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CINTURA FORMATION—AN EARLY CRETACEOUS DELTAIC SYSTEM IN NORTHEASTERN SONORA, MEXICO

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ABSTRACT

The 1,146-m-thick Cintura Formation strata in northeastern Sonora represent a shallow-water fluvial-dominated delta system, developed along the northern edge of the Bisbee embayment in the latest Early Cretaceous time. This formation comprises three stratigraphic members which represent deltaic depositional elements. The basal Marquechi member (396 m) is made up of facies A, B and C, and was deposited in a subaqueous delta. The medial San Marcos member (498 m) is represented by the marginal marine to fluvial deposits of facies D1, D2, E, and F, that characterize the lower deltaic plain. The San Juan member (252 m) at the top, represents the upper deltaic plain where the sediments were deposited in fluvial and interdistributary environments (facies D3, G, H and I).

Paleocurrents and provenance data suggest that this delta prograded southward and its immediate source area was to the north.

Key words: Stratigraphy, Early Cretaceous, Sonora, Mexico.

RESUMEN

La Formación Cintura, en el noreste de Sonora (1,146 m), representa un sistema de depósito deltaico de aguas someras dominado por procesos fluviales, desarrollado en la parte septentrional de la cuenca Bisbee, a finales del Cretácico Temprano. Esta formación está constituida por tres miembros estratigráficos, los cuales representan los elementos de depósito de este delta. El miembro Marquechi (396 m), en la base, está constituido por las facies A, B, y C, y fue depositado en el delta subacuoso. El miembro San Marcos (498 m) está representado por los sedimentos marinos marginales y fluviales de las facies D-1, D-2, E y F, que caracterizan la planicie deltaica inferior. El miembro San Juan (252 m), en la cima, representa la planicie deltaica superior donde los sedimentos fueron depositados en ambientes fluviales e interdistributarios (facies D-3, G, H, e I).

Los datos de paleocorrientes y de procedencia sugieren que este delta progradó hacia el sur, y que su área fuente se encontraba predominantemente al norte.

Palabras clave: Estratigrafía, Cretácico Temprano, Sonora, México.

INTRODUCTION

The Early Cretaceous time in southeastern Arizona, northeastern Sonora and adjacent areas in the United States and Mexico, was dominated by three marine invasions (González-León and Jacques-Ayala, 1991). Sediments deposited at this time are represented by the Bisbee Group and its correlatives, which filled an elongated NW-SE oriented basin. The Glance Conglomerate constitutes the base of this group and is overlain by the Morita Formation, the Mural Limestone, and finally the Cintura Formation at the top.

The oldest marine invasion into the Bisbee basin, resulted in the deposition of limestone and calcareous sandstone of the Cerro de Oro formation in shallow marine environments, as is suggested by González-León and Jacques-Ayala (1988) in central Sonora; at this time, the Glance Conglomerate was deposited as alluvial fans associated with high-angle faults in the northern part of the basin (Bilodeau, 1982). As the sea retreated, the Morita Formation was deposited. In southeastern Arizona and northwestern Sonora, this formation is composed of an interbedded sequence of sandstone, mudstone, siltstone and minor limestone and conglomerate, that have been inferred to be of mixed fluviatile, floodplain, deltaic, tidal and shallow-marine origin (Hayes, 1970a; Klute, 1991; Jacques-Ayala, 1992a). In the Cerro de Oro area, the lower part of the Morita Formation is of fluvial origin, whereas its upper part represents coastal environments associated to mouth bars and tidal flats (González-León and Jacques-Ayala, 1988).

A second marine invasion began in the late Aptian; during this time, the Mural Limestone was deposited as shallow-marine lime mud with patch reefs, probably in shallow lagoons (Warzeski, 1987). The sea retreated in middle Albian time and the Cintura Formation was deposited in shallow seas, deltas and alluvial plains (Hayes, 1970a; Klute, 1991) of a regressive episode.

The youngest marine invasion is indicated by the fossiliferous limestones intercalated with the uppermost rocks of the Cintura Formation reported by González-León (1994) in the Arizpe area in Sonora, and of the Mojado Formation (correlative to this formation) in New Mexico (Mack *et al.*, 1986).

Recognition of a deltaic system in the geologic record depends upon the identification of their principal elements

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(Coleman and Prior, 1982): a subaqueous delta where the depositional processes are mainly marine; a zone of interactive marine-fluvial processes called lower deltaic plain; and an upper deltaic plain where the fluvial processes are responsible for the deposition. All the critical elements of a paleo-delta can be recognized in the Cintura Formation strata that crop out in the study area, a NW-SE elongated valley of about 30 km^2, located 25 km to the southeast of Agua Prieta and 16 km to the east of Cabullona, in northeastern Sonora (Figure 1).

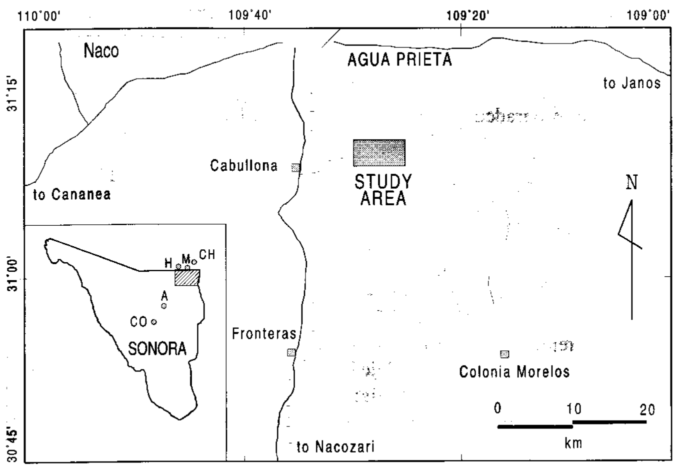


Figure 1. Location of the study area in northeastern Sonora, Mexico. A: Arizpe area, CH: Chiricahua Mts., CO: Cerro de Oro area, H: Huachuca Mts., M: Mule Mts.

In this paper, the lithofacies and interpreted depositional environments of the Cintura Formation in the study area are described. The purpose of this report is to describe an Early Cretaceous deltaic system represented by the Cintura Formation, in order to get a better understanding of the paleogeography of northeastern Sonora at this time.

STRATIGRAPHY

The Cintura Formation was defined by Ransome (1904) as the youngest formation of the Bisbee Group as typified in the Cintura Hills of southeastern Arizona. The Glance Conglomerate is at the base of the group, followed by the Morita Formation and the Mural Limestone.

The Bisbee Group has been widely studied in southeastern Arizona. Hayes (1970a, b) reported its stratigraphy from the Mule and Huachuca mountains and presented the first regional paleogeographic fluvial and deltaic model for deposition of this group, and Drewes (1991) extended this interpretation into a broader tectonic framework. Klute (1991) defined its lithofacies and interpreted the depositional environments as well as the provenance analysis of sandstone samples from southern Arizona and northern Sonora strata. Other works on the stratigraphy of the Bisbee Group are those by Finnell (1970), Hayes and Drewes (1978), Archibald (1982), Bilodeau and Lindberg (1983), and Dickinson and others (1986).

