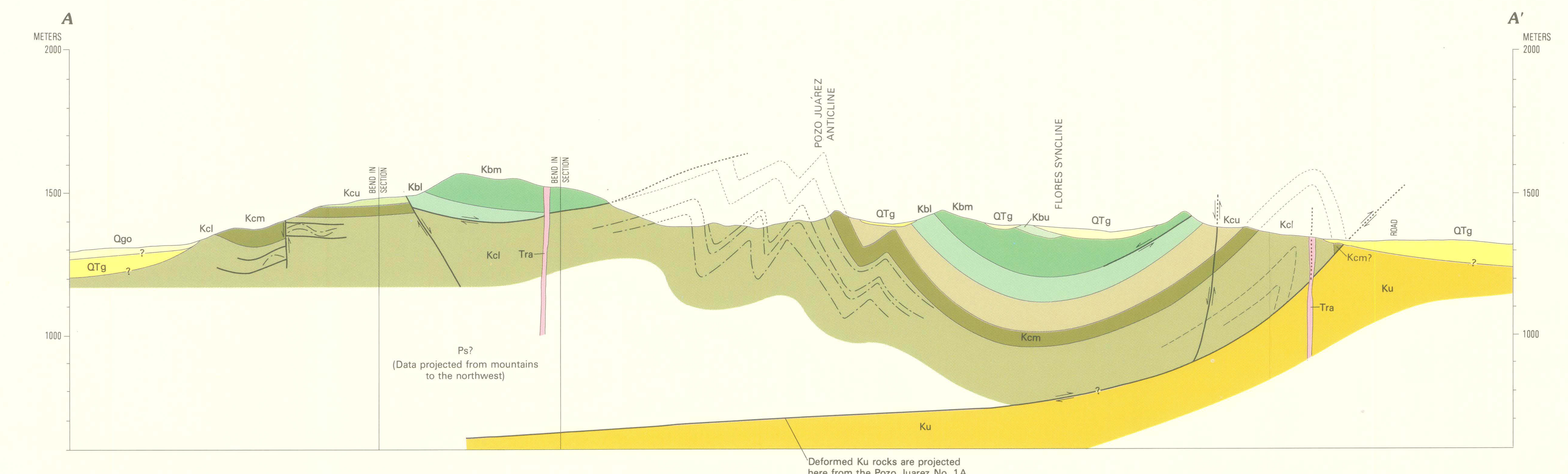
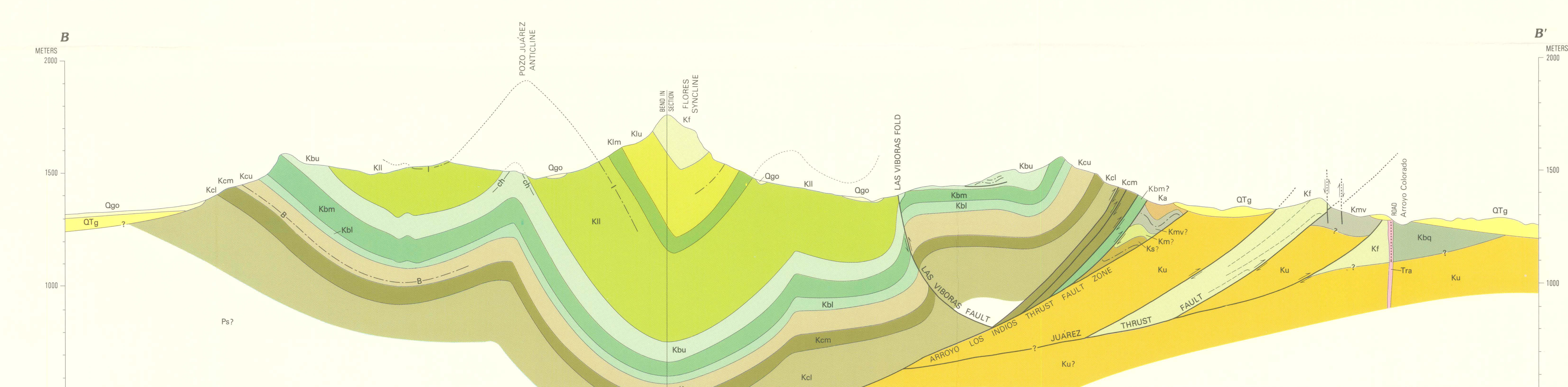
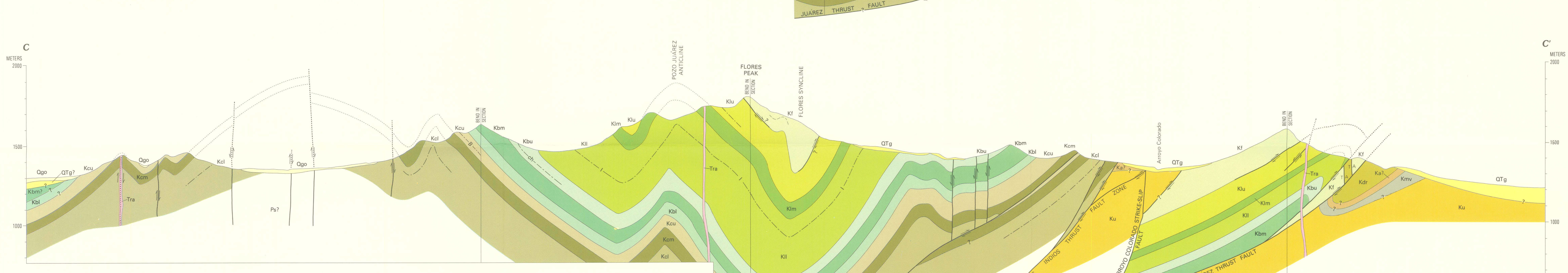
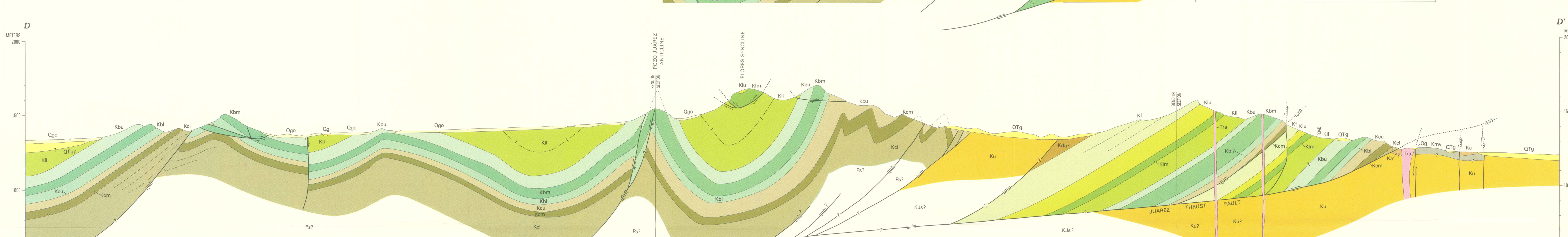
U.S. DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

