Geological Society of America
Special Paper 340
1999

Geology of the basement below the decollement surface, Sierra de Catorce, San Luis Potosi, Mexico

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ABSTRACT

The Sierra de Catorce, one of the most important silver producers in the world, straddles the transitional boundary between the Mesa Central to the west and the Sierra Madre Oriental to the east. Stratigraphically, it consists mainly of marine carbonate rocks that range in age from Late Jurassic to Late Cretaceous. These rocks are grouped, from top to bottom, into the following lithological units: Caracol, Indidura, Cuesta del Cura, La Peña, Cupido, Taraises, La Caja, and Zuloaga Formations. Underlying this carbonate rock sequence, and separated from it by a structural discontinuity, is a very thick transgressive section of redbeds that is stratigraphically correlatable to the La Joya Formation. Its age is probably early Late Jurassic. The La Joya Formation redbeds unconformably overlie both the Triassic Huizachal Formation and the upper Paleozoic green beds, which are correlated with the Guacamaya Formation of the Huizachal-Peregrina anticlinorium. This sierra is part of the Mexican fold and thrust belt, which is believed to connect to the Cordilleran orogenic belt. This tectonic feature extends along the western parts of North and South America. The evolution of this belt is ascribed to the gradual convergence of the Pacific Ocean and the North and South American plates.

INTRODUCTION

The Sierra de Catorce area, is north of the Mexican state of San Luis Potosí; it is limited by long 100°40′ and 101°00′ W and lat 23°22′ and 23°52′ N, and covers ~1925 km^2. Its highest elevation is Cerro Grande mountain, which is 3180 m above sea level and has a local relief of about 1220 m. The long axis of the Sierra de Catorce extends 52 km north to south, and its maximum width is 20 km east to west. The most important population center is El Real de Catorce, a old city built in the 1770s: at its peak, the population was almost 25,000 (Cabrera-Ipiña, 1975), but at present it is only 650. The town is located on top of the Sierra de Catorce range at 2700 m above sea level (Fig. 1).

The Sierra de Catorce range straddles the transitional boundary between two physiographic provinces: the Mesa Central to the west, which is considered a major but little recognized part of the Basin and Range province (Henry and Aranda-Gómez, 1992; Stewart, 1978), and the Sierra Madre Oriental to the east (the Hidalgoan fold and thrust front), which is a structural unit coincident with the Sierra Madre Oriental physiographic province (Mixon, 1963). The Sierra de Catorce climatic region is considered, in general terms, as a zone in which the moisture taken up from plants and ground water by evapotranspiration and evaporation, respectively, and held by the atmosphere is greater than the moisture added to the land by precipitation. This low-latitude steppe climate appears worldwide chiefly in semiarid lands between 15° and 35° latitude, (Koeppe and De Long, 1979). In the Sierra de Catorce region the prevalent mean annual temperature is higher than 21 °C with a mean annual temperature range lower than 14 °C (dry-hot). The rainy season

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Franco-Rubio, M., 1999, Geology of the basement below the decollement surface, Sierra de Catorce, San Luis Potosi, Mexico, *in* Bartolini, C., Wilson, J. L., and Lawton, T. F., eds., Mesozoic Sedimentary and Tectonic History of North-Central Mexico: Boulder, Colorado, Geological Society of America Special Paper 340.

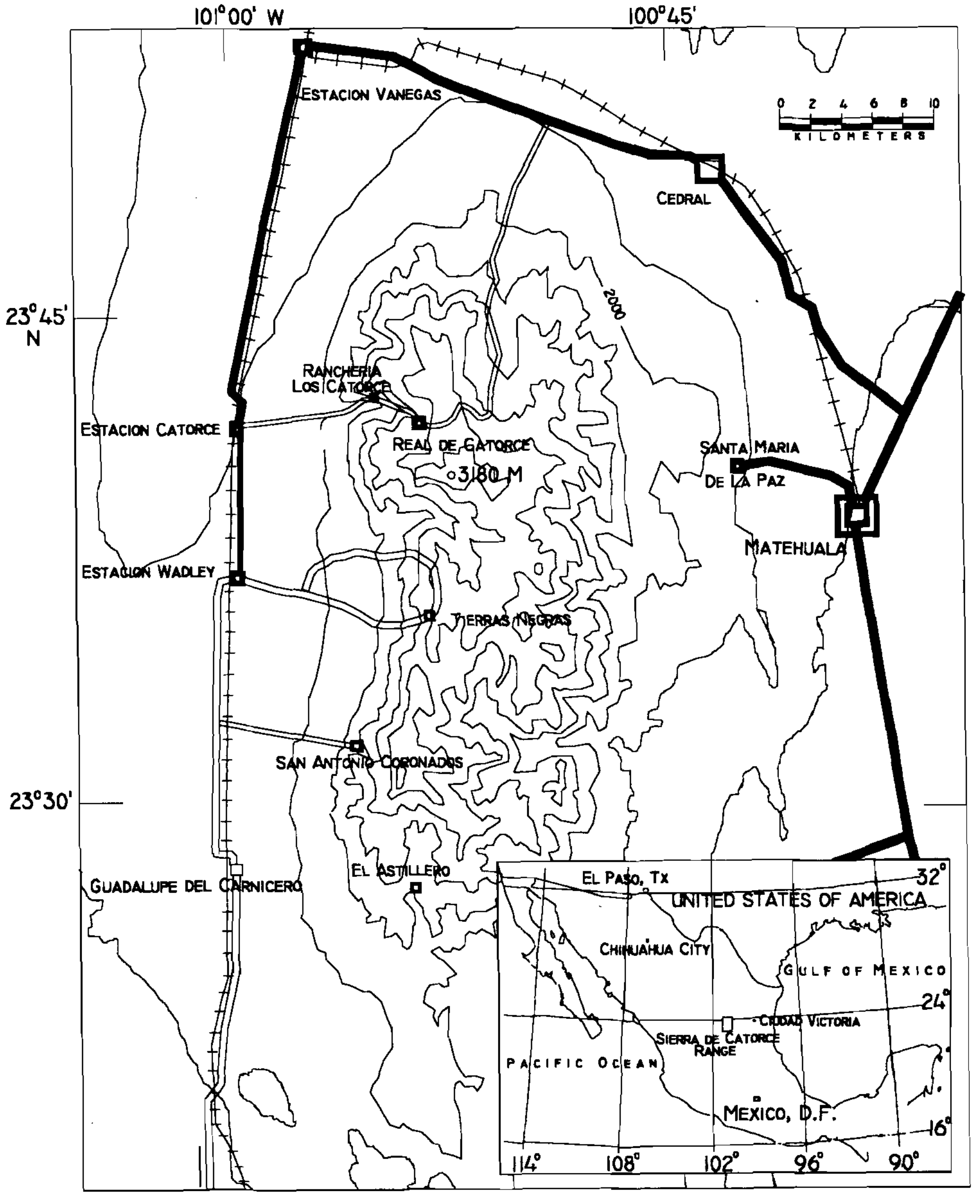


Figure 1. Topographic map of study area, covering entire Sierra de Catorce.

is short and characterized by heavy thunderstorms. With a 254–889 mm yearly rainfall, at least 5 winter months with <25.4 mm precipitation, and a heavy rainy summer season, this region is an example of a low-latitude steppe.

Ground areas are covered by prairie grasses, creosote bushes, cardenches, and tall yucca plants called palmas. The higher parts of the study area support a somewhat different flora, such as sotol, cholla, maguey, ocotillo, lechuguilla, candelilla, several types of beavertail cactus, and biznagas. Animals native to the area are seen throughout the seasons. Reptiles, such as horned toads and other lizards as well as rattlesnakes, are common. Mammals are represented by some bobcats and coyotes.

GEOLOGIC SETTING

The Mexican fold and thrust belt is a region of major contractional deformation that is characterized by string of mountain ranges. Drewes (1978) and Campa and Coney (1983) proposed that the fold belt is the southward continuation of the Cordilleran orogenic belt of western North America, a tectonic feature that extends along the western parts of North and South America. The evolution of this belt is ascribed to the gradual convergence of the Pacific Ocean and the North and South American plates. The Sierra de Catorce, located within this orogenic belt, is a good tectonic area to study the style of deformation of this belt (Fig. 2).