Although the Bisbee Group has been broadly studied in Sonora (Rangin, 1977; GYMSA, 1981; González-León, 1989; Jacques-Ayala and Potter, 1987; Navarro, 1989; García y Barragán, 1992; Jacques-Ayala, 1993), sections of Cintura Formation have only been described in detail by Jacques-Ayala (1992b) from Sierra El Chanate in northwestern Sonora, and by Grijalva-Noriega (1994) from the area here reported. Because the Cintura Formation contains coal beds in the study area, there are other works done by Salas (1976), Verdugo and Arriaga-Arredondo (1984), Obregón-Andría and Arriaga-Arredondo (1991) and Grijalva-Noriega and Arriaga-Arredondo (1993), which present the physical and chemical characteristics of the coal of this area.

One stratigraphic section was measured in three parts to establish and describe the stratigraphy and lithofacies of the Cintura Formation in this area (Plate 1). Total thickness of the unit is 1,146 m. Another 18 sections were also measured in less detail, to learn what is the lateral continuity of some lithologies. In order to define the lithofacies, large-scale lithologic relationships were considered. Primary sedimentary structures were used as aid to interpret the depositional environments, because fossils are scarce. A few fossils were collected, and even these few are poorly preserved and were not diagnostic.

In the study area, the Cintura Formation was divided into three informal stratigraphic members, by Grijalva-Noriega (1994), that from bottom to top are the Marquechi, San Marcos and San Juan members. The uppermost 35 m of the original San Marcos member are considered to be part of San Juan member, because of its close sedimentological relationship with rocks of this member. Otherwise, the stratigraphic subdivision is retained herein.

The Cintura Formation consists of interbedded mudstone, sandstone and siltstone, forming both some coarsening-upward and fining-upward sequences. Fossiliferous limestone and conglomeratic lenses, as well as some coal beds, are intercalated locally. In the San Marcos area, the Cintura Formation overlies with transitional contact the Mural Limestone, and it is overlain with sharp erosional unconformity by Late Cretaceous conglomerates (Plate 1).

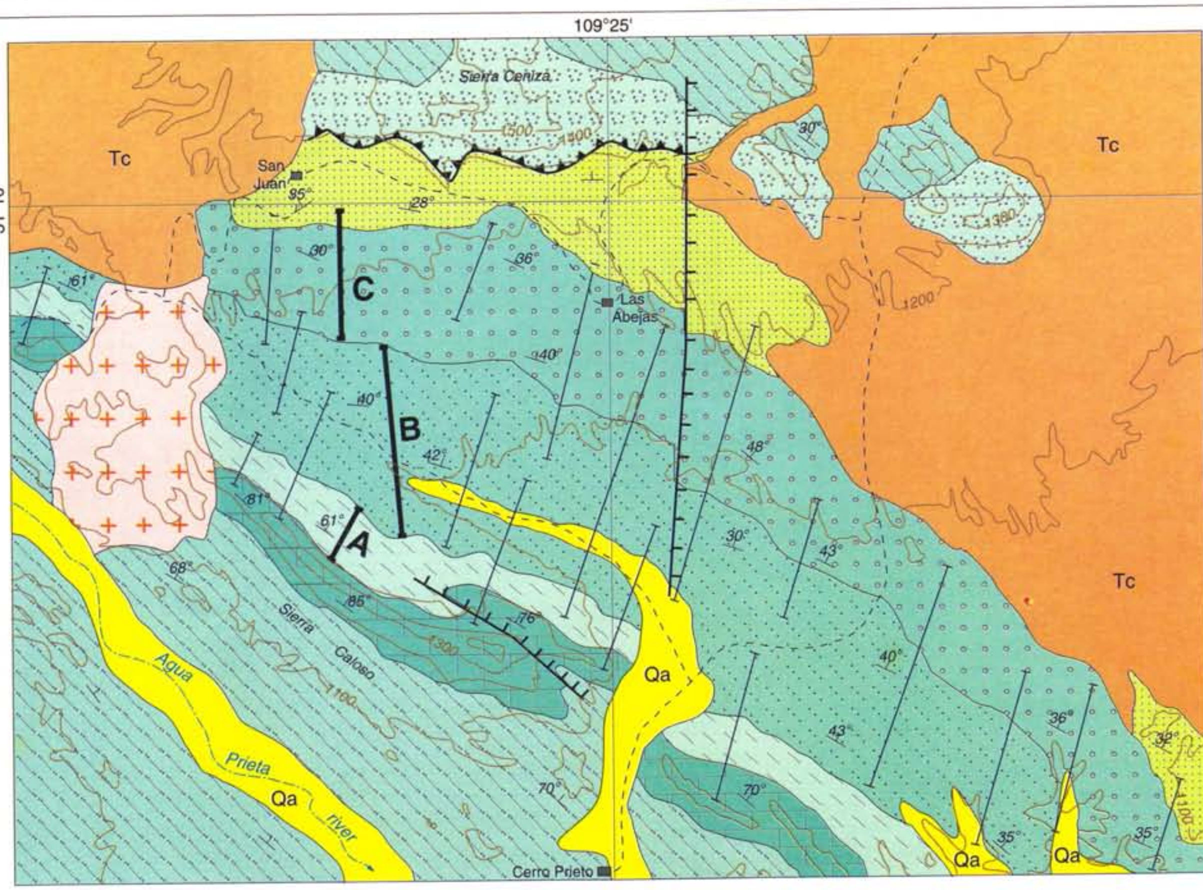
Nine lithofacies (facies A through I) were recognized in the Cintura Formation of the San Marcos area. Table 1 summarizes facies descriptions and interpretations.

MARQUECHI MEMBER

The Marquechi member (396 m) consists of a mudstone-sandstone sequence with intercalated fossiliferous limestone and siltstone at the base (Figure 2). This member includes facies A, B and C.

