Geology of Cerro de Cristo Rey Uplift, Chihuahua and New Mexico

by EARL M. P. LOVEJOY

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MEMOIR 31 New Mexico Bureau of Mines & Mineral Resources 1976

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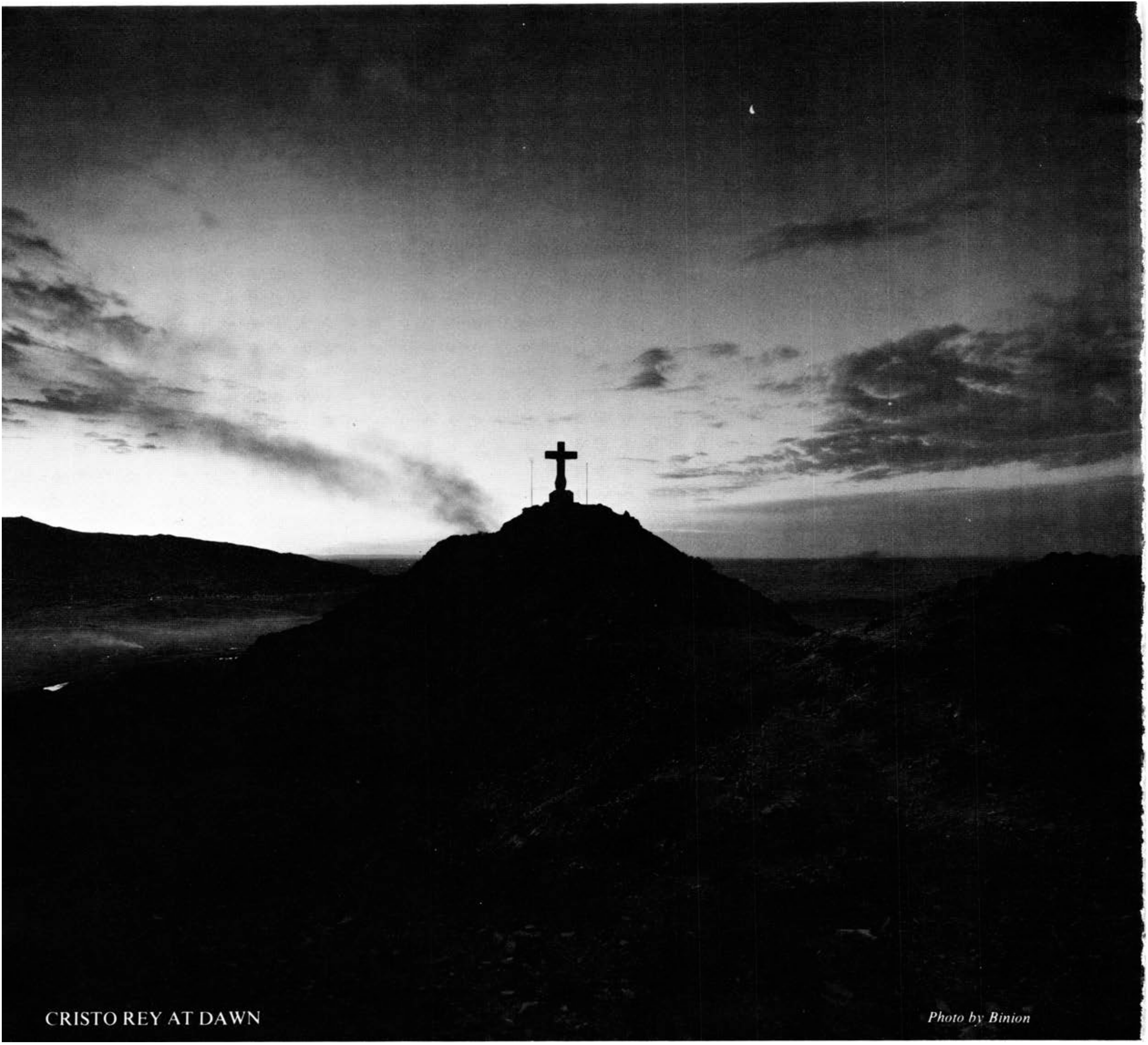
"You never can tell with bees."

—from **Winnie The Pooh** by A. A. Milne
E. P. Dutton & Co.. Inc., N.Y., N.Y.
205th printing, 1952



CRISTO REY AT DAWN

Photo by Binion

View toward southeast at summit of Cerro de Cristo Rey (from Binion, p. 22). The following question and answer was printed in the *Quien Sabe* column of the El Paso *Times* of April 12, 1971:

"Question—In what year was the Cristo Rey [statue] built? Who built it? How much did it cost? Who were the people who helped pay for it? Who invented the Cristo Rey?

Answer—The driving force of the completion of the 42-foot statue atop Cristo Rey was the late Rev. Lourdes F. Costa, a longtime pastor of the Smeltertown parish, who in 1934 led a pilgrimage to the top of the then Cerro de Muleros (Peak of the Mule Drivers). The birth of the idea of the Cristo Rey monument stemmed from this pilgrimage and Father Costa enlisted the support of the late and then El Paso Bishop Anthony J. Schuler with funds for the statue gathered in 1937. The late internationally known sculptor Urbici Soler was selected to design the statue and after some two years of sculpturing, the statue was completed. Cost of the edifice was placed at $100,000 but estimates put the cost of the entire project at close to $500,000. The peak was redesignated Sierra de Cristo Rey after a petition was submitted by Smeltertown residents after the original pilgrimage. The statue, made of Cordova cream sandstone, stands a few feet from where the boundaries of Texas, New Mexico, and Chihuahua converge." Binion (1970) also commented on the shrine.

Memoir 31

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by Earl M. P. Lovejoy

with an article, NEW FORMATION NAMES IN THE CRETACEOUS AT CRISTO REY,
by William S. Strain in Appendix 1

SOCORRO 1976

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First printing, 1976

Published by Authority of State of New Mexico, NMSA 1953 Sec. 63–1–4
Printed by University of New Mexico Printing Plant, December 1976

Available from New Mexico Bureau of Mines & Mineral Resources, Socorro, NM 87801 Price $12.00

Foreword

Many geologists have watched the awesome flow of lava from volcanic vents on the surface of the earth, but they have been denied the opportunity of witnessing the deep-seated intrusion of lava or magma, as sills, laccoliths, or stocks, beneath the earth's surface. To be sure, there are telltale contacts and structures that permit reasonable and plausible interpretations of intrusive processes, but the generalities of such interpretations fall far short of eyewitness accounts.

In this Memoir—probably a first in the geologic literature—the reader will find the nearest approach to firsthand observation of the actual penetration of magma into overlying sediments. Erosion has unroofed the Cristo Rey laccolith to a level at which the relentless movement of the magma, the rupture of the overburden, and the penetration of the molten liquid into new stratigraphic positions can be traced almost as convincingly as if the reader were seeing it all happen.

The accident of erosion in just the right amount, however, is but one of the coincidental factors in the production of this Memoir. Like the flowers "born to blush unseen and waste their fragrance on the desert air," Cristo Rey was just a topographic variation on the landscape until Earl M. P. Lovejoy saw its significance and, with infinite patience, unraveled the intricately woven skein of magmatic events. It is a work of dedication which, in its detail, might well have deterred any publisher from accepting. All credit, then, to the New Mexico Bureau of Mines and Mineral Resources for recognizing the unique value of Earl Lovejoy's work, thereby adding to the literature of geology a descriptive classic on volcanism.

Tulsa, Oklahoma
January 8, 1976

Howard A. Meyerhoff

Preface

The Cerro de Cristo Rey uplift is a well-exposed hypabyssal plutonic complex, located strategically near the intersection of the Rio Grande trench and the Texas lineament, which is the boundary between the Chihuahua tectonic belt on the south and the Basin and Range structures on the north. So little is known about local pre-Pleistocene structural geology that detailed mapping of the few mountain masses seems required. The tectonic significance of Cristo Rey is not yet fully appraised, although it is probably great in this region. For this reason I have tried to determine as precisely as possible the development of the structure of the uplift. To some the amount of detail might seem excessive, yet only with all this mapping could the structures be understood. On the other hand, those readers who want even more detail may find the cross-referenced explanatory notes in Appendix 1 helpful, perhaps interesting.

Quarrying is changing the face of the uplift at an increasing rate, and many outcrops soon will be gone. This report is an attempt to preserve the data from outcrops that are disappearing. Detailed descriptions aid in understanding maps and interpretive cross sections. Interpretations may be incorrect, perhaps the product of contemporary thought, incomplete analysis, oversight, or poor mapping. Tectonic interpretations change as knowledge increases. My hope is that future workers will find this paper of value in their own endeavors.

Earl M. P. Lovejoy
Professor of Geology
The University of Texas at El Paso

El Paso, Texas
March 1976

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(contents listed on pocket)

Abstract

The Cerro de Cristo Rey uplift is about 3,000 m (10,000 ft) in diameter. It stands astride the Mexico-United States boundary 8 km (5 mi) west of El Paso, Texas and is bounded on the east and north by the Rio Grande. An andesite central pluton and a felsite partial-ring confocal pluton about 45 to 49 million years old have intruded and deformed about 300 m (1,000 ft) of Cretaceous marine strata. Deep erosion of the order of hundreds of meters around the uplift has exposed the pluton; evidence is excellent for two major subsidences about 2,500 m (8,200 ft) and 2,250 m (7,380 ft) in diameter. The pluton formed after tectonism ceased in the Sierra de Juarez of the Chihuahua tectonic belt, perhaps early during the tectonism that produced the Basin and Range province.

North-trending prepluton folds have been arched up by the intrusion. Trapdoor faulting and major ascent of magma on the west side of the pluton gave rise to gravity gliding of roof strata on the north and northeast, resulting in accentuation of preintrusion folds that now strike around the east side of the pluton. Sundering of a large block into the magma chamber also produced cascade folds from the roof on the east side. Several episodes of expansion and contraction are evident.

Although the pluton is situated on the Texas lineament (with the long axis of the pluton and minor structures in the uplift trending N. 60° W., parallel with the Texas lineament trend) evidence is lacking for any activity along the Texas lineament.

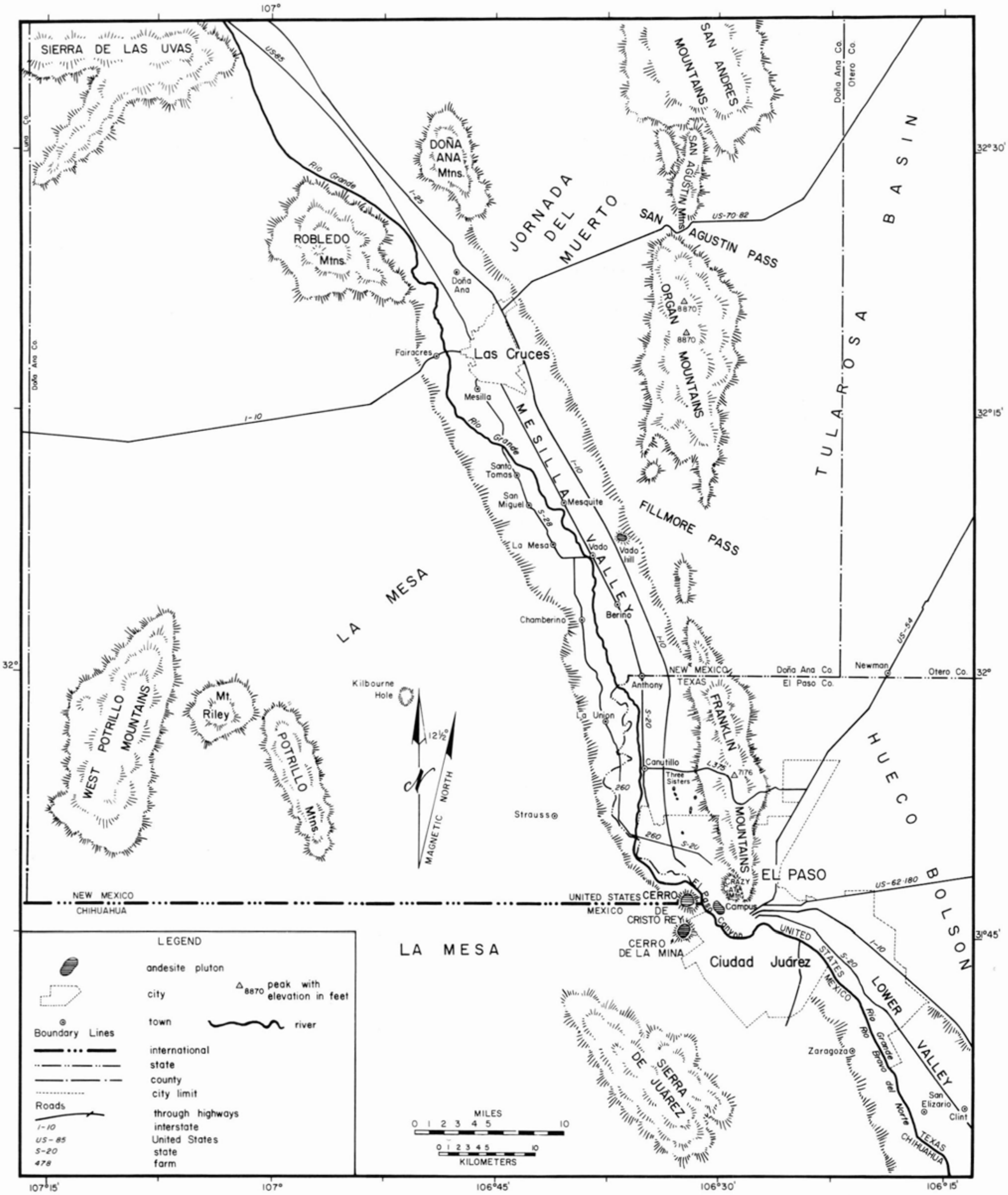

FIGURE 1—LOCATION MAP, SOUTHERN NEW MEXICO, WESTERN TEXAS, AND NORTHERN CHIHUAHUA.

Introduction

LOCATION

Cerro de Cristo *Rey* (Frontispiece) is the name given a prominent peak which lies on the international border between Mexico and the United States, in the states of New Mexico and Chihuahua (fig. 1). The mountain, earlier named and still called by some the Cerro de Muleros (Mount of the Mule Skinners) and locally called by others the Cerro de la Cruz because of the large statue of Christ on the cross (photo 1) at its crest, has an elevation of 1,425 m (4,675 ft). This is almost 300 m (1,000 ft) above the valley of the Rio Grande, Mesilla Valley. Because the Cerro is surrounded by more prominent ranges such as the Franklin Mountains and the Sierra del Paso del Norte, or the Sierra de Juarez west of Juarez, Chihuahua, it is not an eminence worthy of much note to the casual observer or tourist (photo 2; Sonnichsen, 1968; Binion, 1970).

PURPOSES OF INVESTIGATION

The principal purposes of this study were: 1) the determination of the surficial geometry of rock around the Cristo Rey pluton; 2) an attempt to decipher the three-dimensional geometry of the pluton; 3) a study of the kinematics or movements of those rocks; and 4) an analysis of the kinetics or forces which produced those movements.

The major contributions of this study are concerned with the surficial geometry and intrusive tectonics of the Cristo Rey pluton. I believe that this uplift is one of the best exposed in the United States, and certainly it is among the most complex in its relations with the country rock.

Cerro de Cristo Rey is an important locale for several geologic reasons. Cristo Rey is near the possible junction of the Rio Grande trench, which is poorly defined in this area, and the Texas lineament. It is the only place in the region where strata of the uppermost part of the Comanchean Series and lower part of the Gulfian Series are well exposed. It is about halfway between the Franklin Mountains and the Sierra de Juarez, each a product of orogenies of strikingly different tectonic styles, yet separated (except for the outcrops of Cristo Rey) by 8 km (5 mi) of essentially undeformed late Neogene strata which mask the tectonic relations between the two ranges.

The structural annulus which surrounds the Cristo Rey pluton has been exceptionally well exposed by recent erosion because of its proximity to the Rio Grande, which has cut the canyon called El Paso del Norte (Sonnichsen, 1968) between the plutons of the Cristo Rey uplift (photo 3) and the Campus Andesite uplift at The University of Texas at El Paso. The excellent exposures, the relatively thin, readily identifiable stratigraphic units, and the complexity of the structure of the annulus permit analysis of the intrusive tectonic relations.

The shales of the annulus are sources of brick clay for El Paso and Ciudad Juarez and the sandstones are sources of silica for a local smelter and cement plant. Structural complexity at Cristo Rey has made mining difficult, costly, and unpredictable. Thus deciphering of the structure should aid the quarry operators.

LOCAL GEOGRAPHIC NAMES

Cross sections are numbered consecutively 1 through 86. The various geologic and structure maps and structural cross sections are placed on six sheets in the pocket at the back of the report. Map designations are given by map number and sheet number, maps in Roman numerals, and sheet numbers in Arabic numerals. Thus, map I, sheet 1, is the geologic map of Cristo Rey. The cross sections are listed by number only (for example, section 23, map I, sheet 1). All cross sections are specifically identified by their own number; hence only initial references cite map and sheet numbers.

To facilitate descriptions, some local geographic features have been named (fig. 2; map I, sheet 1). Bowen Gulch between cross sections 6 and 7 (fig. 2; map III, sheet 2), named for the abandoned railroad station of Bowen, and Deep Gulch between sections 7 and 8, are names given to the major north-trending drainages on the north side of Cristo Rey. Arroyo de las Tetillas between sections 21 and 22 is the drainage at the

Left
PHOTO 1—Cristo Rey by Soler (*photo by Binion*). This statue of Christ stands on the peak at Cerro de Cristo Rey (Binion, 1970, p. 18).

Right
PHOTO 2—Apache Canyon (*photo by Binion*). Tourist trail to the peak begins in Apache Canyon, which was eroded on a fault in the andesite (Binion, 1970, p. 23).

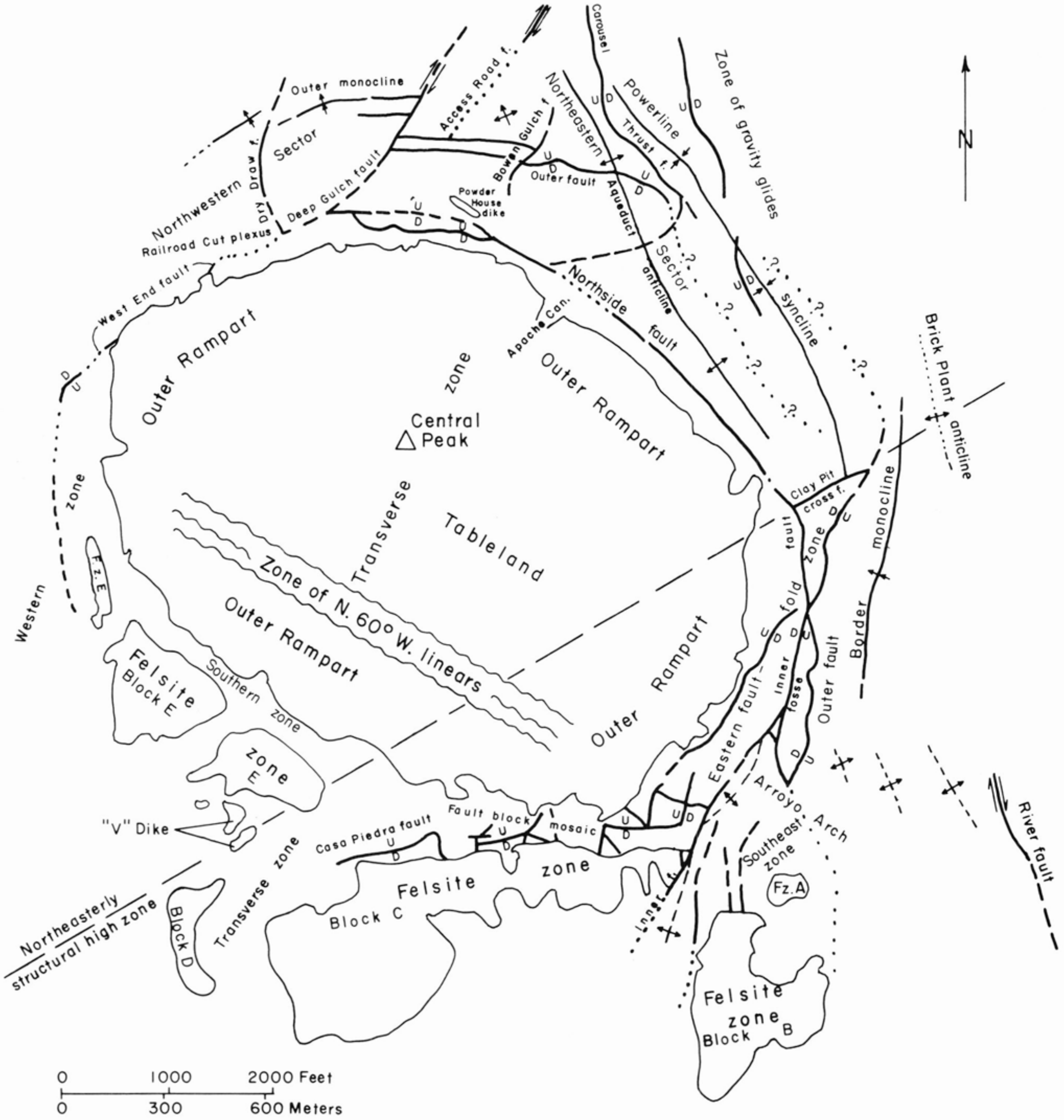

FIGURE 2—SIMPLIFIED INDEX MAP OF STRUCTURAL REGIONS AND FEATURES.

southeast corner of the Cristo Rey uplift; Arroyo de la Ladrillera between sections 22 and 23 extends to the Rio Grande south of Ladrillera de Juarez S.A.; Arroyo de la Fronteriza at section 24 is the drainage along the border at the east side of the uplift; Brick Plant Gulch between sections 25 and 26 is the major drainage just south of the eastbound Southern Pacific Railway track; and Refinery Canyon between sections 2 and 3 is the major drainage which cuts across both tracks at the northeast side of the uplift. Power Line Ridge (sections 3 through 5) extends northwestward between the two tracks on the northeast side of the uplift, and Railroad Ridge (section 8) is between the two tracks west of Deep Gulch. On the west side of Railroad Ridge is Dry Draw between sections 8 and 9. The main canyon into the pluton, through which the main trail has been cleared, is called Apache Canyon (photo 2; Binion, 1970, p. 23; see Schmidt, 1972, for general geographic data).

PREVIOUS WORK

The Cerro de Muleros uplift (photo 3) was examined by Emory (1857), Stanton and Vaughan (1896), Richardson (1909), and Bose (1910). Böse (1910) studied the paleontology at Cerro de Muleros and subdivided the Cretaceous strata into 11 units based on lithology and fauna. Richardson (1909) made a reconnaissance study of the stratigraphy and structure and mapped the uplift at a scale of 1:250,000 (see also Nelson, 1958; Small, 1958; Dane and Bachman, 1965). Garcia (1970, esp. p. 17-22) studied the petrology of the andesite plutons in the El Paso region. He concluded that the Muleros Andesite was intruded as a laccolith, in accordance with Böse's (1910) conclusions. His cross sections showed the andesite to have intruded near the northwestern end of the pluton and to have been injected as a sill or laccolith toward the southeast. pushing aside the overlying strata and thereby forming the intricate folds at the eastern end of the intrusion.

Strain (1968a) modified Böse's classification of the Cretaceous stratigraphy and proposed the names which are used in this report. Cordoba (1969b) mapped Cerrc de Cristo Rey and the Sierra de Juarez, the Cretaceous strata of which underlie the beds that crop out at Cristo Rey.

PRESENT INVESTIGATION

This study began in the fall of 1965 during field-mapping and structural-geology studies associated with

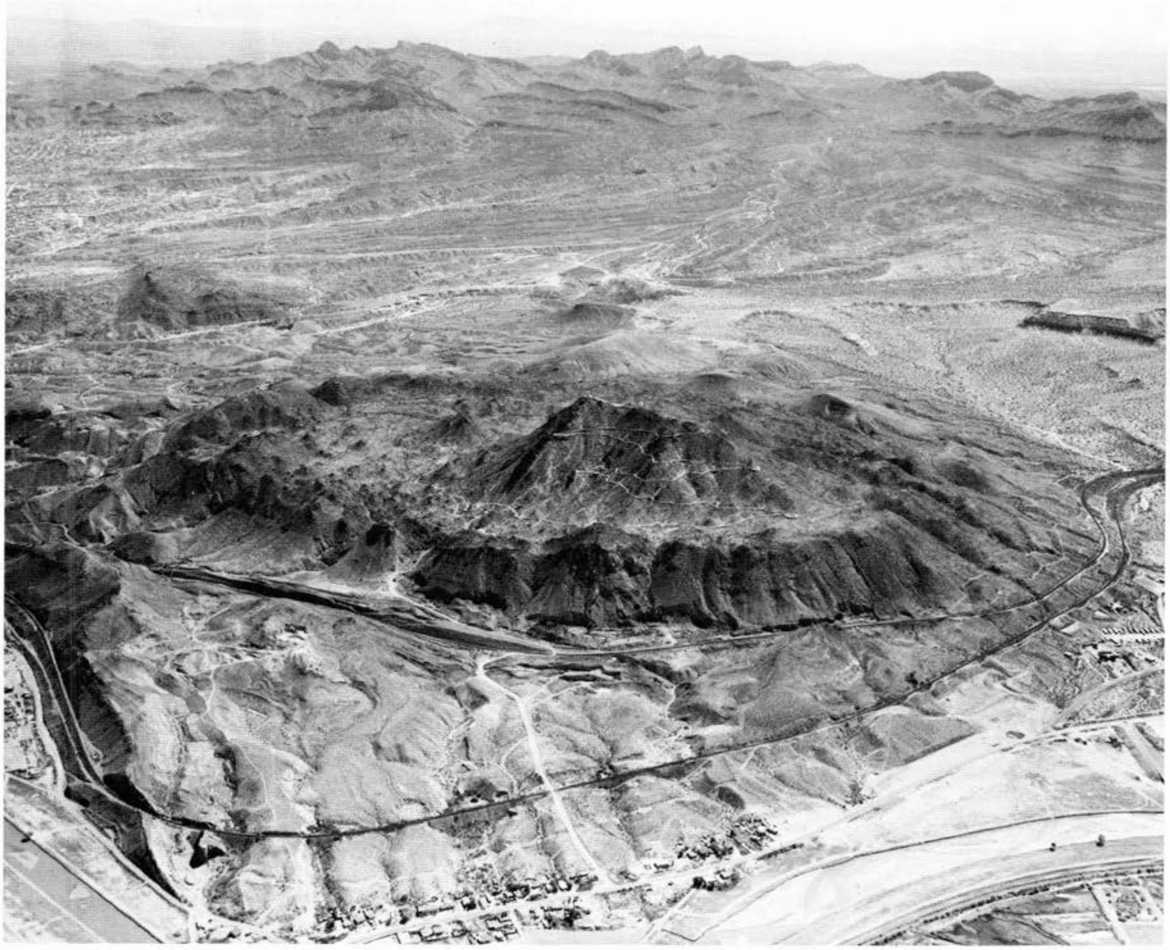

PHOTO 3—Low-oblique airview of Cristo Rey uplift and Sierra de Juárez, taken 1973 (*Photo A837-2, courtesy of Darst-Ireland Photography, El Paso, Texas*). View toward south-southwest of northeast flank of Cerro de Cristo Rey uplift with Sierra de Juárez in background. Notable features include: the northwest trend of folds in the Sierra de Juárez, and northerly trend of trace of the Carousel thrust and Power Line syncline (lower left, foreground); generally conformable relation of annulus with pluton on the northwest (right) side of the andesite pluton; complex Eastern Fault-Fold zone on southeast (left) side of pluton; normal faults in central peak of the pluton, especially between peak and Apache Canyon. Apparent in the pluton are the central peak, the tableland, and outer ramparts.

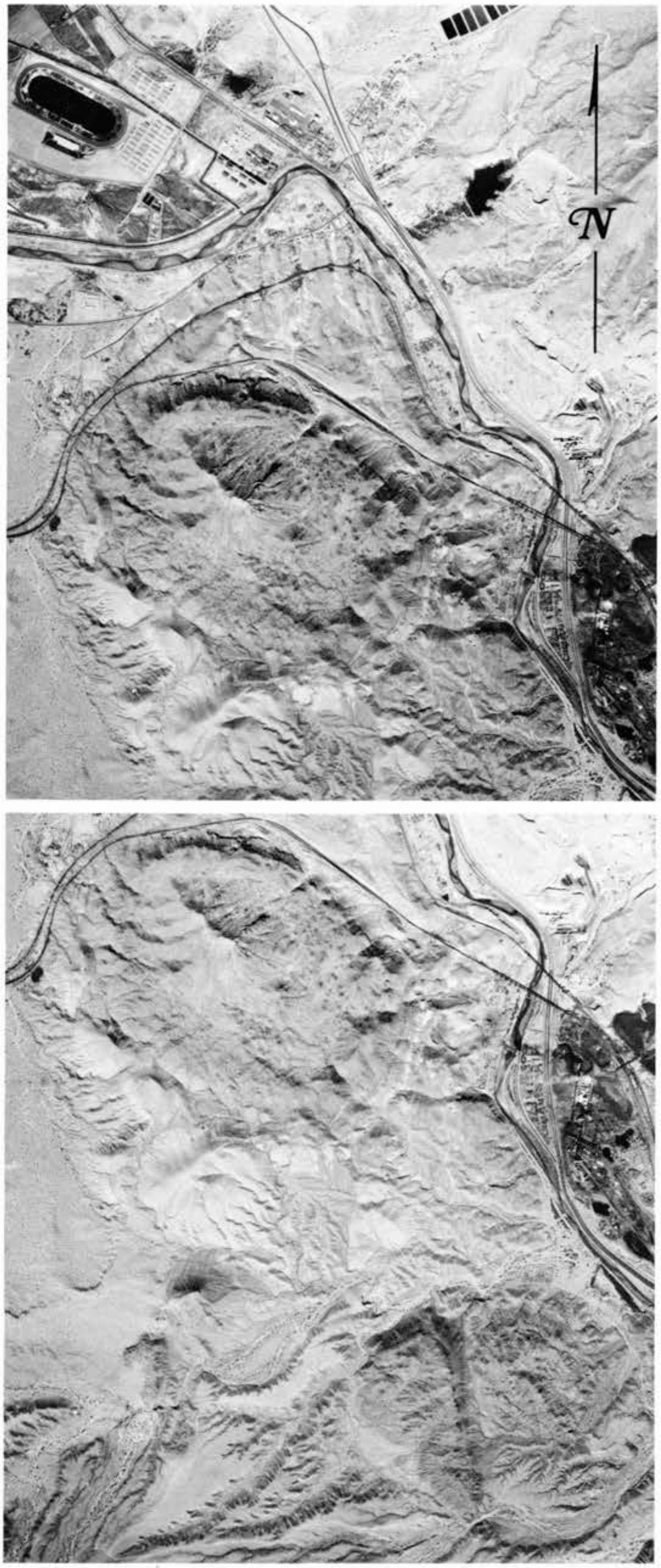

PHOTO 4—Cerro de Cristo Rey (*photos courtesy Texas Highway Department*). Stereo airphoto pair EL PUR 198-199, 1965.

course work at The University of Texas at El Paso. Mapping on the aerial photographs began in 1968 and was completed in 1971. At least two full months have been devoted exclusively to airphoto mapping at the scale of 533 ft to the inch.

The plane-table maps were made at various times, some with student help during normal course work. Plane-tabling of the more complex areas began in December 1970 and ended in November 1971.

Stratigraphic sections were studied at various places as the comprehension of the structural geology developed. Photographic interpretation of the area has not proved to be of much value except to study areas subsequently defaced by mining operations. Linears in the andesite are more readily apparent on the aerial photographs than they are on the ground (photo 4).

MAPPING PROCEDURE

The original mapping utilized an aerial photograph, with an average scale of one inch equals 533 ft (163 m; approximately 1:6,400). This photo was used as an uncorrected base for plotting the geology. Plane-table maps at scales of one inch equals 100 ft (1:1,200) and one inch equals 50 ft (1:600) were made of the more complicated areas using a K & E self-leveling alidade in good adjustment.

AERIAL PHOTOGRAPH

The base aerial photograph (photo 4) used in this project was supplied by the Texas Highway Department. The enlarged photo used for the base of the geologic mapping was made from photo no. EL-PUR 1-11-199 dated 10-26-65. The principal point of the photo is in the Loma Blanca Felsite hill between sections 18 and 19, about 98 m (320 ft) west of section 19 and 229 m (750 ft) south of the andesite contact. Calculations indicate that the photo was taken from a flight altitude of 3,353 m to 3,444 m (11,000 to 11,300 ft) above the smelter smokestack or about 4,572 m (15,000 ft) above mean sea level. Distortions caused by elevation changes around the uplift probably are significant, as can be seen by the displacement of the top of the smelter smokestack with respect to its base. For this reason, the higher parts of structures appear to be farther from the principal point than do the lower ones, and the straight international border appears bent on sheet 1 (pocket; see also fig. 3). This distortion must be considered in any attempt to evaluate the significance of trends of outcrop traces of structural features (faults, fold axial planes, and beds) where they cross major topographic relief. This probably is true in the zones of major relief in the Power Line Ridge and Eastern Fault-Fold regions. However, those areas were plane-tabled, with minimal distortion and with minor closure error.

There has been little photo interpretation except in the pluton. In areas mined subsequently, geology depicted on the two sets of aerial photographs has been interpreted. All geologic data were located on the photo in the field and readings plotted directly on a Mylar acetate overlay. The photo is uncorrected; hence there is a scalar difference across the map. In general the annulus does not have great relief and differences caused by elevation or distance from the principal point

FIGURE 3—TOPOGRAPHIC MAP OF NEW MEXICO SIDE OF CERRO DE CRISTO REY. Reduced to 1:48,000 from Smeltertown, New Mexico-Texas 7½-minute quadrangle, U.S. Geological Survey. Contour interval is 20 ft.

of the photo should not affect the major conclusions. Dips and strikes were taken to the nearest five degrees.

Stratigraphic sections were made with a 5-ft Jacobs staff and Brunton compass. Thicknesses were checked with plane-table map cross sections. Measurements were carried to the nearest foot, and dip measurements were made to the nearest degree.

ACKNOWLEDGMENTS

The owners and management of the El Paso Brick Co., Inc., of El Paso, Texas, and of the Ladrillera de Juarez, S.A., Ciudad Juarez, Chihuahua, Mexico, have been very kind in permitting me to wander freely over their holdings. I hope that this report will repay their generosity during the past 40 years, in permitting students of the then Texas College of Mines and now The University of Texas at El Paso to map on their property. Certainly, the availability of the superb geology of Cristo Rey has been a major teaching aid for the Department of Geological Sciences.

The students who operated the plane table were George Etheridge in the Bowen Gulch area east of the Cristo Rey access road; Chester Callahan, between Deep Gulch and the Cristo Rey access road; Jack Dowdney, in the area south of the southern railroad and west of the Cristo Rey access road west to cross section 8; Eric Lovejoy and Mark Lovejoy, at the south end of the Eastern Fault-Fold zone, south of Arroyo de las Tetillas; and Kim Klager, in the Gravity-Glide region of the Power Line syncline. Robert Sepulveda, who plane-tabled the rest of the map area, worked with me for four years, starting as a draftsman and becoming a superb plane-table mapper. He has been a tremendous field assistant and draftsman and has contributed greatly to the project. Stephen Balough, Margaret Hoenig, and Thomas Lau did excellent drafting of the final copies of all maps, cross sections, and text illustrations. The quality of this report has been enhanced greatly by their superb work.

Charles H. Binion has provided five beautiful photographs (frontispiece; photos 1, 2, 28, 29) of Cristo Rey from his book (Binion, 1970). The addition of these photographs to this report is most deeply appreciated. Permission for their reproduction was graciously granted by the Texas Western Press, The University of Texas at El Paso. Low-oblique airphoto of the uplift (photo 3) was kindly supplied by Darst-Ireland Photography of El Paso.

Frank E. Kottlowski, then Chief Geologist and now Director, New Mexico Bureau of Mines and Mineral Resources, suggested Bureau support for this project, visited the field area, and offered many vital comments which helped in preparation of this report. I am indebted to him for his understanding and help. The financial support for mapping and drafting of the maps and the typing granted by Don H. Baker, Jr., former Director of the Bureau, is very greatly appreciated.

William S. Strain, Department of Geological Sciences, The University of Texas at El Paso, who has worked in the region for many years and who has studied the stratigraphy of Cristo Rey in detail, was kind and generous with his advice and help. Bill Strain and I would also like to thank William A. Cobban, United States Geological Survey, and Stephen C. Hook, New Mexico Bureau of Mines and Mineral Resources, for advice on the age and correlation of the Cretaceous rocks exposed around Cristo Rey.

Stratigraphy

Near the Cristo Rey uplift Precambrian, Paleozoic Cretaceous, and late Cenozoic strata crop out. Around the pluton are exposures of Cretaceous and late Ceno zoic strata, but only the Cretaceous units have bees deformed by the intrusion.

PRE-CRETACEOUS STRATIGRAPHY

In the Franklin Mountains, the nearest outcrop o pre-Cretaceous rocks, there are about 1,219 m (4,000 ft of Precambrian sedimentary rocks overlying an un known thickness of older units (Harbour, 1972), ant about 1,829 m (6,000 ft) of Paleozoic strata, most o which are massive limestone beds (Richardson, 1909 Harbour, 1972; Kottlowski, 1970). No Triassic or Juras-sic strata are present near Cristo Rey. Although then are diabase sills and dikes in the Paleozoic (Lovejoy anc Hoffer, 1971) and Precambrian (Richardson, 1909) sequences, the andesites have not been found in strata older than Cretaceous (Garcia, 1970). Apparently *a* major control of the andesite plutons is stratigraphic. In the Chihuahua tectonic belt the pre-Cretaceous units. are highly deformed in this region, as are the Lowei Cretaceous units (Bridges, 1970).

Regional emplacement of the andesite plutons in the El Paso region appears to have been structurally controlled inasmuch as the alignments of intrusions in the Mesilla Valley are about N. 20° W. (Garcia, 1970; Lovejoy, 1972), parallel with the older Franklin-San Andres lineament and the younger Rio Grande trench lineament. The local guiding controls appear to have been primarily stratigraphic. The presence of the more variable Cretaceous strata lying directly above massive and competent pre-Cretaceous units gave rise to the varied forms of andesite intrusions in the El Paso region. (See Richardson, 1909; Harbour, 1960, 1972; Nelson, 1940; LeMone, 1968; McAnulty, 1968; Mc-Glasson, 1968; and Seewald, 1968, for more specific data on the local Paleozoic and Precambrian stratigraphy.)

CRETACEOUS STRATIGRAPHY

The classification proposed by Strain (1968a, p. 82) for the Cretaceous rocks of Cristo Rey is shown in table 1, and is used in this report. After this report was prepared, edited, and drafted, Strain introduced some modifications of two units. Strain's proposed terminology is presented as Appendix 2 of this Memoir. Strain (personal communication) has suggested that the Courchesne Formation is the equivalent of the Finlay Formation. *He* also has suggested that the Del Rio, Buda, and Boquillas names be applied to the upper three units because their fauna and lithologies are similar to those of the same-named formations farther east in the Big *Bend* country.

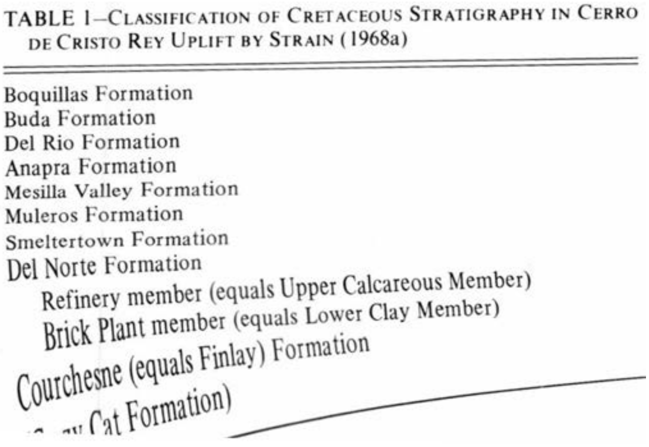

TABLE 1—CLASSIFICATION OF CRETACEOUS STRATIGRAPHY IN CERRO DE CRISTO REY UPLIFT BY STRAIN (1968a)

Boquillas Formation
Buda Formation
Del Rio Formation
Anapra Formation
Mesilla Valley Formation
Muleros Formation
Smeltertown Formation
Del Norte Formation
  Refinery member (equals Upper Calcareous Member)
  Brick Plant member (equals Lower Clay Member)
Courchesne (equals Finlay) Formation
Cat Formation)

Còrdoba (1969b, map in pocket of guidebook) placed the Cretaceous formations around "Cerro *de* Muleros o Cristo Rey" in the "Grupo Ojinaga" and subdivided the Ojinaga Group as shown in table 2. He first proposed the name "Ojinaga Group" in 1968 (Cordoba, 1968, p. 86).

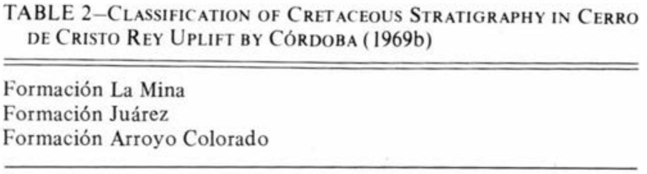

TABLE 2—CLASSIFICATION OF CRETACEOUS STRATIGRAPHY IN CERRO DE CRISTO REY UPLIFT BY CÓRDOBA (1969b)

Formación La Mina
Formación Juárez
Formación Arroyo Colorado

In Cordoba's (1969b) classification, the Arroyo Colorado Group seems to include the sequence Del Norte-through-Anapra Formations; the Juarez Group seems to include the Del Rio and Buda Formations; and the Rio Bravo Group seems to include the Boquillas and younger Cretaceous formations. Córdoba (1969b) included the Finlay Formation in his "Grupo Chihuahua." Thus, in the terminology used by Còrdoba, all of the Cretaceous strata belong to the Chihuahua and Ojinaga Groups with most of the strata belonging to the latter.

Subdivision of the formations proposed by Strain (1968a) has been utilized for mapping (table 1). The units shown in table I are readily identifiable in the field, are present in all parts of the Cerro de Cristo Rey uplift, and clearly manifest changing conditions of deposition. Thus they should be considered as distinct and mappable entities. Use of the names Del Rio, Buda, and Boquillas on the basis of lithologic similarities to formations of the same names in the Tierra Vieja and Big Bend may be questionable. Future work may indicate lack of correlation, but the formations are useful for structural mapping at Cristo Rey and their names are retained for that purpose.