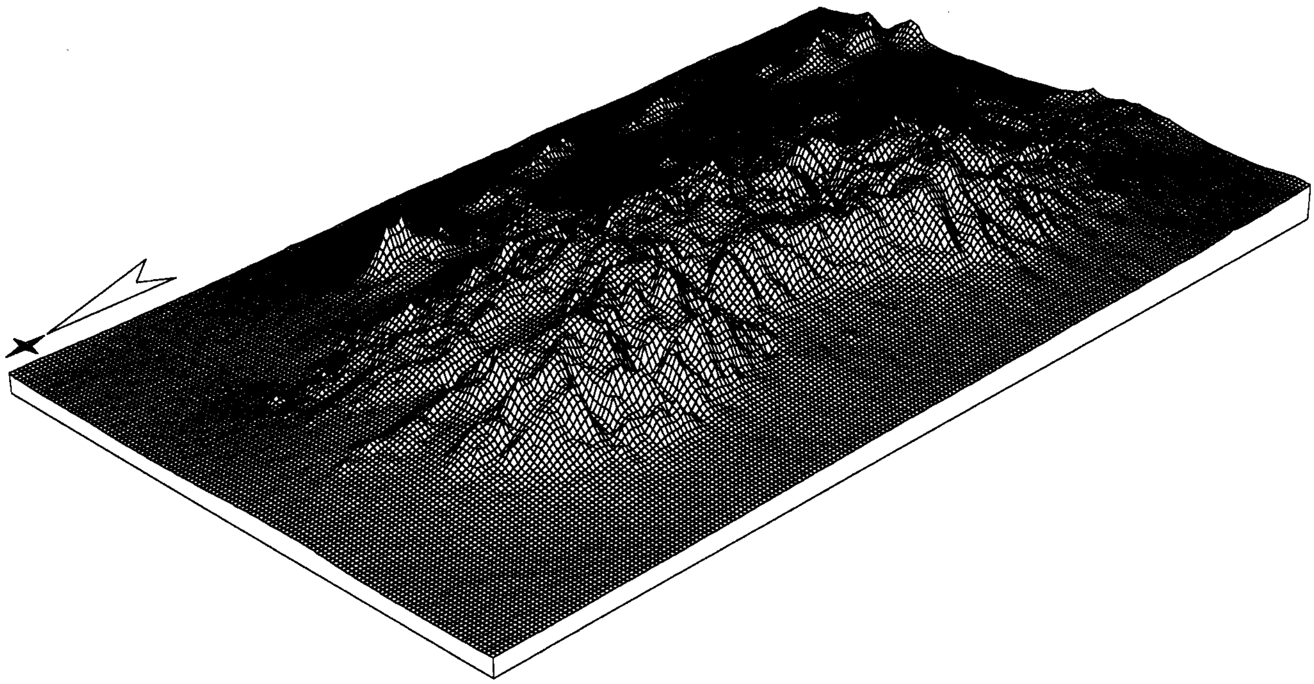


Figure 2. Tridimensional view of Sierra de Catorce. Vertical scale is exaggerated.

Previous studies

One of the world's most productive silver deposits was exploited in the Sierra de Catorce region. For that reason, the area was and still is the site of numerous geologic studies, focused mainly on economic aspects.

Earlier contributors to our knowledge of the stratigraphy of the Sierra de Catorce region were Nikitin (1890), Castillo and Aguilera (1895), Burckhardt (1906a, 1906b), Imlay (1936, 1937, 1944, 1953), and Erben (1956). Mixon et al. (1959) and Mixon (1963) did extraordinary research on the stratigraphy of the Triassic-Jurassic Huizachal Group. Verma and Westerman (1973) studied the paleontology and stratigraphy of the calcareous Jurassic and Early Cretaceous formations of Sierra de Catorce. University of Texas, Arlington, students have worked on Sierra de Catorce. Bacon (1978), Blauser (1979), Ice (1979), Ross (1979), and Wiedman (1979) were concerned with the stratigraphy and structure of the north and central portion of the Sierra de Catorce Range. Their research represents the most extensive work done in this area.

Several studies have been carried out by foreign and Mexican researchers. Baker (1922) did a reconnaissance study on the general geology of the Catorce mining district. Other geological works include Gonzalez-Reyna (1947), on stibnite deposits of San Jose de Tierras Negras, in the Mexican state of San Luis Potosí; Pesquera-Velazquez (1954), on the silver deposits of the Catorce mining area; McLeroy and Clemons (1970), on the mineralization of the silver deposits of the Santa Ana mine; McGibbon (1979), on the origin and paragenesis of ore and gangue minerals of the La Paz mining district, east of Sierra de Catorce; Zarate-del-Valle (1979), on the study of antimony minerals from Sierra de Catorce, San Luis Potosí; and W. N. McAnulty (1991, written commun.), who has been doing a reconnaissance geology for economic geology purposes.

Although much has been written on various topics about Real de Catorce and its vicinity, only a few have been published. As Wallace (1984, p. 104) stated, "enthusiastic and knowledgeable people . . . can find treasures in the old archives of the churches and the Palacio Municipal from El Real de Catorce town." In his *Political Essay on New Spain (1804),* Baron Alejandro Von Humboldt mentioned the Real de Catorce area and reported on the superior grade of the silver in the ores (Verma and Westerman, 1973).

Objectives

The objective of this study is to map the Sierra de Catorce range geologically and to reexamine the stratigraphy and structural features present in this sierra. Basic stratigraphic, structural, and petrographic information in Sierra de Catorce range should contribute to a better understanding of depositional environments and regional relations in the Sierra Madre Oriental physiographic province.

REGIONAL STRATIGRAPHY

The Sierra Madre Oriental, the surface expression of the Mexican fold and thrust belt in central, eastern, and northern Mexico, comprises ~8000 m of Cretaceous rocks and 2000 m of Jurassic and Triassic rocks. This Mesozoic sequence directly overlies units of Carboniferous and Permian ages (Drewes, 1978).

Precambrian

Precambrian rocks underneath sedimentary deposits of Paleozoic age are known in a few areas of the Sierra Madre Oriental. The Huizachal-Peregrina anticlinorium, 160 km east of the Sierra de Catorce in the Sierra Madre Oriental physiographic province, contains a middle-Paleozoic schist (Boucot et al., 1997) and both orthogneiss and paragneiss of late Precambrian age (Carrillo-Bravo, 1961; De Cserna, and Ortega-Gutierrez, 1977, 1978; Ortega-Gutierrez, 1978; Ruiz et al., 1988; Ortega-Gutierrez et al., 1993; Silver et al., 1994). In the state of Chihuahua, Precambrian metaigneous rocks crop out at Cerro Carrizalillo (Quintero-Legorreta and Guerrero-García, 1985). Allochthonous blocks of Precambrian age (Grenville) are included within Permian sedimentary rocks in the Sierra del Cuervo in central Chihuahua (Mauger et al., 1983).

Paleozoic

Paleozoic rocks crop out in small areas within the Mexican fold and thrust belt. The most complete section is in east-central Chihuahua (Bridges, 1966) within the Placer de Guadalupe area. In addition, the Huizachal-Peregrina anticlinorium also contains an important Paleozoic section (Carrillo-Bravo, 1961; Lopez-Ramos, 1981). Other Paleozoic localities along the Sierra Madre Oriental physiographic province are the Sierra del Cuervo area (King, 1942; Ramirez and Acevedo, 1957), the La Delicias basin, where the most fossil-rich localities of Pennsylvanian and Permian rocks in northern Mexico exist (King, 1942; McKee et al., 1988), the Apizolaya quadrangle (Córdoba-Mendez, 1963), and the Sierra de Catorce area (De Cserna, 1956).

Cambrian System (590–505 Ma). Age assignments herein are based on the time scale of Harland et al., (1982). Outcrops of this system are widespread in the Caborca region of northwestern Mexico (Lopez-Ramos, 1980). Around the Sierra de Catorce area, exposures previously considered to be Cambrian in age are found near Ciudad Victoria, Tamaulipas. The Conglomerado Naranjal, which was considered to be Cambrian due to its stratigraphic position and lithologic characteristics, even though no fossils have been found in it (Carrillo-Bravo, 1961; Lopez-Ramos, 1980), now is considered to be late Paleozoic and may in part be equivalent to a conglomerate at the base of the Pennsylvanian Del Monte Formation (Ramirez-Ramirez and Gursky, *in* Stewart et al., 1999).

Ordovician System (505–438 Ma). Ordovician marine sediments are fairly widespread in Sonora. They are generally found near Cambrian outcrops. The Calizas Victoria Formation found in the Peregrina Canyon at the Huizachal-Peregrina Anticlinorium, west of Ciudad Victoria, Tamaulipas, was considered to be Ordovician. *Rafinesquina trentoensis* (Conrad) and *Rafinesquina sp.* are brachiopod invertebrate fossils found within this formation (Carrillo-Bravo, 1961). As Stewart et al. (1999) have established, "restudy by Boucot and Blodgett of the original faunal collections from the Victoria Limestone indicate that it is Silurian in age, and that this limestone is actually the same as a widespread limestone unit (the Santa Ana Limestone Member) in the lower part of the Silurian Cañón de Caballeros Formation."

Silurian System (438–408 Ma). The first Silurian rocks identified in Mexico in November 1958 were found along the Caballeros Canyon at the Huizachal-Peregrina anticlinorium by Carrillo-Bravo (Lopez-Ramos, 1980). Here, the Cañón de Caballeros Formation of late Llandovery to Ludlow age exhibit a complete section of this formation. Shales from the top of the section contain a fossiliferous horizon with *Rhynchotreta sp.* (Carrillo-Bravo, 1961). According to Boucot et al. (1997), this formation is composed of an unnamed basal member, 10 m thick, of sandstone to conglomerate. The 2.5-m-thick Santa Ana Limestone member, and an unnamed upper member, 100 m thick, of shaly siltstone and sandstone.

