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**The Cretaceous in the Caborca-Santa Ana region, northern  
Sonora, Mexico**

Jacques-Ayala, César, Ph.D.

University of Cincinnati, 1993

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**THE CRETACEOUS IN THE CABORCA-SANTA ANA REGION,  
NORTHERN SONORA, MEXICO**

A Dissertation submitted to the

Division of Graduate Studies and Research  
of the University of Cincinnati

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requirements for the degree of

**DOCTOR OF PHILOSOPHY**

in the Department of Geology  
of the College of Arts and Sciences

**1993**

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DOCTOR OF PHILOSOPHY

in

GEOLOGY

It is entitled

THE CRETACEOUS IN THE

CABORCA - SANTA ANA REGION,

NORTHERN SONORA, MEXICO

Approved by:

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## ABSTRACT

Stratigraphic, sedimentologic and petrographic studies of the Lower and Upper Cretaceous in northwest Sonora show that deposition of the Bisbee Group occurred at the northern margin of a back-arc marine basin, and of the El Chanate Group and El Charro volcanic complex in a closed continental foreland basin. This study also finds that the Proterozoic-Paleozoic formations in northwest Sonora (Caborca terrane) were not part of the Cretaceous landscape, thus raising doubts about the existence of the Mojave-Sonora megashear.

The Bisbee Group in northwest Sonora documents the southwest extension of the Bisbee basin, with coeval volcanic activity. Sandstone petrography indicates the presence of a rhyolitic volcanic arc to the north and south, and the absence of the Caborca terrane as a source area.

The El Chanate Group is a sedimentary sequence with minor volcanics unconformably overlying the Bisbee Group. It consists of three major fining-upward cycles, each characterized by different conglomerate compositions: quartz sandstone, andesite and rhyolite. Abrupt facies and thickness variations indicate that the basin was tectonically unstable. Sandstone petrography and conglomerate-clast composition (e.g., quartz-sandstone clasts at the base of the unit) indicate that sediments were derived from a rhyolitic volcanic arc and also probably from a distant 'cratonic' source, favoring a foreland basin setting.

The Laramide phase is the most important deformational phase of the Cordilleran orogeny in northwest Sonora. The age of this phase is constrained by the folded and foliated El Charro volcanic complex (71 Ma,  $\text{Ar}^{39}/\text{Ar}^{40}$ ) and the undeformed San Jacinto andesite (51 Ma, K/Ar). Laramide deformation in northwest Sonora is present in a northwest-southeast trending belt immediately north of the interpreted trace of the Mojave-Sonora megashear. The deformation of this belt could thus not be caused by the *Jurassic* Mojave-Sonora megashear.

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To our children, César and Angela I dedicate this work, hoping that it will serve as an inspiration. I also dedicate it to the memory of my mother, Aurora, my father, Jesús, my sister Dolores, and my brothers Rodolfo and Jesús.

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## INTRODUCTION

Northwest Sonora displays a complex array of rock types ranging in age from Early Proterozoic through Cenozoic. Most of northwest Sonora, however, has not been mapped geologically at an adequate scale to make sound tectonic interpretations and reconstructions. I therefore mapped the geology of some key areas in the Caborca-Santa Ana region that can help to understand the tectonic history of northwest México.

The Mesozoic and Cenozoic was a period with great tectonic activity in northwest Sonora: basin formation, mountain building, volcanism and emplacement of batholiths, metamorphism, compression and extension of the crust. Most of these events can be studied in rocks of Cretaceous age.

Before I began working in the Caborca-Santa Ana area in 1979 the age of most of the rocks was considered Jurassic or older. Many of the rocks that I have dated as Cretaceous (Jacques, 1983; this study) are still mapped as Jurassic (Stewart *et al.*, 1986; Tosdal *et al.*, 1989) leading to erroneous interpretations. For example, the Bisbee basin (Bilodeau, 1982; Dickinson *et al.*, 1986; 1989) and the Mojave-Sonora megashear (Silver and Anderson, 1974; Anderson and Silver, 1979) cannot be interpreted properly without knowledge of the age of the rock formations.

The Late Jurassic-Early Cretaceous Bisbee basin was thought to be restricted to southeastern Arizona and northeastern Sonora. Cretaceous rocks had been identified in northwest Sonora (Keller, 1928; Flores, 1929; Cooper and Arellano, 1946; Salas, 1968; Jacques and Potter, 1987) but only recently were these rocks in the Caborca-Santa Ana area (Navarro, 1989; Jacques *et al.*, 1990b; Jacques, 1992a; this study) assigned to the Bisbee Group. In two recent studies González and Jacques (1988) and Jacques *et al.* (1990b) postulated that deposition of the Lower Cretaceous in northwest Sonora occurred in the same basin as that of the Bisbee Group in southeastern Arizona and northeastern Sonora. This new geometry of the Bisbee basin requires a reinterpretation of its tectonic setting.

The Cabullona Group (Taliaferro, 1933) and the Fort Crittenden Formation (Hayes, 1970; Drewes, 1971) were the only Late Cretaceous sequences recognized in

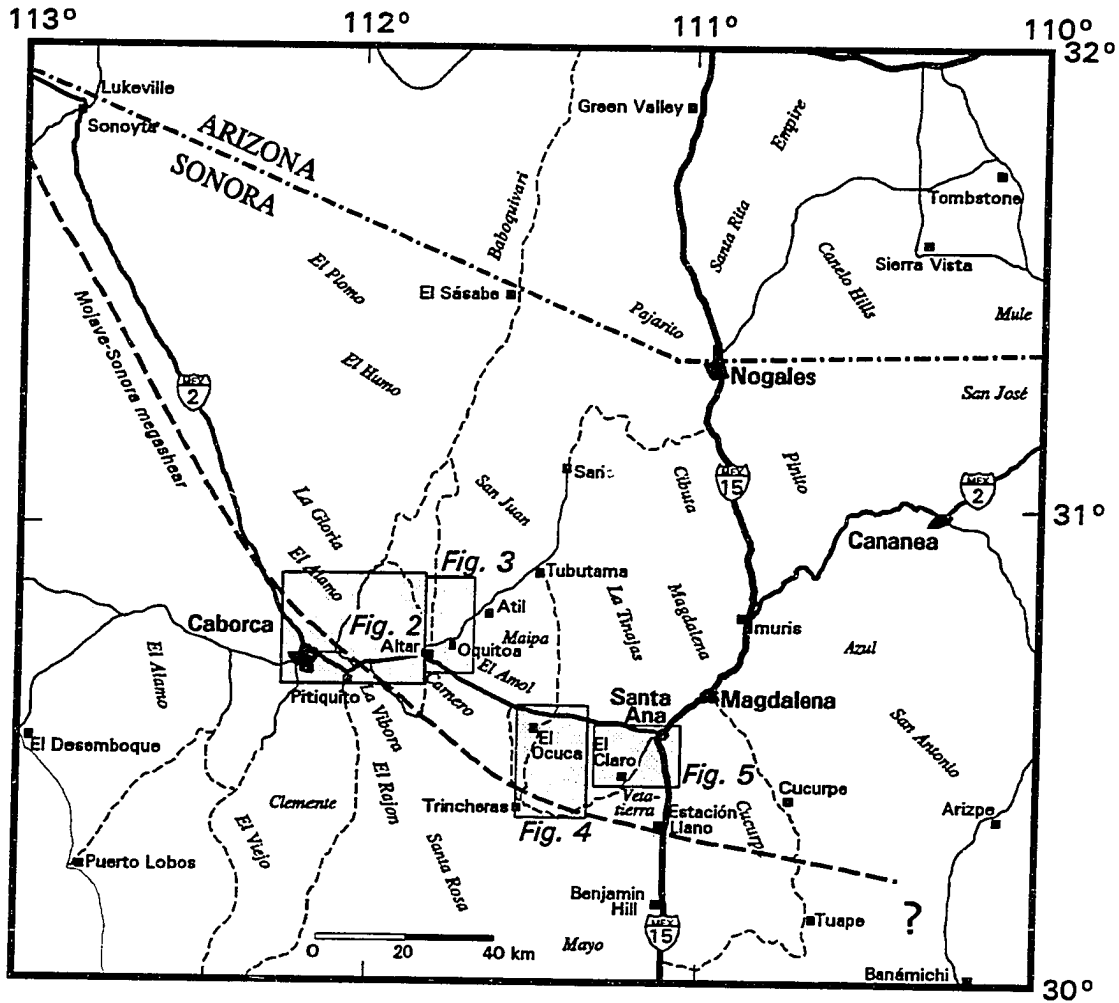


Figure 1. Map of northwest Sonora showing the location of the study areas.

Sonora and southeastern Arizona, respectively. The Cabullona/Fort Crittenden basin was thought to be small, restricted to southeastern Arizona and northeastern Sonora. Recent work in east-central Sonora (Pubellier, 1987; Grajales *et al.*, 1990) suggests that it probably stretches as far south as Arivechi.

The Upper Cretaceous in northwest Sonora has only recently been recognized (Jacques, 1983; Jacques and Potter, 1987; McComb, 1987; Willard, 1988; Harrar, 1989; Jacques *et al.* 1990b; García, 1992; this work). The rocks now assigned to the Upper Cretaceous were previously thought to be of Jurassic age. The Late Cretaceous of northwest Sonora stretched probably from Santa Ana to Sonoyta.

The presence of the Bisbee Group and El Chanate Group in northwest Sonora may have a bearing on the enigmatic McCoy Mountains Formation basin of southeastern California and southwestern Arizona (Harding, 1980; Harding and Coney, 1985; Stone *et al.*, 1987). The Cretaceous section in Caborca may link the Cretaceous section of the McCoy Mountains Formation and the Bisbee and Fort Crittenden/Cabullona basins in southeastern Arizona and northeastern Sonora.

### **Methods of Investigation**

The main purpose of this study is to describe the stratigraphy of the Cretaceous rocks in the Caborca-Santa Ana area and to reconstruct the geographic and tectonic evolution during the Cretaceous-early Tertiary. After establishing the stratigraphic basis for the Cretaceous by measuring stratigraphic sections and preliminary geologic mapping in the Sierra El Chanate (Jacques, 1983; Jacques and Potter, 1987), several areas were mapped: Sierra El Chanate, Cerros El Puerto, Cerros Cabeza Colgada, Cerro La Pima and the area south and east of Santa Ana (Plates 1-5). The map of the Sierra El Chanate-Puerto El Alamo (Plate 1) incorporates the geologic maps of McComb (1987), Willard (1988) and Harrar (1989).

The Lower Cretaceous Bisbee Group is the stratigraphic unit easiest to identify and map. The Upper Cretaceous is more difficult to map because of differences of facies and thickness. It is also structurally more complex, as was observed in the Cerros El Amol (García, 1992; García *in* Jacques *et al.*, 1990b). The work in that area by García (1992) led to a re-interpretation of the mapping of El Batamote (Harrar, 1989; McComb, 1987) and Puerto El Alamo (Willard, 1988).

Part of this study concerns the petrography of the sandstones in the Lower Cretaceous of the region. Jacques and Potter (1987) published the first description of Cretaceous sandstones in the area; Willard (1988) and García (1992) made detailed petrographic studies of the Puerto El Alamo and Cerros El Amol, respectively. Their results are incorporated in this work. The petrographic description by Klute (1991) of sandstones sampled in the El Chanate and Cerro La Pima areas are also incorporated in this study.

I studied 70 sandstone samples: 32 from the Bisbee Group in Sierra El Chanate, Cerros Cabeza Colgada and Cerros La Pima; 16 from the Bisbee Group in Cerro Mayo and Cerro de Oro (outside the study area), and 22 from the El Chanate Group in the Sierra El Chanate.

Thin sections were stained for potassium feldspar at the Instituto de Geología by Pablo Peñaflores; some thin sections were stained for potassium feldspar and plagioclase. The grain types counted are listed in Table 1, following Dickinson (1982) and Dickinson *et al.* (1983). An average of 500 grains per thin section was counted.

**Table 1. Counted grain types for sandstone petrography.**

Qm	Monocrystalline quartz
Qpw	Polycrystalline quartz with crystals >0.062 mm, without tectonic fabric.
Qpt	Polycrystalline quartz with crystals >0.062 mm, with tectonic fabric.
Lc	Polycrystalline quartz with crystals <0.062 mm = chert.
Qpol	Polycrystalline quartz with crystals >0.062 mm
P	Plagioclase
K	Potassium feldspar
Lvf	Volcanic lithic fragments with felsitic texture.
Lvm	Volcanic lithic fragments with microlithic texture.
Lvl	Volcanic lithic fragments with lathwork texture.
Lv	Volcanic rock fragments; includes three previous categories and those in which a monomineralic grain >0.062 mm was counted.
Ls	Sedimentary rock fragment with grains <0.062 mm. Includes grains in which a monomineralic grain >0.062 mm was counted.
Lm	Metamorphic rock fragment with grains <0.062 mm. Includes grains in which a monomineralic grain >0.062 mm was counted.
M	Detrital mica
HM	Heavy minerals
Carb.	Carbonate rock fragments
Misc.	Replaced grains, unidentified grains and others.

The counting procedure was the so called Gazzi-Dickinson method, with the addition suggested by Marsaglia and Ingersoll (1992) of counting aphanitic rock fragments to differentiate them in three textural categories: felsitic, microlithic and lathwork. The calculated parameters (Table 2) are those of Dickinson *et al.* (1983) modified by Marsaglia and Ingersoll (1992) to include the different aphanitic volcanic

rock fragments. The results are presented in tabular form (Tables 4 and 5), in ternary diagrams similar to those used by Dickinson *et al.* (1983) and Marsaglia and Ingersoll (1992), and in columnar graphs to integrate the whole Cretaceous sequence of the Sierra El Chanate.

**Table 2. Parameters used for sandstone compositional graphs.  
Grain-types in Table 1.**

Total quartz: $Q = Q_m + Q_{pw} + Q_{pt} + \text{chert}$ Lithic quartz: $Q_p = Q_{pl} + \text{chert}$ Total Feldspar: $F = P + K$ Unstable lithics: $L = L_v + L_m + L_s + \text{chert}$	Total lithics: $L_t = L + Q_{pl}$ Volcanic lithic grains: $L_v$ Sedimentary lithic grains: $L_s$ Metamorphic lithic grains: $L_m$
Calculations performed as indicated in Marsaglia and Ingersoll, 1992.	

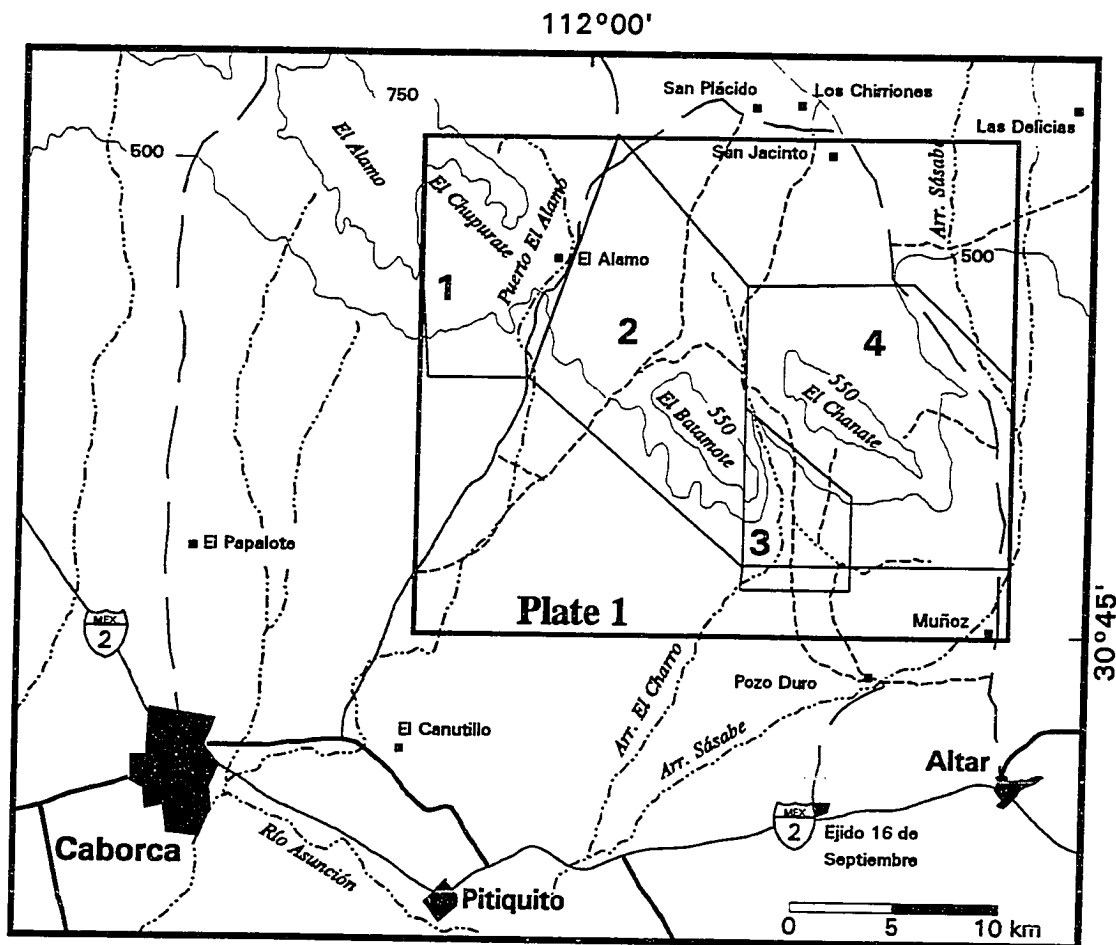
#### Location and Access

Five areas were studied in the Caborca-Santa Ana region (Fig. 1). The first area includes the Sierra El Chanate, Sierra El Batamote and Puerto El Alamo. It is located north of Federal Highway 2 between the towns of Altar and Caborca (Fig. 2). The western Sierra El Batamote and the Puerto El Alamo can be reached over a paved road that departs from Caborca to the east, and branches after 8 km to the north toward the mountains. Most of the area is accessible over dirt roads, and the Sierra El Chanate can be circled over a dirt road. During the rainy season (July-August, and December-January) the arroyos can get flooded.

The second area studied includes the Cerros El Puerto, located north of Oquitoa (Fig. 1). State Highway 64 cuts across the southern part of the mountain, and the road from Altar to Sásabe is on its west side (Fig. 3).

The Cerros Cabeza Colgada area is located about 30 km west of Santa Ana and north of Trincheras (Fig. 1). The area can be reached over Highway No. 2 and the dirt road to Nuevo Ocuca (Fig. 4). This is an ejido less than 2 km from the highway; the road continues southward toward Trincheras crossing the western part of the study area.

The Cerro La Pima, about 15 km west of Santa Ana (Fig. 1), can be reached over a dirt road which begins 13 km west from Santa Ana along Highway 2 (Fig. 5). The



**Figure 2.** Location of the Sierras El Chanate and El Batamote and Puerto El Alamo. Sources of information are: 1) Willard (1988); 2) Harrar (1989); 3) McComb (1987); 4) Jacques *et al.* (1990b).

study area south of Santa Ana can be reached over several dirt roads and the paved road to El Claro (Fig. 5).

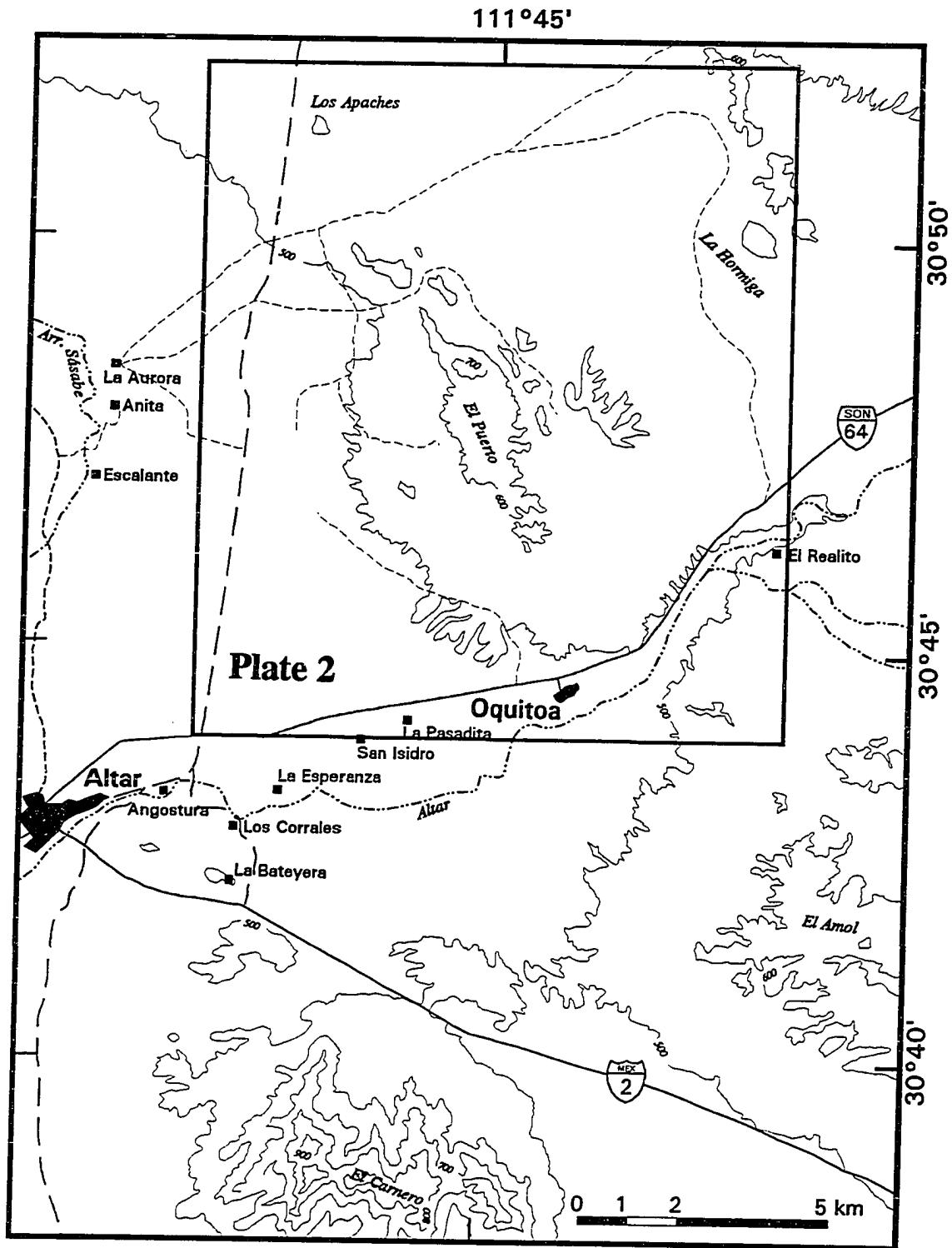


Figure 3. Location map of the Cerros El Puerto.

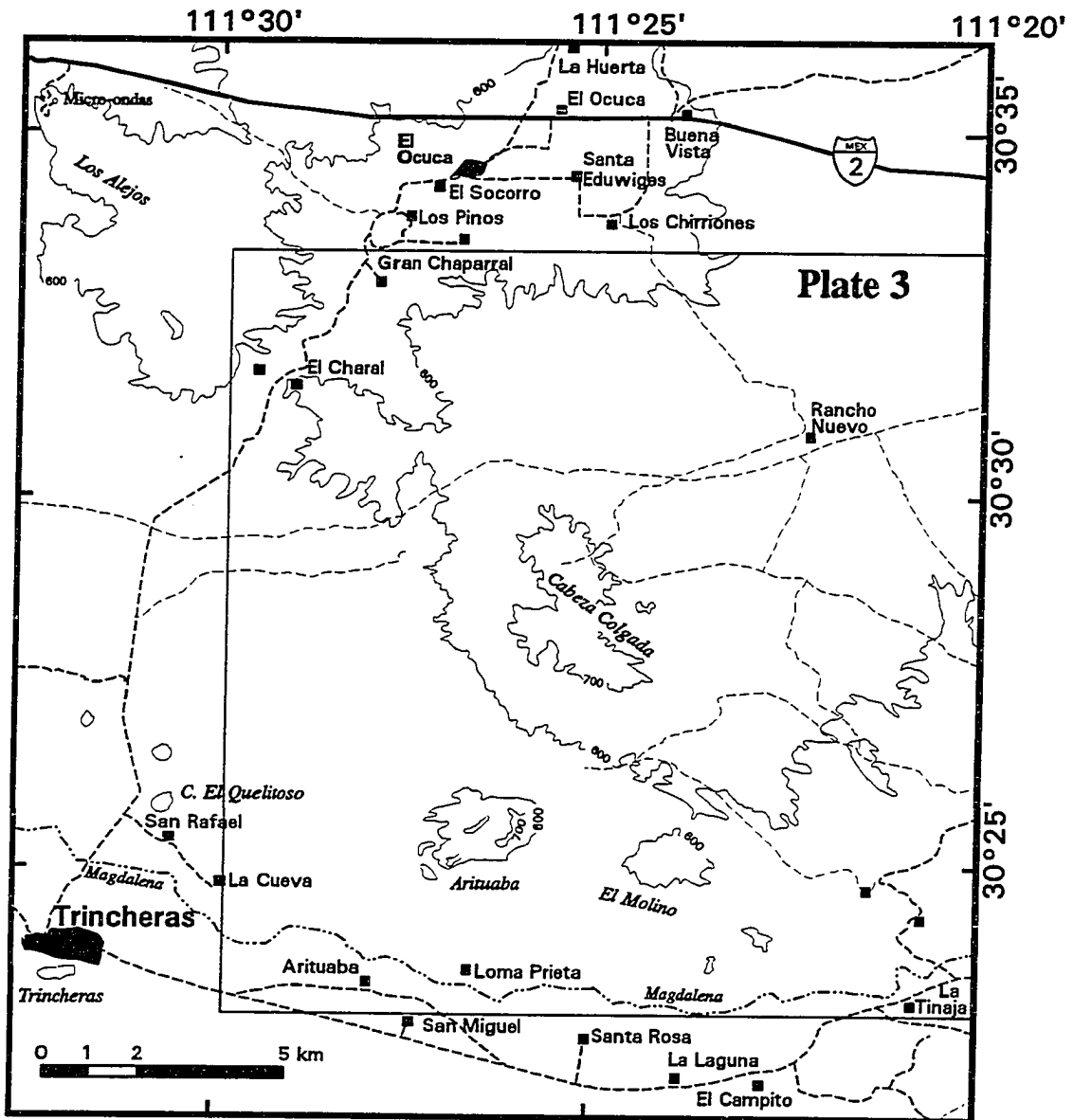


Figure 4. Location map of the Cerros Cabeza Colgada.

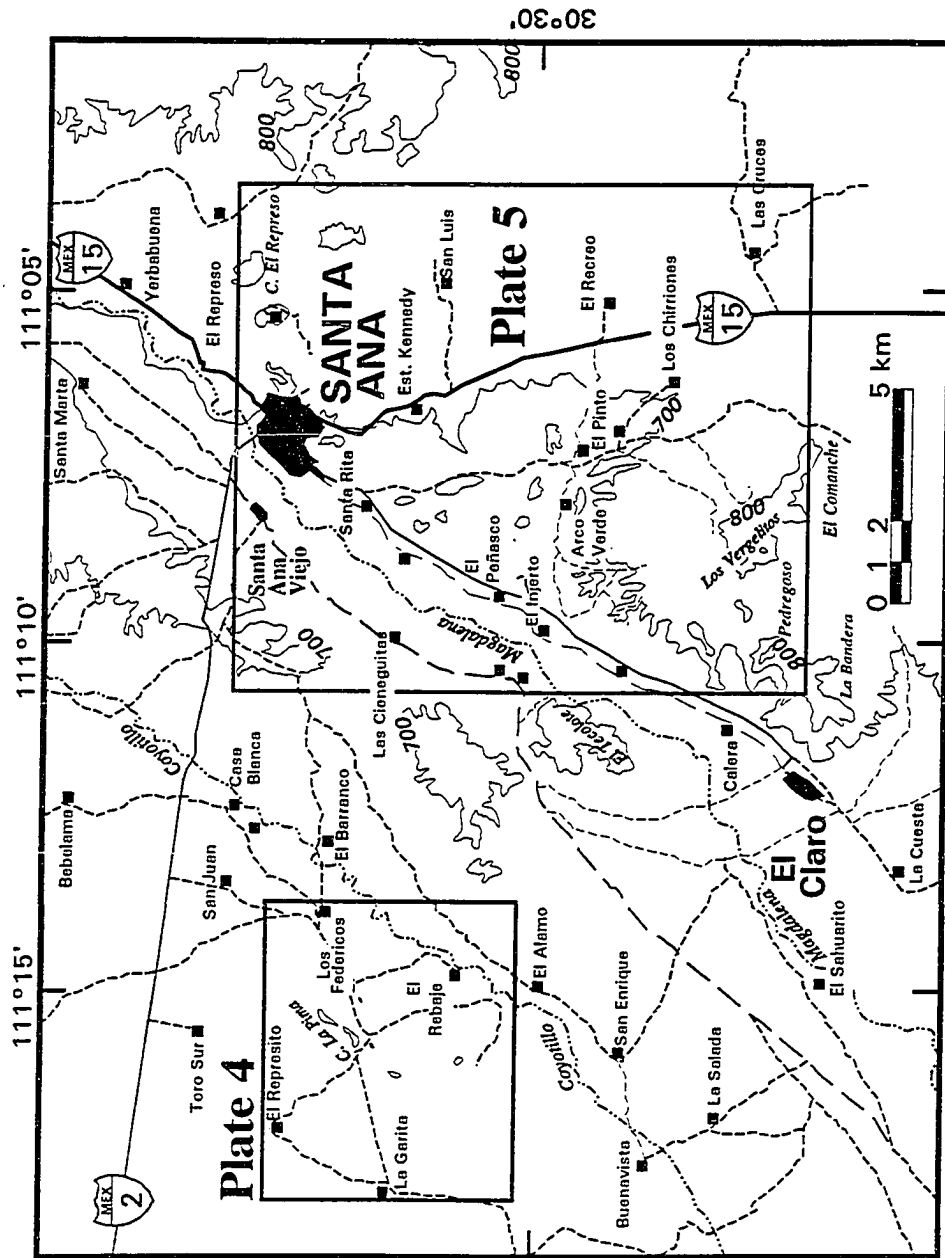


Figure 5. Location map of the Cerro La Pima and Santa Ana areas.

## REGIONAL OVERVIEW

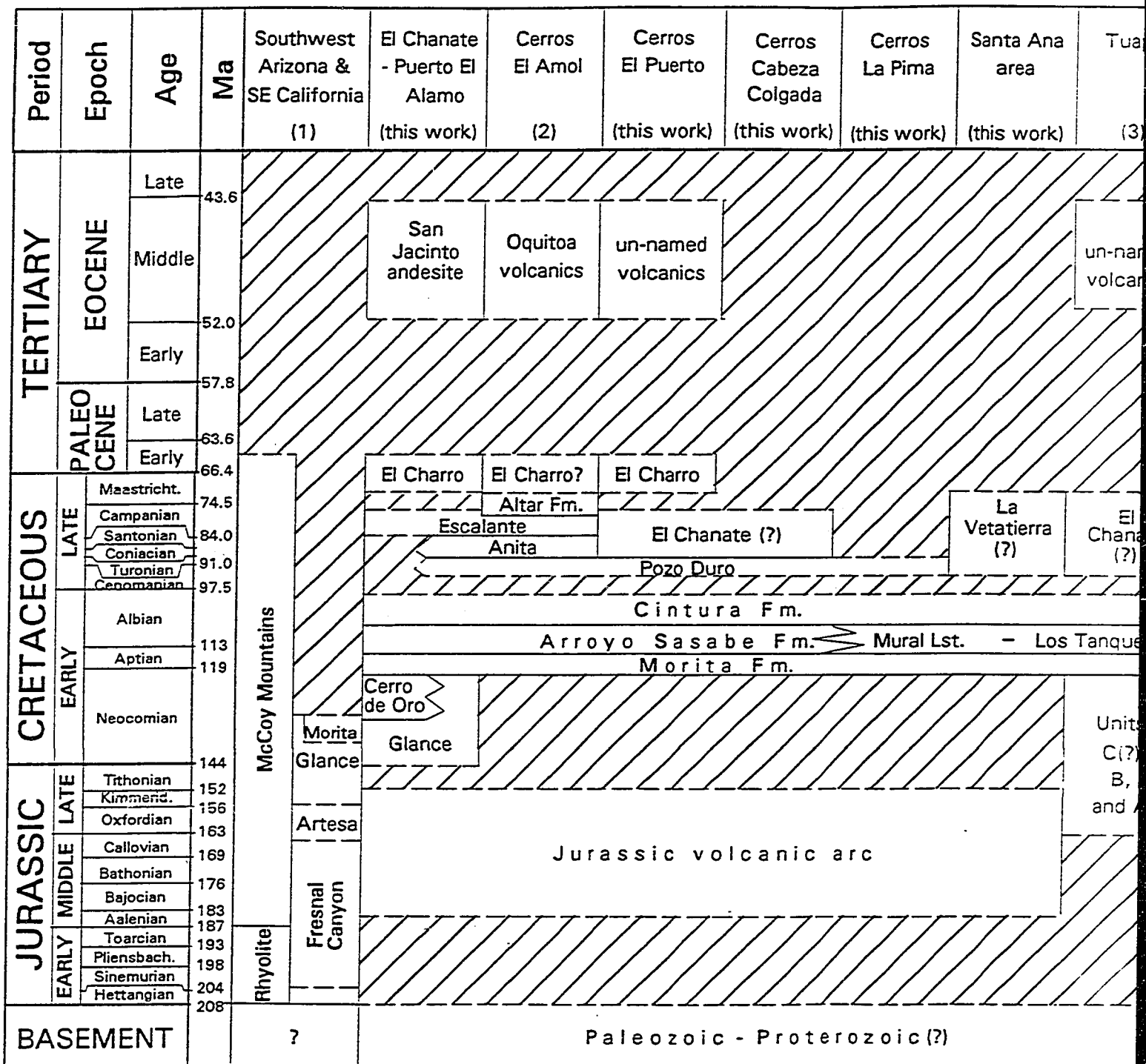
### Pre-Cretaceous regional geology

Rocks older than the Cretaceous are rarely exposed in the studied areas (Fig. 1) although rocks as old as the Early Proterozoic are widely exposed nearby (Fig. 6). The Lower-Middle Proterozoic consists of intrusive rocks and high-grade metamorphic rocks. The Upper Proterozoic sediments were deposited upon this basement. They consist of quartz sandstone, dolomite and shale. Sedimentation was probably continuous through the middle Cambrian (Cooper *et al.*, 1952; Stewart *et al.*, 1984). The Paleozoic is exposed in scattered, isolated hills, and consist mainly of carbonate rocks (Cooper *et al.*, 1952; Cooper and Arellano, 1946). The Upper Proterozoic-Paleozoic sequence was deposited on a shallow marine platform, with the deeper basinal deposits located to the south (Peiffer-Rangin, 1979; Gastil *et al.*, 1991). According to Gastil *et al.* (1991) the Paleozoic basin continuous westward into Baja California and California. The pre-Mesozoic units have only been reported south of the El Batamote structural complex (B in Fig. 6). Along this belt of metamorphosed rocks Anderson and Silver (1979) proposed the trace of the Mojave-Sonora megashear.

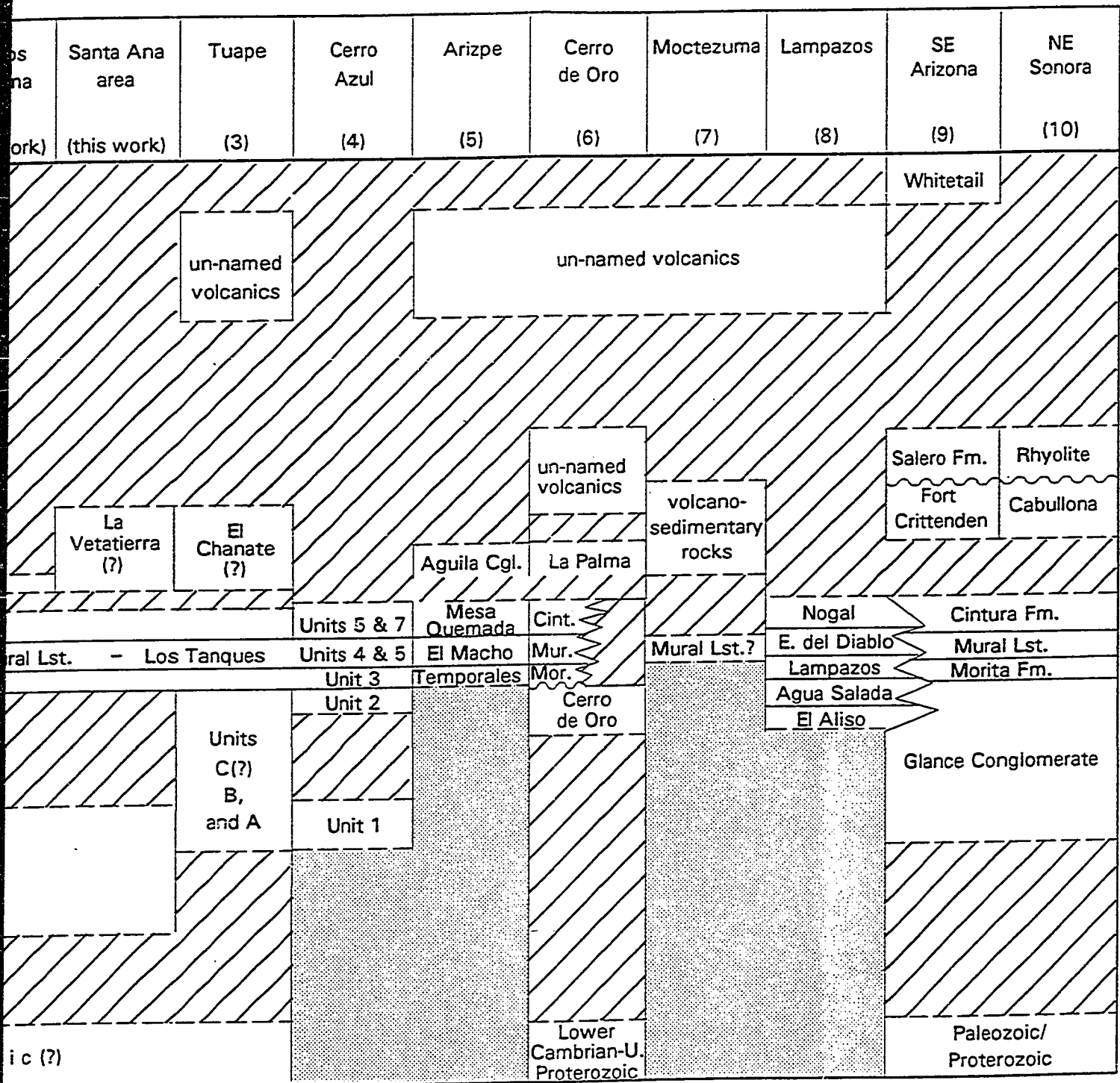
The El Antimonio Formation (González, 1980; González and Stanley, 1993; Lucas, 1993) is exposed in the Sierra El Antimonio, 45 km west of Caborca. Its age is well constrained as Late Triassic-Early Jurassic. The lower part consists of siltstone, mudstone and limestone; the upper part consists of sandstone and quartz-pebble conglomerate, and shale with ammonites (*Vermiceras* sp. among others). The sequence represents shallow marine to subaerial environments. In the Sierra Santa Rosa, Hardy (1973) described the Santa Rosa Formation of Late Triassic(?)–Early Jurassic age. Both the Sierra El Antimonio and the Sierra Santa Rosa are located south of the trace of the Mojave-Sonora megashear. From the northeastern Sierra La Gloria (Corona, 1979, 1980), 10 km north of Caborca and in the El Batamote structural complex an ammonite of Sinemurian (Early Jurassic) age (*Vermiceras* sp.) was found (Nuñez and DeJong, in prep.) suggesting that an Early Jurassic basin may have straddled the trace of the

**Table 3.** Correlation table of Jurassic - Eocene stratigraphic units of northern Sonora, southern Arizona and southeasternmost California. Ruled area: erosion or non-deposition; gray areas: basement unknown.

References: (1) Stone *et al.* (1987) and Tosdal *et al.*, (1989); (2) García (1992); (3) modified after Rodríguez (1988); (4) McKee (1991); (5) González (1978); (6) González and Jacques (1988); (7) Roldán (in prep.); (8) Scott and González (1991); (9) Dickinson *et al.* (1989), Scarborough (1989); (10) Rangin (1982), González *et al.* (1993).

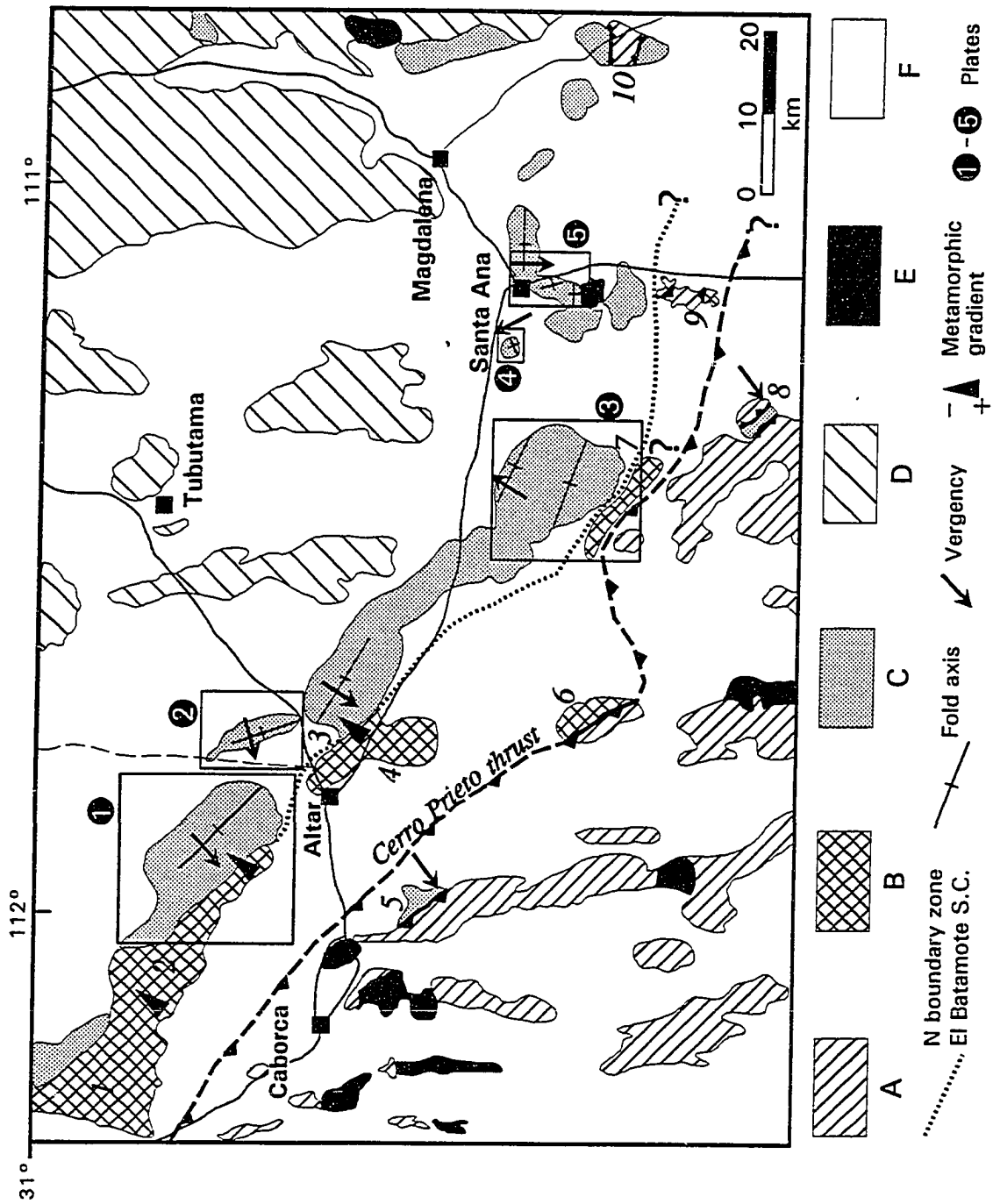








**Figure 6.** Simplified geological map of northwest Sonora. Legend: A) Caborca terrane (Proterozoic intrusive, metamorphic and sedimentary rocks, Paleozoic sedimentary rocks, and Mesozoic sedimentary and volcanosedimentary units); thrust faults, and locally cleavage in lower plate. B) El Batamote structural complex of poorly constrained age, probably including Early Jurassic to latest Cretaceous clastic and volcanic rocks which are variably deformed: folded, foliated, stretched and locally metamorphosed to green schist. C) Upper Jurassic to Upper Cretaceous and lowermost Tertiary sedimentary and volcanic rocks (Bisbee and El Chanate Groups and the El Charro volcanic complex). D) various Mesozoic supracrustal and intrusive rocks, variably deformed, and "metamorphic core complexes". No pre-Mesozoic rocks have been reported. E) Undeformed Cretaceous-early Tertiary granites. F) Cenozoic sedimentary and volcanic rocks. Localities: 1) Sierra La Gloria (Corona, 1979, 1980); 2) Cerro El Alamo 3) Cerros El Amol (García, 1992); 4) Cerro Carnero (Hayama *et al.*, 1984); 5) Sierra La Víbora (DeJong *et al.*, 1988); 6) Cerro Prieto (DeJong, pers. comm., 1993); 7) Cerro El Molino (R. Padilla, pers. comm., 1991); 8) Cerro Picacho (DeJong and Jacques, unpub. map); 9) Estación Llano (Herrera and Pérez, 1990; Calmus *et al.*, 1992); and 10) Rancho La Lámina (Stephens, 1987).



Mojave-Sonora megashear. However, Stewart *et al.* (1990) consider the El Antimonio sequence as an "outboard terrane".

Middle Jurassic rhyolites are widespread in the northern part of Sonora and southern Arizona (Stewart *et al.*, 1986; Riggs, 1987a, 1987b; Segerstrom, 1987; Lipman and Hagstrum, 1992). These igneous rocks are part of the Jurassic volcanic arc that extended along the Pacific coast of North America. In south-central Arizona sandstone beds of eolian origin are intercalated in the volcanic sequence. (Busby-Spera, 1988). In Sonora, Segerstrom (1987) described the Las Avispas formation southwest of Nogales. It is a volcanic-volcaniclastic unit with intercalated sandstone. South of the Mojave-Sonora megashear Jurassic volcanic rocks like those found in southern Arizona have been reported from an area northwest of Hermosillo (Avila, 1990).

The Upper Jurassic (Table 3) in northern Sonora and southern Arizona includes rhyolites (Abbot and Smith, 1988) and two types of sediments. One type consists of marine sediments with intercalated tuffs and andesitic volcanic rocks, present in Pozo Serna (Beauvais and Stump, 1976) and marine sediments with andesitic volcanic rocks in Cucurpe (Rangin, 1977a; Rodríguez, 1988; Araujo and Estavillo, 1987). Lawton and Olmstead (in prep.) have found in the Chiricahua Mountains, southeastern Arizona, marine sedimentary rocks with intercalated volcanic rocks of Late Jurassic age.

The other Upper Jurassic sedimentary rock type is the Gance Conglomerate, which includes near its base andesitic volcanic rocks dated as Late Jurassic (Marvin *et al.*, 1978; Krebs and Ruiz, 1987). This is a continental deposit overlain by the Early Cretaceous marginal and marine deposits of the Bisbee Group. In south-central Arizona, the Gance Conglomerate was deposited on the Artesa sequence, also a clastic sequence with intercalated volcanic rocks (Tosdal *et al.*, 1989).

The Pozo Serna and Cucurpe sequences were considered by González (1989b) as accreted terranes. The Chiricahua Mountains sequence described by Lawton and Olmstead (in prep.) was undoubtedly deposited on the North American craton. This could indicate that the Pozo Serna and Cucurpe sequences are autochthonous and not accreted terranes as considered by González.

An additional line of evidence linking these sequences is provided by Grajales (1990, written comm.) who studied the geochemistry of the volcanic rocks in the Cucurpe sequence and found it to be similar to that of the Canelo Hills volcanics and the volcanics in the lower Glance Conglomerate (Krebs and Ruiz, 1987).

### **Cretaceous regional geology**

The Cretaceous is widespread in northern Sonora and southern Arizona. The Late Jurassic-Early Cretaceous Bisbee Group is the reference stratigraphic unit in the region. It has been documented in many areas, and is relatively well dated. It was first described as the "Bisbee beds" by Dumble (1902) in the Mule Mountains near Bisbee, southeastern Arizona. Ransome (1904) named the sequence the Bisbee Group, with four units: the Glance Conglomerate (oldest), the Morita Formation, the Mural Limestone and the Cintura Formation (youngest). The type locality of the Morita Formation is in the Morita Hills, west-southwest of Agua Prieta, Sonora, whereas the type localities of the Glance and other Bisbee units are in the Mule Mountains.

In northwest Sonora Lower Cretaceous rocks have been reported in the Sierra El Chanate, east of Cerro Rajón and near Trincheras (Keller, 1928; Cooper and Arellano, 1946). Flores (1929) reported Lower Cretaceous in Santa Ana. Salas (1968) mapped the same area and named the Cretaceous sequence the Represo Formation; Morales (1984) made a regional map keeping the same nomenclature. Pérez (1986) studied the fossils of the Cerro La Pima and Santa Ana areas. Navarro (1989) renamed the Represo Formation as the Bisbee Group, but did not map the different units. Jacques *et al.* (1990b) extended the Bisbee Group into the Caborca-Altar area, and in the present study the Bisbee has been identified in several other areas.

Rocks of the Bisbee Group have been described in different areas, but with different names (Monreal, 1993). The units are in general characterized by having been deposited along the margin of the basin, the Mural/Arroyo Sásabe representing the maximum transgression phase, for they were deposited in open marine to lagoonal environments. This was not the only transgression in the Early Cretaceous. An older (Neocomian) transgression is documented by the Cerro de Oro Formation (González and

Jacques, 1988) and the El Aliso and Agua Salada Formations (González and Buitrón, 1985; Scott and González, 1991); and a younger transgression (late Albian) has been documented near Arizpe (González, 1978) and near Sahuaripa (Pubellier and Rangin, 1988).

The tectonic setting of the Bisbee basin is controversial. Different workers have proposed different hypotheses, invoking an aulacogen (Bilodeau, 1982), a rift related to a back arc (Dickinson, 1989), a back arc basin (Aubouin *et al.*, 1977; Servais *et al.*, 1986; Jacques *et al.*, 1993) and a foreland basin (Drewes, 1991). The geographical extent of the Bisbee basin is also a controversial topic. First it was thought that the basin was restricted to southeasternmost Arizona and northeasternmost Sonora (Hayes, 1970; Bilodeau, 1982; Klute, 1987; Dickinson *et al.*, 1989). Navarro (1989) and Jacques *et al.* (1990b) extended the Bisbee basin to northwest Sonora, and González and Jacques (1988) to central Sonora (Cerro de Oro). According to González and Jacques (1990) the Bisbee basin was a relatively shallow basin that occupied present-day southeastern Arizona and most of Sonora, except for its western-southwestern part, deepening toward the southeast. Kitz and Anderson (1988) and McKee (1991), on the other hand, interpret redeposited platform-limestone beds(?) within basinal(?) shale as an indicator of a deep sub-basin in the Cerro Azul area, north-central Sonora. Nourse (1993) postulates the presence of a positive land area between Magdalena and Cananea from where Jurassic rhyolitic volcanic rocks were shedding detritus toward the southwest into what he calls the Magdalena-Tubutama basin and toward the northeast into the Bisbee basin.

By the end of the Early Cretaceous a regression, probably related to a regional uplift associated to folding and thrusting, took place. Folding of the Bisbee Group prior to the deposition of the Upper Cretaceous has been documented in northeast Sonora (Rangin, 1977b), in east-central Sonora (Pubellier, 1987; Pubellier and Rangin, 1988; Roldán, in prep.).