The mapping of the Cristo Rey uplift was undertaken primarily to decipher the structure. No attempt was made to study in detail the stratigraphic units, depositional environments, faunal assemblages, or facies changes. However, by subdividing the formations, units only several tens of feet thick could be used for unraveling the structural complexities.

PRE-FINLAY FORMATIONS

The oldest Cretaceous strata exposed at Cristo Rey are limestones and associated rocks of the upper Finlay. However, Córboda (1969a, p.91-96) described older Cretaceous rocks in the Sierra de Juarez, 8km (5Mi)

TABLE 3—STRATIGRAPHIC SUBDIVISIONS OF SMELTERTOWN, MULEROS, MESILLA VALLEY, AND ANAPRA FORMATIONS

- Anapra Formation
  - Upper sandstone unit
  - Upper siltstone unit
  - Middle sandstone unit
  - Lower siltstone unit
  - Lower sandstone unit
- Mesilla Valley Formation
  - Upper shale unit
  - Lower shale unit
- Muleros Formation
  - Upper limestone unit
  - Middle shale unit
  - Lower limestone unit
- Smeltertown Formation
  - Upper sandstone unit (not specified in sheet 1)
  - Upper shale unit
  - Limestone unit
  - Lower shale unit

southwest of Cristo Rey, and similar beds probably underlie the Finlay at Cristo Rey.

Cordoba listed the units in Sierra de Juarez (see table 4). These units, generally limestone with some shale and sandstone, probably underlie the Finlay at Cerro de Cristo Rey. These strata in the Sierra de Juarez have *been* intricately folded and thrusted (Wacker, 1972; Campuzano, 1973).

TABLE 4—MAJOR CRETACEOUS FORMATIONS IN SIERRA DE JUÁREZ WITH THICKNESSES

Finlay Limestone	130 m
Lágrima Formation	339 m
Benigno Formation	206 m
Cuchillo Formation	280 m
Total thickness	955 m (3,153 ft)

The Crazy Cat Formation (Strain, 1968a)—below the Finlay, which has been found at the south end of the Franklin Mountains—does not crop out at Cristo *Rey*. Swift (personal communication) correlated the Crazy Cat Formation with the upper part of the Las Vigas Formation, which lies below the Cuchillo Formation. Swift (1973) considered the lower 82 m (270 ft) of the section in the Sierra de Juarez to be the upper part of the Las Vigas Formation.

FINLAY FORMATION

The Finlay Formation, called the Courchesne Formation by Strain (1968a) and the Finlay Limestone by others, consists of nodular and massive limestone beds with thin shaly partings. The limestones crop out only along the Rio Grande near the railroad bridges and form distinctive cliffs along the river. The exposed section is 40 m (130 ft) thick just north of the eastbound Southern Pacific railroad tracks. Cordoba (1969a) assigned a thickness of 130 m (426 ft) for the unit in the Sierra de Juarez. The base is not exposed at Cristo Rey.

The Finlay is a fairly competent unit cut by small north-trending normal faults with relatively minor drag. It has been folded into the broad, open Brick Plant anticline in the northern part of its outcrop area. At the southern end of its outcrop, south of the southern railroad tracks, locally it is tightly folded, probably as a ***result of drag along a fault.***

DEL NORTE FORMATION

The Del Norte Formation (Strain, 1968a; see Strain, Appendix 2), consisting of two parts, the lower Brick Plant member (lower clay member, Appendix 2) and the upper Refinery member (upper calcareous member, Appendix 2) overlies the Finlay in the area between the two railroad tracks, and as far south as the El Paso Brick Company plant. The Brick Plant member is a poorly exposed shale, the slopes of which commonly are covered with colluvium from the Refinery member. The overlying Refinery member is well exposed across the outcrop area. It is very fossiliferous, thin- to medium-bedded, tan limestone which forms a distinctive marker bed.

The Brick Plant member is 13 m (44 ft) thick. The Refinery member is 2.1 m (7 ft) thick. The total thickness of the formation is about 15 m (50 ft). At Strain's type section (Appendix 2), the total thickness is 17.2 m (56.5 ft). The Del Norte shale is the first important shale unit above a great thickness of more competent strata.

SMELTERTOWN FORMATION

The Smeltertown Formation consists of a lower shale member, a limestone-shale member, an upper shale member, and an upper shale-sandstone member. The lower shale member, a black shale difficult to distinguish from the overlying Mesilla Valley shale, is nonsilty and fissile. The limestone-shale unit contains thin lenses and nodules of limestone which constitute about a quarter of the unit. On erosional surfaces the limestone fragments form lag colluvial gravels. The upper shale member is similar to the lower shale member. The upper shale-sandstone member contains interbeds of fine-grained quartzose sandstone which closely resemble sandstone beds in the uppermost part of the Mesilla Valley Formation.

The limestone units of the Smeltertown Formation resemble some of the upper limestones of the Muleros Formation, but there are many specimens of *Gryphaea* in the Muleros.

The Smeltertown Formation was determined originally to be 44 m (145 ft) thick (lower shale member: 17 m [55 ft]; limestone-shale member: 11 m [35 ft]; upper shale member: about 9 m [30 ft]; and shale-sandstone member at the top: 7.6 m [25 ft]). This thickness determination is in error. Strain (Appendix 2) has measured the unit and determined the type section to be 61.4 m (201.5 ft) thick.

The formation is well exposed at the northeast side of the Cristo Rey uplift between the two railroads, and southward in the Border monocline along the low hills just west of the El Paso Brick Company plant and the Ladrillera de Juarez plant. It also crops out along the intrusive contact area on the south and southwest sides of the andesite pluton, where the lowest unit exposed is the limestone member.

In *general*, the lower and upper shale members are nonresistant units, the slopes of which are covered with colluvium derived from the limestone-shale member or from the overlying Muleros Formation. The **limestone-**shale member, detected on natural slo*pes abundance of limestone cobbles, generallyis s aby the former. The upper shale-sandstone slope membe*r *flay be* detected by abundant sandstone fragments on an otherwise shaly slope; sandstone outcrops are not prominent.

The Smeltertown Formation is the lowest unit observed in contact with the andesite intrusion.

MULEROS FORMATION

The Muleros Formation consists of three members—a lower limestone member, an overlying shale-siltstone member, and an upper thin-bedded limestone-shale member. The Muleros Formation is best exposed in the railroad cut at the west end of the eastbound railway bridge, but it is also very well exposed in the Fold zone in upper Refinery Canyon and adjacent to the intrusion just south of the Powder House dike. The lower member consists of thin- to medium-bedded argillaceous limestone beds, many of them nodular to varying degrees. The shale-siltstone member contains many thin beds of siltstone that differentiate this unit from the shales of the upper part of the Mesilla Valley Formation which it closely resembles. The upper limestone member consists of thin beds of marl. The one diagnostic feature of the Muleros limestones which helps distinguish them from other limestones in the Cretaceous sequence is the locally great abundance of *Gryphaea*. The contact between the Muleros and the Mesilla Valley Formations is the highest limestone bed containing abundant *Gryphaea*. However, a higher thin limestone bed containing scattered *Gryphaea* is present in the Mesilla Valley Formation.

The lower limestone member is 20 m (64 ft) thick; the shale-siltstone member is 13 m (44 ft) thick; the upper limestone-shale member is 4.6 m (15 ft) thick. The total thickness is 38.1 m (125 ft) at section 6, but the section may be incomplete. The section measured by Strain (Appendix 2) is 32.4 m (106 ft) thick.

The Muleros Formation is exposed widely around the contact zone of the intrusion. It has been severely folded from the northeast side in upper Refinery Canyon to the north boundary south of Railroad Ridge. Where it is adjacent to the andesite, the limestone locally has been metamorphosed into a microskarn containing epidote and minor garnet. Recrystallization into a fine-grained, low-grade, noncommercial marble is more common. Shaly interbeds and marls have been metamorphosed into low-grade calc-silicate masses. Locally there is some manganese or iron. There is no indication that the Muleros, or underlying limestones, were loci of economic mineralization.

As a consequence of its reaction to the magma, the limestone locally is resistant to erosion and forms prominent ridges around the contact. The Smeltertown, Muleros, and Mesilla Valley Formations form more than 95 percent of the outcrop-contact units adjacent to the andesite, and of these the Muleros is by far the most resistant. In places (sections 11 and 18, map I, sheet 1), the Muleros limestones apparently were assimilated by the andesite.

MESILLA VALLEY FORMATION

The Mesilla Valley Formation is primarily shale with two members, a lower carbonaceous black shale and an upper shale containing some siltstone, clayey, fossiliferous limestone and, near the top, ironstone and fine-grained sandstone beds. The lower carbonaceous, black shale member is best exposed in the eastbound railroad cut about 244 m (800 ft) east of the Cristo Rey access road crossing, in the quarry adjacent to the intrusion about 183 m (600 ft) west of the access road crossing, and in the quarry southwest of the El Paso Brick Company plant. The very shiny appearance of the shale suggests a high carbon content. The lower unit appears to be a very clayey, silt-free shale. The upper member contains some limestone-hash beds with abundant *Trigonia,* and finely crossbedded limestone and siltstone with locally abundant *"Haplostiche."* The contact between the two members is not readily apparent in all places. The carbonaceous member is distinctive locally and helps in determining the stratigraphic position in complex zones. Strain (Appendix 2) has since renamed this unit as the Mesilla Valley Shale.

The thickness of the Mesilla Valley Formation is 55 m (180 ft) determined in three places. 1) Along the southwest flank of Power Line Ridge in the eastbound railroad cut, the Muleros-Mesilla Valley-Anapra sequence is exposed on a steep hill. The Mesilla Valley Formation is covered with Anapra colluvium. Detailed mapping here (scale 1:1,200) indicated a stratigraphic thickness of 55 m (180 ft) (section 55, map V, sheet 3). 2) Between cross sections 25 and 26 (map VI, sheet 3) on the flank of the Border monocline, a thickness of 55 m (180 ft) was determined by measuring the cross section of the map. 3) Along the eastbound railroad on the east side of the Power Line syncline (section 42, map VI, sheet 3), the formation is 55 m (180 ft) thick. Apparently thicker sections farther west (78-90 m equalling 256-295 ft) may be the result of thrusting. At the type section, Strain (Appendix 2) determined the unit to be 64 m (210 ft) thick.

The Mesilla Valley Formation crops out in large areas around Cristo *Rey* and is found in all parts of the uplift. It has been extensively quarried, constituting one of the principal units mined for brick clay near El Paso and Juarez.

The Mesilla Valley Formation, an incompetent unit, is strongly folded in all exposures adjacent to the andesite.

ANAPRA FORMATION

The Anapra Formation is a sandstone, containing some shaly siltstone interbeds. It has been subdivided into five members: 1) a lower massive sandstone; 2) a lower shaly siltstone; 3) a middle sandstone; 4) an upper shaly siltstone; and 5) an upper sandstone. These members have not everywhere been separately mapped. Strain (Appendix 2) has renamed the unit the Anapra Sandstone.

The lower massive sandstone member is quartzose, medium grained, and poorly bedded. Its dip cannot be determined readily in highly deformed strata. Above this is a variable sequence of bluish to purplish shaly siltstone which has been quarried on the northeast side of Cristo Rey for its special brick-making properties. Above this is a massive arkosic crossbedded sandstone which locally has pebble conglomerate beds near the base. The pebbles consist of quartz and aphanitic intermediate volcanic rocks, such as light-colored, latitic, welded tuffs. Above this member is another bluish to purplish siltstone member which has been quarried just south of the border. The uppermost unit is a massive, poorly bedded sandstone consisting of clean quartzose, medium-grained sand particles. *Exogyra* is present in the very top of this unit at the base of the Del Rio Formation.

The thicknesses of the five members have been determined in the overturned sequence at the east end of the pluton, and also east of the Cristo Rey access road where Bowen Gulch cuts through the Anapra strata. The lower sandstone member is 19 m (63 ft) thick; the lower siltstone member is about 18 m (60 ft) thick; the middle sandstone member is 11 m (36 ft) thick; the upper siltstone member is about 11 m (36 ft) thick; and the highest sandstone member is about 4.5 m (15 ft) thick. The total thickness is 64 m (210 ft). Strain, at his type locality (Appendix 2), measured 52.6 m (172.5 ft).

The Anapra sandstones crop out widely around the Cristo Rey pluton and exhibit excellent outcrops on hogbacks and cuestas. Their dip slopes form stripped surfaces. The Anapra Formation is the most competent unit of the supra-Finlay section. However, the siltstone interbeds are less competent; hence local structures in the Anapra are complex. In the Power Line syncline and in the Eastern Fault-Fold zone, local surfaces of sliding have formed on the two siltstone members of the Anapra resulting in cascades and flaps. At section 19 (map I, sheet 1), the Anapra is in intrusive contact with the andesite.

DEL RIO FORMATION

The Del Rio Formation consists of shale with some limestone beds and nodules near the top and bottom, making a gradational upper contact with the overlying Buda. The base of the lowest massive limestone of the Buda Formation is the top of the Del Rio. Del Rio outcrops weather yellow. Unweathered Del Rio shales are dark gray; the limestones are nodular to thin bedded.

The total thickness of the formation is 24-27 m (80-90 ft). The Del Rio everywhere forms colluvium-covered slopes. It has been stripped widely from above the Anapra sandstones and is preserved only beneath the overlying Buda limestones; therefore, the Buda and Del Rio occur together in outcrop bands around the pluton. The Del Rio is an incompetent shale, the locus of sliding in several places because it is between the Buda and Anapra Formations. *Exogyra* are abundant in the lower part of the Del Rio Formation.

BUDA FORMATION

The Buda Formation is a massive to nodular limestone containing some thin clay seams. The formation is about 12 m (40 ft) thick, but crops out in many places because it lies between the readily erodable Del Rio and Boquillas Formations. It is on the outer edges of the uplift except at the eastern end, where the formation has been dropped by faults to points near the edge of intrusion. Nowhere is its outcrop in contact with the andesite. Locally, the Buda Formation contains many gastropods, but only a *few Gryphaea*, so that there is little chance of confusing the Buda and Muleros Formations. The Buda limestone beds act as competent units between two incompetent shales; therefore, some of the structures developed in it are locally very complex.

On the south side of the Cristo Rey uplift the Buda limestone has been contact-metamorphosed by the intrusion of the Loma Blanca Felsite, with minor silicification, epidotization, and garnetization. A small manganese deposit is present along a fault in the Buda and probably is lithologically controlled.

BOQUILLAS FORMATION

The Boquillas Formation is dark-gray, generally unfossiliferous shale which weathers buff yellow, and is similar in appearance to the Del Rio Formation. However, the lower Boquillas shale contains diagnostic thin-bedded limestone laminae not found in the Del Rio shale, and the Del Rio contains abundant *Exogyra* which has not been found in the Boquillas. Böse (1910) gave its thickness as 110 m (360 ft). The unit forms slopes and is only sparingly exposed near Cristo Rey. The formation is an incompetent unit. South of the Cristo Rey pluton, andesite sills have intruded the Boquillas shales. See Strain's comments on the Boquillas Formation and Bose (1910) classification in Appendix 2.

CENOZOIC STRATIGRAPHY

Cenozoic strata near Cristo Rey include fluviatile and lacustrine deposits of the Blancan Fort Hancock Formation, landslide deposits, younger Pleistocene river deposits (which lie above the present river flood plain), as well as modern river deposits, colluvium, sand dunes, and artificial fill.

FORT HANCOCK FORMATION

Overlying the Cretaceous formations around Cristo Rey and above the Cretaceous and older strata in the Franklin Mountains are lake and fluvial sediments of early Pleistocene age (Kottlowski, 1958; Strain, 1968b, 1969; Hawley and Kottlowski, 1969). These deposits, the Fort Hancock Formation, cover all pre-Cenozoic strata (Cliett, 1969) of the region except for those around local intrusions and in the Franklin Mountains. This thick cover hides the complexities of bedrock geology and enhances the importance of what little can be learned at the few available outcrops. During the period of bolson filling, this deposit covered all of Cristo Rey below elevations of about 1,250-1,280 m (4,1004,200 ft).

The Fort Hancock Formation consists of a basal conglomerate and interbedded sand and clay beds. The basal conglomerate consists of abundant cobbles and boulders of rock types which crop out uphill from the present deposit. Andesite boulders and andesite grus are the principal constituents on the north and east sides of Cristo Rey. Felsite is abundant on the south side. Fragments of resistant members of all formations of the Cristo Rey area are found in the basal conglomerate.

The basal conglomerate forms most of the Fort Hancock Formation outcrop in the map area. It generally is very poorly bedded and not well exposed except in excavations. Most of its surface is covered by colluvium derived from the conglomerate. The thickness of the basal conglomerate is variable but generally is on the order of tens of feet. It does not extend very far from the pluton or annulus; the younger sands and clays crop out around the uplift on all sides.

The sand and clay beds are probably different sediments deposited under different conditions. At times the area was a flood plain on which fluviatile silts and sands were spread. At other times the area was inundated by a fresh-water lake, Lake Cabeza de Vaca (Strain, 1966), when finer grained silt and clay were deposited. These fine-grained sediments locally inter-finger with the basal conglomerate, as can be seen along the railroad tracks on the west side of the uplift. In general, however, they overlie the basal conglomerate, as can be seen clearly on the south side of the uplift between sections 16 and 17. At that locality there are calcareous sandstones unlike materials elsewhere in the Fort Hancock Formation. The calcite is cementing material which may have been deposited as the result of soil formation during Pleistocene time.

The total thickness of the Fort Hancock Formation around the uplift is not known, but is tens of feet in the map area. Just south of the uplift the erosional scarp of the La Mesa surface exposes more than 30 m (100 ft). The age of the Fort Hancock Formation is Blancan (Strain, personal communication, 1973).

The Fort Hancock Formation contains fossils of Blancan age (Strain, personal communication), but the bottom of the formation has not yet been found. The depth of valley fill on the east side of the Franklin Mountains is 2,743 m (9,000 ft) (Cliett, 1969), and in the La Mesa surface unsubstantiated drillers' reports indicate a minimum thickness of the order of 1,219 m (4,000 ft) (Strain, personal communication). Inasmuch as the base of this sequence could be as old as Miocene, the Fort Hancock is of Tertiary-Quaternary age *(T-Qfh* on maps and cross sections).

LANDSLIDE DEPOSITS

Along the northeast side of Power Line Ridge, Anapra sandstone beds and some Mesilla Valley shale beds have been eroded by mass wasting. The entire east side of the Power Line syncline near sections 3 and 4 slid into the Rio Grande valley. About 24 m (80 ft) above the river level, a small berm on the landslide near section 3 indicates a Wisconsinan age for the landslide. The slide has been cut by the westbound railroad excavations and there is no evidence of renewed movement.

Another landslide deposit, composed of angular blocks of andesite up to 1.5 m (5 ft) across, is present between sections 1 and 2 (map I, sheet 1) just northeast of the andesite contact. The small extension of the andesite pluton adjacent to this deposit, the steep southwest dip of the andesite contact, and the resulting structural relation of andesite overlying Mesilla Valley shale suggest that this mass of fresh andesite blocks is the remnant of a landslide produced by undercutting of the readily erodable Mesilla Valley shale beneath the overhanging protuberance. The slide now occupies a high ridge position, suggesting that the slide occurred in Wisconsinan time, sliding out on a higher, now removed, topographic surface.

Deposition of Fort Hancock material on the landslide would have filled the landslide interstices with sand, but none has been found; hence the slide is of post-Fort Hancock age. The large topographic reentrant *(Qcol) at* the southwest end of section 2 may represent the source of a block which may have broken loose at the same time; all evidence of the landslide mass hypothetically derived from that reentrant is now gone.

HIGHER LEVEL RIVER GRAVELS

On the northwest, north, and east sides of the Cristo Rey uplift, at elevations as much as 52 m (170 ft) above the present river level there are extensive deposits of old river gravels. They consist of well-rounded exotic rock types, including quartzite and fine-grained igneous rocks. Many of the fragments are of rhyolite from the Franklin Mountains. (See p. 56 for a discussion of the geomorphology and ages of those deposits.)

An interesting outcrop between sections 7 and 8 (map I, sheet 1) and between NM-28 and the westbound railroad tracks reveals the presence of angular cobbles of the Loma Blanca Felsite which form a small, isolated local facies of the high-level river gravels. The gravels east and west contain no felsite. How this deposit formed, inasmuch as the felsite crops out only on the west and south sides of the pluton, is difficult to determine. The facies is rich in felsite, but search failed to disclose any outcrop of the sill. This concentration of felsite in an otherwise mixed gravel deposit would require special conditions in the Rio Grande during Wisconsinan time. Perhaps this is a remnant of older alluvium buried during later backfilling. If the felsite sill does extend this far, it increases the felsite arc by almost 90° around the andesite.

ALLUVIUM AND SAND DUNES

Alluvium fills most of the major washes and all of the flood plain of the Rio Grande. In many places the alluvium can be differentiated from the older Fort Hancock materials and the younger colluvium, but this was not everywhere practicable. Several levels of alluvium are in some of the washes, indicating two and perhaps three levels of alluviation that were not mapped separately (see explanatory note I in Appendix 1). In some places differentiation between the modern alluvium and some older river gravels was not made. The depth of alluvium in the Rio Grande in El Paso del Norte is about 26 m (86 ft) (Richardson, 1909, p. 6).

The Fort Hancock Formation once extended across all of the Cretaceous units of the annulus, the outer rampart of the andesite pluton, and most of the felsite. Lag gravels (Strain, personal communication), consisting of rhyolite from the Franklin Mountains, quartzite from exotic sources, and other types of resistant pebbles and cobbles, all derived from the gravels that were in and on the Fort Hancock deposits, are found in many places around the Cristo Rey region.

The alluvium was not specifically mapped except in the largest arroyos, gulches, and canyons. Alluvial fans debouching onto the present flood plain of the Rio Grande, hence of slightly younger age than that river alluvium, also were not differentiated.

Sand dunes, generally only a few feet high, are present locally along the edge of the present river flood plain and along the big arroyo southwest of the pluton. There is a field of high sand dunes south of the felsite. Only the larger dune fields were mapped separately. Others are included in the alluvium designation. They do not mask any important structure in the pluton, and they cover only alluvium or Fort Hancock strata. Most of the sand was derived from the flood plain or from the Fort Hancock material.

COLLUVIUM

There is colluvium across most of the map area. If all of it were mapped, however, much less bedrock geology of shale units would be mapped. In general, colluvium was mapped where it covers structural complexes and where structural interpretation was speculative. Where the stratigraphic units were not complexly deformed, colluvium was not mapped. For example, across most of the area the Mesilla Valley and Smeltertown shales are covered widely by colluvium. Although only minor outcrops of these units are present on natural slopes, on the main geologic map (map I, sheet 1) most of the Mesilla Valley and Smeltertown Formations are shown as outcrop. On the plane-table maps this same rule was followed, but more colluvium was shown on those maps than on the main geologic map. Thus, there may be local map differences.

Locally near the andesite, especially on the north side of it, thick (to 6 m [20 ft]) deposits of andesite boulders have been mapped as colluvium. This material merges with modern alluvium in many of the washes, yet identical material south of the pluton merges with Fort Hancock basal andesite gravels. Differentiation of this older colluvium on the basis of age (that is, younger alluvium or older basal Fort Hancock Formation) was not attempted.

FILL AND DISTURBED GROUND

Artificial fill, including quarry floors, railroad fills, road fills, and miscellaneous areas, is included locally with colluvium. All fill masks, and in general does not provide clues for, the nature of the underlying structure.

IGNEOUS ROCKS

Two distinct types of igneous rocks are in the Cristo Rey uplift—the Muleros (hornblende) Andesite and the Loma Blanca Felsite. Although the principal uplift was caused by the andesite intrusion, an **undetermined** amount of deformation may have accompanied intrusion of the felsite. Both types figure prominently in the structure of the Cristo Rey uplift.

MULEROS ANDESITE

The Muleros Andesite at Cerro de Cristo Rey was named by Garcia (1970, p. 17) who described its petrography as follows (p. 19-21):

> Microscopic examination shows that the rock is holocrystalline and porphyritic with a very fine-grained groundmass. It is composed largely of plagioclase, hornblende, biotite and magnetite. The principal constitutent is plagioclase of andesine composition. An 33 to An 38. Almost all of the subhedral andesine phenocrysts are clouded by alteration products. Plagioclase phenocrysts constitute about 31.3 percent of the Muleros andesite. They are highly zoned and range in size from 0.1 to 5.5 mm., averaging about 1.0x 0.6 mm. . . a sample taken at the contact of the andesite with the shale shows abundant fresh labradorite, (An 54), which probably formed by reaction of the magma with the shale. A few phenocrysts of K-feldspar occur in the contact zone.
>
> Corroded and embayed brown and olive-green hornblende is the most abundant mafic mineral. Most of the crystals are euhedral; the green hornblende appears more resistant to alteration than the brown. Some hornblende phenocrysts are partially coated with bluish chlorite(?). Hornblende phenocrysts make up 13.4 percent of the rock, and range in size from 0.1 to 2.8 mm., averaging 0.8 x 0.4 mm.
>
> Reddish-brown biotite phenocrysts, stippled with magnetite, occur in euhedral flakes and elongated subhedral crystals. They range in size from 0.1 to 2.7 mm. with an average size of 0.7 x 0.3 mm. Many of the crystals are fringed with chlorite; some are completely replaced by magnetite, chlorite, and (or) epidote.
>
> The groundmass is very fine-grained, averaging 0.05 mm., and is difficult to identify. Its composition is believed to be plagioclase with minor amounts of K-feldspar, hornblende, biotite, magnetite, and quartz. . . .
>
> Accessory minerals include apatite, magnetite, and epidote. Secondary alteration products are calcite, kaolinite, sericite, chlorite, limonite, and magnetite.

In the andesite pluton near sections 19, 20, and 22 (map I, sheet 1), several acres of sericitized andesite furnish the only major pervasive alteration feature in the pluton. Two small apophyses of sericitized andesite are present in the Cretaceous strata between sections 19 and 20 (petrographic description furnished by Michael *Bersch*).

Garcia (1970) studied the petrography of andesite intrusions near El Paso, including the Cristo Rey (Muleros) Andesite and Campus Andesite plutons on the southeast (Hoffer, 1969, 1970). The Cristo Rey pluton is the best exposed, and the only one in which the entire contact zone can be seen. It is probably one of the best exposed plutons in the United States, because of the proximity of the rapidly downcutting Rio Grande.

The Cristo Rey pluton is one of a series which are arranged in a N. 15° W. lineament extending from the Sierra de Juarez, several miles south of Cristo Rey, northward beyond the New Mexico state line to the Vado Hill Andesite (Vado Hill is shown on fig. 1). This series seems to be structurally controlled and may be genetically associated with Rio Grande trench or Franklin Mountains tectonism (Lovejoy, 1972). Kottlowski (personal communication; Hoffer, 1970) has obtained a whole rock K-Ar radiometric date for the Campus Andesite of 47.1 ± 2.3 m.y. (middle Eocene). Thus, the Cristo Rey pluton also is believed to be of middle Eocene age.

LOMA BLANCA FELSITE

The Loma Blanca Felsite is a creamy yellow, nonporphyritic aphanite. It ranges in thickness from a few tens of feet at section 13 to perhaps many hundreds of feet at section 17. No accurate measurements are possible because the felsite is buried by felsite colluvium, upper contacts are covered, and dips are observable only locally.

The felsite is semiconcordant; blocks A, B, and C (map III, sheet 2) cut across the strata and the faults of the Mosaic fault zone, hence are younger than the Mosaic fault zone, yet they have been emplaced essentially an equal distance from the andesite contact. This suggests that the felsite and andesite are synchronous.

The center of the outcrop arc of the felsite lies within the andesite pluton. The felsite dips away from the andesite. The contacts of the south side of the andesite and the felsite appear to be subparallel.

In felsite zone blocks A, B, and C the felsite has been forcefully injected. Many small Boquillas shale masses adjacent to the felsite are faulted against Del Rio and Anapra beds, indicating felsite movement down section. This suggests that the andesite pluton had formed a dome prior to felsite intrusion. Local contact metamorphism of the Del Rio Formation between sections 20 and 21 (map I, sheet 1), about 40 m (130 ft) from the andesite and 15 m (50 ft) from the felsite, suggests that heat from both intrusions affected the Del Rio at the same time, thus producing the intense thermal metamorphism so far from either intrusion. This observation further indicates the essential contemporaneity of the intrusions (explanatory note 2). No radiometric dates for the felsite have been published.

As shown in the Fault Block Mosaic discussion, the Loma Blanca Felsite is older than the last circumferential faulting at Cristo Rey associated with andesite pluton emplacement, dated to 45-49 m.y.

Structural Geology

The Cerro de Cristo Rey uplift consists of: a central andesite laccolith; a confocal, semicylindric, contemporaneous, locally discordant felsite sill on the west and south sides of the laccolith; and an annulus of domed, folded, and faulted Cretaceous marine strata, locally strongly deformed by gravity-glide structures triggered by andesite intrusion. On the west side of the laccolith, major high-angle faults in the annulus appear to have been formed by trapdoor-like intrusion of the laccolith. In the annulus on the north side, complex, strike-slip and compressional, fault-fold zones radiate from an annular, down-to-the-pluton circumferential fault, probably associated with pluton collapse. On the northeast side, preintrusion folds have been compressed and deflected. On the east Toreva-block-like slumps of the annulus have slid into the andesite magma chamber on concave-inward normal faults; these slumps have been accompanied by large outward-moving gravity-glide thrusts associated with overturned folds; the result is a very complex structure. On the south side, the felsite sill lies concordantly in the annulus about 100 m (328 ft) from the andesite. Complex fault zones produced during andesite injection are cut by the felsite, but circumferential faults that cut the felsite prove that the andesite and felsite are contemporaneous.

STRUCTURES IN CRISTO REY ANDESITE PLUTON

Cristo Rey andesite in this report is the Muleros Andesite of Garcia (1970; explanatory note 3).

Primary flow banding and flow lineation are poorly developed in the andesite pluton. Some primary flow banding was noted in fresh rock cuts along the trail to the summit and in major washes, but is not seen in deeply weathered bedrock; there is no evidence of flow lineations. Flow banding, locally well developed in the felsite, appears to parallel the contact with the country rock.

Secondary joints and faults cut the two plutons. Joints in the andesite were not recorded. A zone of N. 60° W. linears, which appears on aerial photograph EL PUR 1-10-199 (fig. 2) near the southwest edge of the pluton is caused by joints parallel with the major axis of the pluton but is not well developed elsewhere; its location may be significant. Joints in the felsite appear to be in sets, one of which is normal to the contacts, with strike in the direction of felsite dip.

In the andesite, faults which strike N. 30° E. and dip 70° SE along the summit trail, are delineated by outcrop and gullies. Possible fracture zones are indicated by canyons trending N. 30° E. along both sides of the pluton.

The N. 30° E. trending faults do not appear to cut the pluton boundary. Apache Canyon (photo 2) which formed apparently on one of these faults, is floored by alluvium and masks the pluton boundary. Alluvium covers all these contacts. If the faults do not cut the pluton boundary, then they may be related to plutonism rather than to regional tectonism. The Bowen Gulch, Access Road, and Deep Gulch faults and the north end of the Dry Draw fault trend about N. 30° E. Photostudy indicates a N. 30° E. trend in and through the pluton contact about 92 m (300 ft) west of section 7 approximately in line with the Bowen Gulch fault. This suggests a N. 30° E. trend through the pluton associated with apparently pluton-induced subradial faults. However, colluvium, fill, and alluvium cover almost all of the trend. This is negative evidence of a structural trend. Some of the faults exhibit epidotization and argillitization.

On the tableland, especially on the northeast, southeast, and south, a pimply topographic texture (fig. 2) is observed. This texture may manifest subtle changes in petrography or geomorphic history, especially with respect to the length of time of weathering and exposure. It also may represent normal andesite weathering which is better developed on the flatter tableland surfaces than on the steep slopes of the central peak and outer ramparts. There is no correlation of the pimply surface with petrographic type. Joint density may be a factor in determining its location. In the zone of N. 60° W. linears, deep weathering along the joints may outline unweathered blocks producing the incipient phase of pimply structures; these structures may be large tors or core stones.

ANDESITE APOPHYSES

Small andesite apophyses outside the main andesite pluton include Powder House dike, at section 7, south of the eastbound railroad track; Quarry dike between sections 7 and 8, south of the railroad track, next to the pluton; and "V" dike at section 16.

Four minor apophyses include number 1, in the Smeltertown Formation about 46 m (150 ft) west of section 18; number 2, in the Anapra Formation midway between sections 18 and 19; number 3, in the Del Rio Formation midway between sections 19 and 20; and number 4, in the Anapra Formation about 30 m (100 ft) south of section 22 and about 76 m (250 ft) southeast of the main pluton boundary (explanatory note 4).

Apophysis 1 appears to cut bedding, but the main andesite pluton contact is only a few meters below. Apophysis 2 is altered to sericite. (Michael Bersch, graduate student at University of Texas at El Paso, made a thin section and examined it.) It cuts a fault which seems to have guided its emplacement. Apophysis 3 also was guided by a fault. Apophyses 4 and 5 seem to have followed overturned beds dipping steeply toward the pluton. These apophyses probably rise from the main pluton which presumably lies beneath them.

The three main dike outcrops appear to be concordant and parallel with the main pluton boundary, suggesting their emplacement in a tensional phase of plutonism. The Quarry dike lies between the pluton and the Northside fault. The Powder House dike is near but outside of the Northside fault. Their parallelism with, and close proximity to, the Northside fault suggest a genetic relation.

SLICKENSIDES

Slickensides indicate the principal directions of tectonic transport (map III, sheet 2). Faults and minor folds in the Anapra contain abundant slickensides. Limestones locally exhibit slickensides in secondary vein calcite along minor faults. There are few slickensides in shales. The distribution of slickenside data is sparse, and the data are not complete.

According to Böse (1910, p. 46), the structures surrounding Cristo Rey resulted from magma emplacement. If so, then all structures should reflect radial vectors of compression or tension. Slickensides should point to a common origin. However, all slickensides are not directed radially from the pluton, although there are some radial slickensides. Several are at the contact of the pluton, but the notable point is that there are so few.

Slickensides in the Finlay Formation differ from those in higher formations. They are associated with normal, dip-slip to right-lateral oblique-slip faults and strike west to west-northwest. Thus, these directions are those of extension or tension. Only a few strike-slip slickensides occur in this formation. The strike of the Brick Plant anticline is about N. 15° W.; an average of the slickenside bearings is about N. 70° W. or about normal to the fold.

Most slickensides in the supra-Finlay formations strike northeast. Many of them are in the Power Line syncline and Northeastern sector faults, a fact which suggests that the forces that produced these structures were primarily directed northeast. This is the direction of tectonic transport in the Chihuahua tectonic bell farther southeast and outside of the mapped area. Many slickensides along the Carousel thrust and Power Line syncline north of their bend near section 6 show westerly strikes which are not directed toward the pluton.

A comprehensive sampling program of slickensides, a statistical study of their orientations, and a detailed study of their relations with all structures will be necessary to solve the problems of tectonic transport and orientation of tectonic forces. Nevertheless, the data presented here suggest one major northeastward tectonic transport—not radial from the pluton—and one major eastward trend.

ANNULUS AND PERIPHERAL RING

The Cristo Rey pluton is surrounded by an outcrop belt of deformed Cretaceous strata, here called the *annulus,* which is surrounded by undeformed Fort Hancock Formation and alluvium (cross sections XII, sheet 6).

Structures in the annulus can be divided into 1) those produced by the intrusion, 2) those which existed before emplacement, and 3) those which formed after it. Differentiation among these was one of the major problems of this study.

The *peripheral ring is* the zone of deformation in the annulus directly adjacent to the pluton where the strata have been deformed essentially vertically by the intrusion.

Around hypabyssal plutons there generally is a zone of vertically deformed rocks, the disruption of which is attributable to intrusion. Essentially horizontal deformation may occur on the outer side of the peripheral ring. The criteria, essentially vertical and essentially horizontal deformation, grade into each other locally; hence boundaries may be arbitrary or determined by local conditions. The extent of deformation is a function of the size, viscosity, temperature, and chemical reactivity of the magma, as well as of the arrangement of country-rock stratal separations, competencies, reactivities, and strengths.

Böse (1910) thought that all of the structural complexities around the Cristo Rey pluton resulted from intrusion. Strain (1968a) noted that, "There is a possibility that folding [by] the intrusions may be superimposed on earlier folds related to northeastward thrusting of Cretaceous strata."

The peripheral ring is here defined as the zone around the pluton which consists primarily of quaquaversally dipping strata steeply arched by the intrusion. The peripheral ring may be traversed by other structures which either predated or postdated intrusion. Such structures may complicate the problem of determining the geometry of the peripheral ring, but they did not prevent its development.

South of the andesite, felsite, which is younger than but essentially contemporaneous with the andesite, adds to the width of the original peripheral zone. However, because the region outward from the felsite is covered by younger deposits, the width of the felsite zone is not known. Nowhere is it less than 152 m (500 ft). Between sections 9 and 20 the width of the ring appears to be no less than 152 m (500 ft) and possibly as much as 213-240 m (700-800 ft).

The incomplete data and geomorphic implications of the pattern of alluvial deposits on the annulus suggest that the widest parts of the peripheral ring are on the northeast, north, and northwest. There is narrowing along the eastern end, the significance of which is explained in the section on the Eastern Fault-Fold zone. The ring appears to be wider at the south end of the Eastern Fault-Fold zone and narrower at the west end of the pluton.

The total maximum width of the peripheral ring on the north and south sides added together may be about 670-854 m (2,200-2,800 ft), or about half the width of the exposed pluton (explanatory note 5).

NORTHWESTERN SECTOR OF ANNULUS

From the west end of the pluton, around its north side to the Bowen Gulch fault, is a zone of local complications termed the Northwestern Sector (map I, sheet 1; map IV, sheet 3). Four major semiradial faults—the Bowen Gulch, Access Road, Deep Gulch, and Dry Draw faults—extend outward from the annular Northside fault, which lies within 92 m (300 ft) of the pluton. The Outer fault, the Outer normal and Outer reverse faults, and their westward continuation, the Outer monocline, crop out about 300-450 m (1,0001,500 ft) from the pluton. At the west end of the pluton, the West End fault is adjacent to the pluton.

WEST END FAULT ZONE

At sections 27 and 28 (sheet 3), the Anapra Formation is faulted down on the north against the Muleros

Andesite on the West End fault (explanatory note 6); stratigraphic separation is almost 122 m (400 ft), and dip slip about 213 m (700 ft). At section 31, only 9 m (30 ft) of Muleros is present; the amount of loss of Mesilla Valley is slight and that of Smeltertown is not known. Apparently the West End fault displacement decreases northeastward. At section 32, the beds are vertical to overturned. Between sections 32 and 33 (sheet 3), Mesilla Valley shales are strongly folded with axial surfaces dipping gently south.

The fault has been either intruded or caused by the pluton, because the Mesilla Valley Formation abuts the pluton between sections 28 and 30. Early upward movement of the pluton may have raised the beds, probably producing radial and annular faults; thus, the West End fault probably is an intrusive fault (fig. 4 and explanatory note 7). Later upward plutonic expansion seems to have engulfed part of the West End fault. Between sections 32 and 33 (sheet 3), the West End fault appears to end, but at the west end of the quarry 114 m (375 ft) east of section 32, cascading of the Mesilla Valley off of the pluton (fig. 4) replaced intrusive faulting. Perhaps the combination of decreasing synthetic fault displacement and steepening of the beds by arching over the pluton compensated each other. The West End fault may be the result of trapdoor-like intrusion of the andesite.

NORTHSIDE FAULT

The major Northside fault can be traced along the north side of the pluton eastward from the Railroad Cut plexus to the northeast corner of the pluton. Dips are primarily toward the pluton, ranging from about 50° S. at section 41 and 70° S. at section 2 (map I, sheet 1) to vertical. At section 41, most of the steeply dipping Muleros limestone beds have been cut out by the Northside fault, so that stratigraphic separation here appears to be at least 30 m (100 ft), but dip slip is greater. Stratigraphic separation at sections 33 and 34 is probably equal to almost all of the Muleros, and about 30 m (100 ft) of the Mesilla Valley. Dip slip at sections 33 and 34 is about 76 m (250 ft) (fig. 5).

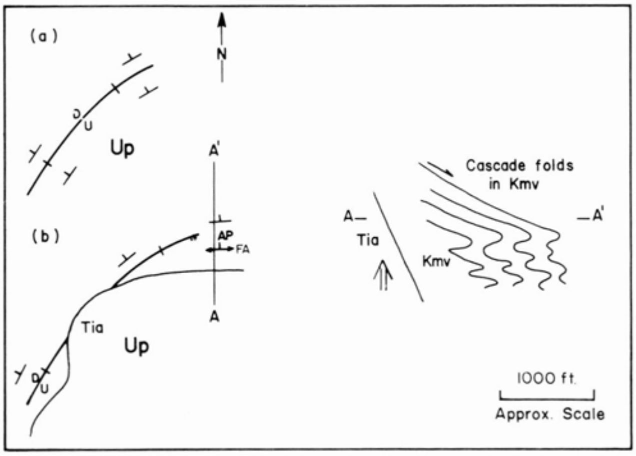

FIGURE 4—West End fault and cascade zone, Cerro de Cristo Rey uplift. Map III, sheet 2; map IV, sheet 3; map VII, sheet 4. This diagrammatic representation of the West End fault shows a) early development, before engulfment of fault by andesite; and b) present structure, after development of West End fault as an intrusive trapdoor fault and engulfment by andesite. Cross section *A-A'* shows how cascading off the andesite replaced trapdoor faulting as a structural response to intrusion.

The anticline 3-9 m (10-30 ft) north of the fault which parallels the Northside fault for its entire length appears to represent normal drag, but also may represent the earliest movement that began along the fault when folding preceded faulting.

BOWEN GULCH STRUCTURAL COMPLEX

In Bowen Gulch at the stream gap through the Anapra sandstone beds is the key to much of the structural evolution of the uplift (fig. 6; photos 5, 6). For purposes of description this structural complex is divided into five blocks, A through E (map VII, sheet 4; fig. 6; photos 5-7).

Block A (map VII, sheet 4; see also map IV, sheet 3) contains a sequence of steeply north-dipping Mesilla Valley, Anapra, and Del Rio Formations. A few minor faults are present in the block. The east side of the block is the Bowen Gulch fault; its north side is the Outer reverse fault.

