Jacques-Ayala, 1990; Jacques-Ayala, 1993; González-León, 1994). However, it seems that those structures could have been produced by uplift and sliding of big rock masses.

Dickinson (1989) stated that onset of Laramide deformation was recorded in southeastern Arizona by deposition of synorogenic clastic successions in locally downfaulted and (or) downfolded basins. These strata, assigned to the Fort Crittenden Formation and correlative units, probably began to accumulate at 75–80 Ma during Campanian time, and analogous coarse clastic sequences have been dated as young as near the Cretaceous-Tertiary time boundary. Dickinson (*op. cit.*) also indicated that folds and thrust faults involving these and older strata that have been mapped in most mountain ranges of southern and western Arizona and northern Sonora (Rangin, 1977) were produced by the Laramide orogeny.

On the other hand, in central and northern Sonora, Cenomanian (?) synorogenic deposits (El Tuli formation) are identified, which have been correlated with the Fort Crittenden Formation. These sediments were accumulated in a controlled fault basin associated to evolution of positive features, the Cananea high and San Antonio uplift (Figure 10) of Jurassic and Late Cretaceous-Paleogene ages, respectively. Two important facts are that rocks from the El Tuli formation and Bisbee Group are not involved in folding, thrusting or affected by mylonitic fabrics similar to those of southern Arizona, or those proposed in northern Sonora; and that structural features in the San Antonio area are the result of vertical movements and associated sliding.

The Neogene event was characterized by deformation associated to the Metamorphic core complex event that began to develop 40 Ma ago. This was a period of low-angle normal and detachment faulting. In addition, NE striking high-angle faults in the study area, which accommodate strike-slip and oblique-slip, are part of the same extensional event. Regional northeast-trending structures have been documented in northeastern Sonora (Turner *et al.*, 1982) and it is suggested that they be major crustal structures.

Deformation in the study area is believed to be the result of displacement along detachment faults. Two detachment movements are postulated. The first one is associated to a proposed structural high that in this paper is called San Antonio uplift (Late Cretaceous). The San Antonio uplift would be located south-southeast the El Tuli formation (Figure 10) and is responsible for: (a) deposits of the El Tuli formation; (b) the northwest-striking detachment faulting west

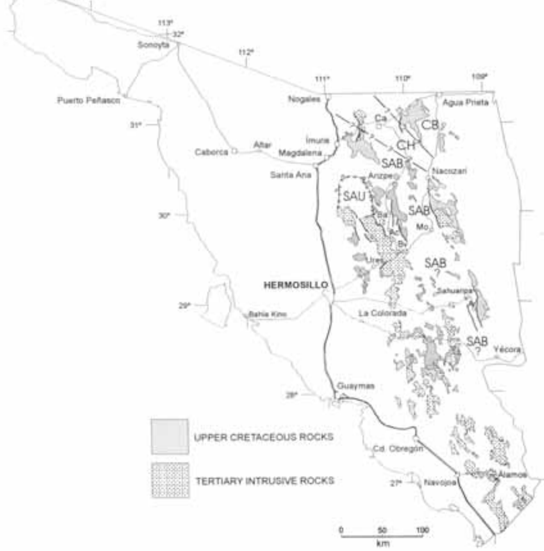


Figure 10. Location of exposures of Upper Cretaceous sediments (dark shading) in central Sonora and large outcrops of Tertiary granitic rocks (light shading). It is speculated that Upper Cretaceous rocks evolved or are intrinsically associated to evolution of these intrusive rocks. Linear features (dark lines) correspond to normal Tertiary faults. SAU = San Antonio uplift, CH = Caborca High (McKee, 1991), CB = Cabullona basin, SAB = San Antonio basin, Ca = Cananea, Ba = Banámichi, Ac = Aconchi, Bv = Baviácora, Mo = Moctezuma, Ar = Arivechi.

of El Batamote ranch and south of San Antonio ranch; (c) the Mural Limestone block north of the El Grasero (Figure 11), that is derived from Mural rocks that crop out south of Mesa La Estaca; (d) the dragging of Mural Limestone showed in Figure 4 west of Cerro El Cacaxtle; (e) the bending of Mural Limestone west and south of Cerro El Tomastión; and (f) possibly the change in orientation (bending) of the Mural Limestone that crops out from Cerro La Tortuga (northwest-striking) to Sierra Los Azulitos (north-striking).