Devonian System (408–360 Ma). The shales and sandstones grouped into the La Yerba Formation found in the Huizachal-Peregrina anticlinorium were considered to be of Devonian age (Carrillo-Bravo, 1961). *Chonetes* and *Orthis sp.* were found in this formation (Lopez-Ramos, 1980). After a restudy of fossil fauna from this formation by Boucot and Blodgett, it was demonstrated to be either Silurian or Mississippian in age (Stewart et al., 1999).

Mississippian System (360–320 Ma). The Vicente Guerrero Formation in the Huizachal-Peregrina anticlinorium northwest of Ciudad Victoria, Tamaulipas, is considered to be Mississippian age. Here, a lower member, 30 m thick, of dark gray sandstones and a minor amount of conglomerate, and an upper member of at least 50 m of siltstone and black shales with Mississippian fauna crop out in the neighborhood of the Vicente Guerrero ranch (Carrillo-Bravo, 1961; Stewart et al., 1993; Boucot et al., 1977).

Pennsylvanian System (320–286 Ma). The dark gray to black clastic limestones of the Del Monte Formation in the Huizachal-Peregrina anticlinorium are considered to be Pennsylvanian age (Carrillo-Bravo, 1961). *Stereocospha sp.* corals, *Profusulina sp., Millerella sp., Eoestafella sp., Stafella cf.,* and *Profusulinella sp.* fusulinid-foraminifers, and *Pseudoparalagoceras amotapence* and *Eosianites sp.* cephalopod ammonoids of the order Goniatitida, came from this formation (Lopez-Ramos, 1980).

Permian System (286–248 Ma). The type locality for the Permian Guacamaya Formation is in the Huizachal-Peregrina anticlinorium. There, 150 m of greenish-gray shales and sandstones with isolated 14-m-thick limestone bodies containing *Schwagerina cf. diversiformis, Triticites cf. Crekensis,* and *Osawainella sp.* fusulinids (Carrillo-Bravo, 1961) can be found.

Mesozoic

Most of the Sierra Madre Oriental physiographic province is composed of Mesozoic rocks.

Triassic System (248–213 Ma). Information concerning Triassic rocks in the Sierra Madre Oriental is only known from limited outcrops. The Sierra de Catorce, the northwest part of San Rafael, San Luis Potosí, the Huizachal-Peregrina anticlinorium, and the west part of Torreon, Coahuila, contain outcrops of either continental or marine Triassic rocks (Lopez-Ramos, 1981).

Jurassic System (213–144 Ma). Upper Jurassic strata are widely distributed within the Sierra Madre Oriental physiographic province. The Zuloaga, La Gloria, Yeso Minas Viejas, and La Casita Formations were widely deposited during Oxfordian, Kimmeridgian, and Tithonian time (Lopez-Ramos, 1984).

Cretaceous System (144–65 Ma). Cretaceous marine strata are widespread in basins of southeast-northwest Mexico. The main Cretaceous rock units are the Navarrete, Las Vigas, La Virgen, Cupido, Tamaulipas, El Abra, El Doctor, Cuesta del Cura, Del Rio, Buda, Ojinaga, Indidura, Caracol, San Felipe, and Mendez Formations (Lopez-Ramos, 1984).

Cenozoic

It is unknown if any marine sedimentation of Cenozoic age occurred within the Sierra de Catorce area. Due to the Hidalgoan orogeny and Cretaceous-Tertiary magmatism, a marine regression left the Sierra Madre Oriental physiographic province emergent.

Tertiary System (65–2 Ma). Most of Mexico started to emerge from the seas during Tertiary time. Contractional deformation (Hidalgoan orogeny) produced the Sierra Madre Oriental within the Mexican fold and thrust belt. Uplift, erosion, and magmatism with sporadic mainly calc-alkaline volcanism were the main geologic processes. Ahuichila Formation (Rogers et al., 1961) is the name adopted for all epiclastic continental deposits of this age found in the Sierra de Catorce.

Quaternary System (2–0 Ma). The Pleistocene and Holocene Epochs are represented by alluvial fan, alluvial calcrete-cemented, and stream sediment deposits, widely exposed on the elongated lowlands between ranges of the Sierra Madre Oriental.

STRATIGRAPHY OF THE SIERRA DE CATORCE

The Sierra de Catorce (Fig. 3) consists mainly of marine carbonate rocks that range in age from Late Jurassic to Late Cretaceous. These rocks are grouped into the following formations: Zuloaga (Oxfordian), La Caja (Kimmeridgian-Tithonian), Taraises (Berriasian), Cupido (Hauterivian-Barremian), La Peña (Aptian), Cuesta del Cura (Albian-Cenomanian), Indidura (Turonian), and Caracol (Coniacian-Santonian). Underlying these rocks and separated from them by a bedding-plane slip surface is a very thick and competent redbed section that is stratigraphically correlatable to La Joya Formation (late Early Jurassic to early Late Jurassic). These redbeds of the La Joya Formation are in turn resting unconformably over both the Triassic–Early Jurassic Huizachal Formation and the Upper Paleozoic green beds, which are correlatable to the Guacamaya Formation. The Guacamaya Formation was first described at the Huizachal-Peregrina Anticlinorium (Carrillo-Bravo, 1961). The Huizachal Formation was deposited over an angular unconformity. Both Paleozoic and Triassic–Early Jurassic rocks crop out along the northwestern portion of the Sierra de Catorce.

Permian System

Guacamaya Formation. The Guacamaya Formation is the oldest unit in the Sierra de Catorce. It is made up of a section of flysch-type sediments which are rhythmic and consist of green siltstones and sandstones (graywackes and subgraywackes). Conglomerate horizons are present. Two of the most important exposure areas are located around the Ranchería Los Catorce and the El Astillero sites (Fig. 1). A stratigraphic column of the formation was measured in and near the Arroyo General de Catorce creek (Fig. 4). Despite the existing primary sedimentary structures present in these beds, secondary geological structures made the column sequence description difficult. About 1260 m of this unit were measured along the Arroyo General de Catorce creek.

The Guacamaya beds are the lowest part of the sedimentary sequence exposed in the Sierra de Catorce region. The stratigraphic relation of these beds with the upper units is structurally unconformable. The buried underlying unit is unknown. The top of these green beds is in contact with two units; the older has been correlated to the Triassic–Early Jurassic Huizachal Formation and the other corresponds to the redbeds of the Late Jurassic La Joya Formation. The contact with the Huizachal Formation is structurally unconformable; both angular unconformity and a fault can be seen, whereas the contact with the La Joya Formation was only observed as an angular unconformity (Figs. 5 and 6).

In general terms, this unit is made up of rhythmic flysch-type sedimentary rocks consisting of predominantly green siltstones and sandstones (graywackes and subgraywackes). The thicknesses of individual layers vary from some millimeters to 90 cm. Some ~2-m-thick conglomerate horizons are sporadically present. Dark gray to greenish-gray siltstones are predominant. There are light grayish-green sandstones (graywackes and subgraywackes) that stand out from the siltstones because of their coloring and greater competence. This entire sequence shows the effects of tangential compression evidenced by its cleavage, which is better shown on its pelitic rocks than on its psammitic or psephitic rocks. Preferential orientation along weakness planes of laminar crystals and the incipient recrystallization of metamorphic minerals (sericite and chlorite) allow us to consider that the sequence was affected by regional metamorphic processes. Zoltan de Cserna, (Instituto de Geología, Universidad Nacional Autónoma de México, 1998, personal commun.) who spent several days in the study area and checked thin-section petrographic descriptions of these rocks, considers that the metamorphism varies from low to diagenetic. Textures and original mineralogy, which are almost completely preserved, petrographically defines them as sedimentary rocks.

Baker (1922, p. 44) mentioned sòme metamorphic rocks found in the General de Catorce Canyon and divided them into two series. He considered that "they might in part be as old as pre-Cambrian or as young as Jurassic." Mixon (1963) described these green beds as greenish-weathered claystones with siltstones and sandstones and named them as Catorce Claystone. McLeroy and Franquesa (1975) considered the quartzites and green schists as the oldest rocks found in the Sierra de Catorce, assigning them a late Paleozoic age. In 1976 rock samples were collected during a reconnaissance study performed by University of Texas, Arlington, students and Instituto de Geología, Universidad Nacional Autónoma de México (UNAM) researchers. These samples were prepared for palinomorph identification at the Mobil Research Laboratory in Dallas, Texas (Salvador Enciso de la Vega, Instituto de Geología, UNAM, 1979, personal commun.). *Lycospora sp.* and *Densosporites sp.* were identified in those samples, suggesting a late Mississippian to Early Pennsylvanian age (Bacon, 1978). Within the green beds found along Los Novios creek, 350 m north of the Rancheria Los Catorce (Fig. 6), some trace-fossil and plant-stem remains (part of any of various extinct treelike plants of the *Calamites* genus that were identified by Ladislau Rozloznik, 1980, personal commun., Instituto de Geología, UNAM) were found. There are many different opinions concerning the age of these green beds: not recognizing that this lithologic unit could have been deposited through a very long time could be one of the reasons; another explanation could be the erosion and tectonic deformation affecting these beds that controlled different exposures at different places.