Facies A

It consists of a mainly grayish red- to pale-purple interbedded sequence of mudstone, siltstone and sandstone. The



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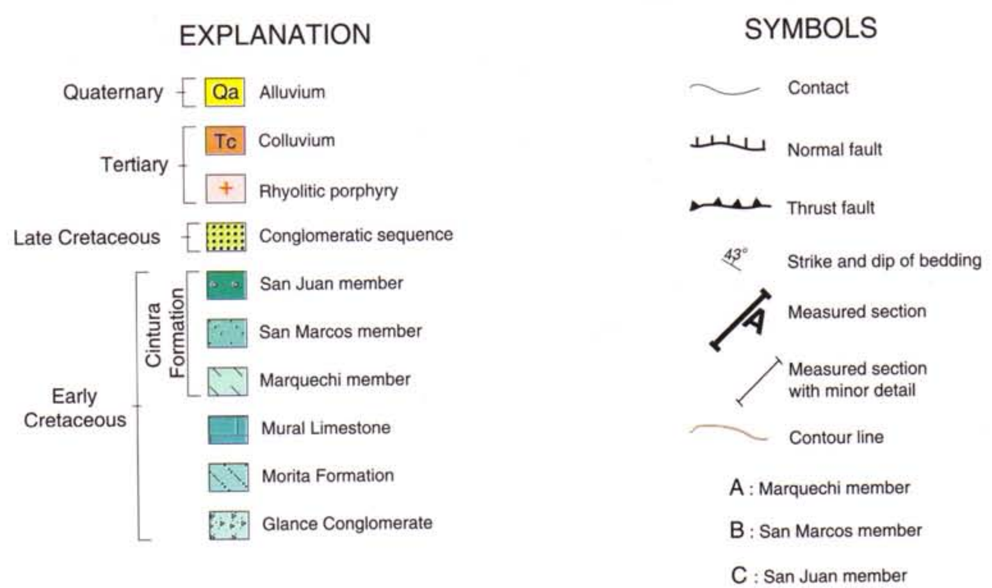

GEOLOGIC MAP OF THE STUDY AREA

Table 1. Facies descriptions and interpretations.

Unit	Description	Characteristics	Interpretation
San Juan Member			
Facies I	Sandstone, siltstone and mudstone form fining-upward sequences	Planar and trough cross-bedding, climbing ripple lamination, current ripples, parallel lamination, fossil wood, calcareous nodules	Floodplain and point bars
Facies H	Coal and carbonaceous mudstone	Carbonized plant fragments	Interdistributary swamp
Facies G	Mudstone, siltstone and minor sandstone form coarsening-upward sequences	Planar cross-bedding, fossils, leaf impressions, fossil wood, trace fossils	Interdistributary lake
Facies D-3	Sandstone	Scour-based surface, rip-up clasts, parallel lamination, planar cross-bedding, lenticular bodies	Channel
San Marcos Member			
Facies F	Sandstone, mudstone, siltstone and minor limestone form fining-upward sequences	Planar cross-bedding, parallel laminations, calcareous nodules	Abandoned distributary
Facies E	Mudstone, siltstone, sandstone and minor limestone interbedded sequences	Lower part: Primary sedimentary structures are absent in sandstone, ophiomorphs and skolithus burrows.	Tidal flats
		Upper part: Siderite concretions, parallel lamination, planar cross-bedding	Crevasse-splays bay-fill
Facies D-2	Conglomerate	Clast-supported conglomerates	Channel
Facies D-1	Sandstone	Scour-based surface, rip-up clasts parallel laminations, planar cross-bedding, lenticular bodies	Channel
Marquechi Member			
Facies C	Sandstone and minor siltstone	Planar cross-bedding, highly bioturbed beds by vertical burrows	Mouth bars
Facies B	Sandstone, siltstone and minor mudstone form coarsening-upward sequences	Planar cross-bedding, current ripples, parallel laminations, single sandstone bed with shell debris	Distal bars
Facies A	Mudstone, siltstone, limestone and minor laminated fine-grained sandstone	Parallel lamination, highly bioturbed and fossiliferous beds, horizontal and vertical trace fossils	Sub-tidal Shallow-marine

fine fraction (mudstone, siltstone and limestone) makes up about 70% of this facies. The lower 48 m of the facies are formed by interbedded greenish-gray limestone and siltstone containing oysters and other pelecypods. The upper 220 m consist of grayish red- to pale-purple mudstone and siltstone in beds ranging in thickness from 0.2 to 1.1 m. Bedding is highly bioturbated by both horizontal and vertical burrows. Grayish-purple to medium-gray, fine-grained sandstone beds, with an average thickness of 0.30 m, show parallel lamination and small-scale planar cross-bedding. Calcareous sandstone in the upper part of this facies is characterized by small asymmetrical ripples.

This facies overlies transitionally the marine deposits of the Mural Limestone, and it is laterally continuous for tens of kilometers. The paleontologic content and the predominance of fine-grained fractions, suggest that facies A was deposited in a shallow marine, low energy environment. The horizontal structures of burrows present in these rocks can be associated with the Cruziana ichnofacies (Seilacher *in* Pienkowski, 1985) and suggest a sub-tidal environment.