Block B is a sequence of north-dipping Mesilla Valley, Anapra, and Del Rio Formations. A few small

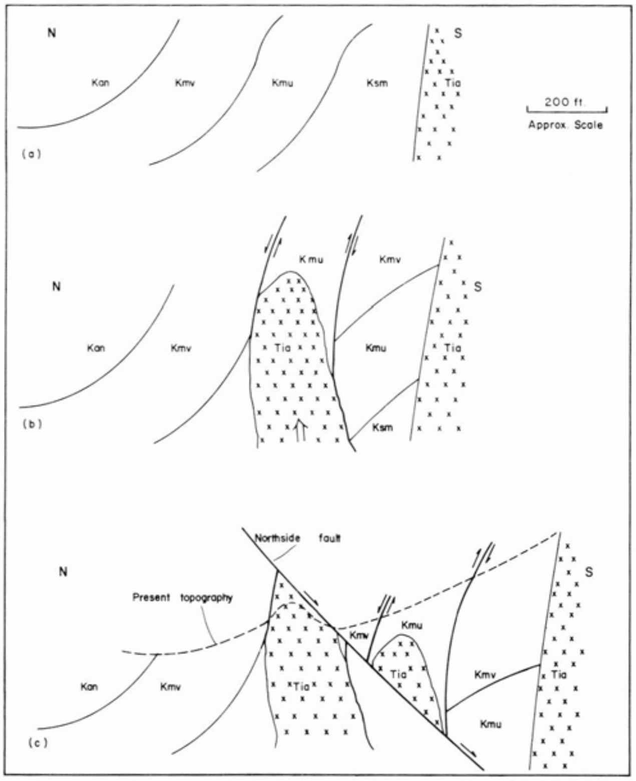

FIGURE 5—Diagram illustrating possible chronological development of structure near Powder House dike, Northwestern sector. Map III, sheet 2; map IV, sheet 3; map VII, sheet 4. Oldest is time (*a*); youngest is time (*c*). At sections 38 and 39 (map IV, sheet 3 and sections; map VII, sheet 4), a slice of Muleros limestone is bounded by faults and the Powder House dike is north of the Northside fault. Forceful intrusion may have raised a block of Muleros limestone. The Northside fault dips 50° S. and its southern block has dropped. The Muleros limestone block at section 39 may be the block of Muleros limestone which first was raised by the Powder House dike now north of the Northside fault, and later downfaulted to its present position south of the Northside fault. Normal dip slip on the Northside fault of at least 76 m (250 ft) would be required to cause this, and is in reasonable agreement with the stratigraphic separation at sections 33 and 34, on a fault dipping 50° S.

faults occur in this block. The west side of the block is the Bowen Gulch fault; the north side is the Outer fault.

Block C is a sequence of Anapra, Del Rio, and Buda Formations in which Buda limestone beds have been folded moderately along fold axes that bear about N. 10-20° W. with shallow plunges and mainly vertical axial surfaces. Block C is bounded on the south side by the Outer normal fault and on the east side by the Bowen Gulch fault.

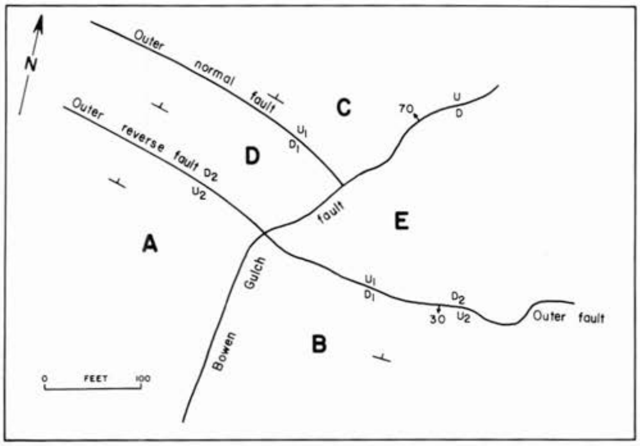

FIGURE 6—STRUCTURAL BLOCKS IN BOWEN GULCH. Fig. 2; map III, sheet 2; map IV, sheet 3; map VII, sheet 4. See text for explanation.

Block D is a sequence of Del Rio and Buda Formations. The Buda limestone beds are very severely folded, with bedding vertical on the south side of the fold, very steeply N. 10° W. plunging fold axes, and steeply southwest-dipping axial surfaces. The block is bounded on the north by the Outer normal fault, on the south by the Outer reverse fault, and on the east by the Bowen Gulch fault.

Block E is a sequence of Anapra and Del Rio Formations. The Anapra sandstone beds have been intensely folded in this block, with fold axes bearing N. 30° W., N. 60° E., N. 30° E., and N. 70° W. Beds in the Anapra Formation cannot be traced easily in block E, but a normal stratigraphic sequence from Del Rio Formation at the northwest side of the block to the lower member of the Anapra at the south side of the block seems probable. The block is bounded on the northwest side by the Bowen Gulch fault, and on the south side by the Outer fault.

North of the Outer normal fault (between sections 6 and 7, sheet 2, map III; see also map I, sheet 1, and map

PHOTO 5—HIGH-OBLIQUE AIRPHOTO OF NORTHWESTERN SECTOR (*courtesy of William S. Strain*). Map III, sheet 2. North toward upper right. Cristo Rey access road (right); Bowen Gulch (lower right); Rio Grande (top). This photo was taken before quarrying operations in Anapra Formation west of access road. Light outcrops are Buda Formation and Del Rio Formation covered by Buda colluvium.

PHOTO 6—Bowen Gulch structural complex. Map III, sheet 2; map IV, sheet 3; map VII, sheet 4; general view. See text for explanation. View is toward northwest.

15 m (50 ft); reverse dip slip is about 30 m (100 ft). South of the Outer normal fault, the Bowen Gulch fault offsets blocks A and B, and may extend to the railroad, although its trace south of the offset Anapra beds is conjectural. Along the Access Road, the Anapra-Mesilla Valley contact has been offset 30 m (100 ft) dextrally (map III, sheet 2). The amount and direction of offset could result from simple reverse movement on a west-dipping reverse fault (although this does not seem to explain all of the offset), or from right-lateral strike slip, a fair amount of which is probable, or from both.

West of the Bowen Gulch fault the Outer normal fault offsets the two Buda outcrops in block D with respect to the Buda in block C. Stratigraphic separation is more than 30 m (100 ft). The Outer fault east of the Bowen Gulch fault dips 30° S., its assumed dip here. Dip slip on the Outer normal fault is about 52 m (170 ft), normal, south side down.

East of the Bowen Gulch fault the Outer fault dips 40° S. Normal stratigraphic separation is nearly the thickness of the Anapra, about 60 m (200 ft). Dip slip is 63 m (210 ft). Intense folds along the Outer fault in this block are far more complex than would be expected along a simple normal fault. Drag folds in the footwall suggest reverse movement, although the overall movement obviously is normal. The fault can be traced west to within 6 m (20 ft) of the Bowen Gulch fault. Its analog west of Bowen Gulch is the Outer normal fault

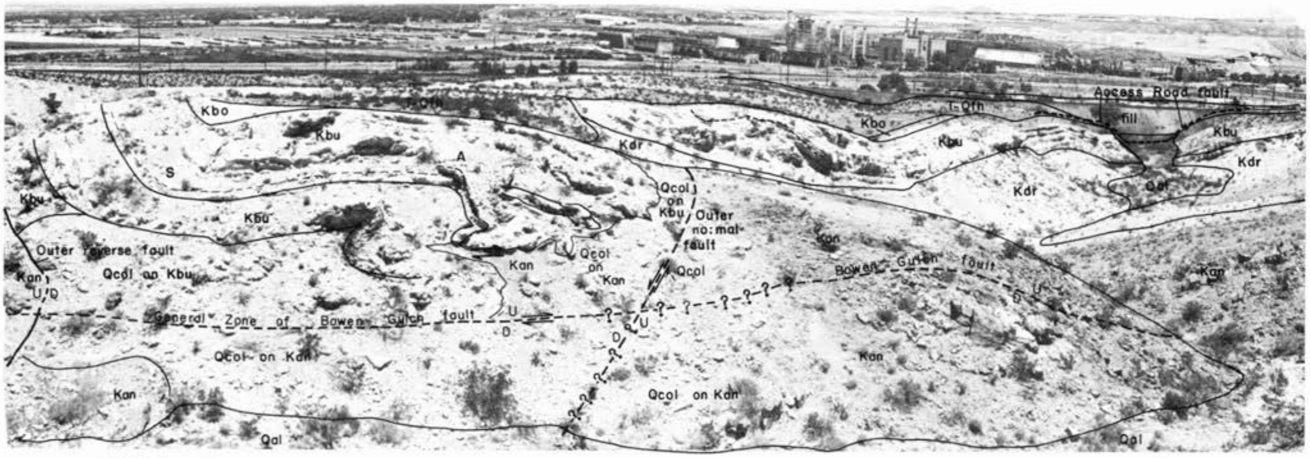

PHOTO 7—Bowen Gulch structural complex. Map III, sheet 2; map IV, sheet 3; map VII, sheet 4; detailed view. See text for explanation. View is toward northwest.

which separates blocks C and D. If this is so, then the Outer fault has been dextrally offset by the younger Bowen Gulch fault. However, the Outer reverse fault west of Bowen Gulch may continue into the Outer fault east of Bowen Gulch. If all of this is interpreted correctly, then the Outer normal and Outer reverse faults west of Bowen Gulch are two structural continuations of the Outer fault east of Bowen Gulch. Thus, major normal movement on the Outer fault preceded lesser reverse movement, and both movements were separated by dextral strike-slip movement on the Bowen Gulch reverse fault (fig. 7).

The folds in the Buda limestone beds at the east end of block D plunge steeply northwest. The folds in the Buda of block C plunge gently northwest. These folds may have been continuous prior to their displacement on the Outer normal fault (fig. 8). Folds in the Anapra sandstone beds of block E which strike northwest may be contemporaneous.

The increase in plunge of the fold axes from block C to block D may have taken place during arching over the intrusion; this is most noticeable in blocks A and B and diminishes northward.

The probable sequence of events which occurred in this complex now appears to be: 1) folding along a N. 10°-20° W. axial trend, 2) arching of the strata over the andesite pluton probably accompanied by 3) normal displacement along the present Outer fault and Outer normal fault, 4) offset of the Outer (and Outer normal) fault by the Bowen Gulch fault, and 5) reverse movement on the Outer (and Outer reverse) fault.

DEEP GULCH STRUCTURAL COMPLEX

The major fault in the Deep Gulch structural complex is the Deep Gulch right-lateral, strike-slip fault which dips 70° W. to 90°, with horizontal slickensides (map VII, sheet 4; map IV, sheet 3). The vertical Anapra-Mesilla Valley contact is offset 30 m (100 ft), but the Buda-Boquillas contact is offset a total of 90 m (300 ft) or 60 m (200 ft) more (explanatory note 8).

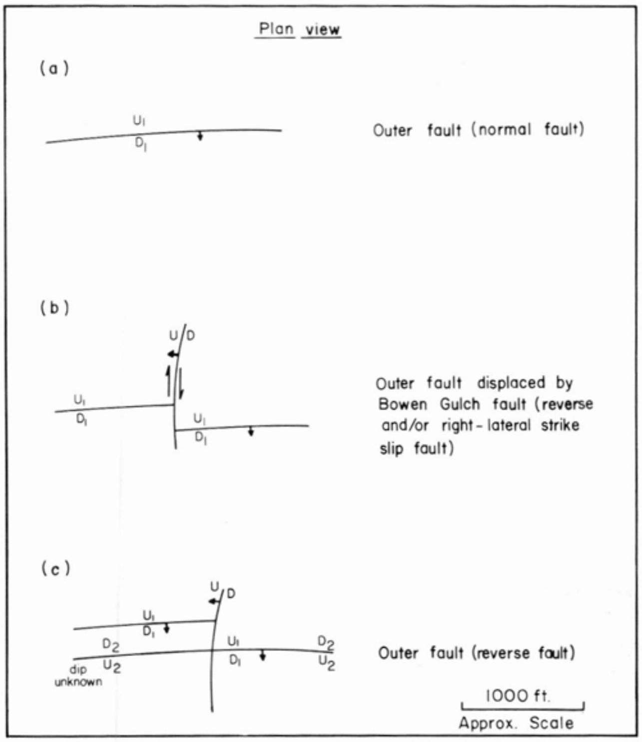

FIGURE 7—SEQUENCE OF DEVELOPMENT OF INTERSECTION OF BOWEN GULCH AND OUTER FAULTS. See text for explanation.

The Outer normal fault extends from the Bowen Gulch fault west to the Deep Gulch fault. West of the Deep Gulch fault it separates two outcrops of Buda limestone beds, but it changes into a structural terrace —the Outer monocline west of Deep Gulch.

The Outer reverse fault continues from Bowen Gulch to the Deep Gulch fault. The nexus of these two faults is complicated in Deep Gulch. West of Deep Gulch the Outer reverse fault appears as F_{11} and F_7; F_9 and F_{10} may also be part of it (map VII, sheet 4).

This interpretation implies that both the Outer normal and Outer reverse faults have been displaced by the Deep Gulch strike-slip fault, which therefore is younger than both the Outer normal and Outer reverse faults, and also slightly younger than the similar Bowen Gulch fault.

The major anticlines in the complex do not strike north; hence they do not appear to be genetically related to the strike slip movement, although the very broad open and poorly defined A2 (map VII, sheet 4) does seem to correspond to a strike-slip-induced fold

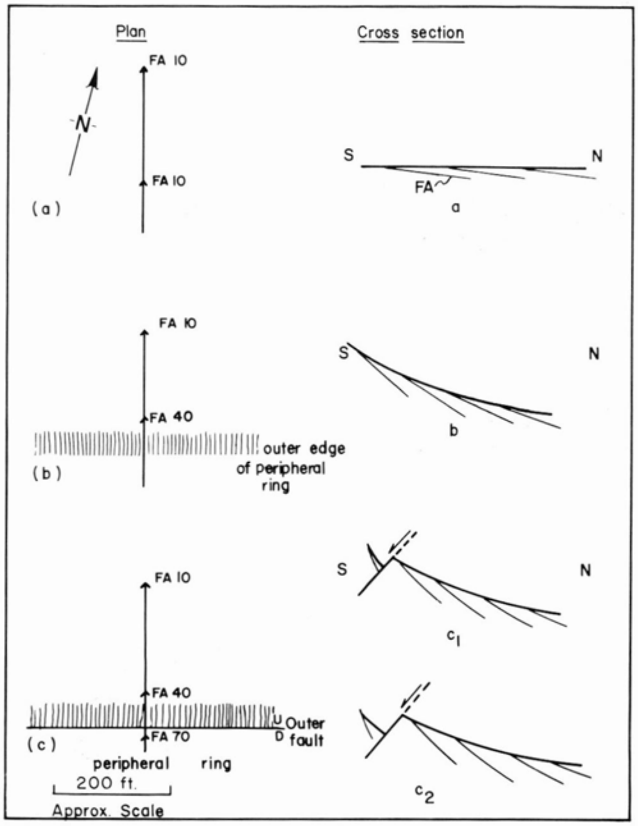

FIGURE 8—PERIPHERAL ARCHING AND FAULTING (OUTER FAULT) OF NORTH-TRENDING FOLD AXES NEAR BOWEN GULCH. a) Preintrusive north-bearing folds on the north side of the pluton near Bowen Gulch plunge gently north; see cross section (*a*). b) Arching produced by intrusion along the outer edge of the peripheral zone increased the northward plunge of fold axes in the southern part of the cross section; see cross section (*b*). c) Faulting on the Outer fault in the peripheral ring displaced the steepened fold axes; see cross section (*c*). Reverse faulting on the Outer reverse fault increased the bed dips to vertical, especially along the Cristo Rey access road west of Bowen Gulch, where the fold axes plunge 70 to 80° N. See text for further discussion.

(Moody and Hill, 1956). However, **A3** is essentially parallel with the Deep Gulch fault and **A4** is parallel with the Outer reverse fault, indicating that compressive stress was exerted normal to the strikes of the Deep Gulch and Outer reverse faults.

West of **F8** there is no evidence of either the Outer normal fault or the Outer reverse fault. The structural terrace on the Outer monocline is an apparent westward extension of the Outer normal fault.

DRY DRAW STRUCTURAL COMPLEX

Dry Draw is along the northern railroad tracks 640 m (2,100 ft) west of the Cristo Rey Access Road (map I, sheet 1; map III, sheet 2; map IV, sheet 3; map VII, sheet 4). North of the tracks vertical Buda limestone beds have been offset right laterally about 60 m (200 ft) by the vertical Dry Draw fault (photo 8 and explanatory note 9). (This outcrop was destroyed in 1976.)

West of the north end of the Dry Draw fault, the Anapra forms an anticline with a vertical fold axis, and a vertical axial surface parallel with the fault (the Anapra outcrop here was destroyed in May, 1973). The amount of strike-slip, about 60 m (200 ft), probably could not cause the Anapra to be folded with a vertical fold axis. The steep dip of the Buda-Del Rio-Anapra sequence presumably was acquired before right-lateral strike-slip movement took place on the Dry Draw fault. Analogy among the Dry Draw, Deep Gulch, and Bowen Gulch faults also suggests that the (younger) Dry Draw fault cut the (older) Outer monocline.

The Dry Draw syncline, east of the Dry Draw fault, parallels the fault between the two railroad tracks. Its axis plunges 70° NE. at the Outer monocline, but more gently farther south. This syncline records compression normal to the Dry Draw fault. The plunge of the axis also indicates that it formed before the Outer monocline. Thus, there were both right-lateral strike-slip movement and eastward compression.

East of the Dry Draw fault abundant subhorizontal to low-plunging bedding plane slickensides (bearing is N. 60° E.) in the Anapra sandstone beds indicate pervasive slippage in the steeply dipping beds of the Outer monocline. The slickensides bear at a high angle to the bearing of the Dry Draw syncline and suggest that both formed within the same stress field. The vertical dip of the Dry Draw fault is not compatible with east-west compression, but is compatible with right-lateral strike-slip movement.

Mapping of the trace of the Dry Draw fault near the southern railroad tracks is based on locations of mesquite bushes on the slope, on color patterns on colluvial slopes, on slope wash material as viewed at many different times of year and day, and on aerial photo interpretation of stereoscopic pairs. The northwest strikes of Mesilla Valley shales in the Railroad Cut plexus (map III, sheet 2; cross section 33 on sheet 3) also suggest that the Dry Draw fault may extend this far south. Displacement south of the northern railroad tracks is unknown. The Dry Draw fault seems to end at the Northside fault.

ACCESS **ROAD FAULT**

The Access Road fault, with strike N. 30° E., dip 60° SE. and relative movement down on the northwest, but with horizontal slickensides (suggesting right-lateral movement), crops out on the east side of Bowen Gulch south of the northern railroad between sections 6 and 7 (map III, sheet 2). It may be connected with a fault west of Bowen Gulch with similar strike and relative displacement. This fault probably continues southwest beneath the Fort Hancock strata near the access road and may emerge near $\mathbf{F}_{17}$ which has a similar sense of movement (map VII, sheet 4). The strike of the Access Road fault is the same as that of the Bowen Gulch and Deep Gulch faults. Slickensides indicate some strike-slip movement. Relative dip-slip movement is down on the west along the Access Road fault.

FOLDS

In the Northwestern sector north-trending preintrusive folds possibly later became associated with synintrusive faults (map VII, sheet 4; explanatory note 10).

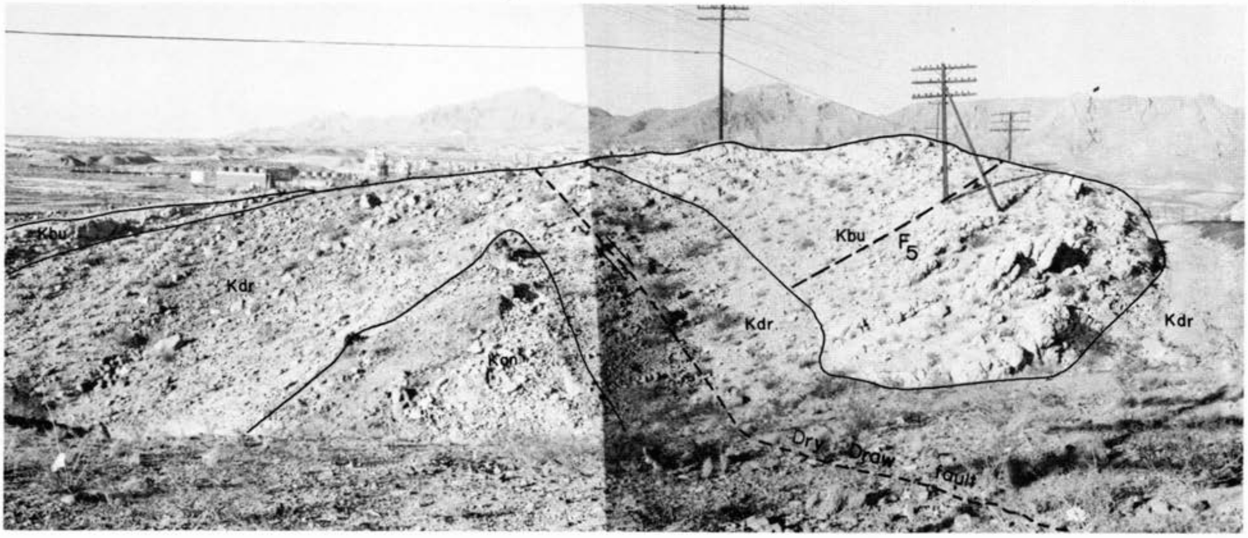

PHOTO 8—NORTH END OF DRY DRAW FAULT. Map III, sheet 2. View north-northeast. The fold axis in the Anapra Formation plunges vertically. Buda Formation of the Outer monocline parallels the northern railroad track (right). The Outer monocline has been right laterally offset by Dry Draw fault. Fault F_5 has duplicated Buda Formation limestone beds east of Dry Draw fault, but not west of it. Therefore F_5 is probably related to Dry Draw fault. See text for further discussion. This entire outcrop area has been quarried out as of June, 1976.

S_1 and **A2** trend northerly. S_1 may be either cogenetic with, or may have guided, the Dry Draw fault. **A2** is not associated with any fault. **A3** fold axes may trend more northerly, for the strata in its eastern flank are vertical adjacent to the Deep Gulch fault; the trace of **A3** is projected from a hillside, so that its true configuration is not accurate on the map.

The small folds at the north ends of sections 37 and 38 (sheet 3) and the very open syncline in the Buda at the north end of section 39 strike north. East of the access road in block C between sections 39 and 40 the folds trend N. 10°-20° W. In the Buda at the east end of block D between sections 39 and 40, the north-trending folds have steep north plunges, apparently the result of arching of the peripheral ring by emplacement of the pluton. These folds seem to be the southern continuation of the folds in the Buda limestone beds in block C northeast of the north end of section 39. If true, this interpretation suggests that the folds are preintrusive. The folds are locally coextensive with minor west-dipping thrust faults. Perhaps the Dry Draw, Deep Gulch, and Bowen Gulch faults originally were preintrusive reverse faults associated with preintrusive folds. Subsequently both were deformed by the intrusion and were reactivated by intrusive-induced stresses.

ANALYSIS OF STRUCTURE

The Bowen Gulch, Deep Gulch, and Dry Draw faults have some remarkable similarities. 1) All offsets of the Outer fault-monocline zone are right lateral. 2) All three fault zones have folds whose axes parallel the faults. 3) Northward-directed thrusts on the west side of each fault suggest that right-lateral movement is the result of absolute northward movement of the western block. 4) None of the right-lateral faults extend to the pluton; displacements seem to cease at the Northside fault. 5) Outward movement seems to have proceeded from east (Bowen Gulch fault) to west (Dry Draw fault).

South of the belt of Anapra sandstone outcrop, the trace of the three strike-slip faults is inferred in the Mesilla Valley shales, where it is impossible to trace them. The Deep Gulch fault may turn more southerly and parallel section 8. There is no evidence indicating where the southern extension of the Bowen Gulch fault might be, although it could extend toward the southeast end of the Powder House dike, or toward a point where the pluton contact is offset 90 m (300 ft) west of section 7. If so, emplacement of the Powder House dike might be related to the Bowen Gulch fault. Although this fault apparently formed before the dike, perhaps room for the dike was made early in the uplift by movement on the Bowen Gulch fault.

Right-lateral movements on the Dry Draw and Deep Gulch faults do not seem to have resulted from outward pressure associated with pluton emplacement if the geometry as shown on the maps is correct.

The Outer normal fault-Outer monocline zone may be the outermost zone of major deformation attributable to pluton emplacement. The Outer normal fault dips 30° S., dip slip, with decreasing stratigraphic separations westward: 60 m (200 ft) at section 40, 46 m (150 ft) at section 38, and 30 m (100 ft) at section 36.

Cockwise couples are present at the north ends of the Dry Draw and Deep Gulch faults as evidenced by local duplications of Buda limestone beds in **E_5** in the Dry Draw fault complex, on **F7b** in the Deep Gulch fault complex, and the vertical fold axis in the Anapra sandstone beds at the north end of Dry Draw fault.

This combination of clockwise rotation and normal compressive stress along the three semiradial faults does not accord well with simple upward or outward expansive forces associated with emplacement of the early sill or the mature pluton. Possibly the forces which earlier had formed the north-trending folds in the Buda limestone beds of the Bowen Gulch structural complex may have continued to act through the period of pluton emplacement and caused this clockwise rotation and compressive stress normal to the radial faults. If so, then the pluton may be a synorogenic-intrusive of this tectonic period. The trends of the three faults are subparallel with the directions of fault in the Basin and Range province, Rio Grande trench, and southern Franklin Mountains. However, **A3,** which parallels the Deep Gulch fault, also is parallel with that same direction. Certainly, east-west compression is not consistent with the concept of a genetic association of these structures north of the pluton with formation of the N. 30°-40° W. fold trends in the Chihuahua tectonic belt. Nevertheless the close association of preintrusive folds with synintrusive faults suggests some overall structural control and syngenesis.

The preceding evidence and analysis suggest the following sequence of structural phases in the Northwestern sector (fig. 9): 1) a period of compression which produced folds trending now N. 20° W. to N. 30° E. but perhaps originally more northerly; such compression may have continued through the period of magma emplacement (fig. 9a); 2) arching of the peripheral zone accompanied by low-angle normal faulting along the Outer (normal) fault (fig. 9b); possibly A (see following paragraph) took place at this time; 3) right-lateral movement with a reverse component on the Bowen Gulch fault which offset steeply dipping strata already arched (fig. 9c); 4) reverse-fault movement on the Outer reverse fault, and on the Outer fault east of the Bowen Gulch fault (fig. 9d); possibly followed shortly by B (below); and 5) right-lateral movement on the Deep Gulch fault (fig. 9e), and possibly later on the Dry Draw fault (fig. 9f) as well, possibly followed by C (below).

Several other events cannot be accurately correlated by crosscutting relations with the above sequence. A) The West End fault formed, probably by trapdoor uplift of the pluton (fig. 4a), including late engulfment of the fault by the rising pluton (fig. 4b). Cascading folds in the Mesilla Valley shales at the east end of this fault suggest that the fault preceded uplift of the beds around the pluton. Hence, this fault may have formed during the second arching phase discussed in the preceding paragraph. B) The Powder House and Quarry dikes were emplaced. C) Major vertical to normal faulting took place on the Northside fault, which probably displaced the mass of Muleros limestone beds that may have earlier been upthrust by intrusion of the Powder House dike (fig. 5c). This normal faulting, which dropped a section of mostly Mesilla Valley shale (with bedding approximately parallel with the andesite contact) probably occurred very late in the sequence of

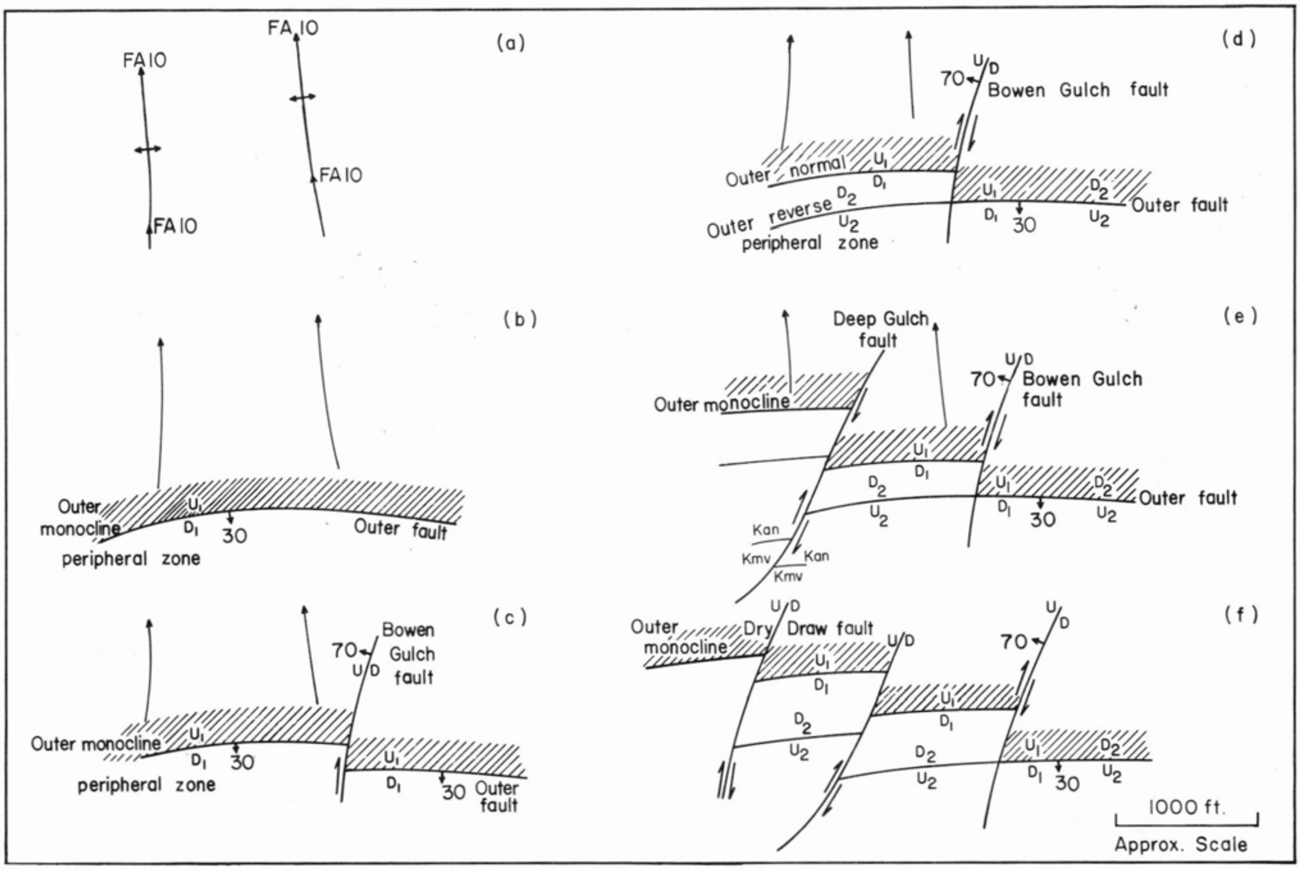

FIGURE 9—Sequence of development of fault structure along Outer fault in Northwestern sector. See text for explanation.

intrusion, as is shown in the sections on the Eastern Fault-Fold zone and the felsite zone.

The Dry Draw, Deep Gulch, Access Road, and Bowen Gulch faults are right-lateral shears. They form an angle of about 40°-45° with the strike of the Carousel thrust fault. Possibly they represent one of two sets of conjugate shears associated with the Carousel thrust fault (map III, sheet 2; map VII, sheet 4). The other set of conjugate shears would be oriented about N. 50° W., which is very nearly the direction of the Texas lineament. Such N. 50° W. shears would be expected to have a left-lateral sense of rotation. No strike-slip faults with this orientation have been found at Cristo Rey.

RAILROAD CUT PLEXUS

The structure along and south of the eastbound railroad between sections 7 and 9, and especially in the vicinity of section 8, is very confusing. Vertically dipping upper Muleros limestone beds crop out on the south wall of the railroad cut at section 8. Vertically dipping lower Muleros limestone beds crop out high on the slope near the pluton above the cut. Between the vertical lower limestone beds and the vertical upper limestone beds, the beds exposed on the slope appear to be strata of the middle member of the Muleros; however, the total thickness of the formation normal to the bedding in this area is much greater than usual for the Muleros Formation, and the beds which appear to be part of the middle member also may include some beds of the Mesilla Valley Formation. The exposures are poor; the two formations have similar lithologies and fossils; and the degree of deformation precludes following distinguishable sequences far enough along strike to identify the formations with certainty. Although the strata are given identifying names on the plane-table map, there are questions of identification, and the structural problem here is not yet solved.

The Northside fault extends east of section 8 as far as the signal light 107 m (350 ft) west of section 8, but probably no farther (map III, sheet 2). This is where the Dry Draw and Deep Gulch faults may extend. This complex zone is called here the Railroad Cut plexus. The rising pluton produced the intrusive West End fault west of here. At the east end of the West End fault, the Mesilla Valley and Muleros Formation beds are essentially vertical. If the Northside fault also is vertical, even a large dip-slip component on the fault would not be manifest in the stratigraphic section. However, west of section 9, the Mesilla Valley and Anapra Formations dip 20-50° NW., and there does not seem to be any place where the Northside fault can be traced through these gently dipping strata. Thus, the Northside fault may terminate between section 8 and 9, and probably at the Railroad Cut plexus, where the Northside, Deep Gulch, and Dry Draw faults seem to converge. The West End fault also seems to terminate in the Railroad Cut plexus.

The significance of this plexus is not known. The intrusion produced trapdoor faults along the west side of the pluton. Late-stage faulting on the Northside fault probably took place near the end of magmatism. Possibly there was some down-on-the-pluton-side faulting along the West End fault during the latest stage of magmatism, and some up-on-the-pluton-side faulting along the Northside fault during the early stages of magmatism. There is no evidence for either of these types of movements.

NORTHEASTERN SECTOR

Eastward from the Bowen Gulch fault to the Rio Grande is a zone of folding and thrusting which contains structures with significant regional implications (map I, sheet 1; map H, sheet 2; fig. 10). The principal structure adjacent to the pluton is the Fold zone. Merging with the Fold zone at section 4 is the Aqueduct anticline. The Outer fault crosses the Aqueduct anticline. The Power Line syncline is northeast of the Aqueduct anticline. The east flank of the Power Line syncline is the west flank of the Brick Plant anticline. The Carousel thrust fault, conjectural south of section 5, follows the west flank of the Power Line syncline.

The exposed Fold zone adjacent to the pluton east of the Cristo Rey access road is in the Mesilla Valley and Muleros Formations (photos 9-11). It extends west of the access road, but the intensity of folding decreases west of the Powder House dike adjacent to the pluton. Near sections 2 to 4 the Muleros limestone has been folded into very tight, in some places chevron, folds (photo 9). Apparently these tight folds formed above a decoupling surface in the Del Norte-Smeltertown sequence, but there is no Smeltertown shale visible in the tight cores of the folds. The Northside fault continues along the north side of the pluton. On the south side of this fault, steeply dipping to vertical and very contorted Mesilla Valley beds (photo 12) are downdropped an unknown but substantial distance (photo 9). The fault dips 90° at section 3.

The Aqueduct anticline at section 1 extends N. 25° W. and curves to N. 13° W. to a point where it disappears beneath the Fort Hancock deposits. The fold is very tight in the Muleros limestones, but the tightness of folding decreases both away from the pluton and at higher stratigraphic levels. This implies that folding may have been a response to decoupling from an interface at depth, produced by the intrusion. The Aqueduct anticline and Power Line syncline are essentially parallel. The age relation between the folds and the Outer fault is not known (explanatory note 11).

Along the west flank of the Power Line syncline there is no proof of the presence of the Outer fault. If the Outer fault continues between sections 1 and 5, it must pass west or east of the Power Line syncline. If the fault follows the eastern limb of the syncline, the dip of the fault parallels the dip of the strata and its trace would be very difficult to find. If the fault follows the west limb of the syncline, where there are few good exposures, its trace is now lost in the quarry area.

The Carousel thrust fault cannot be traced southeast of section 5 (photo 10). Perhaps it dies out adjacent to the zone of gravity gliding in the Power Line syncline and extends no farther south than section 5 (explanatory note 12).

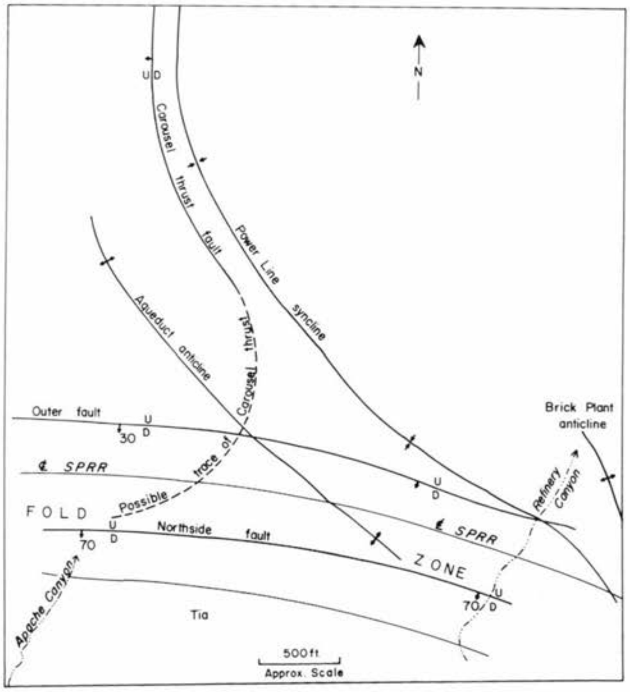

FIGURE 10—DIAGRAMMATIC MAP OF MAJOR STRUCTURES IN NORTHEASTERN SECTOR. See also map III, sheet 2.

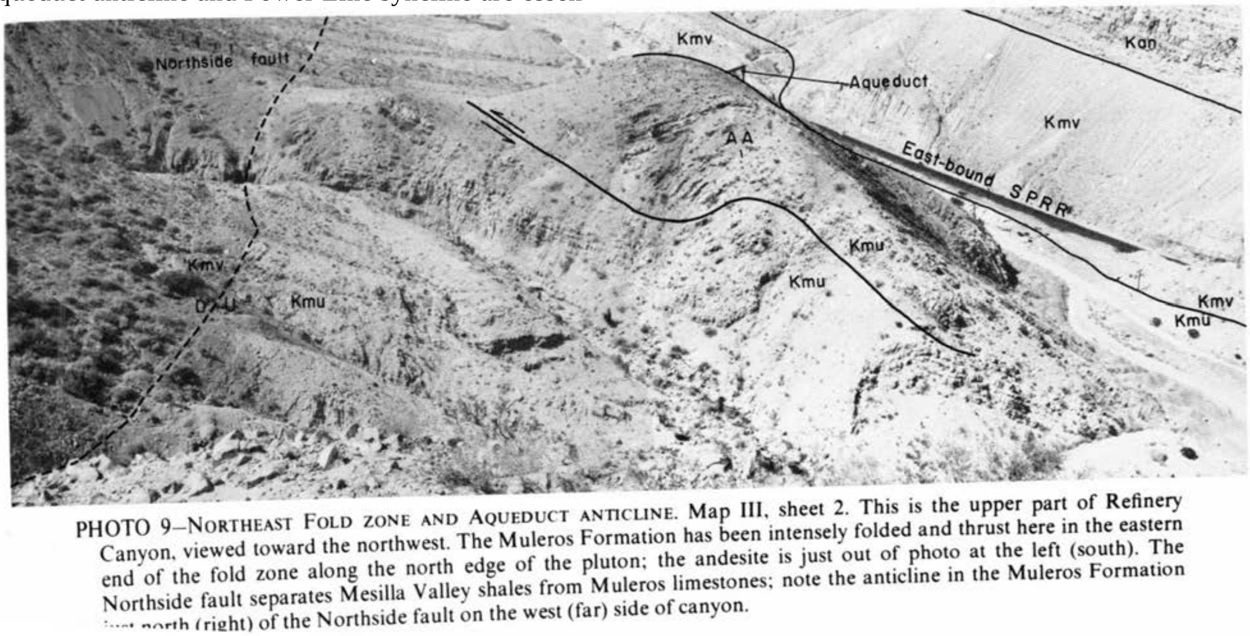

PHOTO 9—NORTHEAST FOLD ZONE AND AQUEDUCT ANTICLINE. Map III, sheet 2. This is the upper part of Refinery Canyon, viewed toward the northwest. The Muleros Formation has been intensely folded and thrust here in the eastern end of the fold zone along the north edge of the pluton; the andesite is just out of photo at the left (south). The Northside fault separates Mesilla Valley shales from Muleros limestones; note the anticline in the Muleros Formation just north (right) of the Northside fault on the west (far) side of canyon.