At the study area, the stratigraphic relations of the green beds were complicated by folding and thrusting, thus making the interpretation and determination of their original thickness difficult. This and the uncertainty of their exact age do not allow for a clear correlation with time-equivalent formations such as the Permian Rara Formation from the Sierra del Cuervo, Chihuahua (Ramírez and Acevedo, 1957), the Triassic Zacatecas Formation from the Zacatecas and Charcas areas (Tristán and Torres, 1992), the Rodeo Formation from the Apizolaya region (Córdoba-Méndez, 1963), and the Guacamaya Formation from the Ciudad Victoria area (Carrillo-Bravo, 1961). The name Guacamaya comes from a lithologic unit in the Huizachal-Peregrina anticlinorium bearing the same name and can be used for designation purposes. As Mixon (1963) stated, correlation of these green beds with the Guacamaya Formation was based on lithic similarity, stratigraphic position, and similar deformation history.

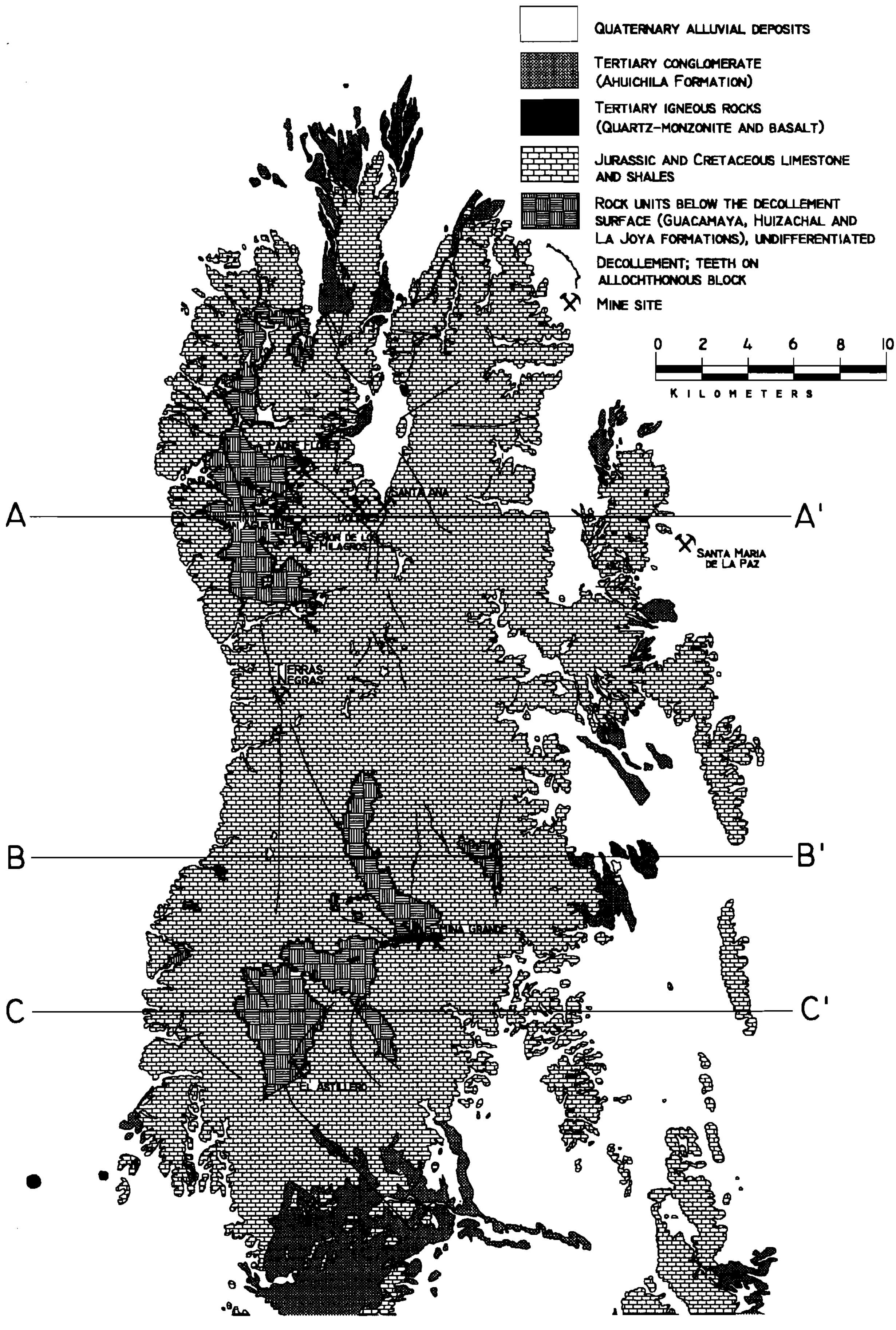
The depositional environment of the Guacamaya Formation in the Sierra de Catorce could be explained by the turbidite model. The essential requirement is an unstable, up-dip sedimentary deposit that fails, i.e., the steep bluff of a terrace bordering the oversteepened front of a fan delta. The delta of a large river or the edge of a shelf provide examples wherein the potential energy of the sedimentary deposit is catastrophically converted into kinetic energy as the sediment mass moves downslope under water. The result is a bottom-seeking density current which, where unconfined, spreads out and decelerates to form an underwater fan at the base of a slope. Some turbidites are deposited on the lower part of slopes and others travel far onto abyssal plains before deposition (Potter, 1985). A constrained basin, in this case caused by the collision of the northern margin of Gondwana (northern South America and northwestern Africa) and the southeastern margin of the North American craton, seems to have been the depositional setting for the Guacamaya Formation. As these opposing plates collided during the late Paleozoic, highland areas were formed that would shed clastic sediments into adjacent basins. Permian clastic sediments were sourced from the mountains produced by the closure of the basin between North America and Africa–South America.

Triassic-Jurassic Systems

Triassic rocks are known to occur north of Zacatecas city, in the neighborhood of the Arroyo La Pimienta creek. Other sites have been located in southwestern Tamaulipas and southeastern Nuevo Leon, where the Triassic consist of >2000 m of mudstone, siltstone, shale, sandstone, and conglomerate (Mixon, 1963). Continental Triassic rock exposures seem to be restricted to the Sierra Madre Oriental physiographic province, but well data suggest a wide distribution in the subsurface of the Gulf of Mexico coastal plain province (Quezadas-Flores, 1961, p. 302). Outside of this area, they were apparently subjected to a period of erosion that continued into the Middle Jurassic (Humphrey, 1956).

Huizachal Formation. Imlay et al. (1948, p. 1753) formally defined the Huizachal Formation as "the 427 meters of red beds directly underlying the normal marine Upper Jurassic rocks in eastern and northern Mexico." Field studies by Mixon (1963, p. 23) in the Huizachal anticlinorium suggest that "the Huizachal Formation be raised to group rank and include the two lithically similar redbed sequences in the Sierra Madre Oriental." He divided the Huizachal Formation into two mappable lithic sequences separated by a pronounced angular unconformity. Both sequences are present in the type section of the Huizachal Formation in the Huizachal Valley near Ciudad Victoria, Tamaulipas. The lower redbed sequence, designated by Mixon et al. (1959) as la Boca Formation and here considered as the Huizachal Formation, according to Carrillo-Bravo (1961), is composed of Late Triassic and Early Jurassic postorogenic sediments eroded from uplifted portions of late Paleozoic folded belts. The La Joya Formation (Mixon et al., 1959) of late Early Jurassic to Late Jurassic age, is the name given to the upper sequence.

Figure 3. Geologic map of Sierra de Catorce study area, San Luis Potosí, Mexico.



QUATERNARY ALLUVIAL DEPOSITS
TERTIARY CONGLOMERATE (AHUICHILA FORMATION)
TERTIARY IGNEOUS ROCKS (QUARTZ-MONZONITE AND BASALT)
JURASSIC AND CRETACEOUS LIMESTONE AND SHALES
ROCK UNITS BELOW THE DECOLLEMENT SURFACE (GUACAMAYA, HUIZACHAL AND LA JOYA FORMATIONS), UNDIFFERENTIATED
DECOLLEMENT; TEETH ON ALLOCHTHONOUS BLOCK
MINE SITE
0 2 4 6 8 10
KILOMETERS
A
A'
B
B'
C
C'
SANTA ANA
SANTA MARIA DE LA PAZ
EL ASTILLERO