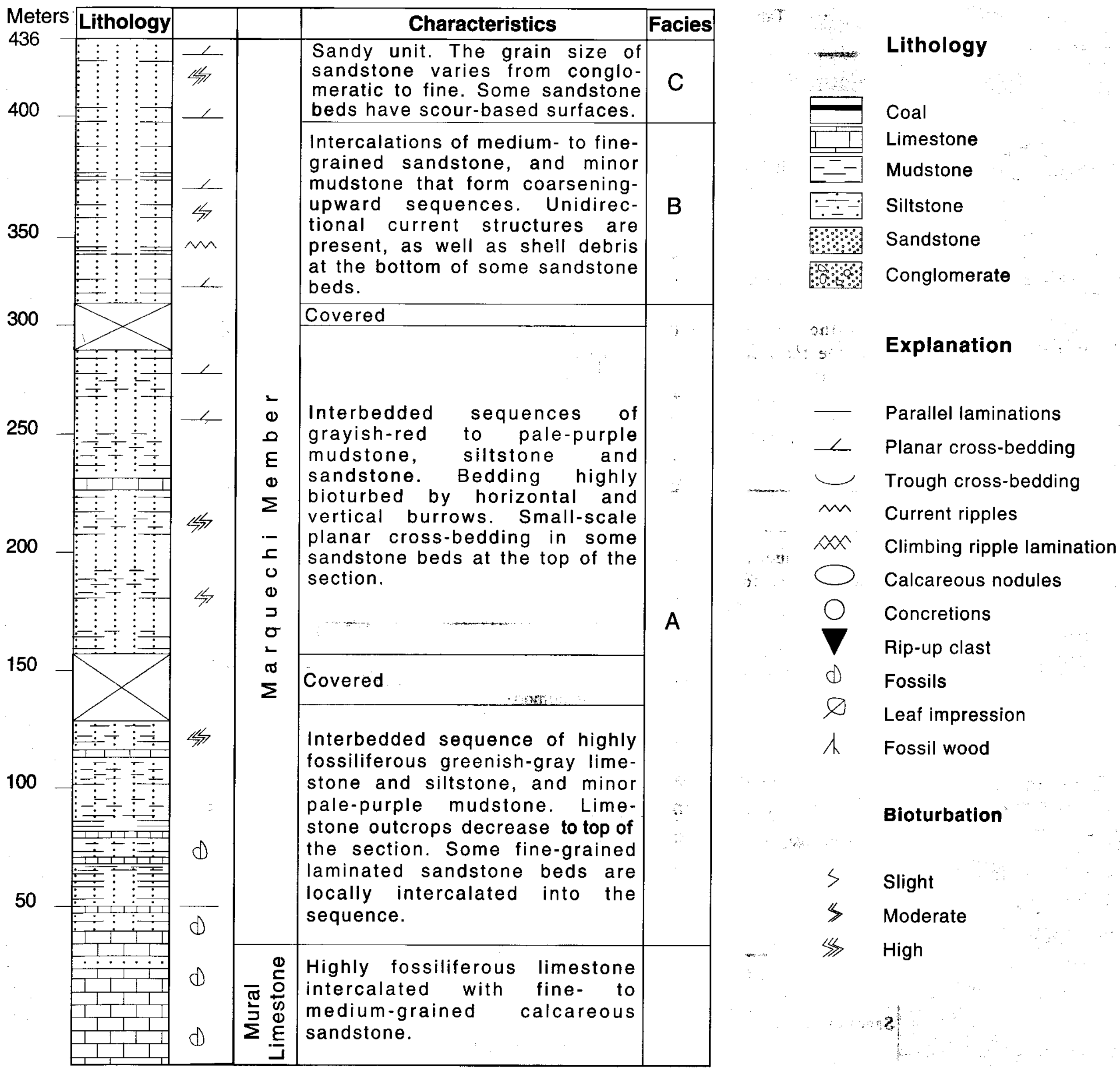

Figure 2. Measured section of the Marquechi member of the Cintura Formation in the study area.

Facies B

Facies B is 100-m thick and consists of brownish-gray to medium-gray, medium-grained sandstone, interbedded siltstone, fine-grained sandstone and some mudstone. The sandstone beds of this facies form coarsening-upward sequences with an average thickness of 16 m. The medium-grained sandstone beds are 1.30 to 2.50-m thick, moderately to well sorted, and have rounded grains. Vertical burrows and small-scale planar cross-bedding are the most common structures. Siltstone and fine-grained sandstone are medium gray and range in thickness from 0.20 to 0.60 m. Locally, the fine-grained sandstone beds contain shell debris at the bottom and small asymmetrical current ripples. Facies B grades upward into the facies C, and its lateral continuity varies from 100 to 400 m.

The development of coarsening-upward sequences, the presence of unidirectional current structures (based on planar cross-bedding and asymmetrical ripples), and a decrease of the fine fraction and horizontal burrowing, suggest the beginning of a zone with higher energy as compared to the facies A environment. An increase of coarse-grained sediment deposition over fine-grained marine deposits, as is marked by facies A and B, is characteristic of distal bar deposits (Coleman and Prior, 1982; Cotter, 1975).

Facies C

It consists of a 28 m-thick predominantly sandy sequence with some silty intercalations. Because of its sandy characteristic, the rocks of this facies form continuous ridges in the field.

Sandstone beds are moderate yellowish brown, have moderate to good sorting, and the grains rounded and range in size from fine to pebbly and conglomeratic sandstone. The beds range in thickness from 0.20 to 0.70 m. Medium-scale planar cross-bedding is the most common primary sedimentary structure, even though medium-scale trough cross-bedding is also present. Strongly bioturbed (vertical burrows) sandstone beds are also present. Some of these sandstone beds are scour-based. Interbedded light brownish-gray siltstone beds range in thickness from 0.30 to 0.55 m, whereas the conglomeratic sandstone beds average 0.20 m. The siltstone beds intercalated with sandstone form coarsening-upward sequences that are about 8-m thick.

The sandy characteristic of facies C, primary sedimentary structures, and vertical trace fossils attributed to the skolithus ichnofacies (Seilacher *in* Pienkowski, 1985) suggest a mouth bar environment of deposition (Coleman *in* Boggs, 1987).

SAN MARCOS MEMBER

The San Marcos member in the study area represents the marginal-marine to fluvial deposits of the Cintura Formation. It is 498-m thick and includes facies D, E and F (Figure 3).

Facies D

This facies includes scour-based sandstone and pebbly conglomerate. The geometry of these bodies ranges from ribbons to sheets which are completely enclosed by other facies. Facies D is subdivided into three distinct types, one of which (D-3) is only present within the overlying San Juan member at the top of the formation.

Facies D-1

It consists of pale yellowish-brown to light brownish-gray, medium- to coarse-grained sandstone beds that range in thickness from 0.70 to 2.10 m. Primary sedimentary structures are bidirectional, small- to medium-scale planar cross-bedding at the base of the beds, and parallel laminations at the top. Rip-up clasts of purple mudstone are common over the scour surface. These sandstones are lenticular, up to 120-m wide and are enclosed by facies E. The internal structures and lateral relationship with facies E suggest that facies D-1 was deposited in tidal channels.

Facies D-2

It consists of lenticular lenses of clast supported conglomerates, as much as 3.50-m thick and 6- to 28-m wide. Clasts are predominantly of well rounded quartzarenite and rhyolite, with an average diameter of about 5 cm. Some of these lenses present clasts imbrication and a better marked basal scour surface. These conglomerates are considered to be distributary channel deposits.

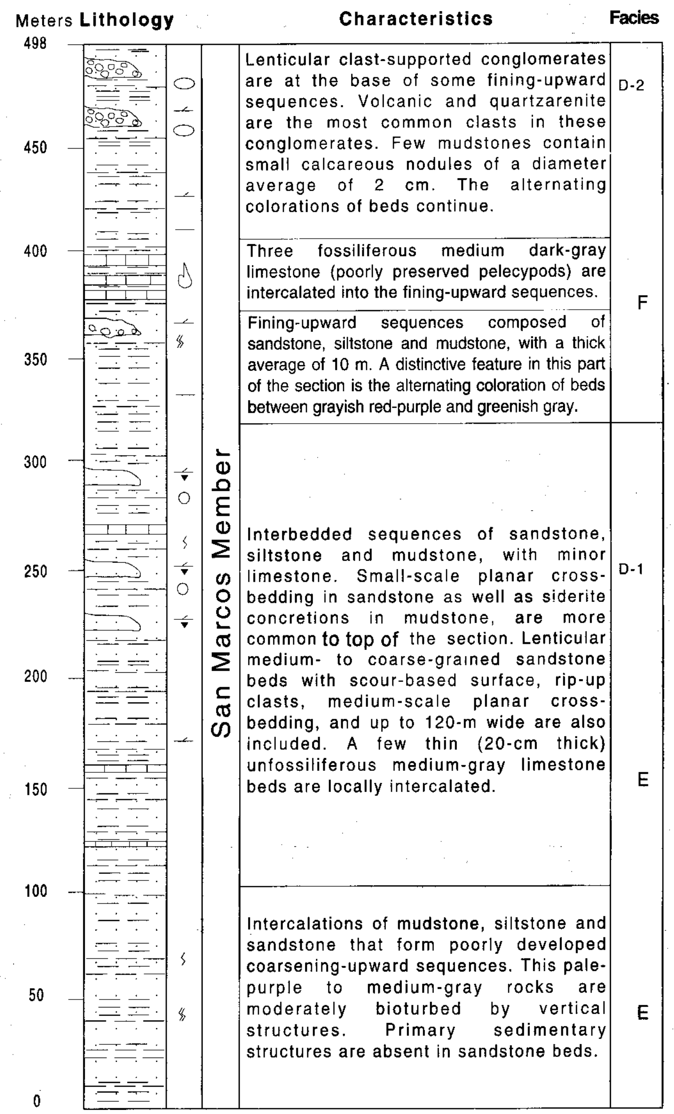

Figure 3. Measured section of the San Marcos member of the Cintura Formation in the study area. For explanation see Figure 2.