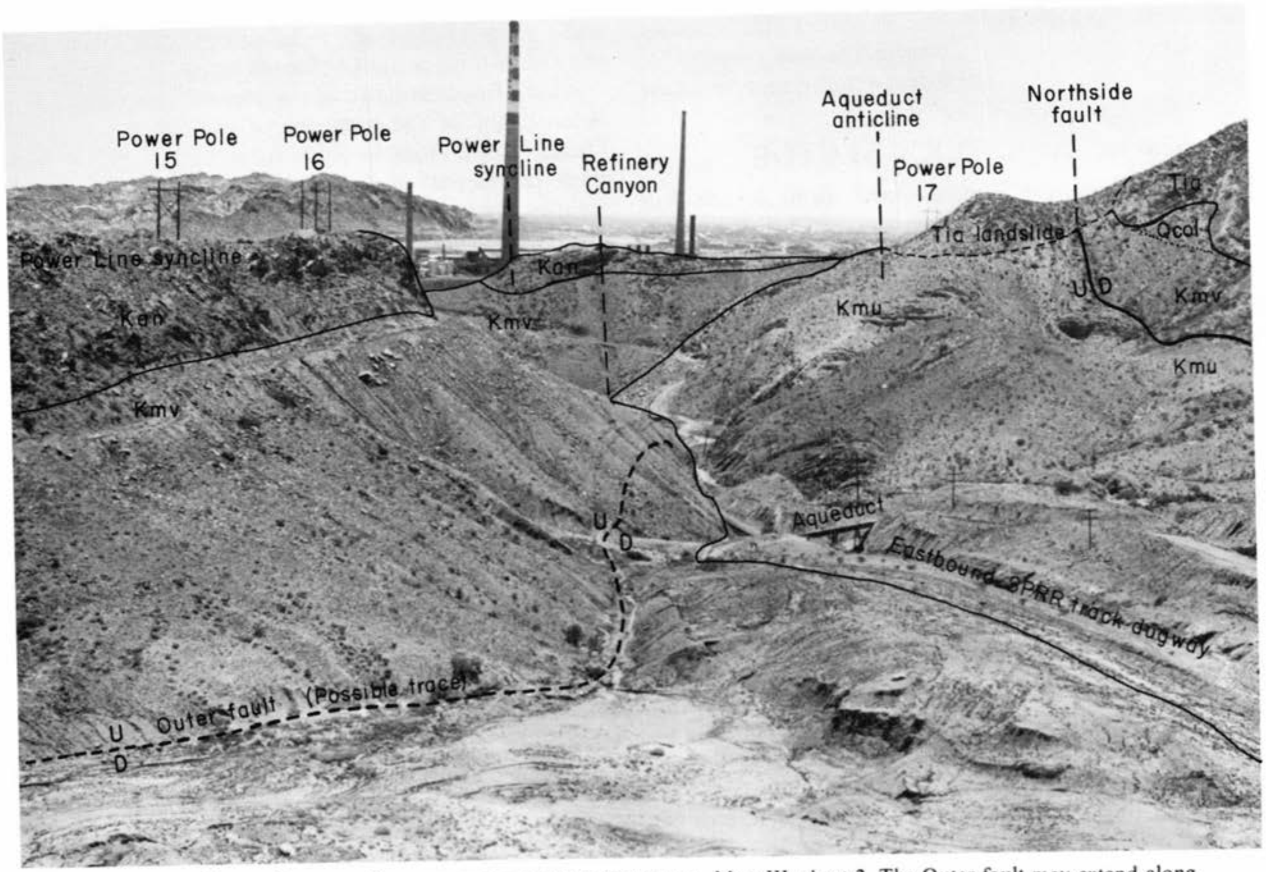

PHOTO 10—UPPER REFINERY CANYON, VIEW TOWARD SOUTHEAST. Map III, sheet 2. The Outer fault may extend along west side of the Power Line syncline as shown by dashed line. The fault may extend across the railroad track and continue southeast toward right-hand smokestack on west side of the Power Line syncline southeast of Refinery Canyon, or toward higher smokestack, through the Power Line syncline emerging from west (right) flank of the syncline, to east flank of the syncline southeast of Refinery Canyon, thereby accounting for erosional development of the canyon through Power Line syncline.

POWER LINE SYNCLINE

The Power Line syncline is an important structure in the Cristo Rey uplift because of its bearing on the relation of the uplift to regional tectonics (map V, sheet 3; map VIII, sheet 4; cross section X, sheet 5). This fact was recognized by Bose 1910 (explanatory note 13).

The "ligero sinclinal" which Böse regarded with suspicion is the Power Line syncline. Böse thought that the pluton formed the syncline.

From the north edge of the map (map I, sheet 1), the Power Line syncline extends S. 11° E., parallel with the Rio Grande, about 300 m (1,000 ft) to section 6, where it changes strike to S. 50° E. under the power line. Near the power pole 11 the syncline again changes strike to S. 32° E. and continues through a quarried zone where its axial *trace cannot be followed (north end of map V, sheet 3; and map VIII, sheet 4). At section 5, the structure becomes complex in the Gravity Glide zone (photos 13, 14). The structure of the syncline remains complex to the south end of Power Line Ridge. The syncline continues southeast across Refinery Canyon and beyond the southern railroad tracks into the Eastern Fault-Fold zone (EFFZ) or "la zona de fracturamiento" of Bose (1910) (see discussion on Eastern Fault-Fold zone).

The Power Line syncline plunges gently north. At the north end of the syncline, the top of the Buda is at river level, elevation 1,140 m (3,740 ft). At sections 5 and 45, the Del Rio-Anapra contact is at an elevation of 1,210 m (3,970 ft). This is a rise of 70 m (230 ft) in about 854 m (2,800 ft) or about 9 percent. However, a small cross monocline near power pole 11 between sections 5 and 6 raises the syncline more steeply than is usual where the trace of the syncline bends. The two changes are spatially and perhaps genetically related, and may indicate where the trend of the syncline was changed by the intrusion. Perhaps early andesite sill injection extended here, and later pluton enlargement and uplift deformed the syncline.

Between section 3 and 5 the structure of the Power Line syncline is very complex. This zone has been separately mapped (map V, sheet 3) as the Gravity Glide zone (explanatory note 14). North of section 6 the syncline is closely bounded on the west by the Carousel thrust fault, with Anapra up on the west on overturned Buda for a minimum stratigraphic separation of 24 m (80 ft) and a dip slip of at least 27 m (90 ft). The thrust and syncline are coextensive. North of section 6 the syncline seems to be a drag fold beneath the thrust. The thrust can be traced with difficulty through the Anapra sandstone as far south as section 5, beyond which it cannot be found in the quarried area. The close spatial association of the thrust and syncline north of section 5 suggests that the thrust trace may parallel the synclinal axis south of 5.

Along the western side of the area of map VIII is shown the interpreted location of the possible Outer fault (see also photo 14), which was traced to a point near the north end of the area of man v. The possible

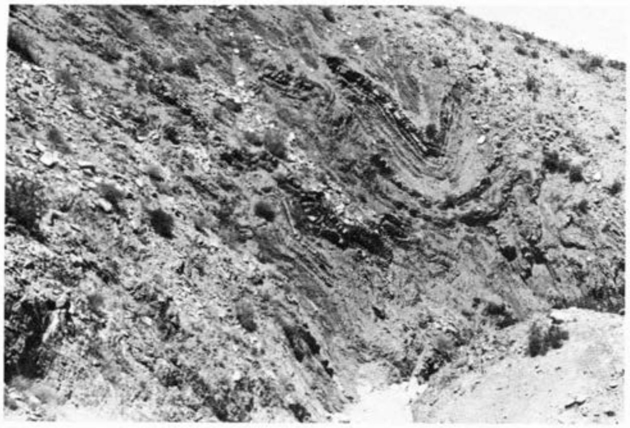

PHOTO 12—MESILLA VALLEY FOLDS IN ANDESITE CONTACT ZONE EAST OF APACHE CANYON. Map III, sheet 2. This is one of the most easily reached good exposures of the andesite contact zone at Cristo Rey, about 182 m (600 ft) east of entrance to Apache Canyon, in which some of the most spectacular folds of the uplift can readily be seen. View is toward the west-northwest. Note that axial planes dip steeply north and south, as well as vertically, and that all fold axes are very gently plunging. Andesite contact is just out of view at left. Mesilla Valley shale, limestone, and siltstone have been contact metamorphosed to hornfels, epidote-bearing marble, and quartzite, respectively, in area on the left (south) of photo.

Mesilla Valley-Muleros contact at sections 48 to 54 (map VIII, sheet 4; sheet 5, cross section 8) suggests that a fault, west side down, may be present in the Mesilla Valley shale on the west slope of Power Line Ridge.

The Carousel thrust fault may extend at least to the small pass at the southwest end of section 42. The thrust may pass through the low valley, now mined out, between Power Line Ridge and the Anapra sandstone beds on the Aqueduct anticline. The trace of the thrust might be in the shale beneath the Anapra sandstone beds in the Aqueduct anticline, rather than along the base of Power Line Ridge. Therefore, if the Carousel thrust does extend this far south, its trace might cross the railroad track where the greatly thickened Mesilla Valley shale is exposed and disappear near Apache Canyon.

The evidence suggests that gravity gliding in the Power Line syncline occurred after formation of the syncline, and probably as the result of the pluton emplacement (explanatory note 15). It further implies that there must have been less of an overburden northeast of the gravity glide then on the southwest, because the landslide had to emerge at the surface toward the northeast. If gravity gliding took place during maximum pluton emplacement, then maximum pluton emplacement was later than the period of *inception* of the N. 15° W. folding of the Power Line syncline and Brick Plant anticline.

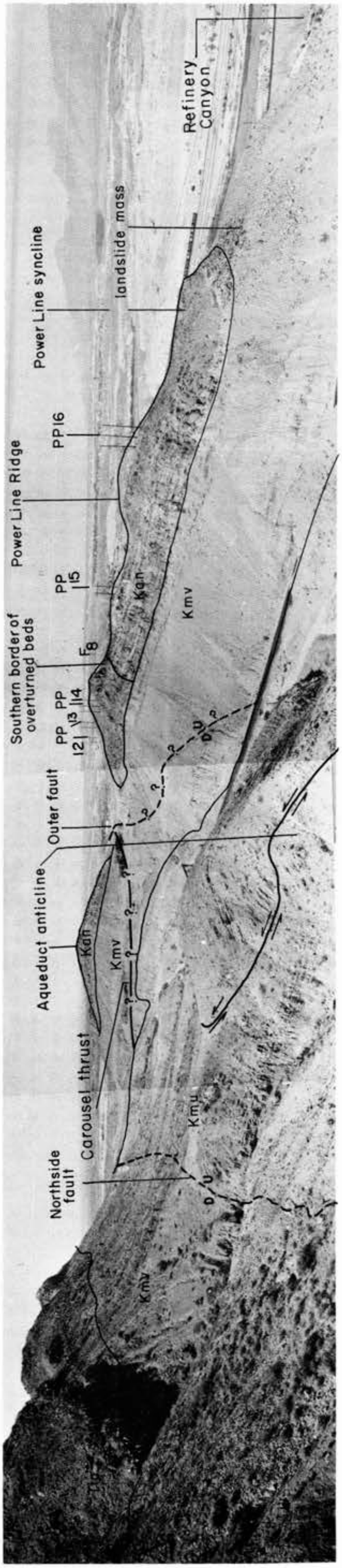

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PHOTO 11—UPPER REFINERY CANYON, VIEW TOWARD NORTHWEST. Map III, sheet 2. This is higher than the view in photo 9, showing northwesterly trends of the Aqueduct anticline and Power Line syncline; hills on the horizon above power pole 14 are the Three Sisters andesite intrusions. N. 20° W. from this point of view the Gravity-Glide region of the Power Line syncline ends between power poles 14 and 15, but there may have been similar gravity-glide faulting at a higher stratigraphic level than that now preserved in the syncline; thus structure in the gravity glide might have allowed development of Refinery Canyon through Power Line Ridge. The dashed line is the trace of the Carousel thrust fault which is beneath the Aqueduct anticline north of railroad.

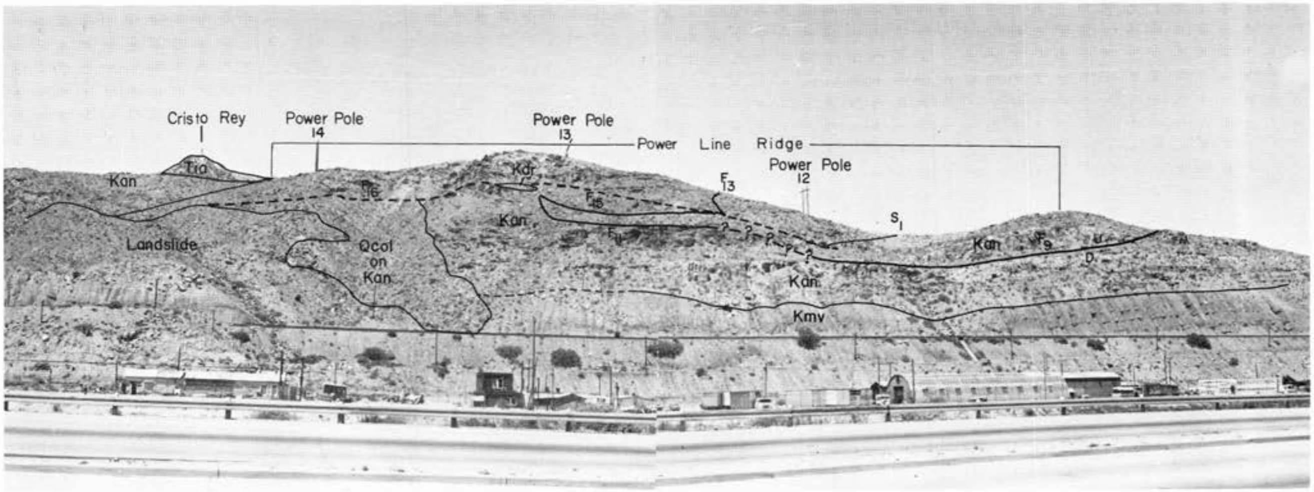

PHOTO 13—East side of Gravity-Glide region, Power Line syncline. Map III, sheet 2; map V, sheet 3; map VIII, sheet 4. View toward the west from the highway through El Paso del Rio del Norte. Landslide and colluvial materials cover east flank of the Power Line syncline along south end of the Power Line Ridge. The small amount of Del Rio just below power pole 13 was important in deciphering the structure in Gravity Glide, because Mesilla Valley-Anapra contact could not be observed south (left) of that point. See text for explanation of structure.

If the Outer fault does extend along the Power Line syncline, it may be associated with a structure which masks its presence. One possibility is that the Outer fault cuts the gravity glide fault complex F_1-E_2 and continues across the Power Line syncline near power pole 14 and merges with Fc (map IX, sheet 4; fig. 11; photo 15). It is also possible that the Outer fault extends along the west side of the syncline beneath the colluvium and fill (sheet 5, cross sections X).

EASTERN FAULT-FOLD ZONE

Along the east side of the pluton, the Cretaceous strata have been completely overturned, folded, and faulted in the Eastern Fault-Fold zone (EFFZ) (map I, sheet 1; map VI, sheet 3; map IX, sheet 4; cross sections XI, sheet 5).

Between sections 62 and 81 (map IX) on the east side is the Border monocline, which is also the western flank of the Brick Plant anticline. The western boundary of the Border monocline is the Outer fault, F_1. West of F_1 is the Interior Complex belt. The western boundary of the Interior Complex belt is the Inner fault, F_4. West of F_4 is the west half of syncline S_4. The pluton is west of S_4.

North of section 62 the Border monocline merges with the eastern flank of the Power Line syncline, S_i, which is right laterally offset by the transverse Clay Pit cross fault F_e. The western flank of S_1 is cut by F_h which is probably the continuation of the Northside fault.

Structural complexity decreases south of section 81, where the principal structures include A_3, F_1, and F_4, and the west half of S_4.

At the north end of the EFFZ, S_1 extends north from section 56 across Refinery Canyon to Power Line Ridge

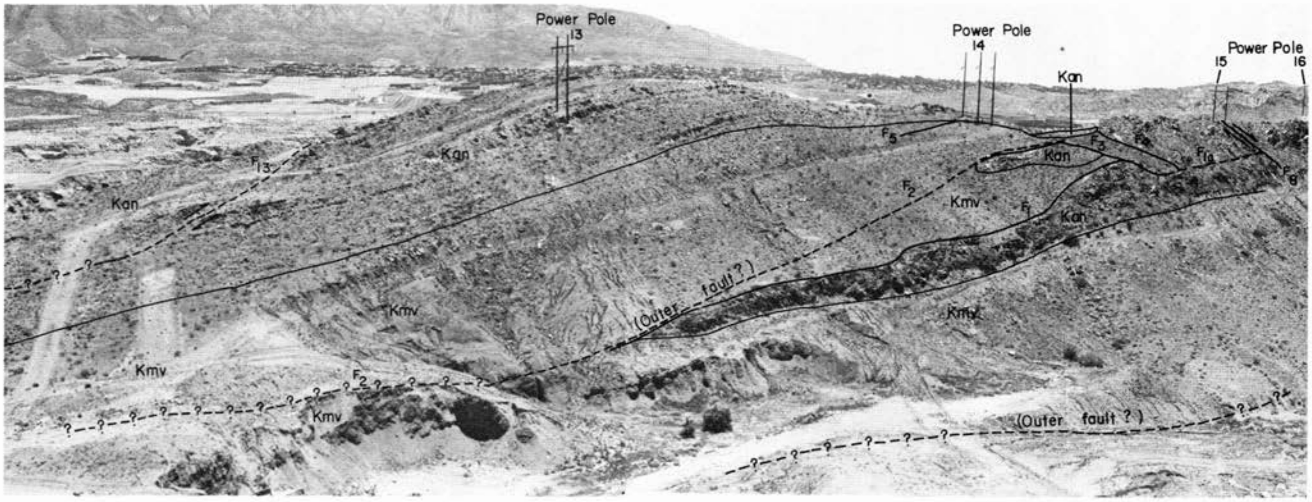

PHOTO 14—West side of Gravity-Glide region, Power Line syncline. Map III, sheet 2; map V, sheet 3; map VIII, sheet 4. Two possible traces of Outer fault are shown. A third possible trace might include F_{13}, which has a relative displacement down on the south (right). F_8 represents a major tear fault in slide; north of F_8 (left) the Anapra beds are vertical to overturned; south of F_8 (right) the Anapra beds dip gently northeast to form a simple syncline. There are abundant flat slickensides along F_1. However, the sharp contact between Mesilla Valley and Anapra beds suggests that F_1 might not be a flat fault, but might have fairly steep dip. Stucture here is not yet completely understood; future quarrying operations might expose critical information. See text for explanation.

(photo 15). The trace of the axial surface north of section 56 is buried by colluvium, which covers the Mesilla Valley shales.

F_c (explanatory note 16) has been traced (map I, sheet 1) to Refinery Canyon near the northern railroad tracks, where it disappears under alluvium, to emerge by the westbound railroad tracks about 60 m (200 ft) southeast of section 3; there the lower Muleros is opposite the limestone member of the Smeltertown. It disappears near section 57 on the south under colluvium and road spill, but in the railroad cut is well exposed. Muleros limestone is down on the west with respect to Smeltertown shale. Stratigraphic separation is equal to the upper three members of the Smeltertown, about 27 m (90 ft), but slip is greater. Although displacement is obviously normal, very tight drag folds indicate that reverse movement followed normal. The amounts of the two separate types of slip have not been determined; drag indicates substantial reverse displacement, and at least 10 m (33 ft) of reverse movement is probable. This is similar to the sequence of events on the Outer fault at Bowen Gulch. Thus, the Outer fault and F_c may be part of a circumferential (to the pluton) normal fault which has had late reverse movement.

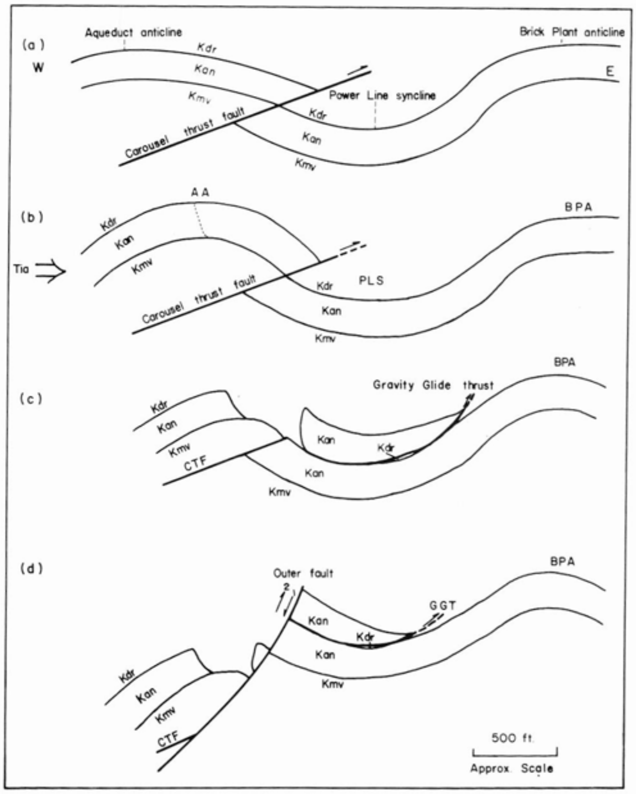

FIGURE 11—POSSIBLE MECHANISM AND SEQUENCE OF DEVELOPMENT OF GRAVITY GLIDE, POWER LINE SYNCLINE. Map III, sheet 2; map V, sheet 3; map VIII, sheet 4. a) In this interpretation, the Carousel thrust fault is associated genetically with the Aqueduct anticline and Power Line syncline. The folds may be drag associated with the thrust. The Carousel thrust formed with the folds, juxtaposing beds of different competence. The Del Rio-Anapra contact is opposite the Anapra-Mesilla Valley contact. The thrust is assumed to have developed before andesite intrusion. b) During andesite intrusion, the intensity of folding increased. Erosion of the Brick Plant anticline may have removed restraint for gravity gliding along the Anapra-Del Rio contact. c) Gravity gliding may have taken place after the Anapra broke near the crest of the Aqueduct anticline. There may have been movement from higher elevations, perhaps associated with the andesite intrusion. d) Subsequent low-angle normal faulting may have taken place along the Outer normal fault. The Outer fault may lie along the eastern flank of the Power Line syncline. If true, the fault parallels the beds, and large dip slip would result in only small stratigraphic separation, most of the fault is now covered by landslide debris and colluvium.

At section 56 on the east flank of S_1 the Mesilla Valley Formation is thinner than elsewhere; hence the presence of **Fd** at 56 (map IX, sheet 4) is postulated (explanatory note 17). For reasons explained in a subsequent section, **Fd** is here thought to be a normal fault with gentle southwest dip.

If F_1 follows the western flank of S_1, it might extend to **Fd**. The advantages of this interpretation are that the cross sections of the Power Line—Gravity Glide region are compatible with it, and the erosional gap of Refinery Canyon through Power Line Ridge is thus explained as a structural break, similar to the breaks at Bowen Gulch, Deep Gulch, and Dry Draw (explanatory note 18). The disadvantage of this interpretation is that there is no structural evidence in the field to support it.

S_1 appears to have been offset by the Clay Pit cross fault, F_e, but the displacement is not simple strike slip. At the west end of F_e there is sinistral offset of the Anapra-Mesilla Valley contact; at the east end there is dextral offset of this contact and the offset of the trace of S_1 is also dextral (fig. 12; photo 16). The dips of the beds on the west flank of S_1 are fairly gentle north of F_e; those south of F_e are steep to overturned. Further, the relative amount of vertical movement on F_e differs along the fault; movement was up on the south at the west and east ends, but up on the north in the middle. This is explained as follows: S_1 has been compressed more intensely on the south side of F_e, but the north side moved relatively farther northeast. Although the overall movement on the fault was right lateral, with the

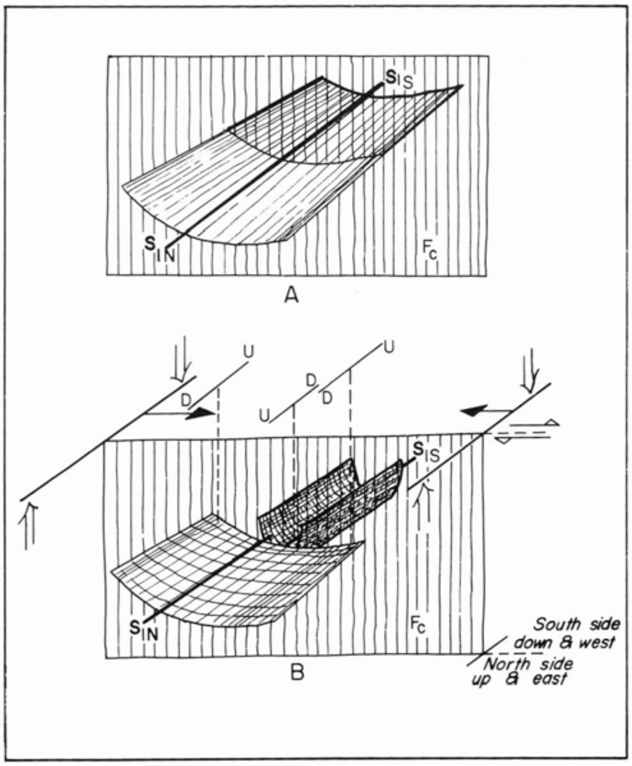

FIGURE 12—DIAGRAM OF A POSSIBLE EXPLANATION OF THE CLAY PIT CROSS FAULT, NORTHERN END OF EASTERN FAULT-FOLD ZONE. Map III, sheet 2; map VI, sheet 3; map IX, sheet 4. See text for explanation.

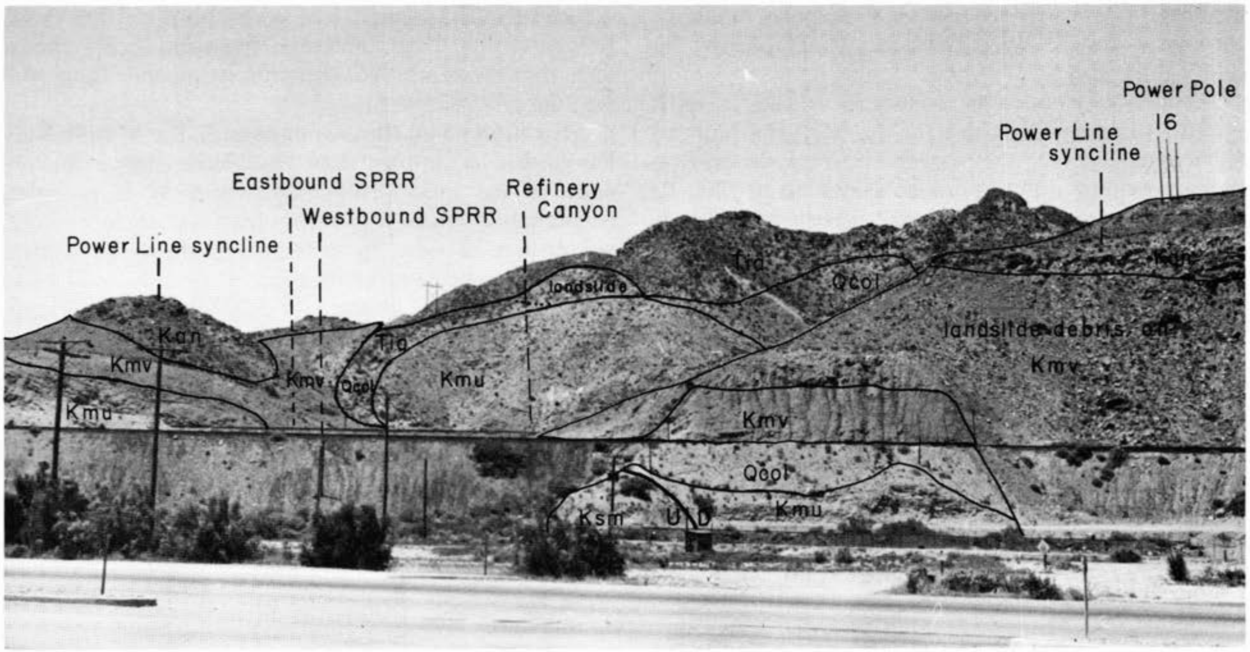

PHOTO 15—LOWER REFINERY CANYON, VIEWED TOWARD SOUTHWEST. Map III, sheet 2; map V, sheet 3; map VIII, sheet 4. This view from the highway in El Paso del Rio del Norte shows where Refinery Canyon cuts Power Line Ridge. Andesite landslide is clearly visible, as is the landslide on the east side of Power Line Ridge. Outer fault may extend along east flank of Power Line syncline on the far side of Refinery Canyon (left of picture) in Mesilla Valley shales, which are thinner than normal at that point. Outer fault may extend through mouth of Refinery Canyon and emerge between river road and railroad (lower middle of picture) where Smeltertown limestone beds are opposite Muleros beds.

south side slightly down, the tighter folding produced the left-lateral displacement and the apparent raising of the south block at the west end. Apparently, S_1 was formed earlier than $\mathbf{F_e}$ and later was compressed and broken on F_e ; thus, the cross fault is a true radial fault (explanatory note 19).

Along the west ends of sections 58-61, $\mathbf{F_h}$ is manifest only by the termination of the Anapra sandstone ridge at section 60, and the outcrop of the fault in the quarry wall at 61. This ridge has been destroyed by mining operations. However, the Northside fault can be traced along the north side of the pluton toward $\mathbf{F_h}$. Thus, **Fh** probably is the Northside fault. There is 30 m (100 ft) of right-handed offset of the Anapra-Mesilla Valley contact between sections 60 and 61. This may be the result either of right-lateral strike slip or of dip slip only, down on the southwest, because overturned strata could be offset in this manner (explanatory note 20).

Between sections 61 and 63 a fundamental change in structure occurs along F_1'' and F_1. The Interior Complex belt between F_1 and F_4 south of F_1' abruptly emerges in all of its bewildering complexity (photos 17-20). (This is the most complex zone in the Cristo Rey uplift; unfortunately, since mapping ended, quarrying has destroyed some of the critical areas, and fill covers others.) If $\mathbf{F_d} = \mathbf{F_f}$ or $F_c = \mathbf{F_f}$ with a gentle to moderate west dip, then the fault trace will be reflected in the topography. This may account for the fault trace curvature north of section 56 and between sections 61 and 63 (explanatory note 21).

The Outer fault on the north side of the pluton may continue around the northeast side and merge with F_1,

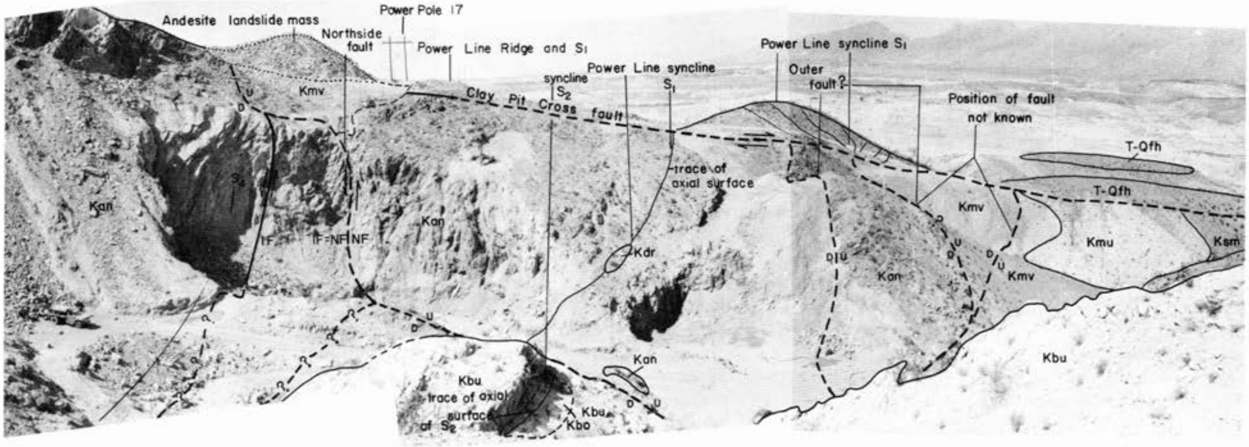

PHOTO 16—STRUCTURE IN THE VICINITY OF THE CLAY PIT CROSS FAULT. Map III, sheet 2. View north from north end of the Eastern Fault-Fold zone (section 63). See text for explanation.

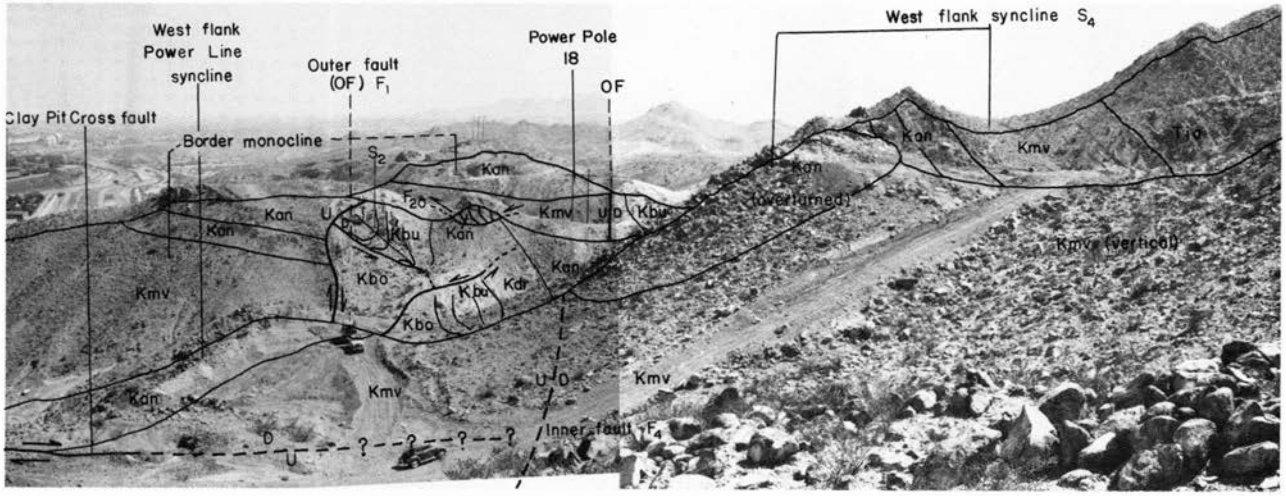

PHOTO 17—General view southward of the north end of Eastern Fault-Fold zone from power pole 17. Map III, sheet 2; map VI, sheet 3; map IX, sheet 4.

the Outer fault of the EFFZ. F_1 = **Ff** and F_1 which are the two sides of the same thick brecciated fault zone (explanatory note 22).

Displacement of F_1 (= **Ff** = F_1) at section 63 is the largest observed in the Cristo Rey uplift (explanatory note 23). At least 9 m (30 ft) of Boquillas shale lies 21 m (70 ft) below the Anapra-Mesilla Valley contact of the Border monocline at section 63—a total of 137 m (450 ft) of displacement. Thus, F_1 from 63 south is a major fault (see table 5). Dip slip on F_1 increases abruptly and greatly south of section 63.

The Interior Complex belt is between F_1 and $\mathbf{F_4}$, from sections 63 through 81 (sheet 5, cross section X). Between sections 63 and 65 is the greatest complexity in this belt. The discussion of the belt is postponed until the structure on both of its sides is examined.

F_1 is a normal fault with Anapra sandstone beds or Mesilla Valley strata in the footwall, and strata as young as Boquillas in the hanging wall. Thus, stratigraphic separation ranges from 91 m (300 ft) at section 81 (see table 5) to 137 m (450 ft) at section 63. A slickensided fault surface of F_1 in an Anapra sandstone bed at section 66 dips 50° W., but several three-point solutions along F_1 (assuming a planar fault surface) indicate dips of 15°, 22°, and 35° W. However, as the distance between the two points at the same elevation increases, the dip decreases. This fact indicates a warped fault surface. Thus, the dip appears to be between 30 and 50° W. In some places F_1 is a zone about 10 m (33 ft) across containing a great amount of brecciated sandstone and strongly folded shale beds as in anticline $\mathbf{A_{ob}}$ (70-74) and the associated folded zone. Slickensides indicate dip-slip movement only on F_1 (explanatory note 24).

$\mathbf{F_4}$, a normal fault, is exposed only near section 85, where it dips 55° W. There is little breccia along the fault; movement appears to be dip slip. (Apparent stratigraphic separations on $\mathbf{F_4}$ are shown in table 6.) West of $\mathbf{F_4}$ the hinge of $\mathbf{S_4}$ is sliced off by $\mathbf{F_4}$ at sections 70-76 and 78-81. S_4 plunges steeply south between sections 58 and 64, but becomes level at 64. At 83 it emerges at the Arroyo arch. $\mathbf{S_4}$ appears to have fallen into a fosse which is bounded on the east by F_1; the steep plunges at both ends may represent the upward bends of $\mathbf{S_4}$ at the ends of the fosse. $\mathbf{S_4}$ is cut by $\mathbf{F_4}$; hence $\mathbf{F_4}$ must be younger than $\mathbf{S_4}$.

Between sections 76 and 81 two parallel folds, A_4c and S_{ob}, are on the west flank of $\mathbf{S_4}$. These appear to be folds which cascaded into the fosse during late stages of formation of $\mathbf{S_4}$. $\mathbf{F_5}$ and $\mathbf{F_6}$ probably formed then. F_{1o}, F_{11}, and $\mathbf{F_{12}}$ are tear faults associated with this cascade fold zone. $\mathbf{S_4}$ extends south to 81 but has been cut by **F4.**

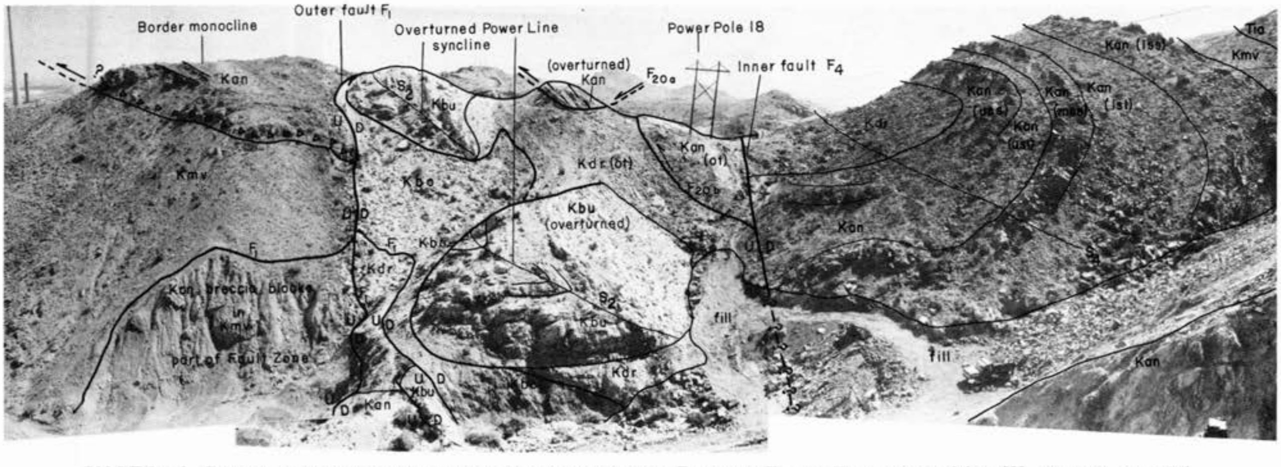

PHOTO 18—Detail view southward of the north end of Eastern Fault-Fold zone. Map III, sheet 2; map VI, sheet 3; map IX, sheet 4.

TABLE 5—STRATIGRAPHIC SEPARATIONS AND DIP SLIPS ALONG FAULT F_1 (OUTER FAULT) OF THE EASTERN FAULT-FOLD ZONE (map VI, sheet 3; map IX, sheet 4)

Cross Section	*Juxtaposed Strata* *E. Side*	*W. Side*	*Strata Separation* *Meters*	*Feet*	*Dip Slip* *Meters*	*Feet*	*Remarks*
56	Sm	Mu	30 ±	100 ±			1
57	Mu	MV	45 ±	150 ±			1
58	MV	MV	0-30 ±	0-100 ±			1, 2
59	Mu	MV	0-30 ±	0-100 −			1
60	MV	MV	0-30 ±	0-100 −			1, 3
61	MV	MV	0-30 ±	0-100 −			1
62	MV	MV	0-30 ±	0-100 −	147	490	Fig. 18
63	Mid MV	Low Bo	137 + (max)	450 + (max)			Fig. 17
64	Top MV	Bo	104 +	340 +			---
65	Top MV	Top DR (complex)	91	300	144	480	Fig. 16
66	Top MV	Top Bu (complex)	104	340			Fig. 15
67	Top MV	DR	67-91	220-300			---
68	Up MV	DR	76 +	250 +			---
69	Mid MV	DR	91 +	300 +			---
70	Low MV	Low Bo	122 +	400±			---
71	Low MV	Low Bo	122 +	400 ±			---
72	Top MV	Low Bo	104 +	340 +			---
73	Nr top MV	Top Bu	91 +	300 +			---
74	Nr top MV	Top Bu	91 +	300 +	105	350	Fig. 14
75	Top MV	Top Bu	104	340			---
76	MV	An	0-122	0-400			---
77	MV	An	0-122	0-400			---
78	MV	An	0-122	0-400			---
79	MV	An	0-122	0-400			---
80	Top MV	Top DR	91	300 ?			---
81	Top MV?	Top DR?	91	300	120	400	Fig. 13

Bo = Boquillas
Bu = Buda
DR = Del Rio
An = Anapra
MV = Mesilla Valley
Mu = Muleros
Sm = Smeltertown
nr = near

1. Dip of the fault is subparallel with dip of beds and stratigraphic separations are very difficult to determine in Mesilla Valley shale, Muleros limestone, and Smeltertown shale. These are estimates or even guesses. Total shift across complexly splayed F_4, Outer fault, zone is probably more significant here. This cannot be measured accurately either, but seems to be more than 30 m (100 ft).
2. Loss of upper limestone member of Muleros Formation indicates a fault here.
3. Intense brecciation of Anapra and loss of Mesilla Valley section indicate a fault here.

PHOTO 19—DETAIL, CLOSEUP VIEW OF THE NORTH END OF EASTERN FAULT-FOLD ZONE. Map III, sheet 2; map VI, sheet 3; map IX, sheet 4.

TABLE 6—STRATIGRAPHIC SEPARATIONS AND DIP SLIPS ALONG FAULT F_4 (INNER NORMAL FAULT) OF THE EASTERN FAULT-FOLD ZONE (map VI, sheet 3; map IX, sheet 4)

Cross Section	*Juxtaposed Strata*		*Apparent Stratigraphic Separation Min.*		*Max.*		*Dip Slip*		*Apparent Sense of Movement of West Side*	*Remarks*
	E. Side	*W. Side*	*M*	*Ft*	*M*	*Ft*	*M*	*Ft*		
63	Low DR	Mid An	15	50	24	80	60	200	Up	1, 2, fig. 17
64	Up DR	Up An	0	0	12	40			?	1, 2
65	Up An	Up An	0	0	12	40	60	200	?	1, 2, fig. 16
66	Up An	Up An	0	0	12	40			?	1, 2, fig. 15
67	Up An	Up An	0	0	12	40			?	1, 2
68	DR	DR-Bu	0	0	24	80			Down	3
69	DR	Bu-Bo	0	0	4	13			Down	4
70	An	DR-Bu	24	80	91	300			Down	5
71	DR	Low Bo	15	50	40	130			Down	6
72	An	Bo	43	140	110	360			Down	6
73	An	Bo	43	140	110	360			Down	6
74	An	Bo	43	140	110	360	52	170	Down	6, fig. 14
75	An	Bo	43	140	110	360			Down	6
76	An	Bo	43	140	110	360			Down	6, 7
77	Low An	DR-Bu	58	190	91	300			Down	7
78	Low An	Up DR	58	190	91	300			Down	7
79	Low An	DR	33	110?	91	300			Down	7
80	An	DR	0	0?	91	300			Down	8
81	Low An	Low Bo	100	330	113	370	113	370	Down	Fig. 13

Bo = Boquillas
Bu = Buda
DR = Del Rio
An = Anapra
MV = Mesilla Valley

1. Anapra sandstone on east side of fault is overturned.
2. Apparent sense of movement seems down on east. However, see figs. 16 and 17 for reconstructions of sections 63 and 65, which show that west side is down. Dip slip is about 60 m (200 ft) as reconstructed.
3. Del Rio on east side probably overturned.
4. Anapra fault slice on east side thoroughly brecciated.
5. Del Rio on east is fault slice. Abundant Anapra breccia nearby.
6. Anapra on east probably right side up.
7. Anapra on east side forms slopes; bedding locally difficult to determine.
8. Faults F_{2a} and F_{2b} complicate this exposure. Across three faults F_4, F_{2a}, and F_{2b}, there is Del Rio on both sides and stratigraphic separation across all of them is very small.