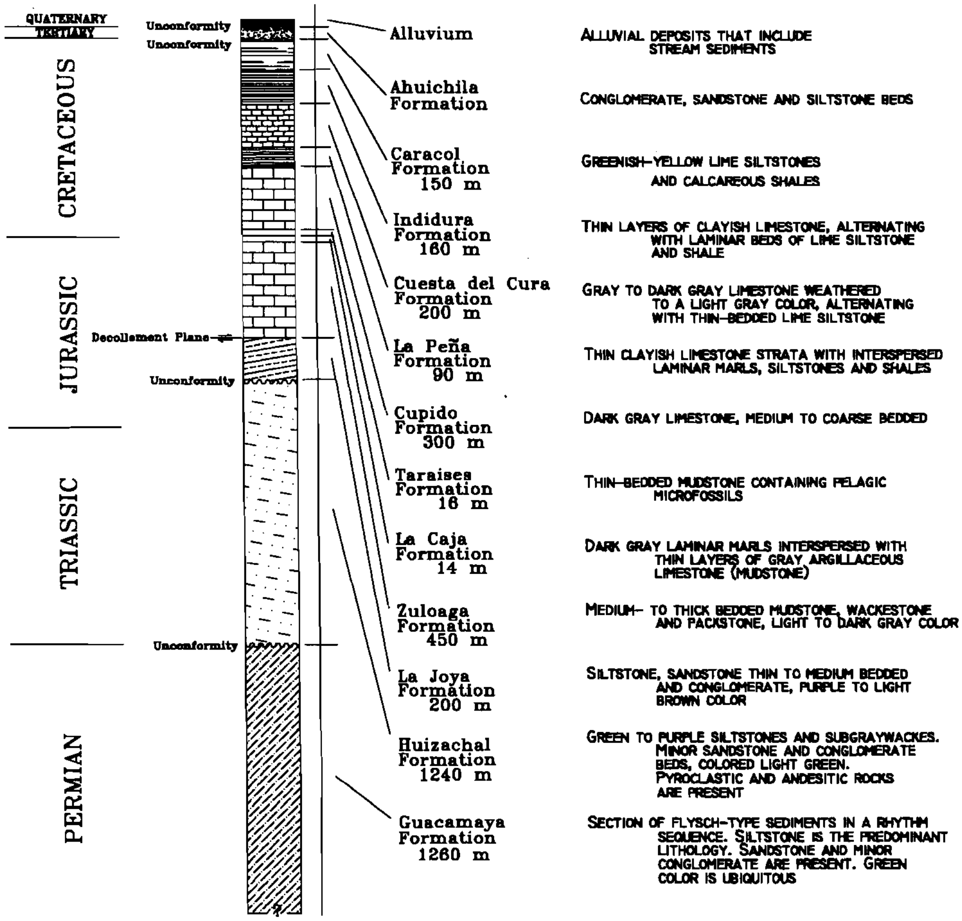


Figure 4. Stratigraphic column for Sierra de Catorce.

The Huizachal Formation was formally redefined by Carrillo-Bravo (1961) in the Huizachal-Peregrina anticlinorium, west of Ciudad Victoria, Tamaulipas, Mexico.

One of the most important outcrops of the Huizachal Formation is located in the General de Catorce canyon (Figs. 5 and 6). Other outcrops can be found in the Cañada El Salto gorge, the San Juan de Matanzas area, and the Rio Grande gorge south of Sierra de Catorce. To the southwest of this range at the Arroyo El Astillero gorge, no Huizachal Formation outcrops were observed despite both the Guacamaya and La Joya units being present. In the Arroyo General de Catorce area, the Huizachal Formation beds gave rise to an anticline structure that has a north-northwest to south-southeast strike and east-northeast dip axial plane. Measuring from the eastern contact between this unit and the Guacamaya Formation toward the Real de Catorce Town, the Huizachal Formation is ~1240 m thick. All these beds are in normal position. However, throughout this section, several faults cut the sequence and probably cause repetitions or duplication. On the western limb of the anticline structure along the General de Catorce canyon, the Huizachal Formation presents a thinner section. It shows some differences as compared with the eastern side that could possibly represent the bottom of the lithological unit. Here, a light green polymictic conglomerate overlies the Guacamaya Formation, forming an angular unconformity.

At the Catorce anticlinorium area, the Huizachal Formation overlies with an angular unconformity the Guacamaya Formation. However, at some places the contact is a fault. In the Sierra de Catorce the Huizachal Formation stratigraphically underlies the La Joya Formation with angular unconformity. At the Arroyo General de Catorce the displacement produced along the Galavios fault (Bacon, 1978) put both the Huizachal and the Zuloaga Formations in fault contact (Fig. 6).

Most of the rocks of this formation show an increasing regional metamorphism, as defined by Miyashiro (1973) as a grand-scale metamorphism in orogenic belts, from a very low intensity metamorphism along the lower part of the formation, to a phyllite-schist facies through the upper portion of the column described. Two different sampling sections were measured. The first was along Arroyo General de Catorce, which covered the lower portion. The second was along the dirt road built on the northern wall of the General de Catorce canyon. The rocks described from the top of this stratigraphic column show a more extensive alteration caused by a much stronger regional metamorphism. Most of the lower part of this lithological unit is green to purple siltstone and subgraywacke. Other minor lithological types are found within the Huizachal Formation. Light green graywacke, sandstone, and conglomerate beds are the second-most common rock types found in this formation. Midway between the towns of Ranchería Los Catorce and Real de Catorce, the Socavón General adit, an infiltration gallery constructed for the purpose of intercepting ground water, was largely excavated in andesitic rock of the Huizachal Formation (Fig. 5). Northwest of the Ranchería Los Catorce an andesitic mass crops out in the Huizachal Formation (Fig. 5). Due to compression an asbestiform-like mineral of tremolite composition (Guadalupe Villaseñor-Cabral, Instituto de Geología, UNAM, 1980, personal commun.) was formed along cymoid fractures. These two andesitic bodies, separated by ~1300 m, are tentatively considered to be volcanic flows or perhaps sills within the Huizachal Formation, due to their parallel structure along bedding planes and the asbestiform minerals present in both masses. These green igneous rocks show porphyritic, holocrystalline, and hypidiomorphic textures, and the groundmass texture is pilotaxitic to trachytic. Much of the component minerals have been altered and transformed totally or partially to saussurite. Nevertheless, in some samples many of the original andesine minerals, such as plagioclases, can be identified. These igneous rock bodies are ~315 m thick and form fault contacts in the General de Catorce canyon walls (Fig. 5). These two igneous bodies

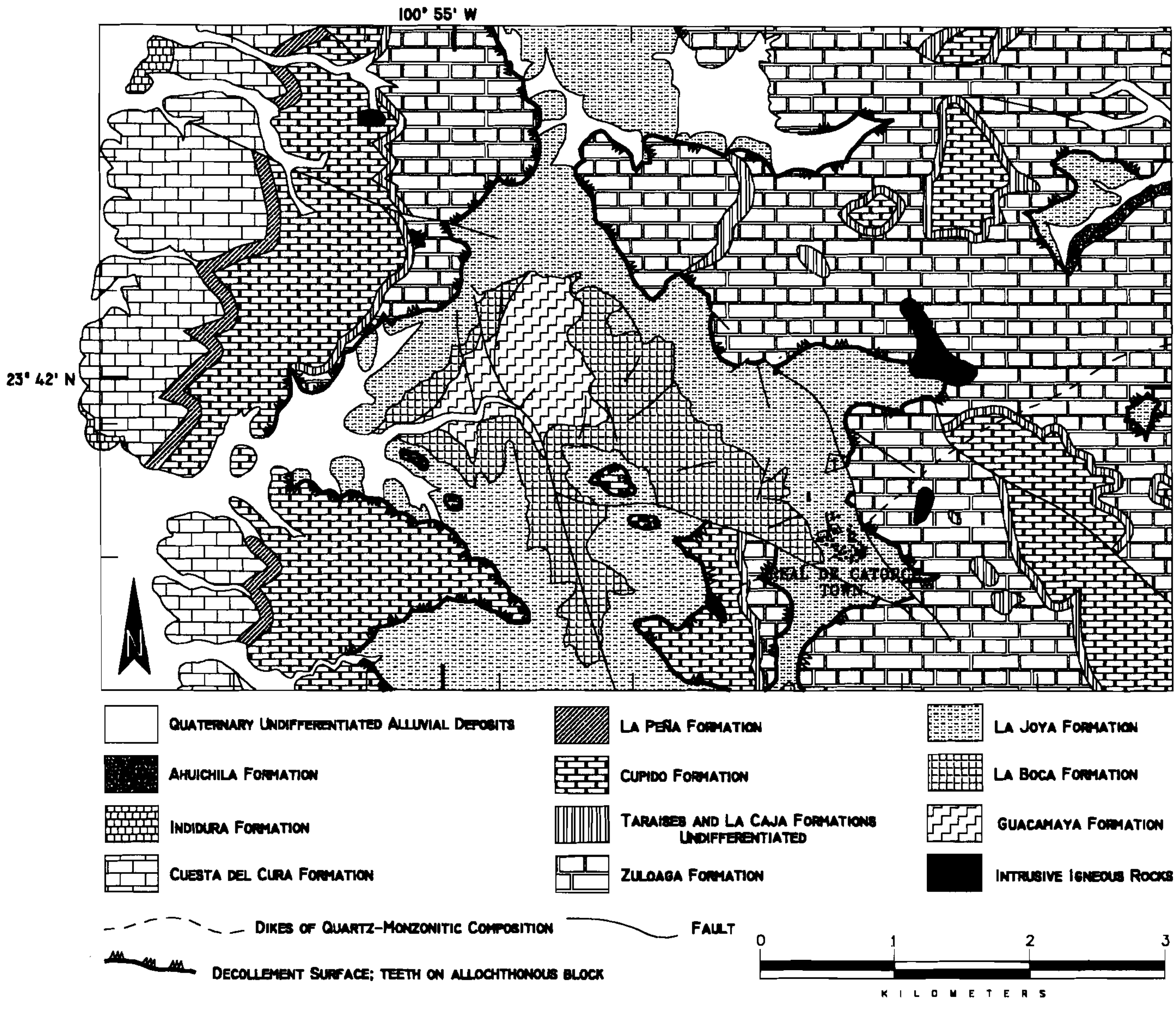


Figure 5. Geologic map of northwestern portion of Sierra de Catorce.