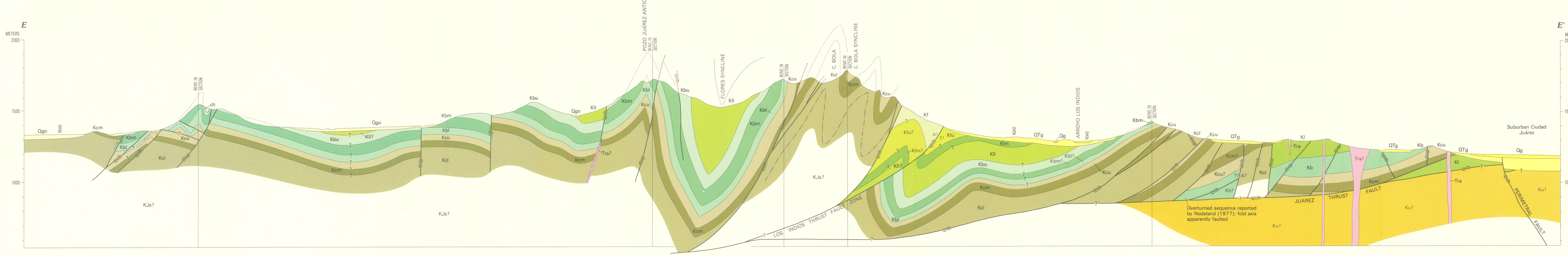
MISCELLANEOUS INVESTIGATIONS SERIES
MAP I–2287 (SHEET 2 OF 2)

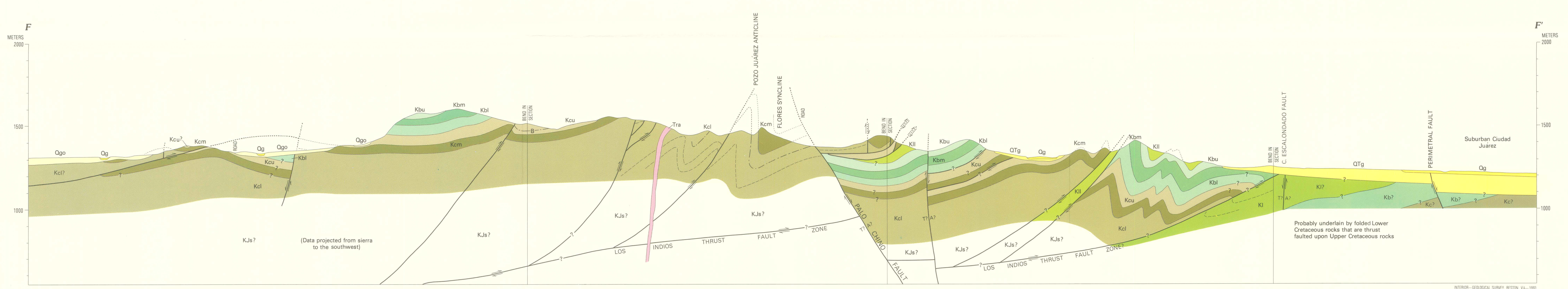
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INTERIOR—GEOLOGICAL SURVEY, RESTON, VA—1993

## EXPLANATION

Major thrust plates

- I
- II
- III
- IV

• 2 Site described in text

**Fault**—Dotted where concealed; queried where uncertain

- **Thrust fault**—Sawteeth on upper plate
- **Thrust fault as shown on inset map**
- **Normal or reverse fault**—Bar and ball on downthrown side
- **Strike-slip fault**—Arrow couple shows relative movement

**Fold**—Showing axis; dotted where concealed

- **Anticline**
- **Overturned anticline**
- **Syncline**
- **Overturned syncline**
- **Monocline**