The Upper Cretaceous in Sonora has not been described previously, except for the Cabullona Group in the northeast (Taliaferro, 1933). Recent work in this unit (Lucas and González, 1990) has yielded abundant vertebrate fauna which places the sequence in the Santonian-Maastrichtian. This is the same age as the Fort Crittenden Formation

in southeastern Arizona. Jacques (1983) and Jacques and Potter (1987) described for the first time the Upper Cretaceous El Chanate Group. Other sequences of Late Cretaceous age include the Altar Formation which overlies the El Chanate Group (García, 1992; García *in* Jacques *et al.*, 1990b), the La Palma formation (González and Jacques, 1988), the Tarachi unit (Pubellier, 1987) and a volcano-sedimentary sequence east of Moctezuma (Roldán, *in prep.*).

In the early Late Cretaceous Sonora and southern Arizona underwent a period of uplifting, folding and thrusting (Rangin, 1977b, 1982; DeJong *et al.*, 1988; Pubellier and Rangin, 1988; Drewes, 1991; Jacques *et al.*, 1993). The early Late Cretaceous orogeny induced the formation of relatively small continental basins, probably elongated in a northwest direction. The largest basin appears to be that of the Tarachi sequence in eastern Sonora (Pubellier, 1987) which extends from Arivechi to the north, and could be the continuation of the Cabullona-Fort Crittenden basin. The age of Tarachi and Cabullona basins is Coniacian?-Maastrichtian (Taliaferro, 1933; Lucas and González, 1990; Pubellier, 1987).

Another Late Cretaceous basin is located south of Moctezuma (Roldán, *in prep.*); it extends northward into de Banámichi area (Bojórquez and Rosas, 1988). In the northwest, the El Chanate basin appears to extend from Cerro La Pima to Tajitos, and probably as far as Sonoyta.

By the end of the Late Cretaceous volcanic activity resumed. It consists mainly of calc-alkaline andesites with subordinated rhyolite tuffs and flows. Locally the volcanic sequence interfingers with conglomerates and sandstones. These have been reported in the study area as the El Charro volcanic complex (Jacques *et al.*, 1990b), in Sierra El Alamo (González, 1979; Cohen *et al.*, 1986), in Moctezuma (Roldán, *in prep.*), in Cerro de Oro (Castro and Morfín, 1988) and in east-central Sonora (Pubellier, 1987). In southern Arizona they have been named the Salero and Demetrie volcanics (Drewes, 1971; Hayes and Drewes, 1978). After this period of volcanism the Laramide deformational phase began, characterized by thrusting, folding and metamorphism (Haxel *et al.*, 1984; Keith and Wilt, 1986).

## **Cenozoic regional geology**

By the end of the Early Eocene compressional deformation, uplift and erosion had largely ceased and volcanic activity resumed (Jacques *et al.*, 1993). After a tectonic pause extensional deformation began in the Late Oligocene-Early Miocene. Major low angle normal faulting formed "metamorphic core complexes". These were exhumed in Sonora as far south as Mazatán, east of Hermosillo (Anderson *et al.*, 1980; Davis and Anderson, 1981; Nourse, 1989). Some of the low-angle normal faults are rejuvenated thrust faults (DeJong and Jacques, 1986). Coarse to fine clastic sediments accumulated in fault-related basins as alluvial and lacustrine deposits (Miranda and Gómez, 1993). In the latest Miocene high-angle normal faulting led to the formation of the Basin and Range of Sonora. Coarse clastic sedimentation continued, locally unconformably upon similar sediments.

## **Structural setting**

The structural evolution of Sonora is poorly understood, largely because of the lack of detailed geological maps. The oldest Phanerozoic deformation is recognized in central Sonora where Paleozoic basinal rocks were thrust over shallow marine late Paleozoic successions during the early Late Mississippian (Stewart, 1988; Stewart *et al.*, 1990; Ketner and Noll, 1987; Poole and Madrid, 1988; Radelli *et al.*, 1987) and the Late Permian to Middle Triassic (Stewart *et al.*, 1990).

There is no indication of deformation in Sonora during the Late Triassic and Early Jurassic. The Lower Jurassic overlies conformably the Upper Triassic in the Sierra El Antimonio (Lucas, 1993), and the Triassic is underlain by the Permian. However, the Sierra El Antimonio has been interpreted as an accreted terrane (Stewart *et al.*, 1990; Lucas, 1993), and the stratigraphic relationships of this sequence may have formed far away from Sonora.

Rangin (1982), observing chevron folds in the Upper Jurassic near Cucurpe overlain unconformably by Bisbee rocks, suggested the presence of a Late Jurassic orogenic phase (Nevadan phase). The Mojave-Sonora megashear is also thought to be of

Late Jurassic age (Silver and Anderson, 1974; Anderson and Silver, 1979; Anderson and Schmidt, 1983) and responsible for some of the deformation observed in the region (Connors *et al.*, 1989; Rodríguez, 1990; Anderson *et al.*, 1992). The trace of the megashear follows a belt of deformed rocks which were thought to be of Early Jurassic or older age. The Lower Cretaceous was reported as practically undeformed (Corona, 1979, 1980). However, my mapping in the Caborca-Santa Ana region provides evidence that the belt of deformed rocks include rocks as young as Late Cretaceous (Jacques *et al.*, 1990b, this study).

Thrusting and folding occurred during the early Late Cretaceous: in Sahuaripa the Paleozoic was thrust upon the Lower Cretaceous before the deposition of the Upper Cretaceous (Pubellier and Rangin, 1988); east of Moctezuma the Lower Cretaceous is cut by an angular unconformity and overlain by an Upper Cretaceous volcano-sedimentary sequence intruded by a 64 Ma granite (Roldán, in prep), and in the Sierra La Víbora, 15 km south of the Sierra El Chanate, a thrust fault cut by an 80 Ma granite emplaces the Proterozoic-Paleozoic upon Mesozoic sandstone (DeJong *et al.*, 1988). This mid-Cretaceous deformation has been called the albo-cenomanian orogeny (Rangin, 1982), the Sevier orogenic phase (Drewes, 1991), and the Bámori "orogeny" (DeJong *et al.*, 1988). Several authors (Calmus and Radelli, 1987; Minjárez, 1991; Sosson, 1993) have considered this as the paroxysmal phase of the Cordilleran orogeny.

The presence of the Laramide orogenic phase (latest Cretaceous-Paleocene) in Sonora has been recognized since King (1939). There is a disagreement, however, about its significance. According to Corona (1979, 1980), Calmus and Radelli (1987), Rodríguez (1990) and Minjárez (1991) it was a minor late orogenic phase; according to Haxel *et al.*, (1984) this phase of the Cordilleran orogeny was an important phase with large scale thrust faults.

Folding of the Lower and Upper Cretaceous has been described in few places. In northeast Sonora, Rangin (1977b) mentions the presence of wide open folds. In northwest Sonora the Lower Cretaceous Bisbee Group and the Upper Cretaceous El Chanate Group are folded, and there is no angular unconformity between the two groups. The folds are

tight and locally overturned as in the Sierra El Chanate (Jacques, 1983) and Santa Ana area (Jacques, 1992a).

Late Cretaceous thrust faults in the study area have been documented in the Cerro Alamo (Willard, 1988) and Sierra El Batamote (Harrar, 1989). In the Cerro Alamo, a sequence of stretched conglomerates composed of quartz sandstone and volcanic pebbles and boulders, has been emplaced upon the Cretaceous Bisbee and El Chanate Groups (Willard, 1988). In the Cerro Picacho, the Lower and Upper Proterozoic are thrust upon sandstone and andesitic conglomerate of the El Chanate Group (DeJong and Jacques, unpublished map). South of Magdalena, near Rancho La Lámina, a Precambrian gneiss has been emplaced upon Jurassic (?) rocks (Stephens, 1987). In my opinion, these Jurassic (?) rocks are similar to the Bisbee Group, as they consists of red mudstone. These occurrences indicate that the Laramide thrusting in northern Sonora cannot be older than early Late Cretaceous, and is likely of latest Cretaceous or Paleocene age.

Crustal extension of northern Sonora in the mid-Tertiary resulted in low-angle faults and metamorphic core complexes. A low-angle extensional fault, with the upper plate moving westward, is exposed a few kilometers south of Altar (Fig. 6) in the western Cerro Carnero (Jacques *et al.*, 1990b). Its age is presumably 16 Ma. In the Tubutama area (Fig. 6) continental clastic deposits of Tertiary age dip steeply against a subhorizontal extensional fault with westward movement of the upper plate (Frye, 1975; Colletta and Angelier, 1983; DeJong *et al.*, 1988).

The Santa Ana area is about 10 km southwest of the metamorphic core complex of the Sierra de Magdalena and Sierra La Madera (Nourse, 1989), and apparently part of the upper plate that moved southwestward at least 10 km (Nourse, 1989, 1992).

The basin and ranges in northwest Sonora are not bounded by recently active faults. Extensive piedmonts have developed, for example south of the Sierra El Batamote and north of the Sierra El Chanate (Fig. 6). Northwest Sonora is part of the Buried Ranges province of Raisz (1964). The faults that border the ranges are now buried; they were apparently active during Late Miocene-Pliocene time. It is not known whether these faults were dip-slip extensional faults or whether a strike-slip component was present as well.

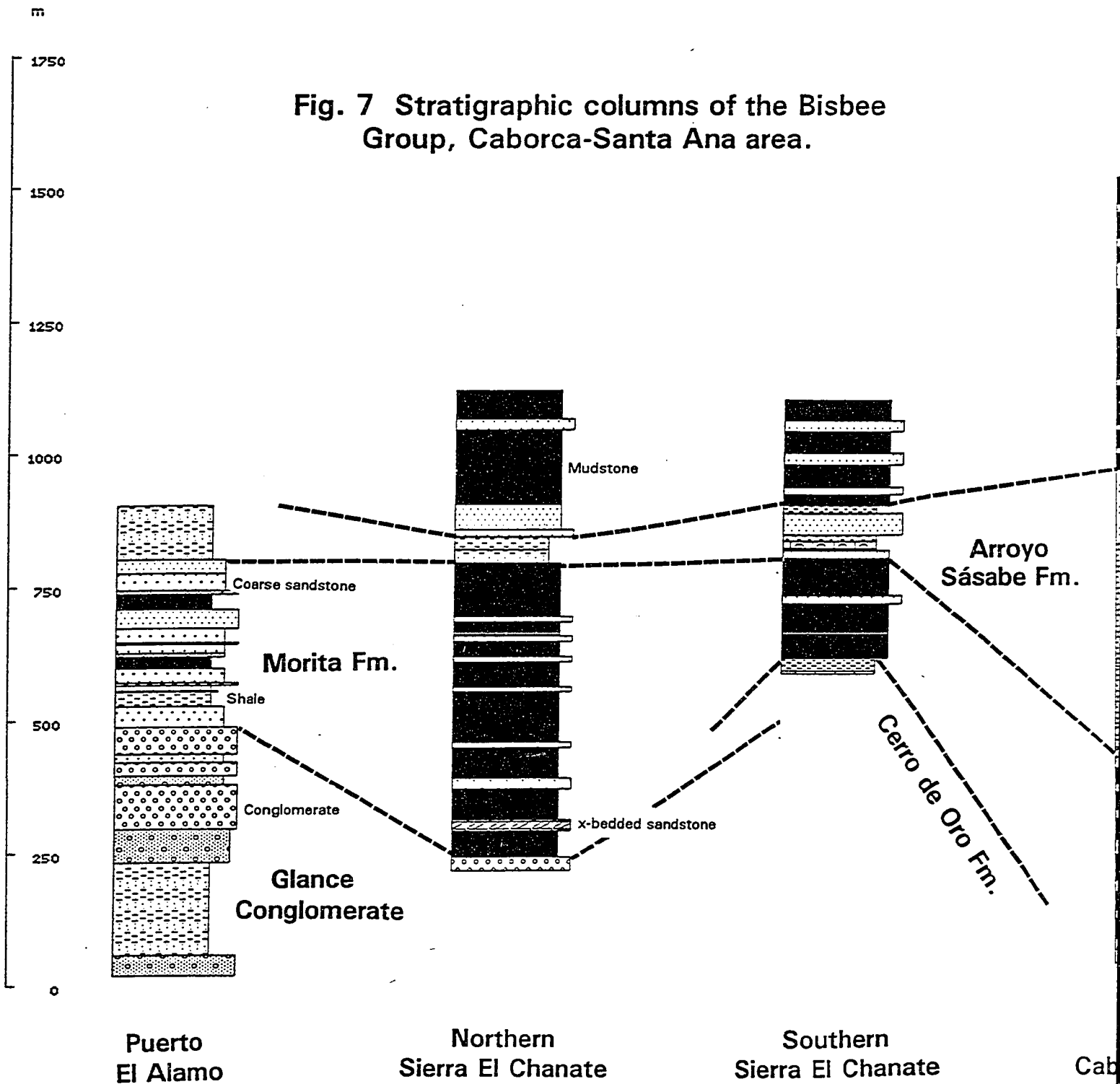
## THE BISBEE GROUP

The Bisbee Group and correlative rocks are widely distributed in northern Sonora; they are also probably the best studied sequences. The group was first described in southeastern Arizona by Dumble (1902). Ransome (1904) divided the unit in four formations: Glance Conglomerate (oldest), Morita Formation, Mural Limestone and Cintura Formation (youngest). In the Caborca-Santa Ana area the three upper units (or their equivalents) of the Bisbee are extensively exposed even though they have been only recently recognized (Navarro, 1989; Jacques *et al.*, 1990b). The lowest unit, the Glance Conglomerate occurs only in the northern Sierra El Chanate and the Puerto El Alamo. A new unit, correlative to the Mural Limestone, is the Arroyo Sásabe Formation (Jacques, 1989). The Arroyo Sásabe is found in the western part of the study area, whereas the Mural Limestone occurs in the eastern part, in the Cerro La Pima and Santa Ana.

The Bisbee Group in the Caborca-Santa Ana area includes the four known formations, but its base is nowhere exposed (Fig. 7). The upper contact is with the El Chanate Group. The Bisbee Group in the Puerto El Alamo area, 890 m thick, includes the Glance Conglomerate, the Morita and the Arroyo Sásabe Formations; the Cintura Formation is missing. In the Sierra El Chanate it is 940 m thick in its northern flank and 520 m in the southern flank. In the Cerros Cabeza Colgada it has an estimated thickness of 1500 m. In the Cerro La Pima the estimated thickness is about 1500 m, and in the Santa Ana area, east of highway 15 the Bisbee attains an estimated thickness of 1900 m. García (*in* Jacques *et al.*, 1990b, 1992) described the Bisbee in the northern Cerros El Amol where it is 1,250 m thick.

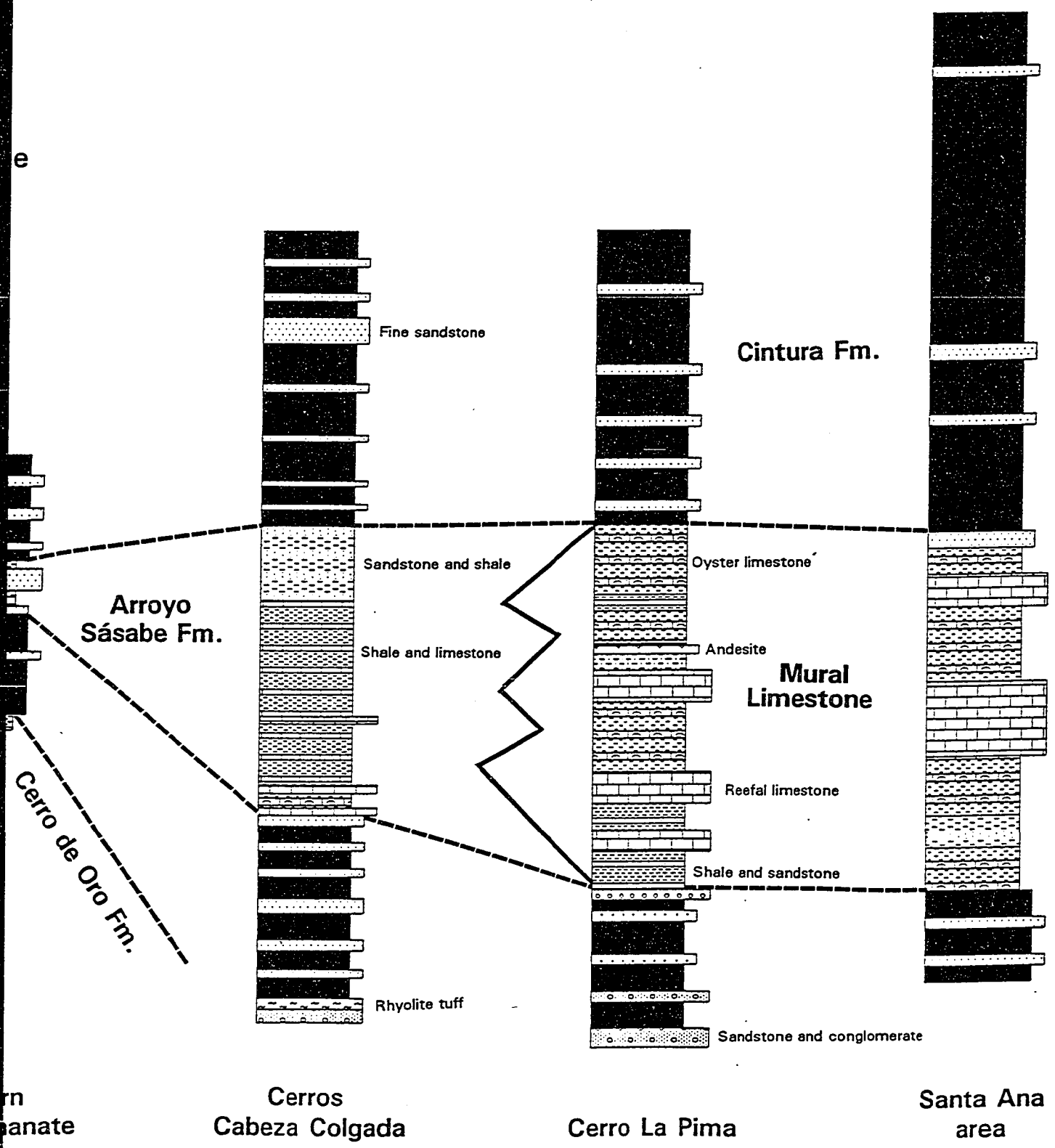
### Glance Conglomerate

The Glance Conglomerate is a coarse clastic sequence forming the base of the Bisbee Group. In the study area it is exposed in northern Sierra El Chanate and Puerto El Alamo. A few thin conglomerate lenses occur near the base of the Morita Formation in Cerros El Puerto and Cerro La Pima but are considered as part of the Morita.





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In Sierra El Batamote and Cerro Alamo conglomerates in the El Batamote structural complex are locally stretched. Some of these coarse clastics could be the Glance Conglomerate.

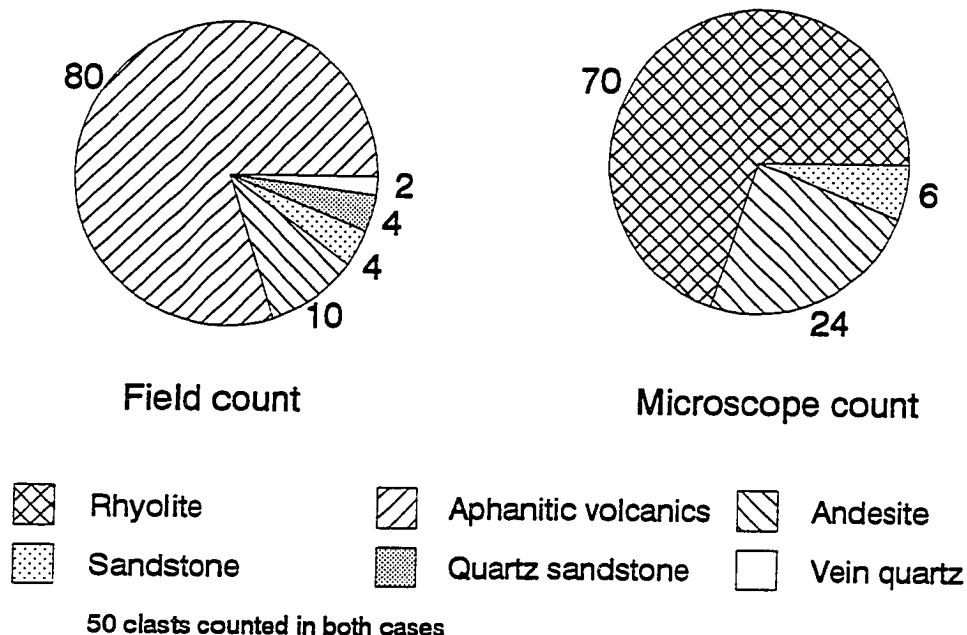
#### **Sierra El Chanate (Plate 1)**

The Glance Conglomerate is exposed off the road to La Laguna Ranch where it crosses the Arroyo Sásabe in the northern flank of the Sierra El Chanate, and along the road to Los Chirriones Ranch. Isolated exposures of andesitic breccias occur in several places near the Glance, but the relationship between the andesite and the Glance is unknown.

The conglomerate is mottled to green, massive, with green, coarse to medium grained sandstone in thin layers. The section is 21 m thick near La Laguna Ranch, and slightly thicker along the road to Los Chirriones Ranch. The pebbles are rounded to angular and consist mainly of fine grained silicified rock fragments in different colors: green, red, black and white. The matrix is a lithic arenite. Under the microscope the fragments are mostly aphanitic volcanic rocks, mainly rhyolite. Also present are fragments of andesite and sedimentary rocks. A field count of 50 pebbles yield the results observed in Fig. 8A. A study of one 5 X 7 cm thin section has the clast composition shown in Fig. 8B. Limited paleocurrent data from cross bedding suggests that the source of these conglomerate was a rhyolitic volcanic arc located to the south.

#### **Puerto El Alamo (Plate 1)**

In the northeastern Cerro Alamo Willard's (1988) Chupurate member of his Sásabe Formation is here considered as the Glance Conglomerate. In this area Willard (1988) measured 485 m of section. The Glance is reddish brown to yellowish brown, and grayish red. Conglomerates occur in lenses with thickness of less than 1 m and up to 5 m. These are clast-supported and form the base of fining upward cycles. Clasts are mainly derived from igneous rocks. In both Puerto El Alamo and Sierra El Chanate few clasts of quartz sandstone and lithic sandstone occur. The intercalated sandstone is medium to coarse grained, fairly to poorly sorted, and immature. It varies from lithic



**Figure 8.** Clast composition of the Gance Conglomerate in the northern Sierra El Chanate. A) Clast-count at the outcrop; B) clast-count in thin section.

arenite to a lithic wacke. The lithic fraction is derived mostly from igneous rocks. In the lower third of the section is a 50 m thick sequence of finer grained sandstone with some intercalations of shale.

### Depositional Environment

The Gance Conglomerate of the northern Sierra El Chanate was deposited most probably in a fluvial environment. The predominance of sandstone over conglomerate suggests a medial distance from the source. Volcanic rocks that appear to be intercalated in the Gance suggest the presence of volcanic activity. The Gance of the Puerto El Alamo area was also deposited in a fluvial environment probably near alluvial fans, as suggested by the thick conglomerates.

The source of the Gance sediments was a volcanic terrain, mainly of rhyolitic composition. This source was likely the Jurassic volcanic arc. Limited paleocurrent indicators suggest that the source was to the south.

In northeastern Sonora and southeastern Arizona the Glance attains thicknesses over 2,000 m. It was deposited in alluvial fans and braided streams with concurrent andesitic-basaltic volcanic activity (Bilodeau *et al.*, 1987; Krebs and Ruiz, 1987).

### **Cerro de Oro Formation**

At one location immediately north of the El Chanate fault (Plate 1) a sequence of thin bedded shale with intercalations of limestone and sandstone is exposed below the Morita. The shale is buff and thin to medium bedded. The limestone is light gray, thinly bedded and locally laminated with sporadic, unidentifiable, fossils. The sandstone is buff, thinly bedded without internal features. It is assumed that this sequence is the Cerro de Oro Formation (González and Jacques, 1988).

This formation erodes easily, as compared to the Morita, forming a low-lying area. The thickness of this unit cannot be determined because it is cut by the El Chanate fault. The exposure is less than 30 m thick.

At another locality, west of the El Batamote Ranch and in the Arroyo El Charro, a buff shale without limestone intercalations, presumably the Cerro de Oro Formation, is exposed. It lies within the El Chanate fault zone, and it is folded, fractured, and hydrothermally altered.

### **Depositional Environment**

The Cerro de Oro Formation was probably deposited in a shallow marine environment, as has been documented in Cerro de Oro (González and Jacques, 1988), thus suggesting that fluvial deposition was not far from a marine setting, at least for a relatively short time.

### **The Morita Formation**

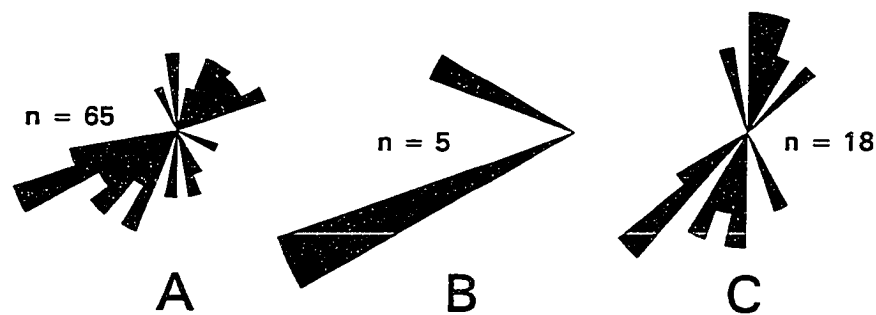
#### **Sierra El Chanate (Plate 1)**

The Morita Formation in the Sierra El Chanate was described as the lower member of the Sásabe Formation by Jacques (1983), as the lower member of the Arroyo Sásabe Formation by Jacques and Potter (1987) and as the Morita Formation by Jacques

*et al.* (1990b) and Jacques (1992b).

The Morita Formation is exposed in the northern flank of Sierra El Chanate (486 m thick), and in the southern flank, where it is cut by El Chanate fault near the base and along strike. On the southwestern side of the sierra, where it is in contact with the Cerro de Oro Formation it is about 200 m thick (Fig. 7).

The Morita Formation is a sequence of mainly red to purplish and grayish red mudstone in thick to massive beds and purplish gray to gray sandstone. The mudstone displays locally some internal stratification-lamination. The sandstone, fine to medium grained, occurs generally in beds less than 1 m thick. Some sandstone beds include at the base a rip-up clast conglomerate. Lenses of conglomerate less than 2 m thick occur near the base of the unit. Clasts consist mainly of igneous rocks and rarely of quartz sandstone. Near the top some floatstone and rudestone beds of coarse mollusc debris are present.



**Figure 9.** Rose diagrams of cross-bedding in the Morita Formation. A) Sierra El Chanate; B) Cerros El Puerto; C) Cerros Cabeza Colgada.

Cross-bedding in the Morita Formation is bimodal, indicating a depositional strand line in a northwest direction (Fig. 9), the source probably to the northeast and southwest.

#### **Puerto El Alamo (Plate 1)**

The Morita is also present in the Puerto El Alamo area. Excellent exposures can be seen where the paved road ends, near the Rancho El Alamo (Plate 1). According to Willard (1988) the thickness of the Morita can be up to 440 m, of which 290 m were measured in detail. This unit extends along the northern limb of the Cerro Alamo, and

to the southeast across the pass into the Sierra El Batamote. In the Sierra El Batamote the Morita is overthrust by the El Batamote structural complex (Harrar, 1989).

In the Puerto El Alamo the Morita is a red to purplish red, massively bedded mudstone, locally with small calcareous nodules. Also present are minor intercalations of gray to purplish gray, medium to thick bedded, fine grained sandstone, and red conglomerate in lenses less than 5 m thick. Conglomerates are similar to those in Sierra El Chanate but appear to be more abundant.

### **Cerros El Puerto (Plate 2)**

A relatively small outcrop of the Bisbee Group is located near the northwestern end of the Cerros El Puerto. It occupies a topographically low area with some limestone ledges sticking out of the ground. The units that occur in this small outcrop are the Morita, Arroyo Sásabe and Cintura Formations.

The Morita Formation, its base faulted out, consists of red to purplish red, massively bedded mudstone. It has some intercalations of gray to purplish gray sandstone and some lenses of conglomerate. These are less than 2 m thick, clast supported, and include rounded to subangular volcanic rock fragments. Few sandstone beds display cross-bedding (Fig. 9).

### **Cerros Cabeza Colgada (Plate 3)**

The Morita Formation underlies the northern part of the Cerros Cabeza Colgada (Plate 3). It forms relatively high, rolling hills from the Rancho Nuevo on the east to the Rancho El Charal on the west. Several low lying hills south and west of the Los Pinos Ranch along the road to Trincheras are also underlain by the Morita.

The Morita Formation has an estimated thickness of 800 m, and consists of red to purplish red, thick to massively bedded mudstone. Locally it displays very thin stratification. Interbedded sandstones are pinkish gray to grayish purple to pale purple and pale blue, medium to thick bedded, commonly with internal thin stratification. Few have tangential or planar cross-bedding. Grain size varies from fine to coarse, and locally can be pebbly. Some beds include a rip-up clast conglomerate at the bottom. Sandstones

with purplish hues are mainly lithic arenites, whereas the pinkish ones are more quartzose. In the north-central part of the area, conglomerates are more abundant. These are lens-shaped, not more than 4 m thick, and consist mainly of volcanic rocks. The amount of conglomerate relative to the sandstone and mudstone is small. Near the base of the section is a 2-3 m thick cream-colored rhyolite tuff which extends for about 2 km from the eastern side of the Cerros Cabeza Colgada.

Cross bedding in this area has a bimodal distribution suggesting a strand line in a west-northwest east-southeast direction (Fig. 9). This kind of distribution is likely to occur in tidal flats.

#### **Cerro La Pima (Plate 4)**

The Morita Formation underlies a topographically low area on the northern side of Cerro La Pima. It is poorly exposed, and few sedimentary structures can be observed. It consists of mudstone with intercalations of sandstone and conglomerate (Fig. 7). The mudstone is red to purplish red, massively bedded. The sandstone is gray to purplish gray, medium bedded, poorly sorted. In few places sedimentary structures indicating overturned bedding could be observed. Conglomerate lenses occur throughout the section but are more abundant toward the base. The lenses, not more than 2 m thick, wedge out over a short distance. They consist of volcanic rock fragments some of which are white rhyolitic tuffs.

The base of the unit is covered by recent alluvial sediments. In the southwestern Cerro La Pima the Morita is in fault contact with the Mural Limestone.

#### **Santa Ana area (Plate 5)**

The Morita Formation occurs in the topographically low area between the old road from Estación Llano to Santa Ana and the paved road to El Claro. Along this road and north of the Arco Verde Ranch are excellent exposures of the Morita. The Morita also occurs east of Highway 15, but exposures are scattered and poor.

The Morita Formation consists mainly of red to purplish-red and purple mudstone, gray to purplish-gray sandstone and purplish-red to mottled conglomerate

forming fining-upward cycles. The base of the typical cycle consists of sandstone, coarse- to medium-grained, with plane-parallel bedding. Mudstones, dominating the typical fining-upward cycle, are massive but locally display very thin stratification as well as bioturbation. No cross-bedding was observed. Local clast-supported, massive and polymictic conglomerate lenses are less than 1 m thick. Clasts consist of volcanic rock, vein quartz and rarely quartz sandstone.

The base of the Morita is not exposed in the area; therefore, the figure of more than 300 m reported by Navarro (1989, p. 23) is its minimum thickness. The upper contact of the Morita Formation is gradational to sharp with the Mural Limestone or Arroyo Sásabe Formation.

### **Depositional Environment**

In the studied area the Morita is interpreted as a fluvial to tidal flat deposit. The red colors and rare desiccation marks suggest a subaerial environment. Rip-up clast conglomerates probably indicate erosion along fluvial or tidal channels and the fining-upward cyclicity of the sandstone and mudstone with the predominance of the finer grained fraction suggests a meandering fluvial system. Cross-bedding in the sandstone displays a bimodal southwest-northeast orientation suggesting that the strand line was northwest-southeast oriented with the sediment source to the northeast. Near the top of the Morita, the presence of limestone with oyster-shell detritus suggests there was a marine influx by that time (Navarro, 1989; Jacques, 1992b).

In southeastern Arizona and northeastern Sonora a meandering fluvial to tidal flat depositional environment has also been interpreted for the Morita Formation (Hayes, 1970; Hayes and Drewes, 1978; Jamison, 1987; Klute, 1987, 1991).

### **Arroyo Sásabe Formation and Mural Limestone**

The Arroyo Sásabe Formation was formally defined as a stratigraphic unit by Jacques (1989). It is time correlative with the Mural Limestone and lithologically equivalent to the Lower Member of the Mural (Warzeski, 1987). The main difference between the two formations is the amount and type of limestone present. The Mural

Limestone is characterized by massive limestone bodies tens of meters thick in its Upper Member (Warzeski, 1987). The limestone, with intercalations of shale and sandstone, consists mostly of a reefal fauna (complete fossils, such as oysters, corals, rudists and other pelecypods, algae, and microfossils (Scott, 1979; Rosales *et al.*, in prep.). The Mural in the Santa Ana and La Pima areas has not been divided in the two members of Warzeski (1987). The Mural forms ridges whereas the Arroyo Sásabe forms valleys.

The Arroyo Sásabe consists mainly of shale and fine-grained sandstone with meter-thick limestone beds. Locally the limestone can be absent, or there can be beds as thick as 3 m. The limestone is generally made of oysters shells or shell detritus forming floatstone and bindstone.

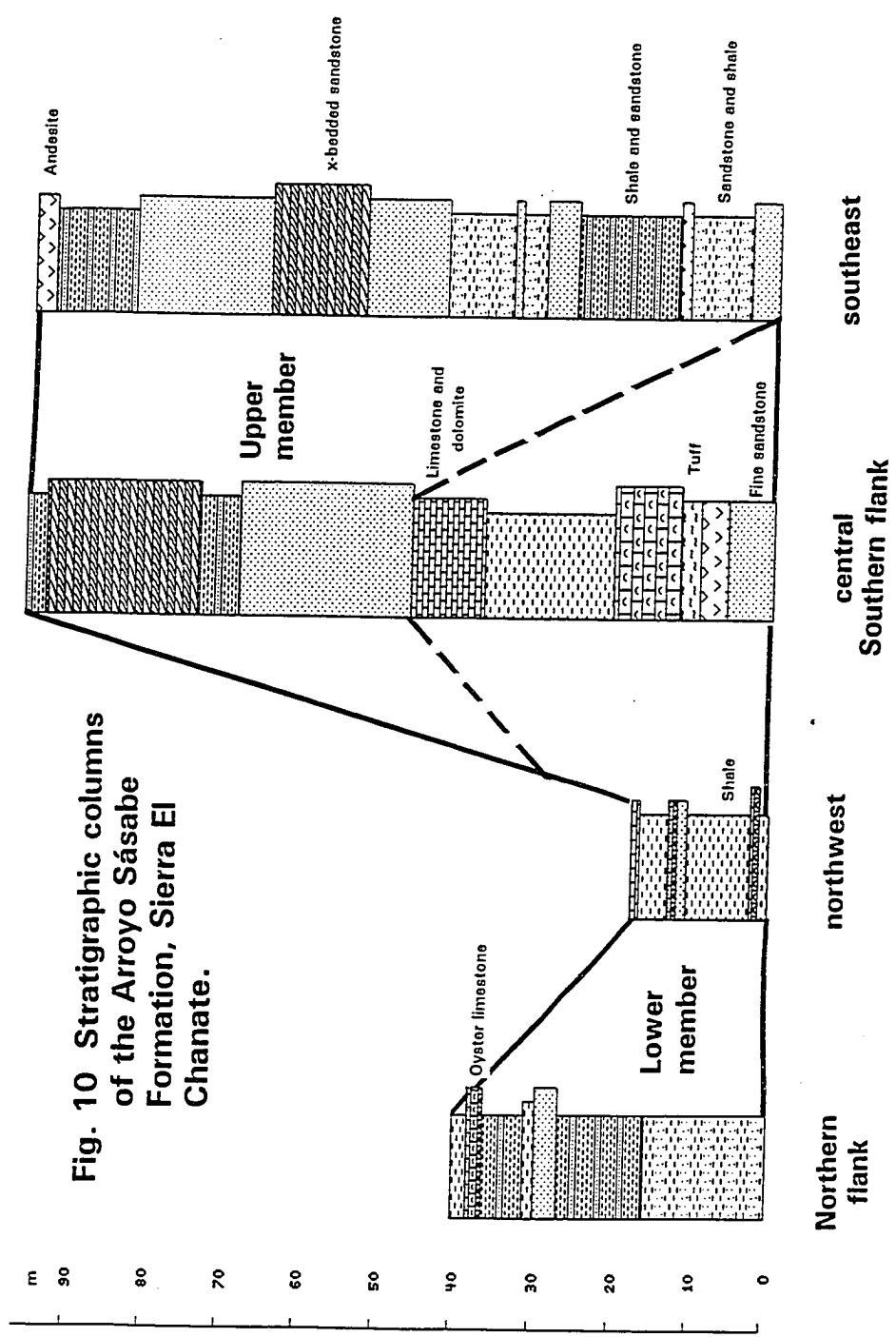
### **Sierra El Chanate (Plate 1)**

The Arroyo Sásabe Formation occurs on both flanks of the Sierra El Chanate. In the southern flank it has a maximum thickness of 96 m, but thins to 0 m, whereas on the northern side it has a thickness of 45 m, and is laterally persistent.

This formation was divided by Jacques (1989) in two members (Fig. 10). The lower member is present in both the northern and southern sides of the Sierra El Chanate. It consists of greenish buff and dark gray shale, green, very fine-grained sandstone, and thin vitric tuffs. Limestone beds are scarce in the northern side and more abundant in the southern side.

The lower member in the northern flank consists of thin interbeds of olive to yellowish green shale and fine-grained sandstone. Some sandstones are thicker bedded and display cross-bedding. Limestone beds are brown to grayish brown, and consist of mollusc detritus and serpulids.

On the southern flank the lower member has its maximum thickness in the central part of the mountain, pinching out toward the northwest and southeast. Toward the west it is almost 17 m thick with limestone beds less than 50 cm thick in predominantly green shale and fine-grained sandstone. The limestone is micstone to wackestone with oyster fragments (framestone). Further west the lower member is only a few centimeters thick before disappearing.



**Fig. 10 Stratigraphic columns of the Arroyo Sásabe Formation, Sierra El Chanate.**

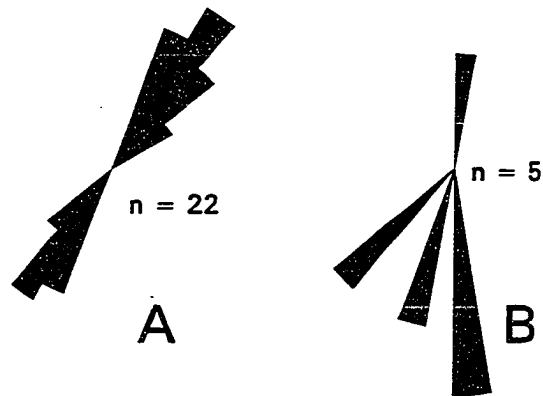
In the south-central part of the mountain the base of the lower member consists of olive green sandstone overlain by a green fine grained tuff. This is covered by oyster-bearing bindstone made mainly of complete and unabraded oysters, rudists(?), equinoids, gastropods, and other microfossils (Jacques, 1989; Jacques *et al.*, 1990a). This unit is 8.5 m thick. Above the limestone are 16.5 m of dark gray to black shale with interbeds of thin limestone with abundant small mollusks, overlain by gray to dark gray limestone and dolomite in thin interbeds. Toward the east the lower member pinches out and is replaced by the upper member.

The upper member is restricted to the south-central and southeastern parts of the mountain. In the south-central part it overlies the lower member, whereas to the east it overlies the Morita Formation (Fig. 10). The upper member includes sandstone, mudstone, conglomerate and some tuffs. The sandstone is olive to light green and gray, medium to thick bedded, fine to medium grained. Cross-bedding is a common feature (Fig. 11); flaser bedding and symmetrical ripples are locally present. Some sandstone beds appear to be volcanoclastic. Mudstone is red to purplish red and green, medium bedded, locally with intercalated olive green sandstone. The mudstone contains small disseminated calcareous nodules and is strongly bioturbated. The few conglomerates are lenticular, 2-3 cm thick, and consist of green mudstone clasts. Generally they occur at the base of sandstone beds. The base of the member locally consists of a 2.5 m-thick, green, aphanitic tuff of andesitic composition.

#### **Puerto El Alamo (Plate 1)**

In Puerto El Alamo Willard (1988) described the Olive member of the Sásabe Formation. The Olive member is here assigned to the Arroyo Sásabe Formation. In this area the Arroyo Sásabe could be as thick as 235 m but Willard (1988) measured only the lower 125 m.

In Puerto El Alamo the Arroyo Sásabe has no limestone. It consists of interbedded olive to yellowish green shale and sandstone. The shale is medium bedded and the sandstone is olive green, thin bedded and fine grained.



**Figure 11.** Rose diagrams of cross-bedding in the Arroyo Sásabe Formation: A) Sierra El Chanate; B) Cerros Cabeza Colgada.

### **Cerros El Puerto (Plate 2)**

The Arroyo Sásabe Formation has a thickness of about 90 m in the Cerros El Puerto. It is poorly exposed except for the limestone beds which make small ledges. In addition to the limestone, the Arroyo Sásabe consists of green to dark red shale and siltstone in medium to thick beds. The shale and siltstone are generally covered by scree. The limestone makes thin, medium and thick beds that can wedge out in a short distance. It consists mainly of mollusc-debris floatstone to wackestone. Toward the upper part of the unit is a 0.5 m-thick bed made entirely of ostracods.

### **Cerros Cabeza Colgada (Plate 3)**

The Arroyo Sásabe Formation underlies a topographically low area extending in a northwest direction. The old road from Santa Ana to Altar follows this valley. To the east, the Arroyo Sásabe is covered by recent sediments, and to the west it is cut by the Arroyo Agua Fría where it is covered by Recent lake deposits. West of the arroyo few exposures can be seen for it is covered by Tertiary alluvial deposits, even in the topographically high areas. Northwest, near the highway, the Arroyo Sásabe is concealed

by recent sediments. Small exposures can be seen about 4 km north of the highway where the oyster-bearing limestone is strongly stretched.

The Arroyo Sásabe consists of shale, sandstone and limestone. The shale constitutes most of the section, especially the upper part, and is buff to reddish buff and gray. It is poorly exposed, but in a few outcrops it is massive. Sandstone is light brown to light brownish gray to pale red, and moderate red; it is thin to medium bedded, and mainly fine to medium grained. Sandstone is more abundant toward the bottom, where it is intercalated with limestone. Some sandstone beds near the base contain abundant 1 to 3 cm-long turritelids. Limestone is thin to medium bedded; a few beds are about 2 m thick, and tend to form ledges and hills. One 3-4 m-thick lens, about 15 to 20 m long, is in contact with the Morita Formation in the central part of the area. The limestone in the lower third of the unit is olive gray to light gray to moderate red and light brown. It is also thin to medium bedded, and displays very thin stratification. Most of the red to brown beds are micritic and shaly and have no fossils. The gray beds contain some broken to complete oysters (*Trigonia?*) and have turritelids, as in the sandstone. The thick lens-shaped limestone consists mostly of oysters, fragmented and complete. The limestone beds in the upper two thirds of the unit are generally gray, rarely red. They consist of wackestone and oyster (*Trigonia?*) bindstone. Some beds extend laterally for 200 to 300 m before wedging out. Thin fossiliferous limestone beds can be observed throughout but are poorly exposed. West of the road to Trincheras, the Arroyo Sásabe is mostly covered, but the few outcrops consist mainly of shale and intercalated thin limestone beds. Black, silicified fossil wood is abundant in the Arroyo Sásabe, especially in its upper part.

In the north-central part of the area, near the contact of the Morita with the Tertiary alluvial deposits, a small outcrop of limestone, similar to that of the Arroyo Sásabe was observed. Its relationship with the Morita is unknown. The extent of the exposure of the Morita suggests that the unit was folded or doubled by a fault. A fold interpretation is preferred because the presence of folds elsewhere and the apparent absence of faults.

### **Cerro La Pima (Plate 4)**

The Mural Limestone in Cerro La Pima forms prominent elongated ridges that can be seen west of Santa Ana south of Highway 2. Navarro (1989, p. 21) measured a stratigraphic section of the Mural, which is at least 650 m thick. The pattern of the limestone ridges suggested to Navarro the presence of normal faults. In the present author's opinion, faults as suggested by Navarro are not present. Some of the limestone units are laterally continuous through one of Navarro's faults, and the difference in thickness and structural trend in the western side of the area can be explained by a normal fault.

The Mural Limestone consists mainly of bioherms, tens of meters thick, of light to dark gray, massive limestone (Fig. 7) with numerous ostreids, pectinids and corals, with some rudists (Navarro, 1989; Pérez, 1986). The space between the bioherms is occupied by biostromal limestone, shale and sandstone. The gray to brownish gray biostromal limestone beds, about 1 m thick, consist mainly of mollusc bindstone. Mollusks are complete or broken. The shale is green to gray, and massively bedded. The sandstone is red to pink, thin to medium bedded, fine to medium grained, and displays rarely internal structures. Both the sandstone and shale are poorly exposed. Near the top of the unit is a brown to greenish buff, altered andesite extending for more than 100 m and 1 to 3 m thick. Locally it is a breccia with some limestone fragments. If it is a flow, it would be the easternmost expression of volcanic activity during Mural time reported in Sonora.

Fossil wood occurs in the upper part of the Mural Limestone, especially near the contact with the Cintura Formation. Wood fragments are small, black and silicified.

### **Santa Ana area (Plate 5)**

The Mural Limestone occurs east of Highway 15 and south of Santa Ana. It forms long, east-west, weathering-resistant ledges east of Highway 15, easily seen over the highway as one approaches Santa Ana from the south.

South of Santa Ana, the east-west Mural trend bends southeastward to the El Pinto Ranch where it again turns east-west forming a "S". West of the Arco Verde

Ranch, the Mural changes laterally to the Arroyo Sásabe Formation. Farther south in the study area, the Arroyo Sásabe Formation occurs exclusively.

South of Santa Rita, the Mural is about 100 m thick, but east of Highway 15 it is almost 500 m thick. Navarro (1989) interpreted the greater thickness as a result of duplication by faults, but in the author's opinion the different limestone ledges represent different patch reefs and not tectonic repetitions of one and the same bioherm. It consists of thick to massively bedded limestone with thicknesses greater than 20 m up to more than 100 m (Fig. 7). The limestone is dark gray but weathers light gray. It has a coarse texture because of the abundant fossil fauna which includes rudists, corals, oysters and microfauna (Navarro, 1989). Between the limestones there is fine grained sandstone and shale, and meter-thick beds of oyster-bearing limestone (rudestone).

The Arroyo Sásabe Formation is a valley-forming, poorly exposed unit. It consists of shale, sandstone, and minor limestone and conglomerate. The shale is green to gray and buff, massively bedded, locally foliated or with pencil structure. The sandstone is green to red, medium to thin bedded, fine to coarse grained. As it is poorly exposed, few primary structures could be observed. The conglomerate is found in thin lenses, generally less than 1 m thick, clast-supported, well sorted and without internal structures. The clasts are rounded to subangular, made of volcanic rock fragments (some white rhyolitic tuffs), vein-quartz and minor sandstone. These sediments form fining upward cycles. Limestone, occurs in beds less than 1 m thick, and is dark grayish buff to dark gray and reddish gray. Fossil content includes oyster shells, mainly with separated or broken valves, forming a floatstone. Some limestone beds are sandy and weather in ocher red. Locally there are some 2-3 m thick lenses of limestone, like those in the Mural. Some contain *Orbitolina*, which is at present the only paleontological basis to suggest its correlation with the Mural.

Southwest of the Arco Verde Ranch (Plate 5) the Arroyo Sásabe Formation has an estimated thickness of 250 m or less. The lower contact of this unit is covered, whereas the upper contact with the Cintura Formation appears to be sharp.

## **Depositional Environment**

The Arroyo Sásabe Formation in the study area was formed in shallow lagoons where oysters built mounds surrounded by mud. This is indicated by the limestone consisting mostly of complete oysters and forming small patch reefs, such as those observed in modern lagoons of the northern Gulf of Mexico. Restricted water circulation probably promoted the reduction of iron making the shale greenish. These lagoons were connected to deltaic or estuarine environments, as suggested by the local increase in sand in the sequence. Dark gray to black shale and limestone with very small pelecypods suggests deposition in a marsh or backswamp.

The Mural Limestone, on the other hand, represents a shallow marine environment (Navarro, 1989), as suggested by the presence of rudists, corals and oysters, which form patch-reefs with thicknesses over 10 m. Between the reefs fine grained sandstone and shale occurs.

A similar depositional setting of the Mural has been proposed in southeastern Arizona and northeastern Sonora to the north, roughly east-west trending lagoonal deposits, and to the south open marine reefal limestones (Scott, 1987; Warzeski, 1987; Klute, 1991).

## **The Cintura Formation**

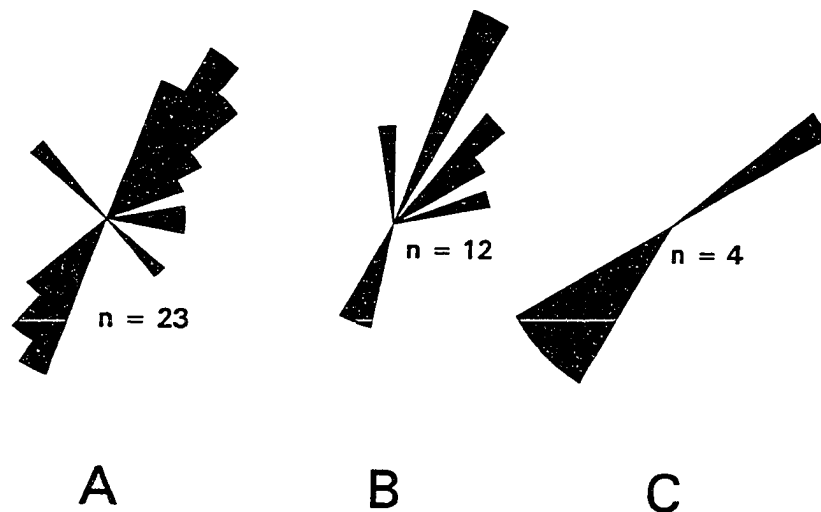
### **Sierra El Chanate (Plate 1)**

The Cintura Formation is exposed on both sides of Sierra El Chanate where Jacques (in press) measured four stratigraphic sections. Its thickness varies from 318 m on the northern flank decreasing to 170 m on the southern one (Fig. 7). It is also exposed on the lower reaches of the northern flank of the Sierra El Batamote where it appears to be in fault contact with the El Chanate Group. In the Puerto El Alamo area the Cintura is missing apparently because of non-deposition. Another possibility is that it has been covered by a thrust plate.

The Cintura Formation is lithologically similar to the Morita Formation. It consists of red to purplish red mudstone and sandstone. Mudstone is the predominant fraction. It forms thick to massive beds with some reddish and purplish gray, thin

bedded, fine grained sandstone and siltstone. Locally it contains small calcareous nodules, disseminated or concentrated along bedding planes. The sandstone is gray to purplish gray, thinly stratified to massive, fine to medium grained. Few cross-beds were observed. Sandstone beds can be as thick as 4 m, but normally they are 1 to 2 m thick. Rip-up clast conglomerates occur at the base of some of the sandstone beds.

Cross bedding in the Cintura Formation is, like in the Morita, bimodal with the main component to the northeast (Fig. 12). This indicates that the strand line was northwest-southeast oriented, and the source of the sediments was probably located southwest of the area.



**Figure 12** Rose diagrams of cross-bedding in the Cintura Formation: (A) Sierra El Chanate; (B) Cerros Cabeza Colgada; (C) south of Santa Ana.