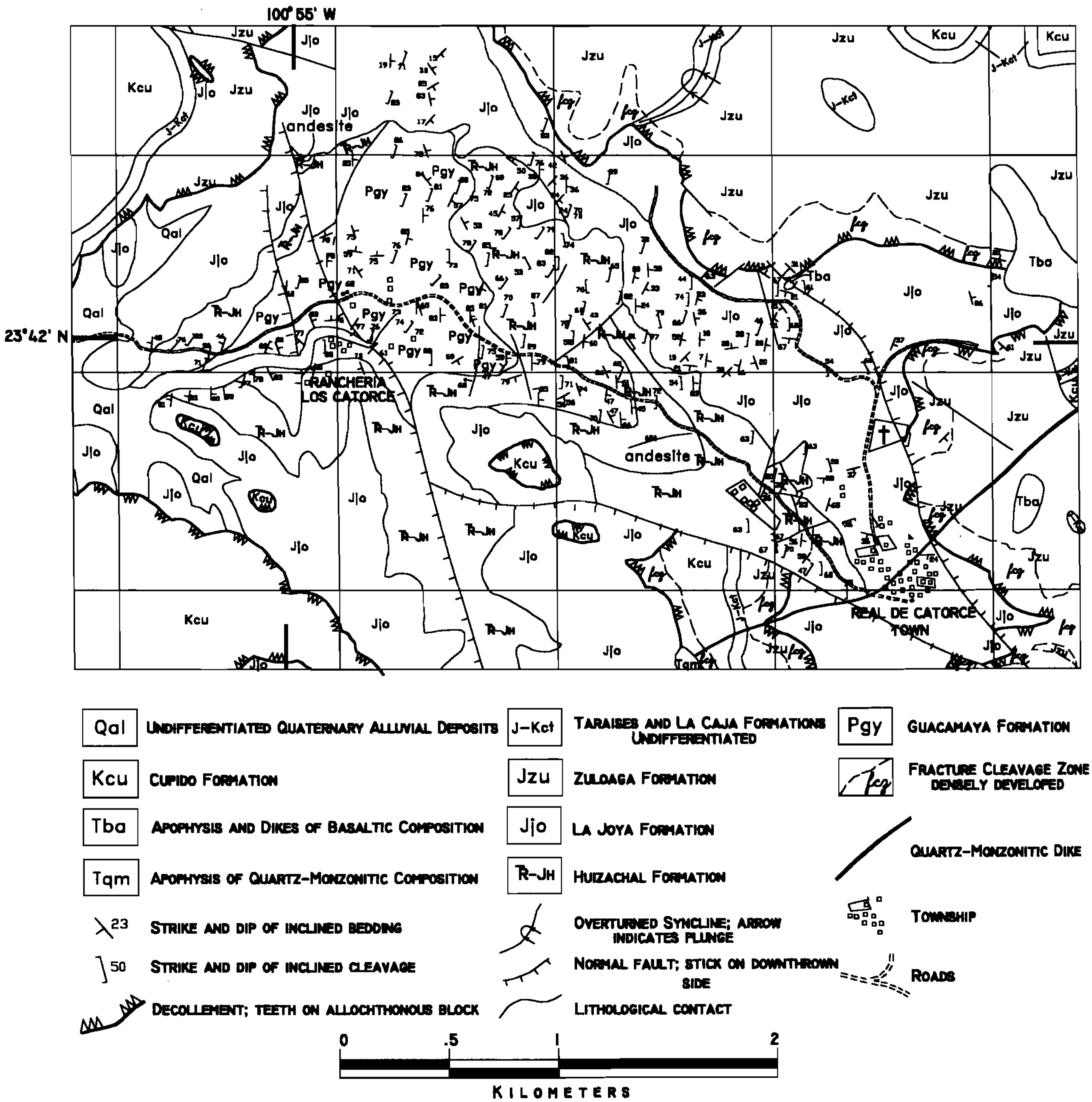


Figure 6. Semidetailed geologic map of Real de Catorce mining area.

have not been found intruding the overlying La Joya Formation. Hydrothermal alteration of this rock made it difficult to make an exact classification. Nevertheless, the minerals identified indicate that this rock tends to be andesitic.

A 200-m-thick steel gray (volcanic?) igneous rock is on top of the Huizachal Formation. Some quartz crystals are present. Other phenocrystals are abundant and almost completely replaced by an unknown black mineral. Some of them, which are not totally replaced, still conserve part of the original plagioclase mineral at the center. Most of this body shows a cleavage structure with sericite and chlorite along planes. Calcite is present as an alteration mineral. The groundmass was not identified under polarizing microscope. The upper portion of this sequence shows a stronger regional metamorphism. It consists of slate, phyllite, and sericitic schist restricted to the Huizachal Formation (Mixon, 1963, p. 40). Neither the Guacamaya nor the La Joya Formations were observed to have reached a phyllite- or schist-grade metamorphism. Like the Guacamaya Formation, the Huizachal Formation strata show numerous cleavage planes, which are better manifested in its fine-grained siltstone.

I found neither fossil flora nor fossil fauna in the Huizachal Formation of the Catorce anticlinorium. However, Bartolini (1998) collected poorly preserved fossil plants from the Huizachal Formation at the General de Catorce canyon. Sidney Ash identified the fossil plants for Bartolini (1998) as cycadeoid *(Bennettitales) Zamites,* which range in age from Late Triassic to Cretaceous. Erben (1956, p. 47) reported *Vermiceras sp.* and *Arnioceras cf. objectum* within phyllitic shales from the Sierra de Catorce area. The age of these fossils is early Sinemurian (206–200 Ma). Mixon (1963, p. 54–59) and Mixon et al. (1959, p. 768–769) found fossil plants within the La Boca Formation (Huizachal Formation). *Pterophyllum fragile* Newberry, *Podozamites sp.*, and *Cephalotaxopsis sp.*, found at the Ciudad Victoria area, suggest an Upper Triassic age for these redbeds (Rhaetian, 219–213 Ma). Carrillo-Bravo (1961) collected additional fossil plants such as *Pterophyllum fragile* Newberry, *Pterophyllum inaequale* Fontaine, *Cephalotaxopsis Carolinensis* Fontaine, *Podozamites sp.*, a silicified wood specimen of the *Araucarioxylon* genus (Permian to Early Triassic), *Equisetites sp.* (Mesozoic), *and Williamsonia Netzahualcoyotl* Wieland (Early Jurassic).

Carrillo-Bravo (1961) did not make any distinction between the Huizachal and the La Boca Formations, considering them to be the same lithologic unit. Mixon et al. (1959) considered that the La Boca Formation (Huizachal Formation) may be time equivalent to the Eagle Mills redbeds of southern United States, the Todos Santos of southern Mexico, and the Barrancas Group of Sonora. In the Charcas quadrangle, southwest of the Sierra de Catorce, the Huizachal Formation is considered to be equivalent to the Nazas Formation (Tristán and Torres, 1992).

All deposits that belong to the Huizachal Formation in the Sierra de Catorce indicate a continental molasse sedimentary facies derived from highland areas with prevailing igneous activity, as can be interpreted from the volcanic rocks(?) and flows (or sills) of this unit (Fig. 6). They are more clastic and less rhythmic than the older flysch facies of the Guacamaya Formation. Mountain chains were built by the closure of the basin between North America and AfricaSouth America, as a result of the Permian-Triassic Coahuilian orogeny (de Cserna, 1956).

La Joya Formation. The upper redbed sequence of the Huizachal Group was formally defined by Mixon et al. (1959) at the Huizachal-Peregrina anticlinorium as the La Joya Formation of middle to early Late Jurassic age (181163 Ma).

A 30-m-thick conglomerate characterizes the base of this unit. The greatest thickness exhibited by the redbeds measured along the Arroyo General de Catorce is ~200 m. Outcrops of this unit are exposed on the northwestern, west-central, and southern portions of the Sierra de Catorce.

The unconformable contacts with both overlying and underlying units are easy to follow throughout the Sierra de Catorce because of the formation's characteristic red color. Its base overlies with angular unconformity both the Huizachal and Guacamaya Formations. Toward the top, the contact with the Oxfordian Zuloaga Formation limestone is structural, caused by the shear stress between the overlying calcareous sequence and the La Joya redbeds. A tectonic breccia composed of both Zuloaga Formation calcareous fragments and La Joya Formation terrigenous fragments characterizes this contact. In some places, entire lithologic units were tectonically abraded by this process. In some locations of the Sierra de Catorce, where the Zuloaga, La Caja, and Taraises Formations were transformed to tectonic breccias, the Aptian Cupido Formation can be seen in contact with the La Joya Formation redbeds (Fig. 5).