General Comments

Apparent stratigraphic separations for sections 63 through 71 involve overturned strata on east side of fault, part of Interior Complex belt where beds have been overturned and complexly folded and faulted. These stratigraphic separations are essentially meaningless in terms of fault displacement of F_4, hence are very misleading. Accordingly, it seems as if stratigraphic separation on F_4 north of 81 generally is 43-91 m (140-300 ft). Dip slip probably is near 60 m (200 ft) between 63 and 80. Increase in elevation of A_3 at 81 probably increases dip slip and stratigraphic separation on F_4.

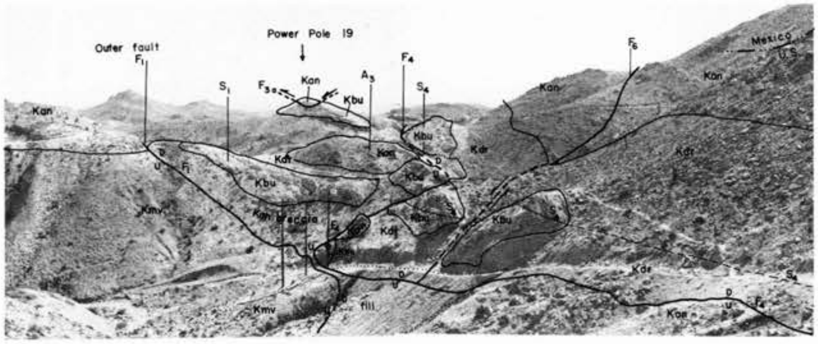

PHOTO 20—GENERAL VIEW SOUTHWARD OF THE EASTERN FAULT-FOLD ZONE IN MEXICO. Map III, sheet 2; map VI, sheet 3; map IX, sheet 4.

Between 77 and 81 the colluvium and **F_4** mask the trace of **S_4** (explanatory note 25).

At the south end of the cascade folds, **F_5** has produced thinning of the Anapra sandstone beds at 81, where the outcrop width of the formation is only 24 m (80 ft). Between sections 81 and 82, **S_4** rises abruptly, and the Del Rio beds change strike 90° in less than 30 m (100 ft). **F_{13}** coincides with the wash at section 84, but the Anapra-Mesilla Valley contact is barely offset, and **F_{13}** must be limited to the Anapra and higher beds southeast of the Mesilla Valley contact. Thus, **F_{13}** is a tear fault at the south end of the fosse. **F_{10} F_{12}, F_{13}, A_{4c}**, and S_o, west of the trace of **S_4** and east of **F_6,** formed as the result of cascading into the fosse from the rising pluton before the formation of **F_4** but late in the development of the EFFZ (explanatory note 26).

At section 81, F_1 displaces the Buda-Del Rio contact downward to a point 6 m (20 ft) above the Anapra-Mesilla Valley contact in the upthrown block, or a total stratigraphic separation of 85-91 m (280-300 ft) (see table 5). The displacement on F_1 seems to decrease toward the south, although it may continue on to the south boundary of the Cristo Rey uplift (map I, sheet 1; map **H,** sheet 2).

It should be remembered that F_1 forms a wide zone; its east side is F_{1a} and the west side **F_{1b}** (explanatory note 27). Locally, as in area B at 76 (map IX, sheet 4), area A at 62, and area C at 80, F_1 dips parallel with the surface slope; hence the map width of the fault zone is great. Where the fault zone is not wide, F_1 is not divided into F_{1a} and **F_{1b}.**

The Interior Complex belt becomes more complicated from section 81 north at 65, where it attains the greatest complexity. A reconstruction of cross section 81 (fig. 13) shows that A_{1a}, **A_3, S_2.** and S_4 form the principal pre-F_4 structures. The sequence of F_1-F_4 faulting has been determined elsewhere. The chronological structural evolution at 81 is: **1) F_1;** 2) A_{1e}, S_2, A_3, and **S_4;** 3) **F_3,** probably late in the sequence of intensive folding; 4) F_5, probably late in the sequence of intensive folding and during formation of the cascade folds A_{4c} and S_o at 76-80; and 5) **F_4.**

A reconstruction of section 74 (fig. 14) shows **S_2** and **S_4** and an anticline between them displaced by **F_4,** F_{1c}', and F_{1c}. This reconstruction is essentially the same as that for section 81 (explanatory note 28).

The outcrop of the Interior Complex belt disappears between sections 68 and 69, where **F_4** and F_1 meet and stratigraphic separation across F_1 and **F_4 is** 110 m (360 ft); the Anapra-Mesilla Valley contact in the eastern block is juxtaposed with Boquillas shale, no less than 9 m (30 ft) above the Boquillas-Buda contact. In addition, F_1 and **F_4** approach each other most closely at low points in arroyos at section 62, between sections 68 and 69, and between sections 79 and **80;** however, at the low point at 71 the two faults are farther apart than they are between sections 68 and 69. Thus, there is a change in strike of the fault traces at the surface, but the faults appear to converge at depth.

The EFFZ fosse has been lowered most between sections 68 and 77 and has been moved farthest eastward structurally between 64 and 75 (explanatory note 29). This also seems to be about the narrowest part of the Interior Complex belt, and there seems to be more folding in the Border monocline block adjacent to F_1 in this narrow range.

The most complicated part of the Interior Complex belt is between 62 and 68 but especially at sections 62 and 65 (sheet 5, cross section X). Cross sections 63 and 65, only 67 m (220 ft) apart and considerably different in some respects, are sufficiently alike that the structures in both of them can be utilized in deciphering the structures in the other.

Sections 66, 65, 63, and 62 (figs. 15-18) indicate: 1) faulting of the Outer fault took place first; 2) major cascading took place during and slightly afterward; and 3) faulting (Inner fault) took place last.

SUMMARY

The Power Line syncline S1 can be traced through Power Line Ridge, across Refinery Canyon to the outcrop of Anapra sandstone at sections 56 and 57, where it has been offset by the Clay Pit cross fault F_e. South of F_e, S_1 has been more tightly compressed, and its eastern limb contains many longitudinal faults which appear to be part of a horsetailed zone at the intersection of F_1 (Outer fault) and the cross fault. S_1 can be traced to section 63 without interruption.

Between sections 58 and 62 the western flank of SE is the western flank of **S_4. Fh,** the connection between the Northside fault and **F_4,** offsets Anapra sandstone on this western flank of SE and **S_4.** Between sections 58 and 66 the eastern limbs of S_1 and **S_2** appear to be continuous, although faulted near 63. Thus, S_1 seems to continue south across 63. However, there are two smaller synclines (S_2 and S_4) and a medial anticline (A_3) or thrust fault at 65 (fig. 16). The overall reconstructed structure at 65 (before faulting) is that of one large syncline, which is the southern continuation of S_1. Puckering to form a medial anticline along a syncline is common in tight synclines, especially above competent strata. Thrusting or gravity gliding and cascading produce minor complications in the overall structure.

The fold zone extends to section 78 and perhaps to section 82, beyond which the axis of S_4 extends along **F_4,** where the strata dip steeply off the pluton west of **F_4,** and **A_3** is east of **F_4. S_1** may extend to section 20 (map I, sheet 1).

S_1 has been faulted at 63 by F_1". S1 appears to be structurally high near 1 and 26 but plunges to its lowest structural point at 25. It rises again at 22, but there is no evidence of another fault between F_1 and **F_4** analogous to F_1" near 22. Therefore, the fosse is probably coextensive with S_E between sections 63 and 81 (22). The fosse formed as the result of displacement on F_1 and F_1". The fosse and F1 appear to be controlled by S_1. F_1 is an early structure in the EFFZ; therefore, S1 seems to have existed before formation of the EFFZ (explanatory note 30).

The strike-slip faulting in the Interior Complex belt took place during the cascade folding. Outward pressure from the magma probably compressed the open cascade folds against the eastern block of the Outer fault (the Border monocline block) and displaced the center of the cascade mass outward in the middle, producing left-lateral strike-slip faults at the north end and right-lateral strike-slip faults at the south end of the Interior Complex belt.

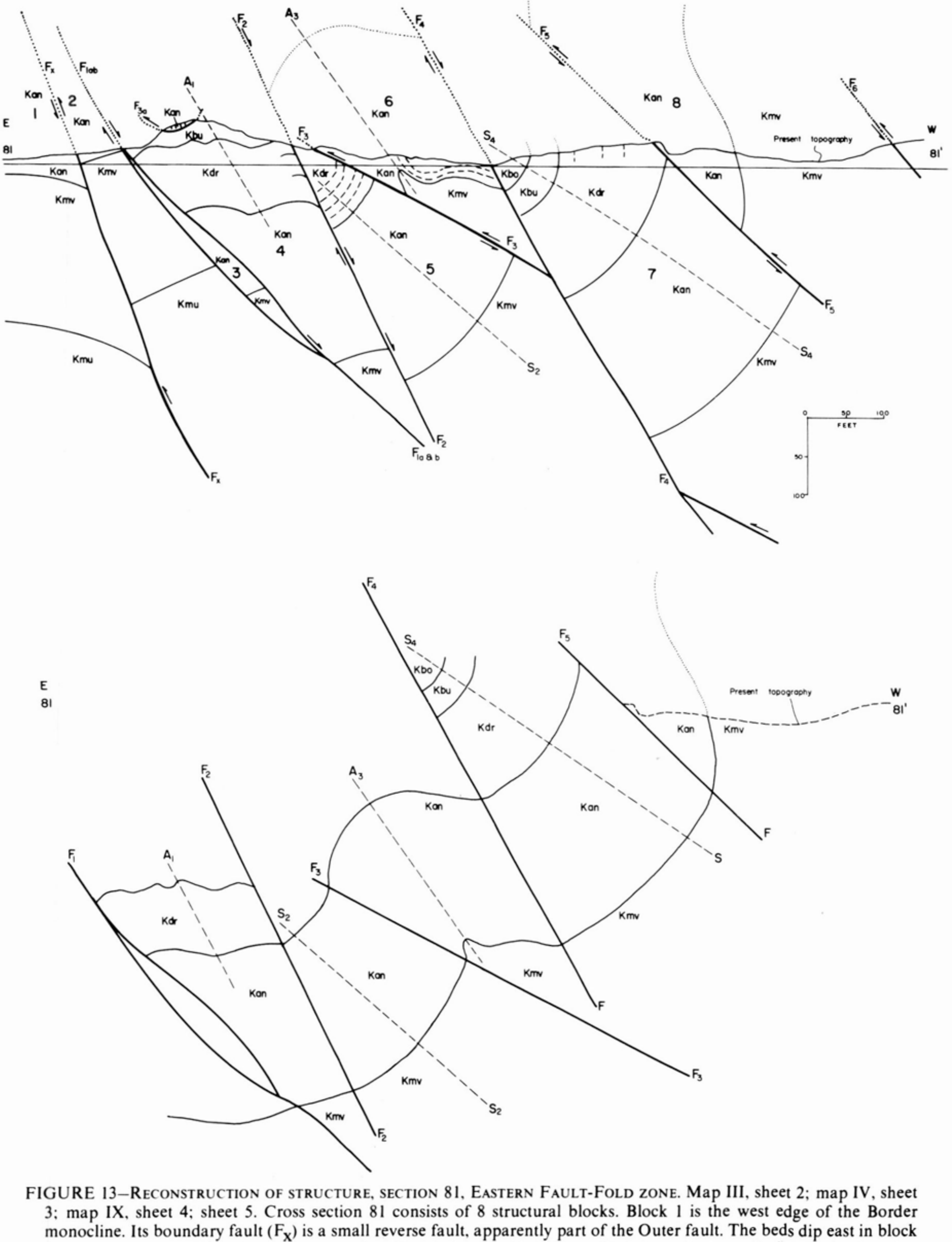

FIGURE 13—RECONSTRUCTION OF STRUCTURE, SECTION 81, EASTERN FAULT-FOLD ZONE. Map III, sheet 2; map IV, sheet 3; map IX, sheet 4; sheet 5. Cross section 81 consists of 8 structural blocks. Block 1 is the west edge of the Border monocline. Its boundary fault (F_X) is a small reverse fault, apparently part of the Outer fault. The beds dip east in block 2. The significance of this fact is unknown, but this block probably is the wall of the main Outer fault (F_{1ab}). Block 3 is a fault slice in $F_{1ab}=F_1$. Block 4 contains rippled Buda and Del Rio strata with short wave-length folds. Vertically dipping, strongly brecciated Anapra sandstone beds overlie the Buda and comprise part of an allochthonous block emplaced from the west. Block 5 is bounded by F_2 and F_3, which are poorly exposed; hence the dips shown are conjectural. Existence of the syncline, S_2, shown between the two faults, is not supported by outcrop evidence. The Anapra sandstone in block 6 is strongly folded and brecciated, and the interpretation of an anticline, A_3, adjacent to F_3, is conjectural. Bedding attitudes in the sandstone are difficult to determine. The western half of block 6 is structurally simple. F_4 is readily apparent. Block 7 contains the axial surface of S_4 and is rather simple. F_5 and F_6 apparently are parts of a series of thrust faults associated with the cascade folding into the fosse. The piece of allochthonous Anapra in block 4 may have been emplaced as a gravity-glide block either from the overturned Anapra sandstone in block 6 or from vertical Anapra in block 8. If the allochthonous piece came from block 8, there may have been considerable sliding from the roof of the magma chamber. This structure should be compared with that in the Gravity-Glide region of the Power Line syncline (fig. 11). Gravity gliding may have taken place the entire length of the syncline between the two areas.

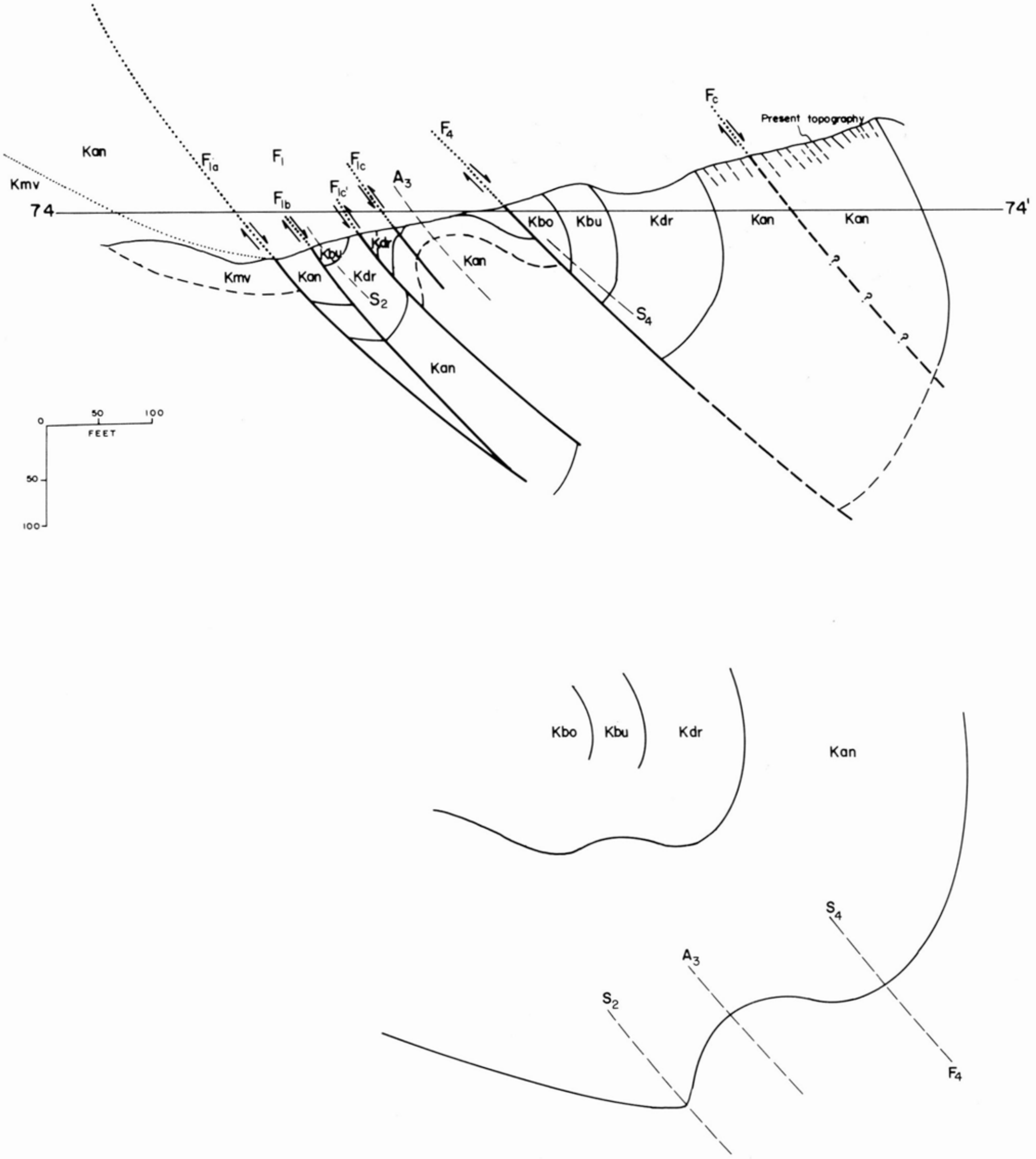

FIGURE 14—RECONSTRUCTION OF STRUCTURE, SECTION 74, EASTERN FAULT-FOLD ZONE. Map III, sheet 2; map VI, sheet 3; map IX, sheet 4; sheet 5. The structure at section 74 is far less complicated than that on the north. Synclines S_2 and S_4 and anticline A_3 are fairly apparent here. A_3 has much lower amplitude than it does on the north; total amount of crushing at this cross section seems much less than on the north. Outer fault is shown as F_{1a} and F_{1b}, two sides of a thick, breccia-filled fault zone. F_{1c}' and F_{1c} may be parts of thrust faults associated with the cascade folding in the Interior Complex belt between F_1 and F_4, or they may represent reverse movement on the Outer fault, F_1. F_6 is not exposed in this cross section, but there seems to be a poorly exposed belt with complicated minor folds, here interpreted as a fault. This fault probably formed during cascading into the fosse.

The "defaulted" reconstruction below shows the two synclines and intermediate anticline. This structure probably never existed, because F_1 formed before or during folding; it is shown merely for illustration of folds at this cross section.

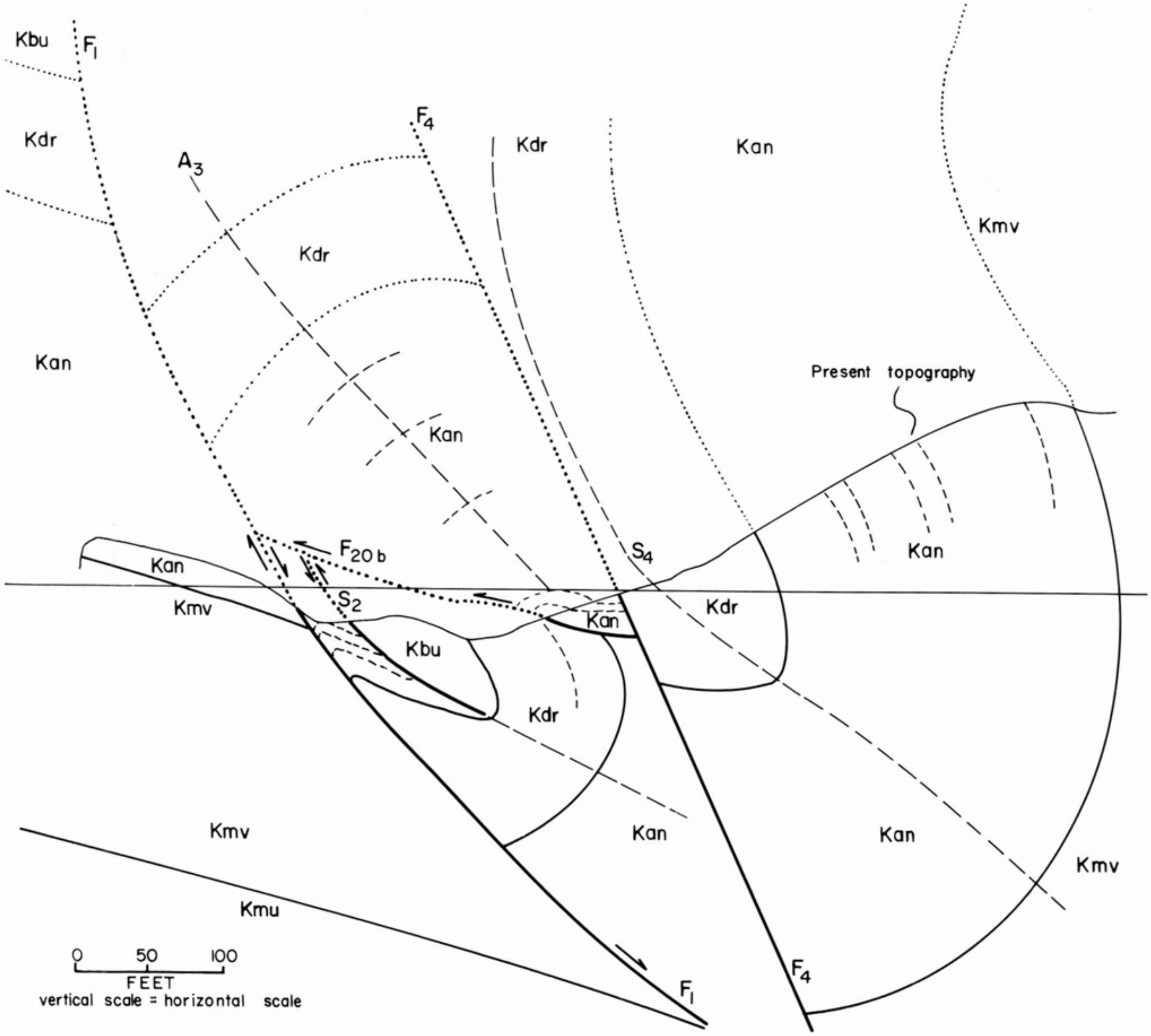

FIGURE 15—RECONSTRUCTION OF STRUCTURE, SECTION 66, EASTERN FAULT-FOLD ZONE. Map III, sheet 2; map VI, sheet 3; map IX, sheet 4; sheet 5. Principal structures in section 66 are S_2, S_4, and F_1 (Outer fault) and F_4 (Inner fault). There must be an anticline A_3 between S_2 and S_4. Anapra lying on overturned Del Rio has been thrust east on F_{20b}. The east end of F_{20b} abuts F_1, implying that F_{20b} formed after F_1. Perhaps displacement occurred simultaneously, with much movement on F_1 before F_{20b}; F_{20b} may have continued east of F_1 as thrust, possibly in Del Rio east of F_1. The small mass of Anapra on the east side of F_4 is probably the west limb of A_3. Anapra beds here are not overturned, as they are at section 65 (fig. 16). The axial surface of A_3 probably is in highly brecciated zone 6 m (20 ft) southwest of power pole 18 (map VI, sheet 3; map IX, sheet 4); Anapra beds west of this breccia zone appear to be right side up and on the west flank of A_3. Defaulting F_4 (replacing west side up on F_4) and defaulting F_{20b} (replacing top side toward west) show S_2, S_4, and A_3 before F_4, but folding probably took place after F_1 had begun and may have continued with F_1 movement. A_3 reappears at 78 (maps VI and IX), but A_1 at sections 76 to 80 may be part of A_3. A_3 may be represented by the Anapra at sections 74 to 75 just east of F_4.

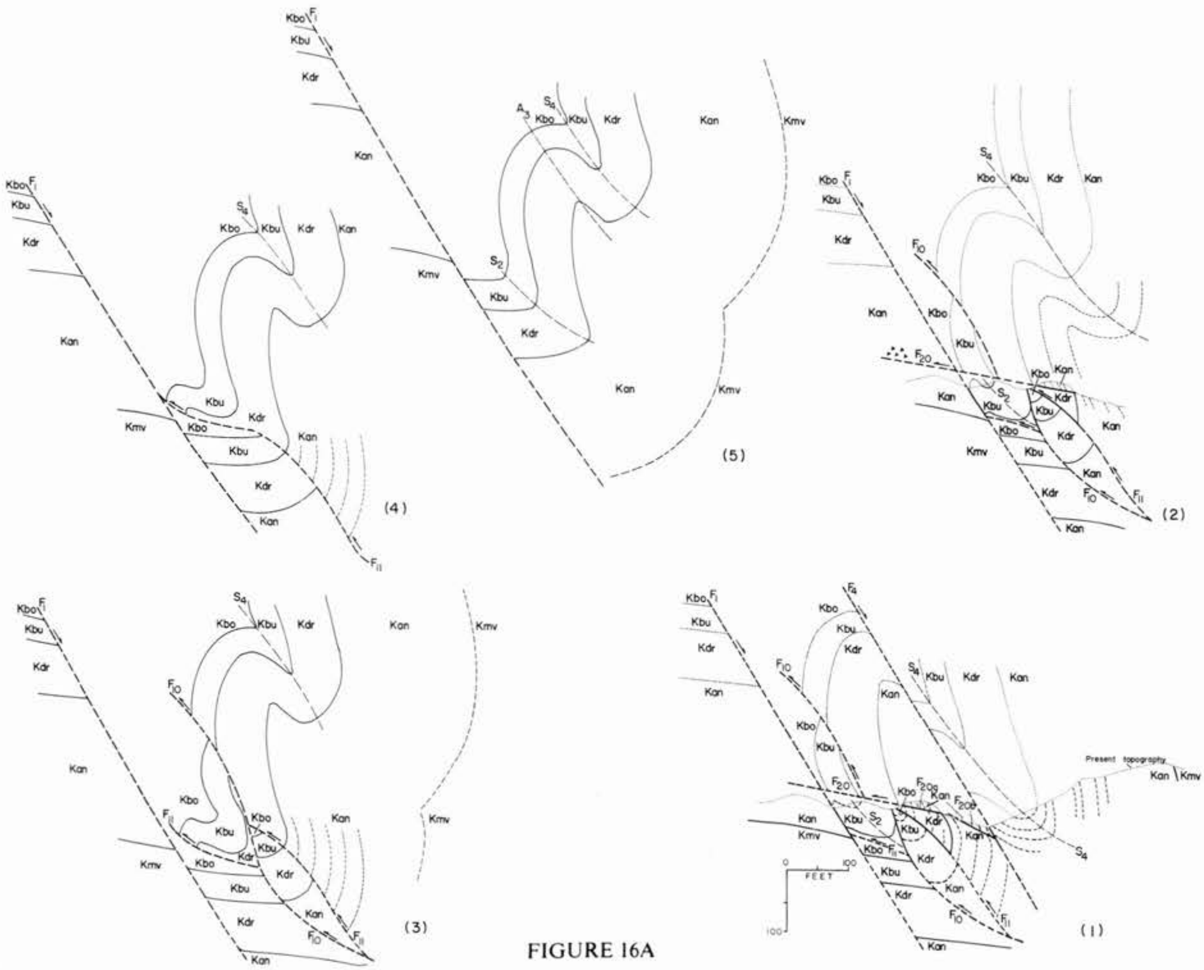

FIGURE 16A

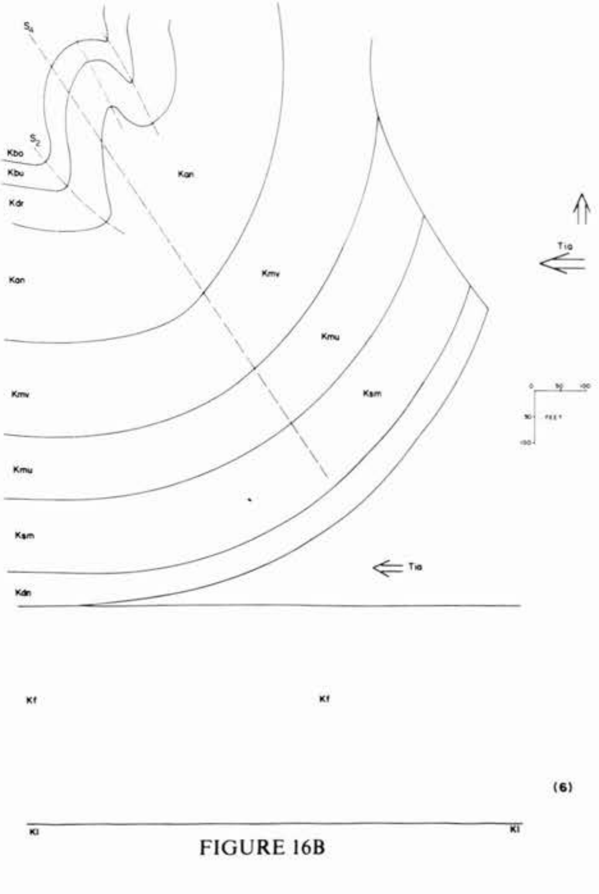

FIGURE 16B

FIGURE 16—RECONSTRUCTION OF STRUCTURE, SECTION 65, EASTERN FAULT-FOLD ZONE. Map III, sheet 2; map VI, sheet 3; map IX, sheet 4; sheet 5. This shows the most probable development at most complicated of all cross sections in the Eastern Fault-Fold zone. Defaulting (replacing the fault block to its original, prefault position) on F_4 is first (fig. 16A-2), because F_4, from evidence obtained in the felsite zone, was the last fault to develop. Thrust faults are most easily defaulted next. F_1 probably began before folding and thrusting, but probably all occurred in part simultaneously. Part 6 (fig. 16B-6) reconstruction of the zone assumes that F_1 completely preceded folding, primarily to give simplified view of folds. A_3 south of here developed as a result of tight synclinal folding during cascading into the fosse. A_3 probably continues south from section 63 (fig. 17, reconstruction of 63).

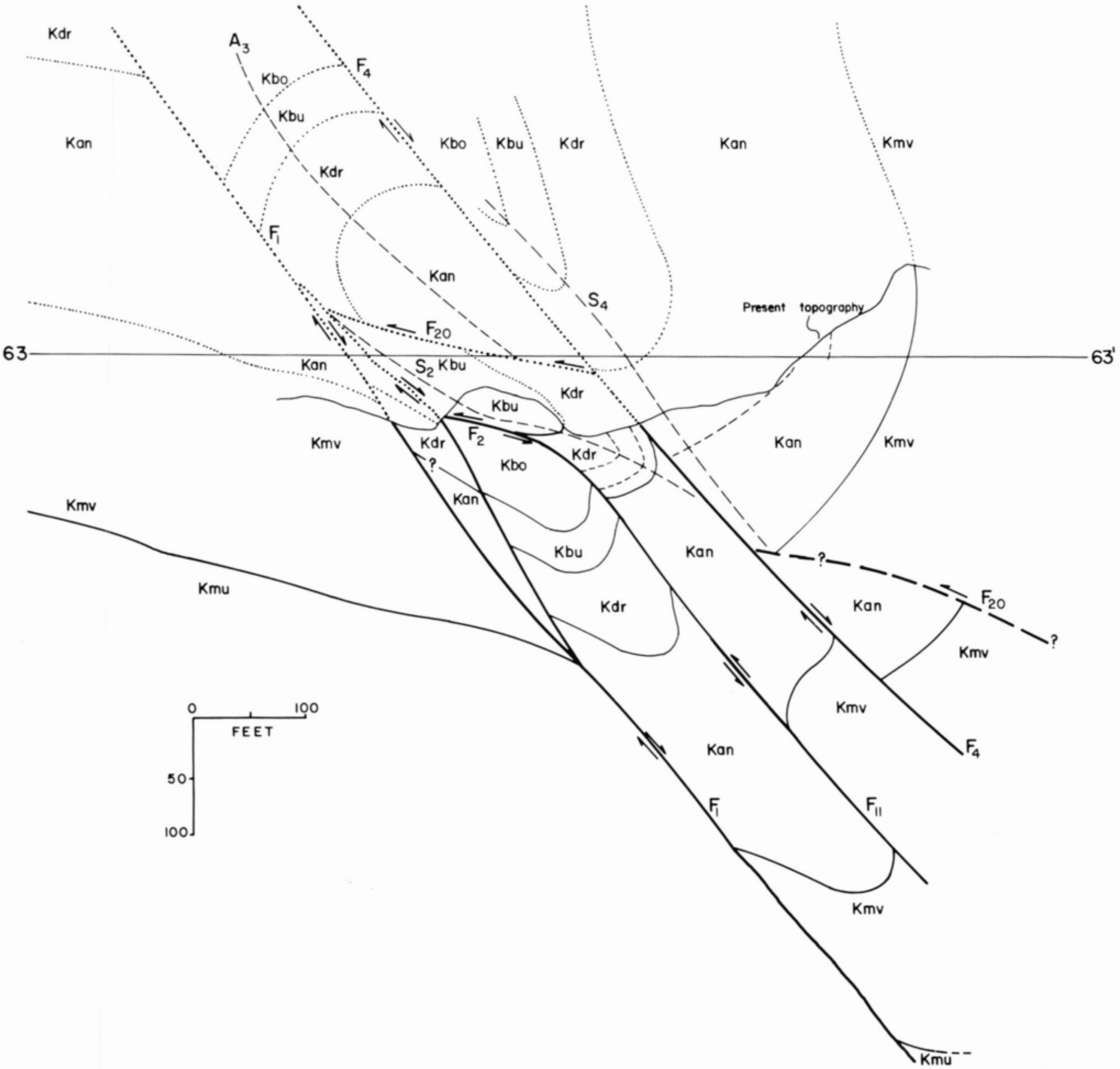

FIGURE 17—Reconstruction of structure, section 63, Eastern Fault-Fold zone. Map III, sheet 2; map VI, sheet 3; map IX, sheet 4; sheet 5. Although minor details of the cross section probably are not correct, the presence of two synclines, S_2 and S_4, an intermediate anticline, A_3, and two west-dipping normal faults F_1 and F_4 seems to be fairly well established here and in the south (figs. 13-16). The original problem associated with reconstructing structure here was the apparent stratigraphic displacement on F_4, which is Anapra up on the west with respect to the Del Rio on the east (see table 6). Until the essential continuity of the Northside-Inner fault (F_4) was understood, this cross section was not understood. S_2 and S_4 implied the presence of an anticline A_3 between them, yet this was the locus of F_4, which implied that F_4 was probably a reverse or thrust fault, thereby corroborating interpretation of apparent movement on F_4 of *up* on the west. However, when it became clear that F_4 probably was normal, and A_3 was needed between S_2 and S_4, reconstruction became quite simple. Puckering in the tightly folded Power Line syncline S_1 produced anticline A_3, therefore, what is S_1 north of 62, has become S_2, A_3, and S_4 south of 62.

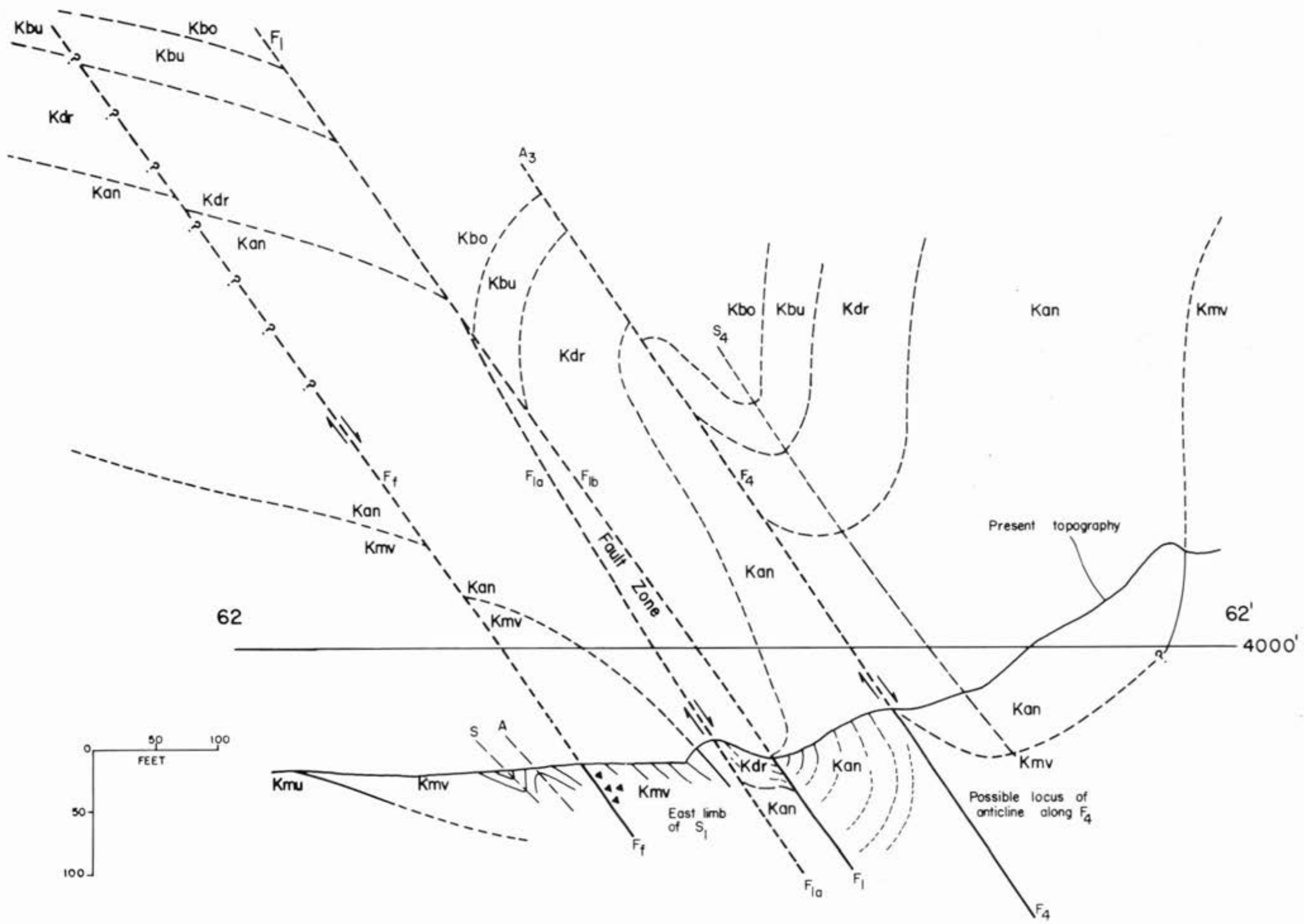

FIGURE 18—Reconstruction of structure, section 62, Eastern Fault-Fold zone. Map III, sheet 2; map VI, sheet 3; map IX, sheet 4; sheet 5. This depicts structure at the north end of the fosse. North of section 62, the Power Line syncline S_1 is clearly developed. At 62 the east limb of S_1 merges with the Border monocline. The west limb of S_1 forms a tight, chevron anticline A_3 with S_4; north of 62 there is no evidence for A_3 and the west flank of S_1 is the west flank of S_4. A_3 has been sheared out. F_4 is closely associated with A_3 and S_4 south of 62. Although the Anapra-Mesilla Valley contact on the west side of F_4 is opposite Anapra on the east, giving an apparent reverse movement on F_4, reconstructions at 74 and 81 (figs. 13, 14) show that F_4 is normal down on the west. Structure here, above present topography, cannot be taken literally, because probably there are thrust faults, as shown in fig. 16, which are not depicted. There may have been thrusting along the east limb of S_4 on bedding planes from the Mesilla Valley upward, with resultant cascading above.

Later deformation in this zone was associated with the smaller cascade folds and minor thrust faults between sections 68 and 82 west of $\mathbf{F_4}$, and with apophysis intrusion. The last stage of deformation was formation of the Inner fault $\mathbf{F_4}$.

BRICK PLANT ANTICLINE

The Brick Plant anticline, the northeasternmost significant structure in the Cristo Rey uplift, is manifested by the dips of the Finlay and Del Norte Formations between sections 3 and 25 (photo 21). The anticline merits discussion because it contains some of the scant evidence pertinent to the problem of the horizon of andesite magma emplacement.

The structural relief between the Power Line syncline and the Brick Plant anticline increases northward from about 107 m (350 ft) at section 1 to 218 m (715 ft) along a N. 25° E. line through power pole 11. The anticline is not well exposed south of section 25.

The structurally highest part of the anticline is on the Northeasterly Structural High zone, a line trending northeast from the northeast corner of the pluton (map III, sheet 2). The culminations of the Aqueduct anticline, Power Line syncline, and the Eastern Fault-Fold zone also lie on this trend.

South of the Northeasterly Structural High zone the common flank of the Power Line syncline and Brick Plant anticline becomes the Border monocline, and the two folds are subordinate to that monocline. The Power Line syncline is involved in the EFFZ, and the locus of the anticline is covered by river alluvium so that the anticline is not clearly defined south of section 1.

The parallelism of the syncline and anticline at their northern ends, their proximate culminations, and their change south of the Northeasterly Structural High zone indicate cogenesis for the folds.

The Brick Plant anticline is cut by numerous longitudinal strike faults striking north to N. 30° W. All are normal, dip-slip to right-lateral, oblique-slip faults mostly with downthrow on the west. Stratigraphic separations generally are less than 15 m (50 ft). These faults are not antithetic; they do not dip toward the anticlinal axial surface. A few faults on the east side of the anticline have strike-slip slickensides. None of the slickensides strikes toward the pluton; rather, they have a bearing that points north of the pluton. No reverse faults are present in the anticline. That the normal

PHOTO 21—General view southward of Brick Plant anticline, El Paso del Rio del Norte. Map III, sheet 2. The beds dipping west dip into the Power Line syncline. South of railroad tracks this common flank of the Brick Plant anticline and Power Line syncline becomes the Border monocline; the anticline disappears beneath the alluvium of the river valley.

faults are not antithetic but are mostly downthrown on the west, that there are no reverse faults, and that the slickensides do not strike toward the pluton indicate that the faults did not result from outwardly directed plutonic compression. The slickensides at the north end of the Power Line syncline also strike west to west-northwest and do not point toward the pluton. Therefore, it is difficult to explain the slickensides in the Brick Plant anticline faults by plutonic expansion, especially in view of the fact that such radially directed slickensides are present in the Power Line syncline closer to the pluton.