Facies E

This is 328-m thick and is composed of interbedded sequences of mudstone, siltstone, sandstone and some limestone. The fine fraction (mudstone and siltstone) makes up about 60% of the facies.

The lower 160 m of this facies are formed by poorly developed coarsening-upward sequences, averaging a thickness of 28 m. Mudstone and siltstone are pale purple to medium gray and locally greenish gray, beds range in thickness from 0.20 to 0.70 m. Sandstone is pale purple and dark to light gray, fine to medium grained, and beds range in thickness from 0.40 to 1.20 m. Primary sedimentary structures are commonly absent. In this part of the facies, slight bioturbation by vertical burrows (skolithus and ophiomorpha) is present.

In the upper 168 m of facies E, sandstone presents small- and medium-scale planar cross-bedding. Some mudstone beds contain siderite concretions,5 to 15 cm in diameter. Evidence of bioturbation is rare. This part of the facies also contains sandstone beds of facies D-1 and a few unfossiliferous gray limestone beds that range from 0.25 to 0.40 m in thickness.

The present author interprets this facies as coastal plain deposits. However, the lower part may represent bay-fill or crevasse-splays deposits, and the upper part may be tidal flat deposits in the deltaic system model of Coleman and Prior (1982).

Facies F

It consists of an interbedded sequence of sandstone, mudstone and siltstone (170 m), which forms well developed fining-upward cycles in which alternating colorations between grayish red-purple and greenish gray are observed in outcrop. Some of these cycles have basal conglomeratic lenses of facies D-2. Sandstone predominates over mudstone and siltstone, and constitutes about 60% of the facies. Sandstones are similar to those of facies E, but the grain size is coarser. Locally, the basal sandstone in the fining-upward sequences is pebbly to conglomeratic. Primary sedimentary structures in sandstone beds have parallel lamination, small- to medium-scale planar cross-bedding and some poorly developed graded beds. Mudstone and siltstone beds are grayish red-purple to light gray and greenish gray, and have an average thickness of 0.60 m. Calcareous nodules, about 2 cm in average diameter, are present in some mudstone beds. These rocks are slightly bioturbed.

Medium-dark-gray, fossiliferous limestone beds, 0.70 m in thickness, are also present. These limestones are believed to be of marine origin because they contain poorly preserved bivalves that resemble those found in the basal portion of the Marquechi member.

The fining-upward cycles and primary sedimentary structures suggest a fluvial environment of deposition, and the intercalations of probable estuarine limestone also suggest a proximity to the coast. Together, these environments suggest that the facies F represents distributary deposits on a coastal plain.

SAN JUAN MEMBER

The 253-m-thick San Juan member is characterized by fluviatile sequences and associated deposits in which the sandstone/mudstone ratio is 3/1 (Figure 4). This member includes facies D-3, G, H and I.

Facies D-3

This facies is represented by greenish-gray sheet-like sandstone (Figure 5), 1.50- to 3.70-m thick and 100 to 300-m wide. This sandstone is medium- to coarse-grained and locally conglomeratic. Facies D-3 sandstone beds are present in the lower part of depositional cycles that fine upward into facies I. Some carbonaceous rocks of facies H terminate abruptly against it in a lateral sense. Green mudstone intraclasts are abundant over the scour surfaces and sandy concretions as much as 10 cm in diameter are locally present. Small- to medium-scale trough and planar cross-bedding is distinctive. The primary sedimentary structures, the geometry of the beds and the relationships with facies H and I, suggest that this facies was deposited in distributary channels. A subordinate variety of facies D-3 is a ribbon-like sandstone, 1- to 3-m thick and 30- to 100-m wide; it is considered to be a minor distributary channel deposit.

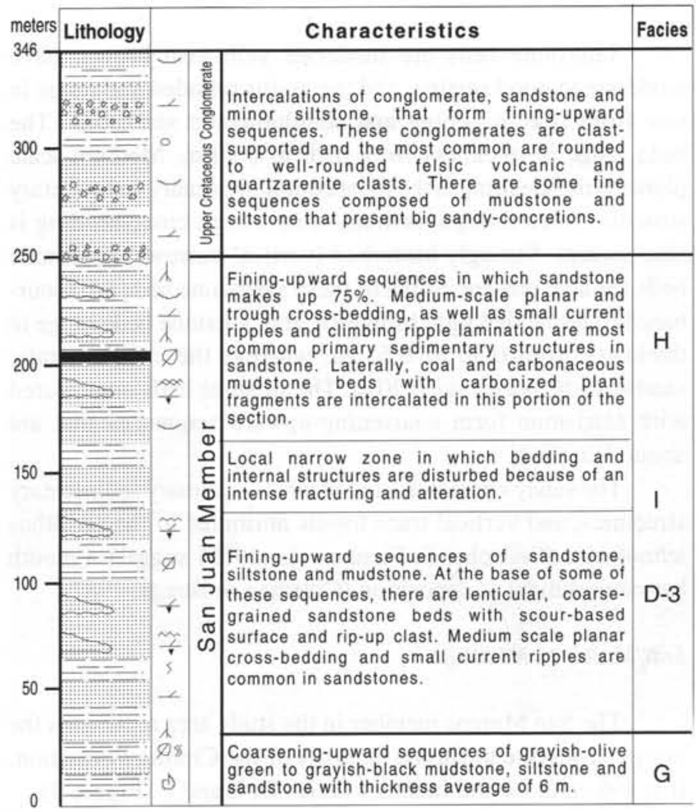

Figure 4. Measured section of the San Juan member of the Cintura Formation in the study area. For explanation see Figure 2.

Figure 5. Sandstone bed of the facies D-3.

Facies G

It consists of mudstone and sandstone with minor interbedded siltstone forming coarsening-upward sequences with an average thickness of 6 m (Figure 6).

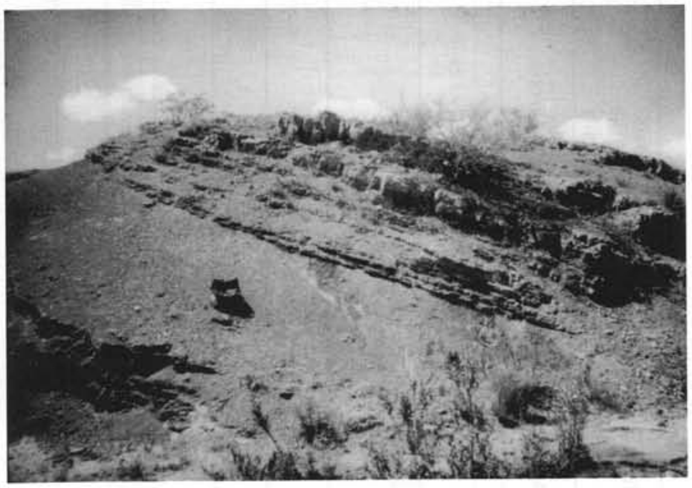

Figure 6. Coarsening-upward cycles of the facies G.