The basal conglomerate of this transgressive redbed unit is composed of round to subangular pebble-size fragments. It consists mainly of quartz and quartzite clasts, igneous (andesitic and quartz latite) fragments, and other fragments derived from the underlying sequence. The different compositions of the source rocks included sandy to silty matrixes that have a grayish-purple color. Medium- to thick-bedded reddish-purple sandstones and siltstones containing little mudstone overle the conglomerate. Abundant ripple marks characterize these strata. A thinly stratified reddish-purple siltstone and fine-grained sandstone sequence gradually appears toward the top. Many ripple-mark and small-scale cross-bedding primary structures are exhibited in these beds. A reddish-purple coarse-bedded siltstone sequence crops out over the previous strata. The sequence is characterized by light green sandstone concretions. At regular intervals, purple to yellowish-brown siltstones are interspersed with thinly bedded sandstones. Locally, along this section, strata exhibit mud cracks.

No fossils have been found in the La Joya Formation in the Sierra de Catorce. In the Huizachal-Peregrina anticlinorium, Carrillo-Bravo (1961, p. 51) described *Natica georgeana* D'Orbigny and *Eonavicula* (Kimmeridgian) from the La Joya Formation. Mixon (1963) considered the La Joya Formation to be late Early Jurassic to early Late Jurassic age.

Redbeds from the La Gloria Formation could be time equivalent to the La Joya Formation (Carrillo-Bravo, 1961, p. 51). Mixon (1963) correlated the La Joya Formation with the Cahuasas Formation, a redbed sequence found in Hidalgo and Veracruz. They are diachronous with the La Gloria (Oxfordian) and Las Vigas (Neocomian) Formations, on the basis of similar lithology and depositional environments.

Sediments of the La Joya Formation were deposited unconformably over the older rocks of the Huizachal and Guacamaya Formations during the advancement of seawater over a subsiding land area. A conglomerate forms a basal stratigraphic unit overlying a surface of erosion, thereby marking an unconformity. The La Joya Formation is thought to be related to a narrow depositional environment, such as an opening rift, where marine epiclastic sediments deposited during the transgressive process became younger in the direction in which the sea was moving, in this case toward the north.

STRUCTURAL GEOLOGY

Regional tectonics

Ouachita deformation. The Ouachita belt, like other orogenic belts, is associated with continental crust convergence. Generally, this deformation was caused by the collision of the northern margin of Gondwana (northern South America and perhaps part of northwestern Africa) with the southeastern margin of the North American craton (Levin, 1988). As a result, at the end of the Paleozoic and beginning of the Mesozoic, the Sierra de Catorce area was part of a very large landmass, the supercontinent Pangea (Salvador, 1987).

Normal faulting is closely related to the Ouachita deformation. Normal faulting follows orogenic contraction in the form of crustal relaxation. This is explained as an original shape-restoration tendency pertaining to all elastic bodies subjected to compression. Faults of this type are located within Huizachal Formation. They do not affect the overlying lithological units (Fig. 6).

Jurassic Taphrogeny. The term taphrogeny groups all structures related to the rift-formation phenomena, characterized by high-angle normal faulting and associated subsidence (Bates and Jackson, 1980, p. 639). Due to the transgressive character of the La Joya Formation, it was assumed that the formation was deposited under a taphrogenic regime (Salvador, 1987; Greier, 1989).

This graben system is supposed to dislocate the Huizachal Formation sedimentary and igneous rocks, protecting them from erosion in the topographic low portions. Taphrogenic normal faults are considered to crop out in the Sierra de Catorce range, where a contact between the Guacamaya, Huizachal, and La Joya Formations exists (Fig. 6).

Structural features of the Sierra de Catorce

All syngenetic sedimentary structures determined by the conditions of deposition (mainly current velocity and sedimentation rate) and developed before lithification of the rock in which they were found are considered to be primary (Bates and Jackson, 1980). They are usually considered as top- and base-defining criteria.

Bedding is a primary feature widely expressed in the Catorce anticlinorium. Inherent to all sedimentary units, each one shows a particular stratification type. Beds of the flysch-type Guacamaya Formation exhibit a consistent repetition and those of the Huizachal Formation frequently show massive and clastic beds.

Ripple marks are primary sedimentary structures produced by the action of a moving fluid on an inconsistant sedimentary material. Wave-action ripple marks are a distinctive feature of the La Joya Formation.

Cross-bedding is a depositional structure where the bedding planes within a body of layers are inclined with respect to the separation planes between different such bodies. This is seen in sandstones and siltstones of the La Joya Formation, deposited by fast-flowing streams.

Burrows are tubular holes perforated in originally soft or loose sediment by mud-eating annelid worms. They were mainly preserved in the La Joya Formation beds.

All those geological structures that originated subsequent to the deposition or emplacement of the rock in which they are found are referred to as secondary (Bates and Jackson, 1980). Within the Catorce anticlinorium area, tension and contraction deformation style characteristics were defined on the basis of these structures.

Joints are planar structures found throughout the Catorce anticlinorium area. Sets of nearly parallel joints were usually measured considering their spacing density (e.g., 10 joints/m). Generally, two sets believed to represent complementary shear sets were found. Most tension joints at or near the surface in the Catorce anticlinorium have been weathered, forming open channels sometimes filled with minerals such as limonite, calcite, quartz, or opaline silica, and sometimes serving as conduits for hydrothermal solutions, which have produced strong alteration halos.

Cleavage in fine-grained terrigenous rocks in the Catorce anticlinorium shows the clearest evidence of the combined effects of metamorphism and deformation. Beds from the Guacamaya and Huizachal Formations may be split into thin sheets along parallel cleavage planes. A fracture cleavage zone is fairly obvious at decollement level. Mechanical effects of shearing and slipping along a detachment surface between the La Joya and Zuloaga Formations are clearly exhibited in the basal coarse-bedded limestone of the Zuloaga Formation (Fig. 6).

Decollements, according to Bates and Jackson (1980), are detachment structures of strata owing to deformation, that result in independent styles of deformation in the rocks above and below. Along the Sierra de Catorce, at the contact between the top of the La Joya and the base of the Zuloaga Formations, a decollement is best exposed. A fault breccia at the decollement level composed of broken or crushed rock fragments from the Zuloaga and La Joya Formations resulted from the orogenic compressive stresses. This tectonic abrasion locally destroyed entire formations, including the Zuloaga, La Caja, and Taraises Formations (Fig. 5).

A fracture cleavage zone occurs at the contact by decollement between the Zuloaga and La Joya Formations, where incipient metamorphism affected both units. The structure is characterized by closely spaced parallel joints and fractures.

Folds are the main secondary geologic structure in the sedimentary formations in the Sierra de Catorce (Fig.7). Folds reflect