Lovejoy (1976) indicates that these faults in the Brick Plant anticline may be part of the Mesilla Valley fault which he considers to be the southern end of the eastern boundary fault zone of the Rio Grande rift system.

BORDER MONOCLINE

The Border monocline extends along the east side of the Cristo Rey uplift from the southern railroad tracks to the Arroyo de las Tetillas (maps I, II). Its northern end merges with the west flank of the Brick Plant anticline and east flank of the Power Line syncline. The eastern boundary is covered by river alluvium and the western boundary is the Outer fault of the Eastern Fault-Fold zone. Its southern boundary is covered by the Fort Hancock Formation.

The Border monocline, a relatively simple west-dipping monocline, locally contains minor north-trending folds especially adjacent to the Outer fault and in the Anapra sandstone beds at the south end of the monocline. The monocline also contains many small dip-slip, north-striking faults, but most of these minor faults which cut the Anapra-Del Rio-Buda sequence at the southeast end of map area have not been mapped. They may be part of the Mesilla Valley fault zone noted above.

The River normal fault which cuts the eastern side of the monocline adjacent to the river alluvium in Mexico has a stratigraphic separation of about 45 m (150 ft), down on the west. Minor northwest-trending folds in the hanging wall suggest a slight right-lateral movement. The River fault cannot be traced very far because of alluvium cover at its ends, but such a large displacement should be detectable elsewhere. The fault major toward the Brick Plant anticline; it may be h extension of all of the west-dipping normal faults in the Finlay Formation at sections 1 and 2. It also is probably part of the Mesilla Valley fault zone.

At its southern end, the general dip is southerly, carrying the Anapra sandstone beds beneath alluvium and Fort Hancock Formation at the southeastern corner of the map area.

The minor folds in the Border monocline adjacent to the Outer fault may have been added to the monocline during andesite emplacement. Anapra sandstone beds crop out on the east side of the Rio Grande at the American Smelting and Refining Company smelter, suggesting that the River fault may have guided superposition development of the river.

SOUTHEASTERN ZONE

The Southeastern zone is defined as the region between the Inner and Outer faults which extends south of the Arroyo de las Tetillas to the Loma Blanca felsite zone, where it is bounded by felsite blocks A and B (map HI, sheet 2). The eastern boundary, the Outer fault, is not exposed. Therefore, the map boundary of the zone is the contact of Fort Hancock strata and Anapra sandstone beds except at the very southeastern corner of the zone, where Del Rio and Buda crop out adjacent to the Fort Hancock Formation.

At the southern boundary the felsite has produced a contact zone in which thrust faults and contact metamorphism have affected the Boquillas, Buda, Del Rio and, locally, the Anapra Formations (explanatory notes 31 and 32). About 60 m (200 ft) east of section 20, the footwall of the thrust has been faulted by a north-trending, west-dipping, normal fault with about 15 m (50 ft) of displacement. On the east side of the fault the Buda limestone directly overlies Anapra sandstone beds in thrust contact. On the west side of the fault only about 12 m (40 ft) of Del Rio shale separates the Buda and Anapra Formations. Apparently the normal fault began to form before the thrust fault, and the thrust trace is just beneath the Buda limestone, cutting out all of the Del Rio east of the fault and only part of the Del Rio west of the fault. The normal fault also cuts the hanging wall of the thrust; thus the normal and thrust faulting episodes overlapped.

A similar fault is present about 21 m (70 ft) west of the first. The Buda limestone on the west side of this fault lies on strongly metamorphosed Del Rio shales; directly below the Buda, intrusive into the Del Rio, is a small apophysis of felsite which produced the intense metamorphism of the Del Rio shales.

The thrust fault, which separates the Buda and Anapra and has cut out some of the Del Rio shale, cannot be traced west of the outcrop of strongly metamorphosed Del Rio. However, at the west end of felsite block B there is a small outcrop of Buda only 1 m (3 ft) thick, with Boquillas above it and Del Rio below; the thrust fault may have extended at least this far to the western edge of felsite block B (explanatory note 33).

The western edge of the Southeastern zone is a north-striking fault, down on the east with Del Rio, Buda, and Boquillas opposite Anapra sandstone. Strati-graphic separation on this fault is 45-60 m (150-200 ft). South-dipping felsite should be offset to the south on the west side of this normal fault, but Fort Hancock strata cover the area. This is surprising, because the felsite seems to be a very resistant unit which ought to stand above the Fort Hancock terrane. This south-trending fault is younger than the felsite. The essentially straight western edge of felsite block B is considered to be a manifestation of this fault. The fault trends north and then seems to bend more northeasterly to parallel the Inner fault. The Inner fault also formed after emplacement of the felsite (see section on Fault-Block Mosaic zone); therefore, these two faults may be related (photo 22).

The western boundary fault of felsite block B (and of the Southeastern zone) and the Inner fault bound a triangular horst between the Southeastern zone and Fault-Block Mosaic zone. As noted, the felsite which should crop out in this triangular horst is not exposed and may be covered by Fort Hancock strata.

FAULT-BLOCK MOSAIC

The Fault-Block Mosaic zone between sections 18 and 21 (map I, sheet 1), which lies between the main plutons, consists of a series of blocks bounded by faults, most of which are cut by the intrusion but are arranged around the pluton as if formed by it (fig. 19; map I, sheet 1, and map II, sheet 2). The faults in fig. 19 are labeled from F_1 on the west to **F_{18}** on the east (explanatory note 34).

F_1 (photo 23) and **F_9** appear to be parts of a continuous, low-angle, north-dipping, normal fault. The east end of F1 projects into the air eastward along strike. The dropped block between F_1 and **F_7** apparently has preserved part of this low-angle fault F_{1-9}, which has been eroded between F_1 and **F_7.** There is no outcrop east of **F_9.** Along the south side of the upper block of F_{1-9} the felsite intrusion has produced local baking, brecciation, folding, and steepening of the beds. In some places the Boquillas, Buda, and Del Rio Formations are metamorphosed; hence the stratigraphic width of the metamorphic contact zone in places is more than 30 m (100 ft). Near F_1 the bedding steepens locally. In places between section 18 and 18_1 (fig. 19), the Anapra touches the felsite, but along this intrusive contact are isolated pods of Boquillas beds between the felsite and the Anapra sandstone. The presence of the Boquillas pods signifies that the felsite must have passed Boquillas beds before it intruded the Anapra sandstone. The origin of **F_{1-9}** is not known, but at least three possibilities exist: 1) the upper block was pushed northward by the massive felsite sill during its emplacement; 2) the upper block slid north toward the andesite pluton during early stages of andesite magma emplacement; or 3) it is a preintrusive fault associated with regional tectonism. The first alternative is considered the most reasonable (explanatory note 35).

F_{1-9} has been displaced by F7 and **F_8.** F7 and F_8 are intruded by the andesite (although apparently related to it); therefore they are slightly older than the andesite emplacement at the andesite contact level here but younger than **F_{1-9}. F_{1-9}** is contemporaneous with the felsite. Thus, here the felsite seems to be slightly older than the andesite. F_{18} (the Inner fault) has displaced and is younger than the felsite; this is also a very important temporal relation because it shows that the felsite is older than the Inner fault which, in turn,

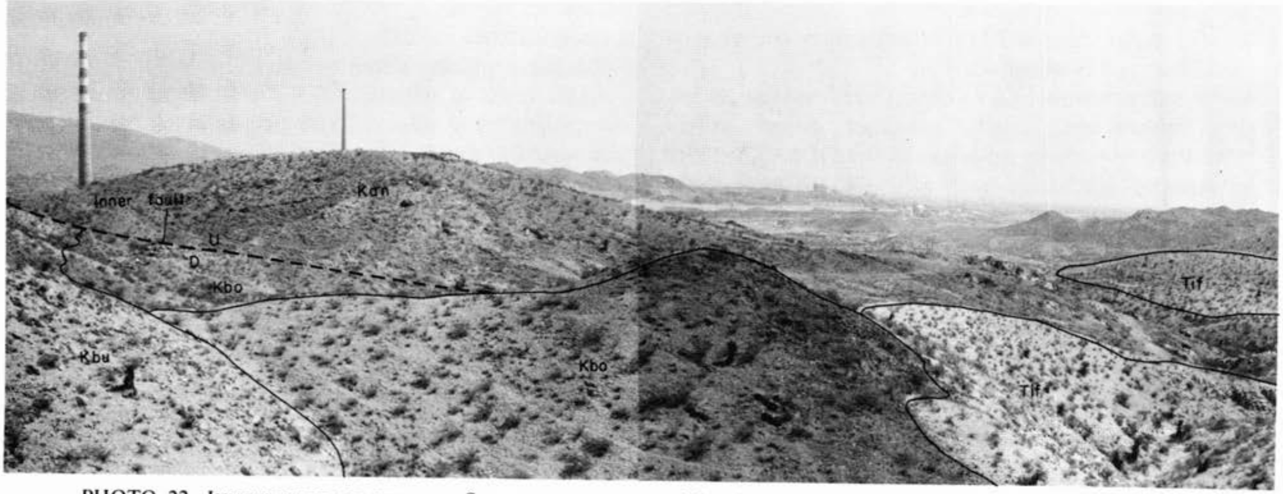

PHOTO 22—JUNCTION OF FELSITE AND SOUTHEASTERN ZONES. Map III, sheet 2. View toward southeast. Inner fault separates Southeastern zone from felsite zone. The fault passes between the two felsite masses at right (south). Boquillas calcareous shale (foreground) is metamorphosed to dark-gray hornfels. Where the Inner fault passes between the two felsite masses, separating Mesilla Valley shale on the east (far) side from felsite on the west (near), and the Mesilla Valley shale is unmetamorphosed. Felsite is strongly brecciated at the fault contact, which is exposed. Thus, the Inner fault developed after felsite intrusion.

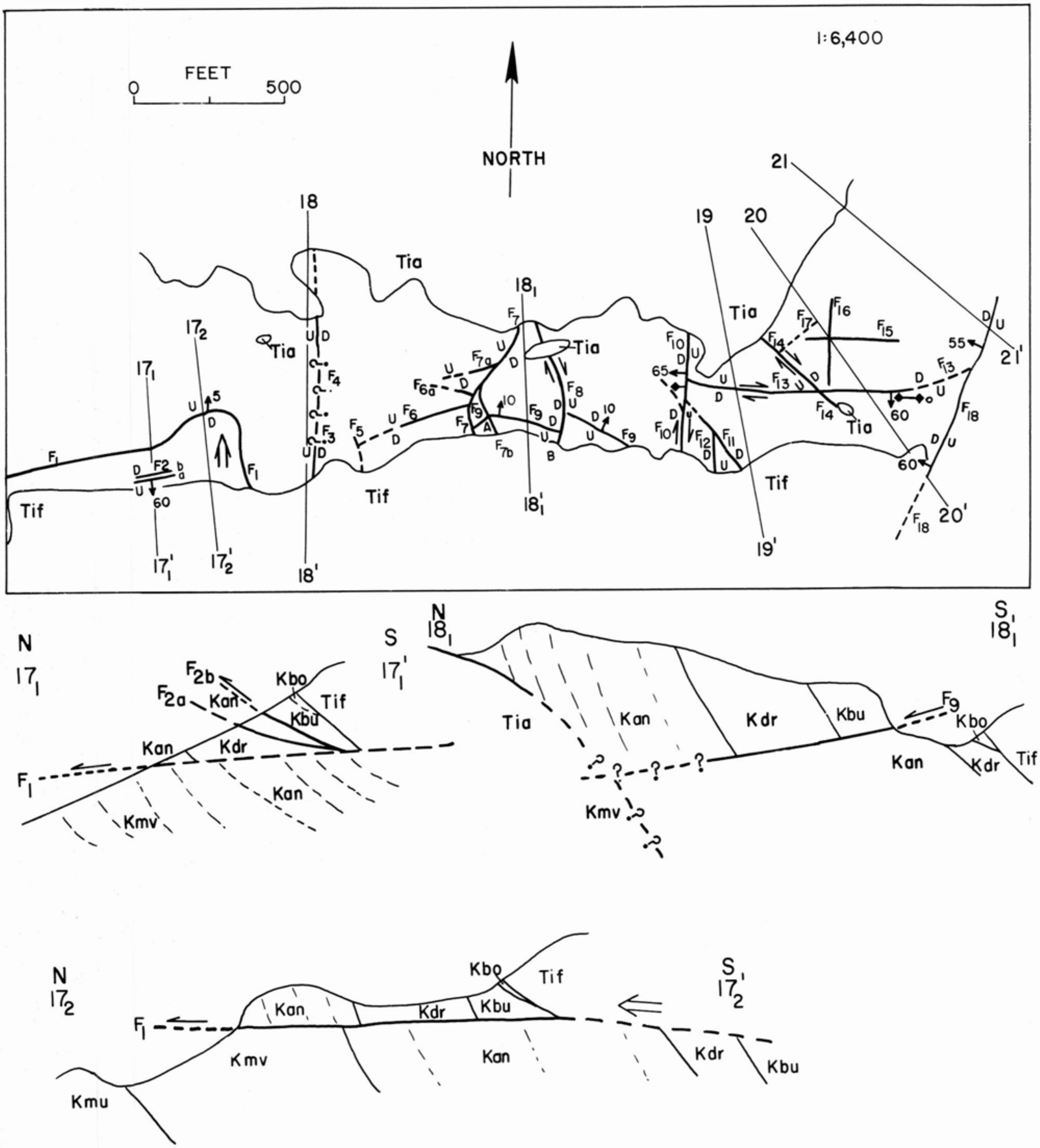

FIGURE 19—STRUCTURAL MAP AND SUPPLEMENTAL CROSS SECTIONS OF FAULT-BLOCK MOSAIC. Map III, sheet 2. See text for explanation. Cross sections are not to scale, but are diagrammatic only.

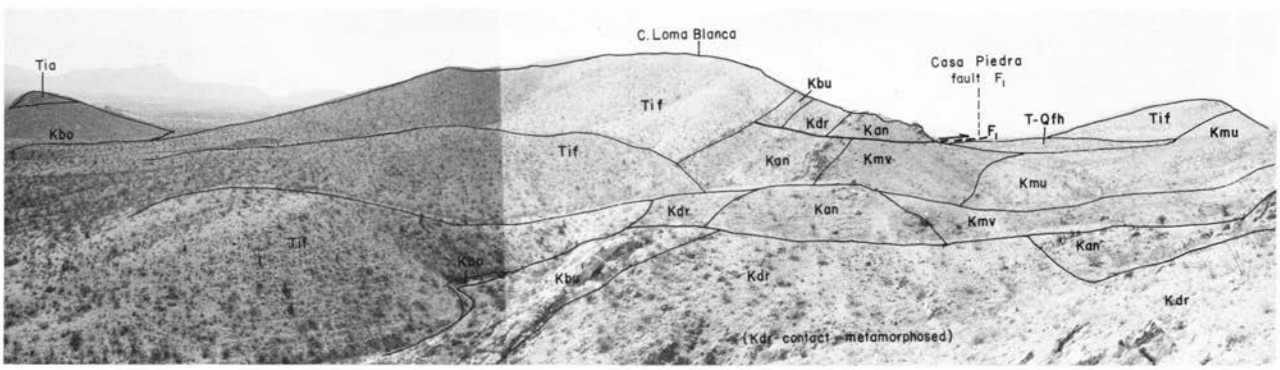

PHOTO 23—FAULT-BLOCK MOSAIC AND FELSITE ZONE. Map III, sheet 2. View toward west of the Fault-Block Mosaic and the felsite zone. The felsite sill here is at least several hundred feet thick. At left edge of photo is an andesite sill intruded in Boquillas shale, not shown on the geologic map because it is off the aerial photo base. Emplacement of the felsite sill of Cerro Loma Blanca appears to have caused the Casa Piedra fault. Fault offsets in the Fault-Block Mosaic produce the offset of Anapra and Del Rio beds in foreground and middle ground.

formed late in the plutonic development of the andesite. That is, the andesite is younger than the felsite (explanatory note 2).

F_{13} seems to end at F_{10}, but because the fault essentially parallels the Anapra beds west of F_{10}, **F_{13}** cannot be traced and may continue west of F_{10} as far as the small lens-shaped andesite intrusion which cuts **F_8**. The east end of **F_{13}** cannot be traced to **F_{18}** primarily because here **F_{13}** is a strike fault. **F_{13}** cuts metamorphosed Boquillas shales and therefore postdates the metamorphism. Thus, **F_{13}** and **F_{18}** are both post-felsite and probably late plutonic. Although **F_{13}** might end at F_{10}, **F_{13}** may exist in the block between F_{10} and **F_7** and may be an extension of **F_{78}** or **F_6** west of **F_7**. Perhaps **F_6**, **F_{68}**, **F_{78}**, and the west end of **F_{13}** represent intrusive faults like the West End fault.

F_{14} has been intruded by an andesite apophysis at its southern end. **F_{13}** intersects **F_{14}** but outcrops are poor in the wash and on colluvial-covered slopes. As a result, the age relations are not known.

All these features indicate that the two intrusions are contemporaneous. The felsite is locally discordant at high stratigraphic levels and concordant at low stratigraphic levels. This observation suggests that two local phases of felsite intrusion took place: 1) an earlier concordant phase intruded the Muleros beds of block E and 2) a later discordant phase intruded the Boquillas of blocks A, B, and C. The later phase may have been intruded while the andesite was magma, perhaps while doming was in progress.

One important point needs restatement here: at section 21 the Del Rio, Buda, and Boquillas Formations have been intensely thermally metamorphosed. The Del Rio Formation here is stratigraphically 50 m (164 ft) from the felsite and 120 m (394 ft) from the andesite, yet it is as thermally metamorphosed here as it is where it is in contact with the felsite. In general, the contact metamorphic aureole around the andesite intrusion is about 15-23 m (50-75 ft), and that adjacent to the felsite is 15-30 m (50-100 ft). This unusual thermal metamorphism of the Del Rio at section 21 probably resulted from contemporaneous thermal metamorphism induced by simultaneous emplacement of the andesite and the felsite. There is no evidence of any other sill in the vicinity, either in place or eroded away, which might have caused this.

As noted in the discussion of the Southeastern zone, a low-angle thrust fault is found along the present limit of felsite block B. This thrust fault probably is analogous to the Casa Piedra low-angle normal fault. The only significant difference between the two faults is that the one at block B dips gently south, and the one at block C dips gently north. Both are thrust faults probably produced by felsite emplacement. The Casa Piedra (thrust) fault formed before some of the vertical block faults; the low-angle thrust fault of block B formed at the same time as the vertical faults. Apparently, thrusting and block faulting were penecontemporaneous. The vertical block faulting adjacent to the andesite seems to have been related to andesite emplacement in the Fault-Block Mosaic area. The vertical block faulting near block B may have been related to the Outer fault zone which is obviously related to andesite emplacement. Here also the evidence indicates contemporaneity of andesite and felsite intrusions.

The Casa Piedra fault cannot be traced to the eastern end of the Fault-Block Mosaic. The low-angle thrust fault in the Southeastern zone seems to extend to the western edge of felsite block B, but there is no evidence for its continuation in the Boquillas Formation at the eastern end of the Fault-Block Mosaic adjacent to the Inner fault. The Casa Piedra fault and the low-angle thrust fault of the Southeastern zone probably are two distinct faults associated with felsite emplacement on either side of the Inner fault zone (explanatory note 36). The fact that there is a greater thickness of Boquillas strata on the western side of the Inner fault indicates that the felsite intruded the Boquillas Formation at two different levels and that the Inner fault had begun to form before felsite emplacement. Thus, emplacement of felsite blocks A-B-C may have taken place in the final stages of andesite magmatism.

SOUTHERN ZONE

The Southern zone separates the andesite pluton from felsite zone block E (map II, sheet 2), and extends eastward around the south side of the pluton to the Fault-Block Mosaic zone at section 18 (map I, sheet 1). The Muleros Formation is concordant with the andesite at the northeast end of the zone, and the Smeltertown Formation is concordant with the andesite at the eastern end. The andesite is in contact with the upper shale member of the Smeltertown Formation in most of this zone, but is in contact with the limestone member near sections 16 and 17. This is the lowest stratigraphic horizon exposed in contact with the andesite, and the highest elevation along the andesite contact (photo 24). Thus, the Southern zone contains the highest structural point around the pluton.

The andesite contact here dips consistently 30° to 45° SW. A small apophysis of andesite intrudes the Smelter-town shale, just west of section 18. At 18, the eastern end of the Southern zone, a cross fault displaces the Muleros limestone down on the east, the beds of which dip into the intrusive contact, providing excellent evidence of assimilation of the Muleros limestone by the andesite.

WESTERN ZONE

The Western zone extends around the western end of the andesite pluton (map I, sheet 1). Its northern boundary is the West End fault zone and its southern boundary is the line where the felsite sill block E occurs. At section 11 the andesite lies beneath vertically dipping Muleros limestone beds (photo 25), evidence for assimilation of the limestone. However, only between sections 21 and 22 are there limestone xenoliths.

The Muleros limestone is marmorized and the Smeltertown shale has been baked to a hornfels where they are in contact with the intrusive. The zone of contact metamorphism generally is 15-23 m (50-75 ft) thick. The strata dip west 40-50°, and steepen northward to the West End fault zone.

The andesite is in contact with Smeltertown shale at section 12. The Anapra sandstone dips 20° W. less than 183 m (600 ft) west of the andesite contact. The stratigraphic sequence above the Muleros limestone might be accommodated here if the intrusive contact dips 50° to a level beneath the Anapra sandstone, but a fault up on the east and analogous to the West End intrusive fault might extend along the felsite through sections 12 and 13. Most of the Mesilla Valley section is cut out at section 14 and the fault may extend at least this far south (map III, sheet 2).

FELSITE ZONE

The Loma Blanca Felsite has been divided (map II, sheet 2) into five blocks, A through E. Blocks A and B probably are part of the same pluton, locally covered by Fort Hancock. Blocks C and D may be either one pluton or two; the scimitar-shaped outcrop of block D may be the outcrop of a gently dipping sill, or the pluton may be curved in plan. The felsite may have intruded a fold in this form, but its eastern end seems to be in Boquillas, and its western end in or near Anapra beds. Block E consists of several isolated outcrops of felsite (map I, sheet 1), but the map pattern suggests that the outcrops are part of one sill. Thus, block A-B is one unit, block C is another unit, block D may be a third unit or it may be part of C, and block E is a fourth unit.

Block A-B intruded the Boquillas Formation a few meters above the Buda-Boquillas contact. The felsite may be about 100 m (328 ft) thick and appears to dip gently south. It has contact metamorphosed the Boquillas, Buda, and Del Rio Formations, which are converted to hornfels and microskarn or micromarble. The metamorphic zone is up to 30 m (100 ft) thick in many places. The felsite contact with the overlying Boquillas shale is not observable. The fact that a sill could metamorphose a sequence of beds about 30 m (100 ft) thick suggests that the sedimentary sequence either was wet or already at an elevated temperature. At the east end of the felsite zone the plutons probably were essentially contemporaneously emplaced, as already noted.

The change of the northern (lower) intrusive formational contact, for felsite block C, from Anapra to Boquillas occurs across the Casa Piedra fault. This low-angle fault appears to have been caused by the emplacement of the felsite and indicates a forceful type of intrusion, in contrast to a passive, sill-like emplacement along a stratigraphic horizon. The Casa Piedra fault (F$_1$, photo 11) does not cross the felsite intrusive boundary (see section on Fault-Block Mosaic).

Along the contact of block C with the Fault-Block Mosaic, good exposure shows that the felsite definitely

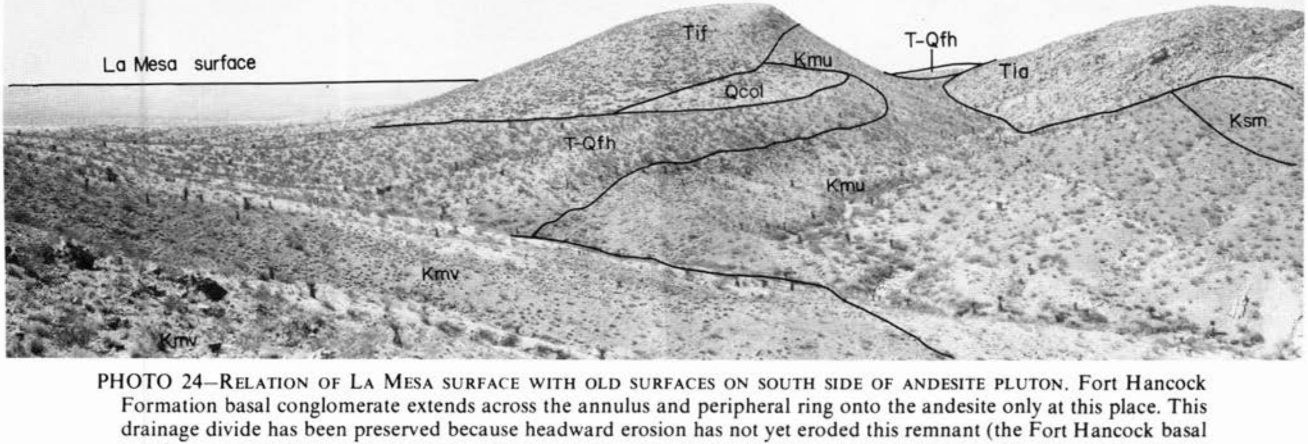

PHOTO 24—RELATION OF LA MESA SURFACE WITH OLD SURFACES ON SOUTH SIDE OF ANDESITE PLUTON. Fort Hancock Formation basal conglomerate extends across the annulus and peripheral ring onto the andesite only at this place. This drainage divide has been preserved because headward erosion has not yet eroded this remnant (the Fort Hancock basal conglomerate has been pedimented in this remnant) between the felsite and andesite (on skyline, right); the pediment is graded to a later, lower surface than the La Mesa surface on the skyline (left). The Smeltertown limestone member is in contact with the andesite at this locality, indicating that this is structurally the highest part of the annulus in contact with the andesite.

PHOTO 25—INTRUSIVE CONTACT OF MULEROS FORMATION WITH ANDESITE. Cross section 11, sheet 6. View toward northeast of contact-metamorphic zone adjacent to West End fault. Probably, early in the history of intrusion, the andesite was intruded as a sill. Later uplift caused by added intrusive pressure broke the country rock at west end of the pluton, raising the roof, and forming a trapdoor intrusion. This contact seems to represent the locus of early intrusion, subsequently raised by intrusive pressures to its present level, with breaking occurring along the West End fault, just out of view on the left. Marmorization and epidotization are the only common types of contact metamorphism found in limestone beds around the andesite.

is not cut by faults of the Fault-Block Mosaic. There is no indication of even slight movements or localized stresses in the felsite at the ends of the faults. Thus either the faults were inactive during felsite emplacement, or the felsite still was a magma during the block faulting. The faults probably were produced by the intrusions.

Block D is not observed in contact with any Cretaceous formations. At section 16, Anapra sandstone crops out 15 m (50 ft) from block D and appears to be slightly silicified. There is not enough room between the felsite and the Mesilla Valley at 16 to include all the Anapra, Del Rio, Buda, and part of the Boquillas Formations. Thus, either 1) a fault is adjacent to the felsite at 16, or 2) the felsite intrudes the Anapra. Block D may be an erosional outlier of block C, separated by the arroyo between sections 16 and 17. There is no structural evidence at 16 of the Casa Piedra fault continuation.

Block E lies in the middle member of the Muleros Formation. The Muleros limestone has been metamorphosed 15 m (50 ft) from the contact. At section 15 the north side (bottom) of block E is on Muleros limestone, and its south side (top) is only a short distance north (below) of the middle member of the Muleros limestone. This block appears to be a sill, perhaps 30 m (100 ft) thick, dipping south. The separation of blocks E and D, therefore, is not the result of faulting, but of horizon of sill emplacement. However, at section 14 the felsite lies within 15 m (50 ft) stratigraphically of the base of the Anapra sandstone. Almost all of the Mesilla Valley Formation and the upper member of the Muleros Formation are missing at section 14. This may be the result of andesite trapdoor faulting (West End fault) or, less likely, of felsite intrusive tectonics.

The change in horizon of emplacement from the Muleros Formation at section 14 upward into the basal Boquillas at sections 17-18 and the form of the intrusive as gently dipping, essentially conformable sills suggest that confining stress was least upward and toward the east, implying near-surface emplacement.

The biotite andesite "V"-dike at section 16 consists of two outcrops which seem to be part of one mass that intruded Mesilla Valley shale near the Anapra contact. The "V" shape may be a result of geomorphic rather than structural causes. If so, it did not inject far laterally. The "V"-dike, section 16', may be interpreted as a crosscutting dike or plug emerging from the andesite pluton and cutting the felsite. This interpretation implies that felsite plutonism of blocks A-B and C ceased before the andesite magma had solidified completely. It could perhaps more reasonably be argued that the felsite sill cut the "V"-dike, having been intruded after dike emplacement. Another possible explanation is that the "V"-dike actually is a sill, emplaced parallel with the bedding and the felsite sill. The field evidence observed to date does not provide a unique interpretation.

The relative ages of the major felsite masses cannot be determined by direct evidence. Forceful intrusion was associated with the eastern mass, but no evidence of forceful intrusion is associated with the western mass. The eastern mass apparently intruded during block faulting (between sections 17 and 20), after the Outer faults formed and definitely before the Inner faults formed, although there may have been very slight time overlap between the beginning of the formation of the Inner faults and late felsite intrusion.

Fosse sundering caused eastward movement of andesite magma, at least at the present erosional level, which probably produced the Fault-Block Mosaic. The felsite blocks A-B and C cut the faults of the Fault-Block Mosaic and thus are slightly younger than the fosse and gravity gliding in the EFFZ. However, the felsite was cut by the Inner fault; hence it is older than the last plutonic tectonism. Thus, the felsite of the eastern block was contemporaneous with the andesite.

NORTHEASTERLY STRUCTURAL HIGH ZONE

A possible structurally high zone trending N. 55° E. (map II, sheet 2) seems to extend through the Cristo Rey uplift. No attempt has been made to make structural contours of a specific horizon. The following features are present along this trend:

1. The Brick Plant anticline and Power Line syncline (map I, sheet 1, and map II, sheet 2) rise to culminations at the outcrop of Finlay limestone beds near the two railroads at sections 1 to 2.
2. The top of the Finlay is at an elevation of about 1,189 m (3,900 ft) northeast of the Rio Grande in the quarried area of the El Paso Cement Company (sections 1 and 2 extended).
3. Between sections 15 and 16 the lowest stratigraphic unit observed in contact with the pluton, the limestone member (Ksm_2) of the Smeltertown Formation, crops out at the highest elevation of the pluton contact with the Cretaceous strata (photo 24; explanatory note 37).
4. The Loma Blanca Felsite rises from its intrusion horizon in the Muleros Formation (block E) to the Boquillas Formation (blocks D, C, and A-B) between sections 16 and 17 along this same trend. The change in level from the felsite-zone block E (map II, sheet 2) to blocks D and C is abrupt.
5. The northeasterly trending Clay Pit cross fault between sections 1 and 26 at the northeast corner of the pluton is essentially on this trend.

The emplacement mechanics and structures change in the same region near section 2. North of this cross section, andesite magma was directed northeastward. South of that cross section, magma was directed eastward. Thus, a major change in resistance to magma pressures seems to have taken place along this zone.

This structural high zone either could have been produced by the emplacement of the pluton, or could have existed before magma emplacement. Evidence for the existence of this zone is circumstantial; the zone may have no significance. It may represent a conjugate shear for the N. 60° W. Texas lineament or for east-west compression.

ARROYO ARCH

Arroyo arch is the name given the region along the Arroyo de las Tetillas in the southeast corner of the map area. At the junction of the Arroyo arch and EFFZ at the Arroyo de las Tetillas is the southern end of the fosse. Arroyo arch trends S. 60° E. Several faults parallel this trend, suggesting that the Arroyo arch influenced their development. The termination of F_5 and F6 (map IX, sheet 4); the alignment of F_{13}, right lateral or up on the south; F_{15}, up on the north; the apparent terminations at their northern ends of F16 and F_1 thesespatial associations suggest a genetic tie with the Arroyo arch. However, Arroyo arch seems to have been displaced by F4. Folds S_4 and A3 culminate at their intersections with the Arroyo arch. Formation of folds A_{4c} and S_{4b} may have taken place partly as the result of cascading off of Arroyo arch, as well as off of the pluton; hence Arroyo arch may have formed before them. The contact of the pluton bulges out along the arch between sections 84 and 85.

The zone of N. 60° W. linears parallels this trend. This is also the trend of the major axis of the pluton.

The joints in the zone of N. 60° W. linears in the andesite suggest northeast-southwest tension. This might have been the result of local arching of a laccolithic-type thin pluton along a N. 60° W. trend, but the zone of N. 60° W. linears lies slightly southwest of the line of the Arroyo arch. Upwelling of magma along a N. 60° W.-trending dike or conduit might have produced a similar alignment of joints. In either event, the Arroyo arch appears to have some geometric and temporal association with the emplacment of the magma. The magma contact bulged significantly along the arch, resulting in local engulfment of the Muleros limestone at sections 84 and 85; whether the Muleros had been displaced before magma emplacement or was displaced by the intrusion is not known. The zone does not seem to be a trend which developed only after magma emplacement to any great extent, but it could have existed before magma emplacement. This zone is parallel with the N. 60° W. lineament.

N. 30° E. TRANSVERSE ZONE

The N. 30° E. Transverse zone is a very poorly defined zone which trends through the "V"-dike on the southwest, through a point less than 100 m (328 ft) southeast of the central peak, through Apache Canyon, Bowen Gulch, and through the Power Line Ridge and syncline at the point where the syncline plunges most steeply. The zone is about 300-450 m (1,000-1,500 ft) wide and not well defined. This trend is normal to the N. 60° W. direction of the zone of linears, the Arroyo arch, and the major axis of the pluton. The significance of this possible lineament is unknown, although this is the direction of a major strike-slip tear fault in the southern part of the Sierra de Juarez (Campuzano, 1973).

In the andesite are normal faults with the same N. 30° E. strike; these faults dip steeply east.

The change in strike and plunge and a local sharp asymmetry in the Power Line syncline on this trend suggests that there may have been some controlling factor associated with magma emplacement and the deflection of the syncline.

The fold zone on the northeast side of the pluton changes northwestward into a generally steep northeastward-dipping sequence of strata (between sections 5 and 6) along the Transverse zone.

The intersection of the N. 30° E. trend, the N. 55° E. trend, and N. 60° W. trend seems to be just about at the center of the andesite pluton only a few meters southeast of the central peak.

Geomorphology and Topographic Form

EARLY GEOMORPHIC HISTORY OF UPLIFT

Certain aspects of the structure of the Cristo Rey pluton are manifest in its topography. At once apparent is the topographic tripartition of the surface of the pluton (map II, sheet 2): the central peak, the outer rampart, and the tableland (photos 26, 27).

Various processes which may account for the surficial appearance of the Cristo Rey pluton include differential erosion of multiple intrusions, the central peak representing one such intrusion, and the outer ramparts and tableland representing the other; an outer ring dike, represented by the outer ramparts surrounding an inner main intrusion; and an original eminence, the central peak, which is the result of a volcanic emplacment, somewhat similar to that of a volcanic plug like Devil's Tower in Wyoming. Several endogenic origins are possible: 1) multiple-phase intrusion, in which the central peak represents one stage, and the outer ramparts and tableland represent another, the difference between the two resulting partly from assimilation of country rock around the periphery which produced a subtle change in petrography and a slightly greater resistance to erosion; and 2) changes in magma composition during emplacement, with the outer ramparts representing one phase, the tableland representing an intermediate composition, and the central peak representing a different phase. Under the climatic conditions prevailing in this area, mafic rocks are less resistant to erosion; felsic rocks are more resistant.

A modification of this latter possibility depends on the erosional history of the dome. If radial and circumferential drainage patterns developed on an originally symmetrical dome, annular drainage on the eroded sedimentary cover would have been superimposed on the andesite, ultimately to produce the tableland; in this situation the outer ramparts represent erosion of the pluton at a lower rate outward from the main annular drainage with the formation of a pattern much like the "Racetrack" around the Black Hills of South Dakota and Wyoming. One can imagine that if the Black Hills "Racetrack" drainage pattern were superimposed on the Precambrian core of the Black Hills, it would leave a geomorphic imprint analogous to the tableland on the Cristo Rey pluton.

Obviously, very detailed petrographic examination and chemical analysis of hundreds of samples of the andesite will be needed to determine any subtle compositional variations. There are few variations apparent in the field. Evidence of multiple intrusions is not present, for the andesite in the field appears to be of essentially uniform composition over most of the pluton. The present topographic form of the pluton appears to be the result of something other than multiple intrusion.

Another possible origin of the present form would involve relatively constant erosion over an intrusion originally shaped similar to the present mountain, an intrusion originally higher in the vicinity of the central peak, lower near the tableland, and higher at the outer ramparts. Thus, the central peak would represent the locus of highest rise of the pluton early in its stage of emplacement, and the tableland and outer ramparts would represent an outward surge of magma emplaced as a sill or laccolith or tongue which formed a relatively thinner, flatter sheet. Differential erosion on the pluton may have been uniform over all the andesite, and the present topographic form merely reflects the erosionally modified original form of the intrusive mass. A detailed study of the barely perceptible flow banding and flow lineation might solve this problem by providing more meaningful information.

All the preceding suggestions are concerned primarily with erosional processes acting on the pluton alone, separate and distinct from the surrounding region. This is too simplistic a view. For a vast region around the pluton there has been a complex history of erosion, deposition, and later erosion in all of the bolsons, a history which must be understood if the topographic form of the pluton is to be appreciated (Strain, 1970; Hawley, 1969).

Richardson (1909) cited R. T. Hill and W. T. Lee in a discussion of the regional geomorphology, outlining the possible early path of the Rio Grande west of Cristo Rey, the earlier infilling of the structural basins with detritus from the mountains, and the burial of an even earlier landscape.

Strain (1966) stated that the bolson deposits (Fort

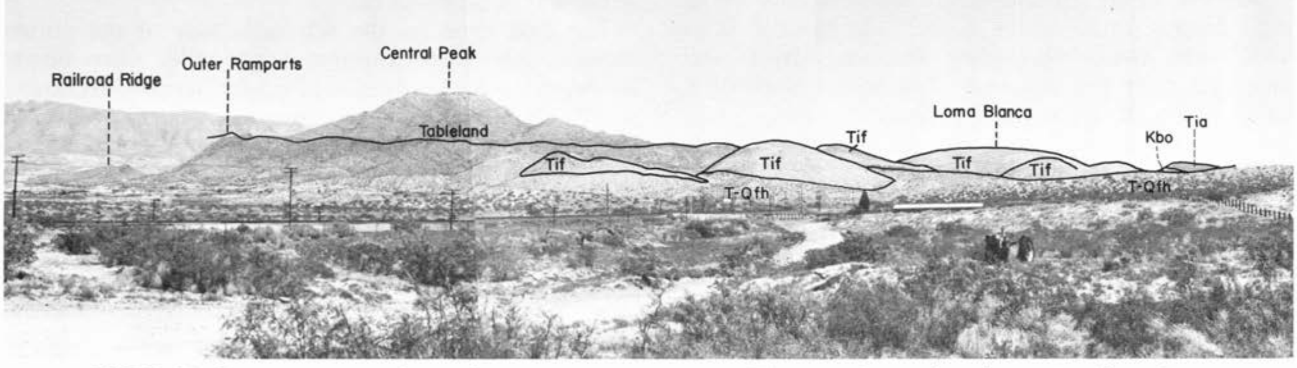

PHOTO 26—GENERAL VIEW OF CRISTO REY UPLIFT FROM THE WEST. View toward east along international boundary, showing central peak, outer ramparts, and tableland of andesite pluton, and the felsite sill around the south side of the uplift.

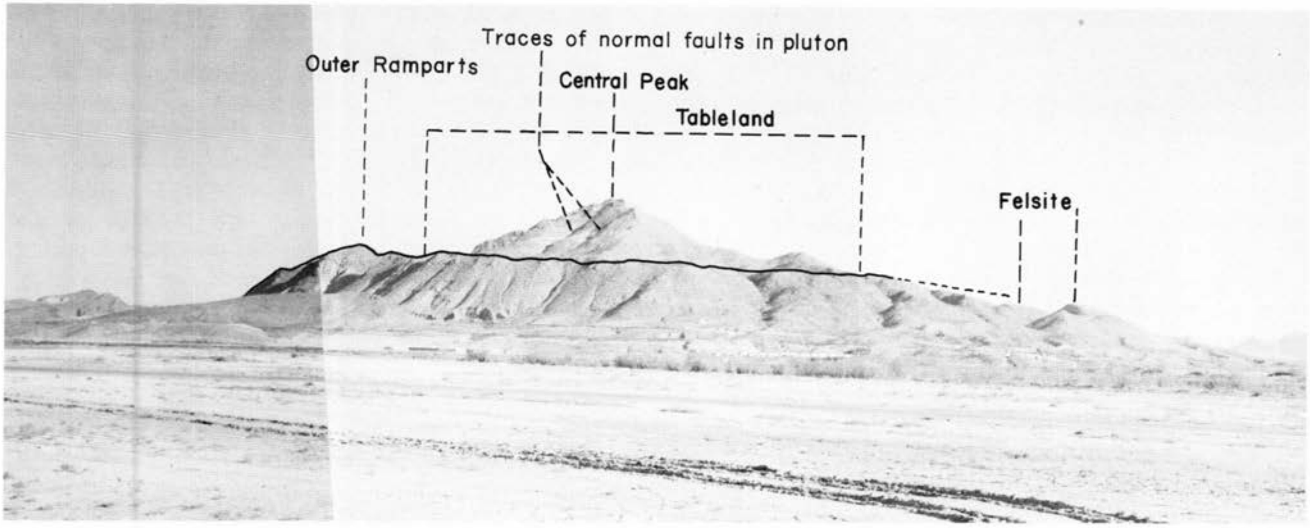

PHOTO 27—General view of Cristo Rey uplift from the northwest. The pluton here presents best its bullseye topographic form, which has suggested to many that the central peak is one intrusion, and the outer ramparts are a ring dike. Traces of several normal faults in the central peak and outward dip of the felsite sill away from the central andesite pluton are evident.