Mudstone and siltstone are grayish olive green, greenish gray to grayish black. Average bedding thickness of the mudstone is 0.25 m, and siltstone beds range from 0.02 to 0.03 m; these rocks form the thickest part of the coarsening-upward sequences. The sandstone is brownish gray to olive gray and fine- to medium-grained. Bed thickness ranges from 0.20 to 1.10 m. Distinctive features in facies G include poorly preserved fresh-water bivalves in the mudstone and sandstone, plant impressions on the bedding planes of grayish olive-green mudstone and siltstone, and fossil wood in the sandstone. Some trace fossils, probably bivalve resting traces (pelecypodichnus) occur in the fossiliferous sandstone.

Lithologic and paleontologic features suggest that facies G was deposited in a subaqueous environment. This inferred depositional environment, coupled with its abrupt lateral contacts with facies F and I, suggests that facies G was deposited in an interfluvial lake. In northern Arizona, similar deposits to facies G in the upper carbonaceous member of the Wepo Formation were interpreted as in Carr's (1991).

Facies H

This facies consists of poorly exposed interbedded coal and carbonaceous mudstone. Coal ranges in thickness from less than 0.30 m to more than 2.80 m, and is the predominant rock type of this facies. Unweathered coal is black and hard, has a poorly developed or irregular bedding and can reach 2 km in lateral continuity, but the average is about 200 m. Coal beds grade laterally into carbonaceous mudstone or abruptly against sandstone of facies D-3 and I. In a few places, thin gypsum layers are present within the coal. Carbonaceous mudstone is black to dark gray and is present in well-developed beds that range in thickness from 0.05 to 0.80 m. Carbonized plant fragments are very common.

Coals indicate a reducing environment, and based on its relationships with sandstone of surrounding facies D-3 and I, the facies H is interpreted as interdistributary swamp deposits. Carr (1991) reported similar deposits in northern Arizona, which he interpreted in the same way.

Facies I

This facies is 252-m thick and consists of interbedded sandstone, mudstone and minor siltstone forming fining-upward sequences, that have an average thickness of 12 m (Figure 7). Sandstone constitutes about 70% of this facies.

Sandstone is greenish to olive gray and fine grained to conglomeratic. Bedding thickness ranges from 0.60 to 3.50 m. Primary sedimentary structures include small- to medium-scale planar and trough cross-bedding, parallel lamination, climbing ripple laminations and asymmetrical ripples. Fossil wood and sandy concretions (15 cm in average diameter) are abundant. Mudstone and siltstone are greenish to dark greenish gray and bed thickness ranges from 0.30 to 0.80 m. Most of these rocks are finely laminated. Calcareous nodules, 2 cm in diameter, are present in some mudstone beds. Facies D-3 sandstones are commonly at the base of the fining-upward sequences of this facies. In a few places, this sandstone erodes completely the mudstone and siltstone beds of the underlying cycle.

Fining-upward sequences and primary sedimentary structures of facies I represent the classic cycles of fluviatile deposits (Miall, 1980). Facies I is interpreted as point bar and floodplain deposits in a meandering river system.

DEPOSITIONAL MODEL

The facies map of the Cintura Formation in the San Marcos area (Figure 8) demonstrates that the percentage of

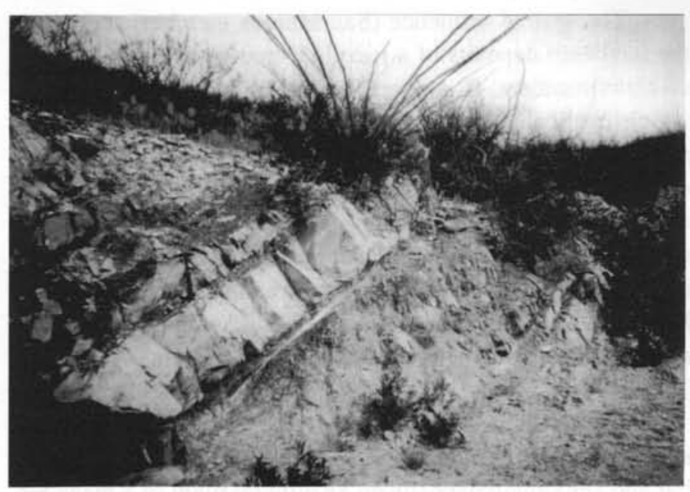

Figure 7. Fining-upward cycles of the facies I.

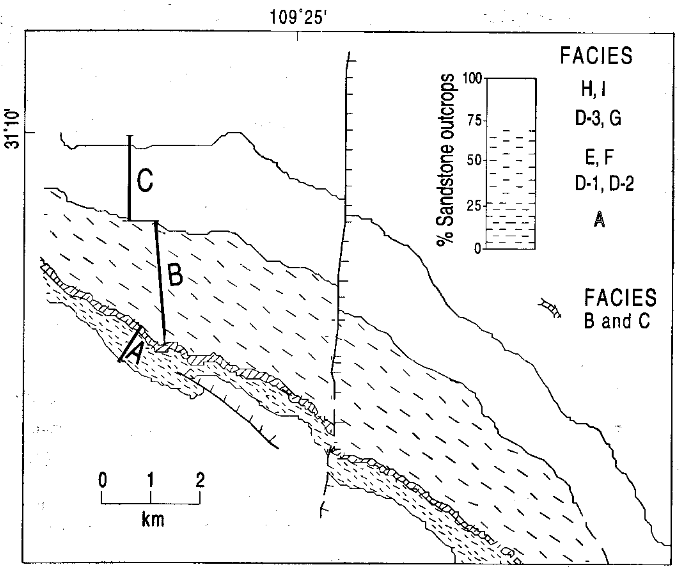

Figure 8. Facies map of the Cintura Formation in the study area.

sandstone versus siltstone and mudstone increases northward, resulting in an overall coarsening-upward sequence. Vertical trends in the distribution of depositional environments interpreted by facies successions show that the Cintura Formation of the study area is composed of three distinctive intervals characteristic of a deltaic system.

In the basal sequence (Marquechi member), the sedimentation was controlled mainly by marine processes. The prodelta mudstones, siltstones and fine-grained sandstones grade upward into coarser sandstones and siltstones of distal bars and mouth bars. Coarser deposits of the delta front, represented by facies B and C, prograded over prodelta deposits of facies A. This delta front presents a broad lateral continuity. Although slump structures are common within this part of the prodelta (Elliot, 1986), these were not observed in the study area. The author attributes this absence to a shallow basin having gently sloping margins. This sequence resembles the subaqueous delta (Figure 9) in the model of Coleman and Prior (1982).