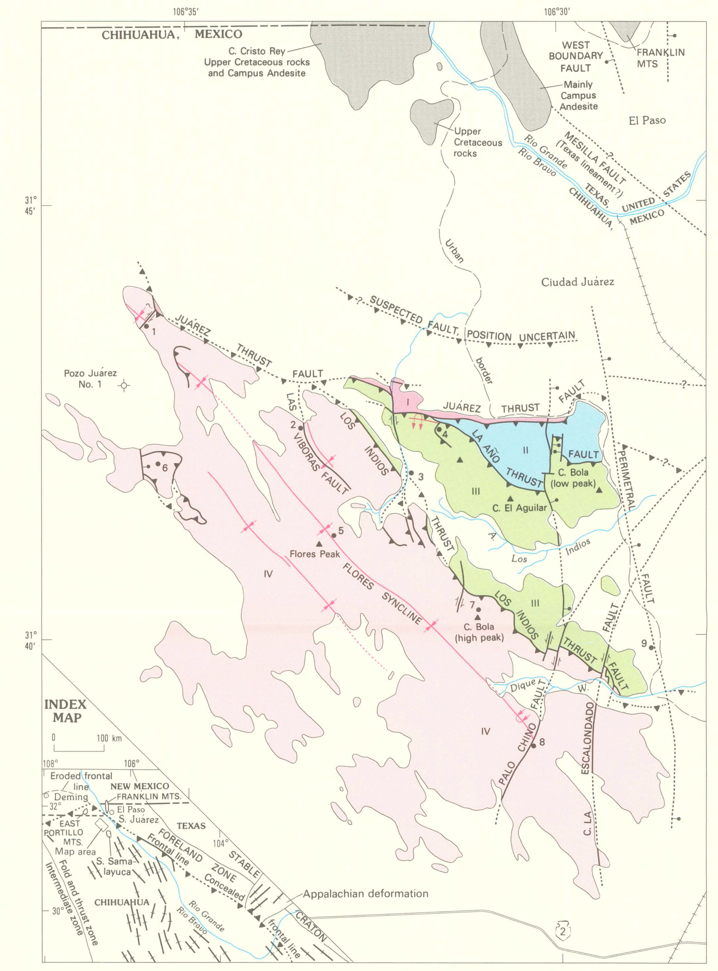


**Figure 1. Map of the Sierra Juárez showing major structural features and its regional setting.**

## GEOLOGIC NOTES

### INTRODUCTION

The Sierra Juárez are immediately southwest of Ciudad Juárez, a border city in northeastern Chihuahua, Mexico. El Paso, Texas, lies across the Rio Grande (Rio Bravo to our Mexican neighbors) from Ciudad Juárez and is only 4 km from the northeastern part of the study area (fig. 1).

The geology of the Sierra Juárez is highly significant to both local and regional problems in that the rocks represent the northernmost large outcrop area of Cretaceous marine embayment deposits and the northernmost exposures of a Paleocene-Eocene fold and thrust belt. On a local scale, the rocks of the sierra form the southwestern exposure of two ranges of strikingly dissimilar stratigraphy and structure. The northeastern range is the Franklin Mountains. The Sierra Juárez are underlain by strongly folded and thrust-faulted Cretaceous sedimentary rocks that have a northwest-trending structural grain. In contrast, the Franklin Mountains, just north of El Paso, are underlain by Proterozoic metasedimentary and igneous rocks that are capped by Paleozoic sedimentary rocks. These rocks have a north-trending structural grain and are internally unfolded, but are faulted to form a west-tilted horst. A major fault has been inferred to separate these diverse geologic terranes (Richardson, 1909).

The geology of the Sierra Juárez is characteristic of the Chihuahuan fold and thrust belt, a northwesterly trending zone that is more than 600 km long (fig. 1). The East Potrillo Mountains, about 60 km northwest of the Sierra Juárez, probably also are underlain by rocks of this fold and thrust belt, but northwest of that range, in a region of extensive young cover, this belt ends, basically due to nondevelopment. However, this ending of the fold and thrust belt is complicated by strike-slip faulting and deep erosion (Drewes, 1988 and in press). Tectonic and erosional complications of various kinds extend across southern New Mexico and Arizona, beyond which a fold and thrust belt is recognized once more. Inasmuch as the Sierra Juárez offers a much larger outcrop area than does the little range 60 km to the northwest, it provides the northwesternmost "anchor point" of a tectonic style near the gap in fold and thrust belt continuity and consequently deserves a comprehensive description.

The deformation of the Sierra Juárez rocks probably is of Paleocene or early Eocene age. Lower Upper Cretaceous rocks are the youngest rocks known to be deformed, and Upper Cretaceous and Paleocene rocks are likely to have covered the region and also to have been deformed (Drewes, in press). The middle(?) Eocene dikes postdate the deformation.

This geological study of the Sierra Juárez was undertaken as an adjunct function with the field camp of the Department of Geological Sciences of the University of Texas at El Paso (UTEP), led by Professor Russ Dyer. The field camp was operating in Mexico under a Memorandum of Agreement (Convenio) with the Universidad Autonoma de Chihuahua, dated 1980 and renewed in 1988. We appreciate the cooperation of the Texas and Chihuahua institutes and their support of our efforts to clarify the geologic history of a scientifically interesting area within sight of the UTEP campus, yet a part of our neighbor's terrane.

The present study resulted from a serendipitous blending of the ongoing field camp operation and a Gilbert Fellowship granted Harald Drewes by the U.S. Geological Survey. Inasmuch as most of the mapping for this study was done concurrently with teaching of field methods, other staff members also contributed to this study. During three consecutive late spring sessions in the sierra, the help of Professors D.V. LeMone, J.D. Hoover, and W.C. Cornell, of teaching assistants M.L. Brown, R.S. Guthrie, and J.W. Handschy, and of many students is gratefully acknowledged. Also, without the unflagging support of Professor G.R. Keller, Chairman of the Department of Geological Sciences, UTEP, this study would not have been possible.

We have incorporated the thesis map of S.K. Nodeland (1977) covering the low hills north and east of Cerro El Aguila near the southwest margin of Ciudad Juárez (fig. 1). The geologic acumen of E.M. Lovejoy, past professor of geology at UTEP, left its mark not only on his students, including Nodeland, but also on his colleagues and ultimately on the authors of this study.

The following descriptions and interpretations of selected stratigraphic and structural features supplement the geologic map and provide some new insights into the tectonic conditions during the deposition and deformation of the sedimentary rocks. The Sierra Juárez has tremendous potential as a field "laboratory" because it combines geologic variety, sparse cover, and close proximity to a major geologic institute.

### STRATIGRAPHIC FEATURES

The Sierra Juárez is underlain almost entirely by Cretaceous sedimentary rocks; a few dozen dikes and small pods of intrusive rock, mostly of dacitic composition, cut both the sedimentary rocks and the structures that deform them. The sedimentary rocks are largely or entirely of marine origin, consisting of a widespread Lower Cretaceous (Aptian-Albian) sequence of Cuchillo Formation, through Finlay Limestone, and an areally restricted uppermost Lower Cretaceous and lowermost Upper Cretaceous (Albian-Turonian) sequence of Del Norte to Boquillas Formations.

The general stratigraphic nomenclature applied by Lovejoy and his students (Wacker, 1972; Capuzano, 1973; Nodeland, 1977; Lovejoy, 1980) is followed herein. However, we refine the subdivisions of some formations and placement of some contacts to reflect what is most practical and informative for the entire sierra. We also see that all of the formations in the lower sequence thicken to the southwest.