Hancock Formation) are of Blancan age, although he has found no fossils in them older than early Pleistocene (Strain, personal communication). The Fort Hancock sands and clays, derived from northern sources far distant from the region, were carried south by the ancestral Rio Grande before its post-Kansan incision and the inception of its present through-flowing path to the sea. The base of the Santa Fe Group or Fort Hancock Formation of Strain (1966) found on the annulus around Cristo Rey is old alluvium, rich in andesite boulders and grus from the pluton formed on the flanks of the uplift. This material was deposited on an early Pleistocene erosional surface, on which the roof of Cretaceous strata that surmounted the pluton had been stripped and reduced to a belt encircling the exposed intrusion. A broad piedmont surface sloped away from the central massif, and on this pre-Fort Hancock surface the andesite-rich early Fort Hancock alluvium was deposited. Recent erosion has bared these basal conglomerates around Cristo Rey. The base on which these deposits lie is now seen to have undergone differential erosion, with early Fort Hancock stream channels following primarily the shales of the Del Rio and Boquillas Formations, emerging from the pluton through structurally controlled gaps in the upturned strata, as at Bowen and Deep Gulches, Dry Draw, and possibly Refinery Canyon.

The surfaces thus covered by the Fort Hancock basal gravels did not extend over the central peak; on the south side of the uplift between sections 15 and 16 (map I, sheet 1) the deposits can be traced directly onto the tableland. The tableland, therefore, was probably formed before Fort Hancock deposition, although there has been recent modification. However, as these deposits do not reach the central peak or the outer ramparts, the latter existed before deposition of the Fort Hancock.

With the termination of basin filling by these clastic sediments, a broad surface, now called the La Mesa geomorphic surface (Hawley, 1965, p. 188), elevation about 1,345 m (4,100 ft), was formed west of the Franklin Mountains. Onto this alluvial-lacustrine aggradational plain were spread alluvial fans or bajadas from the Franklin Mountains and Sierra de Juarez (Hawley, 1965, p. 188; Lovejoy, 1971), now represented by gently sloping piedmont slopes asymptotic to the La Mesa surface. Viewed from the tableland westward toward the La Mesa surface, the concordance of these elements is apparent. The tableland is not necessarily an extension of the La Mesa surface, but more probably represents a pre-Fort Hancock surface modified by a post-Fort Hancock pedimentation. The outer rampart of the pluton slopes gently westward (photo 27), possibly representing the remnant of an earlier piedmont surface sloping westward from the Franklin Mountains, all other vestiges of which were destroyed by pre-Fort Hancock erosion.

Obviously, the landforms on the Cerro de Cristo Rey pluton may be the result of complex erosional processes. Possibly the present topographic form of the pluton does not reflect in a simple way, or in any way at all, the original pluton geometry as it formed beneath the vault of Cretaceous strata which contained it. Perhaps the boundary between the central peak and the tableland is a simple knickpoint. Thus, an early annular drainage pattern produced on the domed Cretaceous strata, superimposed on the andesite by downcutting, and later modified by Pleistocene pedimentation, formed the present surface on the andesite. On the other hand, the present topographic form of the Cristo Rey pluton may simply represent the erosionally modified original emplacement configuration of the magma body.

LATE GEOMORPHIC HISTORY OF UPLIFT

Around the perimeter of the uplift on the west, north, east, and southeast sides are river-gravel deposits associated with planar terraces or surfaces cut on the annulus in connection with the post-Kansan downcutting of the Rio Grande. Kottlowski (1958) defined two major terraces for the El Paso area associated with this downcutting phase of the river, an older and higher Kern Place terrace, and a lower and younger Gold Hill terrace. Kottlowski showed that the Kern Place pediment graded to an elevation about 40 m (130 ft) above the present Rio Grande flood plain, and that the Gold Hill pediment graded to an elevation about 20 m (70 ft) above the flood plain. Younger pediment surfaces are located from 2-6 m (5-20 ft) above the present flood plain. Hawley (1965, p. 192) correlated the Kern Place surface with the Tortugas surface, the Gold Hill surface with the Picacho surface, and the lower surfaces with the Fort Selden surface.

The highest surface, Tortugas or Kern Place, is preserved between the railroads between sections 1 and 2, where well-developed river gravels lie on a beveled surface of basal gravels of the Fort Hancock Formation. Another similar deposit is present 183 m (600 ft) west of the El Paso Brick Company plant on section 26. Another is 30 m (100 ft) north of section 25. These surfaces are about 52 m (170 ft) above the present river flood plain, but they slope 10° toward the river and grade to a level about 36 m (120 ft) above flood plain. Exotic river gravels abound on these surfaces, even though they slope toward the present river level and are 15 m (50 ft) higher than the graded river surface of Tortugas time.

Another planar surface, cut on Fort Hancock basal conglomerate but not capped by river gravels, is at an elevation of 1,189 m (3,900 ft), approximately 91 m (300 ft) north of section 12 on the west side of the uplift, just below the Muleros Formation outcrop. This also seems to correlate with the Tortugas or Kern Place surface.

A river-gravel deposit on the basal Fort Hancock conglomerate is present in Mexico between sections 21 and 22 about 45 m (150 ft) west of the power line. The elevation has not been determined, but it appears to be part of the Tortugas or Kern Place surface.

Erosion surfaces at various places around the uplift, especially on the south side, appear to be remnants of the Tortugas or Kern Place pediment, but detailed correlation has not been made.

Remnants of a river-gravel-strewn surface are present south of the westbound railroad tracks on the north side of the uplift between section 6 and 8 at elevations of 1,146-1,171 m (3,760-3,840 ft). The surface slopes northward toward the river but seems to be essentially horizontal at an elevation of about 1,146 m (3,760 ft) beneath the power line north of the westbound railroad tracks near the north end of section 6. River elevation is 1,137 m (3,730 ft). Thus, the higher of these gravels seems to correlate with the Picacho or Gold Hill surface, and the lower with the Fort Selden surface. The Picacho surface is fairly well preserved along the Cristo Rey access road just south of the westbound railroad tracks. The gravel pebbles, cobbles, and boulders are all exotic, well rounded, very resistant quartzites, dense extrusive volcanic rocks, and minor extraneous rock types of various origins. The river gravels just above the westbound railroad tracks, about 91 m (300 ft) east of the power line between sections 5 and 6, are probably remnants of the Picacho surface.

Erosional surfaces at various places around the uplift appear to be remnants of both of these surfaces, but no systematic attempt to map them was made in this study.

The river gravels which cap the broad terrace at the very southeastern corner of the map area, adjacent to the Rio Grande at the southeast end of section 22, lie on the Fort Hancock basal conglomerate. These gravels are not more than 23 m (70 ft) above river level and are locally less. Thus, they appear to be part of the Picacho or Gold Hill pediment surface, but they may represent younger surfaces as well.

Metcalf (1969) studied these surfaces in the El Paso region correlating them by means of mollusk species and thereby determining paleogeographic and paleoclimatic conditions. Metcalf (1969, p. 162) summarized knowledge of the age of the Tortugas or Kern Place surface as follows:

> If the Picacho alluvium is actually Altonian-Farmdalian in age, as suggested above, and if some sediments below the older Jornada and La Mesa surfaces are actually Kansan in age . . . , then a general Illinoian/Sangamonian time assignment seems applicable to the Tortugas cycle. The marked period of downcutting, mentioned above, that involved canyons on both sides of the Franklin Mountains before deposition of the Tortugas alluvium may be correlative to the major interval of Pleistocene canyon cutting in the Rocky Mountain region, which Richmond . . . believes to have occurred between equivalents of the Kansan and Illinoian glacial maxima. Possibly such a regionally widespread episode of downcutting might also have been related to initial ingress by headward butting of a lower Rio Grande tributary into the Hueco and Mesilla bolsons and to its early entrenchment in the bolsons. Deposition of the Tortugas alluvium may, then, have occurred in late Illinoian time . . . and genesis of the strong soil of the Tortugas surface during the Sangamonian stage. The Sangamonian soil has been widely reported in the central United States and Rocky Mountain region as an especially strong and salient feature compared to later Pleistocene soils. . . .

Metcalf (1969, p. 160) summarized the work of Hawley, Ruhe, Dunham, and others in determining the age of the Picacho or Gold Hill surface. Soil radiocarbon dates from the Picacho surface range from 14,000 to 27,900 years *B.P.* With margin for error, the alluvium seems to be of early Wisconsinan age (Altonian time).

These facts indicate that river downcutting has proceeded relatively rapidly since Illinoisan time in the Cristo Rey uplift, thereby accounting for the superb exposures of bedrock around the uplift. Post-Illinoisan downcutting has resulted in exposure of most of the structure present around the uplift, because the Fort Hancock basal conglomerate at that time was present over the Eastern Fault-Fold zone, in all of the canyons where the faults of the west, north, and northeast sides of the uplift have been exposed, and along the contact of the intrusion itself. Were it not for this rapid late Pleistocene downcutting associated with the Rio Grande, the pluton and uplift would still be flanked by Fort Hancock deposits and younger alluvium, and the superb exposures of the complex structure of the Cristo Rey cauldron would have been deeply buried. One can only imagine, of course, what remains to be exposed on the south and west sides of the uplift.

Horizon and Depth of Emplacement of Pluton

Although the three-dimensional structure of the Cristo Rey pluton cannot be determined from the work done, analysis of the complexities of the annulus and the peripheral ring permits some tentative conclusions.

The zone of folding along the northeast edge of the pluton contains chevron-folded massive Muleros limestones (section 4). This type of folding suggests that the Muleros has been decoupled from the underlying Smeltertown and Del Norte Formations. However, it seems more reasonable that the Muleros, Smeltertown, and Del Norte strata would have been stripped from the much more massive Finlay and infra-Finlay sequence, because the Smeltertown and Del Norte shales are the lowest highly incompetent beds in the Cretaceous section exposed at Cristo Rey.

One of the indications of the horizon of magma emplacement is circumstantial but suggestive. Both the Inner (including the Northside fault) and Outer faults seem to intersect the andesite at a depth which is near the top of the Finlay Formation. If one assumes a flat-bottomed laccolithic shape for the pluton at its basal contact, then the shape of the peripheral ring, and the dips and geometry of the Inner and Outer faults indicate a magma chamber floored by the top of the Finlay Formation. This hypothetical laccolithic shape of the pluton is depicted in the two major cross sections (sheet 1).

The source of the andesite magma is not known. I have shown (composite cross section 16'-5', sheet I) a source for the pluton beneath its southwestern side. A similar sill-like source is reported for the Elephant Mountain sill by McAnulty (1955, p. 558-559). The abundance of sills and dikes in the infra-Del Norte sequence in the Sierra de Juarez (Wacker, 1972; Campuzano, 1973) suggests a possible source in the southwest. However, magma may have been injected into the infra-Del Norte sequence either through a small stock, perhaps beneath the central peak, or along a dike parallel with and below the zone of N. 60° W. linears. Early injection might have been as a sill, with later swelling forming the laccolith.

The floor of the pluton is shown on the composite cross sections to be slightly folded. The anticline on section 1 l'-22' is the N. 60° E. structural high which may have existed prior to andesite intrusion. The anticline 152 m (500 ft) northeast of the intersection of section 11'-22' and shown on section 16'-5' is the N. 60° W. trending Arroyo arch; the anticline beneath the Northside fault is the Aqueduct anticline, perhaps predating the andesite—the age considered probable for the Power Line syncline and Brick Plant anticline at the level of the Finlay Formation.

The annulus is, in general, a broad dome whose areal extent exceeds that of the peripheral ring and the exposed pluton. This dome might indicate the presence of a very broad, thinner, sill-like pluton at depth which produced a structure larger than that formed by emplacement of the presently exposed andesite. However, the steep walls of the pluton on the north and east, and the generally concordant contacts at the west and southwest do not indicate the existence of a pluton of much greater size than that now exposed. The location of the peripheral ring might indicate the maximum plan-view extent of the pluton at depth.

Neither the total thickness of Boquillas and supra-Boquillas Cretaceous marine or terrestrial deposits, nor that of possible Tertiary terrestrial and volcanic rocks above the Cretaceous strata is known. Andesite plutons are widely distributed in this area (Garcia, 1970), and andesite volcanism may have been widespread. The Eocene Palm Park Formation, north of Las Cruces, contains andesite. Thick sheets of lava, pyroclastic rocks, and associated terrestrial deposits might have existed as they did above the late Oligocene-early Miocene Pine Valley Mountain laccolith in southwestern Utah (Cook, 1957) and above the Oligocene-Miocene intrusive rocks in the southern Jeff Davis Mountains of west Texas (McAnulty, 1955). There are early Tertiary volcanic rocks in the Organ Mountains, Florida Mountains, Dona Ana Mountains, and other ranges near Cristo Rey in southwestern New Mexico (Dane and Bachman, 1965). Preservation of early Tertiary continental deposits in the Big Bend region of Texas (Maxwell, 1968) indicates that early Tertiary volcanics may have existed here as well.

Cascading of Anapra, Del Rio, Buda, and Boquillas beds off the pluton in the Eastern Fault-Fold zone; of Anapra and younger beds in the complex area of the Power Line syncline; and of Mesilla Valley strata near section 9 suggests that near-surface intrusive conditions prevailed. Such sliding would probably have been inhibited by the presence of massive, competent sheets of volcanic rock or by the buttressing effect of great thicknesses of strata above and around the pluton. This cascading constitutes very strong evidence, in my opinion, that magma emplacement occurred near the surface.

If so, there may have been escape to the surface of some of the andesite. The large amount of Anapra sandstone which cascaded into the Eastern Fault-Fold zone strongly suggests a loss of much of the cover above the magma chamber. Great stretching and attenuation of this massive unit to contain the magma seem improbable.

Uplift Structure and Regional Tectonics

The structures in the annulus exhibit characteristics indicative of their guidance by regional stresses, and the regional setting of the uplift suggests regional controls.

The Texas lineament passes N. 60° W. through the region between the southern Franklin Mountains and the Sierra de Juarez (Albritton and Smith, 1957; DeFord, 1969; Muehlberger and Wiley, 1970).

The western boundary fault of the southern Franklin Mountains trends N. 15° W., and the eastern boundary fault strikes north. The western boundary fault of the northern Franklin Mountains also strikes north. Numerous andesite intrusions are present in Mesilla Valley west of the Franklin Mountains (Garcia, 1970), including the Three Sisters group of andesite plutons, which trend N. 25° W., and the Vado Hills (fig. 1). The overall trend of these intrusions from the vicinity of Cristo Rey is about N. 10° W. or parallel with the trend of the western boundary fault of the southern Franklin Mountains.

King (1969) showed a major change in structural trends between the ranges of the Chihuahua tectonic trough and the Basin and Range province. The present study indicates that this change in trend is not quite as sharp as is shown on King's tectonic map, but is more gradual—probably because of the great differences in the scale of the maps. Nevertheless, there is a definite change in structural trend between the Laramide, that is, pre-andesite, structures of the Sierra de Juarez and the Cenozoic structures of the Franklin Mountains. In the Franklin Mountains there are no major thrust faults or folds. The internal structure of the range is very unlike that of the Sierra de Juarez.

The major folds on the north flank of the Cristo Rey annulus range in strike from about N. 20° W. to nearly north, remarkably parallel with the Basin and Range trend, but different from the Chihuahua tectonic trend. Also, many slickensides on the north side of the uplift strike east, normal to many of the fold axes, but neither radial from the pluton nor normal to the Chihuahua tectonic trend. The Power Line syncline obviously has been dislocated by the pluton from its originally N. 10° W. trend, indicating that the syncline had begun to form by mid-Eocene time. The folds on the north have been arched by the pluton; hence they and their associated thrust faults also had been formed by mid-Eocene time.

Many faults within the Cristo Rey uplift are best developed along the northerly Basin and Range trend. The Outer and Inner faults both achieve maximum dip slip where they strike north. The major strike-slip reverse faults on the north side of the pluton trend more northerly at their northern ends. The gravity-glide structures developed primarily along northerly striking faults. The felsite-induced, low-angle thrust faults strike east, and many of the normal faults which formed prior to that thrust in the southeastern section and Fault-Block Mosaic have northerly strikes. Dip slip on the Carousel thrust seems to be greatest where it strikes north at the north end of the uplift.

The major axis of the andesite pluton is N. 60° W., the Texas lineament direction, which is also the direction of the N. 60° W. linears and the Arroyo arch. The Eastern Fault-Fold zone is also best developed in this direction.

These features suggest that, during mid-Eocene time, there was an eastward-directed compressional regional stress field in which the Cristo Rey pluton was emplaced. The regional tectonic overprint on the plutonic tectonism, although not strong, is evident.

Tentative History of Cristo Rey Pluton

PREPLUTON TECTONISM

The Paleozoic(?) Texas lineament (N. 60° W. direction) is between the Franklin Mountains and the Sierra de Juarez, and presumably near Cristo Rey. There is no significant evidence of displacement of the Cretaceous strata in the lineament direction.

The northerly trending thrusts and normal faults and folds north and east of Cristo Rey parallel the Basin and Range system of the Franklin Mountains. Perhaps Basin and Range faulting had begun by mid-Eocene time.

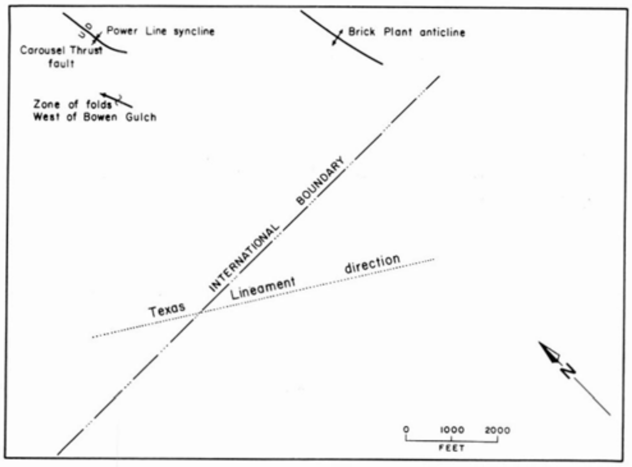

FIGURE 20—PREPLUTON TECTONIC FEATURES. See text for explanation.

EARLY SILL EMPLACEMENT OF PLUTON

Possible positions and orientations of the feeder dike or stock include: 1) beneath the central peak as a circular stock; 2) beneath the southwestern edge along the zone of N. 60° W. linears as a dike; 3) beneath the central peak as a dike aligned a) N. 10° W., b) N. 60° E., or c) N. 30° E.; and 4) beneath the south side of the pluton as a southwest-dipping sill. The andesite presumably intruded along the Del Norte-Finlay contact. It may have been blocked on the east by the Brick Plant anticline. There is no evidence elsewhere of structural limits. Spreading probably stopped because injection into cold rock chilled the magma as it moved along the contact. Its advance stopped when its periphery froze and limited spreading of the sill, thereby initiating arching and magma-chamber inflation.

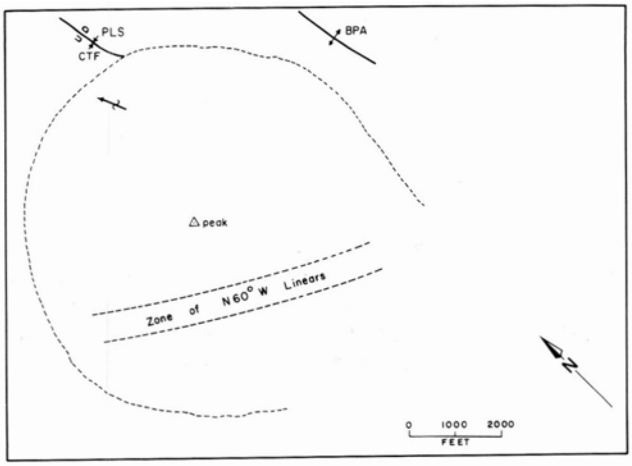

FIGURE 21—EARLY SILL EMPLACEMENT OF PLUTON. See text for explanation.

The sill may have been emplaced to a line beneath the present Outer monocline, Outer fault, Power Line syncline as far as the bend, Border monocline, and felsite zone. On the west it may have extended to a line beneath the present Cretaceous-Pleistocene contact. Its extent southeast is not known. The peripheral ring may coincide with the edge of the sill.

DOMING AND FIRST SUBSIDENCE (STAGE 1)

The sill expanded vertically as magma pressure exceeded lithostatic pressure. Slow arching and stretching of the cover occurred early when dips in the roof beds were low. However, rapid magma rise at the northwest end produced intrusive West End faulting and trapdoor intrusion as the western end of the pluton rose faster than the rest. At the north end of the West End fault, northward cascading replaced intrusive trapdoor faulting. The low-angle, inward-dipping, normal Outer fault resulted from magma motion in the central part of the pluton. The magma raised the roof, pulling it inward as it rose, much as the edges of a tablecloth slide inward when it is lifted vertically from the center of the table. Increasing height of the magma chamber steepened the walls in the peripheral ring on the north and east sides inside the Outer fault. This led to the second stage of magma-chamber inflation.

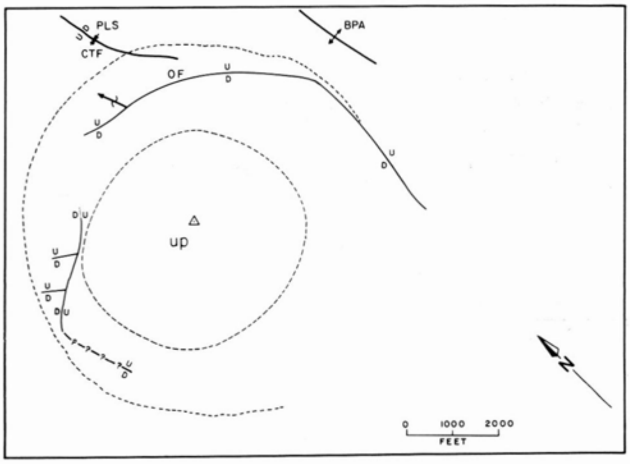

FIGURE 22—MAGMA-CHAMBER INFLATION, STAGE ONE. Doming and first subsidence. See text for explanation.

ROOF FLOATING (STAGE 2)

With disruption of the roof from east to northwest on the Outer fault and on the west side on the West End fault, the roof was partly floating on the magma chamber, but still connected on the south side. Higher temperatures made the roof beds plastic.

Upwelling on the west was accompanied by slow sliding of the roof toward the north and southeast. At the southeast side of the pluton the Power Line syncline and the Aqueduct anticline were compressed. Overturning of the west limb of the syncline accompanied sinking of the synclinal trough into the newly developing fosse as the magma engulfed part of the sliding roof. The gravity gliding along the full length of the Power Line syncline probably began at this stage. South of the Clay Pit cross fault the Aqueduct anticline was raised above the pluton, but north of the cross fault the fold was compressed and pushed aside.

Along the north side between the Outer monocline-Outer fault and the present pluton boundary the roof also was floating. Reverse movement formed on the Outer fault as the magma chamber continued to expand. With continued sundering into the fosse, there was high-level eastward mass movement of magma. This produced the east-dipping N. 30° E. normal faults in the pluton as the semiplastic magma failed by fracture under high rates of stress. In the floating roof it also produced down-on-the-east displacement consecutively on the Bowen Gulch, Deep Gulch, and Dry Draw fault complexes as the magma moved eastward beneath the roof. As the western side of the pluton rose above the eastern side, there was slow minor northward sliding off the roof by the blocks now separated by the Bowen Gulch, Deep Gulch, and Dry Draw faults; each more westerly block slipped off later and farther north than its neighbor on the east, thus accentuating the sill border in the roof and producing the Outer monocline west of the Deep Gulch fault. This sliding was the culmination of the gliding that had begun at the north end of the West End fault. The complex movement of blocks sliding off the unevenly rising pluton chamber, coupled with infraroof drainage of magma eastward during sundering into the fosse, produced the complex strike-slip, subradial faults, with compression normal to the faults along the Bowen Gulch, Deep Gulch, and Dry Draw faults. Perhaps there was an early movement on the Northside fault because none of the subradial faults seems to extend to the pluton; all seem to end at the Northside fault.

Eastward movement of magma into the fosse produced right-lateral shearing in the still-attached roof along the southeastern part. As the magma moved eastward from beneath the gently south-dipping roof, the roof was dragged and broken into blocks to form the Fault-Block Mosaic.

INFLATION AND FIRST FELSITE INTRUSION

West of the major fault in Apache Canyon, magma pressure was directed northward normal to the bottom of upturned roof beds, and the beds were simply raised normal to their bedding. Southeast of Apache Canyon, magma intruded the southwest-dipping beds of the southwest flank of the Aqueduct anticline and pushed against the tops of the beds, shoving them away from the pluton on the Finlay Formation and decoupling folds on the Del Norte and Smeltertown shales. This was one part of a couple which produced right-lateral movement on the Clay Pit cross fault; the other part of the couple was the sinking of the fosse and its rotation inward toward the pluton. These two processes acted together.

With sliding movement of the roof, space may have developed for felsite sill intrusions along the south side of the andesite pluton where the roof was still attached to the country rock. Roof sliding may have aided in opening strata for felsite intrusion, but cessation of andesite emplacement also may have occurred at this time. Early felsite intrusion may have been in the west (in the Muleros Formation) although evidence is lacking; nevertheless, the interpretation seems more in accord with the concept of andesite magma movement toward the east.

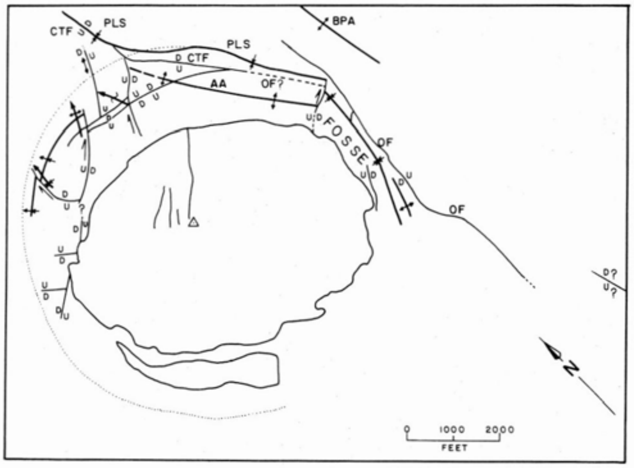

FIGURE 24—CONCLUSION OF STAGE TWO OF MAGMA-CHAMBER INFLATION AND FIRST FELSITE INTRUSION. See text for explanation.

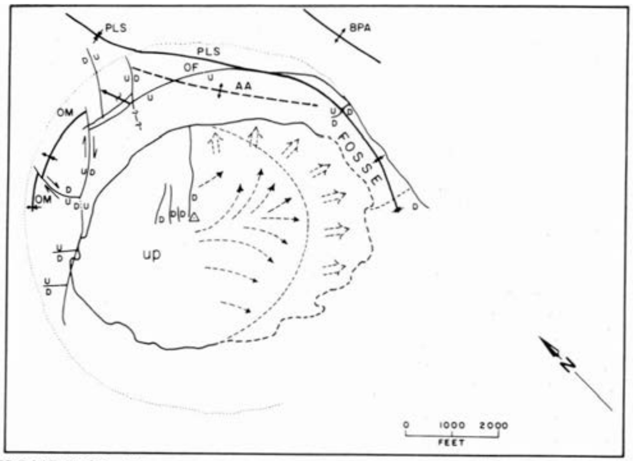

FIGURE 23—MAGMA-CHAMBER INFLATION, STAGE TWO. Roof floating. See text for explanation.

SECOND FELSITE INTRUSION

The two discrete plutons of felsite may have been emplaced simultaneously, but the fact that they follow two different horizons and produced different intrusive structures implies that there were two different periods of felsite intrusion. Emplacement of the higher (overlapping) felsite first would have acted as a deterrent to emplacement of the lower (underlying) felsite; hence the western pluton (intrusive into the Muleros) probably was emplaced first. The general tendency for structural development was from west to east. Emplacement of the western felsite pluton may have taken place during andesite magma movement eastward into the fosse. During this time the Fault-Block Mosaic was formed, but the eastern felsite was not frozen during the time of movements on the faults of the Fault-Block Mosaic. Possibly the second felsite emplacement occurred penecontemporaneously with andesite magma movement eastward into the fosse, because the Anapra sandstone may have been thrust into andesite magma by the eastern felsite intrusion. The sandstone was faulted by the Fault-Block Mosaic, but the felsite was not displaced by the Fault-Block Mosaic which could have completed its development while the felsite was liquid. This analysis suggests that the eastern felsite pluton was emplaced after the western.

The eastern boundary of the felsite pluton may have been the Outer fault. Movement down on the west may have lowered the horizon of felsite intrusion against a barrier in the upthrown block beyond which the felsite intrusion did not penetrate. Although this implies that the felsite was emplaced after the Outer fault formed, displacement of the felsite by the Outer fault is not disproved.

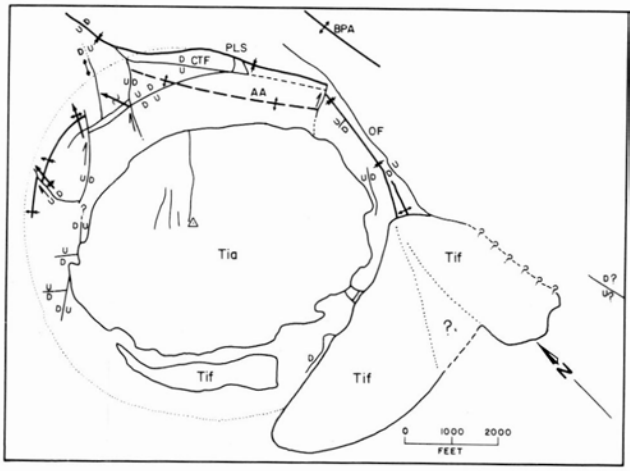

FIGURE 25—SECOND FELSITE INTRUSION. See text for explanation.

SECOND SUBSIDENCE—PRESENT STRUCTURE

Following emplacement of the eastern mass of felsite up to the Outer fault at the southeast corner of the uplift, major movement occurred on the InnerNorthside ring fault, probably as the result of magma withdrawal from the chamber, either back down the vent or up through volcanoes. Perhaps the dikes around the pluton represent the sources of adventive volcanoes. Subsidence of the magma was accompanied by faulting of the country rock adjacent to the magma chamber. Apparently magma had already formed a frozen ring to which the Country rock adhered, and both rocks subsided within the ring fault around the east and north sides of the pluton. The outer ramparts may represent this frozen perimeter of the pluton and the pimply topography may manifest the then unfrozen magma.

The wedge-shaped horst between felsite masses A-B and C displaced the probably once continuous felsite pluton. The possible extension southeast of the Outer and Inner faults, the implied presence of the andesite under the felsite, and the supposed southwestward extension of the felsite imply that the andesite extends southwest, possibly beyond the limits of the map. Plutonism then ceased at Cristo Rey.

POSTINTRUSION DEFORMATION

South of Cerro de Cristo Rey is a small intrusion of similar andesite in the Boquillas Formation, the La Mina Andesite (Garcia, 1970). This andesite apparently has been cut by a north-trending fault that has displaced the La Mina Andesite down on the east less than 30 m (100 ft).

The Franklin Mountains formed during Cenozoic time, and movements on their boundary faults generally are younger than the faults around the Cerro de Cristo Rey pluton.

The zone of N. 60° W. linears in the andesite may have formed as a result of very late and very slight folding along the Arroyo arch trend. There was slight post-andesite deformation by high-angle normal(?) faults in the Sierra de Juarez (Wacker, 1972; Campuzano, 1973), but there also may have been barely detectable folding there as well after andesite emplacement. The andesite is late tectonic in the Sierra de Juarez. Perhaps very minor folding could have taken place with tectonic transport directed about N. 30° E. The N. 25° W. trending River fault probably is the southern end of the Mesilla Valley fault of Blancan-Irvingtonian age. This is the southern end of the east boundary of the Rio Grande rift.

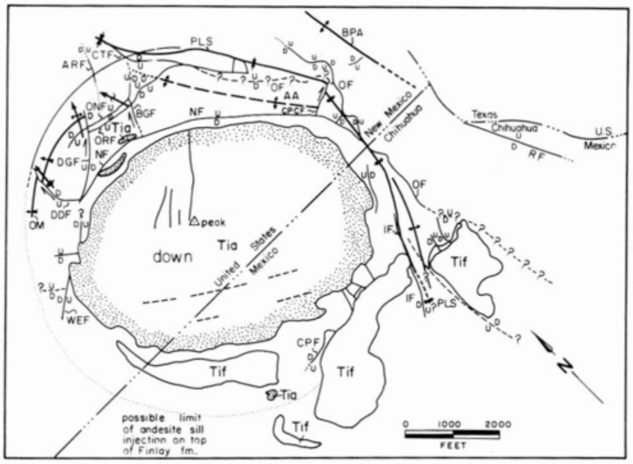

FIGURE 26—SECOND SUBSIDENCE, PRESENT STRUCTURE. See text for explanation.

Faults	
ARF	Access Road fault
BGF	Bowen Gulch fault
CPF	Casa Piedra fault
CTF	Carousel thrust fault
DDF	Dry Draw fault
DGF	Deep Gulch fault
IF	Inner fault
NF	Northside fault
OF	Outer fault
ONF	Outer normal fault
ORF	Outer reverse fault
RF	River fault
WEF	West End fault

	Folds
AA	Aqueduct anticline
BPA	Brick Plant anticline
OM	Outer monocline
PLS	Power Line syncline

	Plutons
Tia	Muleros Andesite
Tif	Loma Blanca Felsite

Problems for Future **Study**

Problems remaining to be solved are:

1. Identification of the Mesilla Valley, Muleros (middle member), and Smeltertown shales along the Northside fault as far west as section 9. Along the Northside fault west of the Cristo Rey access road, the shales include those of the Mesilla Valley, Muleros, and Smeltertown Formations. Incomplete sections, caused by faulting, prevent ready identification of some of these units, and as a result structural interpretations may be incorrect. Very detailed sedimentological and paleontological studies will be required to solve these shale-identification problems.

2. Analyses of all important faults. I strongly suspect that there are other possible interpretations of the sequences of events than those given here, and some of these may completely invalidate some of the conclusions of this report. There still are major problems associated with the Bowen Gulch fault, the Deep Gulch fault, the Northside fault, and the Eastern Fault-Fold zone. I believe that detailed (1:240) plane-table mapping of these is necessary.

3. Analyses of the geomorphic form of the pluton. The geomorphic tripartition of the pluton seems reasonable, but its genesis is not understood. If the pluton were part of a cauldron then the outer ramparts could be a deep source of a ring dike.

4. Geophysical problems. The great amount of magnetite in the andesite indicates that magnetic studies of the pluton should help to outline its geometry. However, the abundant magnetite in the basal conglomerate of the Fort Hancock Formation will create difficulty. Detailed gravity studies should be of great value in determining the structure of the pluton now that thicknesses, density values, and general distributions of the various sedimentary rocks are reasonably well understood. Seismic-reflection studies may define the pluton thickness. Seismic studies around the peripheral ring might give depths to the top of the andesite.

5. Geochemical and petrographic problems in the pluton. Detailed trace-element studies are needed to determine the zoning within the pluton as well as affinities with regional petrologic suites. Petrographic studies of the plutons will augment these geochemical studies and will give a better understanding of the cooling history of the magma. Both are needed to determine the role of assimilations of wall rock by both magmas.

6. Petrofabric problems. In the alluvium around the pluton there are many boulders which contain very well developed flow banding; thus, there must be places in the pluton where flow banding occurs. Detailed petrofabric studies may determine flow directions.

7. Structural studies of the pluton. The joints and faults within the pluton should be mapped in detail to determine the cooling history of the andesite. The zone of N. 60° W. linears is only the most obvious of these joint trends and the N. 30° E. faults are only the most obvious of the faults. Faults with other orientations seem to be confined to the pluton. A detailed study of these joints and faults will decipher the late-stage cooling history of the pluton.

8. Cretaceous stratigraphy. No serious attempt has been made to study the Cretaceous stratigraphy in this project, but now that the distribution of the rocks is well known, detailed study and correlation of the units among Cristo Rey, Sierra de Juarez, and the Franklin Mountains can be made. The units are similar. There seem to be no major changes in stratigraphy between the ranges. If true, then there probably has been no major strike-slip movement on the Texas lineament between the Franklin Mountains and Cristo Rey and the Sierra de Juarez since Albian time. This conclusion has great significance in geotectonic interpretations of North America.

PHOTO 28—"LIGHT AT CRISTO REY" (*photo by Binion*). Andesite boulders in an arroyo in the Cristo Rey pluton (Binion, 1970, p. 20).

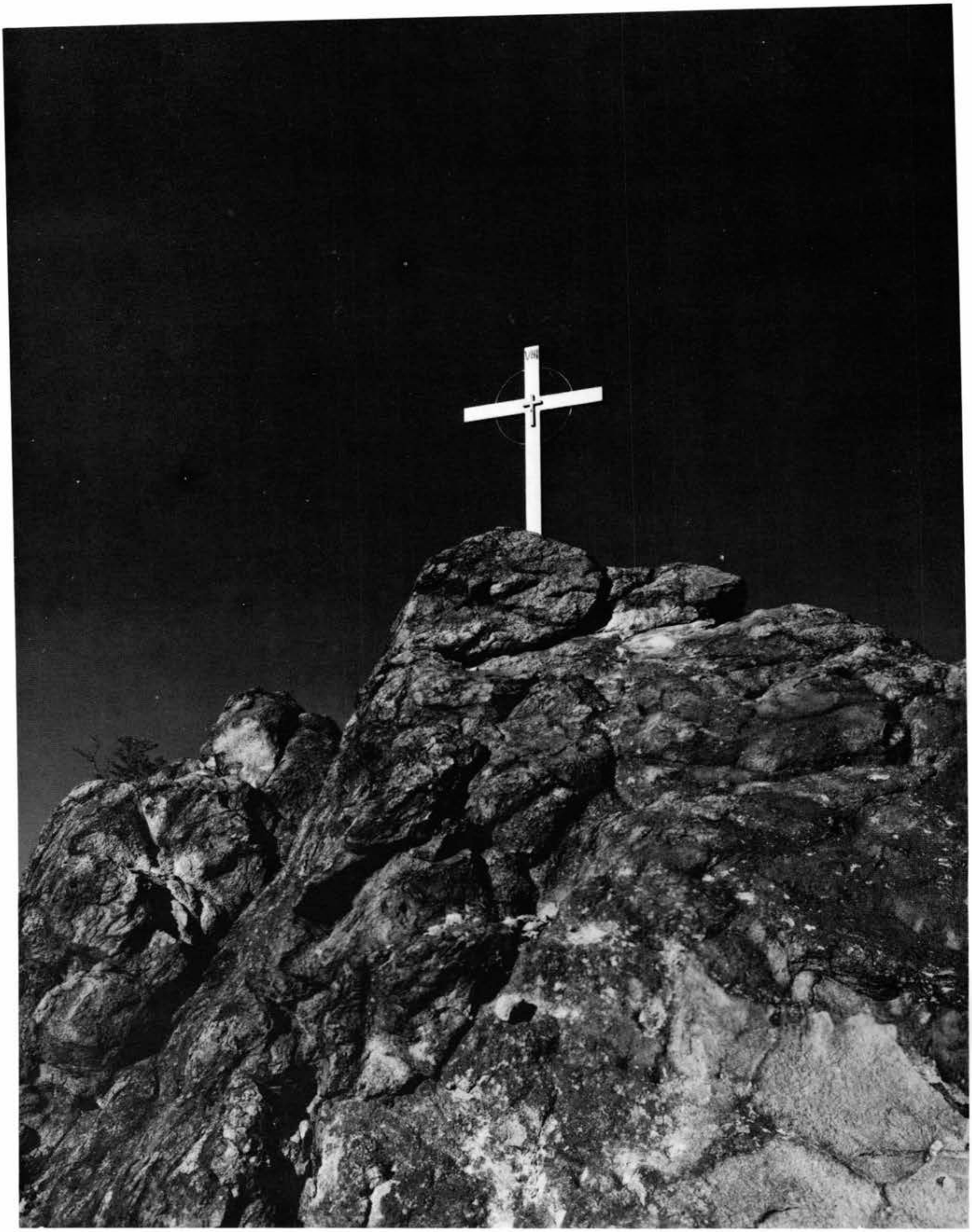

PHOTO 29—STATION OF THE CROSS (*photo by Binion*). One of the stations of the Cross on the trail to the peak at Cristo Rey (Binion, 1970, p. 23).

Summary and Conclusions

The Cerro de Cristo Rey uplift is between the Franklin Mountains of the Basin-and-Range province, and the Sierra de Juarez of the Chihuahua tectonic belt near the alleged Texas lineament. There is little evidence in the Cristo Rey uplift for the presence of the Texas lineament, and only minor circumstantial evidence that there has been active tectonism along a N. 60° W. trend since emplacement of the pluton 45 to 49 m.y. ago.

The uplift was produced by hypabyssal, apparently laccolithic emplacement of a plagioclase-hornblende andesite porphyry into a 300 m (1,000 ft) sequence of Lower Cretaceous marine strata. Around the south and west sides of the andesite pluton is an outward-dipping, synchronous, confocal felsite pluton, primarily a sill 100 m (328 ft) thick.

Major structures associated with the two plutons include: 1) Outer and Inner normal faults, with dip slips in the order of hundreds of meters inclined gently and steeply, respectively, toward the pluton; the faults extend about 180° around the andesite from the northwest to the southwest; 2) a trapdoor fault along the west end of the andesite pluton along which magma uplift raised the magma chamber roof about 213 m (700 ft); 3) a great fosse of country rock in the east end of the andesite pluton which collapsed into the andesite magma chamber, thereby producing alpine-type complex folds and thrust faults, and possibly resulting in partial deroofing of the andesite magma chamber; 4) east-trending, flat thrust faults along the base of the felsite sill which manifest forceful felsite intrusion; 5) normal faults in the andesite pluton apparently caused by slumping of the viscous to partly frozen magma, probably during fosse development; 6) combined reverse- and strike-slip semiradial faults striking obliquely from the andesite pluton on the north side, primarily associated with the pluton emplacement but perhaps associated with prepluton regional tectonism; and 7) small dikes and apophyses near and subparallel with the Inner fault.

The pluton is asymmetrical, with a high central peak northwest of the center of the exposed pluton, and with a high mass at the northwest end. Around the border of the pluton are hills of the outer rampart. Between the central peak and the outer rampart is a tableland lower than both. These three subdivisions of the surface of the andesite pluton form a type of topographic bullseye feature. There is no megascopic evidence of changes in lithology in the three parts of the pluton, but the origin of this tripartite subdivision is not understood.

The exposed pluton has a length (N. 60° W.) to width (N. 30° E.) ratio of about 1.5:1; the length is about 2,000 m (6,560 ft). Strata arched by the pluton and deformation zones around the pluton form a peripheral ring roughly circular in plan about 2,440 m (8,000 ft) in diameter.