### **Cerros El Puerto (Plate 2)**

The Cintura Formation is poorly exposed in this area.

It consists of a red to purplish red mudstone with few intercalations of siltstone. Bedding is thick to massive. The lower contact with the Arroyo Sásabe is covered, and the upper contact is a fault against the El Chanate Group. The thickness of this unit is

unknown.

### **Cerros Cabeza Colgada (Plate 3)**

The Cintura Formation forms rolling hills, like the Morita. West of the road to Trincheras, the Cintura underlies the northern slope of the high hills that extend northwestward to the highway and into the Cerros Los Alejos. The Cintura along the highway and along the road to the microwave station is strongly fractured, stretched and foliated. Toward the east the Cintura is less deformed, and consists mainly of red and green mudstone. The best exposures are found in the arroyos, whereas on the hills it is mostly covered by scree.

The Cintura has an estimated thickness of 550 m, and consists mainly of red to purplish red, massively bedded mudstone and subordinated pale red to light brownish gray to pale yellowish brown sandstone. The sandstone is medium bedded, and medium to fine grained.

### **Cerro La Pima (Plate 4)**

The Cintura has a minimum thickness of about 500 m (Navarro, 1989, p. 39). The exposure is mostly covered by scree. It consists of red mudstone with some intercalations of greenish to reddish gray sandstone. Sandstone beds are generally less than 1 m thick.

### **Santa Ana area (Plate 5)**

The Cintura Formation occurs in the nucleus of an overturned syncline southeast of Santa Ana, and south of the Arco Verde Ranch. It tends to form valleys, and south of the Arco Verde Ranch it forms rolling hills. Navarro (1989) reported a thickness of 500 m for the Cintura in this area. East of Highway 15 it is at least 1000 m thick.

Good exposures of the Cintura are found only along the arroyos. Lithologically it consists of gray to purplish gray and green sandstone intercalated in red to purplish red and green mudstone; these form fining-upward cycles. The mudstone is dominant. Locally the sandstone displays cross-bedding.

## **Depositional Environment**

The Cintura Formation of the study area, like the Morita, was deposited in tidal flat to alluvial flood plains. The presence of the stromatolite *Columnacollenia* Korolyuk (1968) in the Sierra El Chanate (Jacques and Potter, 1987) supports the tidal flat environment. Sandstone is relatively minor compared to the mudstone, suggesting a transition from a tidal flat to an interfluvial environment. In southeastern Arizona and northeastern Sonora deposition took place in similar environments (Hayes, 1970; Hayes and Drewes, 1978; Klute, 1987, 1991).

The Cintura Formation unit represents the regressive phase of the Bisbee Group, which had its maximum sea advance during Mural/Arroyo Sásabe time (Warzeski, 1987). The regressive nature of the Cintura is not clearly observable in the Sierra El Chanate, for there is no coarsening-up of the sequence as in southeastern Arizona and northeastern Sonora (Klute, 1991; Grijalva, 1993). The sequence is characterized by fining-upward cycles, although a few coarsening-up cycles occur as well. The number of conglomerate beds is negligible.

## **Stratigraphic relationships**

The base of the Bisbee Group is not exposed in the study area. It is covered by younger units or it is faulted. On the basis of clast composition in the Glance and Morita units it is assumed that the basement upon which the Bisbee was deposited is the Middle Jurassic volcanic arc exposed in north-central Sonora and south-central Arizona (Riggs, 1987a, 1987b; Segerstrom, 1987).

In the Sierra La Gloria, Lower Jurassic sedimentary rocks (Nuñez and DeJong, in prep.) appear to underlie a thick sequence of conglomerate, perhaps the Glance (García y B., oral. comm.). In northeastern Sonora (northeast of Cananea) and southeastern Arizona the Bisbee Group was deposited upon a Paleozoic sedimentary sequence or the Proterozoic Pinal Schist. In Cerro de Oro, northeast of Hermosillo, the Bisbee overlies the Cerro de Oro Formation, which in turn overlies the Proterozoic sedimentary rocks. Between Cananea and Cerro de Oro there are exposures of Proterozoic-Paleozoic rocks, that could have acted as a basement.

In the Sierra El Chanate and Puerto El Alamo the base of the Glance Conglomerate is not observed. However, northwest of La Laguna Ranch (Plate 1) some andesitic volcanic breccias appear to underlie or to be intercalated in the Glance.

The contacts between the different units that make the Bisbee are both sharp and transitional. The upper contact of the Glance Conglomerate is transitional with the Morita Formation. At the southern flank of the Sierra El Chanate, the Cerro de Oro Formation underlies with a sharp contact the Morita Formation.

The Arroyo Sásabe Formation (or Mural Limestone) overlies the Morita Formation with a transitional contact. If the Morita is defined to include limestone beds, the contact is almost impossible to locate. Following Jacques' (1989) definition, it is defined by the first appearance of limestone, and it is easily located. The Arroyo Sásabe (or Mural) is overlain conformably by the Cintura Formation. This contact can be difficult to locate where the green sandstone and shale that occur near the top of the Arroyo Sásabe are also found near the base of the Cintura. In such case the contact is placed where the color changes from green to red, or where the red becomes predominant.

The upper contact of the Cintura Formation with the Pozo Duro Formation of the El Chanate Group is locally conformable, but, in general, it is erosional and in places there appears to be a shallow angular unconformity. The lower Pozo Duro is characterized by the presence of red mudstone with intercalations of quartz-sandstone pebble conglomerate lenses or quartz-rich sandstone. Where the conglomerate or the sandstone are not present, the contact is difficult to locate.

#### **Age and correlation (Table 3)**

The age of the Glance Conglomerate in the study area is based on indirect evidence. In southern Arizona interbedded volcanic rocks in the lower part of the unit have been dated as Late Jurassic (Marvin *et al.*, 1978; Kluth *et al.*, 1982). The upper part of the Glance is older than the Morita and Cerro de Oro Formations, both without age diagnostic fossils in the Sierra El Chanate. The Cerro de Oro Formation in its type locality is assigned to the Barremian-early Aptian (González and Jacques, 1988). The

Glance Conglomerate may thus represent the latest Jurassic and the Neocomian.

The Arroyo Sásabe Formation is assigned a late Aptian-Albian age based on the presence of *Quadratortonia* cf. *Q. mearnsi* (Stoyanow), *Pterotortonia* sp., *Macraster* cf. *M. dartoni* (Cooke) (Alencaster, and Buitrón in Jacques *et al.*, 1990a). The Mural Limestone has been assigned to the late Aptian-middle Albian by Scott (1987), Warzeski, (1987), Pérez (1986) and Scott and González (1991), among others.

The Cintura Formation in the Caborca-Santa Ana area does not contain fossils, so its age is unknown. In the Cerro Ceja, northwest of Arizpe (González, 1978) C. González collected *Inoceramus* from a thick limestone unit capping the Cintura Formation. These fossils are of late Albian age (González, oral comm., 1992). Therefore, the Cintura Formation in the Sierra El Chanate is assigned a late Albian age. Araujo and Estavillo (1987, p. 21), and Pubellier and Rangin (1988) report late Albian fossils near the top of the Bisbee-equivalent sequence in the Nácori Chico and Sahuaripa areas. In conclusion, the age span of the Bisbee Group is Late Jurassic (Oxfordian) through Early Cretaceous (Albian).

The Bisbee Group is extensively exposed in southeastern Arizona and northeastern Sonora. Bisbee rocks other than those of the study areas have been described as far west as the Pajarito Mountains (Drewes, 1981; Riggs, 1987a, 1987b), and as far south as Cerro de Oro (González, 1989; González and Jacques, 1988). In other areas the Bisbee formations have been described with different names, as in Arizpe (González, 1978), Tuape (Rodríguez, 1988), and Cerro Azul (McKee, 1991). In the Santa Ana-Caborca area the Bisbee occurs northeast of Cerros El Amol (García, 1992), in the Cerro Mayo area west of Benjamin Hill (PEMEX, 1987) and east of Cerro Rajón (Keller, 1928).

The Glance Conglomerate has been reported in several areas in southeastern Arizona and northeastern Sonora (Drewes, 1971; Hayes, 1970; Bilodeau, 1978; Bilodeau and Lindberg, 1983; Bilodeau *et al.*, 1987). It also has been reported in northeast and north central Sonora (Taliaferro, 1933; Rangin, 1982; Nourse, 1989; Grajales *et al.*, 1990), and as far southeast as Arivechi, where it has been named Zarapuchi

Conglomerate (Pubellier, 1987, p. 64). Equivalent rocks are probably present in the Cerro Rajón and Cerro Chino south of Pitiquito and in the Sierra La Gloria northwest of Caborca.

Other rocks that are time-correlative to the Gance Conglomerate are the sedimentary and volcanoclastic marine deposits in Cucurpe (Rangin, 1982; Rodríguez, 1988) and Pozo Serna (Beauvais and Stump, 1976; Carrasco, 1987). Lawton and Olmstead (in prep.) have found in southeastern Arizona a marine sedimentary and volcanic sequence with Late Jurassic fossils underlying the Gance Conglomerate.

Marine shale and limestone units that underlie the Morita formation in the Cerro de Oro area have been described by González and Jacques (1988). A similar unit occurs in Lampazos (González, 1987; Scott and González, 1991).

In northwest Sonora the Arroyo Sásabe Formation is exposed in the northern part of the Cerros El Amol (García, 1992) and Cerro Mayo.

The Mural is present in Tuape as the Los Tanques unit (Rodríguez, 1988), in Cerro Azul as units 4 and 5 (McKee, 1990), in Arizpe as the El Macho Formation (González, 1978), in Cerro de Oro (González and Jacques, 1990), and in Lampazos as the Lampazos and Espinazo del Diablo units (González, 1987; Scott and González, 1991).

The Cintura Formation is widely exposed in northeastern Sonora and southeastern Arizona (Ransome, 1904; Taliaferro, 1933; Drewes, 1971; Hayes, 1970; Rangin, 1982; Archibald, 1987). García (*in Jacques et al.*, 1990b; 1992) reported the presence of the Cintura Formation in the northwestern part of the Cerros El Amol, 5 km east of Oquitoa. González and Jacques (1988) indicated that the Cintura Formation in the Cerro de Oro area is more than 290 m thick. In the Tuape area the Cintura Formation is well exposed between Tuape and the Los Tanques Ranch (Rodríguez, 1988). In central and east-central Sonora time equivalent units in Lampazos consist mainly of marine limestone and shale (González, 1987; Scott and González, 1991).

### **Sandstone composition**

One of the purposes of this work is to use sandstone composition as a means to

understand the provenance and tectonic setting of the Cretaceous rocks in the region. Fifty four thin sections from the Bisbee Group in the Sierra El Chanate, Cerros Cabeza Colgada, Cerros La Pima, Cerro Mayo and Cerro de Oro were point-counted (Table 4). Included in this work are the results obtained by Willard (1988) and Klute (1991).

All the samples fall in the lithic-arenite category of Dott's sandstone classification as modified by Pettijohn *et al.* (1987). The sandstones are immature, even though there is very little matrix. Some grains were compressed losing their original shape, making them unrecognizable; they were classified as matrix. Other lithic grains could be differentiated from surrounding grains on the basis of their texture.

The sand grains are mostly angular to subangular and poorly to moderately sorted. Packing is compact. Quartz is mainly monocrystalline and mostly subangular to subrounded; few grains are well rounded. Polycrystalline quartz is rare, as is chert. Some polycrystalline quartz grains show the outline of a quartz sandstone, but most were probably derived from vein quartz or metamorphic quartz sandstone as suggested by crystal boundaries. Plagioclase and K-spar are subangular and commonly subhedral. In few cases the plagioclase has been fractured intensely. The irregular shape of lithic grains can be the original grain form or the result of deformation. In some cases rock fragments, especially the aphanitic and devitrified(?) fragments, fill the voids between more resistant grains.

Diagenetic changes are common, especially in the feldspar fraction. Some plagioclase and K-spar grains have been replaced by sericite and/or calcite. In some cases they could be recognized because the original shape and/or twinning were preserved. Sericite is present in variable amounts as cement, as an alteration product within crystals (along cleavage planes), and as a replacement of minerals within lithic fragments. Calcite, quartz and chlorite are also present as cement. Some grains, including quartz, show corrosion by calcite.

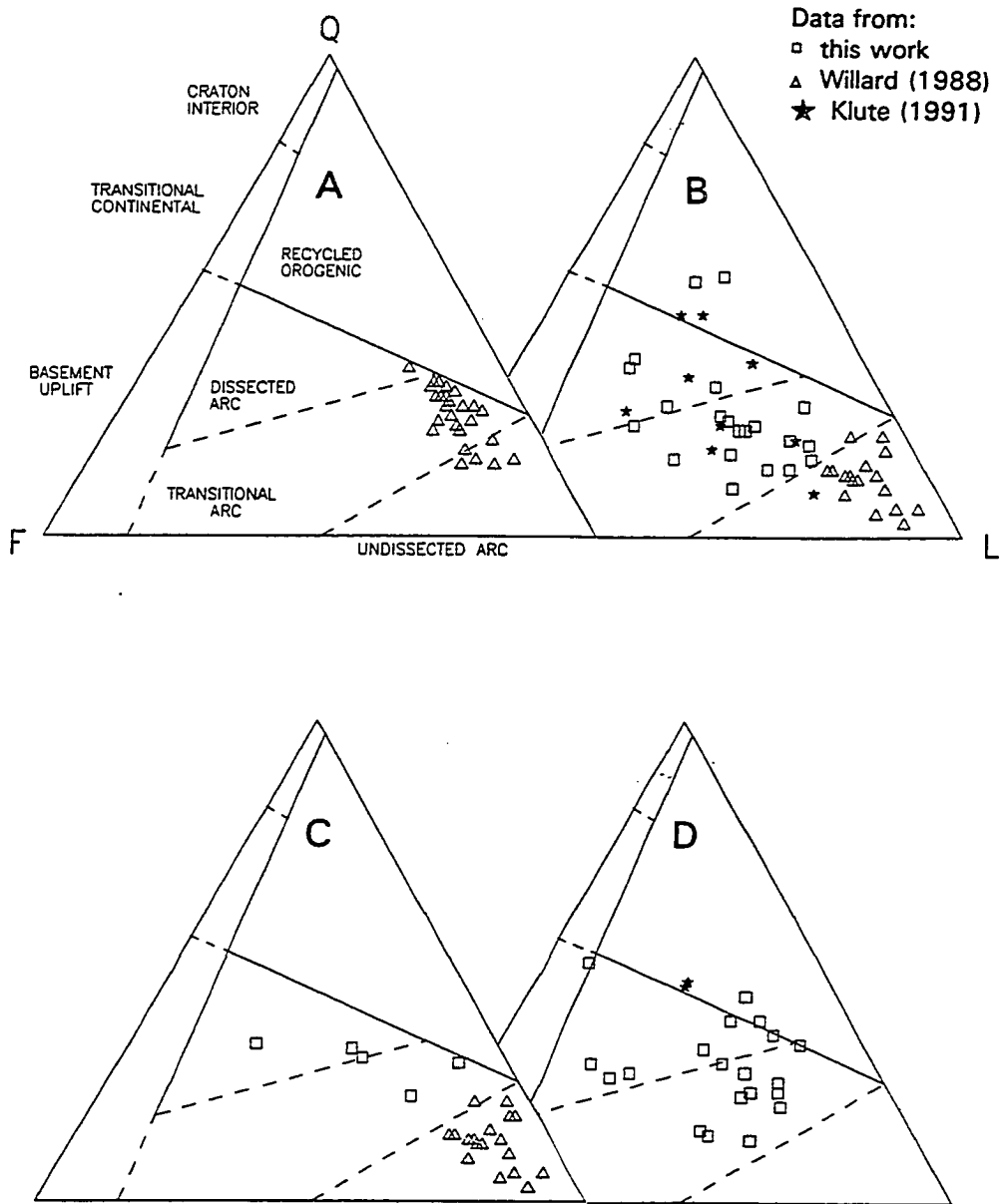
Sandstone composition of the different units in the Bisbee show very little variation, indicating stable conditions of sediment input. The different stratigraphic units have the following averages: Glance ( $Q_{25}F_{13}L_{62}$ ), Morita ( $Q_{20}F_{28}L_{52}$ ), Arroyo Sásabe/Mural ( $Q_{28}F_{24}L_{48}$ ) and Cintura ( $Q_{27}F_{25}L_{48}$ ). These are plotted in a QFL diagram

**Table 4. Ternary plot values from sandstones of the Bisbee Group in the Caborca - Santa Ana area.**

Sierra El Chanate																
Morita Formation																
	Q	F	L	Qm	F	Lt	Qm	P	K	Lv	Lm	Ls	Lvf	Lvm	Lvl	Mtx
Pto. 238	20	22	58	16	22	62	43	40	18	98	0	1	68	19	13	2
TM-1	23	27	50	20	27	52	42	46	12	100	0	0	54	26	20	6
TM-2	27	17	57	23	17	60	57	30	13	92	7	1	79	17	5	9
TM-5	10	37	53	9	37	53	20	72	8	98	1	2	20	70	10	7
102-79	14	28	57	12	28	60	29	42	30	88	0	9	48	40	11	0
TP-1	31	30	39	30	30	41	50	39	11	99	0	1	71	29	0	0
TP-4	14	26	61	11	26	63	31	44	26	94	0	3	52	33	15	0
TQ-13	22	29	49	20	29	51	41	52	7	90	10	0	63	24	13	6
TQ-24	17	33	49	15	33	52	30	40	30	100	0	0	96	4	0	16
Avg.	20	28	53	17	28	55	38	45	17	95	2	2	61	29	10	5
Arroyo Sásabe Formation																
TO-9	32	27	41	30	27	43	53	30	17	99	0	1	60	37	3	0
TN-16	30	26	44	27	26	47	51	39	10	99	0	1	70	26	4	0
TN-18	22	21	57	18	21	61	47	41	12	100	0	0	58	40	1	10
Avg.	28	24	48	25	24	50	50	36	13	99	0	1	63	34	3	4
Cintura Formation																
TN-26	27	25	48	25	25	50	50	34	16	99	1	0	69	15	15	1
TG-14	38	22	40	27	22	51	55	19	26	95	1	4	99	1	0	0
TQ-5	20	22	58	18	22	60	46	24	30	92	2	6	68	28	4	0
TQ-7	25	21	55	22	21	57	51	34	15	88	5	7	64	26	10	9
TQ-23	32	30	38	30	30	40	51	20	29	97	2	2	77	18	5	0
TQ-23-1	29	27	43	25	27	47	48	29	23	98	2	0	68	19	13	2
TP-7	23	26	51	19	26	55	42	30	28	88	3	6	69	18	13	4
TP-8	22	29	50	19	29	52	40	33	27	93	5	2	64	22	14	7
Avg.	27	25	48	23	25	25	48	28	24	94	2	3	72	18	9	3
Cerro La Pima																
Morita Formation																
LP-2	19	19	62	15	19	66	45	45	11	96	1	3				
LP-2-1	16	20	64	10	20	70	34	42	23	97	0	3		No		
LP-5	25	32	43	24	32	44	43	40	17	98	1	1				
Avg.	20	23	57	17	23	60	41	42	17	97	1	2		data		
Cintura Formation																
LP-7	41	13	45	38	13	49	74	14	12	95	1	4		No		
LP-23	43	17	40	36	17	47	67	28	5	91	6	1				
Avg.	42	15	42	37	15	48	70	21	8	93	4	3		data		

Table 4, continues

Cerros Cabeza Colgada													
Arroyo Sásabe Formation													
	Q	F	L	Qm	F	Lt	Qm	P	K	Lv	Lm	Ls	No
EO-14	33	44	23	32	44	25	42	38	20	98	2	0	
EO-16	29	8	62	26	8	66	76	13	11	91	9	0	data
EO-27	44	14	42	35	14	51	72	12	16	99	0	1	
Avg.	35	22	43	31	22	47	63	21	16	96	4	0	
Cintura Formation													
EO-08	33	12	55	31	12	57	71	23	6	93	6	1	No
EO-09	35	17	49	26	17	57	61	25	14	95	4	1	
EO-10	38	17	45	26	17	57	61	16	23	98	2	0	data
EO-11	23	21	56	20	21	60	49	29	22	96	3	1	
Avg.	32	17	51	26	17	58	60	23	16	96	4	1	
Cerro Mayo													
Morita Formation													
CM-10	28	40	32	22	40	38	36	60	4	88	0	12	
CM-12	16	46	39	10	16	45	18	82	0	95	0	5	No
CM-14	22	30	48	14	30	56	32	68	0	91	2	7	
CM-15	25	31	45	16	31	53	34	66	0	79	2	19	data
CM-16	23	48	28	16	48	36	25	75	0	86	4	10	
Avg.	23	39	38	16	39	45	29	70	1	88	2	10	
Cintura Formation													
CM-5	15	39	46	13	39	48	25	71	4	96	0	4	No
CM-3A	13	31	56	12	31	57	27	57	16	94	0	6	
CM-8	15	38	48	12	38	51	23	77	0	95	0	5	data
Avg.	14	36	50	12	36	52	25	68	7	95	0	5	
Cerro de Oro													
Morita Formation													
COM-1	54	17	29	43	17	39	71	27	2	54	0	46	No
COM-2	35	44	21	30	44	26	41	59	0	53	0	47	
COM-6	53	23	24	39	23	39	63	37	0	36	2	61	data
COM-7	37	42	21	30	42	28	41	59	0	64	1	35	
Avg.	45	32	24	35	32	33	54	45	0	52	1	47	
Cintura Formation													
COC-1	50	42	8	47	42	11	52	48	0	79	0	21	No
COC-2	27	46	27	22	46	32	32	68	0	86	0	14	
COC-4	29	53	19	24	53	23	31	69	0	92	3	4	data
COC-5	26	49	24	20	49	31	28	72	0	87	7	7	
Avg.	33	48	19	28	48	24	36	64	0	86	2	11	



**Figure 13.** QFL diagrams of sandstones of the (A) Glance, (B) Morita, (C) Arroyo Sásabe and (D) Cintura Formations. Samples from Puerto El Alamo, S. El Chanate, C. Cabeza Colgada, C. La Pima, C. Mayo and C. de Oro.

in Figure 13. A QmFLt diagram is similar to a QFL diagram, mainly because the content of polycrystalline quartz is minor.

The composition of the sandstones, when plotted by locality, does not indicate major variations. From Puerto El Alamo to Cerro La Pima and Cerro Mayo the composition is the same (Fig. 14). In Cerro de Oro, however, where there is an increase in quartz content at the expense of the lithic fraction. This may be the result of minor sediment input from the basement.

The lithic fraction consists almost entirely of volcanic rock fragments. In the Cerro de Oro area the amount of sedimentary rock fragments increases slightly, suggesting an influence from a Paleozoic/Proterozoic source.

In the samples from the Caborca-Santa Ana area the aphanitic volcanic rock fragments were counted (Table 1). The volcanic rock fragments are mainly of rhyolitic composition with minor amounts of andesite and traces of basalt. The source of these sediments was most likely the Middle Jurassic volcanic arc. This arc is widely exposed in northern Sonora and south-central Arizona. It must have also been present in the area south of Caborca-Santa Ana as indicated by provenance studies; The arc is there not exposed at present, most likely because it was covered tectonically by the Caborca terrane.

In southeastern Arizona and northeastern Sonora the sandstones in the Bisbee Group are mostly quartz-rich, indicating that the cratonic source included Lower Paleozoic sedimentary rocks and the Proterozoic Pinal Schist (Klute, 1987, 1991; Jamison, 1987). In the Glance Conglomerate a change in composition of the clasts can be observed, from Paleozoic rocks at the bottom to Proterozoic rocks at the top (Bilodeau, 1982). There are in the Bisbee Group intercalations of volcanically derived lithic arenite beds (Klute, 1987, 1991). These volcanic-rich sandstones could be air-borne tuffs or reworked tuffs. Intercalations of tuffs have been documented in Sonora by Rangin (1982), Jacques (1989) and Rosales *et al.* (in prep.).

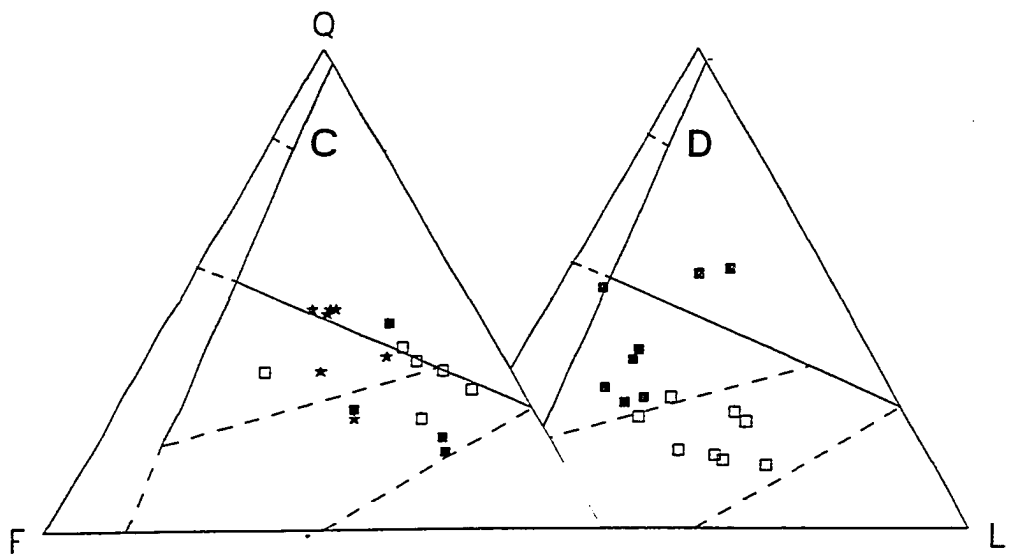
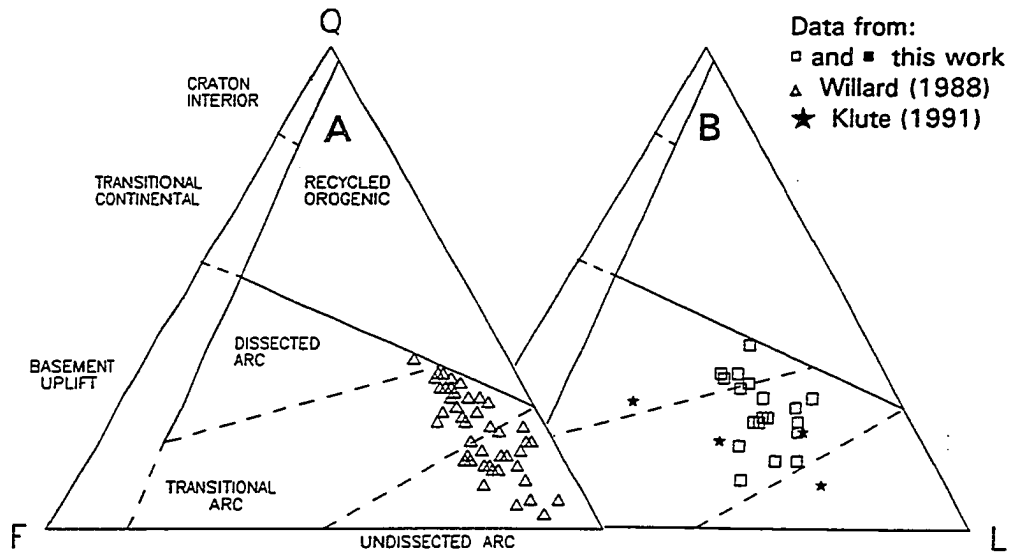
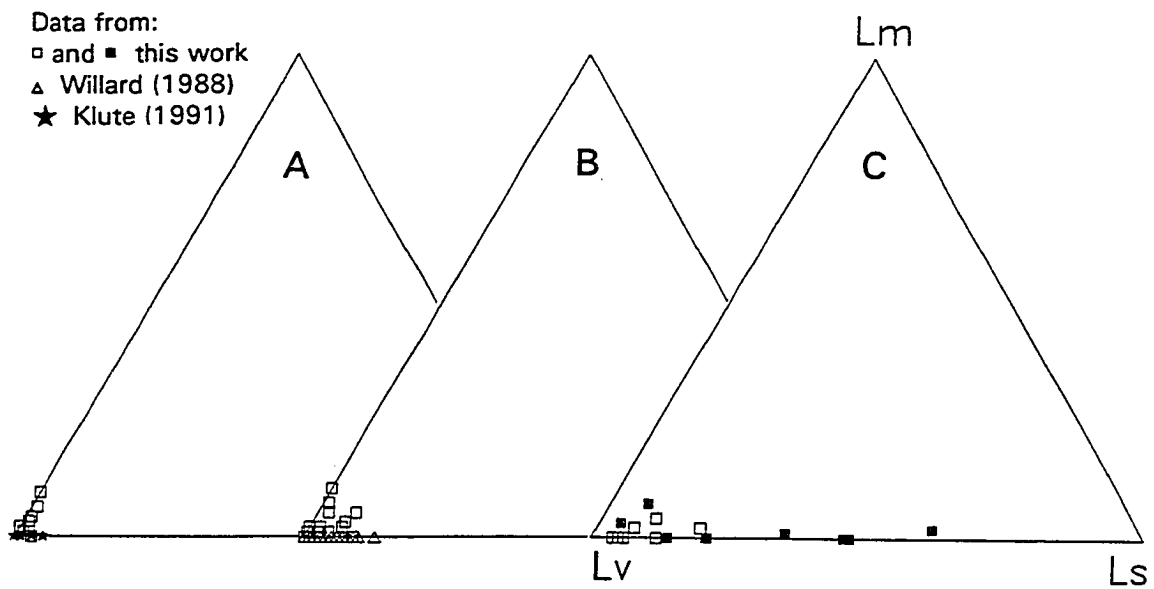
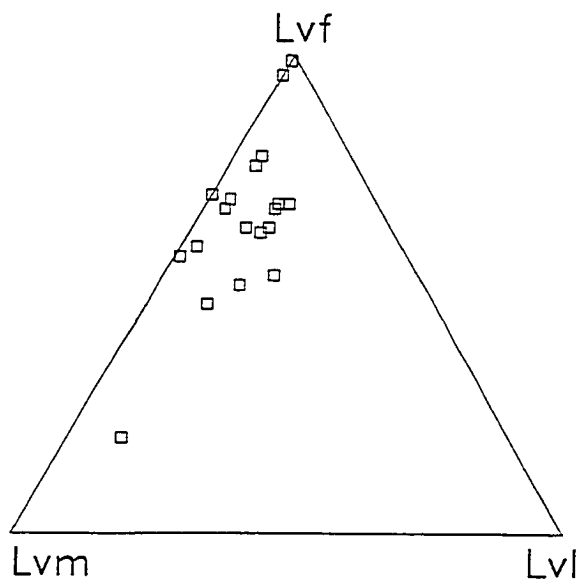


Figure 14. QFL diagram of the Bisbee Group plotted by areas: (A) Puerto El Alamo; (B) Sierra El Chanate; (C) Cerros Cabeza Colgada (□) and Cerro La Pima (■); (D) Cerro Mayo (□) and Cerro de Oro (■).



**Figure 15** LmLvLs diagram of the sandstones of the Bisbee Group: (A) Puerto El Alamo and Sierra El Chanate; (B) Cerro Cabeza Colgada and Cerro La Pima; (C) Cerro Mayo and Cerro de Oro.



**Figure 16** Ternary diagram of the aphanitic volcanic rock fragments (LvLvmLvI) in sandstones from the Bisbee Group in the Sierra El Chanate. Meaning of parameters in Table 1.

## EL CHANATE GROUP

The El Chanate Group is a continental sequence of Late Cretaceous age. The type locality is in the Sierra El Chanate. Jacques (1983) measured four stratigraphic sections: one in the northern side of the mountain and three in the southern side. He named it El Chanate Formation and divided it in two members. The reader is referred to the Appendix in Jacques (1983) for a detailed description of the sections. Jacques and Potter (1987) continued to name it as a formation, but divided the sequence in the northern side of the sierra in seven members, and that on the southern side in three members. Jacques *et al.* (1990b) raised the formation to group status and divided it in three formations in the northern Sierra El Chanate. This new division was based on the composition of the pebbles in the conglomerates as well as on textural distribution; each formation represents a fining-upward cycle in which the conglomerates have a different pebble composition. In this work, the section in the south could also be divided into three formations, the same as those in the northern side: Pozo Duro (oldest), Anita, and Escalante (youngest) Formations. The sequence in the northern side is more than 2,800 m thick whereas the sequence in the southern side is only 750 m thick. It includes, even though drastically reduced in thickness, the three mentioned formations (Plate 1) and there is no evidence that a part of the sequence has been excised. The bounding stratigraphic units (Bisbee Group and El Charro volcanic complex) match from one side to the other, and the difference in thickness appears of primary synsedimentary origin, and not of secondary, structural origin. The difference in thickness suggests strongly that the El Chanate basin was compartmentalized, with some parts subsiding much faster than other parts but with sedimentation always able to keep up with the subsidence.

The El Chanate Group occurs also in the other study areas with the exception of the Santa Ana area.

### Pozo Duro Formation

The Pozo Duro Formation is named after the Pozo Duro Ranch, which encompasses most of the area of the Sierra El Chanate. It is also present in Cerros El

Puerto, in western Cerros Cabeza Colgada, and northern and eastern Cerros El Amol (García, 1992). Small exposures of the base of the unit have been identified in Cerro La Pima and west of Cerros Cabeza Colgada. It is probably present in Puerto El Alamo, but has not been clearly identified.

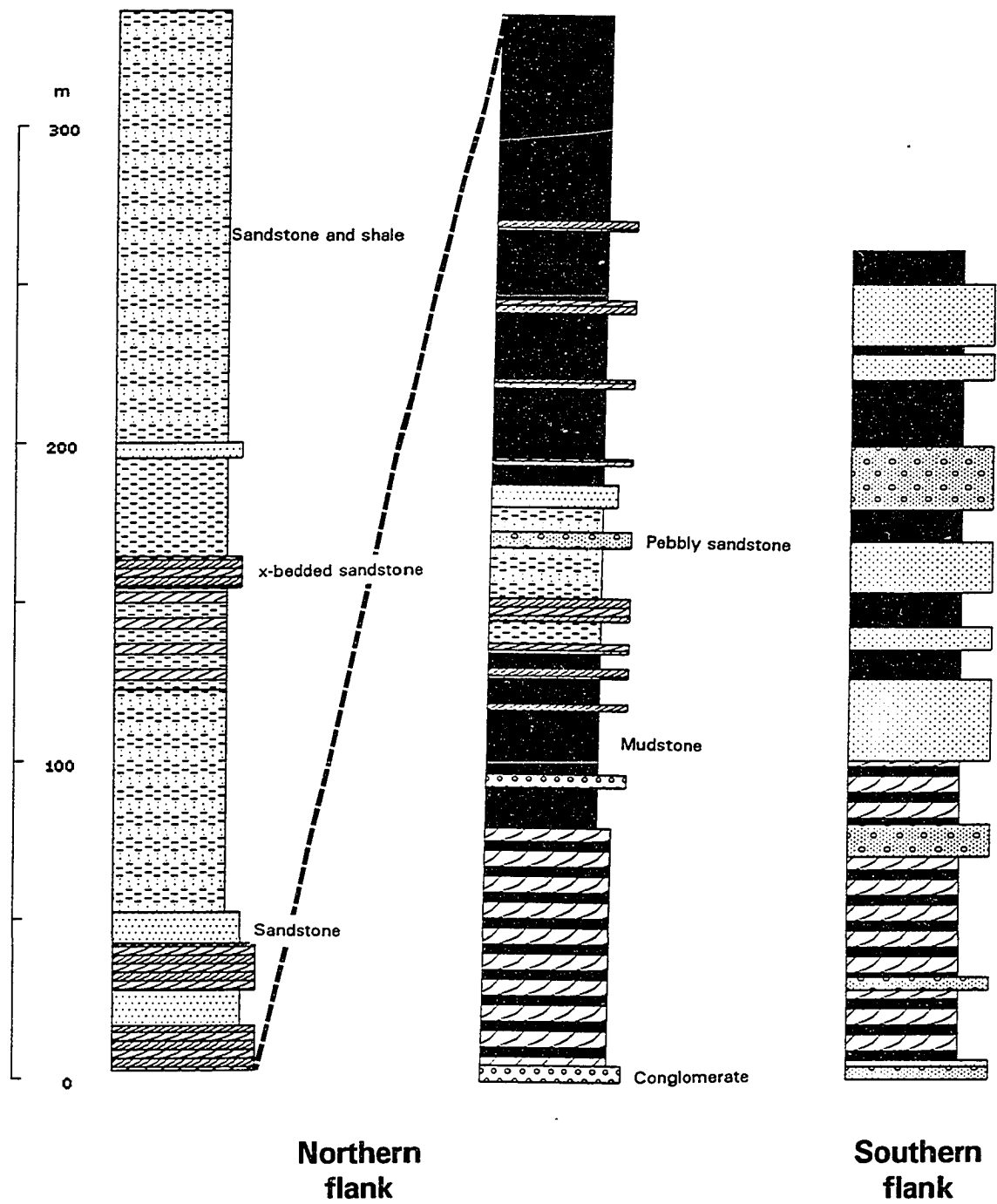
### **Sierra El Chanate (Plate 1)**

The Pozo Duro Formation in Sierra El Chanate includes members NEC-1 and the lower part of NEC-2 of Jacques and Potter (1987). This formation, 675 m thick in the northern limb of the Sierra El Chanate, underlies a nearly flat area except at the base where it forms hills elongated parallel to the strike. These hills form because the conglomerates that make the base of the unit are more resistant to erosion. The arroyos generally cut across the unit where the conglomerates are absent or very thin. In aerial photographs and satellite images the base of the unit is clearly marked by the white streaks of conglomeratic lenses.

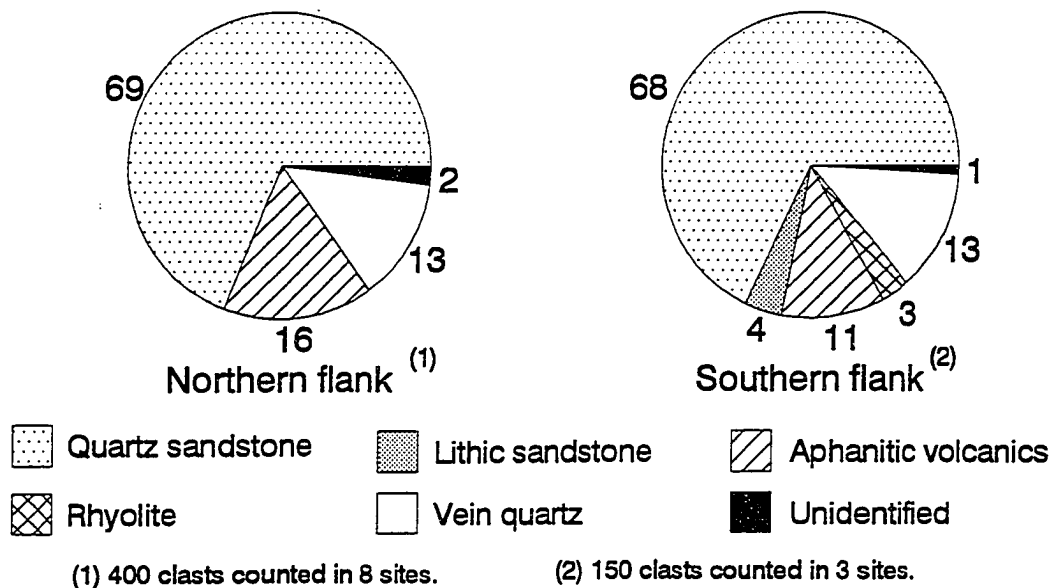
In the southern side of the sierra the Pozo Duro is only 210 m thick.

The Pozo Duro Formation is a sequence of mudstone, shale, sandstone and conglomerate (Fig. 17). Most of the unit consists of red to purplish red and brown, massively bedded mudstone. The sandstone is red to purplish red, medium to thick bedded. Locally there are intercalations of cream-colored sandstone, especially in the lower half of the unit. Beds display plane-parallel bedding and cross-bedding. Grain size ranges from fine to coarse. Coarse grained sandstone are predominant near the bottom, finer grained ones predominate toward the top. The gray to purplish red sandstones are mainly lithic arenites, whereas the cream-colored ones are quartz-rich and coarser grained and conglomeratic. The conglomerates are cream-colored, lens-shaped, and generally less than 2 m thick. Pebbles and granules are rounded and subrounded, and consist mainly of quartz sandstone and small amounts of volcanic rocks and vein quartz (Fig. 18). Toward the top of the section the conglomerate becomes brown, and quartz-porphyry and andesite pebbles are common.

In the northern El Chanate, in the lower 200 m of the Pozo Duro, the conglomerates are thicker and more frequent near the base. The amount of sandstone also



**Figure 17.** Stratigraphic columns of the Pozo Duro Formation in the Sierra El Chanate.



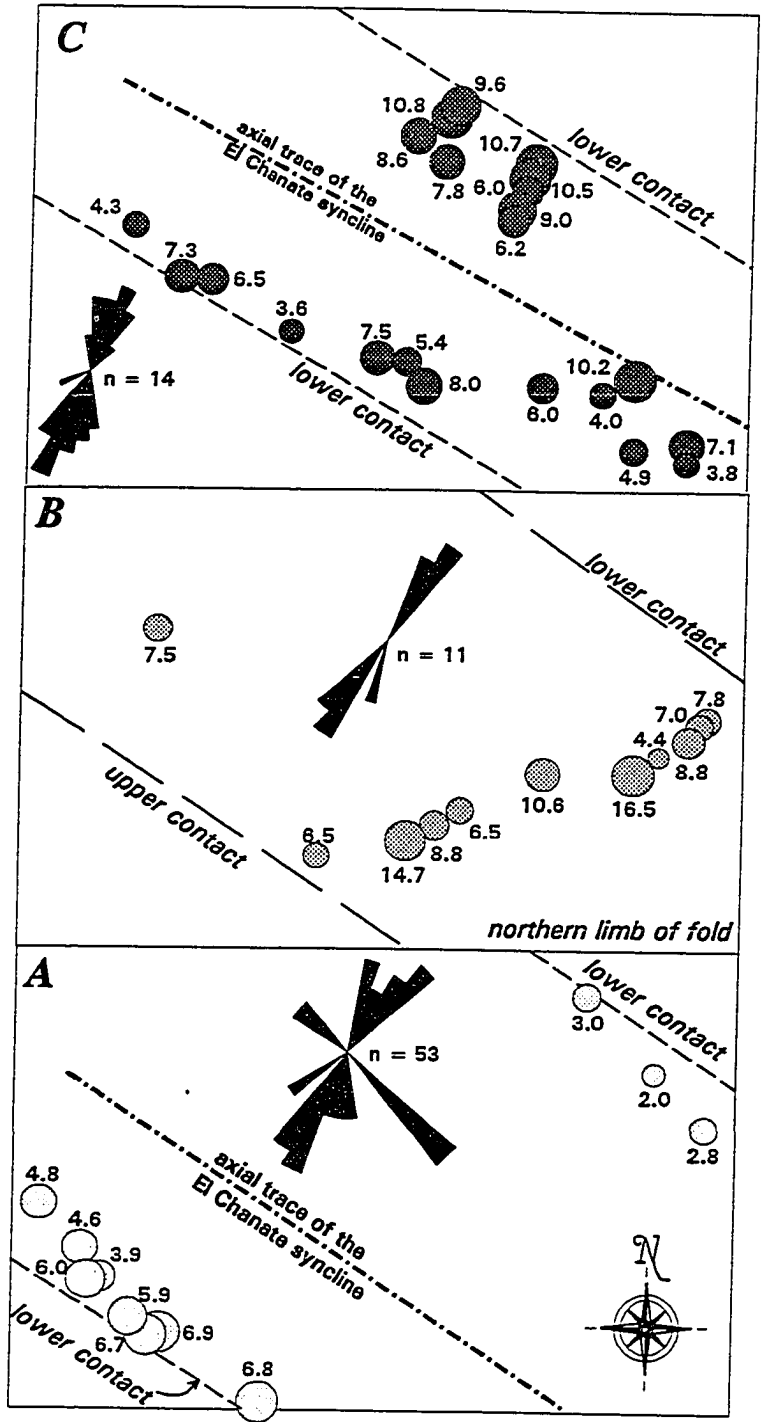
**Figure 18.** Clast composition (%) of conglomerates of the Pozo Duro Formation, Sierra El Chanate.

diminishes upward acquiring gray to red and green colors. It is also finer grained. Near the top, the sequence consists mainly of mudstone.

In the southern side the conglomerates are thicker, and the clasts are larger than those on the northern side (Fig. 19A). The sequence in the southern side also fines upward. Near the top, in the central portion of the sierra, several lenses of volcanic-pebble conglomerate occur. Sparse fragments of black silicified wood occur in different places within the unit. In one place a tree trunk about 50 cm in diameter was found.

### **Cerros El Puerto (Plate 2)**

The Pozo Duro Formation in the Cerros El Puerto is at least 800 m thick and forms generally fining-upward cycles from pebble conglomerate to mudstone. The finer grained rocks are red to purplish red, purple and green. They are medium to thick bedded, and locally display internal bedding and lamination. Sandstone is greenish gray to buff, ranges from coarse and pebbly to fine and silty, and is medium to thick bedded. The composition of the sandstone varies from quartz-rich to lithic-rich. The conglomerate



**Figure 19.** Conglomerate clast size distribution (in cm; average of 50 clasts/site) of El Chanate Group in Sierra El Chanate, and cross-bedding rose diagram. (A) Pozo Duro Fm. (both flanks); (B) Anita Fm. (northern flank); (C) Escalante Fm. (both flanks). Diagrams at different scales.

is cream-colored, forms lenses not thicker than about 2 m, and is matrix supported. The pebbles are rounded and consist mainly of quartz sandstone and minor volcanic fragments. In the high hills in the core of the syncline the El Chanate Group becomes sandier and more conglomeratic.

The contact with the Bisbee Group is a fault, and the Anita and Escalante Formations are absent. The contact with the El Charro volcanic complex of latest Cretaceous age is the Oquitoa fault.

### **Cerros Cabeza Colgada (Plate 3)**

The Pozo Duro Formation in the Cerros Cabeza Colgada is resistant to erosion and forms the hills in this area. Outside this area, west of the road from El Ocuca to Trincheras, the Pozo Duro can also be found in the highest parts of the hills extending northwest into the eastern Cerros El Amol. In the Cerros Cabeza Colgada the younger El Chanate formations occur in the core of the major fold but the formation boundaries were not mapped. Total thickness of the El Chanate is at least 1000 m.

The Pozo Duro Formation consists of red to purplish red mudstone and siltstone, and gray to purplish gray sandstone. At the base there are lenses of quartz-sandstone pebble conglomerate. In the western part of the area (Plate 3) the conglomerate lenses are thin and matrix-supported, and the pebbles are small. In the surroundings of Rancho San Pascual, in the eastern Cerros El Amol, the Pozo Duro Formation has several conglomerate lenses about 3 to 4 m thick, of rounded, quartz-sandstone pebbles and cobbles.

### **Cerro La Pima (Plate 4)**

The Pozo Duro Formation is barely exposed in the northern Cerro La Pima, near Rancho El Represito. The exposure is a few meters thick and consists of thin veneers of quartz-sandstone pebble conglomerates intercalated in red to reddish purple mudstone. These red mudstones are similar to those in the underlying Cintura Formation.

### **Depositional environment**

The depositional environment of the lower Pozo Duro is interpreted as fluvial. The presence of fining upward cycles in which vertical accretion deposits (red mudstone) are predominant suggests alluvial flood plains with relatively narrow in-channel deposits. Up-section, the conglomerates disappear and the amount of sandstone decreases, suggesting that the area was dominated by alluvial flood plains. The source of the sediments was located to the south, as indicated by the presence of the largest clasts in the conglomerates in the southern side of Sierra El Chanate (Fig. 19A). Cross-bedding indicates a northwest-southeast strand line with northeast flowing rivers. Subsidence was larger toward the north as indicated by the difference in thickness on both sides of Sierra El Chanate.

### **Anita Formation**

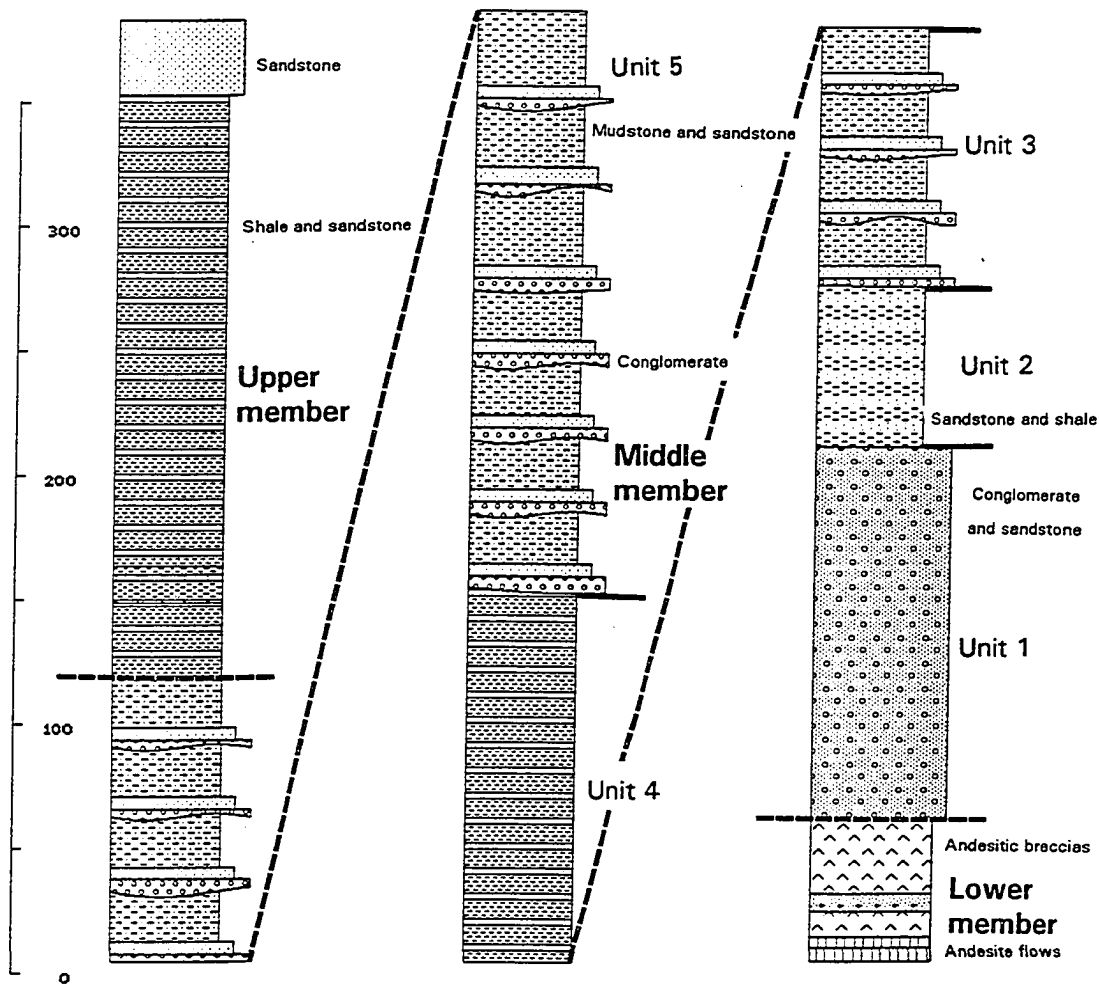
The Anita Formation, middle unit of the El Chanate Group, is named after the Rancho Anita, located on the eastern end of Sierra El Chanate across the Arroyo Sásabe and south of the Rancho Aurora. The Anita Formation includes the upper part of member NEC-2, and members NEC-3, NEC-4 and NEC-5 of the El Chanate Formation of Jacques and Potter (1987). The Anita Formation has been identified only in Sierra El Chanate.

### **Sierra El Chanate (Plate 1)**

The Anita Formation is exposed in the northern side of Sierra El Chanate where it is 1,130 m thick, and in the southern side where it is at maximum 140 m thick. There it wedges out completely toward the northwest.