The rocks of the lower sequence, underlying about 90 percent of the sierra, are composed, in ascending order, of the Cuchillo, Benigno, and Lagrima (also spelled "La Grima") Formations. An additional 5 percent of the area is underlain by the Finlay Limestone, highest of this sequence. The rocks of the upper sequence (about 5 percent) are composed mainly of gray to black shale and some interbedded sandstone and limestone. Because they are so sparsely present in the Sierra Juarez and so severely faulted in most of their outcrops, the characteristics of these rocks are poorly known. Indeed, we are obliged to W.C. Cornell for the identification of many of these units along Arroyo Colorado.

#### Cuchillo Formation

This formation is characterized by a brownish-gray color and abundance of clastic material. It is divided into three informal members: two members contain mainly siltstone, sandstone, and some conglomerate, and a medial cliff-making member is made up mainly of reefal limestone. Where the medial member is absent, the other two members have not been separated from one another. Where the Cuchillo Formation is thickest, such as along the range front 1–2 km south and southeast of the Pozo Juárez No. 1A drill hole, and also 1–2 km southwest of the upper basin of Dique Wash, the lower part of the formation is particularly sandy. Some of these beds may belong to an underlying Las Vigas Formation, which is exposed in the Sierra Samalayuca to the southwest (fig. 1). Although some of the thickest and most indurated beds are shown as marker beds, these few sandier units have not been separated from the siltier units. In any case, a review of the type Las Vigas is needed to establish the presence or absence of this formation in the Sierra Juárez.

The gray to black siltstone beds and interbedded reddish-gray shale of the lower member of the Cuchillo Formation commonly include thin, calcareous sandstone beds and lentils, and nodular limestone, some containing fragments of pelecypods. The interbedded sandstone typically consists of graded bedding and crossbedding. Most clasts are quartz; some feldspar is also present. Coarse sandstone and grit occurs low in many sandstone units, and scattered pebbles as much as 1 cm across and thin white-pebble conglomerate beds are present, particularly within a few tens of meters of the top of the member. Although generally only moderately indurated, locally the sandstone beds are well indurated and thus weather out to form conspicuous brownish-gray outcropping ribs or ledges. Scattered pieces of silicified wood are weathered from the lower member, apparently carried to the marine environment not far from shore. *Turritella* and *Exogyra* are common.

The medial member of the Cuchillo Formation forms a major cliff that is characteristically browner than those consisting of other cliff-making units and also thinner and less lenticular than the Finlay and the medial Benigno cliffs. The Cuchillo cliff also has a less angular or blocky weathering habit than the other cliff-forming units. Despite these three differences—color, thickness, and subtle weathering habit—the medial Cuchillo cliff and the medial Benigno cliff are, in some places, difficult to distinguish if fossils are absent or if overlying or underlying beds are covered or absent. For example, 1.5 km southeast of the drill site, a low-angle fault (that locally becomes a high-angle fault) juxtaposes, side by side (not one over the other), in one cliff a segment of very light gray middle member of the Benigno Limestone (containing diagnostic *Orbitolina* foraminifera) and a segment of brownish-gray middle member of the Cuchillo Formation (with coralline and rudist material in biostromal structure). Without the fossils, the two units would be difficult to distinguish in this type of structural setting.

We mapped the upper member of the Cuchillo Formation somewhat differently than did previous workers (Nodeland, 1977), for we found the color change from brown (underlying) to light gray (overlying) to be a more practical and informative distinction than the change from thin-bedded (underlying) to thick-bedded or massive (overlying) units. Previously, the top of the Cuchillo was taken at the top of thin-bedded rocks (or the base of the very light gray cliff-making unit). The change in color marks the fairly sharp horizon at which there was either an abrupt decrease in input of coarse clastic detritus in the depositional basin or an increase in distance from the shore. The upper member of the Cuchillo Formation is similar to the lower member. Some oolitic limestone occurs in the upper member, and pebble conglomerate, while scarcer, is also more conspicuous because it is reddish-brown. Clams, oysters, and gastropods are usually present in these rocks. The *Orbitolina* previously mentioned as occurring in this unit probably came from beds now assigned to the lower member of the overlying Benigno Limestone

#### Benigno Limestone

This formation is very light gray and consists of three members, two thin-bedded ones and a medial thick-bedded or massive member. The upper and lower members have interbedded marly or shaly rocks, and have thinner limestone beds away from the medial reefal unit than near it. These features, as well as an angular or blocky weathering habit, give both upper and lower members a characteristic regular stair-step weathering habit. Typically, the limestone in these members is micritic. Low in the upper member is a narrow zone (locally just one bed) containing sparse dark-gray nodular chert. This bed or zone was mapped over only part of the Sierra Juárez, after its usefulness was recognized. Likely it is more widespread along the southwest flank and in the northwestern end of the sierra than shown. Whereas *Orbitolina* fossils are common in all three units, the upper member has some *Orbitolina* packstone beds.

The middle member of the Benigno Limestone makes the thickest cliff in the sierra, but due to biohermal development along the mostly biostromal reef, the thickness of the member fluctuates locally; apparently where the reef rocks thin a bit, one or both of the adjacent lithologic types fill in the intrareef low areas. Coral, algal, and rudist material is common in the middle member, the rudists usually being most abundant high in the member (and even making up rudist beds low in the overlying member).

#### Lagrima Formation

Most of this formation is a marlstone or an alternating shale and thin-bedded, fine-grained limestone, but it also has a medial cliff-forming limestone member. The formation is the most easily eroded of the widespread units of the lower sequence in the sierra and thus commonly underlies broad longitudinal valleys in which gravel caps and terrace remnants conceal the bedrock along interfluves. The limestone is mainly micritic, very light gray, and, in some beds, nodular. *Orbitolina* are common, corals and pelecypods are also found, and echinoids are sparsely present. Pectens and oysters (*Exogyra*?) are also locally present in the upper member and the foraminifera *Texigryphaea* sp., most diagnostic of the overlying Finlay Limestone, occurs in some limestone beds of the upper member of the Lagrima Formation.

The middle member of the Lagrima Formation is a limestone that forms a thin but nearly unbroken cliff in the central part of the sierra that is difficult to traverse. Farther southeast in the sierra the unit is thicker, is more thinly bedded, and forms gentler slopes. The medial limestone member also contains corals, rudists, and, in some places, small thin-shelled pelecypods.