To the west of the area, the San Antonio uplift seems to be responsible for the Upper Cretaceous rocks located north of Arizpe and between Arizpe and Banámichi.

The second detachment movement is caused by the Metamorphic core complex event that accommodates south to southwest detachment faulting. It is believed that the Magdalena detachment fault of Nourse (1990) has a continuation to the east around Sierra Azul and extends at least to the Arizpe region. South of Sierra Azul is a fault zone that is more than one hundred meters wide and shows similar characteristics as the Magdalena fault; penetrative foliation and metamorphism occur there. This detachment is responsible for: (a) the broken block of Mural Limestone that appears west of Cerro El Tomastión, and (b) the deformation that occurs along the Arroyo El Cable. Folds, squeezing of beds and a fault zone are part of this deformation. At this time, the Early Cretaceous transfer fault was probably reactivated.

Basin and range normal faulting formed NW faults that affected all the sequences in the study area.

The detachment fault that affects the Upper Cretaceous El Tuli formation and the Morita Formation is interpreted to be associated with uplift evolution that occurred south of the study area, with transport movement on top to the north-northeast. An important point is that Upper Cretaceous rocks are not folded and thrusted, as has been reported in other parts of Sonora. High-angle normal faults are common in the sequence. Detachment is part of the middle Tertiary extensional faulting present in northern Sonora.

EVOLUTION

Documented Mesozoic extension in the Cordillera took place in the Late Triassic to Middle Jurassic (Busby-Spera, 1988), where extension has been closely associated in time and space with magmatism. However, Late Jurassic extension (160 Ma) is recorded in southeastern Arizona by Titley (1976), Bilodeau (1982), and recently by Lawton and Olmstead (1996). In northern Sonora, a Late Jurassic extensional event has been described (Nourse *et al.*, 1994; Grijalva-Noriega and Rodríguez-Castañeda, 1994). The Jurassic magmatic arc in northern Sonora was broken by northwest-striking faults during Late Jurassic time. Those faults gave origin to the basin or basins that received syntectonic sediments and younger Cretaceous rocks. During Early Cretaceous, differential vertical movements have been recognized in southeastern Arizona (Bilodeau, 1982). This extensional back-arc tectonic setting is very different from the compressional setting that has been found in other localities of Sonora. Rodríguez-Castañeda (1994) recognized extensional deformation in central Sonora that occurred in Late Cretaceous time.

Nourse (1989, 1990), and Nourse and collaborators (1994) postulated an extensional event in late Paleogene, the Metamorphic core complex extensional deformation. Rodríguez-Castañeda and Anderson (in preparation) characterize the Tertiary Basin and Range normal faulting that prevails in central Sonora.

The Upper Cretaceous rocks of the study area are supposedly deposited in a marine basin, that includes both-sedimentary and volcanic rocks. This up-to-now unrecognized Late Cretaceous basin is named here as "San Antonio-Banámichi basin" that is a physiographic feature as well as a depositional site (Figure 10). The San Antonio-Banámichi basin is limited to the south by the San Antonio uplift and to the north by the Cananea high. A pull-apart origin is suggested for the basin, that evolved from Late Jurassic to at least the Neogene. Location, extension, and width for this basin are not precise. However, it has been recognized, from north to south, in the Cocóspera (northwest of the area), San Antonio-Santa Teresa, Arizpe, Banámichi, Tehuachi, El Tuli, Aconchi, Cerro de Oro (Castro-R. and Morfín-V., 1988), Oposura (Roldán-Quintana, 1994), Arivechi (Almazán-Vázquez and Fernández-A., 1988; Palafox and Martínez, 1985; Pubellier, 1987), and La

Figure 11. Slide block of Mural Limestone as a result of top to the north detachment displacement. Block is located west of the area, north of the El Grasero.

Dura, Suaqui Grande regions (McDowell *et al.*, 1994) (Figure 10). At these places, the relationship (unconformity) between Lower Cretaceous or older rocks with Upper Cretaceous rocks indicates extension along this basin.