The Anita Formation is divided into three members: the lower member, middle member and upper member. In the northern side all three members occur (Fig. 20), whereas on the southern side only the lower and middle members are locally present.

Lower member.- The lower member is an andesite: it consists of flows and volcanic breccias with sparse volcanic conglomerate intercalations. In the southeastern part of the



**Figure 20.** Stratigraphic column of the Anita Formation in the northern Sierra El Chanate.

northern flank it is about 300 m thick, but it is only 30 m in the northwestern part. Poorly exposed flows, predominant in the southeastern part, consist of light olive-gray, massive, aphanitic to porphyritic, highly altered andesite with plagioclase and amphibole phenocrysts. The volcanic breccias are made of angular to subrounded fragments

embedded in a volcanic matrix of the same composition. Locally, the matrix can be sandy with a strong hematitic color. The conglomerate is mainly of andesite fragments in a sandy to tuffaceous matrix. The contact with the middle member is covered, but appears to be transitional for the angular breccias grade up into rounded conglomerates and the matrix, first of volcanic origin, becomes sandier upsection.

In the southeastern part of the southern flank, a minimal 50 m section of the lower member of the Anita consists of volcanic conglomerates, thick tuffs and volcanic breccias covered by the middle member. The massive stratification is indicated by size and roundness differences of the clasts.

In the central part of the southern flank the lower member, 110 m thick, consists of andesite flows and a few thin volcanic breccias near the top. Farther northwest, it wedges out and disappears. Locally, volcanic breccias a few meters thick can be observed. The contact with the middle member is conformable but abrupt.

Three samples from the lower member of the Anita Formation were analyzed geochemically by Grajales *et al.* (1989). These rocks of the Anita can be classified as trachy-andesites and basalts. In a  $2\text{Nb}-\text{Y}-\text{Zr}/4$  diagram of Menschede (*in Grajales et al.*, 1989) the samples plot in the intraplate alkaline and tholeiitic basalts field. In a Ti-Zr-Sr diagram (Pearce and Cann, 1973, *in Grajales et al.*, 1989) the samples plot in the calc-alkaline basalts field. These two diagrams suggest that the volcanic rocks of the Anita Formation were emplaced on continental crust.

Middle member.- The middle member of the Anita Formation in the northern side of the mountain is 815 m thick, and consists of thick shales and sandstone, and mudstone, sandstone and conglomerate in fining upward cycles. In contrast with the Pozo Duro Formation the clasts of the Anita conglomerates consist mainly of andesite with minor amounts of rhyolite (Fig. 21). Average clast size is much larger in the northern side than in the southern side where the middle member of the Anita is practically absent. Mean diameter of clasts increases upward (Fig. 19B).

The Anita Formation records local volcanic centers with clastics derived from these centers. It is the only Cretaceous formation in NW Sonora in which the age of the

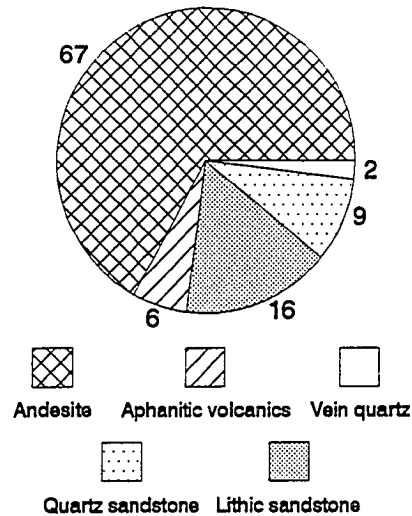
source is known conclusively and therefore the middle member of the Anita Formation is described in detail in the following paragraphs. This member can be divided in five units:

**Unit 1.-** This basal unit, 150 m thick, consists of lenticular, thick-bedded or massive conglomerate with sandstone intercalations (Fig. 20). The conglomerate is clast supported; it is mottled to red and grayish red. The matrix is sandy to silty and the clasts are rounded to subangular, poorly sorted, and mostly andesite. The sandstone is red, medium bedded, and coarse to gravelly. Sandstone becomes more abundant, finer grained, and with plane-parallel bedding toward the top. Locally upward coarsening occurs. The contact with the overlying unit is sharp.

**Unit 2,** 65 m thick, consists of shale with intercalations of sandstone and some conglomerate. The shale is red to gray to dark gray, massive, and contains some calcareous nodules. Sandstone is red, medium- to thick-bedded, and medium- to fine-grained. The upper contact of the sandstone is gradational with the shale.

**Unit 3** consists of 100 m conglomerate, sandstone and shale in fining-upward cycles. The conglomerate is massive, clast-supported, poorly sorted, with cobbles as large as 30 cm. The clasts are mainly andesite, but quartz- and lithic-sandstone and vein-quartz are also present. The sandstone is red, medium- to coarse-grained and pebbly, medium to thick bedded. Plane-parallel and cross bedding are common, as well as bioturbation structures. The shale is red, massive to thick bedded, with disseminated calcareous nodules and intercalations of red, fine-grained sandstone and silt.

**Unit 4,** 150 m thick, consists mainly of shale with minor intercalations of sandstone and conglomerate. It is similar to unit 2, but the coarser fraction is more



**Figure 21.** Clast composition (%) of the conglomerates of the Anita Formation, northern Sierra El Chanate. Counts done in 8 sites, 50 pebbles per site.

abundant.

**Unit 5** (formerly Member NEC-4 of Jacques and Potter, 1987), 350 m thick, consists of conglomerate, sandstone and shale forming fining-upward cycles. The conglomerate is red to gray and mottled, thick to medium-bedded and lenticular. It is grain supported, poorly sorted, with clasts in the cobble range. The composition of the clasts is mainly andesite, with some quartz sandstone and chert. Locally the conglomerates can consist almost entirely of quartz-sandstone pebbles. The sandstone is medium- to thick-bedded, pebbly to coarse- and medium-grained, and displays plane-parallel and cross-bedding. The shale is red, thick bedded with thin intercalations of red siltstone. It contains small calcareous nodules.

Upper member.- The upper member of the Anita Formation, 270 m thick, consists of shale with some interbeds of sandstone and minor limestone. The shale is red to green and purplish brown, but weathers to tan and ocher. It is thick bedded and contains disseminated calcareous nodules. About 30 m above the base is a 12 m-thick zone of dark gray (weathering to olive green and ocher) shale with thin intercalations of dark gray to black limestone and calcareous shale. The limestone is micritic and shaly, and contains the pelecypod *Crassatella (Pachythaerus)* Conrad sp. and the gastropods *Rissoa dupiniana* d'Orbigny and *Tellina bogotina* d'Orbigny (Jacques *et al.*, 1990a). The sandstone is buff to purplish gray and ocher green, thin to medium bedded, fine to medium grained. The upper part of the member is a coarsening up sequence.

### **Depositional environment**

The base of the Anita Formation represents the onset of andesitic volcanism. Volcanic centers were located east of the Sierra El Chanate, for the lava flows and volcanic breccias are more abundant in that direction. On top of the lower Anita member sedimentary breccias and conglomerates were deposited. The clasts in these sediments were largely derived from the same volcanic centers.

Unit 1 of the middle member probably accumulated as alluvial fans formed as the result of the increase in relief due to volcanic activity. Units 2-5, consisting mainly of

fining upward cycles were deposited by meandering rivers. In most of these fining upward cycles the amount of mudstone is larger than that of conglomerate and sandstone, thus suggesting that overbank deposits were predominant.

The upper member of the Anita is interpreted as being deposited mostly in lacustrine environments. Lake deposits include dark gray shale and limestone with fresh water pelecypods and gastropods. A similar environment has been documented in the Cabullona Group and Fort Crittenden Formation in northeastern Sonora and southeastern Arizona (Taliaferro, 1933; Hayes and Drewes, 1978; Lindberg, 1987; Inman, 1987; González, oral comm., 1992).

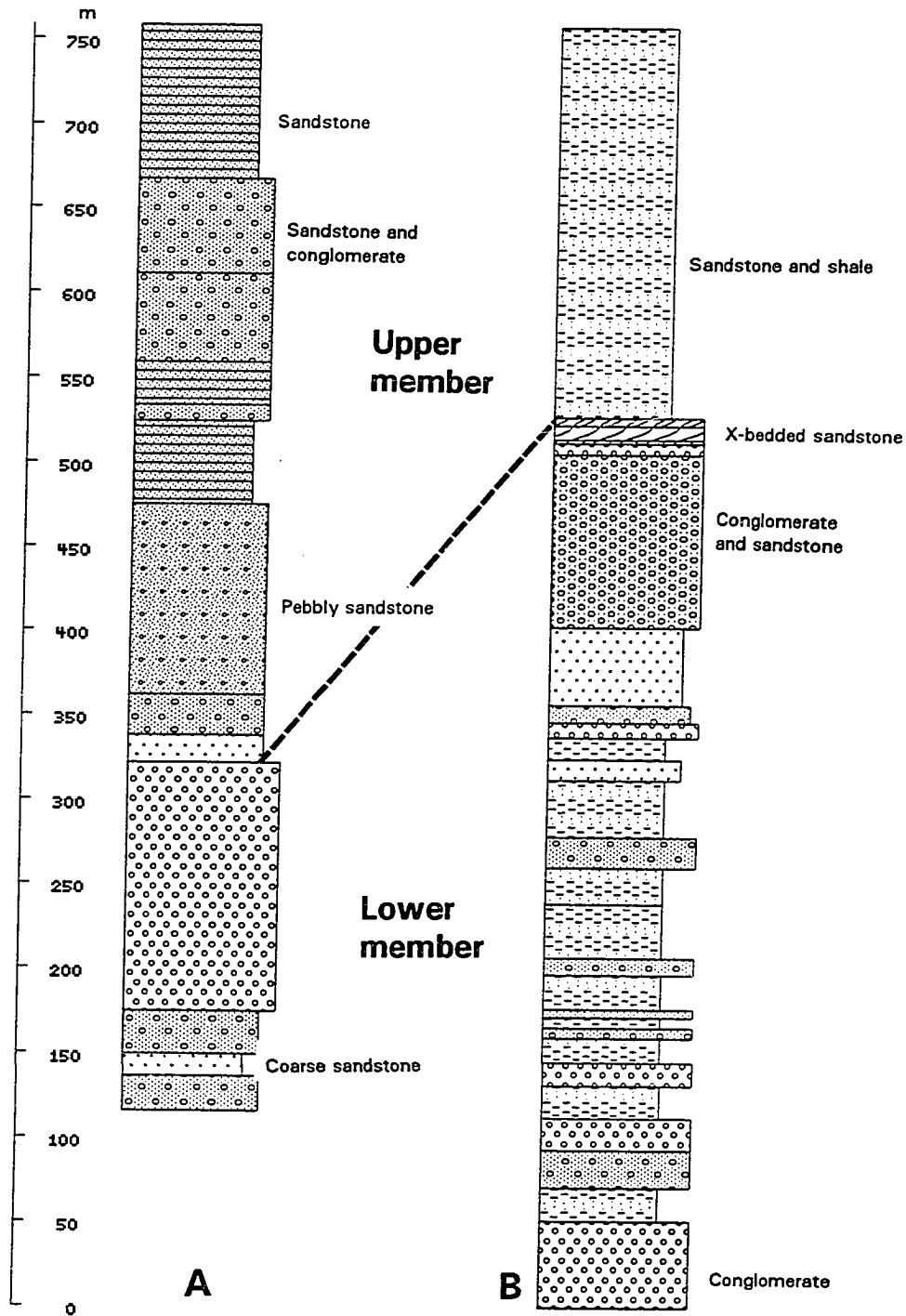
### **Escalante Formation**

The Escalante Formation is named after the Rancho Escalante, located on the eastern end of Sierra El Chanate across the Arroyo Sásabe. This formation, 730 m thick in the northern Sierra El Chanate, is divided in two members. The lower member includes thick conglomerates, sandstone, and mudstone. The upper member is a valley-forming unit, and consists of sandstone and shale pairs. The Escalante is well exposed on both sides of the El Chanate, even though it is much thinner in the southern side.

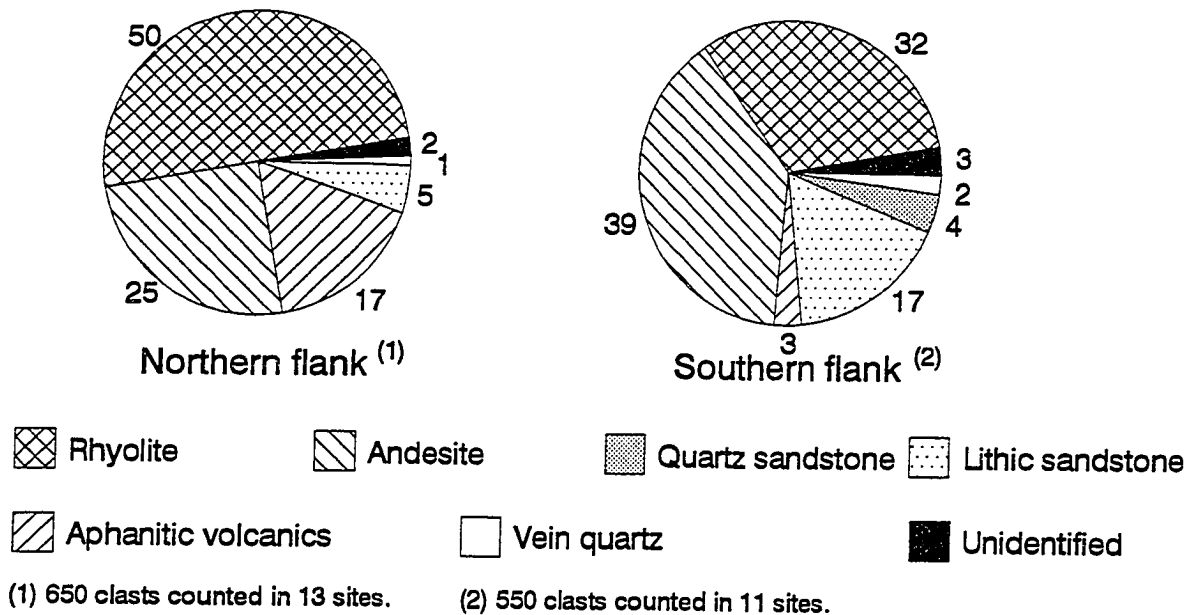
The Escalante Formation contains small fragments of black fossil wood, most of which are silicified.

#### **Sierra El Chanate (Plate 1)**

Lower member.- The lower member of the Escalante Formation, 510 m thick on the northern flank of the mountain, consists of thick conglomerate wedges with intercalated sandstone and mudstone in fining upward cycles (Fig. 22). The conglomerate is gray to purplish gray and reddish buff and in thick beds. It is clast-supported with a sandy matrix. Conglomerate wedges can be as thick as 30 m. The clasts consist of quartz porphyry, flow-banded rhyolite, and subordinated amounts of andesite, quartz sandstone and lithic sandstones (Fig. 23). Clasts are well rounded to subangular; average size is between 10 and 15 cm, but clast size can reach 40 cm; larger clasts occur in the northern side than in the southern side (Fig. 19C).



**Figure 22.** Stratigraphic column of the Escalante Formation. (A) Puerto El Alamo (after Willard, 1988); (B) northern Sierra El Chanate.



**Figure 23** Clast composition (%) of the lower member of the Escalante Formation in the Sierra El Chanate.

Sandstone is gray to purplish gray and green, medium to thick bedded, coarse pebbly to medium grained. It displays graded, plane parallel and cross bedding. Where the underlying lithology is a conglomerate, the contact is normally transitional; where it is a shale, it is scoured. Some sandstone beds have a conglomeratic base.

Mudstone is common, forming the upper part of the fining-upward cycles. The mudstone is green to red and purple, medium to thick bedded. Calcareous nodules, generally not more than 10 cm in diameter are locally concentrated in bedding planes. Intercalations of red siltstone and fine grained sandstone in medium to thin beds are common. In the southeastern side of the northern limb of the sierra the mudstone is red, massive and resistant to erosion. It resembles the mudstone in the Morita and Cintura Formations.

In the southern side of Sierra El Chanate the lower member attains in two sections a thickness of 225 and 250 m. The sequence is lithologically similar to that in the north, but is half as thick. The size of the pebbles is slightly smaller than those in the northern

side.

Upper member.- The upper member of the Escalante Formation is a valley-forming lithologic unit consisting of sandstone and shale pairs. As it erodes easily, it forms gentle slopes. Two sections measured on the northern slope of the Sierra El Chanate are 207 and 195 m in thickness. In the eastern part of the southern flank the sequence is 142 m thick.

The upper member consists of brownish and reddish green to purple and reddish purple sandstone. Beds are laterally persistent (sheet-like) with thicknesses varying from a few centimeters to almost a meter; most common is about 0.5 m. The sandstone is coarse to medium grained, and locally pebbly. Some beds include a conglomeratic base. Beds are thick at the base and thinner upsection. Near the contact with the El Charro volcanic complex they become coarse grained. Shale is brownish to olive green and purple, and forms laterally persistent beds generally less than 0.5 m thick with some beds reaching few meters thick. Thick shale beds display pencil structure. In the eastern part of the southern flank of the sierra occur stromatolitic limestone lenses less than 0.5 m thick, and not more than 2 m long. In the upper part of the section are grayish white rhyolitic tuffs, generally less than 10 cm thick. They are similar to the thick, greenish gray tuffs at base of the El Charro volcanic complex.

#### **Sierra El Batamote (Plate 1)**

In the valley between Sierra El Chanate and Sierra El Batamote a conglomeratic sequence displays variable amounts of deformation, from undeformed to strongly foliated and stretched. These rocks were included in the El Batamote Formation by Jacques (1983). Harrar (1989) placed them within the El Chanate Group. In this work they are identified as lower member of the Escalante Formation. Part of this member is located in the El Chanate fault zone: the conglomerates are stretched and hydrothermally altered.

In the northern slope of Sierra El Batamote is the upper member of the Escalante Formation. It consists of brown to buff and greenish brown sandstone and shale pairs, apparently thinner than those in Sierra El Chanate. The beds are mostly covered by

debris from the El Charro volcanic complex.

### **Puerto El Alamo (Plate 1)**

The 630 m-thick sequence described by Willard (1988) as the El Chanate Formation in the Puerto El Alamo is here considered as the Escalante Formation (Fig. 22). The Pozo Duro and Anita Formations are apparently absent. The presence of quartz porphyry rhyolitic clasts, in light-colored thick-bedded conglomerates is typical of the Escalante Formation, as described above.

The lower member of the Escalante Formation, 220 m thick, consists of conglomerate and sandstone, in fining upward cycles. The conglomerates are brown and gray, massively bedded, and consist of pebbles and cobbles made of quartz porphyry and, rarely, quartz sandstone. Interbedded sandstone is grayish red to dark reddish brown, poorly to moderately sorted, and mainly of volcanic origin.

The upper member is at least 350 m thick. Total thickness is unknown because its top is cut by a fault. The upper member consists mainly of brown, greenish brown to gray and maroon sandstone and siltstone, locally with thin conglomerate lenses. This unit contains silicified fossil wood. In the Puerto El Alamo-El Chanate area fossil wood has been collected only from the El Chanate Group and never from the Bisbee Group. Fossil wood has been found, however, in the Bisbee Group of other study areas.

### **Depositional environment**

The depositional environment of the thick, water-laid conglomerates of the lower member of the Escalante Formation are interpreted as an alluvial basin with alluvial fans and braided streams. Clast size in the conglomerates decreases upward and the amount of mudstone increases, suggesting that the fluvial system changed from braided to meandering. Cross-bedding shows a bimodal orientation, indicating that the strand line was northwest-southeast oriented (Fig. 19C). Pebble size distribution indicates that the source was toward the north (Fig. 19C). The conglomerates at the base of the Escalante Formation suggest renewed period of uplifting.

Grajales *et al.* (1989) made a chemical analysis of boulders from the Escalante

and compared it with Jurassic rhyolite rocks from the Planchas de Plata area (Segerstrom, 1987) and a Cretaceous (108 Ma, K/Ar) rhyolite sample collected from Sierra La Comancha, about 10 km northwest of Sierra La Gloria (Jacques *et al.*, 1990d). Chemical data of these three units plot closely together in a Rb vs Y+Nb diagram (Pearce *et al.*, 1984, *in* Grajales *et al.*, 1989), thus suggesting that the boulders were derived from rocks such as those in the Planchas de Plata and La Comancha areas.

The lithology and geographic extent of the upper member of the Escalante Formation suggest that it was deposited in deltas in lakes, large enough to accommodate 200 m of section. A similar sequence in the Cabullona Group in northeastern Sonora has also been interpreted as a lacustrine deposit (González, oral comm., 1992). The Fort Crittenden Formation also includes thick lake deposits (Lindberg, 1987; Inman, 1987) even though they appear to be less sandy than the upper member of the Escalante. At the end of the lacustrine time, volcanic activity occurred probably at a relatively large distance from the vent source for the tuff beds are thin.

### Stratigraphic relationships (Table 3)

The El Chanate Group is separated from the Bisbee Group by an erosional unconformity. In the Sierra El Chanate the hiatus appears to be relatively minor, but the absence of the Pozo Duro and Anita Formations in the Puerto El Alamo indicate that it can be a major hiatus.

The Anita Formation appears to rest conformably upon the Pozo Duro Formation: the contact was not observed, but the bedding in both units is parallel. The contact between the Escalante and Anita Formations is probably an erosional unconformity: the thick conglomerates of the Escalante cut the upper member of the Anita in the northern Sierra El Chanate, or rest directly upon the Bisbee Group in the Puerto El Alamo.

The contact between the Escalante Formation and the El Charro volcanic complex appears to be erosional. The time lapsed between the end of the El Chanate and the beginning of the El Charro is thought to be short, mainly because of the presence of thin rhyolitic tuffs in the upper part of the Escalante Formation similar to the rhyolitic tuffs in the lower El Charro. Bedding in Escalante and the El Charro is parallel.

### Age and correlation (Table 3)

Several fossils were collected from the upper member of the Anita Formation in the northern Sierra El Chanate (Jacques and Potter, 1987; Jacques *et al.*, 1990a). Of these, the gastropod *Rissoa dupiniana* d'Orbigny yields an Albian age. However, the specimen collected in the Sierra El Chanate is incomplete and slightly larger than the ones described in France (Buitrón, *in* Jacques *et al.*, 1990a). Specimens of *Tellina bogotina* d'Orbigny (Cretaceous) and *Crassatella (Pachythaerus)* Conrad sp. (middle Cretaceous to Middle Eocene) were also collected (Buitrón, *in* Jacques *et al.*, 1990a). The age determination of the El Charro volcanic complex (see next chapter) places the top of the El Chanate Group in the Maastrichtian. Thus, the age of the El Chanate Group may range between Albian and Maastrichtian. The lithologically similar Cabullona Group and Fort Crittenden Formation have been assigned a Campanian-Maastrichtian age (Drewes, 1971; González *et al.*, 1993; Kietzke *et al.* 1993; Lucas *et al.*, *in prep.*). Shafiqullah (*in* Hayes, 1987) dated biotite (K/Ar) from a volcanic andesite intercalated in the Fort Crittenden Formation of the Canelo Hills area:  $75.0 \pm 1.7$  Ma (K/Ar).

Assignment of the El Chanate Group to the Albian (Jacques and Potter, 1987) is not accepted in the present study. Instead, because of the remarkable lithologic similarity with the Fort Crittenden Formation and Cabullona Group, a Campanian-Maastrichtian age of the El Chanate Group is favored.

The Pozo Duro Formation, the basal unit of the group, occurs outside the study areas in western Cerros El Amol (García *in* Jacques *et al.*, 1990b; García, 1992) and in eastern Cerros El Amol.

The Anita Formation occurs in the Cerros El Amol as a thin andesitic breccia and andesite-pebble conglomerates similar to those in the Sierra El Chanate. In the Cerro Picacho (Fig. 6), west of Benjamin Hill, sandstone and conglomerate resembling the upper middle member of the Anita are structurally overlain by Proterozoic rocks.

The Escalante Formation with its characteristic quartz porphyry clasts was not recognized by García (1992, and *in* Jacques *et al.*, 1990b). However, the El Recodo

member of the El Amol Formation has at its base a conglomerate wedge with quartz porphyry clasts remarkable similar to those of the Escalante Formation. It is at present impossible to exclude the possibility that the lower El Amol Formation is heteropic with the Escalante Formation.

Other units that can be correlative to the El Chanate Group are the Chino Group and probably part of the El Rajón Group (Longoria and Pérez, 1979). A conglomeratic sequence overlying the Cintura Formation east of Tuape (Rodríguez, 1988) could also be correlative to the El Chanate. The Cabullona Group occurs in northeastern Sonora (Taliaferro, 1933) extending into Arizona with its correlative the Fort Crittenden Formation (Dickinson *et al.*, 1989). Hayes and Drewes (1978) described the Fort Crittenden in the Santa Rita Mountains, southeastern Arizona (p. 205):

"... a lenticular conglomerate made up of dominantly well rounded cobbles of lower Mesozoic volcanic and sedimentary rocks. Above this is a 160-m-thick sequence of gray shale and subordinated siltstone in which are found a varied fauna including freshwater mollusks, fish, turtles and dinosaurs of Santonian to Maastrichtian age (Miller, 1964). Above this fossiliferous shale unit in the Adobe Canyon area is more than 1,800 m of variable grayish red and brown conglomerate, arkosic sandstone and subordinated shale. High in the unit are several thin rhyolitic tuff beds".

This description is practically that of the upper half of the Anita Formation and the Escalante Formation. Further more, Hayes and Drewes (1978, p. 205) mention that in the Canelo Hills:

"beds of sandstone, conglomerate and shale and minor tuff are overlain by Upper Cretaceous andesite breccia. These may represent the top of the Fort Crittenden Formation"

Hayes (1987) reports the presence of andesitic volcanic rocks in the Fort Crittenden in the Canelo Hills area. These andesites are covered by about 350 m of andesite conglomerate. Above the andesite-derived sequence are conglomerates with granite clasts.

Extensive volcanic and volcano-sedimentary units correlative to the Cabullona Group have also been reported in east-central Sonora (Grajales *et al.*, 1990; Pubellier, 1987).

Rocks of the El Chanate Group can be part of the El Batamote structural complex, which extends along a discontinuous belt from Estación Llano to Sonoyta. The presence

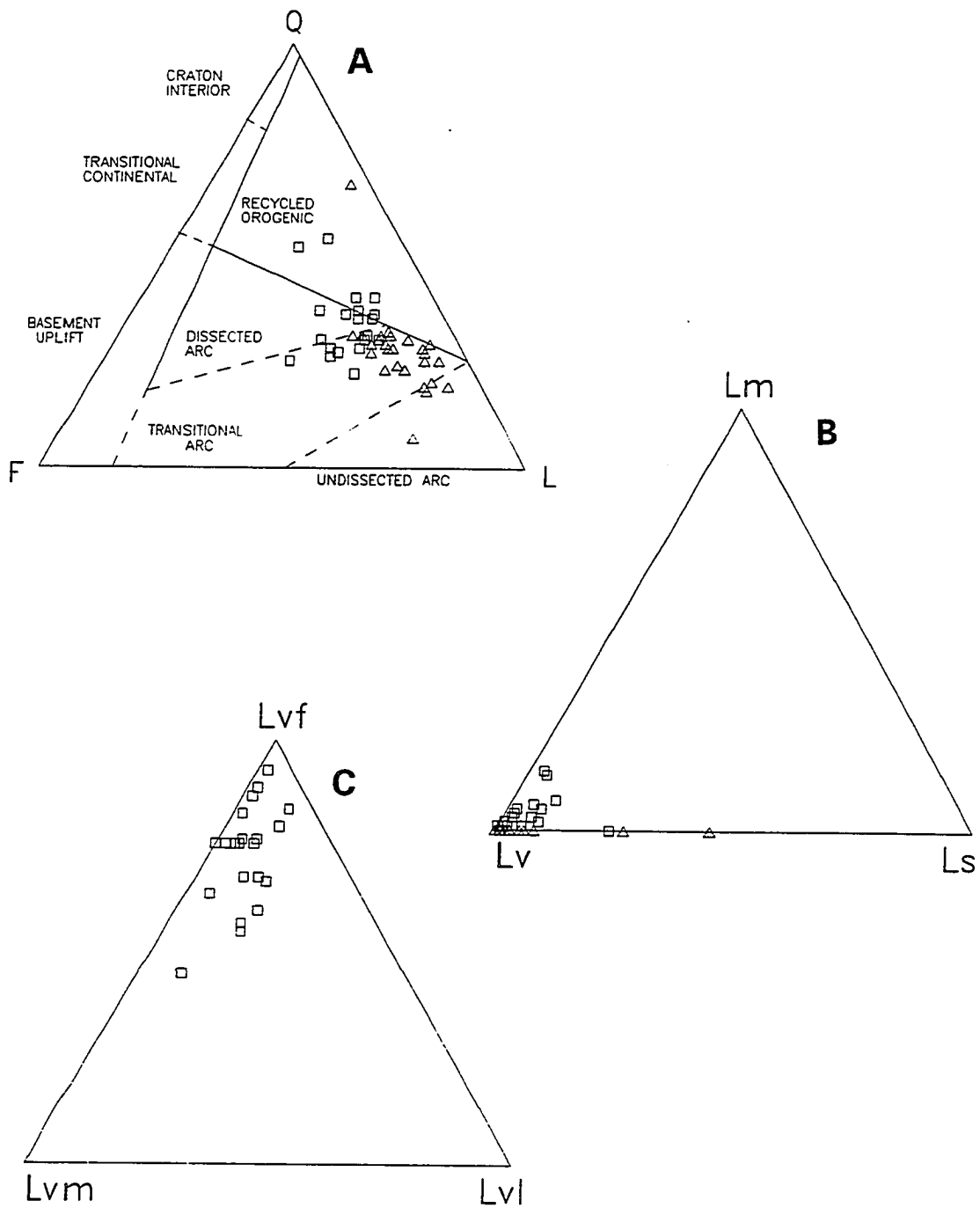
of the El Chanate Group west of the Puerto El Alamo is suspected, *e.g.*, in the Sierra La Gloria where Corona (1979, 1980) described a sequence of strongly deformed conglomerates and sandstones. Further northwest, a similar sequence of stretched conglomerates is found in Quitovac (Connors *et al.*, 1989; Caudillo and Oviedo, 1990) and in El Sahuaro (Calmus, 1993). These authors assigned a Jurassic age to these sequences based on the intensity of their deformation. In the author's opinion some of these rocks could be equivalent to the El Chanate Group.

### **Sandstone and conglomerate composition**

The sandstones in the El Chanate Group are similar to the sandstones of the Bisbee Group. Texturally they are poorly to moderately sorted, well packed arenites. The amount of matrix is small but cement is slightly more abundant in the El Chanate. Grains are angular to moderately rounded, and tend to be irregular in shape. Monocrystalline quartz is well rounded to subangular. Polycrystalline quartz is made mainly of a mosaic of crystals larger than 0.062 mm with straight to irregular contacts. Some polycrystalline quartz grains appear to have outlines of rounded sand grains suggesting that they are reworked sandstones. Few grains have stylolitic or tectonic fabric. Chert and chalcedony occur in small amounts (Table 5).

The QFL average composition of the Pozo Duro ( $Q_{38}F_{22}L_{40}$ ), Anita ( $Q_{35}F_{18}L_{46}$ ) and Escalante ( $Q_{31}F_{22}L_{47}$ ) formations in the Sierra El Chanate are similar, and also similar to the Bisbee Group. Willard (1988) obtained a similar average for the Escalante Formation ( $Q_{27}F_{13}L_{60}$ ). When plotted in a QFL diagram (Fig. 23) the sandstones of the El Chanate Group fall in the volcanic arc field with few samples in the craton-derived field. As polycrystalline quartz is minor (Table 5), the QmFLt diagram does not change much from the QFL diagram.

Rock fragments are the most abundant grains. They are irregular in shape, many of them being deformed by the surrounding, more resistant grains. The bulk of the lithic fraction is made of igneous rock fragments (Fig. 23) with variable texture and composition. Most of them are porphyritic or aphanitic. Chert-looking grains could be identified as microcrystalline felsic volcanic rocks because some fragments include



**Figure 24.** Ternary diagrams of sandstones from the El Chanate Group in Puerto El Alamo and Sierra El Chanate. (A) QFL diagram; (B) LmLvLs diagram; (C) LvfLvmLvl diagram. Parameters in Table 1.

feldspar or quartz phenocrysts. Some are phaneritic to microphaneritic, and include quartz, K-spar, and rarely plagioclase. Some fragments with granophyric or graphic texture were observed. Few sedimentary fragments were observed, and even less metamorphic fragments. Some of the "metamorphic" fragments are actually sericitized volcanic fragments with a flow structure. They were placed in the metamorphic category because of their "oriented" fabric.

As in the Bisbee Group, aphanitic volcanic rock fragments were counted on the basis of their texture: microgranular rock fragments, by far the most abundant, are derived from felsic rocks such as rhyolites; microlithic grains indicate the presence of an andesitic source, and traces of fragments with lathwork texture suggests that some basaltic rocks were also present. The composition of the igneous rock fragments strongly suggests that during El Chanate time the rhyolites of the Jurassic volcanic arc were the main source of sediments. A minor input from quartzose sandstone is recorded in the Pozo Duro Formation.

The composition of the clasts in the conglomerates does not always reflect the composition in the sand fraction. In the Pozo Duro Formation the conglomerate clasts consist of quartz sandstone; the sandstone shows an increase in polycrystalline quartz but is mostly felsic. In the Anita Formation the sand fraction shows an increase in aphanitic volcanic fragments of the microlithic type (derived mainly from andesitic rocks) but felsic fragments (derived from rhyolites) are predominant. Only in the Escalante Formation the lithology of the conglomerate clasts correspond with that of the sandstone grains.

**Table 5. Ternary plot values from sandstones of the El Chanate Group of the Sierra El Chanate**

Pocho Duro Formation																
	Q	F	L	Qm	F	Lt	Qm	P	K	Lv	Lm	Ls	Lvf	Lvm	Lvl	Mtx
TM-16	54	15	31	40	15	45	72	22	6	84	4	12	93	5	2	1
TN-30	37	20	43	28	20	52	58	24	18	99	1	0	89	9	2	7
TP-09	22	25	53	20	25	55	44	33	23	92	2	6	68	17	15	5
TP-10	52	21	27	33	22	45	61	15	24	92	1	7	84	14	2	2
97-79	27	26	47	25	26	49	49	32	19	75	0	25	76	24	0	11
Avg.	38	22	40	29	22	49	57	25	18	94	1	5	82	14	4	5
Anita Formation																
TP-27	35	15	50	27	15	58	65	18	17	99	1	0	57	28	15	1
97-79	30	28	42	28	28	44	50	39	11	97	0	3	77	21	2	9
TO-24	36	14	50	30	15	55	67	19	14	91	3	6	64	31	5	1
SC-3050	40	16	44	31	16	53	65	16	19	90	2	8	45	46	9	0
Avg.	35	19	46	29	18	53	62	23	15	95	1	4	60	32	8	3
Escalante Formation																
TO-22	22	25	53	21	25	54	46	32	22	98	0	2	80	9	11	10
TO-24	40	12	48	35	12	53	74	16	10	82	7	11	77	18	5	7
TO-33	37	25	38	33	25	42	56	27	17	82	13	5	77	15	8	2
TO-35	30	16	54	25	16	59	61	28	11	87	6	7	76	19	5	4
TN-45	26	28	46	23	28	49	45	47	8	99	0	1	68	19	13	0
TN-50	31	18	51	26	18	56	59	33	8	88	5	7	84	5	11	5
TN-52	25	37	38	19	37	44	34	57	9	95	3	2	60	23	17	0
TP-90	28	21	51	23	21	56	53	35	12	96	1	3	76	16	8	4
TP-94	30	19	51	25	20	55	56	30	14	93	1	6	76	20	4	0
TP-106	35	18	47	30	18	52	63	24	13	81	14	5	68	22	10	6
TQ-45	28	27	45	25	27	48	48	30	22	97	2	1	55	29	16	5
115-79	36	20	44	32	19	49	62	24	14	91	5	4	87	11	2	7
Avg.	31	22	47	26	22	52	55	32	13	92	5	3	74	17	9	4

## LATE CRETACEOUS-EOCENE VOLCANIC UNITS

In Sierra El Chanate two volcanic sequences of latest Cretaceous and Eocene age were identified: the El Charro volcanic complex (oldest) and the San Jacinto andesite (youngest). They are both andesitic in composition but the El Charro includes sediments and is folded.

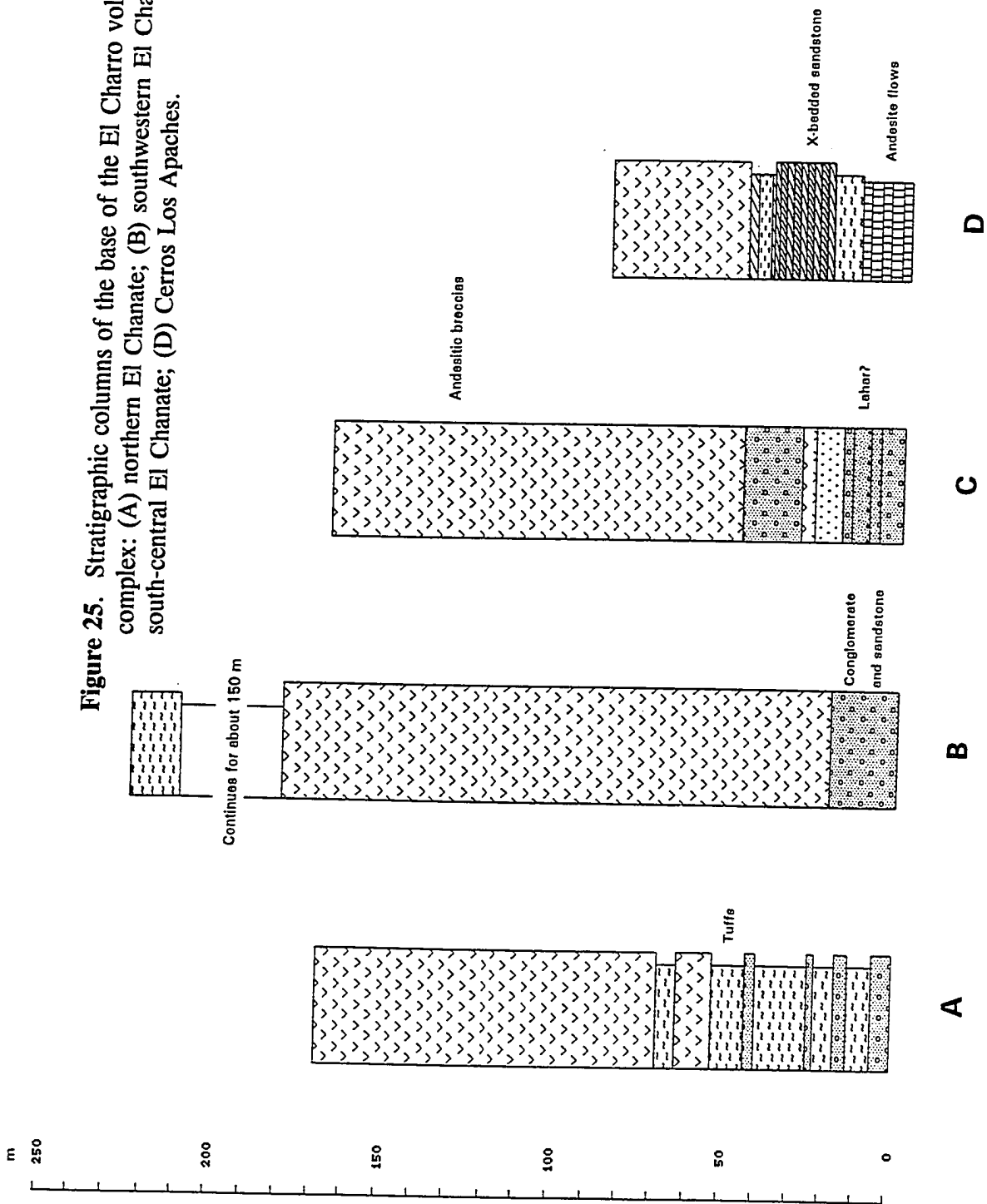
### **El Charro volcanic complex**

The El Charro volcanic complex is named after the Arroyo El Charro in the valley between Sierra El Chanate and Sierra El Batamote. This unit was described by Jacques (1983) as El Charro Formation. Detailed field work reported in this and other studies (e.g. Harrar, 1989) showed however, that the El Charro is lithologically much more complex than thought initially, and that it includes various types of volcanic, subvolcanic and sedimentary rocks. It therefore appears more appropriate to call it volcanic complex instead of formation.

El Charro volcanic complex underlies the backbones of the Sierra El Chanate (forming the nucleus of the syncline) and the Sierra El Batamote (Plate 1). It also occurs in the area north of El Batamote mine south of Sierra El Chanate, north of Puerto El Alamo, and in Cerros El Puerto (Plate 2), and is probably present in the northern part of Cerros El Amol.

### **Sierra El Chanate (Plate 1)**

In this area the El Charro volcanic complex, about 600 m thick, consists of andesitic breccia and flows, rhyolitic and andesitic tuffs, conglomerates and sandstones. On the steep northern side of the mountain beds are generally overturned, dipping steeply toward the northeast. A section 95 m thick was measured (section IV of Jacques, 1993) at the base of the unit (Fig. 25). The lower part of the measured section consists of gray andesitic breccias, cream-colored to greenish white rhyolitic tuffs and pebbly sandstone. The thick andesitic breccias consist of lappilli-size fragments of andesite in a matrix of the same composition. Few thin beds of ash tuff are present. The rhyolitic tuffs are



**Figure 25.** Stratigraphic columns of the base of the El Charro volcanic complex: (A) northern El Chanate; (B) southwestern El Chanate; (C) south-central El Chanate; (D) Cerros Los Apaches.

crystal-lithic ash or lapilli tuffs. Some beds show inverse graded bedding. There are intercalations of red, medium bedded, poorly sorted sandstone, pebbly sandstone and conglomerate. Upsection the purple to purplish gray andesitic breccias and flows become predominant.

On the southern side of the mountain the base of this unit is better exposed. Several sections which record facies changes in short distances were examined. On the westernmost part, the base of the El Charro consists of gray to grayish red and purplish gray, thin bedded, andesitic tuffs. The ash or lapilli tuff display normal and inverse graded bedding, and contain abundant plagioclase locally. In some places there are intercalations of a pink sandstone. Upsection, andesitic breccias become predominant. A few mud supported breccias were observed near the top of the mountain.

Toward the east (section I of Jacques, 1983) the tuffs pinch out, replaced by a 20 m-thick conglomerate of volcanic fragments with few intercalations of red sandstone. The conglomerate is lenticular and poorly sorted. It is overlain by andesitic breccias at least 300 m thick (Fig. 24). The massive andesitic breccia is gray to purplish gray and red. Bedding features can be observed locally. Gray, thick bedded andesitic tuffs occur higher in the section.

Further eastward, a few hundred meters from the section in Fig. 24, the base of the El Charro consists of 60 m of buff to gray, coarse grained, poorly sorted sandstone with intercalations of matrix supported conglomerate (lahar deposits?) (Fig. 24). The pebbles consist mainly of andesite, and minor quartzite and granite (Fig. 25). Above the sandstones is a series of lapilli tuffs followed by massive andesitic breccias.

About 1 km eastward of the

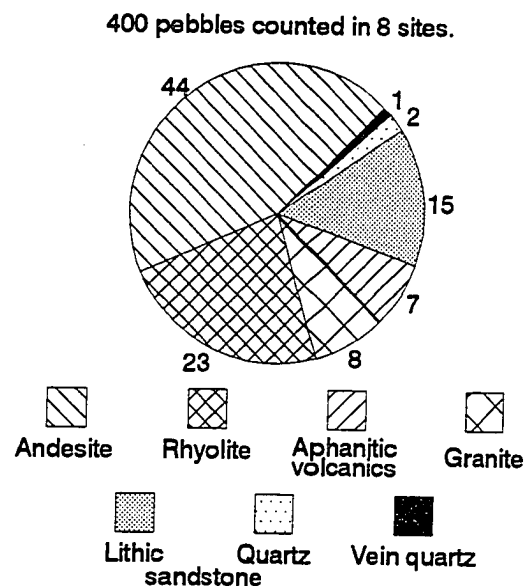


Figure 26. Clast composition of conglomerates near the base of the El Charro volcanic complex, southern Sierra El Chanate.

previous section another section (section II of Jacques, 1983) shows at its base a cream-colored rhyolitic tuff similar to the tuffs on the other side of the mountain. It has a thickness of 36 m and pinches out toward the east. It is overlain by andesitic breccias with intercalations of thin gray ash tuffs. Further east, green pebble conglomerates at the base are overlain by andesitic breccias.

The highest peaks of the central Sierra El Chanate consist of brown conglomerates and sandstone. Because of their inaccessibility it was impossible to describe a section. The contact with the underlying andesitic breccias was not observed.

### **Sierra El Batamote (Plate 1)**

The backbone of Sierra El Batamote is underlain by the El Charro volcanic complex. It consists here mainly of andesitic volcanic breccias, flows and subvolcanic porphyries with minor sedimentary breccias and conglomerates. Thin lenses of stromatolitic limestone occur locally. In the southern Sierra El Batamote subvolcanic rocks —El Batamote stock of Harrar (1989)— strongly resemble the subvolcanic porphyries of the backbone, and they are here interpreted as belonging to the El Charro volcanic complex (*cf.* Harrar, 1989).

### **Puerto El Alamo (Plate 1)**

The El Charro sequence in Puerto El Alamo is exposed in the northernmost part of the area. It consists of light gray to yellowish rhyolite, light greenish-gray to purplish andesite and dacite (Willard, 1988, p. 62). North of Puerto El Alamo, outside of Willard's study area, a massive rhyolitic breccia wedging out toward the east and west, is easily seen in aerial photographs and satellite images. Thickness of the El Charro in this area is at least 1.5 km.

### **Cerros El Puerto (Plate 2)**

The series of massive, generally unlayered, volcanic rocks ranging in composition from rhyolite(?) to andesite in the Cerros El Puerto is tentatively assigned to the El Charro volcanic complex (Plate 2). Sediments are conspicuously absent, except in Cerro

Los Apaches.

The rhyolite(?) is pink to grayish pink, but weathers brown and black. It is aphanitic to porphyritic, with plagioclase and probably sanidine phenocrysts. Characteristic of this unit are the ignimbrites with flow banding. In the northern part of the area, the flow banding is dipping about 50 degrees toward the northeast.

The andesite is dark gray to dark brown to red and green. It is porphyritic, with plagioclase in a fine grained matrix. The andesite may be volcanic (flows) or subvolcanic (intrusives). Clast in andesite breccia are formed by small lapilli and volcanic cobbles, mostly angular, in a matrix of the same composition. Toward the south the andesitic and rhyolitic rocks appear to be sub-volcanic forming tabular bodies intruding one into the other. It could not be established which one intruded the other. In some places the andesite has cavities filled with epidote, zeolites(?) or, more rarely, quartz. Hydrothermal alteration is widespread, but appears to be more intense toward the south, near the highway (Plate 2).

In the northwestern part of the area in a small hill named Cerro Los Apaches (Plate 2) a sequence of andesitic to rhyolitic rocks with intercalated sandstone is exposed. This sequence is assigned to the El Charro volcanic complex because of the presence of sediments and rhyolitic ignimbrites as well as the apparent structural continuity with the volcanic rocks to the south.

A stratigraphic section was measured in the southeastern part of the hills (Fig. 24). The base of the exposed sequence consists of 23 m of gray, porphyritic andesite. Phenocrysts of plagioclase and amphibole are present. It has vesicles filled with zeolites and quartz. Thin intercalations of ash tuff with quartz, plagioclase, epidote and unidentified mafic minerals are present, as well as red siltstone beds containing fragments of the andesite. The andesite is covered by 25 m of pink, thick bedded sandstone. Tangential cross-bedding is common. Cross-bedding indicates a paleoflow toward the south-southwest. The quartz-rich sandstone is coarse grained. The upper 7 m of this unit are finer grained and have intercalations of red, thinly bedded siltstone.

Capping the sequence is a pink (weathers ocher to brown and black) ignimbritic rhyolite(?). Small phenocrysts of plagioclase, sanidine? and amphibole are present.

### **Stratigraphic relationships**

In Sierra El Chanate the El Charro volcanic complex is separated from the Escalante Formation in an unconformity. The hiatus between the two units appears short: in the upper part of the Escalante Formation thin rhyolitic tuffs are remarkably similar to the thick rhyolitic tuffs in the basal El Charro volcanic complex. The thin tuffs may have been the prelude to the El Charro!

The El Charro volcanic complex was folded and then eroded before the San Jacinto andesite was deposited.

### **Age and correlation**

A  $^{40}\text{Ar}/^{39}\text{Ar}$  plateau age of  $71.6 \pm 0.7$  Ma (Fig. 26) of an amphibole separate was determined from a sample near the base of the El Charro volcanic complex (X=415730 and Y=3408800; Hoja Los Olivos; INEGI, 1980). It was determined by Margarita López-Martínez (CICESE) in the Geoscience Department, University of Alaska. This age places the base of the El Charro in the Maastrichtian (Palmer, 1983).

In Cerro de Oro (Castro and Morfín, 1988) and in the Moctezuma area (Roldán, pers. comm., 1991), central Sonora, volcano-sedimentary rocks of similar age have been reported. In these two localities these rocks overlie the Lower Cretaceous and are intruded by Laramide batholiths. Pubellier (1987) dated volcanic rocks ranging from  $74.6 \pm 3.7$  to  $52.9 \pm 2.6$  Ma in the Sahuaripa area, east central Sonora. These probably extend into central Sonora as the Tarahumara Formation. Grajales *et al.* (1990) reported the presence of volcanic and volcanoclastic sequences near Cabullona and Nácori Chico, and dated them radiometrically as latest Cretaceous and Paleocene. In southeastern Arizona, the Fort Crittenden is overlain by the Demetrie Volcanics and Salero Volcanics (Hayes and Drewes, 1978) and Muleshoe volcanics (Goodlin and Mark, 1987). Goodlin and Mark (1987) also report that the Cascabel Formation, a sequence of conglomerates, overlies the latest Cretaceous to Paleocene Muleshoe volcanics.

### **The San Jacinto andesite**

In the northwestern part of Sierra El Chanate the area is underlain by andesitic

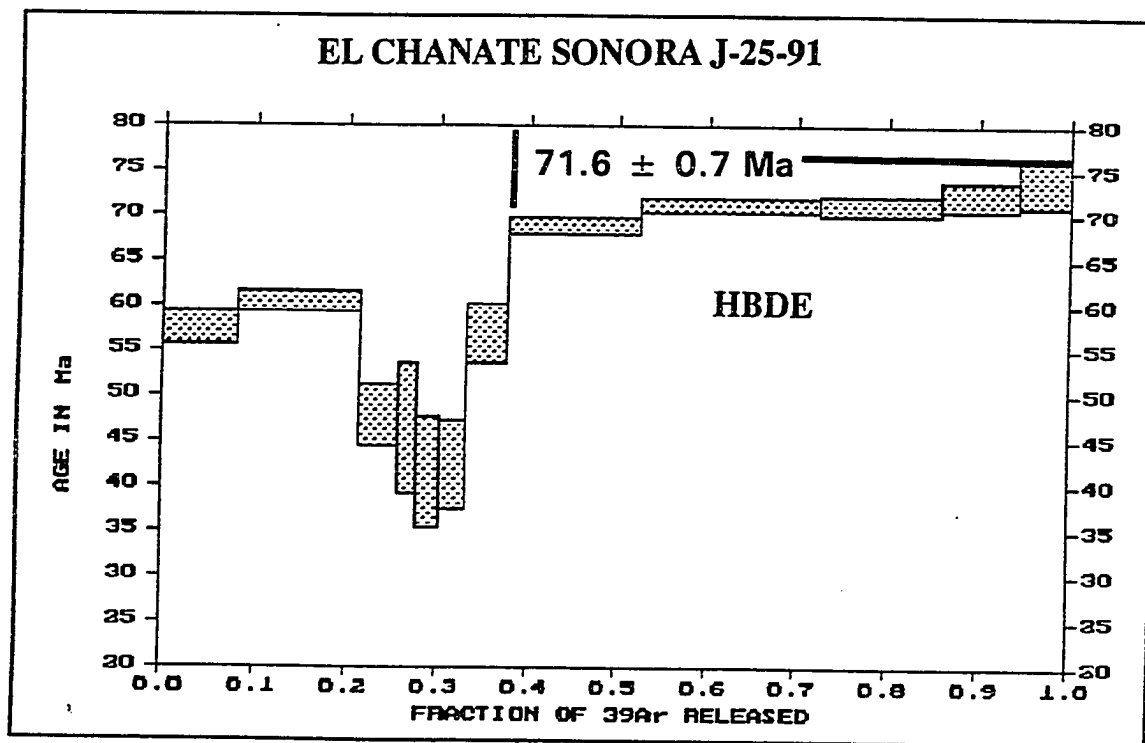


Figure 27  $\text{Ar}^{40}/\text{Ar}^{39}$  incremental release diagram for amphibole from the base of the El Charro volcanic complex.

volcanic rocks. They are here named San Jacinto andesite after the ranch of the same name located north of the exposure area (Plate 1). These volcanic rocks extend north and south of the western Arroyo El Charro (Plates 1).