#### Finlay Limestone

This formation is yet another thick-bedded to massive, light-gray reef limestone, with sparse, thin, marly interbeds. Its full thickness is present only on Flores Peak, at the lowest structural sag along the core of the Flores syncline. Because the formation there is virtually doubled up on itself, its apparent thickness is misleading. Typically, small, fault-bounded or alluvial-bounded outcrop areas of Finlay Limestone closely resemble the middle member of the Benigno Limestone in lithology, so that identification of the Finlay depends on the presence of its diagnostic fauna or stratigraphic position. The large foraminifera *Dictyoconus walnutensis* is most diagnostic; *Texigryphaea* and ammonoids are also helpful in identifying the Finlay Limestone.

The Cerro Cristo Rey area (fig. 1) has the best exposed and most thoroughly studied outcrops of the upper sequence, which includes shales and subordinate sandstone and limestone of latest Albian to Turonian age (Lovejoy, 1976).

Dikes and irregularly shaped intrusive pods of porphyritic (rarely aphanitic) rhyolite, dacite, and andesite cut the Cretaceous rocks of the Sierra Juárez. In some places they intrude northeast-trending strike-slip faults and thrust faults and in other places are emplaced as sills along steeply dipping beds. The classification of these rocks is based mainly on hand specimens supplemented by a few thin sections, and so groundmass composition is poorly known. These sparse observations indicate that the dikes to the northwest more commonly are rhyolite or rhyodacite and those from the southeast are dacite or andesite. One dike from 1.5 km east of the Pozo Juárez No. 1A drill hole has been radiometrically dated as $47.8\pm2.2$ Ma (amphibole) and $48.2\pm1.7$ Ma (biotite), (R.F. Marvin, H.H. Mehnert, and E.L. Brandt, written commun., 1985), essentially the same age ($47.1\pm2.3$) (LeMone, 1984) obtained from the Campus Andesite (the outcrop area of fig. 1 between Cerro Cristo Rey and the Franklin Mountains).

The three lowest and most widespread formations, Cuchillo Formation, Benigno Limestone, and Lagrima Formation, and probably each of their members as well, thicken 50–100 percent northeast to southwest. The "Description of Map Units" reflects this range of thickness, the greater value being scaled from structure sections and the lesser obtained from undesignated sites along the northeast flank of the sierra. Even comparison of outcrop widths of units, duly adjusted for dip variation, gives the impression of such changes in thickness. The variations in thicknesses are indications of thicknesses at sites of deposition, originally separated by considerable distances, that have been juxtaposed by thrust faulting. The thicker sections of the southwestern part of the sierra were apparently deposited farther from Cretaceous shorelines and have been transported the greatest distance toward the northeast.

### STRUCTURAL FEATURES

Large northwest-trending folds and associated thrust faults were mapped previously in the Sierra Juárez by Lovejoy (1980) and his students, and were designated I–IV, in rising succession (see fig. 1). This style of deformation is characteristic of the Chihuahua fold-and-thrust belt which, enigmatically, seems to end to the northwest of the Sierra Juárez, probably just beyond the East Potrillo Mountains in southernmost New Mexico (fig. 1). A structural synthesis of the region between the northwestern end of one fold-and-thrust zone segment of the Cordilleran orogenic belt and the southern end of another such fold-and-thrust zone segment in southern Nevada is offered by Drewes (in press). The structural features of the sierra thus are a sort of "tectonotype" of one of several major tectonic zones of the orogenic belt.

In broadest overview, the structures of the Sierra Juárez make up a small synclinorium, or a composite syncline, of older Cretaceous rocks, which was thrust faulted northeastward over younger Cretaceous rocks. The axis of this synclinorium trends northwest and its central sag is gentle; thereby the youngest rocks of the upper plate (covering most of the sierra) crop out near the center of the sierra and the older rocks form annular outcrop bands about this center. To the northwest, these folds are covered by the bolson deposits flanking the sierra; to the southeast, the folds abut the northeast-trending Palo Chino strike-slip fault, beyond which the fold system is different.

Viewed in more detail, the folds include the major Flores syncline and many flanking anticlines and synclines. The Flores syncline is both large in amplitude and long, is generally asymmetric, top inclined toward the northeast, and, in one area, is even overturned to the northeast. At its northwestern end the fold abuts an underlying minor(?) bedding-plane thrust fault and has no obvious extension (and thus is not offset from) a syncline in the lower plate. The syncline is relatively open near its northwest end and becomes gradually tighter and more overturned to the southeast, indicating that structural level (the major plate above the Juárez thrust fault) underwent a counterclockwise rotation about a more or less horizontal axis as the southeast end of the fold became more compressed. In other words, it is likely that the southeast end of the syncline moved farther northeast than did the northwest end.

The other folds of this small synclinorium also vary in geometry from place to place. On the northeast flank of the synclinorium the folds of the upper thrust plate (most of the sierra) are more closely spaced, have tighter limbs, and are more inclined and more commonly overturned. On the southwest synclinorium limb the folds are more widely spaced, more open, and more nearly upright or only slightly inclined.

Folds in the block southeast of the Palo Chino strike-slip fault are generally open, except for one small part of the east side of the block, between the Palo Chino and another strike-slip fault. Possibly the synclinorium was shifted, as a block, to the northeast, which also is indicated by a change in geometry along the Flores syncline.

Folds in other thrust plates, beneath the one that encompasses most of the sierra and on the northeast flank of the sierra, are shorter, are of lesser amplitude, and have more diverse trends than the folds in the upper plate, but are still inclined toward the northwest. Some of these are so closely associated with other structural features that they are described together with the other features at key sites, in the following section.