The second sequence (San Marcos member) represents the landward deposits of a marginal-marine to fluvial regressive environment. It is characterized by an extensive area in which cyclically interbedded mudstone, siltstone and sandstone were deposited on a marginal marine coastal plain (Figure 9). In this interval, the deposits represent mainly environments among channels such as bay-fill, tidal flats, crevasse-splays, and estuarine deposits. Fluvial deposits were also present in this coastal plain environments (facies D-2 and F). An interaction of marine and fluvial sedimentation processes characterizes the lower deltaic plain (Coleman and Prior, 1982).

The third interval is represented by thick sandstone bodies of fluvial origin. Facies D-3 and I represent channel, point bar and floodplain deposits on an alluvial plain of a meandering river system. Facies G and H represent interdistributary

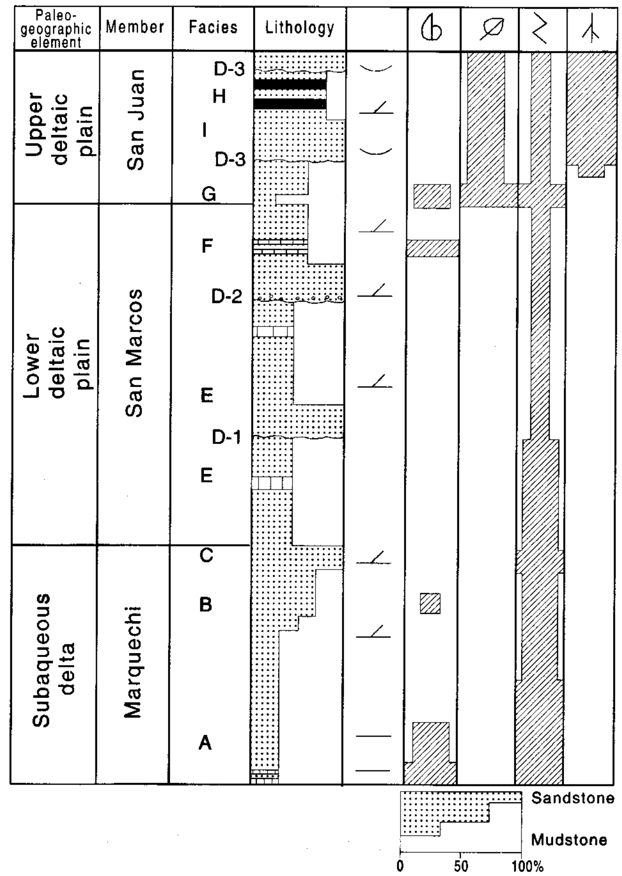

Figure 9. Relationships between the delta elements and facies of the Cintura Formation in the study area. For explanation see Figure 2.

lakes and swamps developed within this alluvial plain (San Juan member). This interval characterizes the upper deltaic plain (Figure 9) which is dominated by fluvial processes.

The environment of deposition, the absence of growth faults, and a laterally continuous delta front, suggest that the Cintura Formation in the study area was deposited in a shallow-water fluvial-dominated delta.

Thirty-four paleocurrent measurements from cross-bedding in the sandy sequence at the top of Marquechi member (Figure 10, a) show a broadly NE-SW bimodal pattern. This was probably produced by tidal or wave action against the bars. On the other hand, within the uppermost strata of the San Marcos and San Juan members, another 34 measurements of cross-bedding in sandstones and clasts imbrication in conglomerate lenses within fluvial deposits (Figure 10, b) also show a bimodal pattern; nevertheless, the majority of them indicates southward transport. These data, together with the facies analyses, suggest that the source area was to the north or northwest.

PROVENANCE

Twenty-three thin sections made from sandstone samples were studied and counted an average of 300 points to each one using the traditional method (Ingersoll *et al.,* 1984); and point-count data were plotted on a QmFLt triangle defined by Dickinson (1985) to provenance analysis. From this petro-

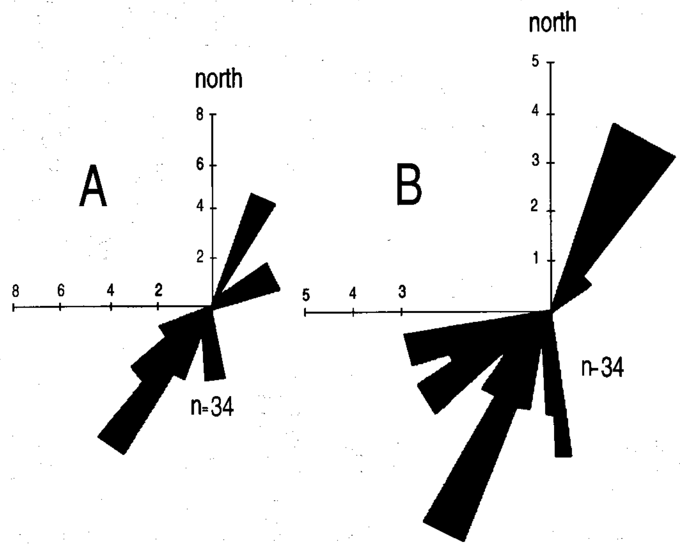

Figure 10. Current rose diagrams for cross-bedding in the Marquechi (*A*) and San Marcos and San Juan (*B*) members of the Cintura Formation in the study area.

graphic study, the Cintura Formation of the study area can be divided in two sandstone petrofacies: quartzose and volcanic (Table 2).

The quartzose petrofacies is predominant in the Marquechi member. Monocrystalline quartz varies from 70 to 85%, and abraded silica overgrowths in well-rounded quartz, as well as Bohem structures in quartz crystals, are common within these samples. Plagioclase, which is replaced by sericite, sedimentary and volcanic rock fragments, is also present but in minor amounts. Potassium feldspar constitutes about 3% of total feldspar. Volcanic petrofacies predominates in the San Marcos and San Juan members, and consists of sandstones with mainly volcanic rock fragments (Lv/ls ratio ranges from 4 to 7), plagioclase and monocrystalline quartz. Potassium feldspar is noticeably absent. Chert and polycrystalline quartz are present in subordinate amounts in both petrofacies.

Klute (1991) inferred the source of the quartzose petrofacies in the Bisbee basin to be the Mogollón highlands and cratonal North America, located to the north and northeast. However, although the QmFLt ternary plot (Figure 11) suggests an evolution from quartzose recycled orogen to dissected arc provenance, the quartz could have been derived from eolian sandstone that is commonly present in the Jurassic magmatic arc strata (Riggs and Haxel, 1990) in southern Arizona. The absence of metamorphic rocks and limestone fragments in sandstone samples of the volcanic petrofacies, and the abundance of plagioclase and volcanic rock fragments, suggest that the source areas for this petrofacies may be the local volcanic rocks of the Canello Hills Formation, and the Jurassic magmatic arc related rocks. Klute (1991) also suggested the same source areas for the volcanic petrofacies in the Bisbee basin. Nevertheless, another area toward the west or northwest could be the source of volcanic detritus to the Bisbee basin, as was proposed by Drewes (1991).