The Late Cretaceous San Antonio-Banámichi basin is separated from the Late Cretaceous Cabullona basin by a positive land. This land is proposed because lithological characteristics between both basins are different. It is postulated that positive land is the Cananea High (McKee, 1991; Grijalva-Noriega and Rodríguez-Castañeda, 1994) that evolved until Late Cretaceous, and whose southwest boundary or flank can be extended perhaps to at least Arivechi, where similar rocks to those in San Antonio crop out. The northeastern boundary is not known for certain; however, in southern Arizona, known and inferred northwest faults in the Santa Rita Mountains, Canelo Hills, and Huachuca Mountains and some that extend into Sonora, could be the boundary for the Cananea high. The Cabullona basin in northeastern Sonora has the characteristics of a synrift basin that connected with the Chihuahua trough of northern Mexico. It is unknown if the two basins—San Antonio-Banámichi and Cabullona—are connected southward.

CONCLUSIONS

The structures found in the study area provide evidence of the effects of extensional deformation characterized by uplift, gravity-sliding, syntectonic deposition, volcanism, and faulting. Lower Cretaceous, Upper Cretaceous, and Tertiary rocks record active extension from late Early Cretaceous to Paleogene, although analysis of older sediments outside of the area suggests that extension took place since the Late Jurassic in northern Sonora. It has been noted that extension in the North American Cordillera occurs from the Late Triassic until the Late Jurassic. It is evident that extension is closely associated in time and space with magmatism.

In Sonora, during Late Jurassic time, extension was probably caused by transtension and emplacement of plutons (154 Ma) (thermal uplift). Sediments associated with the Glance episode have been recognized in northern Sonora (Grijalva-Noriega and Rodríguez-Castañeda, 1994). They are directly related to uplift associated with vertical normal faulting (Bilodeau, 1982; Lawton and Olmstead, 1996). Others (Anderson *et al.*, 1995) suggest transtensional environment during Glance deposition.

During Early Cretaceous time, extension is recognized by gravity sliding and associated structures recorded mainly by the Mural Limestone blocks. Regionally, Lower Cretaceous rocks display contrasting structures to extension. This regional extension is associated to upwelling due to plutonism and stress regimes. Early Cretaceous magmatism is not documented in this region; although some volcanic beds have been found intercalated with the Lower Cretaceous sediments southward of the study area, in the Tuape region.

During Late Cretaceous to Paleogene, the beginning of extension is recorded by sediments and volcanic rocks (El Tuli formation) that have been deposited into a subsiding basin. An angular unconformity between a basal conglomerate of the El Tuli formation and older rocks that have a regional extent, suggests also a regional extension process that occurs at least in eastern Sonora. This extension is closely associated with plutonism (the Sonora batholith of Damon *et al.*, 1983; Anderson and Silver, 1978; Anderson *et al.*, 1980). To the east, similar strata far from the Sonora batholith do not record extension.

Tertiary extension represents delayed unroofing of the Sonora batholith. Tertiary gneisses and schists, the metamorphic core complex, and northeast striking faulting characterize this regional metamorphic and extensional period. A speculative idea suggests that at this time detachments occur in the area involving the Bisbee Group; also, a mass-gravity deformation took place. Evidence of this deformation is found around Banámichi, in central Sonora, where big block masses are surrounded by younger Báucarit sediments. The deformation in the Cerro de Oro area could be related to the same process. The Magdalena detachment fault (Nourse, 1990) is interpreted to continue to the east, north of Arizpe.

Regional Basin and Range extensional normal faulting caused the dominant morphology along eastern Sonora and is recorded in the area by NW trends.

TECTONIC SYNTHESIS

In Sonora, during Middle to Late Jurassic (170-154 Ma) time widespread volcanism and plutonism, plus extension and transpression, occurred. Transpression associated to the evolution of the Mojave-Sonora megashear seems to be followed by extension (transtension) and emplacement of plutonic rocks.

In late Early Cretaceous (100 Ma) documented deformation is driven by extension associated with uplift and resulting gravity sliding.

Early Late Cretaceous to early Tertiary plutonism was widespread (90-36 Ma) with associated thermotectonic uplift and sliding was followed by emplacement of dikes.

Middle Tertiary (36-15 Ma) extension was caused by inflation due to Tertiary granitic plutons and associated detachment.

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