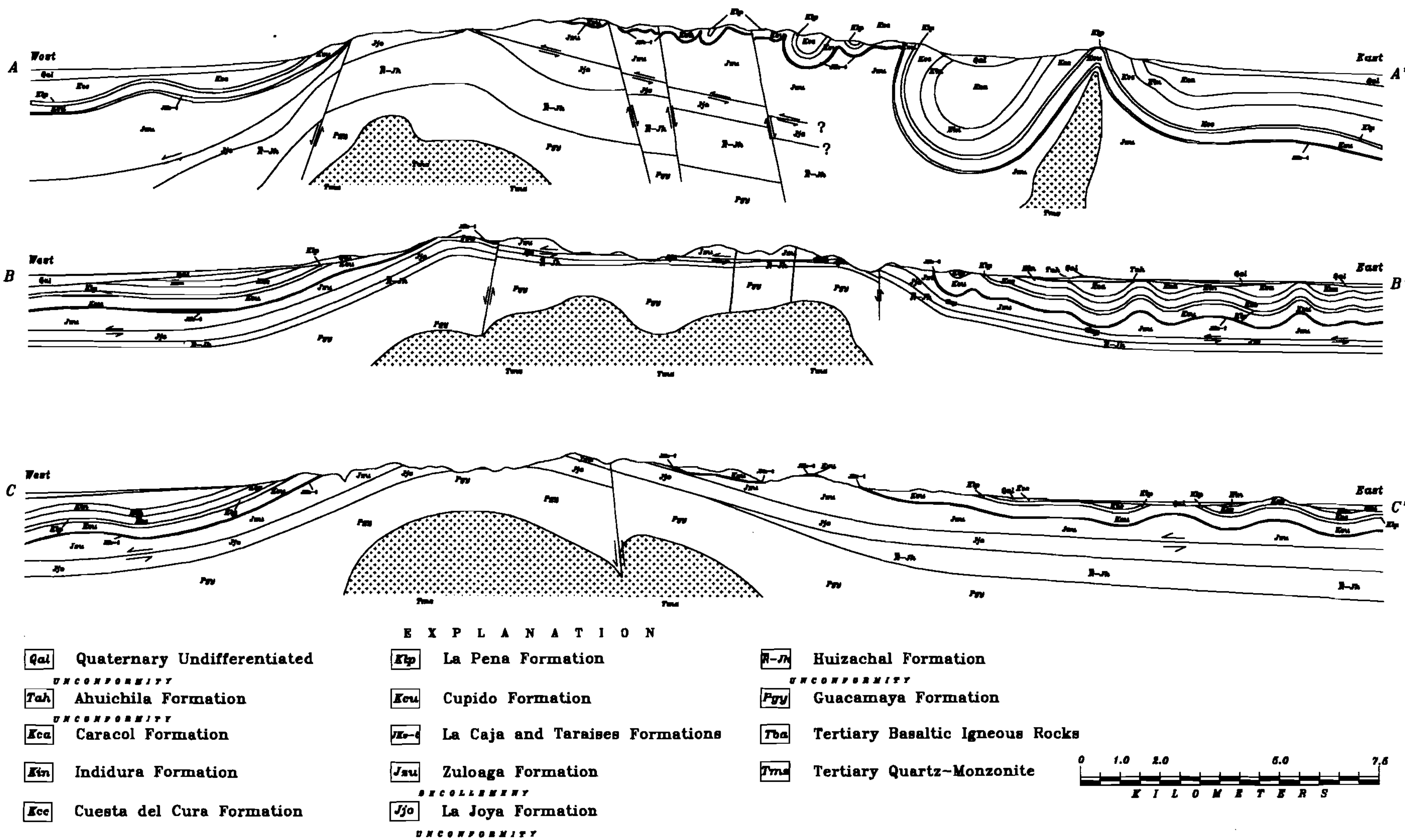


Figure 7. Geologic structure sections of Sierra de Catorce.

SYSTEM	SERIES	STAGE	TEXAS	NORTHEAST MEXICO	HUIZACHAL PEREGRINA	CATORCE
QUATERN	HOLOCENE PLEISTOCENE					ALLUVIAL DEPOSITS
TERTIARY	PLIOCENE					BASALT
	MIOCENE					
	OLIGOCENE					AHUICHILA FM
	EOCENE					QUARTZ-MONZONITE
	PALEOCENE					
CRETACEOUS	GULFIAN	MAASTRICHTIAN	NAVARRO TAYLOR	MENDEZ / DIFUNTA	MENDEZ FORMATION	CARACOL FORMATION
		CAMPANIAN				
		SANTONIAN	AUSTIN	SAN FELIPE	SAN FELIPE FORMATION	INDIDURA FORMATION
		CONIACIAN				
		TURONIAN	EAGLE FORD	AGUA NUEVA / INDIDURA	AGUA NUEVA FM	
	COMANCHEAN	CENOMANIAN	WOODBINE-BUDA	TAMASOPO / CUESTA DEL CURA	CUESTA DEL CURA FM	CUESTA DEL CURA FM
		ALBIAN	FREDERICKSBURG TRINITY	AURORA	AURORA FORMATION	
		APTIAN	PEARSALL	LA PEÑA-OTATES	LA PENA FORMATION	LA PENA FORMATION
	COAHUILAN	BARREMIAN	SLIGO	CUPIDO	CUPIDO FORMATION	CUPIDO FORMATION
		HAUTERIVIAN				
		VALANGINIAN	HOSSTON			
		BERRIASIAN		TARAISES	TARAISES FORMATION	TARAISES FORMATION
JURASSIC	SABINAS	TITHONIAN	COTTON VALLEY	LA CASITA	LA CASITA FORMATION	LA CAJA FORMATION
		KIMMERIDGIAN	BUCKNER	OLVIDO		
		OXFORDIAN	SMACKOVER NORPHLET	ZULOAGA / MINAS VIEJAS	OLVIDO FORMATION	ZULOAGA FORMATION
		CALLOVIAN			ZULOAGA FORMATION	DECOLLEMENT
		BATHONIAN	LOUANN WERNER			LA JOYA FORMATION
		BAJOCIAN		LA JOYA	LA JOYA FORMATION	
TRIASSIC	UPPER	RHAETIAN		HUIZACHAL FM	HUIZACHAL FM	HUIZACHAL FM
		NORIAN				
		CARNIAN				
PERMIAN			HUECO GROUP	PALEOZOIC PRECAMBRIAN	GUACAMAYA FORMATION	GUACAMAYA FORMATION ?
PENNSYLVANIAN			MAGDALENA GROUP		PALEOZOIC PRECAMBRIAN	
MISSISSIPPIAN			HELMS FM RANCHERIA FM LAS CRUCES FM			
DEVONIAN			PERCHA SHALE CANUTILLO FM			
SILURIAN			FUSSELMAN DOL.			
ORDOVICIAN			MONTOYA GROUP EL PASO GROUP			
CAMBRIAN-ORDOVICIAN			BLISS SANDSTONE			

Figure 8. Stratigraphic correlation between northeastern lithological units from Mexico.

a north-northwest preferential direction of axial planes. Magmatism is considered to be the main cause for upwardfolding.

GEOLOGIC HISTORY

Pennsylvanian-Permian

Although deformation began late in the Paleozoic, formation of mountain ranges was probably caused by several orogenic pulses from the Late Permian to the Late Triassic (de Cserna, 1970; Pindell and Dewey, 1982), folding and faulting Permian and Triassic strata at the Sierra de Catorce. Another Permian-Triassic disturbance in the southwestern United States (Sonoma orogeny) was probably caused by the collision of an eastward-moving island arc against the North American continental margin around west-central Nevada. Oceanic rocks and remnants of the arc were thrust onto the edge of the continent, becoming part of North America. This event marks the Permian-Triassic limit at 249 Ma (Levin, 1988, p. 307). Barth et al. (1997, p. 290) established that "cordilleran magmatism first developed in southern California in Triassic time, succeding a Paleozoic passive margin and marking the onset of east dipping subduction beneath the continental edge." This orogeny could have influenced the deformation of sediments in the Sierra de Catorce, in addition to that caused by the Ouachita deformation. In central Chihuahua, deposition of flysch-type sediments in the basin between the North and South American cratons probably occurred from Precambrian to Permian time. Concerning Permian flysch-type sediments, Mauger et al. (1983, p. 165) mentioned "the pegmatite contains a few xenoliths which are very similar to the surrounding sedimentary rocks. The pegmatite may have been emplaced when the Precambrian rocks were elsewhere; if so, the xenoliths would not be derived from local strata. Alternatively, the xenoliths may be locally derived and perhaps part of the sedimentary section is Precambrian."

The same type of sedimentary rocks crop out in Hidalgo del Parral, Chihuahua. These sedimentary rocks, dated as Cretaceous (Tarango-Ontiveros, 1993), as well as the flysch-type sediments from central Chihuahua, are considered to have been deposited in a environment similar as those of the Guacamaya Permian green beds of the Sierra de Catorce area (Fig. 8). These flysch-type strata are lithologically correlated with the Permian Guacamaya Formation from the Huizachal-Peregrina anticlinorium (Carrillo-Bravo, 1961), and crop out in the Sierra de Catorce (Fig. 5); they are considered to have been deposited in a basin between the North and South American cratons. The Mississippian-Pennsylvanian rocks described by Bacon (1978) and those here reported as Permian green beds on the western flank of the Sierra de Catorce, are probably allochthonous blocks that were derived from older sedimentary sequences deposited in distant areas. Sediments from this basin were folded and faulted during the collision of the South American craton.

Triassic through Mid-Cretaceous

The closing of this marine sedimentary basin by collision of the South American craton against the North American continental margin favored a southward-dipping subduction zone underneath the continental crust (Pindell and Dewey, 1982, p. 182). During Late Triassic–Early Jurassic time one or perhaps several continental magmatic arcs formed (Bartolini and Marsaglia, 1996, p. 117) and the Huizachal Formation was deposited over ancient and rugged continental topography.

CONCLUSIONS

Schists and phyllites at the top of the Huizachal Formation are believed to have been generated by a regional metamorphism, related both geographically and genetically to a large orogenic belt. Isolated blocks of andesitic dike within an intensely deformed Guacamaya Formation, plus regional metamorphism on rocks of the Late Triassic–Early Jurassic Huizachal Formation, could be evidence of prevailing orogenic deformation throughout Late Triassic–late Early Jurassic time. This orogeny could be related to late pulsations of the Ouachita deformation. Normal faults involving both the Guacamaya and the Huizachal Formations, and a transgressive depositional environment of the overlying La Joya Formation, seem to fit well into a rifting model, rifting that could have started after the end of the here mentioned orogenic deformation, in late Early Jurassic time.

ACKNOWLEDGMENTS

I thank Zoltan de Cserna, Instituto de Geología, Universidad Nacional Autónoma de México (UNAM), for his assistance both in the field and in the laboratory. His literary and practical knowledge of geology were an invaluable asset to this project and his constant encouragement and undying patience provided great inspiration. I am grateful to Salvador Enciso de la Vega (deceased), Instituto de Geología, UNAM, who first suggested the mapping project, and José Cerrillo Chowell and Javier Cerrillo Chowell of the Negociación Minera Santa María de la Paz y Anexas, Sociedad Anónima, for their moral and logistic support at Sierra de Catorce.

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MANUSCRIPT ACCEPTED BY THE SOCIETY FEBRUARY 8, 1999