The San Jacinto andesite consists of andesite flows and breccias and andesite porphyries that are probably of subvolcanic origin. Color varies from red to purplish red, to purplish gray, to greenish gray and olive green. No intercalated sediments were observed. Locally, in small outcrops along arroyos a strongly weathered granite to granodiorite is exposed; most likely a pre-San Jacinto intrusive.

The lower contact of the San Jacinto andesite was not observed. Its location was inferred after the radiometric determination had demonstrated the presence of volcanics that were definitely much younger than the volcanics of the El Charro volcanic complex. The lack of sediments in the San Jacinto contrast also with the relative abundance of

sediments in the El Charro. The lower contact is an angular unconformity separating sub-vertical beds below from  $\geq 10^\circ$  northwest-dipping beds above.

### Age and correlation

A sample collected from the San Jacinto andesite (X=410100 and Y=3413650; Hoja Los Olivos, INEGI, 1980) was dated (K/Ar) by Manuel Grajales of the Instituto Mexicano del Petr leo. The results are shown in Table 6. The virtually identical ages of feldspar phenocrysts and matrix suggest that the radiometric age represents the time of formation of the San Jacinto andesite.

<b>Table 6. K/Ar analysis and age of one sample of the San Jacinto andesite, Sierra El Chanate, NW Sonora.</b>				
Analyzed Mineral	% K	Mol $^{40}\text{Ar}^*/\text{g}$	% $^{40}\text{Ar}^*$	Age, Ma
Feldspar	1.21	$1.09\text{E}^{-10}$	49	$51 \pm 2$
Matrix	2.61	$2.31\text{E}^{-10}$	68	$50 \pm 3$

## EL BATAMOTE STRUCTURAL COMPLEX

El Batamote structural complex is the name given to a series of sedimentary and volcanic rocks which are deformed (foliated and stretched), locally metamorphosed, and generally of unknown or questionable age. The complex occurs in a northwest-southeast belt in northwest Sonora (Fig. 6), and its deformation was thought to be product of the Mojave-Sonora megashear (Anderson and Silver, 1979; Corona, 1979; Anderson *et al.*, 1992).

Rocks that can be included in the El Batamote structural complex occur in the study area and in neighboring areas (Fig. 6). In Sierra La Gloria Corona (1979, 1980) described a series of rocks ranging from undeformed to strongly stretched and foliated, supposedly of Middle Jurassic age. Nuñez and DeJong (in prep.) report on an ammonite (*Vermiceras* sp.) of Sinemurian age collected from a folded sequence in Sierra La Gloria. In Puerto El Alamo and Sierra El Batamote Willard (1988), Harrar (1989) and McComb (1987) described La Máquina, El Alamo and Los Olivos Formations of Jurassic(?) age.

El Batamote stock (Harrar, 1989) is a locally foliated andesitic rock similar to some rock types in El Charro volcanic complex, and probably of the same age. García (in Jacques *et al.*, 1990b; 1992) observed that the Altar Formation in the Cerros El Amol overlies the El Chanate Group, and is therefore of Late Cretaceous age. The upper part of the Altar is strongly foliated, stretched and metamorphosed, and was named Altar Schist by Damon *et al.* (1962).

In Cerro Carnero Hayama *et al.* (1984) mapped a sedimentary sequence which includes green schist and unmetamorphosed sandstone and conglomerate. Metamorphism diminishes toward the northeast and the age is unknown. Rare volcanic clasts in the conglomerates of the Cerro Carnero exclude, however, a Paleozoic or Proterozoic age. In northern Cerro Prieto DeJong (pers. comm., 1993) mapped a strongly deformed Mesozoic sequence overthrust by Proterozoic rocks. Further east, the El Batamote structural complex occurs in Cerro El Molino, northeast of Trincheras (R. Padilla, pers. comm., 1991) where it appears to be overthrust by Proterozoic limestone (Plates 3 and

8) (PEMEX, 1987), and perhaps also west of Estación Llano as the Coyotillo Group (Herrera and Pérez, 1990; Calmus *et al.*, 1992). This group, overthrust by Proterozoic metamorphic rocks (Pérez and Cheilletz, 1992), is a metamorphosed clastic sequence very similar to the Altar Formation in Cerros El Amol (García, pers. comm., 1990). The Gauna rhyolite in fault contact with the Proterozoic is considered as Late Cretaceous-Eocene by Herrera and Pérez (1990) and as Jurassic by Calmus *et al.* (1992). In the author's opinion, the Coyotillo Group belongs to the El Batamote structural complex on the basis of its lithology and metamorphism.

Jacques (1983) interpreted the El Batamote structural complex (naming it El Batamote formation) as the basement upon which the Bisbee Group was deposited, therefore tacitly accepting the Jurassic age of deformation proposed by Anderson and Silver (1979). Subsequent studies by Harrar (1989), García (*in* Jacques *et al.*, 1990b; 1992) and the author led to the conclusion that the deformed sequence was, at least in part, younger than Jurassic.

### **Lithology**

The El Batamote structural complex consists mainly of clastic sediments (from shale to boulder conglomerate) and igneous rocks.

Conglomerates in the southern part of Cerro Alamo, southern Sierra El Batamote, Cerros El Amol and Cerro Carnero form ridges and make the mountain tops. The conglomerates are lenticular and vary in thickness from about 100 m (as in Cerros El Amol, García, 1992) to just a few meters. Clast size ranges from pebbles to boulders up to 1 m in length.

Clast composition varies from bed to bed, and even within a bed (García, 1992). The most widely distributed clasts are those of quartz sandstone followed by volcanic rocks (andesite, rhyolitic ignimbrite and quartz porphyry) in variable amounts. Granite, metamorphic rock and carbonate rock clasts are rare.

The conglomerates display different degrees of deformation. In Sierra El Batamote the clasts can be undeformed (Harrar, 1989) or stretched into pancake or cigar shapes (McComb, 1987). The same occurs in Cerros El Amol (García, 1992), and in the Puerto

El Alamo area (Willard, 1988). Clast deformation varies: undeformed volcanic clasts and undeformed quartz-sandstone clasts; deformed volcanic clasts and undeformed quartz-sandstone clasts, and strong deformation of volcanic clasts and minor deformation of quartz-sandstone clasts (pressure shadows and tension fractures). In the low hills in and near Altar the upper part of the El Amol member of the Altar Formation (García, 1992) has been metamorphosed to green schist facies (Altar Schist of Damon *et al.*, 1962). Metamorphic rocks extend south into Cerro El Carnero (Hayama *et al.*, 1984).

Sandstone is abundant throughout the unit. Colors range from brown, red, green, gray and purple, and grain size varies from coarse and pebbly to fine grained. Bedding can be very thick or thin, and is generally without sedimentary structures, although cross-bedding is locally observed. In the field, sandstone does not display deformation as clearly as the conglomerate. Deformation is, however, obvious in thin section. In many places foliation can be observed in outcrop, especially where the sandstone is intercalated with shale.

Siltstone and shale are also abundant. They are green to red to gray and purple, foliation is strongly developed, and a sheen due to sericitization is common.

Limestone lenses in the sandstones of the El Batamote structural complex are gray to dark gray but weather brown to yellowish brown. They are sandy, unfossiliferous, and laminated; probably stromatolitic limestones. Thickness of the lenses is generally a few decimeters, but they can be 1 or 2 m thick. They are most abundant in the southern Cerros El Amol, in the Cerro Carnero, and in Puerto El Alamo. They also occur in Estación Llano (García, pers. comm., 1990). Corona's (1979, 1980) Basura marble (a black, thinly laminated metamorphosed limestone several meters thick in the western Sierra La Gloria) is here considered as part of the El Batamote structural complex.

Black silicified fragments of wood are common in the El Batamote structural complex. Willard (1988) reports the presence of wood fragments within the deformed sequence. Silicified fossil wood is also common in the Bisbee and El Chanate Groups. In the Bisbee they have been collected by the author from the Arroyo Sásabe Formation in Cerros Cabeza Colgada, Cerro La Pima and east of Santa Ana, and from the Cintura Formation in the Cabullona area. González (pers. comm., 1992) collected fossil wood

from the Mural Limestone in Cerro de Oro. Fossil wood is also present in the El Chanate Group in Puerto El Alamo (Willard, 1988) and in Sierra El Chanate (Jacques, 1983).

Igneous rocks in the El Batamote structural complex are common in the southern flank of Sierra El Batamote but practically absent in Puerto El Alamo and Cerros El Amol, and toward the east. The backbone of the Sierra El Batamote is formed by extrusive and subvolcanic rocks of the El Charro volcanic complex. South of the backbone are intrusives (El Batamote stock of Harrar, 1989) that are lithologically very similar to those in the El Charro volcanic complex.

The boundary between the Batamote structural complex and the El Charro volcanic complex and other Cretaceous rocks, is transitional over a wide zone. Foliation diminishes gradually toward the north, so the boundary is placed where the foliation becomes less common. The boundary has been mapped as a thrust fault (Plates 1 and 6) (Jacques, 1983; Willard, 1988; Harrar, 1989) but the main thrust is probably covered by the valley fill to the south. The boundary shown in Plate 1 and 6 as a thrust fault is not a discrete fault plane but the transition boundary of foliation interpreted as caused by thrusting.

Green schists occur near Altar (Damon *et al.*, 1962; Hayama *et al.*, 1984) in what García (1992) named the El Amol, Los Corrales and La Bateyera members of the Altar Formation. Green schists are also reported in Sierra El Batamote (Harrar, 1989), in Puerto El Alamo (Willard, 1988), in Sierra La Gloria (stretched pebble conglomerate, Corona, 1979, 1980), and in Estación Llano (Coyotillo Group, Herrera and Pérez, 1990; Calmus *et al.*, 1992).

Hayama *et al.* (1984) studied the metamorphic facies of the Altar Schist in Cerro Carnero and Cerros La Bateyera, south and east of Altar. The highest metamorphic grade is in southwestern El Carnero, where it reaches green schist facies, and diminishes towards the north and northeast. García (1992) found that metamorphism continued to decrease towards the north into stratigraphically older and structurally lower formations that are not metamorphosed: the metamorphic gradient is thus inverted. Inverse gradient metamorphism is also observed in Sierra El Batamote (Harrar, 1989) and Puerto El

Alamo (Willard, 1988).

### **Age and correlation**

The undated sedimentary formations of the El Batamote structural complex are assumed to belong, at least in part, to the Upper Cretaceous El Chanate Group. They do not resemble the Upper Jurassic formations of Pozo Serna (Beauvais and Stump, 1976) or Cucurpe (Rangin, 1977a; Rodríguez, 1988) as these consist of finer grained marine rocks; they are unlike the Bisbee Group which is easily recognized on the basis of its color, fine grained clastics, and the volcanic rock fragments of the Glance. The El Chanate Group includes quartz-sandstone and volcanic clast conglomerates, thin lenses of stromatolitic limestone, and fossil wood; all features of the El Batamote structural complex. In addition, the El Chanate Group of Puerto El Alamo and Sierra El Chanate is petrographically similar to the El Alamo and La Máquina Formations of Willard (1988), here included as the El Batamote structural complex.

The undated sedimentary and volcanic rocks of the El Batamote structural complex may also belong to the Middle Jurassic Artesa sequence (Tosdal *et al.*, 1989). This sequence consists of conglomerates and sandstones with intercalated volcanics, and is widely exposed in south-central Arizona. Tosdal *et al.* (1989, Fig. 5) extend the presence of the Artesa into the Caborca - Santa Ana area. The age assignment of the Artesa is based on its stratigraphic position beneath the Glance, its composition and degree of deformation.

### **Discussion**

Stretched, foliated and metamorphosed rocks similar to those described above occur farther to the northwest: near Estación Sahuaro (Calmus, 1993), Quitovac (Connors *et al.*, 1989; Caudillo and Oviedo, 1990), La Choya (A. Reyna, pers. comm., 1989), and Tajitos (Pérez, E., pers. comm., 1990). They probably extend to the east, occurring in the Rancho La Lámina area south of Magdalena (Stephens, 1987), and the Tuape area (Rodríguez, 1988).

Stretched and foliated rocks, however, do also occur outside of the belt of the El

Batamote structural complex: e.g., near Cerro Colorado northeast of Cerros El Amol, in Sierra de Magdalena (Nourse, 1989) and Sierra Las Jarillas (Morales, 1984).

The age of this belt is uncertain. Anderson and Silver (1979), Corona (1979, 1980) and Anderson and Schmidt (1983) assigned it to the Late Jurassic as a result of strike-slip faulting along the Mojave-Sonora megashear. As shown above, some definite age assignments of the El Batamote structural complex are now possible, not only to the Jurassic but also to the Late Cretaceous. The absence of angular unconformities other than the post-Laramide unconformity in the clastic upper Mesozoic sequence of the Caborca-Santa Ana area suggest strongly that the major deformation of the El Batamote structural complex occurred in Laramide time.

## STRUCTURAL GEOLOGY

The Cretaceous rocks in the study area have been deformed by different processes: thrusting, folding, stretching, metamorphism and normal faulting. This complex history of deformations has made the understanding of the stratigraphy and structural geology rather difficult. As the purpose of this work is mainly stratigraphic and sedimentologic, only a general overview of the tectonic structures will be presented in this chapter.

### Thrust faults

A major thrust fault is thought to be present south of the Puerto El Alamo and Sierra El Batamote area ((Willard, 1988; McComb, 1987; Harrar, 1989). The lower plate consists of the Bisbee and El Chanate Groups, El Charro volcanic complex and El Batamote structural complex (Plate 6) which includes rocks from the underlying units. Southwest dipping thrust faults are common (McComb, 1987; Harrar, 1989). The upper plate is thought to be the Caborca terrane. In the Sierra El Batamote-Sierra El Chanate area the superposition of the Caborca terrane is not observed. Its (hidden) presence is based on the superposition of Proterozoic sedimentary sequences upon rocks of the El Batamote structural complex in Cerro Prieto (Fig. 6; DeJong, pers. comm., 1989). This 10-20° southwest dipping fault is a thrust fault rejuvenated as a normal fault in the Miocene (DeJong and Jacques, 1986). Cerro Prieto is the only locality where the tectonic superposition of the Caborca terrane upon the El Batamote structural complex can be observed in the field.

A similar superposition, Proterozoic upon the El Batamote structural complex, is inferred in an area north of Trincheras (Fig. 6). Here, Cerro Arituaba is underlain by Late Proterozoic dolomite and limestone and toward the east Cerro El Molino is underlain by the El Batamote complex (R. Padilla, pers. comm., 1991). PEMEX (1987) interpreted the Arituaba rocks as thrust upon the Cerro El Molino.

West of Benjamin Hill, in the northern reaches of the Cerro Mayo is the Cerro Picacho. In this area several Proterozoic to Cambrian(?) units were thrust upon Upper

Cretaceous sandstone and conglomerate (Fig. 28). The thrust fault was subsequently folded.

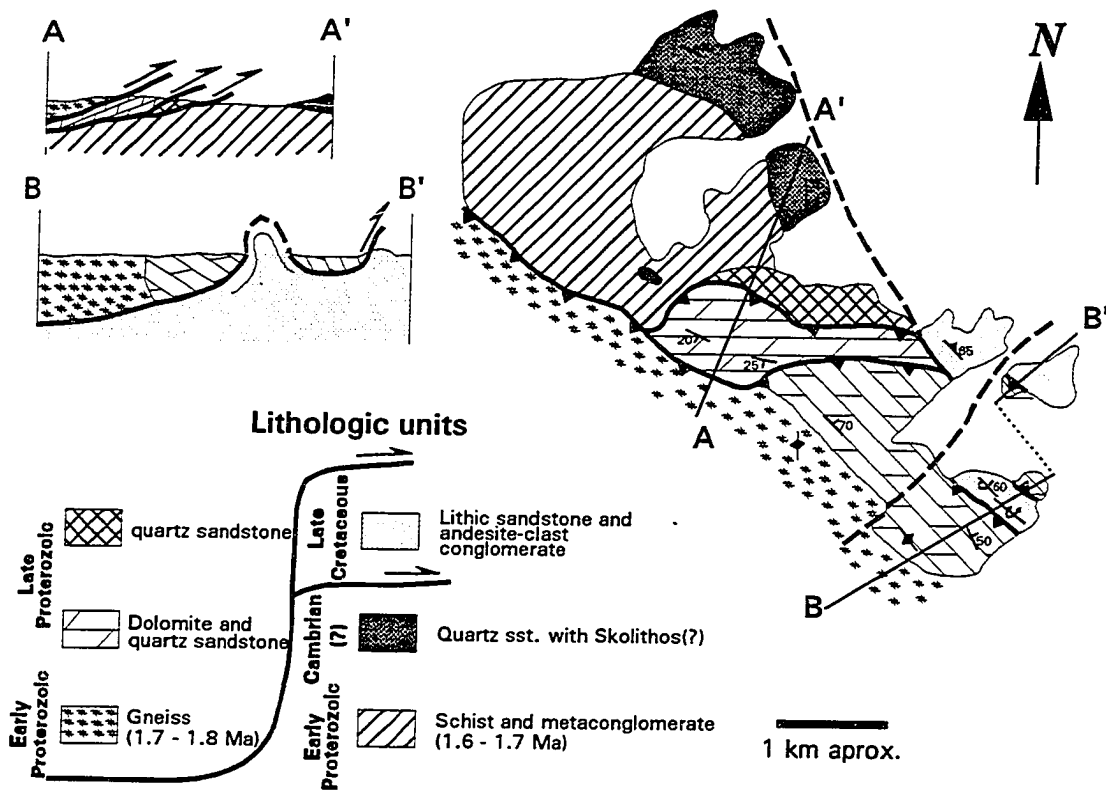
Thrust faults have been reported in several localities near the study areas. In Sierra La Víbora DeJong et al. (1988) document a thrust fault emplacing Proterozoic-Paleozoic rocks upon Mesozoic sandstones. The thrusting is older than the 80 Ma Pitiquito granodiorite which cuts through the thrust plane, and younger than the clastics that yielded Cretaceous fossils about 10 km to the south (Keller, 1928). The eastward thrusting in Sierra La Víbora is thought to be caused by the Bámori (mid-Cretaceous) phase of the Cordilleran orogeny. During the Laramide phase the Caborca terrane with its Bámori structures was thrust northeastward.

In the Rancho La Lámina, east of Santa Ana (Fig. 6), a Proterozoic gneiss has been thrust upon a sequence assigned by Stephens (1987) to the Jurassic. The similarities between Stephen's "Jurassic" sequence and the Bisbee Group are remarkable indeed, and according to the present author this unit is part of the Bisbee, with thrusting during the Cretaceous or Paleocene.

### Folds

The Cretaceous units are folded in large scale folds trending generally in a northwest to southeast direction. This trend is different in Santa Ana and Cerro La Pima perhaps because of block rotation caused by strike-slip faulting. The vergency of the folds is to the southwest in Sierra El Chanate (Plates 1 and 6), Cerros El Puerto (Plates 2 and 7), Cerros El Amol (García, 1992), and east of Santa Ana (Plate 5) and to the north-northeast in northern part of Cerros Cabeza Colgada (Plate 3 and 8) and Cerro La Pima (Plate 4). Folds are upright in Puerto El Alamo (Plates 1 and 6) and Cerros Cabeza Colgada (Plates 3 and 8). All large-scale folds in the study areas are synclines with the exception of two anticlines in the Santa Ana area.

Along the valley between Sierra El Chanate and Sierra El Batamote an anticline could also be present, but the core of this hypothetical fold was cut by numerous faults making it difficult to identify with certainty. The southern limb of this anticline would be the northern slope of Sierra El Batamote. In Puerto El Alamo the Bisbee and El



**Figure 28** Preliminary geological map of the Cerro Picacho area, west of Benjamin Hill. Location in Fig. 6.

Chanate Groups form the southern limb of an anticline (Plate 1) cut by a fault that places the Bisbee against the El Charro volcanic complex.

The Santa Ana area is characterized by folds with east-west and north-northwest-

south-southeast trends (Plate 5). The San Luis syncline (Plate 5) appears to be the continuation of El Durazno syncline. The two folds are thought to have been a straight east-west(?) fold subsequently folded around a vertical axis (Plate 5). The folds south of the El Durazno syncline were folded similarly. The folding may be actually the result of a counterclockwise rotation of at least 90° of a faultblock between two northwest-southeast oriented strike-slip faults.

### **Normal faults**

The Caborca-Santa Ana area is located within the Basin and Range province. Physiographically, the region consists of ranges with wide valleys. Active faults are absent, and faults bordering the ranges are not exposed. A normal fault within a range is the El Chanate fault. The fault zone, in which the rocks have been deformed and hydrothermally altered, extends more than 6 km along the southern limb of the El Chanate syncline (Plate 1). Toward the east, the fault zone apparently disappears in Cretaceous formations. Extensive fracturing suggests that the fault continues but the trace cannot be followed. The width of the El Chanate fault zone varies between about 50 m to almost 400 m. The widest area lies in the western half of the fault, between the El Batamote and El Chanate ranges, perhaps because it coalesces with other faults.

The El Chanate fault zone cuts through the base of the Morita Formation in the northern block and places it against a sequence of steeply dipping andesitic breccias, conglomerates and sandstones. In the area east of the Arroyo El Charro these are part of the El Charro volcanic complex. In the area to the west, the Morita is placed against the Escalante Formation. In both cases, the younger rocks are on the southern block, which suggests that the down-thrown block is the southern one. The presence of a Tertiary alluvial fan north of the El Batamote Mine could support such an interpretation. However, the fault plane, as well as many secondary faults, dip toward the north with the northern block moving down. This suggests that the Sierra El Chanate block has moved down relative to the Sierra El Batamote. This type of displacement is more likely because it juxtaposes the less deformed rocks in the Sierra El Chanate with the more deformed rocks in the Sierra El Batamote. Paleomagnetic work done by Harrar (1989)

suggests that the Sierra El Chanate rotated 22 degrees to the north along a horizontal axis parallel to the El Chanate fault.

The amount of displacement along the El Chanate fault is unknown. It is assumed to be in the order of hundreds of meters on the basis of the width of the fault zone. Deformation of the rocks in the Sierra El Batamote indicates that they were deformed at a deeper level than that of the rocks now exposed in the Sierra El Chanate. Juxtaposition of the rocks in the two sierras most likely occurred as the result of normal faults with the Sierra El Chanate rocks in the downthrown block.

In the northern part of the Puerto El Alamo area Willard (1988) mapped a high angle normal fault trending in a northwest direction (Plate 1). It cuts through the base of the Bisbee Group placing it against the El Charro volcanic complex. This fault could be part of, or a strand of the El Chanate fault. The amount of displacement is unknown, but it could be in the order of at least 1 km.

The Cerros El Puerto are cut by the Oquitoa fault trending in a north-northwest direction (Plate 3). The fault dips steeply toward the east-northeast with a narrow fault zone. It extends across the whole mountain, placing the El Chanate Group against the El Charro volcanic complex. The amount of displacement is unknown.

The Altar River fault (Plate 2) is a normal fault or a strike slip fault. This hypothetical fault explains the offset between the Cretaceous formation boundaries on the southern margin of the river (northwestern Cerros El Amol) and those in the Cerros El Puerto.

Low-angle faults have been observed in several of the studied areas. In the south-central part of the Sierra El Chanate the practically undeformed El Charro volcanic complex overlies subhorizontally a foliated red mudstone, probably the Morita Formation. An exposure in the Arroyo El Charro shows that foliation and minor fault planes dip toward the south.

In the southern part of the Cerro La Pima area a block of thick bedded Mural Limestone is placed against the lower Morita Formation (Plate 4). The northern part of this block is a thick vertical limestone ledge trending east west and the southern part dips about 20 to 30 degrees southward. These blocks are interpreted as a disarticulated

anticline in the hanging wall of a low-angle normal fault.

Several normal faults dipping less than  $45^\circ$  are exposed along the road and stream cuts south of Santa Ana. Some strike  $N45^\circ W$  dipping toward the northeast. Others strike  $N45^\circ E$ , and dip either to the northwest or to the southeast. These normal faults indicate extension in an east-west direction. Colletta and Angelier (1983) documented similarly oriented low-angle normal faults in the Tubutama area.

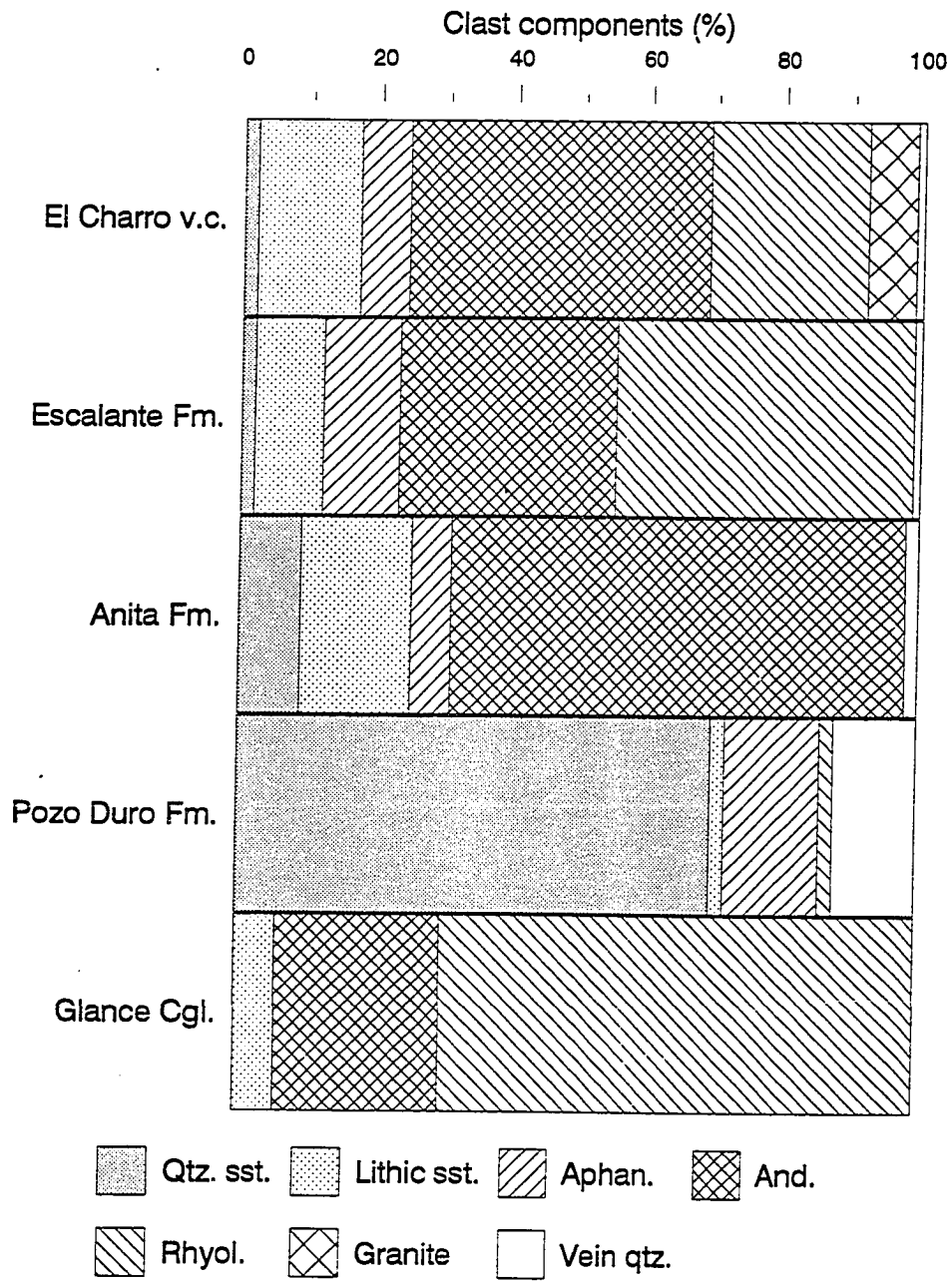
## PETROLOGY AND PROVENANCE OF THE CRETACEOUS IN THE CABORCA - SANTA ANA AREA

### **Conglomerate composition**

The sandstones and conglomerates of the Cretaceous Bisbee and El Chanate Groups give excellent information about the geology during the time of deposition. The Glance Conglomerate, the oldest unit of the Early Cretaceous Bisbee Group, is exposed in a few areas only, with clasts derived largely from rhyolitic rocks (Fig. 29). These rhyolites were most probably part of the Middle Jurassic volcanic arc that is extensively exposed in north-central Sonora and south-central Arizona. The westernmost exposure of the Glance is in Puerto El Alamo, but it is very well possible that some of the not yet dated conglomerates of the Sierra La Gloria could be part of the Glance. The Bisbee sediments entered the basin in the Caborca-Santa Ana area from the north and from the southwest (Fig. 34).

Clast composition in the conglomerates of the Late Cretaceous El Chanate Group changes from mostly quartz sandstone in the Pozo Duro Formation to mostly andesite in the Anita Formation, and rhyolite and andesite in the Escalante Formation. Andesite and other volcanic rocks, sandstone and granite constitute the clasts of the El Charro volcanic complex (Fig. 29).

The clasts in the conglomerates in the Pozo Duro Formation are mostly derived from a sequence consisting predominantly of quartz sandstone located south of the study area (Fig. 35). The most likely source is the Jurassic arc, or the Fresnal Sequence of Tosdal *et al.* (1989), which includes eolian quartz sandstones (Busby-Spera, 1988; Riggs, 1987a; Nourse, 1989; Tosdal *et al.*, 1989) and rounded quartz-sandstone pebbles (Tosdal *et al.*, 1989). This source explains the mixture of quartz-sandstone pebbles and rhyolitic sand-sized sediment. It would also explain the scarcity of quartz-sandstone pebbles in the sequence. The Caborca terrane is ruled out as the source because of the virtual absence of carbonate as well as metamorphic fragments, quite abundant in this terrane. The Alisitos arc is also excluded mainly because it consists of basic and intermediate volcanic rocks, and minor rhyolites (Gastil and Krummenacher, 1974; Rangin, 1982). The input



**Figure 29** Bar graph depicting clast composition in the conglomerates of the Bisbee and El Chanate Groups and El Charro volcanic complex, Sierra El Chanate.

of volcanic rock fragments during the Pozo Duro time was minor.

During Anita time the source of the clasts were nearby volcanoes. Quartz-sandstone pebbles continued to be brought into the basin, but much less than previously.

The Escalante Formation shows an increase in clasts derived from a rhyolitic source, probably from Jurassic rhyolites to the north. Local input from andesitic volcanoes continued and, by this time, the input of quartz-sandstone fragments had become negligible.

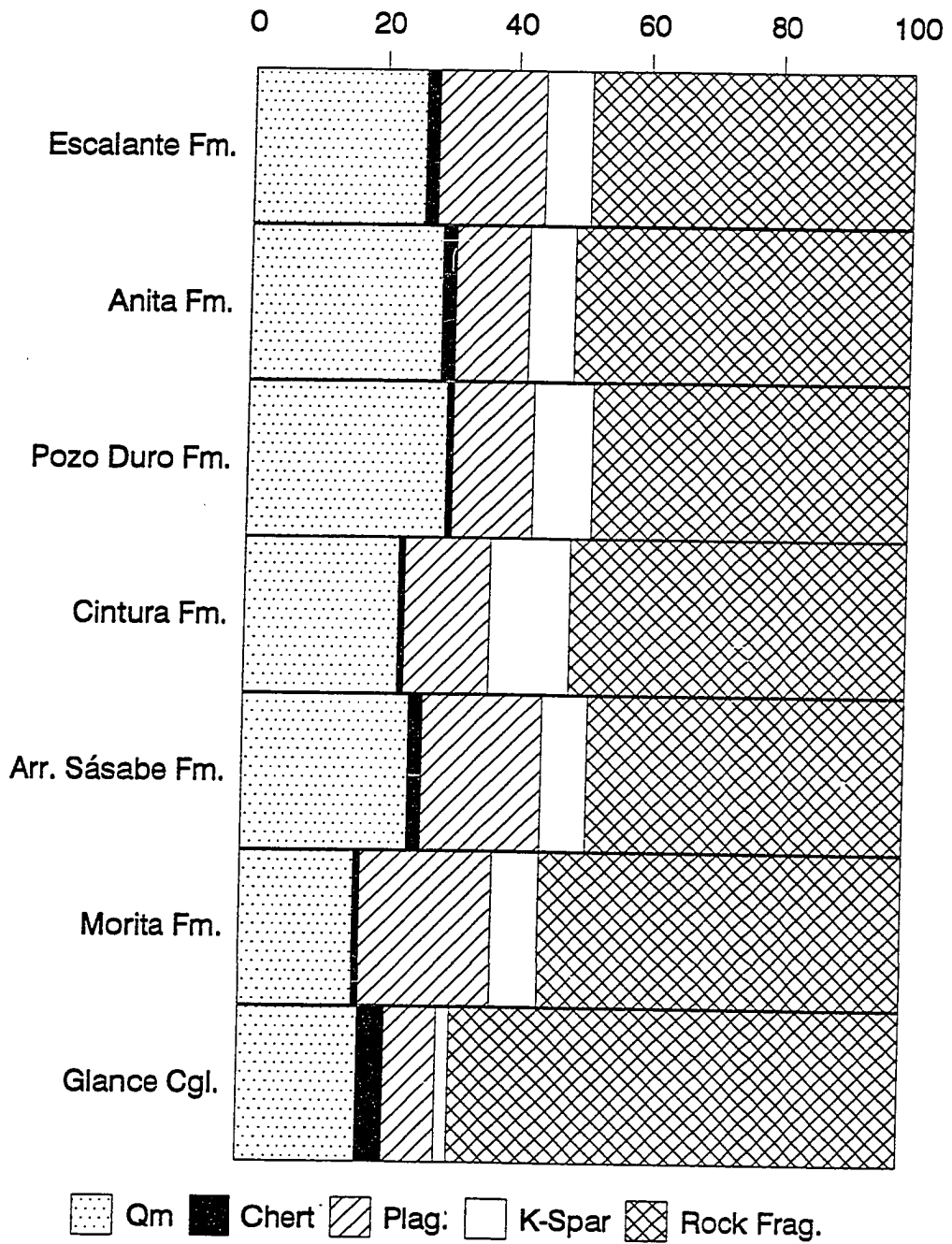
Volcanoes during El Charro time, like in Anita time, provided sediments into a local basin that continued to receive detritus from Jurassic rhyolitic rocks. Granite clasts are for the first time present in the sequence; they may have been derived from the roots of the Jurassic arc, or from Late Cretaceous intrusives such as the 80 Ma Pitiquito granodiorite (DeJong *et al.*, 1988).

Conglomerate clasts record an almost continuous input of volcanic rock fragments throughout the Cretaceous. Only during Pozo Duro time, in which an uplift documented by an erosional unconformity is recorded, clasts were derived from a probable "cratonic" source located south of the Pozo Duro basin (Fig. 19). Remarkable is that the source was short-lived because clast composition in the Anita and in particular in the Escalante formation closely resemble that of the Glance Conglomerate, without abundant quartz-sandstone clasts.

### **Sandstone composition**

Sandstones from the Glance Conglomerate in Puerto El Alamo consist mainly of rock fragments (Fig. 30). Monocrystalline quartz is less than 20 percent, and K-spar and plagioclase are minor. In Sierra El Chanate the sandstones of the Bisbee Group are also lithic arenites; rock fragments constitute about 50 percent of the rock. Monocrystalline quartz is always less than 20 percent, but plagioclase and K-spar content increases relative to the Glance. In the El Chanate Group the lithic fraction is also about 50 percent.

Of the lithic components (Fig. 31), the volcanic component is by far the most abundant throughout the sequence. In the Pozo Duro Formation polycrystalline quartz



**Figure 30** Bar graph showing sandstone composition variations through time in the Bisbee and El Chanate Groups of the Sierra El Chanate.

increases, but the volcanic fraction continues to be predominant.

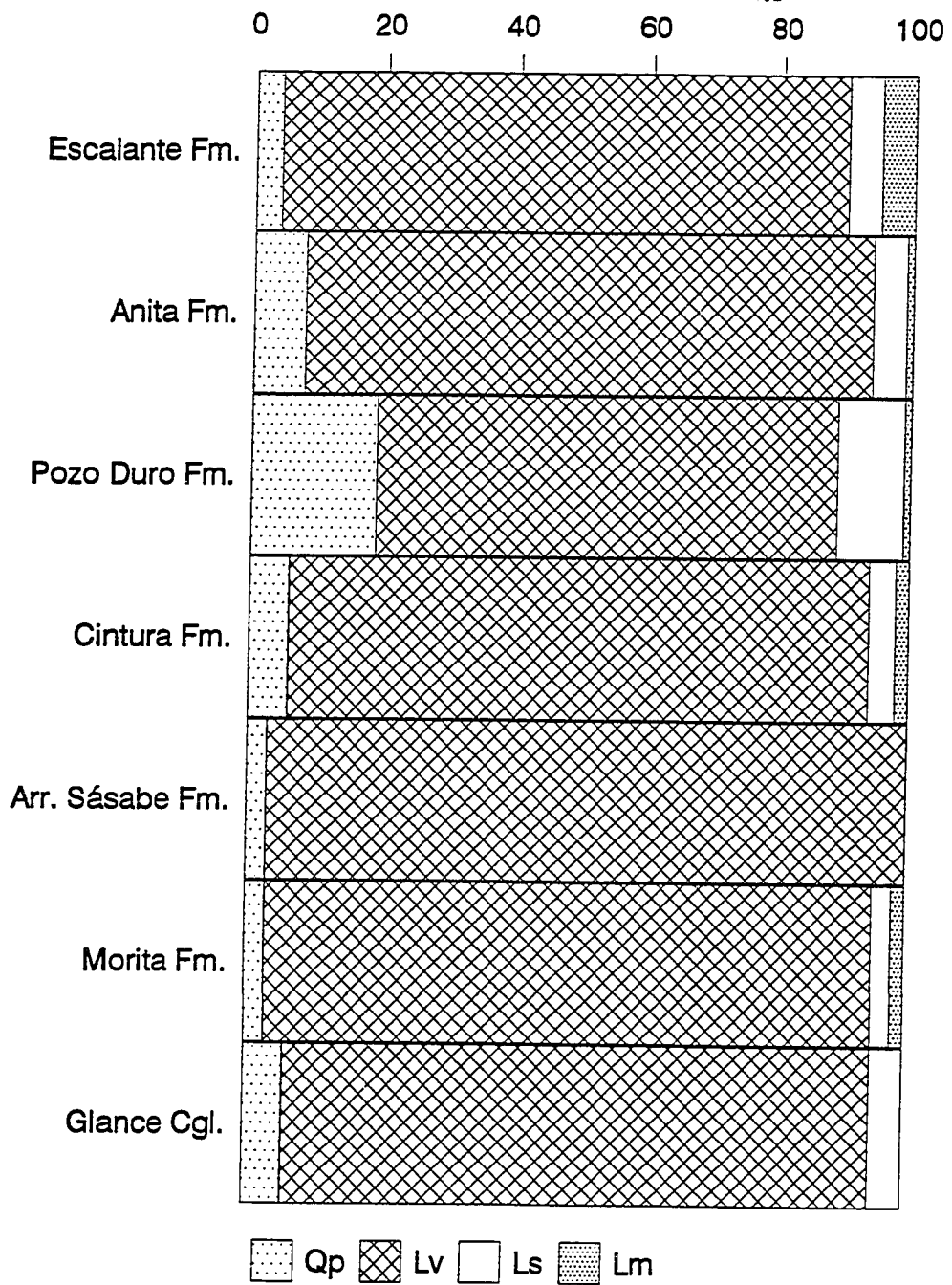
The graph of aphanitic rock fragments (Fig. 32) shows that fragments with microgranular (felsic rocks, including rhyolite) and microlithic (andesitic rocks) textures constitute more than 80 percent throughout the section. Aphanitic rock fragments with lathwork texture (basaltic rocks) are minor, as well as the other types of fine-textured fragments.

Throughout the deposition of Cretaceous rocks (Bisbee and El Chanate Groups) in Sierra El Chanate (this work) and Puerto El Alamo (Willard, 1988), the main source of sediments was a rhyolitic volcanic arc. Sandstones from the Bisbee Group in Cerros Cabeza Colgada and Cerros La Pima indicate the same source type (Figs. 14 and 15). McKee (1991) reports that the sandstones in the Cretaceous of the Cerro Azul area are also derived mostly from felsic rocks.

The Altar Formation (García, 1992) is petrographically different. It tends to be quartz-rich and feldspar-rich and not as rich in volcanic fragments as the El Chanate Group.

In southeastern Arizona the sandstones of the Bisbee Group were derived mainly from a cratonic source. In a QFL diagram most sandstones plot near the Q pole according to Archibald (1987), Jamison (1987), Klute (1987, 1991) and Inman (1987). However, these same workers found intercalations of volcanically derived sandstones. For example, Jamison (1987) studying the Morita Formation in southeastern Arizona and northeastern Sonora found a volcanic sandstone of about 70 m thick. Most of the volcanically derived intercalations occur toward the west where the Jurassic volcanic arc was exposed. Farther east, discrete beds of volcanically derived sediments also occur; they are interpreted as derived from uplifted Jurassic basement (Jamison, 1987; Klute, 1987, 1991). Rangin (1982) and Rosales *et al.* (in prep.) report the occurrence of tuffs in the Morita Formation.

The sandstones of the Fort Crittenden Formation in southeastern Arizona are dispersed in a QFL diagram, and tend to be more lithic-rich than those of the Bisbee Group (Inman, 1987; Hayes, 1987). According to Lindberg (1987) the Fort Crittenden contains mostly felsic volcanic fragments.



**Figure 31** Bar graph showing variations in composition of the lithic fraction in the Bisbee and El Chanate Groups, Sierra El Chanate.

The tectonic significance of the composition of the clastic rocks of the Bisbee is twofold. First, it suggests that the west-to-east passage of volcanic-to-cratonic sources is transitional and not localized by faults, as has been proposed by Pubellier (1987). Second, the source of the sediments was cratonic in the northeastern margin of the basin and volcanic in the western and southwestern margin. This implies that during Bisbee time the Caborca terrane, now present south of Caborca, was not a source, thus suggesting that the Mojave-Sonora megashear, if it existed, was located farther south.

Tectonically, the Upper Cretaceous in Sonora and southern Arizona has been considered a synorogenic deposit. Grain size, thickness variations in the sequence and apparent geometry of the basins support such an interpretation. But detailed stratigraphic field study as well as sandstone petrography of the El Chanate Group clearly show the continuing presence of a volcanic arc.

During early Pozo Duro time the conglomerates evidence a southerly source consisting of quartz sandstone and sand-size fraction consisting mostly of rhyolitic volcanic rocks. This source was most likely the Jurassic volcanic arc, which includes both types of rocks. This suggests that during the early Late Cretaceous the Jurassic arc extended to the area south of the study area. The predominance of rhyolitic rock fragments in the sandstone precludes the Alisitos volcanic arc as a possible source, and the virtual absence of sediments derived from carbonate and metamorphic rocks excludes also the Caborca terrane as a possible source.

Another possible sediment source of the Pozo Duro Formation could have been the uplift of a cratonic sequence as a result of thrusting or folding (Rangin, 1977, 1982; Pubellier, 1987; Pubellier and Rangin, 1988; DeJong *et al.*, 1988; Sosson and Calmus, 1990; Sosson *et al.*, 1990; Sosson, 1993; Minjárez, 1991). If the cratonic source would have overthrust the Jurassic arc a gravel fraction derived from the upper plate was followed by the volcanic sand fraction after erosion of the upper plate.

The main source of El Chanate sediments was a volcanic terrain, thus suggesting that the Caborca terrane arrived into the area after El Chanate time.

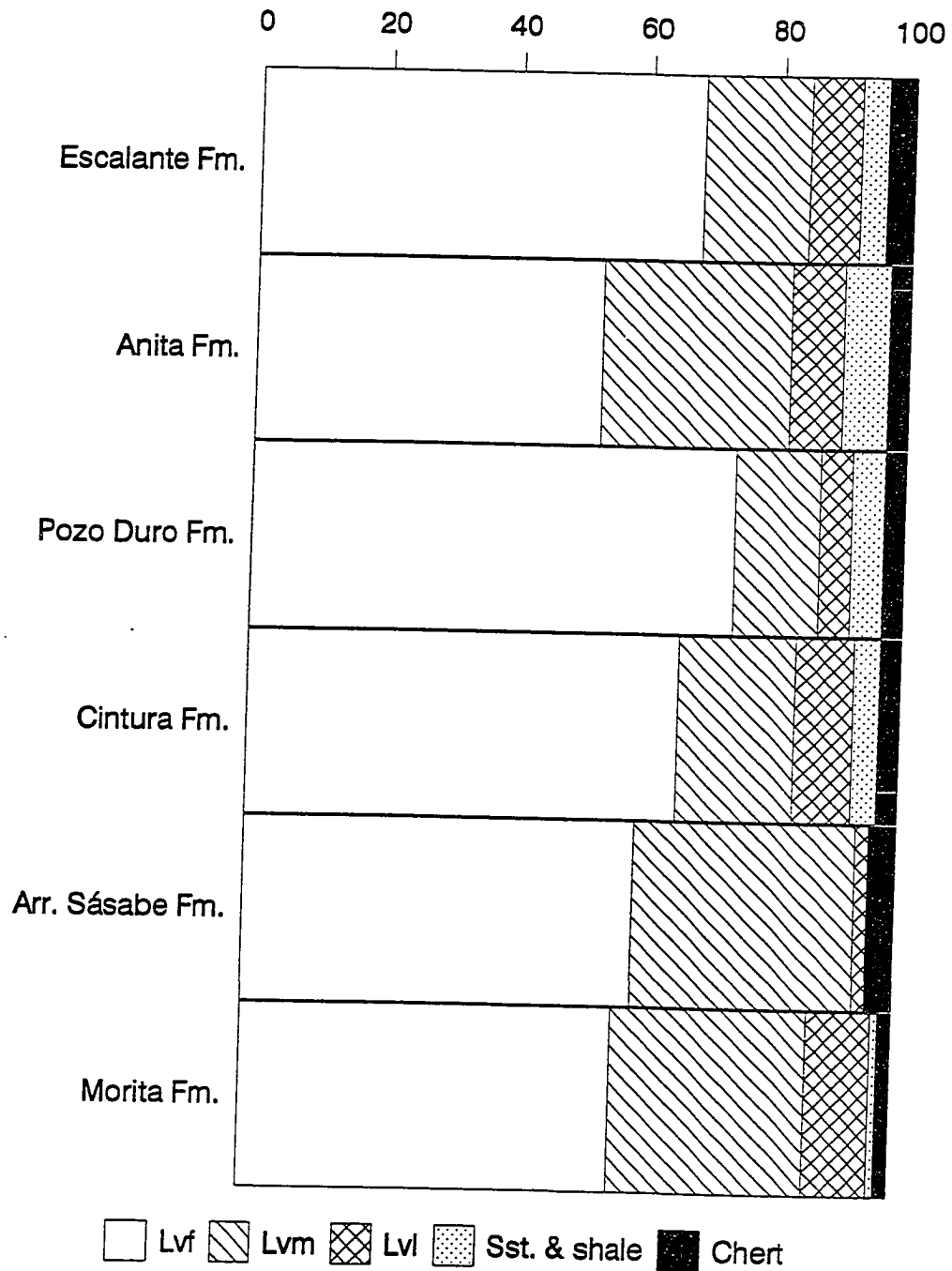


Figure 32 Bar graph of the aphanitic lithic fraction of the Bisbee and El Chanate Groups, Sierra El Chanate.

## TECTONIC SETTING AND PALEOGEOGRAPHY

### Tectonic setting of the Bisbee basin

Two major tectonic and paleogeographic domains have been proposed for the Mesozoic of México: the Tethys domain to the east, and the Cordilleran domain to the west (Aubouin *et al.*, 1977). Trailing edge or Atlantic type domains, such as the Tethys, are characterized by extensive carbonate platforms and deep basins. In eastern México sedimentation evolved from extensive marginal and evaporitic deposits (Late Jurassic) to carbonate platforms and deep basins (Early Cretaceous) to foreland basin deposits (Late Cretaceous-early Tertiary) (Tardy and Maury, 1973; Tardy, 1980; Enos, 1983; Padilla, 1986, among others). The Cordilleran domain is characterized by a convergent margin with active volcanic arcs along the western coast of the North American plate during the Jurassic, Cretaceous and Tertiary (Dickinson, 1981, among others). Arc-related rocks have been reported in western México as far south as Guerrero.

During Early and Middle Jurassic along the western coast of North America, from Alaska to México, a volcanic arc formed upon continental crust (Anderson and Silver, 1978; Haxel *et al.*, 1984). This arc has been well documented in south-central Arizona (Tosdal *et al.*, 1989; Busby-Spera, 1988), northern Sonora (Seegerstrom, 1987), and north-central and central México (Damon *et al.*, 1984; Grajales *et al.*, 1992).

In the Late Jurassic-Early Cretaceous the Alisitos arc (Fig.36) developed on the western side of the previous arc in Baja California (Busby-Spera and Boles, 1986) and in west-central Sonora (Gastil and Krummenacher, 1977). The back arc region of the Alisitos arc appears to have developed on the older arc. The Bisbee basin developed in the back arc region connecting eastward with the Chihuahua trough (Dickinson, 1981; Dickinson *et al.*, 1986, Bilodeau, 1982).

Several models have been postulated to explain the tectonic setting of the Bisbee basin.

**The "aulacogen" model.**- Dickinson (1981, 1989) proposed the Bisbee basin as a rift related to the formation of the Gulf of México and located in the back of the

Cretaceous volcanic arc. The Glance Conglomerate was deposited during the rift stage. As the crust cooled, subsidence continued as the result of increasing crustal density (thermotectonic subsidence) during the deposition of the Morita and Mural formations. According to Bilodeau (1982), deposition of the Glance was related to normal faults in an aulacogen extending northwestward from the proto-Gulf of México. The aulacogen branched to form the Chihuahua trough and the Bisbee basin. Bilodeau (1982) and Bilodeau and Lindberg (1983) defined the depocenter of the Bisbee basin by means of isopachs. These isopachs were constructed with only a few data points from northeastern Sonora. The isopachs, presenting thicknesses of the whole Bisbee Group, gave unrealistic results because two different depositional regimes were plotted together: early rifting (highly localized and with major thickness variations over short distances) followed by thermotectonic subsidence (with gradual thickness variations). Other sources of possible errors include the thickness of the Morita Formation (probably deposited on a surface with major relief) and of the Cintura Formation (partially eroded). The geochemistry of the volcanic rocks intercalated near the base of the Glance support the hypothesis of rifting (Krebs and Ruiz, 1987). Klute (1991) favors the aulacogen model with influence from back arc-extension on the basis of the east-west orientation of the Bisbee basin.