Also in overview, the main thrust faults are seen to trend generally northwest along the northeast flank of the Sierra Juárez and to dip southwest, but small thrust faults are scattered throughout the sierra. Three major thrust faults, the Juárez, La Año, and Los Indios, separate the rocks into four major plates (labeled I–IV on fig. 1). We infer that the lowest rocks beneath the Juárez thrust fault are underlain by another thrust fault that remains totally concealed. This inference is based on the internal deformation of the lowest rocks, which resembles in pattern the type of deformation associated with disharmonic cross faults. These types of faults are commonly bounded, above and below, by thrust faults. Because the site of this inferred fault is unknown, it is not shown on the geologic map, and its placement on figure 1 remains conjectural. Some thrust faults were mapped by Nodeland (1977), and so his names are herein retained. Other thrust faults are modified from older work and so new names are applied to avoid confusion. We also number the thrust plates I–IV in rising sequence, except we correlate Nodeland's autochthon with our plate I. Along each of these major thrust faults older rocks have been emplaced upon younger ones. Among the minor thrust faults both older-over-younger and younger-over-older relations occur.

The Juárez thrust fault is the lowest exposed major thrust fault. In most places, the underlying rocks are shales of the upper sequence, which are much folded and faulted; locally some Finlay Limestone is shown as part of the lower plate. Where the fault overlies the shales, the fault dips moderately to steeply southwest, but where the fault overlies the Finlay it is inferred to dip gently southwest. We concur with previous workers that the dip of the fault probably decreases downward or southwestward, thereby giving a sled-runner profile to the fault, as is common in frontal areas of orogenic belts.

La Año thrust fault branches off the Juárez thrust fault, separating our thrust plates II and III, much as shown by Nodeland (1977). Along most of its trace, Cuchillo Formation has been brought over Finlay Limestone or Lagrima Formation, but to the southeast La Año fault splays out and each splay has diverse stratigraphic relationships that mimic, in small scale, the relationships among the major thrust faults.

Los Indios thrust fault, separating thrust plates III and IV, coincides with the west side of a lowland following Arroyo Los Indios and part of Arroyo Colorado. It actually forms a zone of subparallel thrust faults that is narrower to the northwest and broader to the southeast. Movement on this thrust fault zone was probably concurrent with that on the Arroyo Colorado strike-slip fault zone, for some of the thrust fault splays merge with the strike-slip fault zone, which, in turn, merges with a low branch(?) of the Juárez thrust fault (or the lower concealed thrust fault?). Through this strike-slip fault, the movement on thrust plate IV has shifted from a lower structural position in the north to a higher one in the south. The lack of fit across part of the Arroyo Colorado fault is due to juxtaposition of different parts of a major thrust plate in which minor thrust slices have generated lenticular platelets during tectonic transport. These outcrop relations and the subsurface relations they infer require essentially concurrent movement of thrust faults and strike-slip faults of the Arroyo Colorado area, although rate or duration of movement of parts of plate IV across the strike-slip fault varied. To the southeast, Los Indios thrust fault also splays out, with development of local complications analogous to those at the southeast end of La Año thrust fault. A possible extension across the Palo Chino strike-slip fault is proposed for the main splay of Los Indios fault, which gives the appearance, once more, that rocks of the southeastern end of the sierra were moved farther to the northeast than the other rocks.

The above general accounts of the major folds and faults are supplemented below with descriptions of various structures at specific localities. The geology at these places provides considerable insight into the deformational style of the fold and thrust belt. Sites are numbered from northwest to southeast on figure 1.

#### Site 1

At the northwestern tip of the range is a fine example of a concurrently developed thrust fault, strike-slip fault, and fold. To the northwest of a saddle in the spur, the middle and upper members of the Cuchillo Formation are warped into an asymmetric syncline whose steep limb dips to the southwest and which plunges 5° to the southeast (Drewes, in press, fig. 9). No such fold affects the Cuchillo Formation southeast of the saddle, where the bedding is nearly flat, as best shown by the contact between the lower and middle members of the Cuchillo. The change in structural condition of the Cuchillo not only requires that a high-angle fault run through the saddle but, since the axial plane of the fold is fairly steep, that the fault have had substantial strike-slip movement. (With vertical movement on the fault, the fold would perhaps have been offset but it would not have vanished over the large extent of outcrop.) The fault itself is concealed through intrusion by a rhyodacitic dike, and so direct evidence on its movement is not available.

Northeast of the saddle the dike ends, but colluvium conceals any traces of the projected strike-slip fault up to a point at which a zone of Finlay(?) Limestone crops out low along the northeast flank of the spur, both northwest and southeast of the projected end of the strike-slip fault, without itself being offset. Identification of the Finlay here remains queried since only a small stratigraphic sequence is exposed and diagnostic fossils were not found.

West of the Finlay outcrop and to the north of the strike-slip fault the lower member of the Cuchillo Formation is very thin compared to the same member south of the fault. Because the lower member weathers readily in this area, it is poorly exposed near the saddle in the spur and its strike-slip fault, so the change of thickness across the fault cannot be explained from direct evidence but depends on the indirect signs of outcrop width and attitude. Neither can the change in thickness be attributed to variations in deposition because the change is large and abrupt.

The last questions to be resolved at site 1 are why the lower member changes thickness abruptly and why the strike-slip fault does not offset the Finlay(?) Limestone, and we propose these questions are linked. We infer the contact between the Finlay and the lower member of the Cuchillo to be a concealed, southwest-dipping, bedding-plane thrust fault against which the strike-slip fault abuts, forming the base of a disharmonic fault, which formed in adjustment to stress that had been built up within the upper plate. The fold would likewise be a disharmonic structure; it probably never had an extension across the strike-slip fault, nor beneath the thrust fault. Furthermore, with its growth linked to the thrust fault, its asymmetry now is evidence that the vergence of the fold was northeast. We do not favor an alternate explanation involving a concealed normal fault of large throw because of the absence of such structures along this flank of the sierra, in contrast to the many southwest-dipping thrust faults. We further suggest that the inferred thrust fault northeast of the gap flattens downdip and is the structure encountered low in the Pozo Juárez No. 1A drill hole.

#### Site 2

Las Viboras Arroyo is the site of a southwest-vergent fold and a reverse fault. Such abnormally oriented structures occur elsewhere in this orogenic belt (and in others) and, in some places, have been needlessly interpreted to represent a second tectonic event. That these structures have close genetic ties to the dominant deformation direction is illustrated at this site.