Table 2. Point-count data of sandstone samples from the Cintura Formation in the study area. M: member; Pt: petrofacies; Qm: monocrystalline quartz; Qp: polycrystalline quartz; P: plagioclase; K: kspar; Lv: volcanic lithic fragments; Ls: sedimentary lithic fragments; Ch: chert; Ct: cement; Ma: Marquechi member; M: San Marcos member; SJ: San Juan member; Q: quartzose petrofacies; V: volcanic petrofacies.

Sample	M/Pt	Qm	Qp	P	K	Lv	Ls	Ch	Ct	Total
SM-1	Ma/Q	186	23	28		31	22	8		298
SM-2	Ma/Q	175	31	25		28	19	13		291
SM-3	Ma/Q	199	29	22	2	25	21	6		301
SM-4	Ma/Q	206	29	19		14	16	8		292
SM-5	Ma/Q	187	22	28	3	26	24	4	3	297
SM-6	M/V	110	25	48		65	8	26	3	282
SM-7	M/V	142	21	40	1	58	13	18	6	299
SM-8	M/V	135	16	51	6	92	4	8		312
SM-9	M/V	104	18	66	1	71	18	29	7	314
SM-10	M/V	108	14	66	2	81	9	12	1	293
SM-13	M/V	89	21	78	4	85	12	26	8	323
SM-14	M/V	96	15	88	3	76	25	20	15	338
SM-15	M/V	84	16	76		96	21	18	8	319
SM-15A	M/V	94	25	60		79	13	25	4	300
SM-16	M/V	105	38	52		72	15	21	4	310
SM-18	M/V	95	21	81	2	84	19	16	7	325
SM-21	M/V	89	39	60	3	73	16	25	11	310
SM-22	SJ/V	93	19	81		75	17	24	5	314
SM-23	SJ/V	91	21	81		68	17	24	3	305
SM-24	SJ/V	76	28	71		86	13	42	15	331
SM-25	SJ/V	86	24	71	4	78	14	18	7	302
SM-26	SJ/V	75	16	64	5	88	19	33	8	308
SM-28	SJ/V	82	20	73		82	16	29	6	308

PALEOGEOGRAPHY

After the second invasion of the Cretaceous sea in the Bisbee basin during Aptian-Albian times (Mural Limestone), a regressive period is evident at the northern portion of this basin, as indicated by the Cintura Formation. A deltaic depositional system was developed during late Albian time, in which paleocurrents and provenance data suggest that some uplands were to the north, and the delta prograded southward; at this time, the marine waters of the youngest invasion into this basin did not reach the study area, this limit was southward in the Arizpe area (central Sonora).

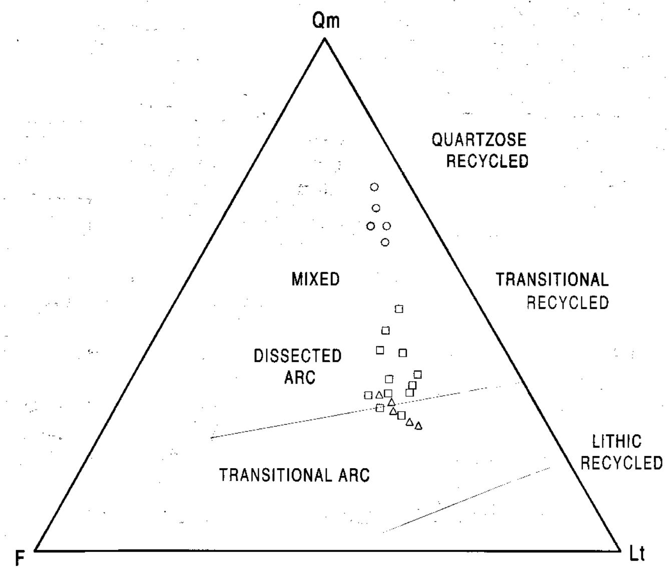

Figure 11. QmFLt diagram from Dickinson (1985) showing compositions of 22 samples from the Cintura Formation in the study area. Marquechi member: circles; San Marcos member: squares; San Juan member: triangles.

Shallow marine and distal and mouth bar environments interpreted in the Marquechi member strata in the study area are not present in adjacent areas in southeastern Arizona. The lower deltaic plain represented by the San Marcos member may be present in the basal 230 m of the Cintura Formation in Mule mountains, which were interpreted as marginal marine deposits by Klute (1991), and may also be present in southern Chiricahua Mountains (Figure 12). Depositional environments interpreted from the upper Cintura Formation strata in Mule, southern Chiricahua Mountains, and Huachuca mountains, are clearly continental associated with meandering rivers, as presented by Klute (*op. cit.*). This portion may correspond to the fluvial system that generated the delta in the study area.

The conglomeratic lenses, like those of San Marcos member in the study area, are reported from the Cintura Formation in Huachuca and Mule mountains (Klute, 1991), probably suggesting a slight regional uplift at this time.

CONCLUSIONS

The stratigraphical and sedimentological studies of the Cintura Formation in the area here reported, allow to differentiate three clearly distinctive members that represent a regressive sequence deposited within the northern portion of the Bisbee basin during latest Early Cretaceous time. The facies analysis suggests a shallow-water fluvial-dominated delta where its three paleogeographic elements are represented by these three members. The Marquechi member (396 m), composed by interbedded sequences of mudstone, sandstone and minor siltstone and limestone, represents the subaqueous delta. The San Marcos member (498 m) sediments of marginal-marine and fluvial origin characterize the lower deltaic plain.

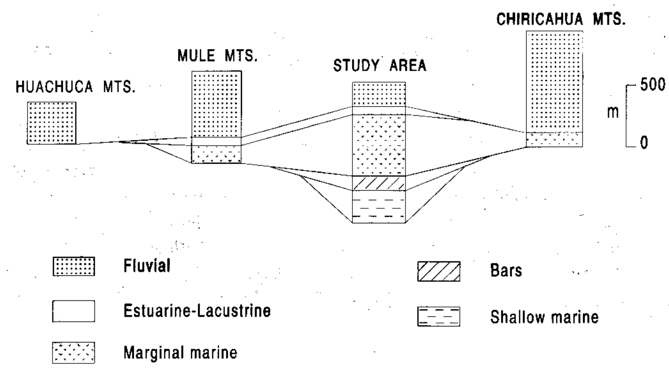

Figure 12. Facies correlations among the study area and other localities of the Cintura Formation in southeastern Arizona (modified from Klute, 1991).

Finally, the San Juan member (252 m), composed mainly by sandstone-mudstone cyclic sequences of fluvial origin, as well as interdistributary lake and swamp deposits, represents the upper deltaic plain.

The paleocurrents and provenance analysis suggest that this delta prograded southward and its lower deltaic plain could be extended northward to the Mule and Chiricahua mountains in southeastern Arizona. Additional work is required in these localities to demonstrate the validity of this model in those areas.

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