**The pull-apart basin model.**- The rift phase of the Bisbee basin may have been due to an aulacogen extending from the Gulf of Mexico, or to strike-slip movement along the Mojave-Sonora megashear (Coney, 1978; Dickinson, 1989) and the Texas lineament (Sosson, 1993). In the latter case the initial basin in which the Glance Conglomerate was deposited would have been a pull-apart basin. According to Klute (1991), pull-apart basins do not explain the position of the Chihuahua trough and the Bisbee basin.

**The rift-to-foreland basin model.**- Mack (1987) studied the Lower Cretaceous in southwestern New Mexico which has the following names: Hell-to-Finish (Morita), U-Bar (Mural) and Mojado (Cintura) Formations. Mack proposed that these formations had been deposited in a basin that shifted from a rift basin to a 'retro-arc' basin in the late Albian. Mack provided several lines of evidence to support his interpretation: an increase in subsidence and sediment supply; a change in sandstone composition from cratonic (quartz-rich) to volcanic, and a change in source direction from north to west.

Sedimentation, uninterrupted in Early and Late Cretaceous, ended in the Maastrichtian.

The Cretaceous in Arizona and Sonora is, on the other hand, characterized by a break in the sedimentary record after the late Albian (at the end of the Cintura Formation) for about 10 to 15 m.y. (Dickinson *et al.*, 1989), after which sedimentation re-initiated in continental basins. Volcanic activity took place near the end of the Cretaceous, before the Laramide orogenic phase. The Bisbee basin, in this interpretation, ceased to exist in the late Albian; the Fort Crittenden-Cabullona and El Chanate deposits represent new basins.

Klute (1991) found that the composition of the Bisbee sandstones does not show the same change as indicated by Mack (1987). In the Bisbee Group in southern Arizona, quartzose sandstones are persistent throughout the sequence. The Bisbee basin in southern Arizona and New Mexico were located next to each other and had the Mogollon highlands as source. Klute (1991, p. 196) considers that the change in composition may be due to other reasons, for example wearing down and burial of uplifted basement blocks to the north.

**The foreland basin model.**- Drewes (1991) proposes that the Cretaceous basins in Arizona and Sonora were part of the Cordilleran orogeny, spanning from the Middle Jurassic through early Tertiary. Drewes places within this orogeny periods of deposition and periods of deformation. He considers a series of events as a continuum in the orogenic process. There are several criticisms possible on his model. One is that he does not accept a Cretaceous age of the upper McCoy Mountains Formation (Stone *et al.*, 1987) thus disregarding the significance of this basin within the tectonic evolution of the region. In Drewes' model, depositional sites were tectonic furrows migrating toward the east, one basin overlying part of the previous one. One such basin, the Bisbee basin, is, however, much wider than previously thought, therefore precluding a narrow, relatively local, synorogenic basin. The Bisbee Group also represents a period of relative stability of about 40 m.y. Thickness distribution and gradual facies changes in the Bisbee do not indicate that it was a foreland basin as suggested by Drewes.

**The back arc basin model.**- Rangin's (1978, 1982) tectonic model for the Cretaceous of the Baja California-Sonora region includes, from west to east, fore arc and

arc in Baja California, and part of the arc and back arc in Sonora. Fore arc deposits along the western coast of the peninsula include the Alisitos Formation (Santillán and Barrera, 1930; Allison, 1974; Beggs, 1984; Busby and Boles, 1986; Almazán, 1988a, 1988b). Arc intrusives (120 - 90 Ma) are exposed in Baja California (Gastil *et al.*, 1986a) and along the coast of Sonora north of Bahía Kino (Gastil and Krummenacher, 1977; Anderson *et al.*, 1969). The volcanic arc extends south in western México (Servais *et al.*, 1986; Ortiz *et al.*, 1992). Rangin (1982) considered the Lower Cretaceous of northwest Sonora as part of the back arc, but not the Bisbee basin, which, he thought, was a small basin in southeastern Arizona and northeastern Sonora. According to the present study the Bisbee basin extends into the Caborca-Santa Ana area and is thus located in the back arc region. The basin continues eastward into the Chihuahua trough in northwestern Chihuahua. Whether this connection continues southward is uncertain. Volcanic rocks of the Sierra Madre Occidental cover most of the Lower Cretaceous rocks that could document this connection.

### **Early Cretaceous paleogeography**

The Bisbee basin has been considered as small and narrow (Bilodeau, 1982; Klute, 1991; Drewes, 1991). Accepting this geometry of the Bisbee basin, several paleogeographic reconstructions of the Early Cretaceous of southeastern Arizona and northern Sonora have been proposed (Hayes, 1970; Hayes and Drewes, 1978; Dickinson *et al.*, 1986; Klute, 1991; Drewes, 1991). González and Jacques (1990) were the first to recognize that the basin was a larger basin and they presented a paleogeographic reconstruction including northwest and central Sonora. In this study, the Bisbee Group is reported to occur in several other areas, identifying formations similar to those of the Bisbee of southeastern Arizona. The margin of the basin can now be extended with confidence into the Caborca-Santa Ana area, redefining the geometry of the Bisbee basin.

### **Basement of the Bisbee basin (Fig. 33)**

The Bisbee basin formed upon a volcanic and a cratonic basement. In the study

areas the base of the Bisbee Group is not exposed, but the composition of the clasts in the Glance Conglomerate and sandstone composition in the Bisbee clearly indicate that the basement and the source were a rhyolitic volcanic terrain, most probably the Middle Jurassic volcanic arc. This arc is exposed in north-central Sonora and south-central Arizona.

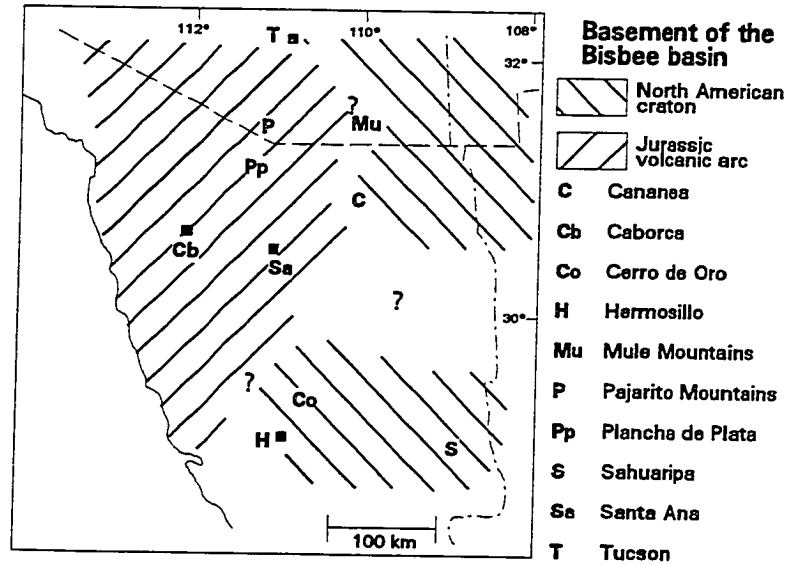
Farther northwest, in southeastern California, the Upper Jurassic-Upper Cretaceous McCoy Mountains Formation (Harding and Coney, 1985; Stone *et al.*, 1987) was also deposited on Middle Jurassic volcanic rocks.

In northeastern Sonora and southeastern Arizona the basin was built upon cratonic basement. This basement, part of the North American craton, consists of Proterozoic schist and granite overlain by Early Paleozoic limestone and quartz sandstones. The Glance Conglomerate in that area has clasts derived from these rocks (Bilodeau, 1978; Bilodeau and Lindberg, 1983) and the sandstone in the younger Bisbee units had the same cratonic source (Archibald, 1987; Jamison, 1987; Klute, 1991; Ingram, 1987).

In Cerro de Oro the Cerro de Oro Formation includes a basal conglomerate consisting of dolomite and quartz sandstone derived from the local basement consisting of Proterozoic and Cambrian(?) dolomite and quartz sandstone (González and Jacques, 1988). The source of the Bisbee Group sandstone, however, was a nearby volcanic arc and not the "cratonic" basement.

The present distribution of the two types of basements suggests that the boundary extends roughly in a north-south direction. This distribution of volcanic and Proterozoic/Paleozoic basement of the Bisbee is not incongruous with Goodell's (1993) hypothesis that blocks of North America "rafted away" to the south with oceanic crust between the blocks.

Because the presence (or absence) of the Mojave-Sonora megashear bears upon the pre-Bisbee paleogeography it is necessary to discuss the megashear in some detail. The Mojave-Sonora megashear is a hypothetical left lateral strike slip fault with an estimated 800 km of slip. The fault was proposed by Silver and Anderson (1974) and Anderson and Silver (1979) to explain similarities in age and rock type of Early



**Figure 33** Distribution of known and inferred basement types for the Bisbee basin in northern Sonora and southern Arizona.

Proterozoic basement and Late Proterozoic sedimentary sequences between Death Valley, California, and Caborca, and differences in basement compositions between southern Arizona (Pinal Schist) and Sonora. Anderson and Schmidt (1983) extended the megashear into central México. Major displacement must have taken place during late Middle and early Late Jurassic time.

The trace of the megashear was thought to be directly south of, or within, the narrow strip of the El Batamote structural complex (Fig. 6). The Caborca terrane would have been emplaced in its present position, before Bisbee deposition, and should have been a source of Bisbee sediments in the Caborca-Santa Ana area. However, Bisbee sediments in this area, which have a southern provenance, are derived almost exclusively from rhyolitic and andesitic source rocks. The virtual absence of sediment derived from Proterozoic/Paleozoic rocks (high grade metamorphic rocks, quartz sandstone, dolomites and limestones) indicates that the Caborca terrane was most likely emplaced in its present position after the Early Cretaceous.

The extent of the Bisbee basin is now well defined in southeastern Arizona and western Sonora (this study). In southwestern Arizona, conglomerates correlative to the

Glance have been reported (Tosdal *et al.*, 1989), and near the border with California and in southeastern California, rocks similar to the Bisbee Group have been described (Tosdal *et al.*, 1989, and references therein). Robison (1980) interpreted the "Mesozoic red beds" in an area southeast of Quartzite as probably part of the Bisbee Group. This sequence was incorporated in the McCoy Mountains Formation and assigned a Jurassic age by Harding and Coney (1985). However, fossil wood in the McCoy demonstrated that at least part of the sequence is of Bisbee age (Stone *et al.*, 1987).

The paleogeographic maps presented in this work are not palinspastically reconstructed because the amount of shortening and subsequent extension is insufficiently known. The Cretaceous layers were shortened during the Laramide orogenic phase and in the middle Tertiary the region was extended (Nourse, 1989). Drewes (1991) made a palinspastic reconstruction based on data from southeastern Arizona, but did not consider the Tertiary extension. In his paleogeographic map of the "middle" Cretaceous (Drewes, 1991, Fig. 38), the sequence of the Mule Mountains would have been located near the Caborca area, about 100 km southwest of the location of the Mule Mountains. If the same amount of shortening would be applied to the Sierra El Chanate, the sequence of the sierra would have been located not far from the coast of Sonora.

#### **Glance Conglomerate (Figs. 34A and 34B)**

The Glance Conglomerate is Oxfordian to Neocomian in age. It is a coarse clastic sequence deposited in alluvial fans and rivers; locally it has intercalated volcanics. The basin had an irregular relief with northwest-southeast fault-bound basins, locally with accumulations over 2000 m thick (Bilodeau *et al.*, 1987). The margin of the basin in northwest Sonora was located to the north and west. In southeastern Arizona and northeastern Sonora the margin was located to the north and west (Hayes, 1970; Hayes and Drewes, 1978; Bilodeau *et al.*, 1987).

Of the same Late Jurassic age are the marine deposits with intercalated tuffs of Pozo Serna (Beauvais and Stump, 1976; Carrasco, 1987), and with intercalated volcanic flows in Cucurpe (Rangin, 1977a; Rodríguez, 1988) and in the Chiricahua Mountains

(Lawton and Olmstead, in prep.). This strongly suggests that marine and continental deposition were both present in northern Sonora during the Late Jurassic. The marine basins probably extended toward the south.

During the early Neocomian deposition of the Gance continued and a second marine transgression took place in central Sonora reaching the Caborca area (Cerro de Oro Formation, González and Jacques, 1988). The two marine invasions during Gance time suggests that the rift became deeper to the southeast and was invaded by the sea.

The Cananea high (McKee, 1991; Nourse, 1989, 1993) may have been a fault-bound peninsula protruding in a southeast direction between Nogales and Cananea. It was underlain by Proterozoic Pinal Schist and Paleozoic limestone and quartz sandstone, and Middle Jurassic volcanic rocks. Limited paleocurrent data collected by the present author from the Gance Conglomerate in the northern Sierra Anibacachi suggests that the paleoflow was to the northeast. The source was probably the rocks of Cerro La Negrita, part of the Cananea high.

#### **Morita Formation (Fig. 34C)**

The Morita Formation in the Caborca-Santa Ana area was deposited by meandering rivers, and perhaps in tidal flats (Navarro, 1989; Jacques, 1992a; 1992b). The source of the sediments was to the north and west, as indicated by the geometry of the basin. Paleocurrent indicators are bimodal indicating a strand line oriented northwest-southeast. In the Cerros Cabeza Colgada and Cerro Mayo areas the strand line was almost east-west. Limited data in Cerro de Oro suggests a flow direction toward the east; the coastline was to the east, with active volcanoes to the west (Gastil and Krummenacher, 1977; Anderson *et al.*, 1969; Anderson and Silver, 1978).

A similar environment has been documented in southeastern Arizona (Hayes, 1970; Jamison, 1987; Lindberg, 1987; Inman, 1987; Klute, 1991). Cross-bedding data collected by the present author from the Morita Formation in the northern Sierra Anibacachi suggest that the sediment source was to the southwest, perhaps the Cananea high. The bimodal distribution of the paleocurrents may have resulted from tidal currents. In southeastern Arizona paleocurrent directions show that the source was to the

north (Hayes, 1970; Klute, 1991).

During Morita time marine sedimentation took place in east-central Sonora. In Nácori Chico black shale underlies the Mural Limestone (Araujo and Estavillo, 1987). In Lampazos, the Aliso and Agua Salada Formations of González (1987) are time equivalent to the Morita, and in Sahuaripa marine limestones are intercalated with conglomerates (Pubellier, 1987). The basin was shallow to the north and west, and deeper in east-central Sonora.

#### **Mural Limestone and Arroyo Sásabe Formation (Fig. 34D)**

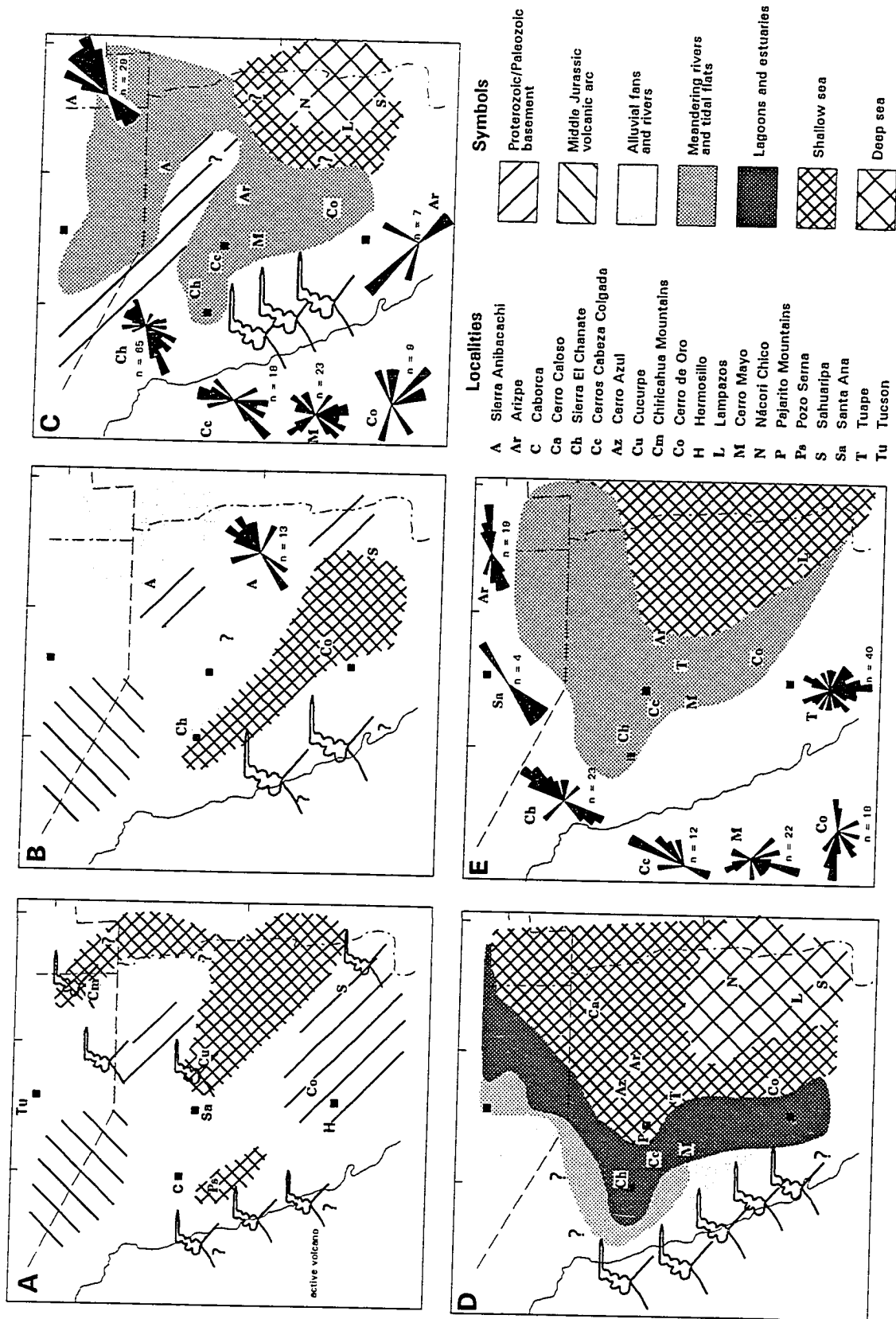
The most important transgressive phase in the Bisbee basin took place during late Aptian-middle Albian. It was during this time that the Mural Limestone and the Arroyo Sásabe were deposited. The Arroyo Sásabe Formation was deposited in a lagoonal environment, with local marshes and estuaries. At the same time, the Mural Limestone was formed in a warm, clear-water, open marine environment.

The Arroyo Sásabe Formation occurs in the study areas west of Cerro La Pima and south of Santa Ana. It is also present west of Benjamin Hill in Cerro Mayo. This distribution defines a belt of lagoonal deposits trending from north of Caborca to Trincheras and El Claro and south into Benjamin Hill. Land with active (?) volcanoes was to the west.

The Mural Limestone occurs in Cerro La Pima and east of Santa Ana, and also in Tuape (Rodríguez, 1988) and Cerro de Oro (González and Jacques, 1988). These four localities define the western margin of a reef tract which probably continues to the northeast in the Cerro Azul (McKee, 1991) and Arizpe areas (González, 1978; Rangin, 1982).

A similar picture has been provided for southeastern Arizona and northeastern Sonora. Fluvial, estuarine and lagoonal environments covered most of the Bisbee basin in southeastern Arizona. Patch reefs were deposited in the Bisbee-Douglas area and farther south in Cerro El Caloso (Klute, 1991, fig. 49; Scott, 1979; Warzeski, 1987). The reef tract probably connected to the southwest with the sequences in Arizpe and Cerro Azul. Deeper marine environments have been described in Lampazos (González,

**Figure 34.** Paleogeography of the Bisbee basin in northern Sonora and southern Arizona. (A) Basement of the Bisbee basin. (B) Late Jurassic ("early" Glance time). (C) Early Neocomian ("late" Glance time). (D) Late Neocomian-Aptian (Morita time). (E) Late Aptian to middle Albian (Arroyo Sásabe/Mural time. (F) Late Albian (Cintura time).



1987). This general facies distribution defines an extensive basin deepening toward the southeast. The axis of the basin extended, more or less, from Magdalena to Sahuaripa (González and Jacques, 1990).

The distribution of the Lower Cretaceous suggested to Nourse (1989, Fig. 7.2) the presence of topographic highs. One of these highs, the Cananea high (McKee, 1991) is proposed by Nourse (in prep.) as a land area separating the Bisbee basin from the Magdalena-Tubutama basin. His interpretation is based on the apparent absence of Cretaceous rocks along a corridor extending in a northwest-southeast direction. The southern margin of the corridor lies north of Arizpe and Nácori Chico, and the northern margin goes from east of Nogales to Sierra de Anibacachi and southeast. This region, like most of eastern Sonora, is characterized by Tertiary batholiths, volcanic rocks and large scale faulting with thick alluvial fans. Exposures of older rocks are small and scattered. Therefore, it is likely that the apparent absence of the Lower Cretaceous is related to these phenomena, or to erosion during the Late Cretaceous, rather than to a paleogeographic high. The presence of a high can be documented with geological mapping. Indeed, Roldán and Clark (1992) show Lower Cretaceous south of Cananea, which is at variance with a Cananea high throughout the Early Cretaceous. The paleogeographic map of Fig. 34 indicates the presence of a Cananea high during Gance and Morita time, and an absence during Arroyo Sásabe/Mural and Cintura time.

McKee (1991) interprets the Bisbee basin in the Cerro Azul area as a deep basin in which reefal limestone bodies slid down from a hypothetical Cananea high, north of the Cerro Azul area. This interpretation is based on lithology and sedimentary structures. Black non-fossiliferous shale is prominent and is interpreted as a marine, below-wave base deposit. The shale has intercalations of fossiliferous limestone and sandstone deposited in shallow water environments. Other features include the sharp contacts of the oyster-bearing limestone with the underlying shale. This suggests to McKee that the oysters did not thrive in the mud, but were emplaced by sliding. She also writes: "...some of the sandstone beds contain structures characteristic of turbidites including basal load structures, grading, parallel laminae, convolute laminae, ripple-scale, cross-lamination...", and "Sharp undulatory, basal contacts of both the coarse-grained

siliciclastic and fossil-bearing limestone beds with the underlying mudstone or shale, and the occurrence of load structures, sole marks, and rip-up clasts of the underlying mudstone and shale indicate transport and rapid deposition of coarse-grained material onto a quiet, muddy bottom" (p. 39).

In order to evaluate McKee's interpretation it is now necessary to present the stratigraphy of units 2-7 in Cerro Azul in semi-detail (McKee, 1991). Units 2 and 7 consist both of red mudstone, minor sandstone, granule to pebble conglomerate and limestone. Locally they contain sand- to cobble-size calcareous nodules. Units 3 and 4 consist of black shale (about 70 to 85 percent), oyster-bearing limestone and sandstone and unit 6, which includes red mudstone, represents the transition to unit 7. Unit 5 consists of thick, shallow water limestones considered as the main slide masses.

Units 2 and 7 are similar to the Morita and Cintura Formations, respectively. The red color in these units strongly suggest subaerial deposition (Collinson, 1986), and the calcareous nodules are diagenetic features that form in soil horizons or above the water table in hot and dry subaerial environments (Collinson, 1986; Reineck and Singh, 1980). Units 2 and 7 have transitional contacts with units 3 and 6, respectively. If units 2 and 7 are subaerial deposits, the transitional contacts suggest a gradual shift to a shallow water and not a deep water environment.

The shale of units 3 and 4 near El Salto Ranch is not black but greenish gray, and has no fossils. Fossils are the best environmental indicators, and to unequivocally prove that the 'black' shale is deep marine, fossils characteristic of such environment should have been found. Thick, dark colored shales can be deposited in back swamps and in subtidal ponds in lagoonal environments. Such shales can be finely laminated, thinly bedded, or with convolute bedding (Reineck and Singh, 1980).

Some of the described sedimentary structures in the Cerro Azul area can be found in different environments. Structures that are considered as typical of turbiditic deposits are also common in fluvial environments (Collinson, 1986). Rip-up clast conglomerates are typical of fluvial and tidal channel deposits. They represent the erosion of indurated mud from channel banks (Elliott, 1986). In present-day environments, clay clasts can be seen in the arroyos of the Sonoran desert, especially after floodings. As for the thick

shale deposits, lagoons provide a protected environment for the deposition of shale, as well as the conditions for the preservation of organic matter which imparts the color. This would explain also the presence of oolitic beds, which can be deposited by strong waves going into the lagoon.

Finally, according to Elliot (1986) offshore facies from below the wave base comprise fossiliferous mudstones and fine siltstone which are usually massive and structureless due to bioturbation.

The interpretation of McKee (1991) is interesting but the evidence provided is not conclusive.

### **Cintura Formation (Fig. 34E)**

The Cintura Formation was deposited in tidal flats and meandering rivers. It is lithologically similar to the Morita Formation. In all the study areas, except south of Santa Ana, the Cintura Formation does not coarsen upward; that is, it is not a regressive sequence. South of Santa Ana the coarse fraction increases upward.

In northeastern Sonora and southeastern Arizona the Cintura Formation is a coarsening-up sequence clearly indicating its regressive nature (Grijalva, 1993; Klute, 1991). In the Arizpe area the Cintura Formation is capped by a marine limestone (González, 1978), documenting the last transgression in the Bisbee basin history (González and Jacques, 1990).

Paleocurrent diagrams in northwest Sonora indicate a west-northwest to east-southeast strand line suggesting an embayed area with land to north and south, Paleocurrents in Cerro Mayo and Cerro de Oro areas were east-west oriented. Marine environments were located in east-central Sonora, from Arizpe to Lampazos (González, 1987; Scott and González, 1991) and Sahuaripa (Pubellier, 1987).

At the end of the Albian the region underwent uplifting, and the Bisbee basin was closed.

### **The Early Cretaceous volcanic arc in México**

In the last few years new discoveries have clarified our perception of the

Cretaceous evolution in México. We now know that during the Early Cretaceous basins extended from Arizona to Guerrero (Campa, 1985) along the Pacific coast. Lawton and Olstead (in prep.) reported in Arizona the presence of marine rocks with intercalated volcanics beneath the Bisbee Group. King (1934) reported Cretaceous limestone in southern Sonora (Alamos area) and in westernmost Chihuahua (Chínipas area). Near the border of Chihuahua, Sonora and Sinaloa, McAnulty (1981) reported Cretaceous limestone intercalated with basaltic rocks. In northern Sinaloa, similar sequences were described by Bonneau (1970, 1972) and Mullan (1978). In the same region, Ortega *et al.* (1979) described an Early Cretaceous ophiolitic sequence, formed as part of oceanic crust related to the volcanic arc. Servais *et al.* (1986) described a series of sedimentary and volcanic rocks of Cretaceous age, proposing the Bacurato-Los Alisos basin as an intra-arc basin between the Alisitos and Sinaloa volcanic arcs. Further south, in Colima, Michoacán and Guerrero, Early Cretaceous volcanic and sedimentary rocks are widely exposed (Campa and Coney, 1983; Campa, 1985). An exploratory well of PEMEX cut a sequence of about 3,000 m of sediments intercalated in andesites (Campa, 1985). Along the coast of Michoacán, Ferrusquía *et al.* (1978) described Cretaceous volcanoclastic continental deposits with dinosaur tracks. Toward the east, in the Teloloapan-Arcelia region, andesitic volcanic rocks with intercalated sediments are overthrust upon the carbonate platform (Campa and Coney, 1983). A similar setting is found in Guanajuato (Ortiz *et al.*, 1992) and Zacatecas (Servais *et al.*, 1986).

In this regional context, the Bisbee basin is interpreted to represent the northwestern margin of a basin which extended along México's coast as far south as Guerrero (Enos, 1983, fig. 5). The regional distribution of volcanic rocks suggests that this basin was a back arc basin. The volcanic arc and intra-arc basins are exposed in the Baja California peninsula (Rangin, 1982; Busby-Spera and Boles, 1986; Gastil *et al.*, 1986a, 1986b), in western Sonora (Anderson *et al.*, 1969; Gastil and Krummenacher, 1977), Sinaloa (Mullan, 1978; Ortega *et al.*, 1979; Servais *et al.*, 1986), and Guerrero (Campa, 1985). Carbonate platforms occupied the area east of the back arc basin.

The Bisbee basin in Sonora and Arizona was built on a continental volcanic arc

and on cratonic basement. The volcanic arc basement was also present in southeastern California, where the Late Jurassic-Late Cretaceous McCoy Mountains Formation was deposited on Jurassic volcanic rocks (Harding and Coney, 1985; Stone *et al.*, 1987). In northern Sinaloa, the Cretaceous arc was built upon continental crust (Servais *et al.*, 1986). In southern California and northern Baja California, the Cretaceous arc was emplaced in part on Upper Triassic-Jurassic volcanics and in part on Paleozoic-Triassic rocks (Gastil, 1985). Farther south in Guanajuato, Michoacán and Guerrero the arc appears to have formed on oceanic crust (Campa and Coney, 1983; Ortiz *et al.*, 1991).

### **Tectonic setting of the Late Cretaceous basins**

According to Enos (1983, fig. 6) the northwestern part of México was uplifted in the Cenomanian. This uplift was recorded by a change in sedimentation patterns in eastern México: carbonate platforms (Aurora Formation, El Abra Limestone, Sierra Madre Formation, etc.) were replaced by large deltaic deposits (Mexcala Formation, Caracol Formation, etc.). In a transect between Sinaloa and San Luis Potosí, Servais *et al.* (1986) interpret the western part of the country being thrust eastward during the mid-Cretaceous, supplying sediments to basins in the east.

In northern Sonora the region was occupied by uplifted ranges (thrust blocks, folds?) and continental basins. The amount of deformation was not the same in the region: in eastern Sonora the Upper Cretaceous overlies the Lower Cretaceous with an angular unconformity, whereas in the Caborca-Santa Ana area the Lower Cretaceous remained practically unfolded.

### **Late Cretaceous paleogeography**

Sedimentation ceased at the end of the Albian in the region covered by the Bisbee basin. Marine sedimentation continued toward the east in the Chihuahua basin (Mar Mexicano of Araujo and Arenas, 1986) in an area now largely covered by the volcanics of the Sierra Madre Occidental. In New Mexico marine sedimentation was continuous throughout the Cretaceous (Cumella, 1983; Mack, 1987; Mack *et al.*, 1988). The uplift

in Sonora was apparently due to an orogenic phase evidenced by folding and thrusting in several areas.

The El Chanate Group is a continental deposit with an extent thought to be relatively small. To the east it appears to pinch out near the Cerro La Pima area, and to the northwest it could extend as far as Sonoyta. In other parts of Sonora and southern Arizona, similar Late Cretaceous basins were present. The Cabullona basin (Taliaferro, 1933; Lucas and González, 1990) was connected with the Fort Crittenden basin to the north (Hayes, 1987), and stretched probably as far south as the Sahuaripa area (Pubellier, 1987). Southeast of Moctezuma, in central Sonora, a thick folded sequence of sedimentary and volcanic rocks was intruded by a Laramide batholith (Roldán, in prep.). This basin extended to the north into the Banámichi area, where stromatolitic limestones are intercalated with volcanic rocks (Bojorquez and Rosas, 1988; Ricalde and Cevallos, 1993).

In the Caborca area, the Late Cretaceous El Chanate Group was deposited in erosional unconformity upon the Bisbee Group, and there may be a minor angular unconformity. In Cerro de Oro, the Late Cretaceous La Palma Formation rests in erosional unconformity on the Bisbee Group (González and Jacques, 1988). The basal conglomerate of the La Palma includes clasts of the Mural Limestone. In northeastern Sonora an angular unconformity is present between the Bisbee and the Cabullona Groups (Rangin, 1977b). Also in Moctezuma, the Upper Cretaceous rests in angular unconformity upon the Lower Cretaceous (Roldán, in prep.).

The El Chanate has great thickness variations over relatively short distances. Its greatest thickness is probably in the northern Sierra El Chanate where it attains about 2800 m. Also, the units that were described in the type locality can be absent in other areas. All these variations reflect a great tectonic instability resulting from an ongoing orogeny.

#### **Pozo Duro Formation (Fig. 35A)**

The Pozo Duro Formation was deposited during or shortly after the middle Cretaceous orogenic phase discussed above. It is a fining-upward clastic sequence

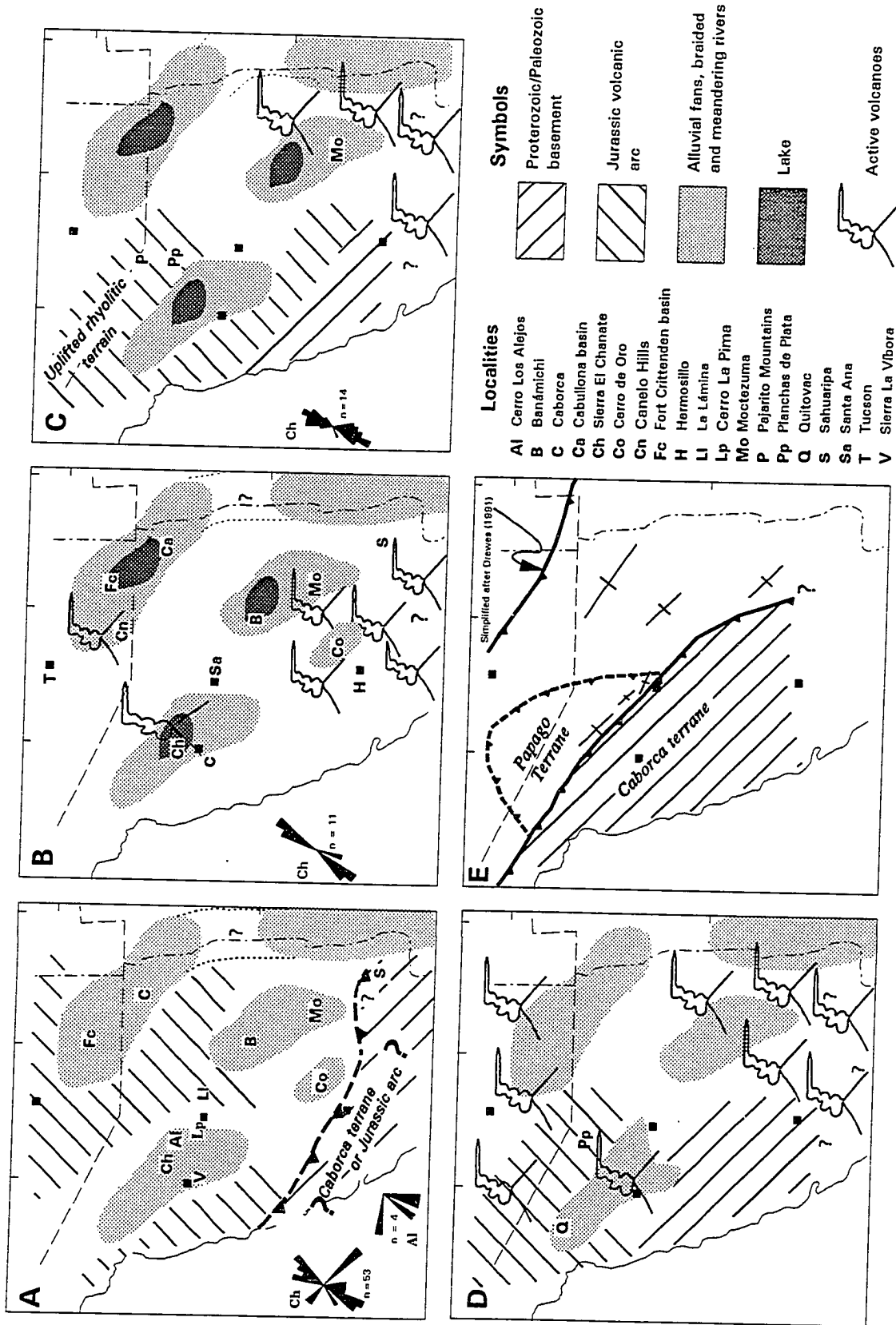
characterized by mudstone, sandstone and minor conglomerates deposited by meandering rivers draining an area to the southwest, as indicated by clast size in the conglomerates (Fig. 19). The basin was relatively small extending in a northwest-southeast direction. Limited paleocurrent data suggests that the strand line was oriented northwest-southeast, probably coincident with the axis of the basin. The clasts of the conglomerate consist of quartz sandstone and are well rounded. The sandstones however, were derived from a volcanic source. As limestone and dolomite are virtually absent in the Pozo Duro the Proterozoic/Paleozoic sequence of the Caborca terrane is excluded as a possible source. The climate during this time was arid (Dickinson *et al.*, 1989) so limestone fragments should have been preserved. The most likely source is the Middle Jurassic volcanic arc, documented in south-central Arizona and northern Sonora (Riggs, 1987; Busby-Spera, 1988; Tosdal *et al.*, 1989; Nourse, 1989), which contains quartz sandstone and quartz-sandstone pebbles. This would explain the rhyolitic source of the sandstones in the Pozo Duro. However, Middle Jurassic volcanic rocks with quartz sandstone intercalations have not been reported south of Caborca. Another possible source of the quartz-sandstone pebbles could have been the Triassic Barranca Group/El Antimonio Formation, which includes quartz-sandstone conglomerates. But it does not explain the abundant rhyolitic detritus.

#### **Anita Formation (Fig. 35B)**

Volcanics in the Anita Formation are the result of the formation of a Late Cretaceous volcano in the eastern Sierra El Chanate. Other volcanoes have not been reported in the study areas. The deposition of thick wedges of andesite conglomerate (lower middle member) suggest an increase in relief. The area was largely leveled by the end of the middle member, characterized by mud-dominated fining upward cycles deposited in meandering rivers. Near the end of Anita time black shales were deposited in a fresh water lake.

The thickness of the Anita on the northern side of the Sierra El Chanate is several times that on the southern side, indicating that the compartmentalized basin was elongated in a northwest-southeast direction.

**Figure 35.** Paleogeography and interpreted tectonic setting of northern Sonora and southern Arizona during the Late Cretaceous. (A) Pozo Duro time; (B) Anita time; (C) Escalante time; (D) El Charro/Altar time.



During the Anita time, the composition of the sands changed only slightly due to the input from local andesitic sources; the rhyolitic components of the lithic fragments continued to be the most important.

#### **Escalante Formation (Fig. 35C)**

The Escalante Formation, a fining upward sequence, was deposited in an alluvial basin: the lower member in alluvial fans, braided streams and finally in meandering rivers. The upper member, a succession of sandstone and shale pairs, was deposited in a lake delta. At the end of Escalante time nearby volcanic activity is indicated by thin intercalations of rhyolitic tuffs.

The basin had a west-northwest south-southeast oriented strand line with the source to the north, as suggested by current directions, clast size studies and thickness differences between the northern and southern flanks of the Sierra El Chanate. The basin during the Escalante time was probably smaller than the basin during Pozo Duro time, as the Escalante has only been reported in the Sierra El Chanate and the Puerto El Alamo, and perhaps in the Cerros El Amol (García, 1992).

Sandstone petrography of the Escalante Formation is similar to that of the underlying units. Sediments were derived from a rhyolitic terrain, probably the Middle Jurassic volcanic arc. In the Escalante Formation, both the sand-sized fraction and the clasts in the conglomerate have the same source.

#### **The Altar Formation (Fig. 35D)**

The Altar Formation (García *in* Jacques *et al.*, 1990; García, 1992) is exposed in the Cerros El Amol, and probably in the Sierra El Batamote and Sierra La Gloria. Its age is, at least in part, Late Cretaceous.

The Altar Formation was deposited in alluvial fans right next to the source, probably representing very rapid, geologically instantaneous deposition. It appears to be geographically restricted, so it could have been shed into a small, rapidly subsiding basin. The source of the coarse sediments was mixed: quartz sandstone cobbles and boulders were derived from Proterozoic/Paleozoic (?) or Triassic (?) formations, and

ryholitic to andesitic volcanic rocks. As this unit shows the strongest deformation in the area, it is thought to be a thrust front deposit that was subsequently covered and deformed by the thrust plate (García *et al.*, 1988).

### **El Charro volcanic complex**

The third manifestation of Cretaceous volcanism began in the latest Cretaceous (Maastrichtian) in the Puerto El Alamo and Cerros El Puerto area (first manifestation during Arroyo Sásabe/Mural time; second manifestation during Anita time). Rhyolitic tuffs were deposited, nearby areas were uplifted, sediments became coarsely grained and poorly sorted with lahar deposits. As volcanism became predominant in the area it changed its composition from rhyolitic to andesitic, depositing breccias, agglomerates and flows.

Latest Cretaceous volcanism in Arizona and Sonora is the result of a magmatic arc related to the Laramide orogeny (Dickinson, 1989). According to Coney and Reynolds (1977) the subducting plate flattened causing volcanism to migrate inland; the flattening of the subducted slab also caused an increase in the compression in the overriding plate, promoting shortening and crustal thickening (Dickinson, 1989).

### **Laramide orogenic phase (Fig. 35E)**

The Laramide orogeny (*sensu stricto*) is a deformational phase that occurred during the latest Cretaceous and early Tertiary. It was defined in Wyoming for basement-cored uplift thrusts and folds. This name has been used loosely (*sensu lato*) to include large scale folding and thrusting of Late Cretaceous and Paleocene age. It is considered as the most important deformational phase in eastern México, responsible for the folding and thrusting of the Sierra Madre Oriental. The Laramide orogeny term (*sensu lato*) will be used here for the deformation (large scale thrusting and folding) that took place during the latest Cretaceous and early Tertiary in southern Arizona and northern Sonora (Haxel *et al.*, 1984; and Dickinson, 1989).

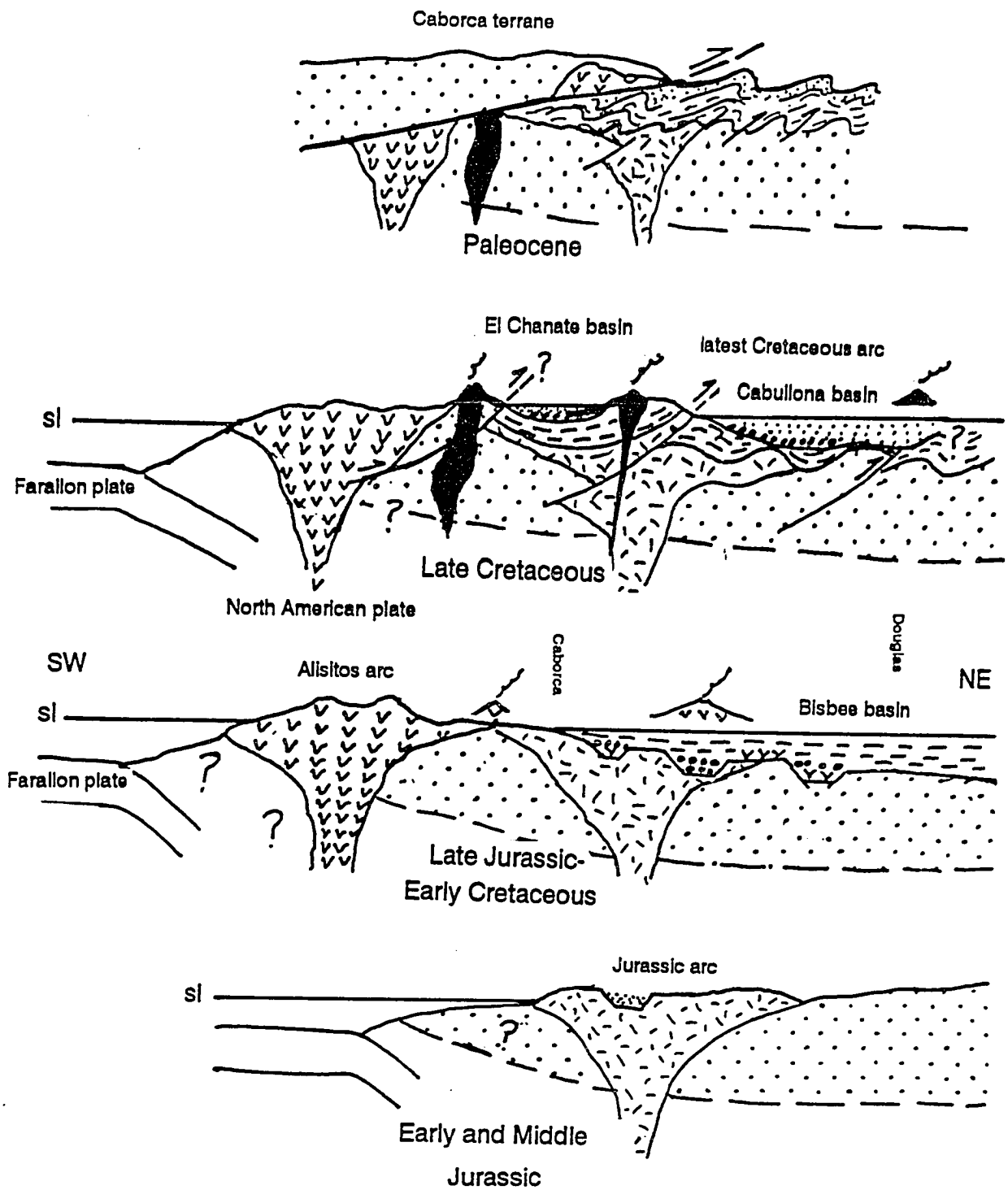
Shortly after, or perhaps even during the emplacement of the El Charro volcanic

complex, the region underwent a phase of strong contraction. The Lower and Upper Cretaceous were folded and thrust, presumably by the Caborca terrane. The thrust plate moved from southwest to northeast as suggested by the distribution of documented thrust faults, and the foliation and lineation in the El Batamote structural complex (McComb, 1987).

In eastern Sonora thrust plates probably reached the Sahuaripa area (Pubellier and Rangin, 1988). In northeastern Sonora, in the Cabullona area, the Cabullona Group rests unconformably upon wide open folds of the Lower Cretaceous Bisbee Group. The Cabullona is also folded but less than the Bisbee (Rangin, 1977b). East of Moctezuma the Upper Cretaceous volcanic and volcanoclastic rocks, folded in wide open folds, are intruded by the 60 Ma granitic batholith of Sierra La Madera (Roldán, in prep.).

Metamorphism is however, restricted to the western part of the orogen, and in Sonora and Arizona this difference is recorded clearly: the Lower and Upper Cretaceous of eastern Sonora and southeastern Arizona are not metamorphosed as observed to the west.

The Laramide structures in northwest Sonora include large scale folds and thrusts. Fold axes are generally oriented in a northwest to southeast direction, and vergency is to the northeast, locally to the southwest. Thrusting is interpreted to be the cause of the deformation and metamorphism of the El Batamote structural complex which can only be explained by burial to depths in the order of several kilometers. Haxel *et al.* (1984) describe a similar type of deformation and metamorphism in south-central Arizona inferring a thickness of 5 to 8 km for the upper plate, and a time interval between thrusting and culmination of metamorphism in the order of 15 to 20 m.y. The age of the basal El Charro volcanic complex (71 Ma) signifies the lower limit of the Laramide orogeny in northwest Sonora; the metamorphism in the El Batamote structural complex (Altar Schist) has been dated as 58.3 +/- 2.8 Ma (Damon *et al.*, 1962) and 54.7 +/- 3.1 (Hayama *et al.*, 1984), and the upper age limit of the Laramide orogeny in the study area is provided by the age of the San Jacinto andesite (53 Ma). These ages give the same age range as proposed by Haxel *et al.* (1984). That in the study area metamorphism did not go beyond green schist facies can be due to the absence of mantle-derived heat influx,



**Figure 36.-** Cartoon illustrating the tectonic evolution of northern Sonora during Jurassic-Paleocene time.

as proposed by Haxel *et al.* (1984) for south-central Arizona. In that region this heat influx is expressed by calc-alkaline biotite-hornblende granitoids, absent in the Caborca-Santa Ana region.

### **Tertiary extension**

The San Jacinto andesite, 50 Ma in age, provides an upper limit for the age of the Laramide deformation in northwest Sonora. The andesite is not deformed, only tilted to the west. Between the Laramide phase (65-50 Ma) and the late Oligocene a tectonic lull was present. Extensional faulting began in the latest Oligocene and was apparently accompanied by extensive volcanism (29-28 Ma) east of Santa Ana (La Ventana volcanics of Miranda and DeJong, 1992). An andesitic dike cutting the El Batamote structural complex in the Sierra La Gloria (Cerro Basura) area (Fig. 6) has a similar age:  $25.6 \pm 1.1$  Ma (Damon, pers. comm., 1989). The tilting of the San Jacinto andesite is probably associated with the extensional faulting.

High angle normal faults are considered to be the youngest phase of the Basin and Range. In the study area, high angle normal faults have been observed in the ranges. Faults bounding the ranges have not been observed. The wide piedmont surfaces north and south of the Sierra El Chanate suggest that range-bounding faults have been inactive since the Pliocene. It is noted that the Sierra El Chanate-Sierra La Gloria has an anomalous orientation relative to the generally north-south trend of the Basin and Range.

## CONCLUSIONS

### Stratigraphy

◆ The stratigraphy of the Late Jurassic-Early Cretaceous Bisbee Group in the study area has been established with confidence. Five formations constitute this group: Glance Conglomerate, Cerro de Oro Formation, Morita Formation, Mural Limestone/Arroyo Sásabe Formation and Cintura Formation. The Arroyo Sásabe Formation is a new stratigraphic unit correlative to the Mural Limestone.

◆ The El Chanate Group of Late Cretaceous age, deposited with an erosional unconformity on the Bisbee Group, was divided into the Pozo Duro, Anita and Escalante Formations. Each formation forms a fining-upward cycle with quartz-sandstone, andesite and rhyolite conglomerate clast compositions, respectively. The El Chanate Group shows major lateral variations in lithology and thickness. In the El Chanate syncline thickness varies from 2,800 m in the northern limb to 700 m in the southern limb.

◆ The late pre-orogenic or synorogenic El Charro volcanic complex is a stratigraphic unit consisting of andesitic intrusives, flows and breccias, and coarse grained sediments. A  $^{40}\text{Ar}/\text{Ar}^{39}$  plateau age was determined as  $71.6 \pm 0.7$  Ma.

◆ The post-orogenic San Jacinto andesite is a newly described volcanic sequence. It consists of andesitic breccias, flows and tuffs. Feldspar and matrix separates from this unit were dated as  $51 \pm 2$  Ma and  $50 \pm 3$  Ma (K/Ar), respectively.

### Sedimentology and paleogeography

◆ The Bisbee Group was deposited at the margin of a basin with rivers and tidal flood plains (Glance, Morita and Cintura Formations), lagoons (Arroyo Sásabe) and a marine platform (Mural). The source area for the sediments was to the north, west and south, and the basin was an embayment of a larger basin.

◆ Four marine transgressions have been documented in the Bisbee basin. In the Late Jurassic the sea probably reached the southeastern part of the study area; a Neocomian transgression (Cerro de Oro Formation) reached as far northwest as the Sierra El Chanate. The most important transgression (Mural/Arroyo Sásabe) occurred in

the late Aptian-Albian, and the last, a minor one, in late Albian.

◆ Sandstone petrography and clast composition in the conglomerates of the Bisbee Group indicate a rhyolitic volcanic arc as major source. No input from a cratonic source has been found, which strongly suggests that the Proterozoic-Paleozoic rocks south of the study area (the Caborca terrane) were not yet part of the landscape.

◆ The El Chanate Group was deposited in a small continental basin. Its clastic character, volcanic intercalations and thickness variations suggest deposition in a foreland basin related to the Cordilleran orogeny (Bámori phase).

◆ Sandstone petrography and clast conglomerate composition in the El Chanate Group indicate a rhyolitic volcanic arc as major source. Occasional input from other sources did occur: quartz-sandstone clasts in the lower unit came from the south, probably from a thrust plate emplaced during the Bámori orogenic phase. The middle unit includes andesite conglomerate of local origin. As in the case of the Bisbee Group, the Caborca terrane was still not yet part of the landscape.

◆ The El Charro volcanic complex marks the end of the Late Cretaceous synorogenic sedimentation in a volcanic arc setting.

### **Tectonics**

◆ Large scale folds, mainly synclines, occur from the Sierra El Chanate to south of Santa Ana. Their trend generally parallels the trend of the El Batamote structural complex to the south. Block rotation in the Santa Ana area is tentatively interpreted as the result of strike-slip faulting associated with Tertiary crustal extension.