Near the mouth of the canyon, where Las Viboras Arroyo turns eastward, Los Indios thrust fault separates underlying folded shale and sandstone of the Del Rio(?) Formation from the overlying lower member of the Cuchillo Formation, which dips gently southwest. Las Viboras fault lies low on the east wall of the arroyo, where it is well exposed except at its junction beneath gravels with Los Indios thrust fault. That thrust fault dips moderately southwest, as do the other thrust faults nearby, but Las Viboras fault dips steeply northeast. The vergence of associated folds shows that the transport direction on Los Indios thrust fault is northeast, whereas that of Las Viboras fault is southwest. In effect, Las Viboras fault is a reverse fault and its associated fold is a monocline to the south and an asymmetric anticline to the north.

About 1 km south-southwest of the junction of Las Viboras and Los Indios faults another fore-directed thrust fault is developed in the Benigno Limestone of plate IV, but it is at least an order of magnitude smaller in extent and displacement than is Las Viboras fault. This structure probably mimics some of the largest Juárez thrust faults: dip of the fault plane decreases downward and, where the fault subparallels bedding, its trace is lost.

The net effect of such nested faults (fore-directed thrust and backthrust or reverse fault) is to thicken the sequence of formations in response to compression. Through such thickening, as well as other mechanisms of thickening, the sequence gains in strength, and thereby is better able to transmit the compressional stress (Price and Montjoy, 1970).

#### Site 3

Many faults converge on Arroyo Colorado, where a right-lateral fault is well exposed along the lower reaches of the arroyo but is concealed beneath gravels along the upper reaches. The overall trace of the fault is sigmoidal and trends north-northeast, splays tailing out to the northwest and the southeast. To the north, an upper splay of the Arroyo Colorado strike-slip fault merges with the Juárez thrust fault and a lower splay merges with an unnamed thrust fault projected to lie just beneath, and parallel to, the Juárez thrust fault. To the south, the Arroyo Colorado fault also forms several splays that merge with minor unnamed thrust faults in the Cuchillo Formation and Benigno Limestone. Slippage on thrust faults seems to have been transferred from one horizon to another by way of the strike-slip segment of a composite fault.

Along the middle reaches of the Arroyo Colorado, the stratigraphic offset on the Arroyo Colorado fault is about 0.5 km, but actual movement on the fault may have been much larger. Rocks northwest of this part of the fault include a thicker and more diverse set of thrust slivers than occur in its structural analog southeast of the fault. Such a change would not be the result of vertical movement or of small horizontal movement, but may be the result of a large horizontal movement, where thickness variations across a tear fault reflect variations along the transport direction of thrust faults, essentially structurally downdip.

#### Site 4

East of Arroyo Colorado 1 km, along the northeast flank of the range, is a large cliff of Finlay Limestone. From the El Paso, Texas, lookout points so commonly used by touring geologists (see local guidebooks), the cliff appears to be warped into a large simple fold, concave to the east. Although the Finlay Limestone is indeed folded, the geometry of the structure is much more complex. From nearby, the warped Finlay outcrop band resembles a large drag fold whose lower limb is sheared out or attenuated upon the Juárez thrust fault. Toward the west the main fold axis breaks down into several parallel recumbent anticlines and synclines that verge to the northeast.

East of the sheared-out lower limb of the major fold and within 1 km of the junction of La Año and Juárez thrust faults is a sliver of shale that probably is of the Del Rio Formation infaulted among older rocks. This is the area which has been referred to, informally, as the "Nexus Plexus." Its structural complications assure continued debate on fault projections and genesis.

At several horizons at site 4 minor thrust faults follow contacts between strong and weak rocks. These are typically inferred through the nearby presence of disturbed bedding disharmonic folds or faults, or drag structures. Such local bedding-plane faults bring younger over older rocks, and imply that some rock is missing along the fault. Similar minor thrust faults occur elsewhere in the Sierra Juárez, including the Flores syncline.

#### Site 5

Flores Peak marks both the topographically highest and structurally lowest part of the highest thrust plate, IV, and is a key site along the Flores syncline. Although the axis of the syncline is nearly straight for most of its length, its trace swings from northwest-southeast to about due south at its southern end by the Palo Chino fault. From northwest to southeast the axial plane of the syncline is nearly vertical, then is inclined northeast, and finally becomes inclined enough that the fold is overturned to the northeast. Likewise, the fold is relatively open to the northwest, tighter near Flores Peak, and tightest to the southeast. Apparently, the southeast end of the plate is the more compressed end.

The northwest end of the Flores syncline is truncated downward along a minor(?) bedding-plane thrust fault. Although the Cuchillo Formation beneath this fault is also folded, these folds are of different amplitude and wavelength and have only short traces, so they are not likely to have been a part of the Flores syncline, but only a part of the response to the stress field. It is likely, however, that the syncline is floored by Los Indios thrust fault, which probably flattens downdip.

Small bedding-plane thrust faults occur not only at the northwest end of the fold, but also along the flanks of Flores Peak. They occur at both the bases of the Finlay Limestone and the middle member of the Lagrima Formation. Segments of these contacts are considered to be faulted because adjacent beds are warped and cut and because 1.5–2 km southeast of Flores Peak, beds within the overlying plate about the bedding-plane along which slip took place. All these bedding-plane faults place younger rocks upon older ones. The extent of these bedding-plane faults may be more widespread than shown on the map.

These minor bedding-plane faults are fairly common and point to an enigma that also concerns some major faults: some geologists would, by definition, view all faults placing younger rocks over older ones as low-angle normal faults and not as thrust faults. However, it is our view that most, or possibly all, of these faults were formed in response to compressional rather than extensional stress and so are, indeed, thrust faults. They are associated spatially with folds and faults unequivocally of compressional origin, and, with possibly one exception at site 6, no extensional features are recognized. In essence, folds are common; normal faults are scarce. The residual question then is what happened to the missing rock—the prisms of rock gone from sites of younger over older rocks, a question not to be pursued herein, but addressed elsewhere (Drewes, in press).