◆ The Bisbee basin was part of the back-arc region of the Alisitos arc. Late Jurassic continental and marine deposits include intercalations of volcanic rocks. The Bisbee back arc basin was built upon the volcanic arc of Middle Jurassic age in the study area and on Proterozoic-Paleozoic continental crust in central and eastern Sonora. This configuration is not easily brought in accord with the Mojave-Sonora megashear.

◆ During the Cenomanian-Turonian the Bámori orogenic phase resulted in uplift, end of Bisbee sedimentation, and minor erosion. Probably in the Campanian the El Chanate basin was formed as a foreland basin surrounded by ranges consisting largely

of the Middle Jurassic volcanic arc. Andesitic volcanoes were present in the El Chanate time.

◆ The Laramide phase is the most important Cordilleran orogenic phase, in the study area. The Caborca terrane was thrust northeastward causing metamorphism and deformation of Cretaceous and Jurassic rocks of the El Batamote structural complex.

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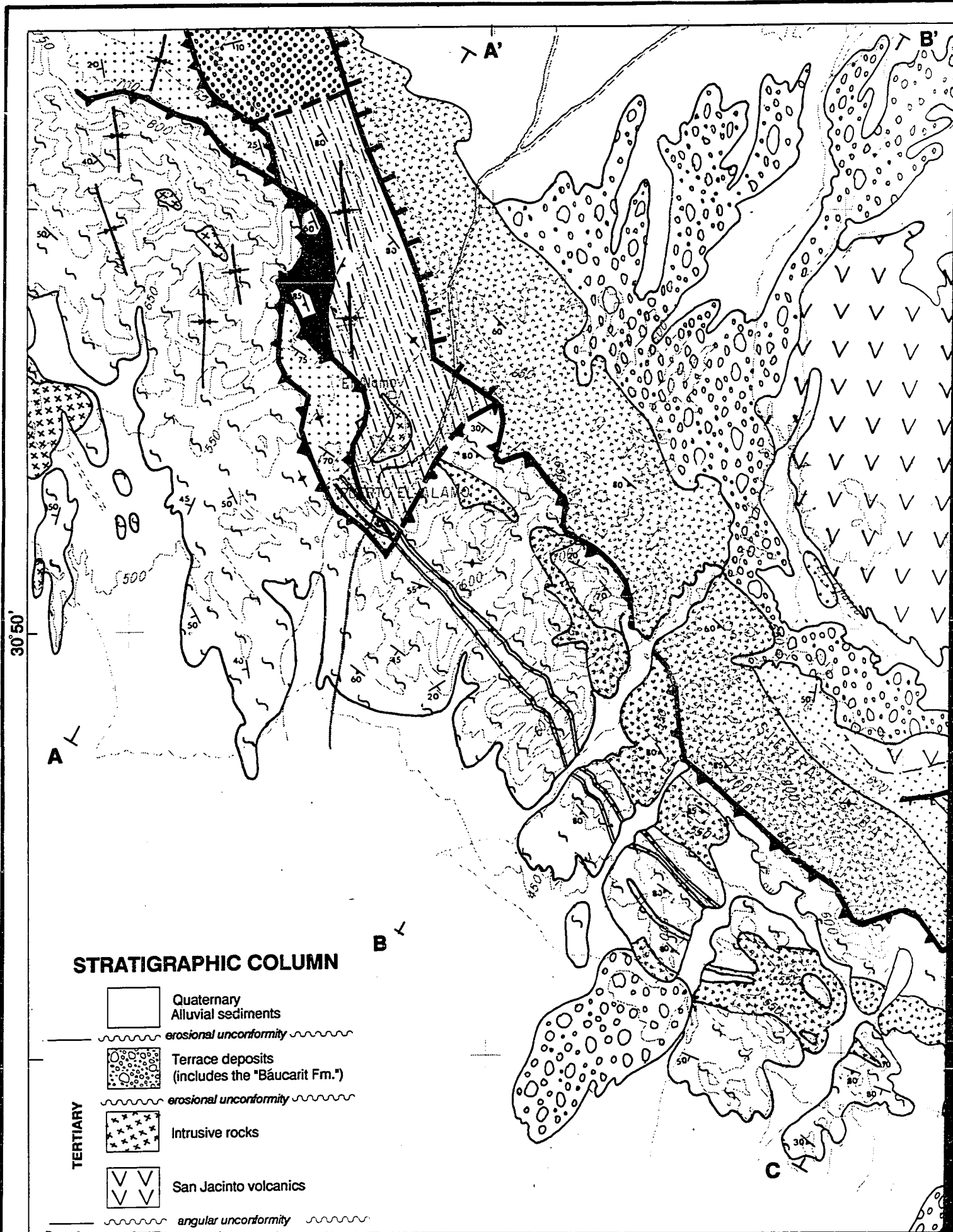
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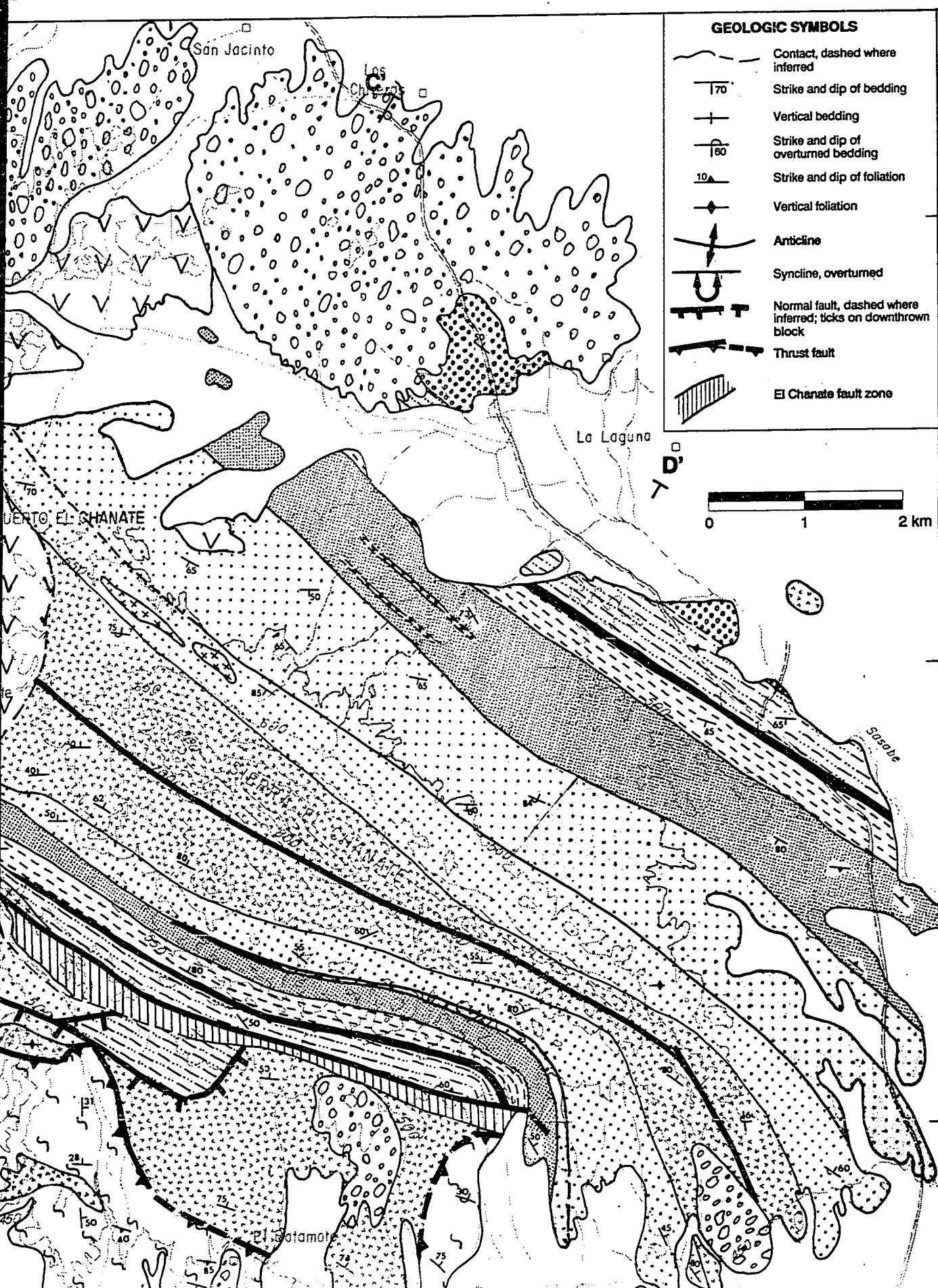
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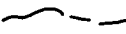
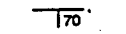
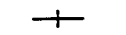
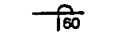
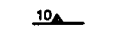


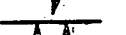





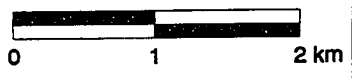


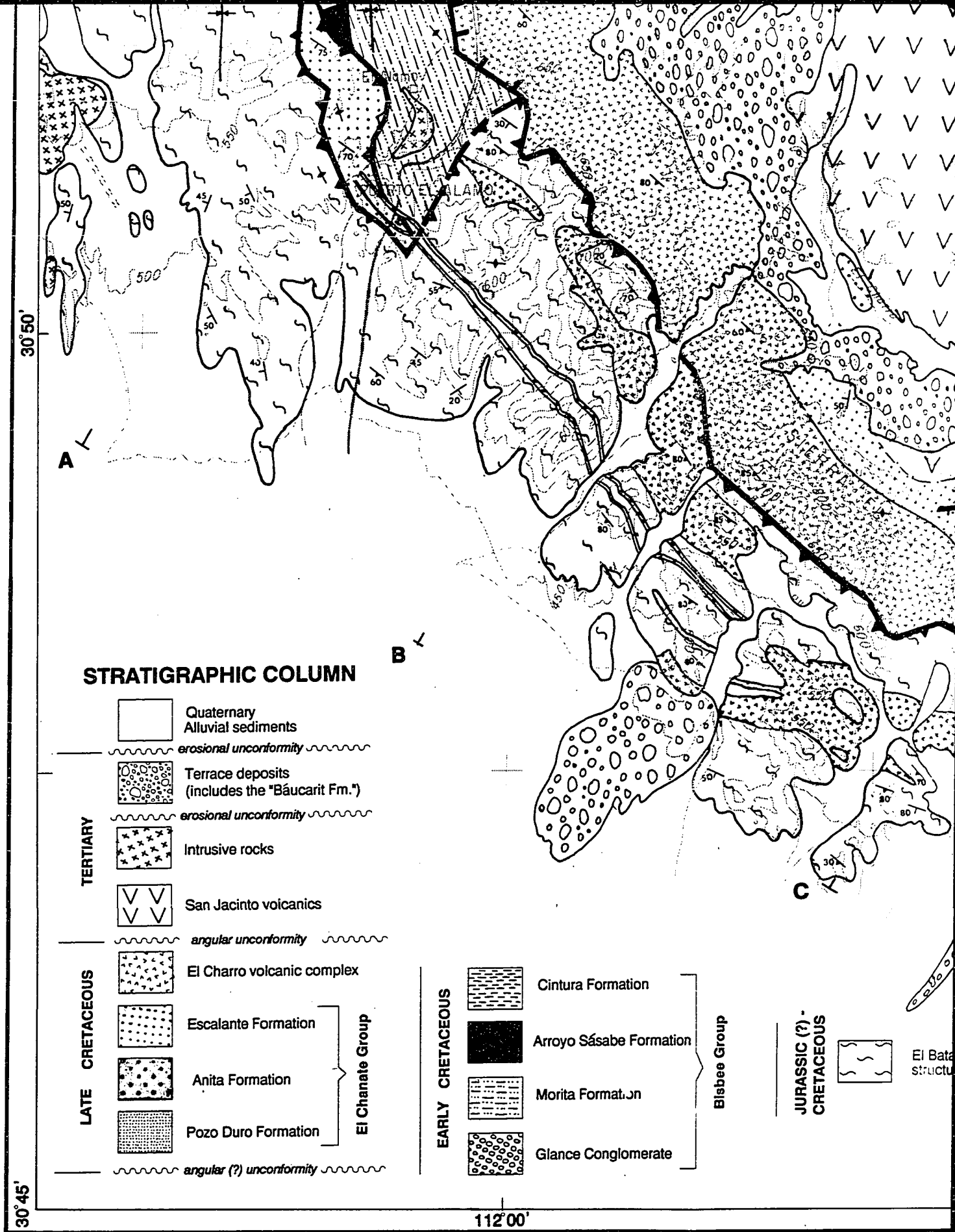
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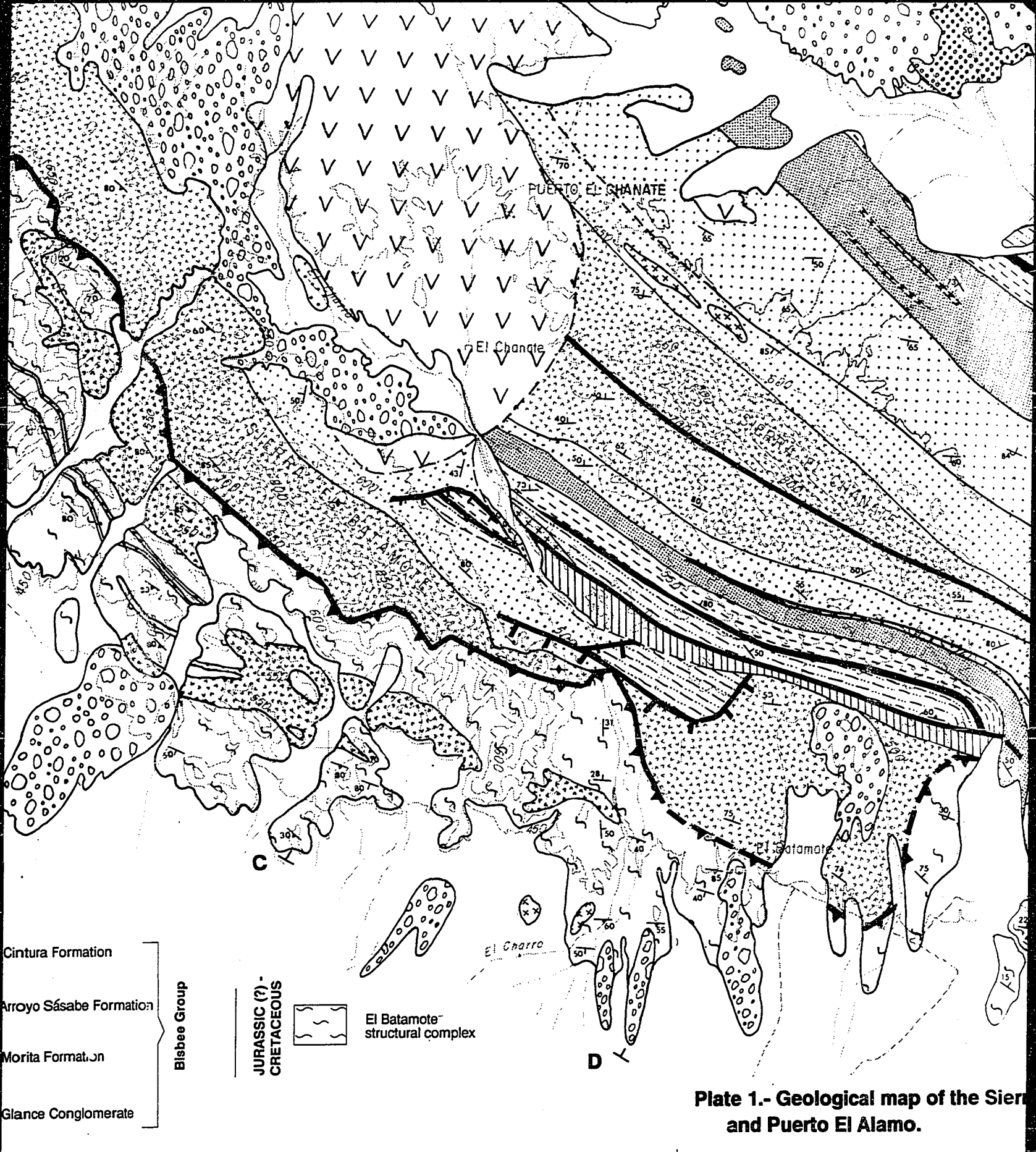


**GEOLOGIC SYMBOLS**

-  Contact, dashed where inferred
-  Strike and dip of bedding
-  Vertical bedding
-  Strike and dip of overturned bedding
-  Strike and dip of foliation
-  Vertical foliation
-  Anticline
-  Syncline, overturned
-  Normal fault, dashed where inferred; ticks on downthrown block
-  Thrust fault
-  El Chanate fault zone

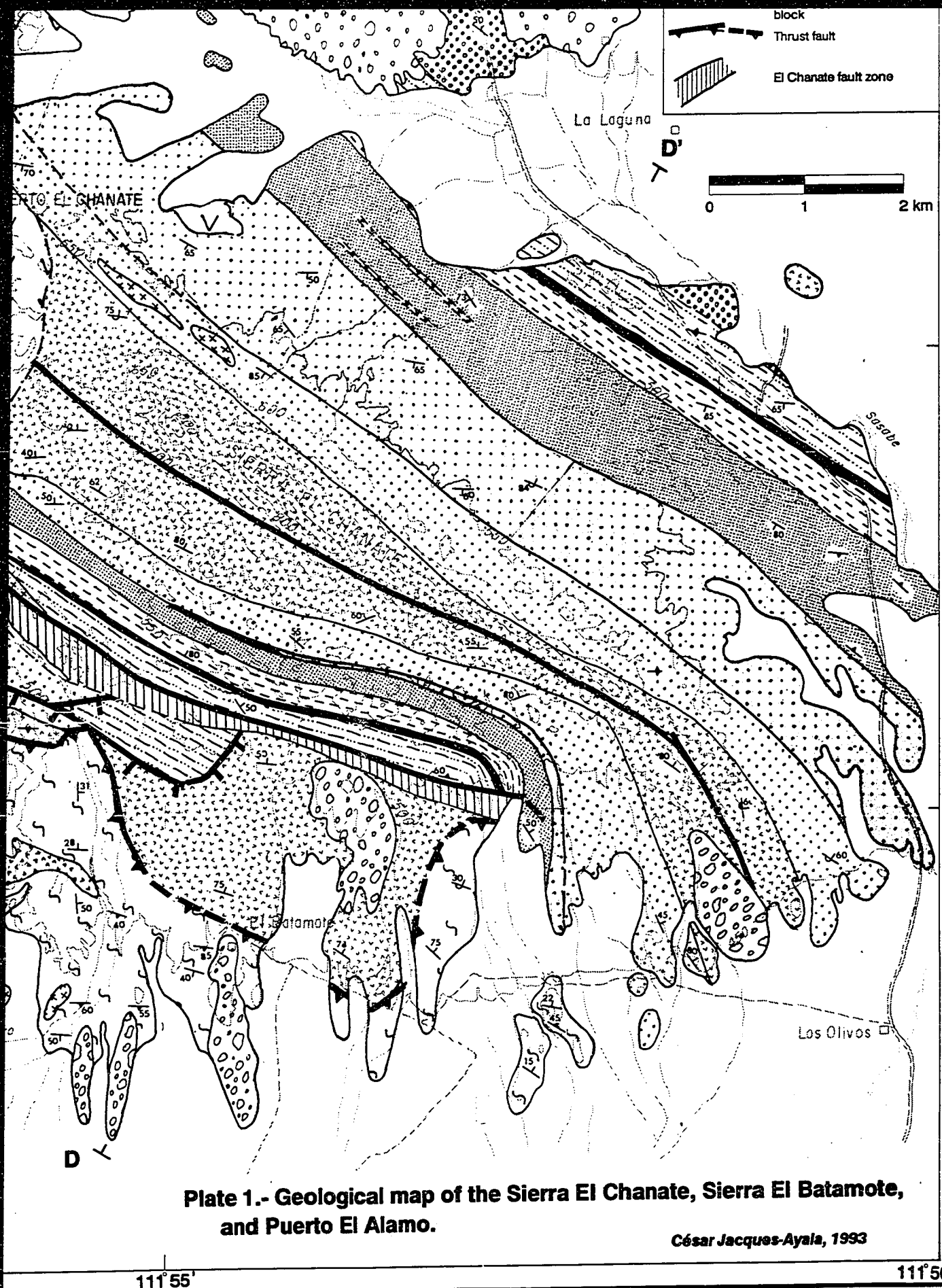






**Plate 1.- Geological map of the Sierra and Puerto El Alamo.**

111° 55'

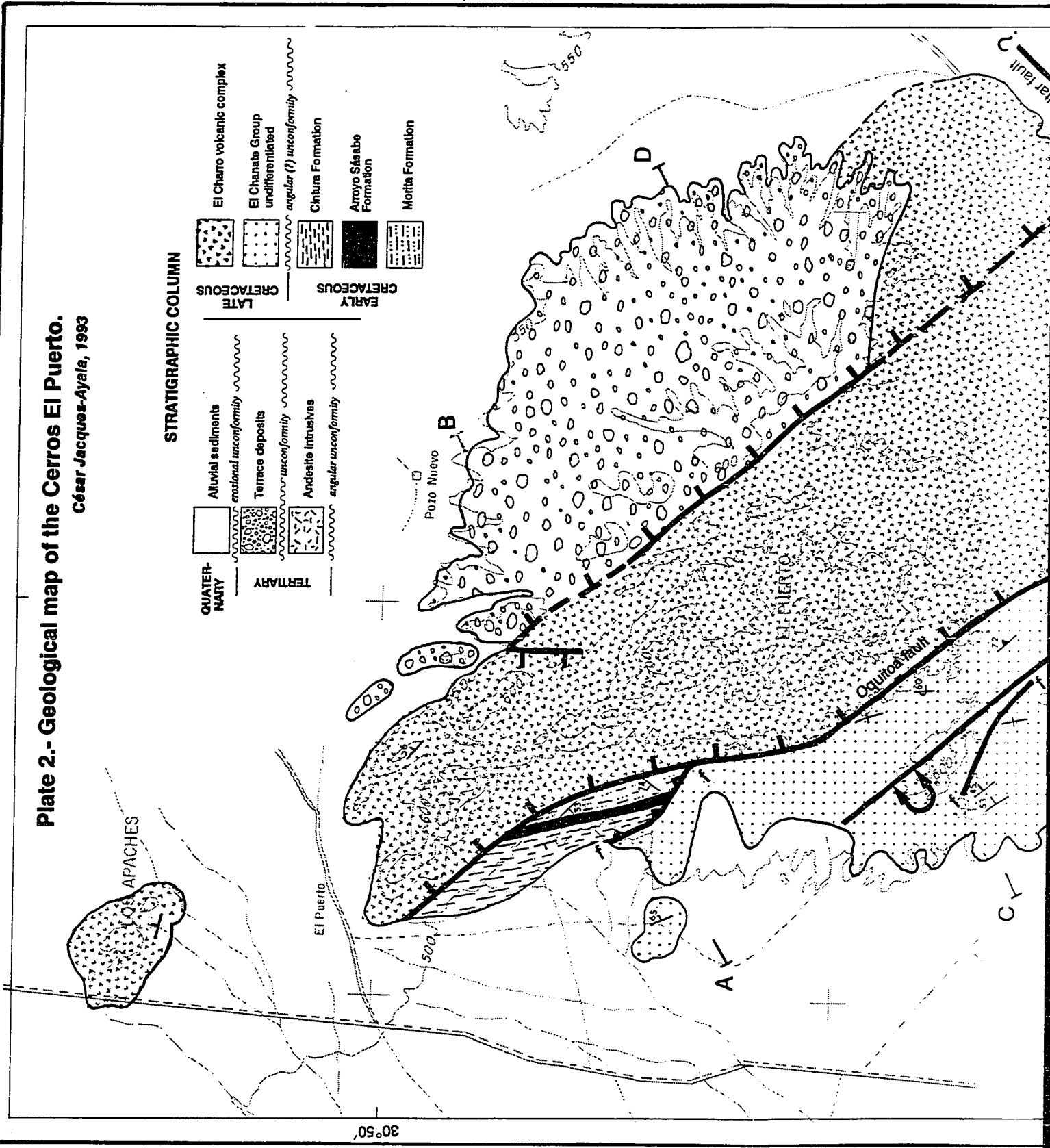
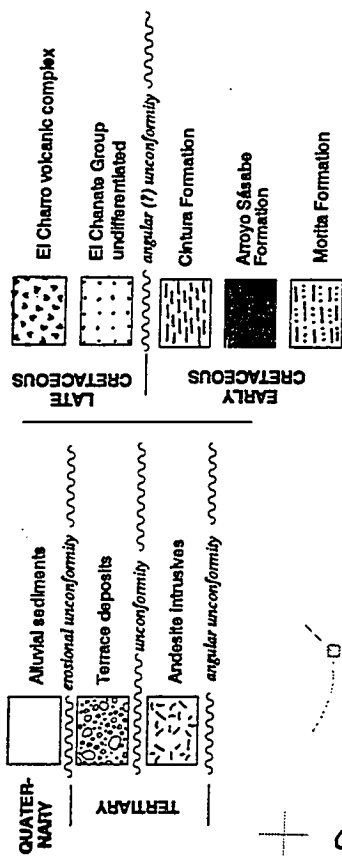


**Plate 1.- Geological map of the Sierra El Chanate, Sierra El Batamote, and Puerto El Alamo.**

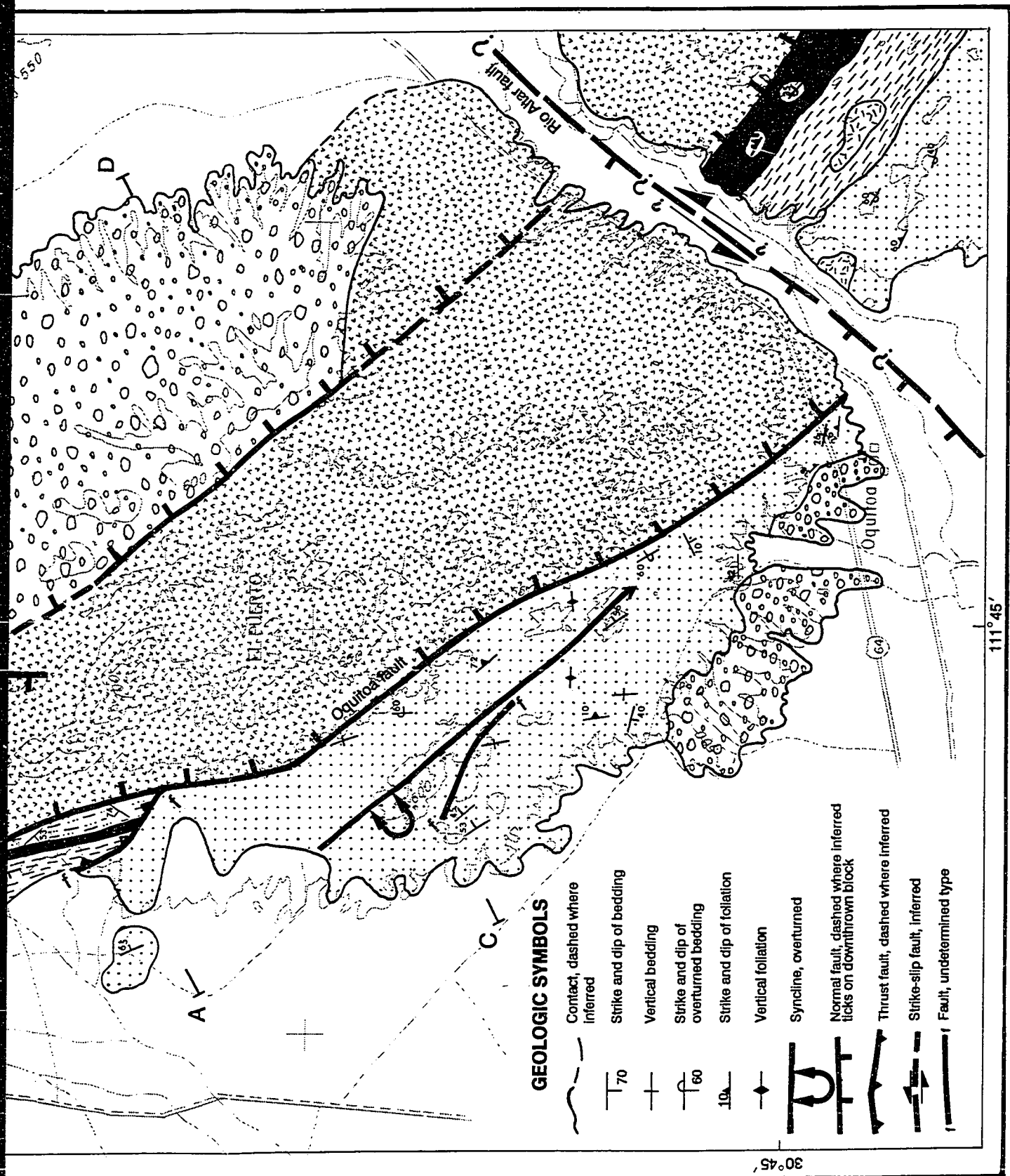
*César Jacques-Ayala, 1993*

**Plate 2.- Geological map of the Cerros El Puerto.**  
 César Jacques-Ayala, 1993

**STRATIGRAPHIC COLUMN**









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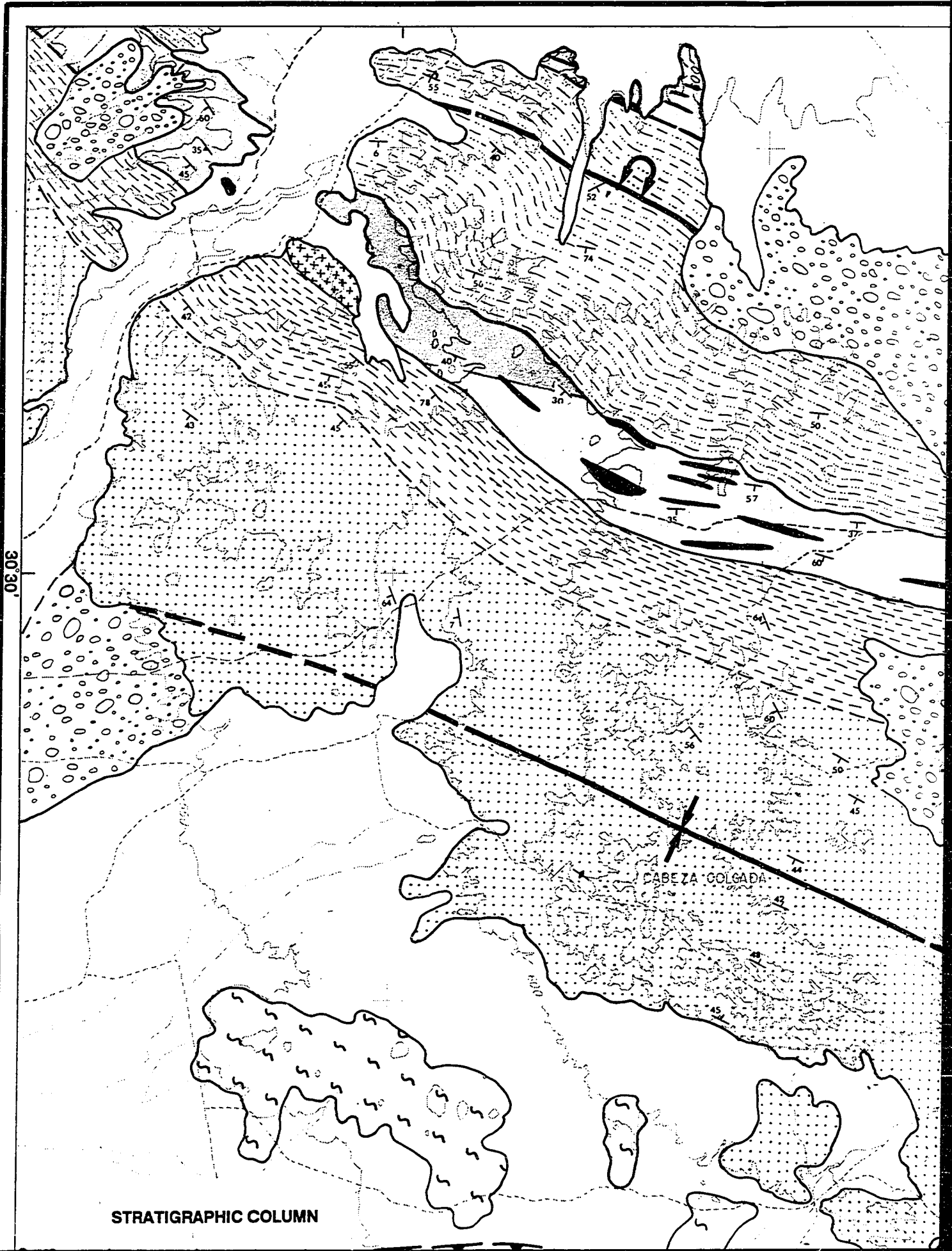
**LEFT TO RIGHT, TOP TO BOTTOM, WITH SMALL OVERLAPS**

The following map or chart has been refilmed in its entirety at the end of this dissertation (not available on microfiche). A xerographic reproduction has been provided for paper copies and is inserted into the inside of the back cover.

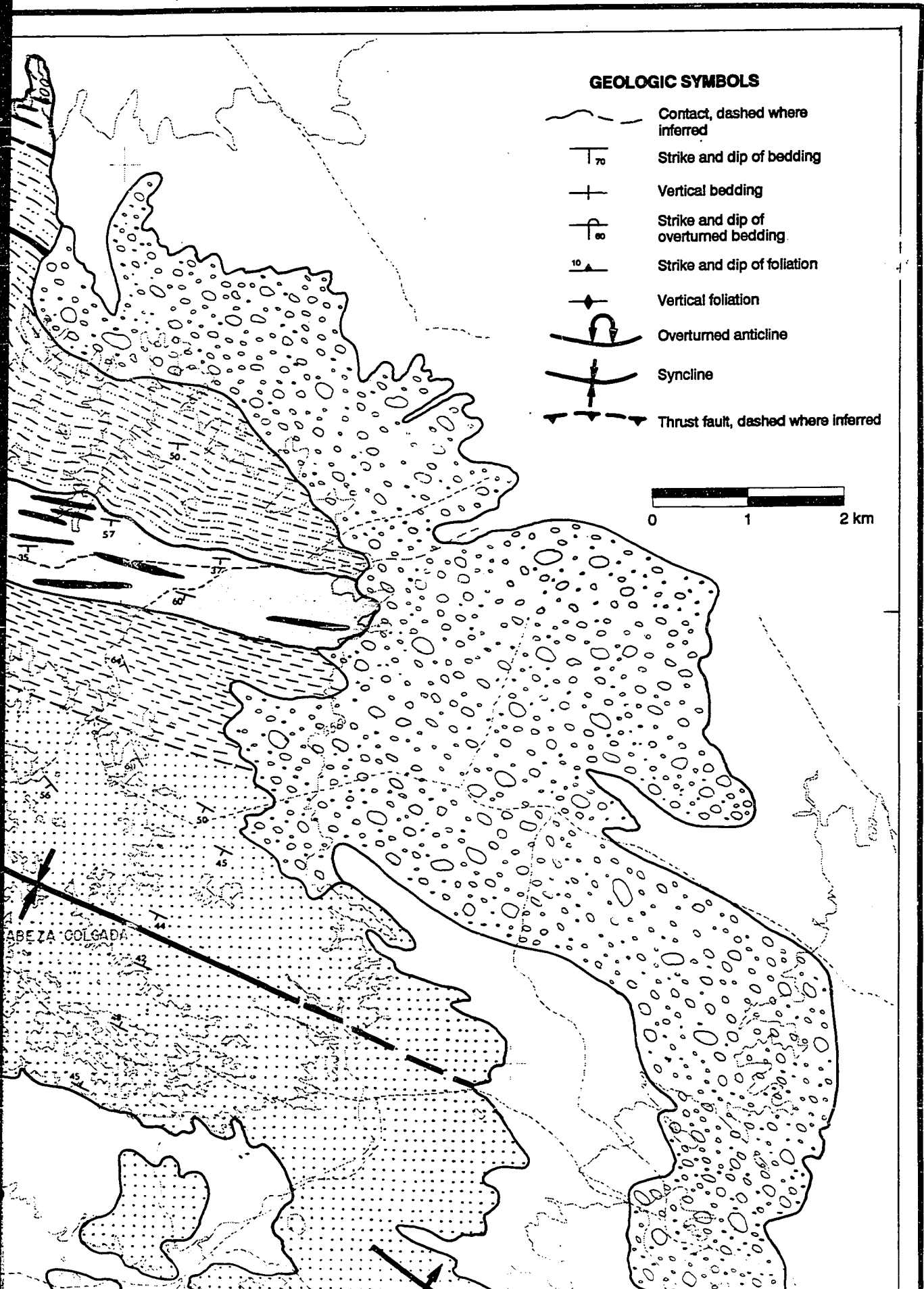
Black and white photographic prints (17" x 23") are available for an additional charge.

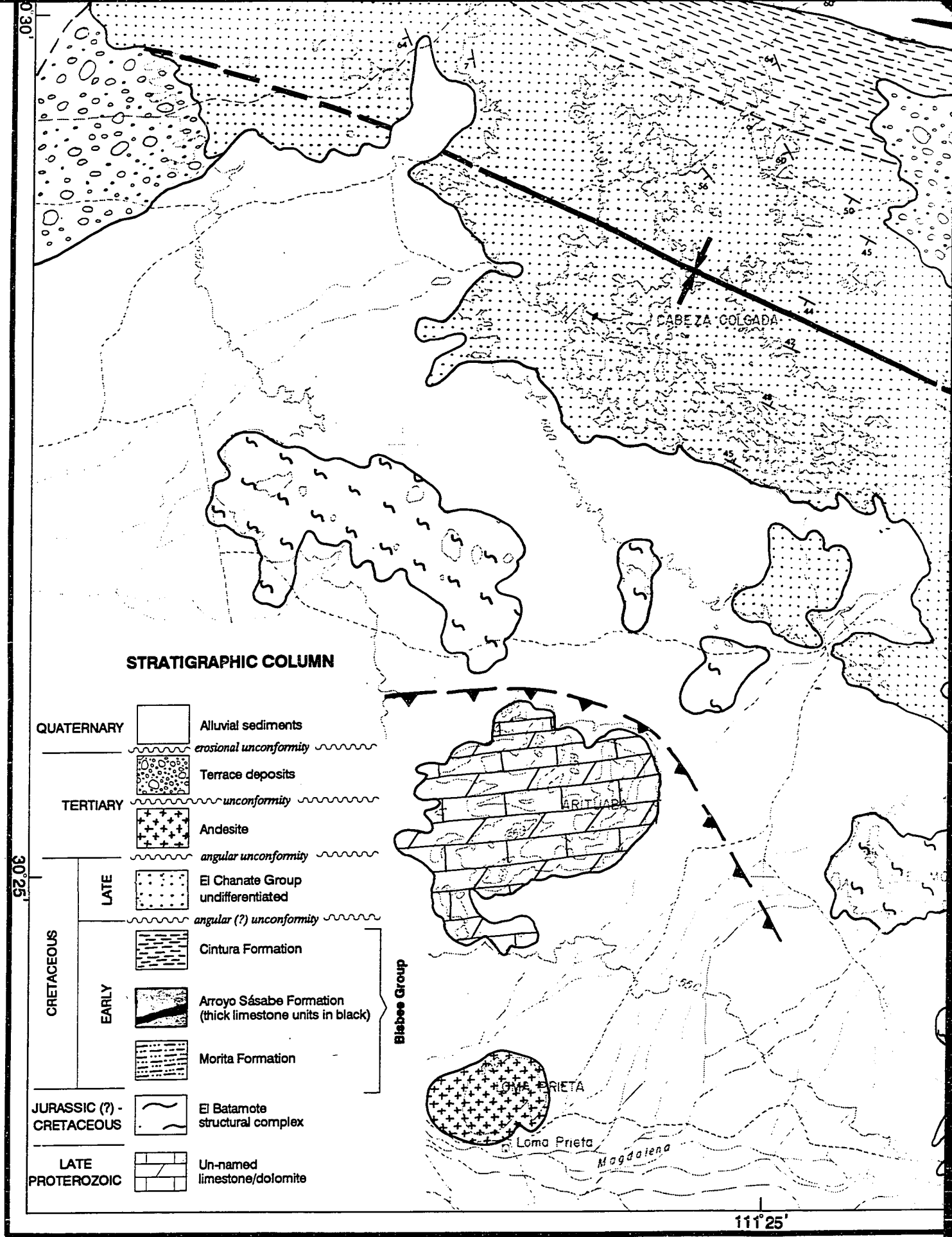
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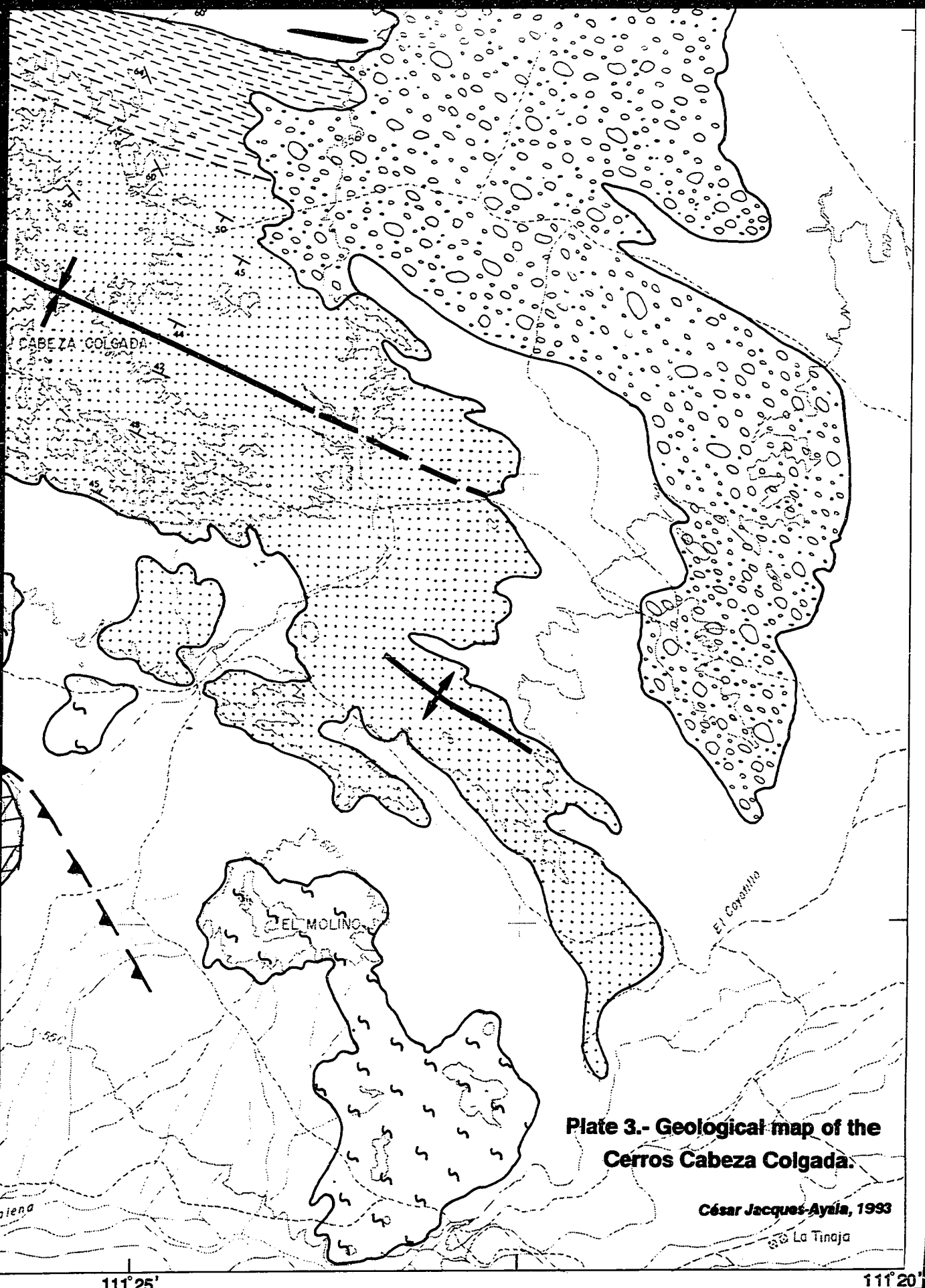




**STRATIGRAPHIC COLUMN**







**Plate 3.- Geological map of the  
Cerros Cabeza Colgada.**

**César Jacques Ayala, 1993**

La Tinaja

111° 25'

111° 20'

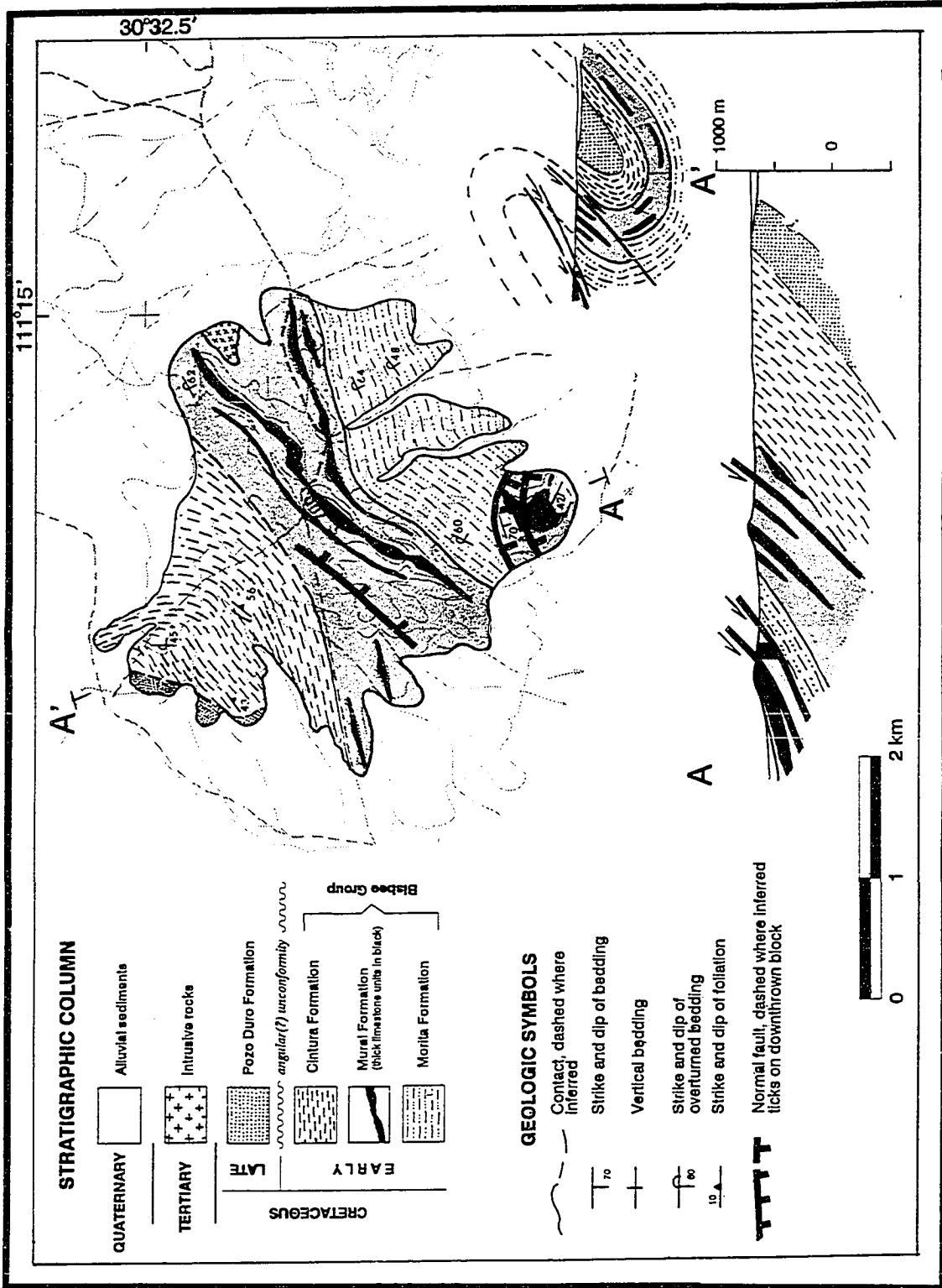
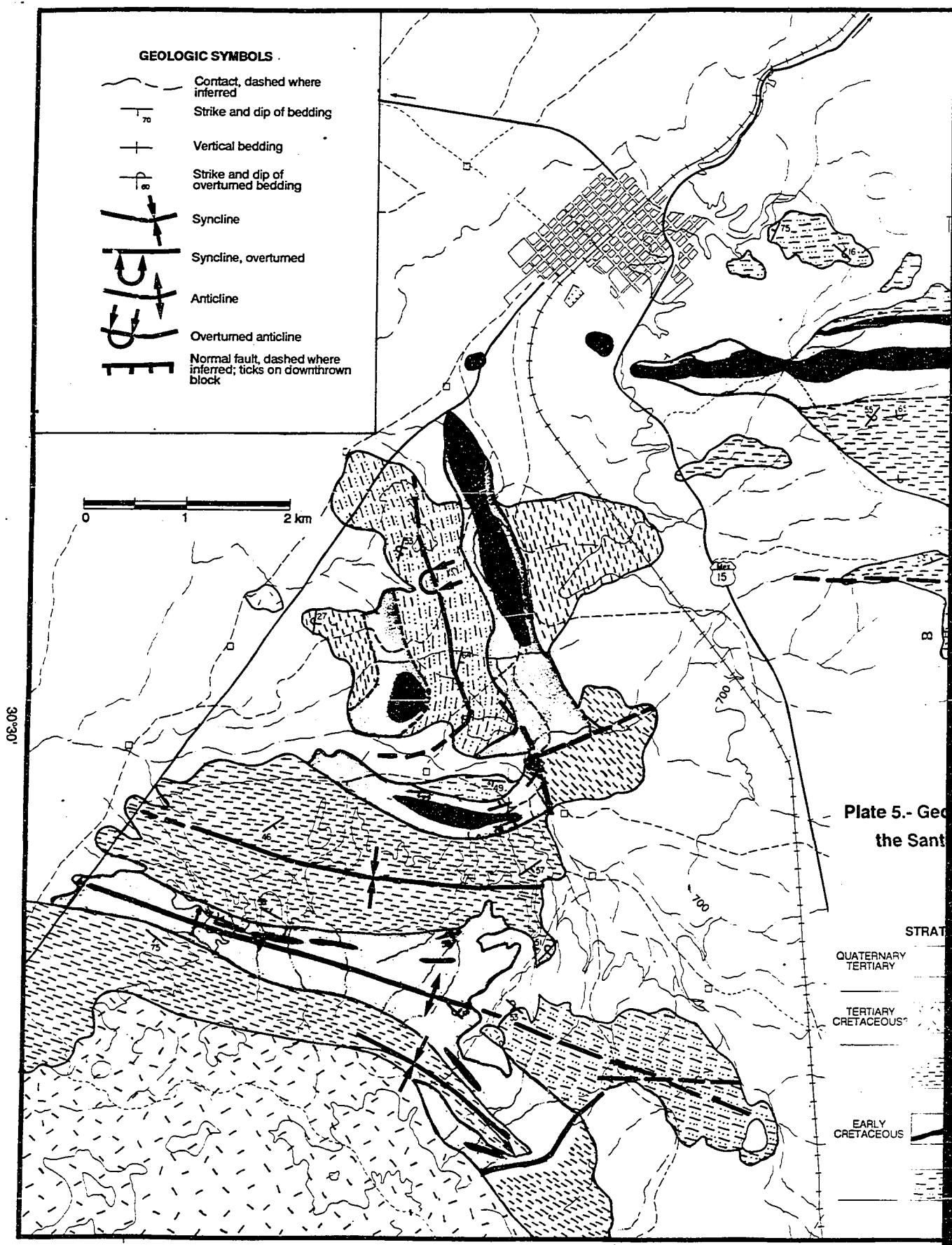


Plate 4.- Geological map, structural cross-section and interpreted fold, Cerro La Pima  
César Jacques-Ayala, 1993





**SYMBOLS**

Fault, dashed where  
 and dip of bedding

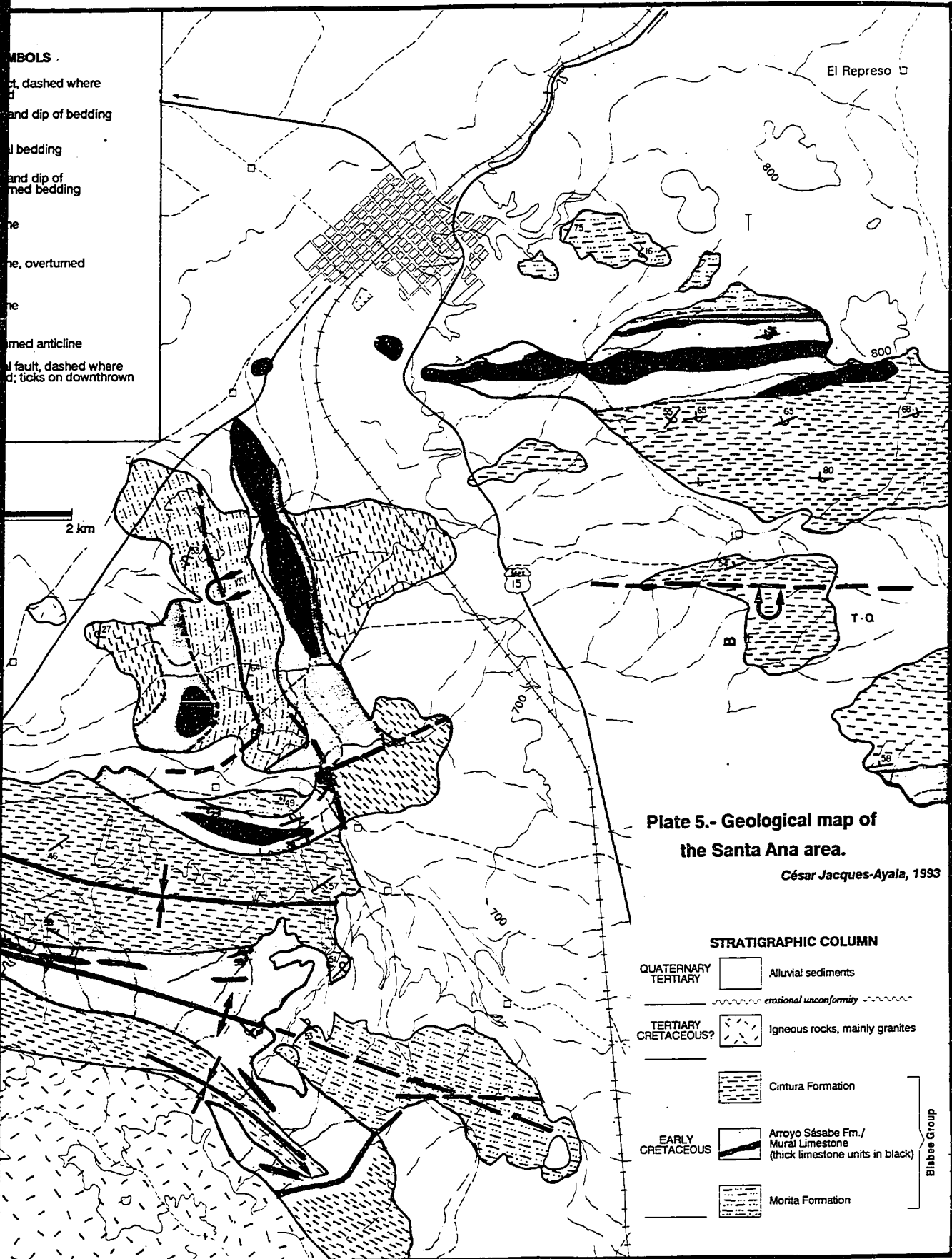
Bedding  
 and dip of  
 overturned bedding

Anticline  
 overturned

Normal anticline

Normal fault, dashed where  
 downthrown; ticks on downthrown

2 km



**Plate 5.- Geological map of the Santa Ana area.**

*César Jacques-Ayala, 1993*

**STRATIGRAPHIC COLUMN**

- |                         |  |   |
|-------------------------|--|---|
| QUATERNARY              |  | Alluvial sediments  |
|                         |  | erosional unconformity  |
| TERTIARY<br>CRETACEOUS? |  | Igneous rocks, mainly granites  |
|                         |  | Cintura Formation   |
| EARLY<br>CRETACEOUS     |  | Arroyo Sásabe Fm./<br>Mural Limestone<br>(thick limestone units in black) |
|                         |  | Morita Formation  |
- } Biabae Group

111°05'



**PLEASE NOTE:**

Oversize maps and charts are filmed in sections in the following manner:

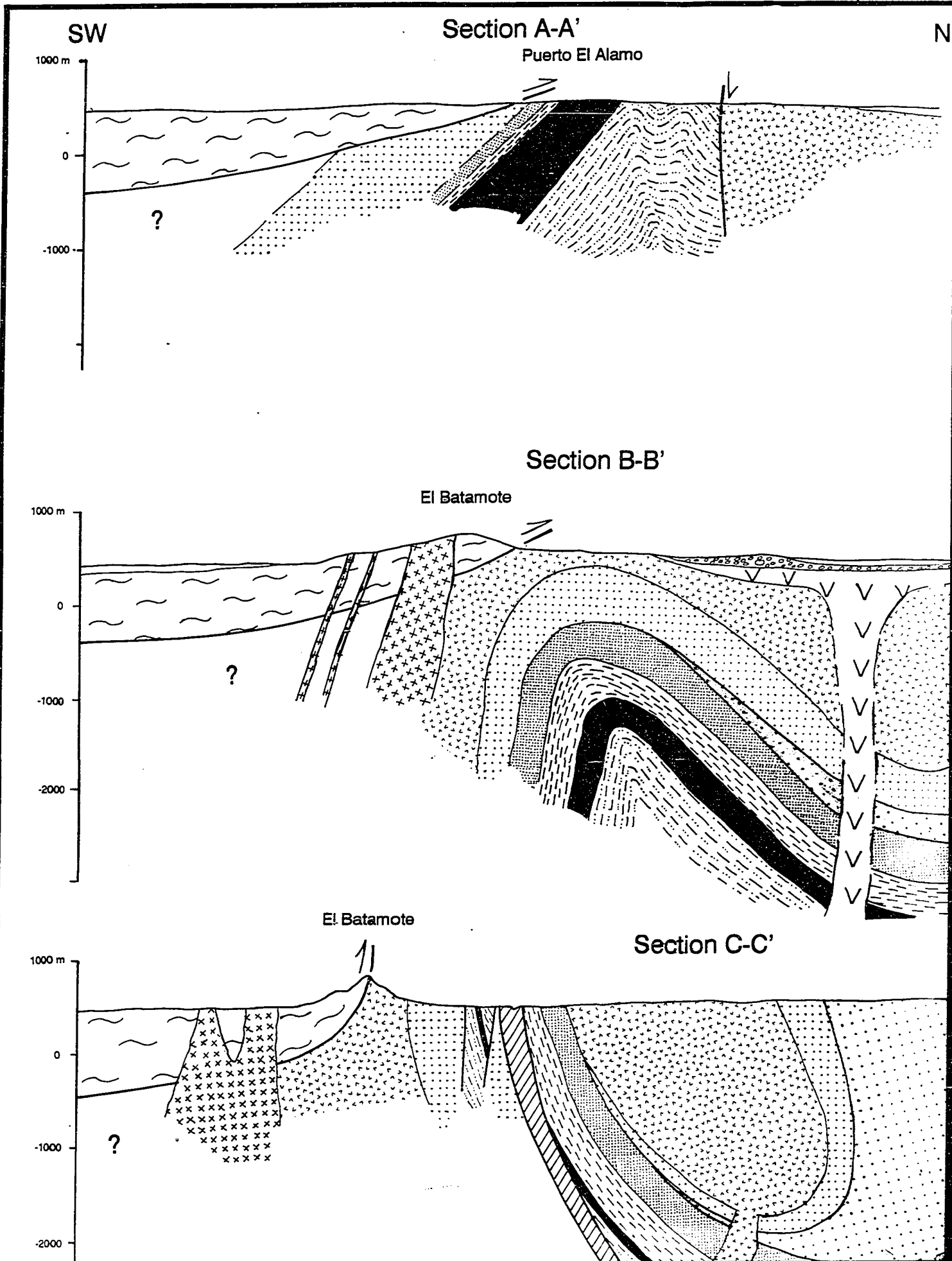
**LEFT TO RIGHT, TOP TO BOTTOM, WITH SMALL OVERLAPS**

The following map or chart has been refilmed in its entirety at the end of this dissertation (not available on microfiche). A xerographic reproduction has been provided for paper copies and is inserted into the inside of the back cover.

Black and white photographic prints (17" x 23") are available for an additional charge.

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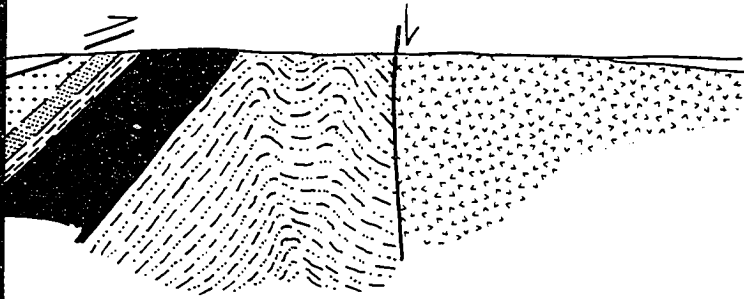




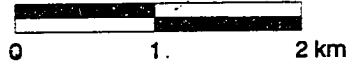
Section A-A'

Puerto El Alamo

NE

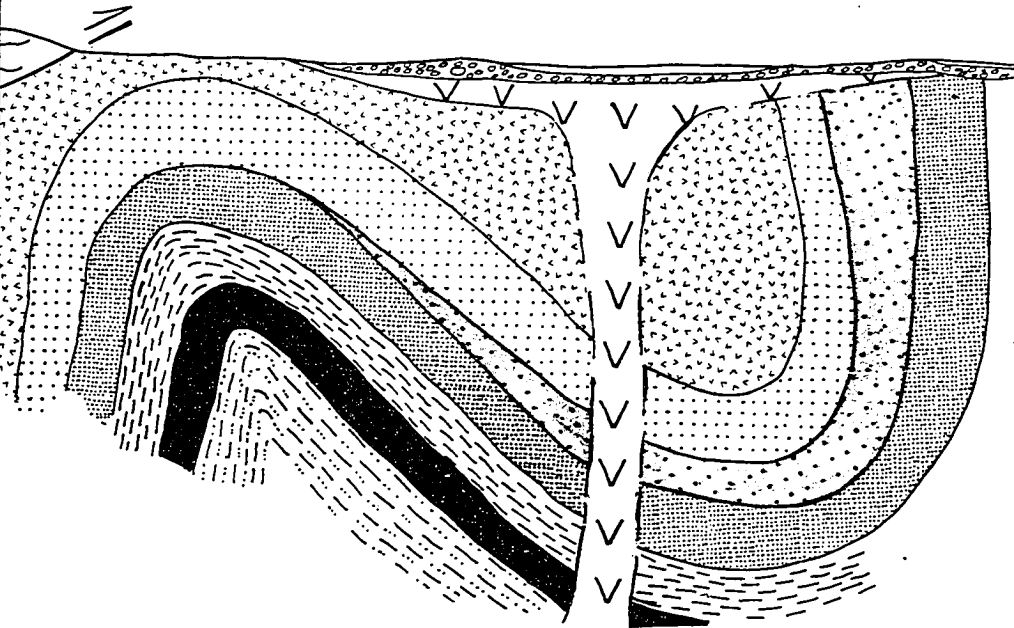


Symbols same as in Plate 1  
All sections have same orientation

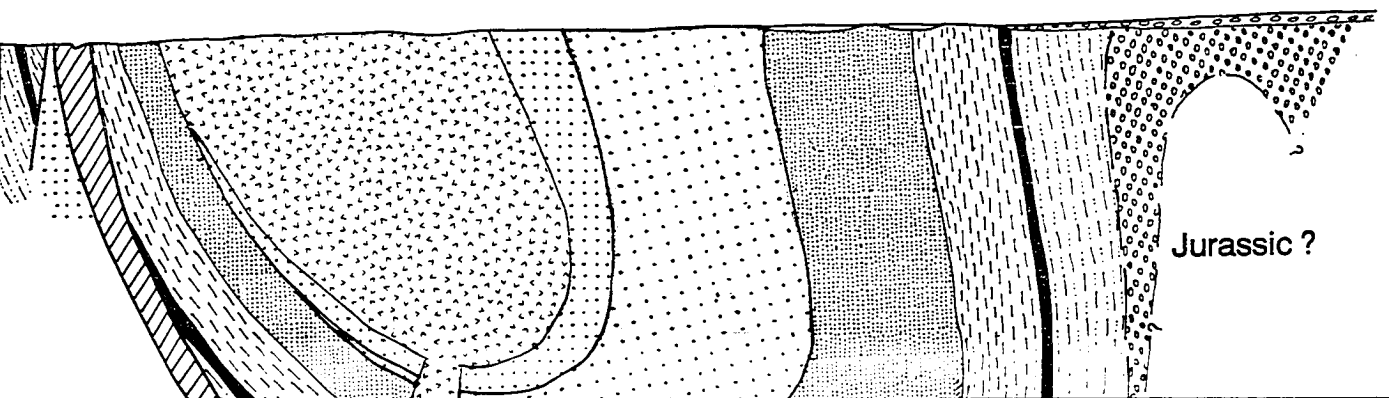


Section B-B'

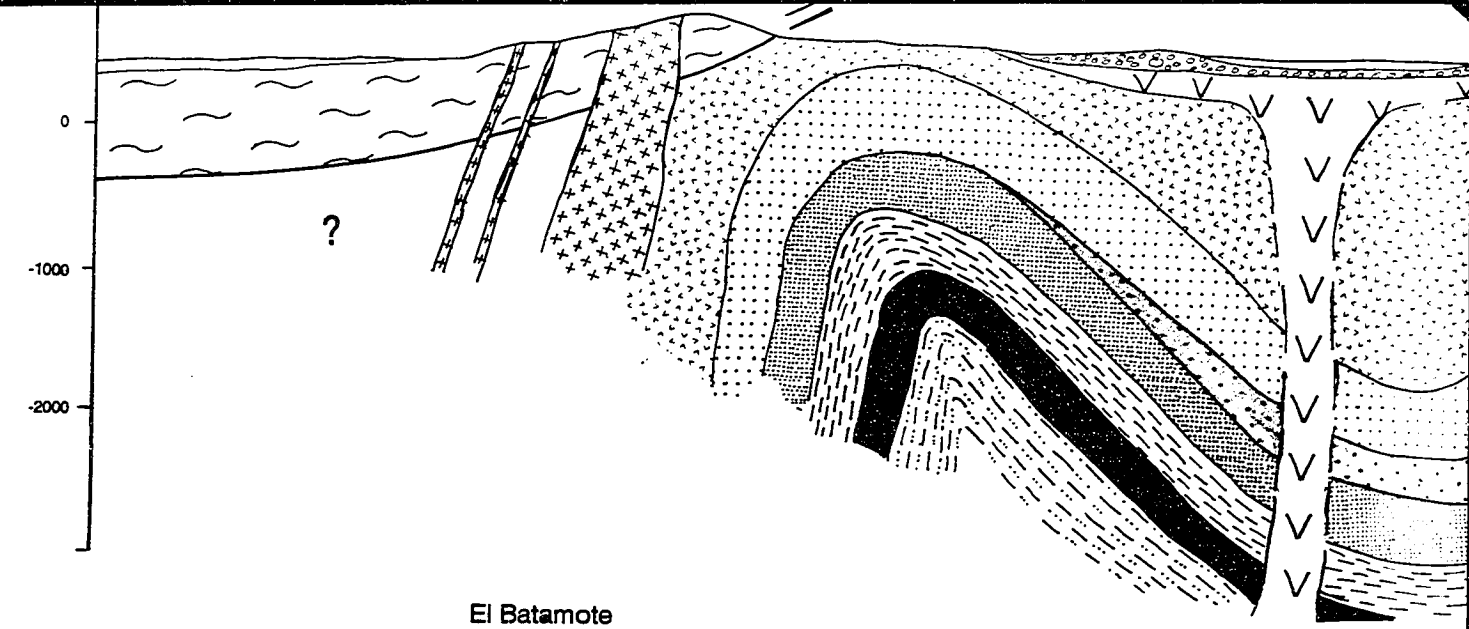
Amote



Section C-C'

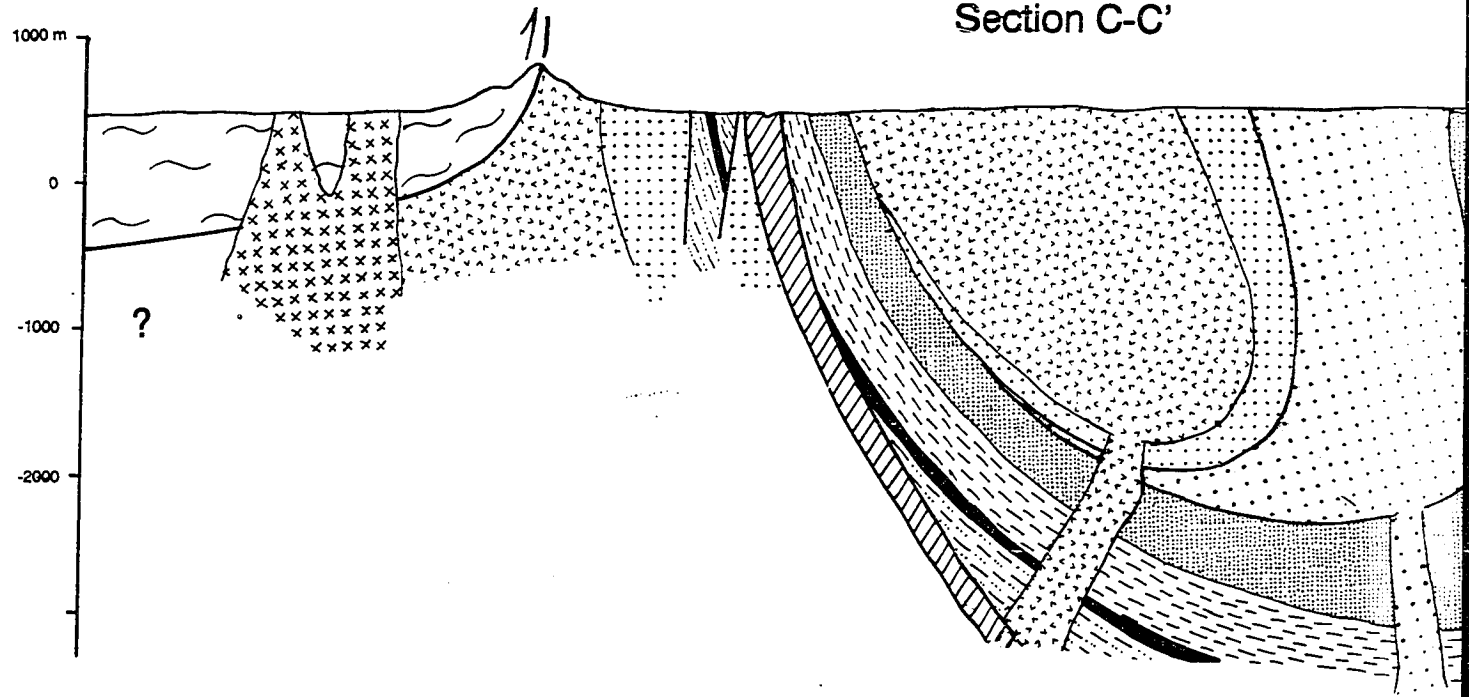


Jurassic ?



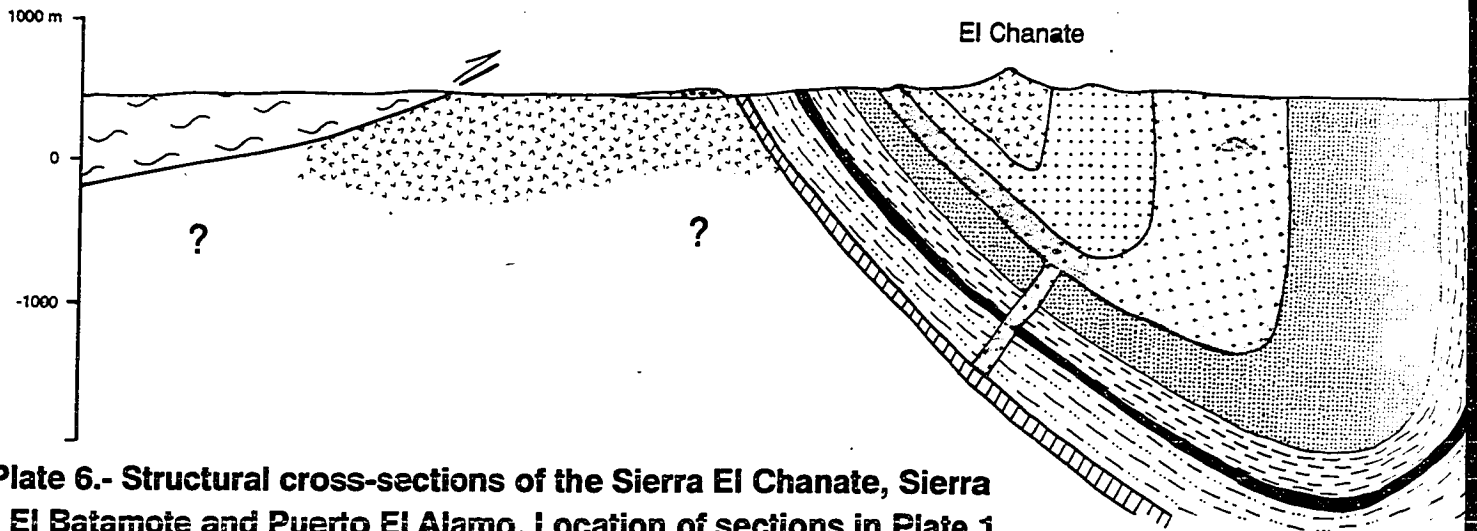
El Batamote

Section C-C'



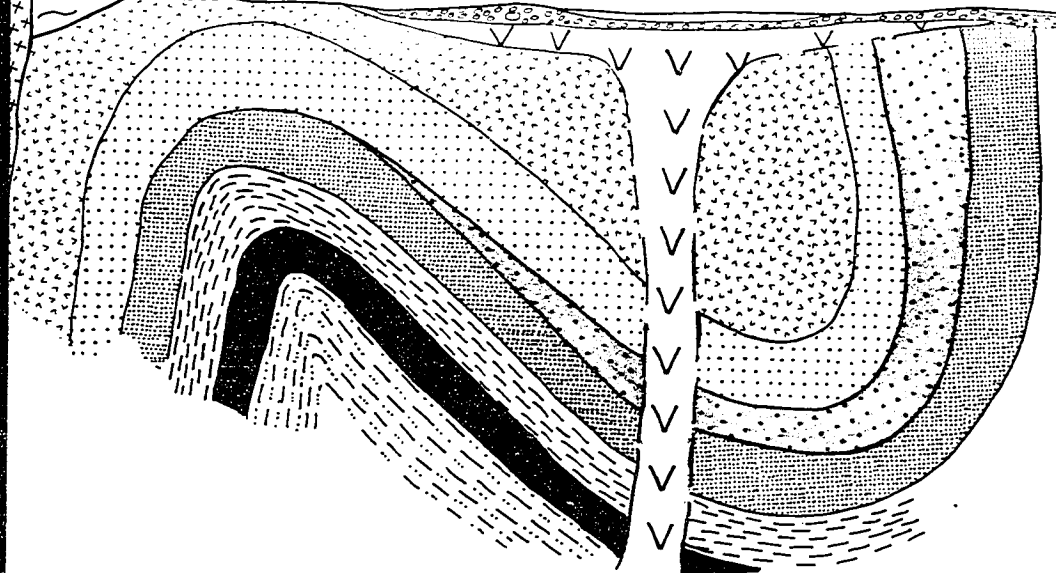
Section D-D'

El Chanate

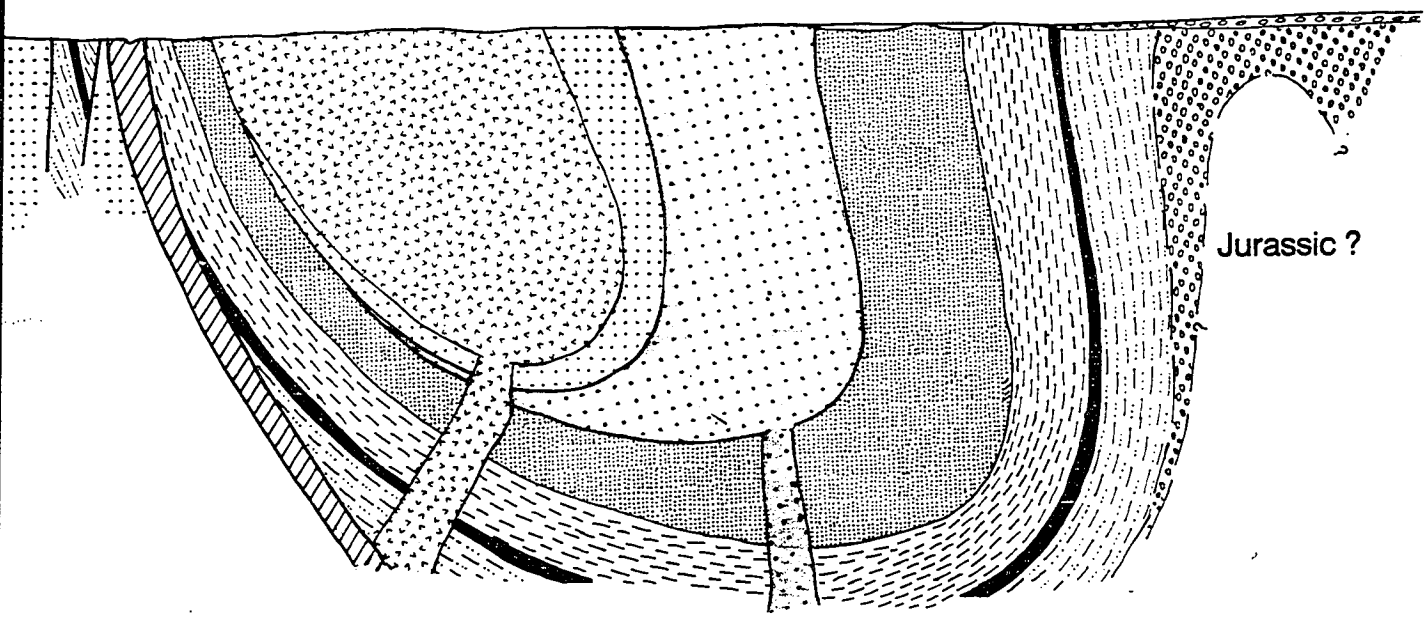


**Plate 6.- Structural cross-sections of the Sierra El Chanate, Sierra El Batamote and Puerto El Alamo. Location of sections in Plate 1.**

*César Jacques-Ayala, 1993*



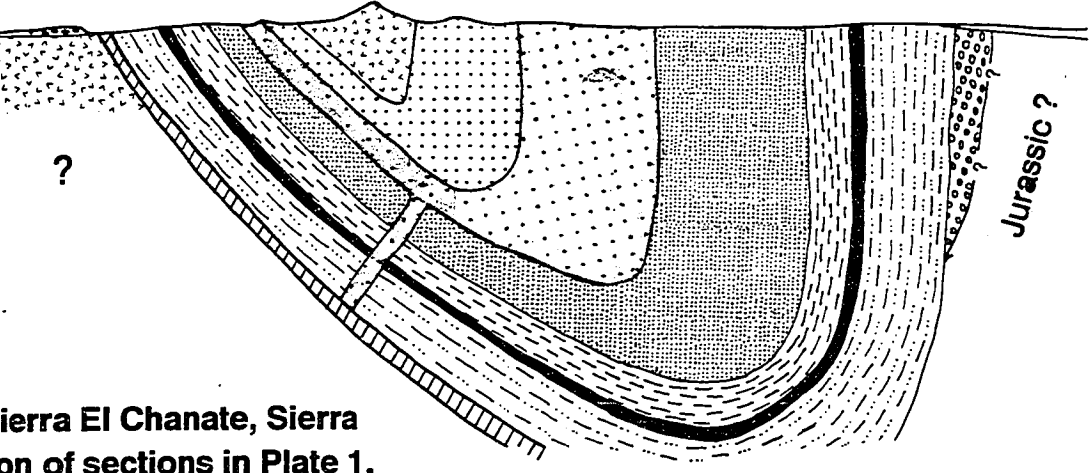
Section C-C'



Section D-D'

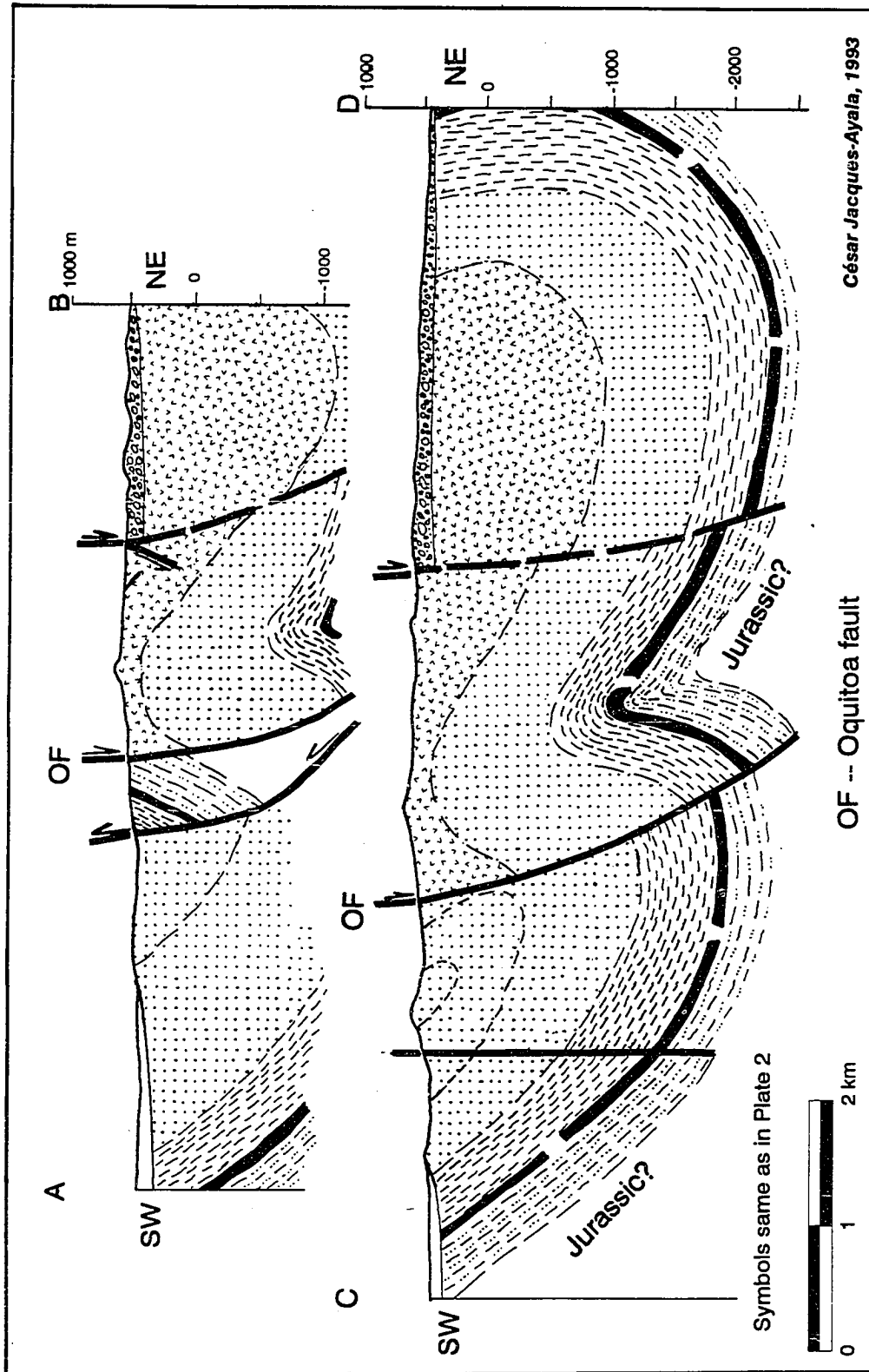
El Chanate

Jurassic ?

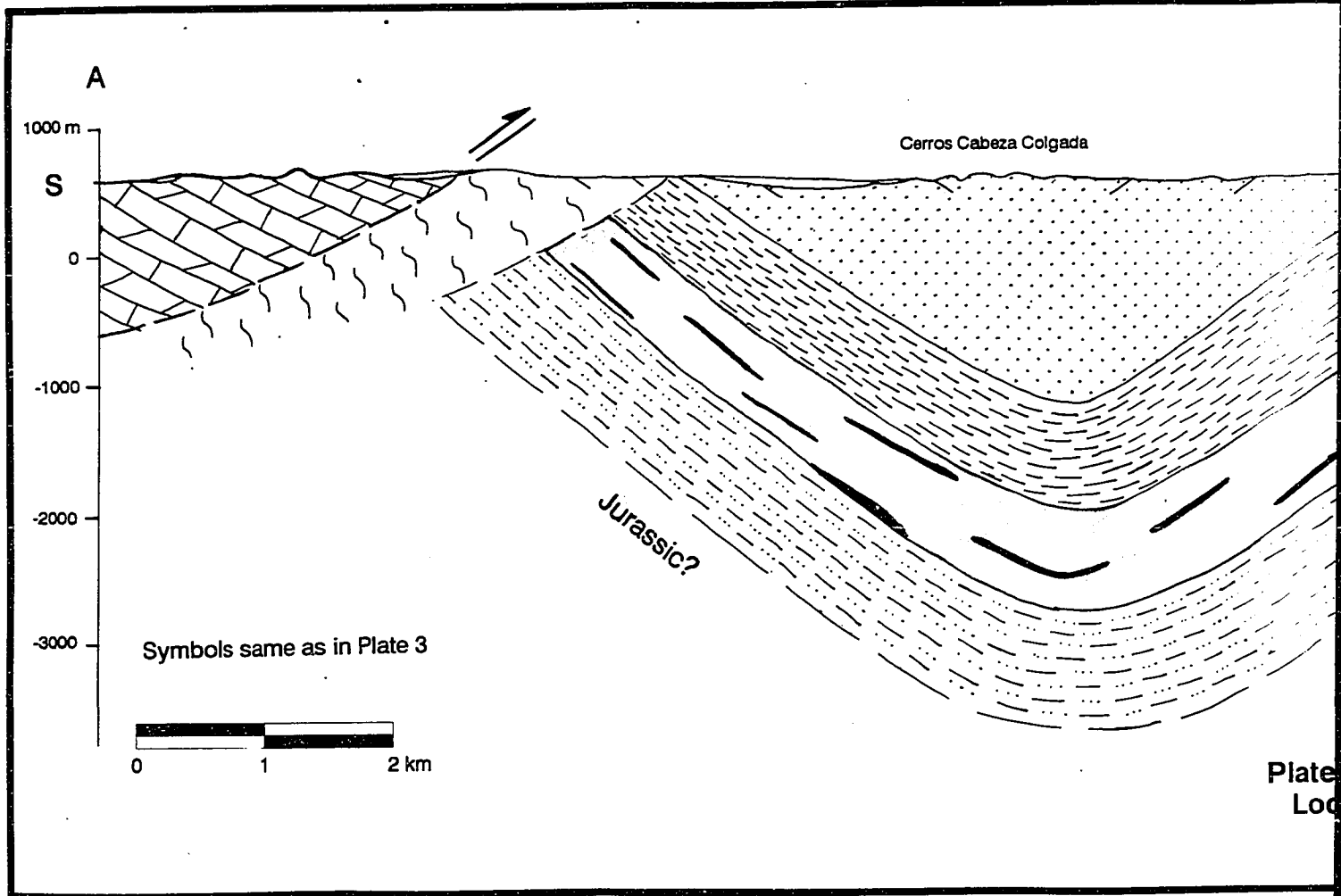


Jurassic ?

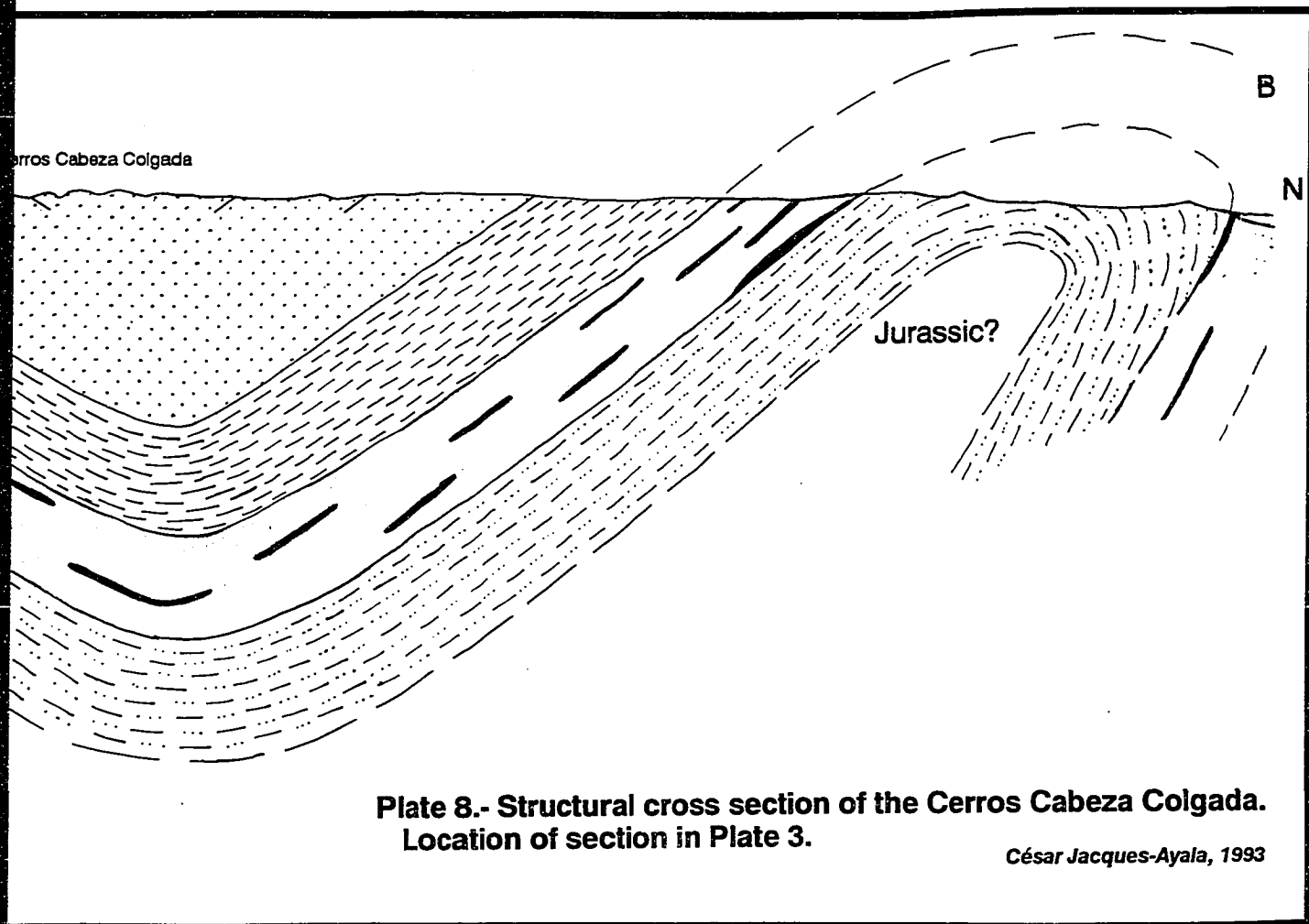
Sierra El Chanate, Sierra  
 on of sections in Plate 1.  
 César Jacques-Ayala, 1993



**Plate 7.- Structural cross sections of the Cerros El Puerto.**  
**Location of sections in Plate 2.**



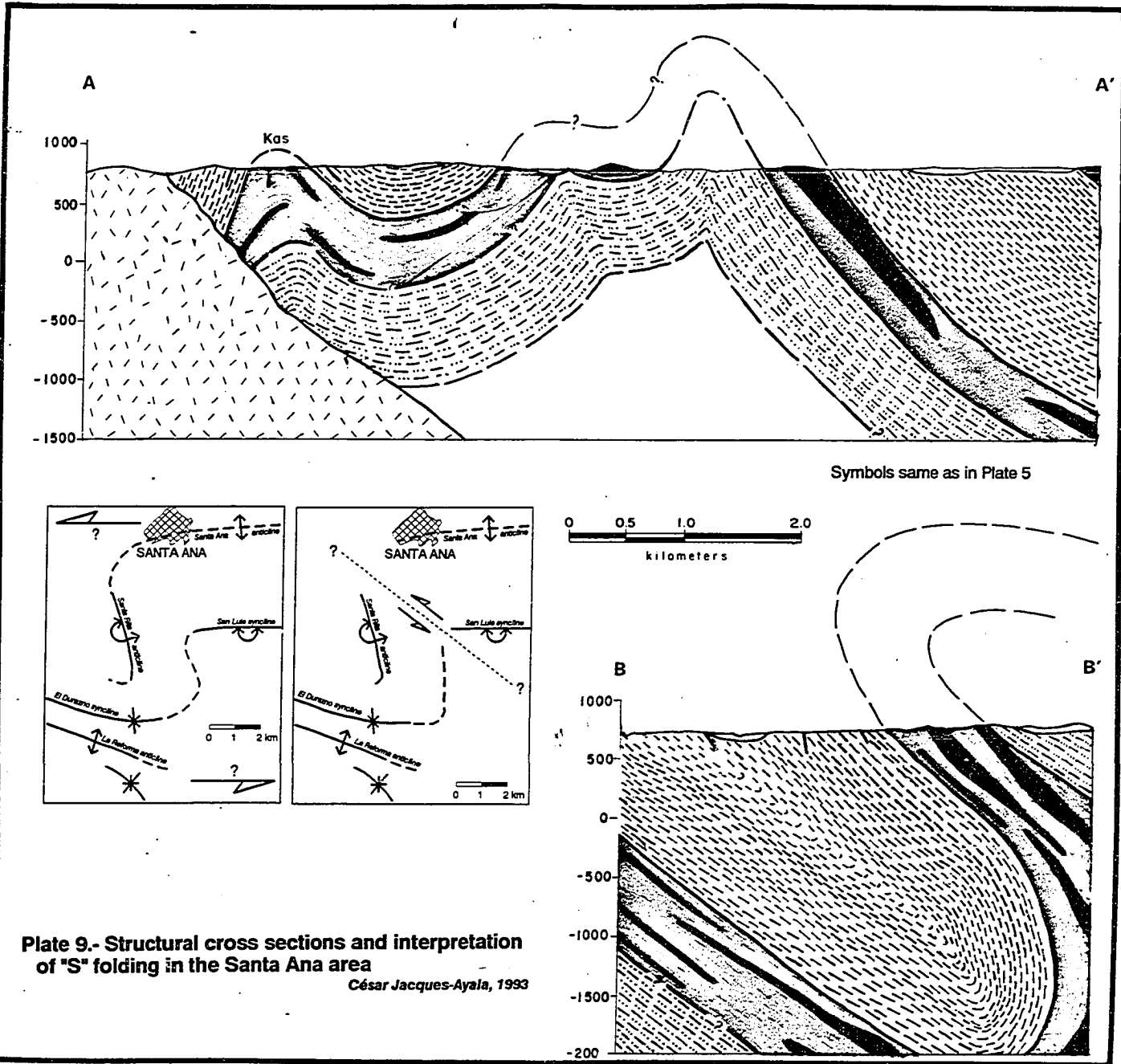




**Plate 8.- Structural cross section of the Cerros Cabeza Colgada.  
Location of section in Plate 3.**

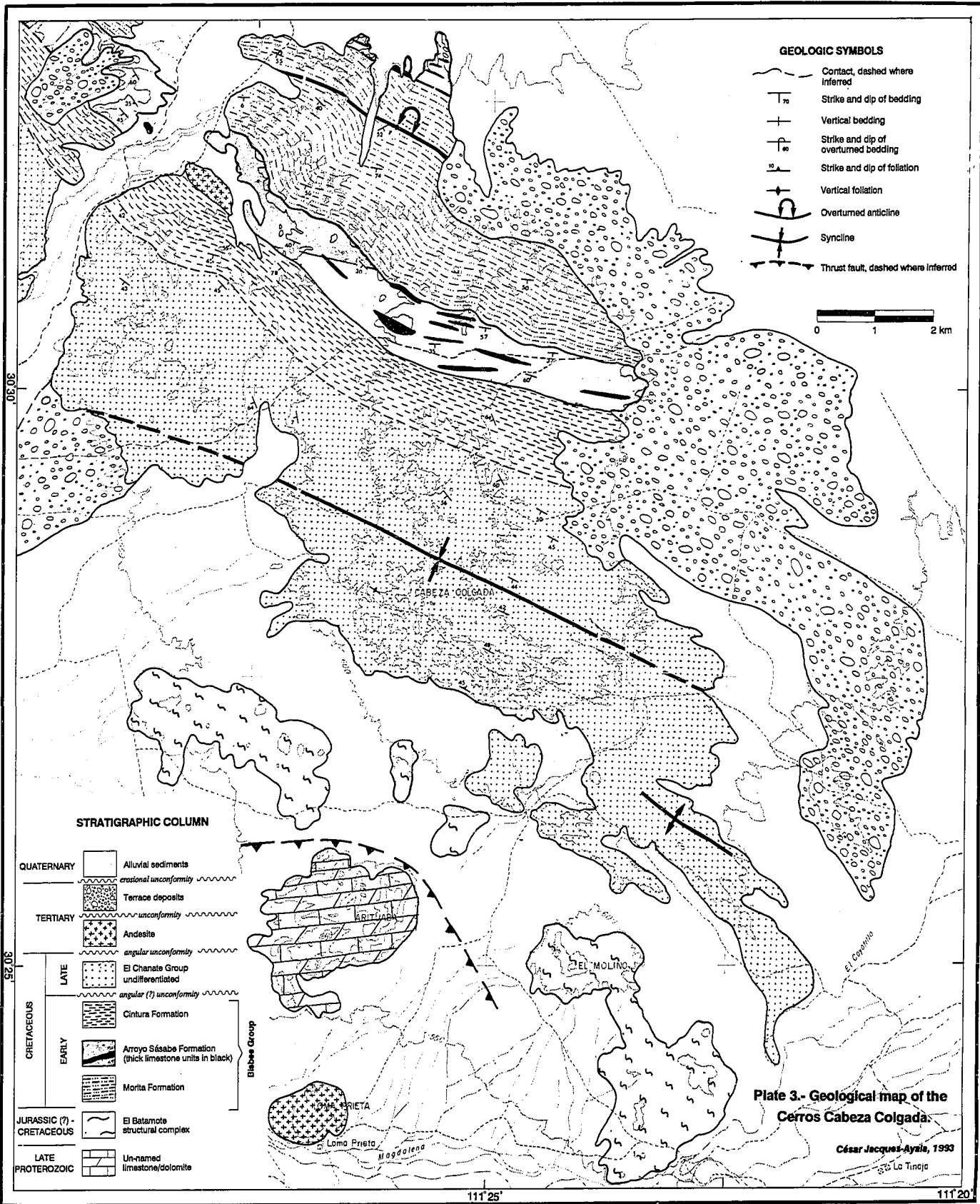
*César Jacques-Ayala, 1993*





**Plate 9.- Structural cross sections and interpretation of "S" folding in the Santa Ana area**  
*César Jacques-Ayala, 1993*





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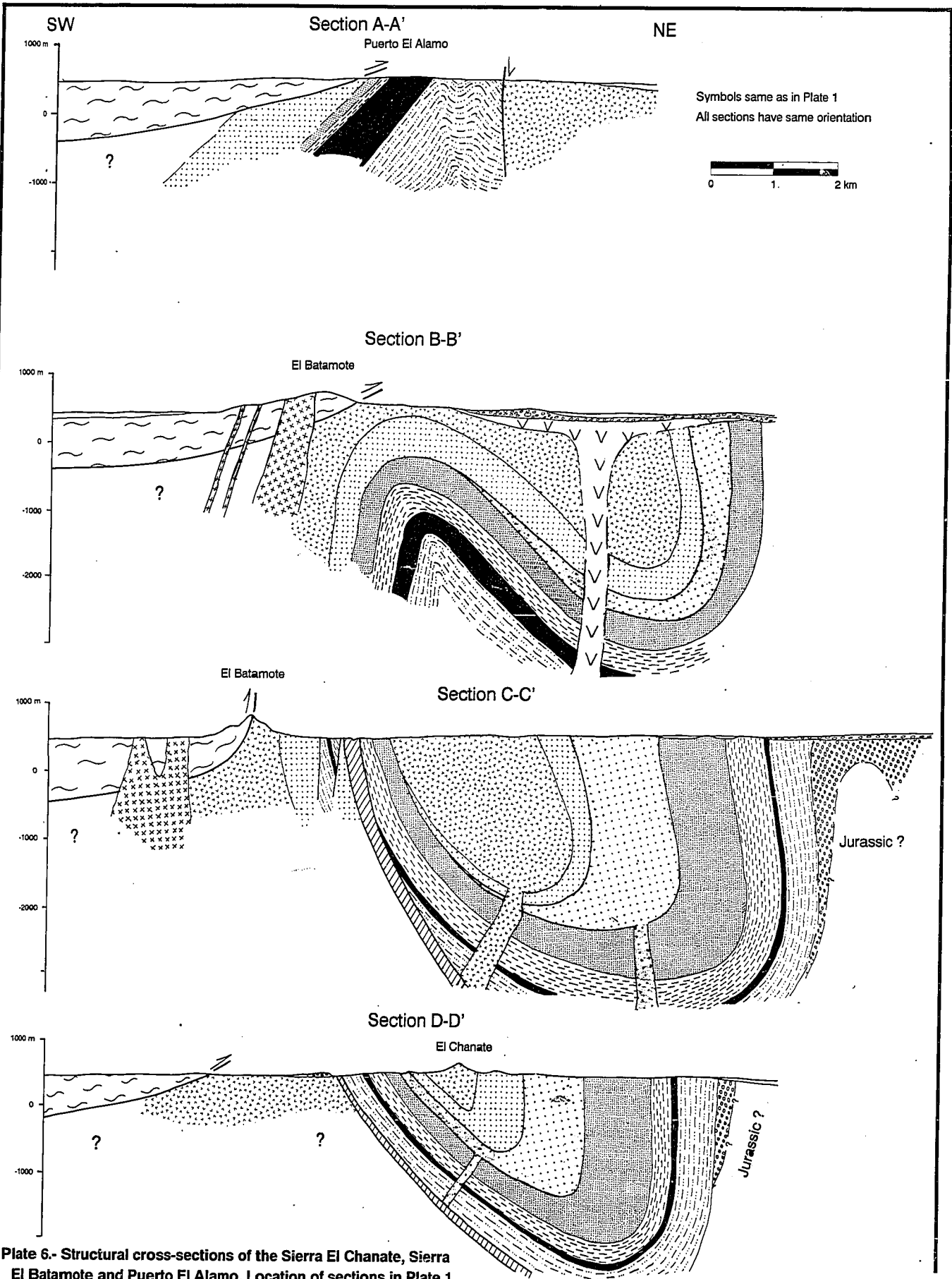


Plate 6.- Structural cross-sections of the Sierra El Chanate, Sierra El Batamote and Puerto El Alamo. Location of sections in Plate 1.  
César Jacques-Ayala, 1993

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