#### Site 6

Along the southwest flank of the Sierra Juárez are several small plates (or parts of one larger plate?) of Benigno Limestone overlying faults (or a fault) that dip gently southwest and that may be either thrust faults, low-angle normal faults, or a combination of both. Commonly, the upper plate rocks cut down-section southwestward, a relationship that may indicate southwest-directed gravitational movement of the plate following compressive deformation. However, the plates (or plate) contain truncated or disharmonic folds, which are features of compressional deformation, and thus suggest that folding and faulting were concurrent. In the absence of more compelling arguments, the interpretation of the origin of the small plates of the southwest flank of the range remains open.

#### Site 7

The Cerro Bola (the higher peak of two having the same name) is underlain by a keel of synclinally folded Cuchillo Formation. Most of the rugged cap of the cerro is made up of the massive middle member of the formation, which is almost doubled up on itself. In the trough of the Cerro Bola syncline, near the summit of the cerro, is an erosional remnant of the upper member.

Two structural features near the peak are of special interest. On the northwest side of the peak is a north-trending right-lateral fault that resembles in style, but not in size, the Arroyo Colorado strike-slip fault. This fault shows displacement of a few hundred meters. Slickensides on a branch of this fault, however, indicate only (late-phase?) vertical movement. The geologic relations are better exposed along this right-lateral fault than along the Arroyo Colorado fault and thus provide guidance in interpretation of the more concealed structure.

On the east flank of the Cerro Bola (high peak), Los Indios thrust fault zone not only separates an upper plate containing Cuchillo Formation from a lower plate of Lagrima Formation, but separates plates in which fold axes trend differently—about N. 40° W. in the hanging wall and N. 60° W. in the footwall. Fold amplitude is also greater in the upper than in the lower plate. This variation in folds may reflect a change in the orientation of stress between the times of an older and a younger phase of deformation, or a different amount of drag along the Palo Chino strike-slip fault of rocks at different structural levels.

#### Site 8

The Palo Chino strike-slip fault is a major northeast-trending structure that cuts, or is abutted by, all Lower Cretaceous rocks and several major structures. Splay faults branch from the main fault and, locally, there are small thrust faults between adjacent splays. The main fault and its splays dip steeply southeast. Slickensides indicate that the latest movement was dipslip or left-oblique-slip. Probable left-lateral offset is shown by most field relations, such as the offset of Los Indios thrust fault zone and the likely thrust movement on the small thrust flaps between splays southeast of the main fault. However, the drag implied on the axis of the Flores syncline favors right-lateral movement. While two movement phases might be inferred to resolve this point of diverse evidence of movement direction, the relationships may also be developed by counterclockwise rotational movement about a horizontal axis lying between the localities of the diverse evidence.

Another noteworthy aspect of the Palo Chino fault is the contrast in deformational styles on adjacent blocks. In that part of the southeastern block lying northeast of Dique Wash, along section *F–F′*, for example, the folds and thrust platelets suggest a tighter structural compaction, or pushing together, than do the folds and thrust platelets in the northwestern block, midway between sections *E–E′* and *F–F′*. Likewise, the strongly developed Flores syncline fold system is well developed northwest of, but is not identified southeast of, the Palo Chino fault. Apparently, there has been differential deformation in the blocks adjacent to the strike-slip (or rotational) fault, probably with a tendency for the southeastern block to have moved farther northeast.

#### Site 9

A linear scarp offsets older gravel along the east flank of the Sierra Juárez. Near Dique Wash the offset is about 15 m. This scarp is typical of Basin-and-Range normal faulting. Similar faults bound the Franklin Mountains; however, there seems to be no link between the normal faults of these ranges. Apparently, the concealed Mesilla fault (fig. 1) disrupts the continuity of the range-bounding normal faults. Possibly, segments of the Mesilla fault were reactivated during Basin-and-Range block faulting.

### CONCLUSIONS

The rocks of the Sierra Juárez provide evidence of mainly compressive deformation, which probably is of Paleocene or early Eocene age. Younger block faulting is also recorded, and a major, steep, northwest-trending fault between the Franklin Mountains and the Sierra Juárez, as well as the tendency for the rocks of the southeast end of the mountains to have been moved farther northeast than the others, are indirect signs that older structures also influenced the development of the Cordilleran orogeny. The age of deformation is typical of the Laramide phase of the orogeny (Drewes, in press), but the style of deformation is typical of a fold-and-thrust zone, rather than of the foreland style characteristic of the classical Laramide.

On the basis of regional data (Drewes, in press) and on geologic mapping, we conclude that the rocks of the Sierra Juárez were deposited along the northeast margin of the basin known as the Chihuahua trough. Following this trough deposition, the sea either became more widespread, or its shoreline shifted eastward, and possibly linked with the Cretaceous epicontinental sea of North America. These depositional conditions may have extended through the Late Cretaceous and into the early Tertiary. In the sierra, record of this continued deposition has been eroded, but 80 km northwest, in New Mexico, it may still be preserved (Drewes and Dyer, 1989).

The sedimentation ended with the propagation into the region of a widespread uplift that was an early response to northeast-southwest-oriented compressional stress. With the retreat of the sea to the northeast and southeast, the uppermost rocks were eroded while the underlying ones were being folded and thrust faulted.

The compressional deformation of the rocks at the structural level currently exposed was directed toward the northeast; folds are vergent northeast, and the genetically related thrust plates were transported northeast. Near Ciudad Juárez, as in other widely scattered places in southern New Mexico and Arizona, the northeastward-moving plates encountered an underlying resistant mass northeast of an older, reactivated, northwest-trending basement fault, in this instance the Mesilla fault (or Texas lineament). The thrust plates in the area of the present Sierra Juárez impinged against the raised block of basement rocks, perhaps in part slipped or ramped over some of the barrier, and may also have slipped along a segment of the fault, with the rocks of the Sierra Juárez rotating slightly, the southeast end moving farther to the northeast than the northwest end. The rocks of the central part of the sierra are more tightly folded and contain more numerous thrust faults than those to the northwest, and the rocks of the southeastern part were also shifted northeast along the Palo Chino strike-slip fault. During middle Eocene time and after deformation ended, the rocks and selected faults were intruded by rhyolitic to andesitic dikes and sills. Much later the block faults of the Basin-and-Range event were activated and the present topography was developed.

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# GEOLOGIC MAP AND STRUCTURE SECTIONS OF THE SIERRA JUÁREZ, CHIHUAHUA, MEXICO

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