These fairly well established facts are interpreted as follows: The Cerro de Cristo Rey uplift is a ring complex. The andesite is the central part, the main magma source. The felsite is a confocal pluton, essentially a sill near the present surface. The Inner and Outer faults probably reached the surface, there to form collapse boundaries along the northern and eastern sides of the pluton. The andesite probably was emplaced as a sill 2,440 m (8,000 ft) in diameter. With continuing rise in pressure the sill bulged up to form an ovoid dome 2,000 m (6,560 ft) long. The west end of the roof was raised on a trapdoor fault. The eastern side of the roof of the andesite pluton fell into the magma chamber much like a Toreva-block landslide, thereby producing very complicated alpine-type structure in a fosse between the Inner and Outer faults. Blocks on the north side of the pluton rotated and slipped as they floated on the magma chamber. Infra-roof magma movement caused these floating blocks to impinge on each other, thereby forming strike-slip movements with major compression normal to the faults. A confocal felsite pluton was emplaced in two separate but connected episodes on the south side of the andesite pluton near the end of andesite pluton emplacement. Late-stage andesite magma withdrawal caused annular subsidence along the Inner fault, which cut the felsite, proving that felsite and andesite emplacements were synchronous.

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Appendix 1 —Explanatory Notes

These 37 notes provide additional details for various subjects treated on the specified pages of the main body of this memoir.

1, p. 21—The origin of some slightly older alluvium on the west side of Cristo Rey about 122 m (400 ft) west of the boundary monument is uncertain. This alluvium is so different in composition from the adjacent modern alluvium and of the basal conglomerate of the Fort Hancock Formation that the alluvium may have originated under different climate conditions. It contains neither andesite nor felsite pebbles, cobbles, or boulders. Deeper weathering apparently produced grus, and no boulders of andesite escaped the deep weathering. Apparently, the felsite also was thoroughly weathered. This climatic condition must have existed a relatively short time ago.

2, p. 23 and 52—Callahan (1972) mapped a felsite dike cutting andesite in the northern Sierra de Juarez, thus showing that the felsite there is younger than the andesite. This does not conflict with the interpretation obtained during this study, but it remains to be demonstrated that all of the andesites are of the same age (which is probably essentially correct, although there might be minor age differences), and that the two felsites observed are cogenetic.

3, p. 24—The Cristo Rey andesite pluton is 2,000 m (6,560 ft) long in a N. 60' W. direction, and 1,380 m (4,530 ft) wide in a N. 30° E. direction with a ratio of 0.68 of width to length or 1.5 of length to width. The outcrop boundary of the pluton consists of arcs of various radii of curvature. From sections 13 to 19 (map I, sheet 1) the radius of curvature is 1,787 m (5,860 ft) with a center midway between on section 5, between 5 and 5', 335 m (1,100 ft) from the pluton contact. From sections 11 to 13 the radius of curvature is 1,787 m (5,860 ft) with the center on section 3, 122 m (400 ft) from the pluton. From sections 19 to 2 the radius of curvature is 1,137 m (3,730 ft) with a center 91 m (300 ft) S. 20° W. from the central peak. From sections 6 to 10 the radius of curvature is 991 m (3,250 ft) with the center at a point about 335 m (1,100 ft) S. 20° W. from the central peak. From section 2 to a point about halfway between sections 4 and 6 the border is essentially straight. Between sections 10 and 11 the radius of curvature is about 418 m (1,370 ft) with the center 418 m (1,370 ft) S. 60° E. of the contact.

4, p. 24—A fifth possible apophysis may have been in the Del Rio Formation just north of section 22; many andesite boulders were observed here very early in the mapping program. It was not known at the time whether these were remnants of the basal part of the Fort Hancock Formation or part of a small apophysis. Since then, the area of the possible apophysis has been quarried and covered with fill, and the exposure no longer exists. The elevation now seems to me to have been much too low for this to have been a remnant of basal Fort Hancock material; hence I believe that this also was an apophysis. Perhaps a magnetic traverse across the locale would detect the apophysis and relocate it.

5, p. 25—Except for the Eastern Fault-Fold zone along the east side of the pluton, and a narrow band in the Fold zone along the northeast side, all Cretaceous strata adjacent to the andesite dip away from the pluton. The width of this zone of quaquaversal dip is not everywhere easily determinable. Along the northeast and east sides of the pluton (between sections 5 and 6; map **I,** sheet 1), the Power Line syncline changes strike wherever it is apparently so close to the pluton that it seems to have been deflected by the intrusive forces. On the basis of major changes of the dips of beds and of strikes of fold axes, the width of the peripheral ring at the various cross sections can be computed. Computations are shown on table 7.

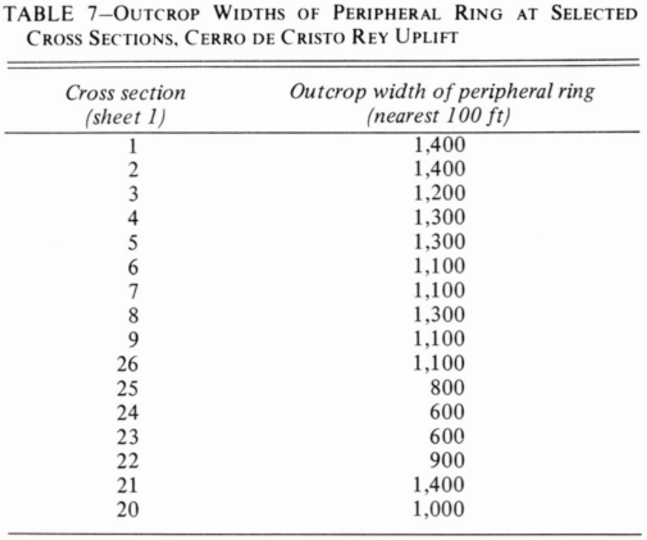

TABLE 7—OUTCROP WIDTHS OF PERIPHERAL RING AT SELECTED CROSS SECTIONS, CERRO DE CRISTO REY UPLIFT

Cross section (sheet 1)	*Outcrop width of peripheral ring (nearest 100 ft)*
1	1,400
2	1,400
3	1,200
4	1,300
5	1,300
6	1,100
7	1,100
8	1,300
9	1,100
26	1,100
25	800
24	600
23	600
22	900
21	1,400
20	1,000

6, p. 26—Several small subradial faults, F_1, F_2 and F_3 are present along the West End fault zone (map VII, sheet 4). F_2 is not located accurately, but is indicated by offsets within and between small isolated outcrops of Buda limestone beds which are surrounded completely by Fort Hancock strata.

7, p. 26—The West End fault (map VII, sheet 4) might have been a preintrusion fault not caused by magma emplacement, but which locally and at a high structural level could have guided the pluton. If so, the strike and dip of the fault before magma emplacement might be determinable, assuming unfolding of the strata and re-rotation of the West End fault to a possible preintrusion orientation.

The beds now strike N. 55° E. and dip 50-70° NW., but before magma emplacement probably were nearly flat. The West End fault now is essentially vertical and strikes N. 50° E. A preintrusion fault therefore may have had a N. 55° E. strike and a dip of 20-40° NW. with displacement down on the northwest (Anapra on the northeast against Muleros). Such a preintrusive fault would have been a northeastward-striking, low-angle, normal fault which was upturned and then engulfed by the andesite. This seems highly improbable; therefore, the West End fault is probably an intrusive fault, caused by trap door plutonic uplift of the sedimentary roof.

8, p. 29—This greater offset may be a result of one of the following: either the Buda-Boquillas contact is less steeply dipping, which, associated with the dip-slip component, could produce a larger offset with unchanged net slip; or there has been shortening of the Anapra section east of the Deep Gulch fault on the Outer reverse fault which caused a change in outcrop width of the Anapra from a normal 67 m (220 ft) to about 37 m (120 ft) west of section 36.

9, p. 30—The Buda limestone beds on the east side of the Dry Draw fault have been displaced and duplicated by F_5 (map V, sheet 3). This fact suggests compression directed at a high angle to, or a clockwise couple applied at, this part of the Dry Draw fault. However, **F5** may be an older thrust fault which has been rotated by movement of the Outer monocline into its present vertical dip (photo 8).

10, p. 30—According to Gussow (1968, p. 19, fig. 1), salt diapirs have steeply plunging fold axes arranged radially around their periphery. These steep to vertical fold axes are produced by the transfer of salt (or other materials) upward through an orifice. Gussow (1968, p. 19) noted "the similarity of Fig. 1 to the Devil's Tower National Monument in northeastern Wyoming. .. ." This is an unfortunate comparison because the vertical columns in the phonolite of the exposed volcanic neck in Devil's Tower National Monument are the result of cooling. The folds which might have been produced in the adjacent intruded Mesozoic strata are not visible at the surface. Thus, there really is no similarity between the cooling columns and the vertical folds to which allusion was made; they are not analogous structures. Another significant difference is that the salt has risen tens of thousands of feet with essentially the same cross section. The direction of tectonic transport (the "a" axis) of the salt is vertical. This is a most interesting feature because the direction of tectonic transport of folds is normal to the axes of the folds, not parallel with them. Of course, a certain amount of material transfer must occur parallel with the "b" axis of a fold (much as a piece of clay is elongated by rolling between the palms), but the essential direction of tectonic transport is normal to the "b" axis of the fold. Thus, in salt diapirs the direction of tectonic transport of the salt and the direction of the "b" axes of the folds are parallel.

Around the contact of the Cristo Rey pluton, fold axes are generally subhorizontal and aligned essentially parallel with the contact of the intrusion. This is best illustrated in the Mesilla Valley shales along the north side of the Cristo Rey pluton (photo 12). Thus, the evidence at Cristo Rey does not support the interpretation offered by Gussow (1968) for salt diapirs.

The fold axes which strike directly toward the pluton need not be considered as the result of pluton emplacement at Cristo Rey. On the contrary, the evidence indicates that the folds which strike directly into the pluton are older than the pluton and have been deformed by it. As is shown in this report, the Power Line syncline seems to have been pushed aside by the pluton. This indicates that the folds were produced before pluton emplacement and were deformed (even if enlarged by pluton-induced pressures) by the pluton.

11, p. 33—The Outer fault is spatially and genetically related to the pluton and is synintrusive. The Aqueduct anticline is now wrapped around the northeast side of the pluton but projects N. 15° W. at its northern end. The Outer fault cuts the Aqueduct anticline at a high angle. The interpretation that the Outer fault follows the west flank of the Power Line syncline implies that the fault and the syncline are genetically related. However, the Outer fault may cross the trace of the Power Line syncline at Refinery Canyon (perhaps forming the structural break through which the canyon was later cut); the fault seems not to follow precisely one flank of the syncline. Perhaps the Outer fault developed at a specific distance from the pluton. Because the syncline trace approaches the pluton at its northeast corner, the Outer fault may have been forced to cross the syncline, even though the syncline may have predated the Outer fault and its western flank partly guided it.

12, p. 33—In the eastbound railroad cut between sections 5 and 7 (map I, sheet 1; map II, sheet 2), the Mesilla Valley shales are exceptionally thick and very strongly contorted. This contortion is apparently not due simply to the great amount of folding in the fold zone but to movements along a fault which trends northeast through this zone. The great amount of folding and faulting and the apparent thickening of the Mesilla Valley shale to more than 91 m (300 ft) suggest the presence of a southwest-dipping thrust or reverse fault, not a normal fault. Between this zone in the railroad cut (between sections 5 and 7) and the southern end of the traced Carousel thrust at section 5, the Mesilla Valley shales are either covered by colluvium or have been quarried out and are covered by fill; therefore, nothing can be determined structurally in this zone. There are some folds in the Mesilla Valley shale in section 5 at the north side of the quarry which could be associated with either the Outer fault or the Carousel thrust. Also, west of the zone in the railroad cut, the Mesilla Valley shale is covered by colluvium or fill. Thus, the excessive thickness of Mesilla Valley in the railroad cut indicates the presence of a fairly large thrust or reverse fault striking northeast which cannot be related to any other fault in the area. If the Aqueduct anticline overlies the Carousel thrust north of 5, the Carousel thrust may underlie the Aqueduct anticline in the railroad cut, and its apparent position can be explained as the result of the intersection of the present very irregular topographic surface and the low southwest dip of the thrust. The trace of this thrust, now upturned where it has been arched by the peripheral ring, might continue toward the southwest under the alluvium near the mouth of Apache Canyon. Thus, the andesite would have intruded the Carousel thrust near Apache Canyon.

13, p. 34—Bose (1910, p. 46) wrote:

> Parece que el sinclinal de la zona de fracturamiento es casi recto; pero en realidad es esto solo aparente y la zona plegada de la vuelta desde el Este del cerro al Noreste y Norte, de modo que los pliegues siguen en lo general el rumbo de la bóveda. Lo ùnico que puede ser considerado como sospechoso es la existencia de un ligero sinclinal en el Norte; pero este se podria quiza explicar por la suposición de que este sinclinal no fuera más que la ùltima ondulación producido por la zona de fracturamiento; puede haberse formado durante el levantamiento de la bóveda, si en su lugar hubo una zona débil; en este caso rompió el pórfiro las rocas sedimentarias y las invirtió pars abrirse paso hacia arriba.
>
> *(Translation:* It appears that the syncline of the fracture zone is almost straight; however, in reality, the straightness is only apparent and the zone is folded from the corner at the east end of the mountain toward the northeast and north, with the result that the folds generally parallel the strike of the [igneous] uplift. The only factor which is suspect is the presence of a gentle syncline in the north; however, this possibly can be explained by supposing that this syncline is just the last fold produced by movement along the fracture zone; it may have formed during the rise of the [igneous] uplift, if a zone of weakness were present there; in such a case the porphyry broke the sedimentary rocks and inverted them to open for itself a passageway upward.)

14, p. 34—Because the landslide debris along the east side of Power Line Ridge (map V, sheet 3) covers the entire Anapra-Mesilla Valley contact, an indirect method of determining the cross sections was followed. First, the position of the trace of the syncline was estimated on the basis of outcrop dip and strike. This is shown on map V, sheet 3. Second, from the elevation of the Del Rio-Anapra contact at section 45, and the elevation of the top of the Buda limestone beds where the Cretaceous strata disappear under the Rio Grande alluvium at the north end of the map, an average plunge gradient of about 11 percent was determined. The elevation of the Anapra-Mesilla Valley contact was placed 64 m (210 ft) below the Del Rio-Anapra contact. Toward the south the contact of the Anapra-Mesilla Valley at section 56, map VI, sheet 3, was compared with the presumed Anapra-Mesilla Valley contact at section 45, and a gradient of **10** percent was obtained south of section 45. Use of these gradients permitted the reconstruction of the assumed locus of the axial surface of the syncline, the dips of the exposed beds, and the average stratigraphic thicknesses.

With the Mesilla Valley-Anapra contact thus determined, the depth to the base of the Mesilla Valley shale was determinable, with the use of a thickness of 55 m (180 ft) for this formation. These reconstructed interpretative cross sections are shown in section B, sheet 5. The structure as interpreted is shown on map VII, sheet 4. As here interpreted, the Power Line syncline locally has been greatly deformed by subsequent gravity-glide sliding, perhaps by two phases of deformation, the earlier involving the formation of the Carousel thrust and the major Power Line syncline itself, and then later producing the gravity sliding. The question of timing is important, however, because the gravity gliding could have occurred either contemporaneously with, but late in, the process of formation of the syncline, or discontinuously at a later time.

The Power Line syncline gravity-glide block was cut off at its southern end by the Cross fault, **F8** at section 52 (see photo 11). North of that fault, gliding occurred on $_a$/ **F**$_{16}$ and F2/F1 6-15. The small triangular mass at section 48 bounded by **F6** and F_7 is thought to be a mass of Anapra sandstone which moved northward from the block south of it, as shown by the slickensides along sections 47-48. Another small glide block was bounded by F_{13} on the west side and possibly F_{10} on the east side. Gliding seems to have taken place as far north as a point midway between sections 5 and 6 (map I, sheet 1), on the east side of Power Line Ridge, where small folds A_1, S_1, and **A2** are in Anapra sandstone strata. This seems to represent the northern end of the zone of gliding.

15, p. 35—The Power Line syncline and Gravity Glide zone could have formed separately or together. If separately, the gravity glide could have formed before or after syncline formation. That the gravity-glide Anapra (allochthonous) beds also are synclinally folded suggests that the allochthon might have formed before synclinal folding. However, evidence and analysis do not favor this interpretation. First, moderately dipping (20°-45°) to vertical Anapra strata on both sides of the syncline are cut at very high angles by northeasterly dipping, subhorizontal faults with highly polished and slickensided surfaces, which suggest that the beds had their present high dips before the formation of these low-angle faults. Rotation of the steep dips of the Anapra sandstone on the west side of the syncline back to the horizontal would produce very steep fault-surface dips (more than 60°) toward the pluton. This suggests rather strongly that the faulting occurred after the Anapra sandstone beds of the syncline had acquired their present steep dips. Second, gravity gliding would have required a difference in elevation, higher on the southwest and lower on the northeast. Before synclinal folding, there would have been no such difference in elevation. Accordingly, gravity gliding occurred either during or after synclinal folding.

If the gravity gliding took place during synclinal folding, it had to take place late in the period of folding, because the highly polished and slickensided fault surface associated with the gravity glide cut across the Anapra beds at high angles; thus, the syncline must already have been formed much as it is now by the time gravity gliding had taken place. Therefore, the gravity glide formed either 1) as the latest stage of synclinal folding, or 2) at a distinctly later time (see fig. 11 for one interpretation).

Slickensides in the Power Line syncline are present throughout the Buda and Anapra Formations (map II, sheet 2). One major set of slickensides strikes west to west-northwest, especially north of the major bend of the syncline. There are few slickensides which point toward the pluton north of the bend of the syncline. This fact strongly suggests tectonic transport not associated with pluton emplacement. South of the bend of the syncline, slickensides which point toward the pluton are more pronounced. All this evidence indicates that the Power Line syncline was formed by major stresses not directed radially outward from the pluton; rather, the evidence implies that the syncline was formed earlier by tectonic stresses and deformed later by plutonic stresses. South of the bend of the syncline, one major direction of slickensides on the flat faults is away from the west end of the pluton, and another major set is away from the center of the pluton. This fact suggests that movement away from the pluton may have taken place in two separate stages, one when pluton emplacement began near its west end, and the second when the pluton expanded toward the east. This suggests that gravity gliding was associated with pluton emplacement.

16, p. 37—F_a (map IX, sheet 4) juxtaposes the Del Norte and Smeltertown Formations, but cannot be traced east or west beneath the alluvium. Its significance is not known. It may be associated with the general structural depression of the region south of the Clay Pit cross fault. Displacement appears not to be more than a few tens of feet.

Fb is in Smeltertown shales and is poorly exposed on the colluvium-obscured slope, but is exposed in the railroad cut. It appears to be dipping west and is a normal fault, with only minor displacement.

17, p. 37—The loss of section indicates two possibilities for this fault; first, it may be a normal fault, dipping west, with dip steeper than the dip of the beds; second, it may be a reverse fault, dipping west, with dip less than the dip of the beds. Either interpretation would account for the loss of Mesilla Valley section. An east-dipping fault does not fit the outcrop pattern of the contact of the Mesilla Valley and Muleros Formations. **Fd** seems to continue around the north side of the Anapra exposure at section 56, hidden by colluvium on the Mesilla Valley shale, and may extend under the alluvium of Refinery Canyon, causing the overturning of the Muleros limestones. If **Fd** is a reverse fault, it may have developed during the formation of S_1. If **Fd** is a normal fault, it would also follow the same trace, but this interpretation would not explain the overturning of the Muleros strata at the edge of the alluvium in Refinery Canyon. However, the Muleros beds are overturned as far south as section 56. This might be the result of both normal and reverse movements on **Fd.** Perhaps this overturning may be explained as the result of tight folding in the Muleros limestone of the Fold zone and not as the result of reverse movement on $\mathbf{F_d}$**.**

18, p. 37—Obviously, the major washes on the north side of the pluton pass through the Anapra sandstone only where there are structural breaks, and the presence of Refinery Canyon implies the existence of a structural break here as well. The only fault which might have produced that structural break seems to be the Outer fault, which was exposed on the west side of the syncline north of Refinery Canyon and on the east side of the syncline south of the canyon.

19, p. 38—South of F_e, Ff (map VI, sheet 3; map IX, sheet 4) must displace the Mesilla Valley Formation, which appears to be only 45 m (150 ft) thick at section 58. Stratigraphic displacement on Ff seems to be less than 15 m (50 ft) and may increase southward, because the measured apparent thickness of the Mesilla Valley Formation decreases from sections 58 to 61. Ff may be the southern continuation of **Fd.** Displacement on Fd seems to be small between the north edge of the map and section 61. Ff may follow the Anapra-Mesilla Valley contact, and may be the southern offset continuation of **Fd.**

$\mathbf{F_b}$ and F_c seem not to continue south of 56 through sections 57-60. The slopes are covered with colluvium; exposures are poor, and $\mathbf{F_e}$ may not terminate those faults. Fc may extend across sections 57 through 58, or it may once have been continuous with Ff and later offset by movement at F_e. The location of the fault in the Mesilla Valley shale at section 58 is conjectural.

F_g and its branch F_g' are reverse faults which could have formed with $\mathbf{F_e}$ and S_1. There is intense brecciation at the junction of g and F_e suggesting contemporaneous formation. If g formed with S_1, possibly Fd and g are offset parts of the same (reverse) fault. g may represent later reverse faulting which accompanied possible late reverse movement on $\mathbf{F_d}$**.**

20, p. 38—Between sections 57 and 61 (map VI, sheet 3; map IX, sheet 4) the Anapra sandstone on the east flank of S_1 is too thin. Several faults must extend along this flank essentially parallel with the strike of the beds. Evidence for F_{100} has been found in new quarry exposures. F_{100} is east of g and includes part of $g_{'}$. F_f, $g_{'}$, $g_{,}$ and F100 together constitute a rather complicated zone.

21, p. 38—Area A (map IX, sheet 4) probably is the brecciated fault zone of F_f. The east side of area A is the footwall of **Ff,** and the west side of area A is the hanging wall. Thus, **Ff =** F_1 and the small block of Anapra west of area A in section 62 is a fault sliver in **Ff =** $\mathbf{F_1}$**.** Also westward dips for $\mathbf{F_f}$ and F_1 would explain the geometry. Because **Ff** may dip parallel with the beds of the Mesilla Valley shales, a large dip slip may manifest itself as only a very slight stratigraphic separation.

22, p. 39—F_1 may continue north as F10**0** **F**g, and $g_{'}$ (map VI, sheet 3; map IX, sheet 4). These faults may represent splays or horsetails at the north end of F_1 near F_e. F_e and F_1 probably formed together and, with each movement on one, there was movement on the other. Thus, no single fault passes through F_e; rather, F_1 split each time there was renewed movement on F_e. For this reason, several faults also may be present north of F_e. $\mathbf{F_b}$**,** $\mathbf{F_e}$**,** $\mathbf{F_d}$**,** $g_{''}$, and possibly a fault west of S_1 are probable structural extensions of Ff, F100 **F**$g_{'}$, and $g_{,}$ but which fault on the south matches with a particular fault on the north might be very difficult to determine. Tentatively, Ff, F_c, $g_{,}$ and $g_{'}$ = $g_{''}$; and F100 = Fd, but the problem is far from solved.

Along F_1 (= Ff) displacement is down on the west side of the trace, approximately equal to almost the entire thickness of the Anapra Formation. At section 61 the Del Rio-Anapra contact is at an elevation of 1,186 m (3,890 ft). The Anapra sandstone is normally 64 m (210 ft) thick, but it is about 45 m (150 ft) thick east of S_1 between sections 60 and 62. Displacement on F^i (= Ff) is at least 58 m (190 ft) up on the east. The actual trace of F_i (= Ff) now is everywhere covered by road and quarry fill, but when I first visited this area in 1966, evidence suggested that east of S, a fault zone might exist where F_i is now drawn.

23, p. 39—Displacement in the F_1 zone midway between sections 62 and 63 (map VI, sheet 3; map IX, sheet 4) is about 113 m (370 ft). Thus F_1 has 24 m (80 ft) less displacement there than it has south of 63. This might be the displacement of Ff at 61. This is not unreasonable for the loss of section in the Mesilla Valley Formation caused by Ff but, again, dip slip on **Ff** may greatly exceed stratigraphic separation; stratigraphic separation on $\mathbf{F_f}$ north of 61 seems to be very small.

F4 probably extends north of section 63 to sections 61 or 60 to merge with the Northside fault. West of **F4** and south of 61 the entire Mesilla Valley and Anapra section has been raised to vertical-to-overturned dips west of the trace of **S4 ;** **S4** extends north to 61.

24, p. 39—Just east of F_1 at sections 69-72 **(map IX,** sheet 4; map VI, sheet 3) there are very sharp folds, including A_{ob}, in the Mesilla Valley shale that do not look as if they were formed by simple normal movement on F_1. These folds may be the result of **1)** pre-fault tectonism, or 2) reverse movement on the normal F_1 as the result of post-normal F, compression. I believe that the second possibility is more consistent with what has been determined. The thick breccia zone in the F_1 fault zone seems to signify either repeated opposite movement on F_1, or faulting very near the surface where confining pressure was low, or both.

In general, the strata of the Border monocline meet F_1 with no major change in dip. But at section 75 through section 79, A_{oa} is east of F_1. **Aoa** is probably the southern continuation of A_{ob} ; A_{oa} is in the east wall block of F_1 and is covered by breccia in the west wall between sections 74 and 76. Thus the Border monocline does not simply depress.the strata toward the west here as it does on the north. A west-dipping normal fault F_m is present along the east flank of $\mathbf{A_{oa}}$**.** A_{oa} and F_1 appear to have trends diverging toward the south. F_m parallels **Aoa**$^{-}$**Aob** could be the result of 1) pre-fault compression, or 2) post-fault compression, or 3) fault compression during reverse movement along F_1.

25, p. 42—Between sections 68 and 81 (map VI, sheet 3; map IX, sheet 4) west of **F4** there is a long, west-dipping reverse fault, **F6** ; which is determined by displacements of 1) the Buda limestone between sections 68 and 69, and 2) the Anapra-Del Rio contact at section 71, as well as duplication of the Anapra sandstone at section 77 (not precisely mapped), and thinning of the Mesilla Valley shale just north of 81. If this fault cuts the Buda, it might join **F4** at 68; **F6**

seems to be cut by, or stops at F_4. The amount of stratigraphic separation on F_6 at 77 appears to be nowhere greater than about 15-20 m (50-66 ft). The trace could not be followed in the field because of colluvial cover on the Mesilla Valley and is entirely interpretive south of 77.

F_6 has a surface trace as constructed parallel with that of F_4 and F_5 south of 78.

26, p. 42—Southwest of section 84, S_4 and F_4 have parallel traces (map VI, sheet 3; map IX, sheet 4). Southwest of section 86 both turn abruptly from S. 40° W. to about S. 15° E. The close spatial relation from 61 to 86 certainly implies a genetic association between F_4 and S_4. The original trend of S_4 was perhaps N. 15° W., and emplacement of the pluton bent S_4, beginning at 86, to form a curved trace around the east end of the pluton between sections 86 and 61. F_4 may have formed on the east flank of S_4 because the west dip of the beds there aligns major zones of bedding-plane weaknesses with the major planes. of maximum shear stress which induced F_4. If this is true, then F_4, which cuts S_4 and is obviously younger than S_4, merely has a close spatial relation, but S_4 and F_4 did not form as responses to the same set of contemporaneous stresses.

A_3 is between F_4 and F_1 at 82. There is a broad, gentle anticline at the south end of the fosse, where a small horst-like block parallels the crest of A_3. At 82 the east flank of A_3, perhaps the west flank of a syncline (S_2) is overturned, and F_3 may extend south in the Del Rio shales. Overturning on the east flank of A_3 may have produced minor thrusting or. F_3. F_3 could have faulted syncline S2 CO. Minor right-lateral strike-slip faults, F_{14a} and F_{14b} adjacent to A_3 between sections 81 and 82, indicate eastward movement of the north side. At 81 just west of F_1 is an outlier of a thrust allochthon composed of Anapra sandstone with vertical bedding, lying on Buda limestone which is gently folded into a broad rippled anticline, A_{1a}. This allochthonous mass of Anapra sandstone may have been emplaced by movement of cascading Anapra sandstone beds off of S_4 during thrusting on F_6, or by movement of cascading Anapra beds off F_3.

F_3 may be the locus of syncline S2, which has been elided at ground level by the thrusting and associated very tight folding. Nevertheless, there seems good reason to place a syncline, S_2, between two anticlines, A_3 and A1a. The overturning of A_3 and subsequent thrusting or gravity gliding from the upper limb of A_3 could have emplaced the Anapra outlier at 81.

F_2 between sections 80 and 81 is a complex fault. Near 80 F_2 seems to split into two faults F_{2a} and Feb, but this is not really the case, because north of this split, F_{2a} is a normal fault with Buda down on the west against Del Rio on the east, whereas F_2 b is a reverse fault with Anapra up on the west brought up against Del Rio on the east. Possibly there have been movements in two different directions on F_2 , just as on F_c in the railroad cut, as noted elsewhere. F_2 b and F_3 may be parts of the same major reverse fault. Very little more can be learned about this complicated fault zone, however, for the two faults are cut by F_4 , and disappear beneath S_4 north of section 80; they must be older than F_4.

27, p. 42—F_1 splits into F_{1a} and F_ib between sections 80 and 81 (map VI, sheet 3; map IX, sheet 4) and becomes two bounding faults for a fault splinter at 80. Thus area C is really only a fault slice in F_1.

F,, east of F_1 is a reverse fault, perhaps genetically related to A_{oa} and A_ob and to reverse movement on F_1. The age relation of this fold and reverse fault east of F_1 is not known.

A_{1a} plunges very gently north at 80 and disappears beneath F_4 between sections 79 and 80. A_{1a}, in Buda and Del Rio strata, appears to have involved Anapra beds at the gully between 79 and 80. Another anticline, A_1b, is present at 78 in the Anapra sandstone. Possibly A_1 a and A_1 b are the same, separated by right-lateral strike slip along an unknown fault which strikes down the gully between 79 and 80. Such a fault does not appear to have offset F_1; thus, it would either be older than F_1 or terminate at F_1. On the other hand, there may be no cross fault, and A_i a and A_1 b may be two different anticlines. As these are not very well defined folds, and the dips on their flanks are very gentle, these two anticlines may represent only slight warping of the Anapra sandstone.

28, p. 42—S_2, in the tightly folded Buda limestone between sections 73 and 75 (map IX, sheet 4), seems to have been cross faulted by a right-lateral strike-slip fault, F_{20}, between 75 and 76. F_{20}, which separates Buda blocks C and D, cannot be traced westward through the Anapra sandstone; it does not displace F_1 or F_4, and thus is confined to the Interior Complex belt. F_{20} must be older than F_4 but could have been terminated at F_1. It also seems that Anapra sandstone has been thrust over the folded Buda limestone on F_3 at sections 76 and 77. There is no Del Rio between the two formations. F_3 is probably genetically associated with A_3; the fold is oversteepened here and becomes a thrust fault.

29, p. 42—Buda limestone blocks A and B, between sections 62 and 67 (map VI, sheet 3; map IX, sheet 4) seems to have been displaced by the left-lateral, strike-slip cross fault, F_{30}. This fault cuts neither F_1 nor F_4 and appears to be confined to the Interior Complex belt. The combination of movements on the three cross faults (that is, the probable one in the arroyo between 79 and 80, F20 between 75 and 76, and F_{30} between 63 and 64) suggests that there was outward and eastward movement of the central part of the Interior Complex belt between sections 63 and 75.

30, p. 42—In general, the Power Line syncline (map VI, sheet 3; map IX, sheet 4) is asymmetrical, with its axial surface dipping west. At its north end, where bounded on the west by the Carousel thrust, the west flank of the syncline locally is vertical, and the east flank dips 30° W. At the bend in the syncline near power pole 12 north of section 5, the west flank of the syncline also is essentially vertical. In the Gravity Glide region the fold is asymmetrical, but this is partly the result of gravity gliding. Nonetheless, the asymmetry is in the same direction. Just south of the Clay Pit cross fault the fold is also asymmetrical, with beds on the west vertical to overturned, and those on the east dipping 35° W. South of section 63 the west flank of S_4 is vertical and overturned; the dips of the flank are as low as 20° (overturned) near 72. The overturned beds steepen to vertical at the Arroyo arch, south of which they flatten to gentle southeast dips. Apparently, this asymmetry of the syncline was formed by the pluton, but whether the syncline originated as the result of pluton emplacement is still a moot point.

31, p. 49—The amount of contact metamorphism in most places depends on the distance from the felsite, but there are local examples of unmetamorphosed materials fairly close to the felsite. All Boquillas calcareous shales are baked hard and appear on the outcrops as dark-gray, thin-bedded hornfels. The Buda limestone is megascopically recrystallized, even within a few feet of the felsite contact, but there are stringers and veinlets of secondary calcite throughout the limestone. The Buda (drier) limestone seems to have withstood the thermal and metasomatic effects of contact metamorphism much more than did the Boquillas and Del Rio (wetter) calcareous shales. The Del Rio calcareous shales are baked locally to a hard, light-colored, dense hornfels, in which unidentified calc-silicate minerals have developed. The Del Rio hornfels is much more massive and much lighter colored than is the Boquillas hornfels, making them generally, but not everywhere, readily distinguishable.

32, p. 49—On the east side of the zone at 21 about 1.5 m (5 ft) of Boquillas hornfels lies in contact with the felsite (map I, sheet 1; cross sections XII, sheet 6). About 2 m (7 ft) of Buda limestone separates the Del Rio Formation from the Boquillas hornfels; the Buda is brecciated and cut by veins of secondary calcite. Bedding in the Buda is not visible. The Del Rio Formation is about 14 m (45 ft) thick; if there has been no thinning of the Del Rio around the uplift as the result of original depositional changes, then the thinning here is tectonic or associated with the intrusion of the felsite. Traced along strike westward in the arroyo, the Del Rio disappears completely and the Buda limestone lies in fault contact on the Anapra sandstone, thrust onto One sandstone apparently by the intrusion of the felsite. One small outlier of Buda limestone rests on the Anapra sandstone, about midway between sections 20 and 21 on the north side of the wash.

33, p. 50—A small isolated outcrop of Buda limestone is preserved within the felsite about 30 m (100 ft) southwest of the southeastern end of section 20 (map I, sheet 1). There is not enough evidence to determine if this is a big xenolith or part of *in situ* country rock. The fact that the Buda here is structurally higher than the Boquillas, which crops out at the edge of the south-dipping felsite 122 m (400 ft) on the north, indicates either that there is a fault between these exposures, or that the Buda beds represent a xenolith carried upward from some point beneath the Boquillas Formation into which the felsite has intruded essentially as a sill.

34, p. 50—F_1, the Casa Piedra fault (map III, sheet 2) is a very low-angle, north-dipping fault (fig. 19, 171-$1_7$1', and 17_2-17_2'; photo 23). Along the east end of the fault Del Rio and Buda beds moved north over Anapra beds. The fault is exposed at those contacts. Northward the Anapra sandstone dips steeply but ends downward abruptly against underlying Mesilla Valley shale and limestone; the actual contact cannot be seen, but the presence of the fault is obvious from the stratigraphy. Its general slight northerly dip can be observed from afar (photo 23). Westward the Anapra sandstone crops out but the fault is covered. Along the straight trend of F_1 on the west, the Anapra sandstone is only 3-6 m (10-20 ft) thick; the fault seems to separate the Anapra from the Mesilla Valley, but a fault, Fla, between the Anapra and the Del Rio dips about 60° S., apparently down on the south. Stratigraphic separation on F_{1a} is about 60 m (200 ft). This particular fault may be significant.

The **F_2** complex is a part of a small but confusing structure (fig. 19, 171-17i'). The stratigraphic sequence from north to south here is Del Rio, Anapra, and Buda. F2a separates Del Rio and Anapra; **F_{2b}** separates Anapra and **Buda.** **F_{2b}** dips about 20° S.; **F_{2a}** is not observable. Along strike neither fault can be traced more than a few tens of feet on the basis of the presence of Anapra outcrop or float (the lengths of the faults as shown on fig. 19 have been exaggerated simply to show them). Hence these do not seem to be major faults. Yet the juxtaposition of Anapra with Buda involves at least 27 m (90 ft) of stratigraphic separation; the low dips imply an even greater slip.

If the hanging wall of F_1 represents an allochthonous sheet, the Del Rio of this allochthon lies on the Anapra of the underlying autochthon. Conceivably, during the emplacement of the allochthon along F_1 there might have been some imbrication which brought slices of Anapra up into the allochthon from the autochthon.

F_3 and **F_4** may not be connected (fig. 19). **F_3** is not major and does not displace the Anapra beds more than a few feet. The felsite contact does not appear to be displaced by **F_3.** Rather, the felsite appears to have been guided by the fault. There is no evidence in the felsite of a fault zone of weakness, but the exposures are not good enough to resolve the problem completely. **F_4** displaces Muleros limestone opposite Smeltertown shale. **F_5** is very minor; its only significance seems to be that the drainage has followed the zone of weakness through the Anapra sandstone at this point.

The **F_6** trace, entirely within Anapra sandstone, is manifest by the loss of the middle sandstone member of the Anapra. The Anapra sandstone is about 30 m (100 ft) thick at the east end of **F_6.** This loss of about 30 m (100 ft) of section in south-dipping beds suggests movement up on the north; there is no evidence here for a low-dip fault. **F_6** does not seem to extend west of **F_5 .**

F_{6a} can be traced through offset Anapra beds into the Mesilla Valley shale, where it cannot be followed.

F_{7a} is manifest by loss of Mesilla Valley section between. a key limestone bed and the base of the Anapra sandstone. The dip is not known.

F_{7b} is a minor branch of **F_7.** The felsite contact with the Cretaceous units is not straight across **$_{\mathrm{Fib}}$** at point A. There is no evidence for the fault in the felsite; therefore, the felsite intrusion probably shifted from one horizon to another during intrusion at **F_{7b}.** Thus, the felsite post-dates the faults. A similar condition was noted at point B at the south end of **F_8.**

F_7 and **F_8** are vertical faults, exposed in washes (fig. 19); their dips are not in question. **F_7** and **F_8** are important cross faults that relatively drop the block they bound, which is the lowest structural zone in the Fault-Block Mosaic. For some reason, gullies have cut deeper into this block and have exposed structure lower in this block than elsewhere. **F_8** is a vertical fault with either right-lateral strike-slip displacement, or with relative movement down on the west. **F_8** displaces **F_9,** but the amount of stratigraphic offset on **F_9** is greater in the western block of **F_8** than it is in the eastern block; thus, **F_8** may have been partly a right-lateral tear fault of **F_9.** East of **F_8, F_9** disappears into the contact zone of the felsite and thus is older than the felsite. The andesite which intrudes **F_8** adjacent to the Cristo Rey pluton is much lighter colored and more iron-stained than the normal andesite. It may be contaminated with silica from the Anapra sandstone. A thin section prepared and examined by Michael Bersch shows a large amount of sericite in this andesite. A similar type is present at point C near section 19 (map III, sheet 2).

F_9 has been exposed in this lowest block. **F_9** dips 10° N.

and has placed the top of the Buda in the upper block opposite the top of the Anapra in the lower block, giving a stratigraphic separation of about 37 m (120 ft) northward in the upper block. Thus **F_9** is a very low-angle normal fault.

F_{10} is a normal fault, with dip-slip slickensides. This may be the east side of the series of dropped blocks, the western side of which is represented by **F_3-$_4$. F_1 $_1$** and F_{12} appear to represent parts of the F_{143} zone.

F_{13} can be easily traced from section 19 eastward to 20 (fig. 19). It may extend west to F_11_3 and east to F_{18}. At its west end it seems to be up on the north, with apparent right-lateral movement; at its eastern end it seems to be down on the north with left-lateral movement. East of section 20 it contains horizontal slickensides and dips 60° S. and thus appears to be a reverse fault. Its relation with F14 cannot be determined in the field. Thus, F_{13} may be a scissors fault produced by upward movement of the pluton at the west end near the major normal fault F_{18}. Horizontal slickensides were noted near the fulcrum point where the scissors movement is locally horizontal; there also may have been some right-lateral translation along F_{13}.

F_{14} is a small cross fault which has been intruded by andesite at its southern end. It offsets the Buda limestone a few tens of feet; F_{15} and F_{16} are cross faults which offset the Mesilla Valley-Anapra contact.

A fault, F_{17}, is required by the thin stratigraphic section of Mesilla Valley shale here; it is not exposed. This fault may extend northeast, because there are contortions in the Mesilla Valley shale between sections 20 and 21 and northeast of 21, but the total thickness of Mesilla Valley shale in those sections is about normal and there is no reason to extend the fault northeast of 20.

F_{18} is a major fault (the Inner fault) which extends around the east end of the pluton. The most important point to note here is that the Mesilla Valley shale and limestone on the east side of F_{18}, in contact with the felsite on the west side of F_{18}, are not contact metamorphosed but are brecciated, as is also the felsite at the fault. Thus, the major Inner fault around the east side of the andesite pluton has displaced the felsite and is younger than the felsite (photo 22). At 21, the Del Rio Formation has been intensely contact metamorphosed, although it is strati-graphically about 122 m (400 ft) higher than the andesite contact, and 49 m (160 ft) beneath the felsite contact.

35, p. 50—These three possibilities require analysis. Obviously, Boquillas shale beds must have been present between the horizon of felsite emplacement and the Anapra sandstone. This implies that the strata near (or over) the pluton were folded or domed prior to formation of F_1-$_9$, (that is, tectonic folding or andesite intrusion preceded felsite intrusion).

First, if the strata were domed by the andesite, then the felsite pushed north from a stratigraphically high but structurally low area, into a stratigraphically low but structurally high area against the andesite pluton. This would be difficult. Perhaps the andesite had not yet consolidated and F1_9 and the Anapra sandstone between sections 18 and 19 penetrated the andesite magma (fig. 19). The andesite just west of 19 is very limonitic around the Anapra contact. Nowhere else is the Anapra in contact with the andesite, nor is the andesite so limonitic. It seems as if the Anapra interrupts the normal arcuate pattern of Smeltertown, Muleros, and Mesilla Valley Formations which form the normal ring of strata in contact with the andesite.

Some parts of the andesite here are very siliceous and colored by Liesegang rings, special conditions not found elsewhere in the pluton. Perhaps the Anapra sandstone was thrust into the andesite magma during felsite intrusion and the andesite has assimilated the quartzose sandstones of the Anapra Formation, as well as the ironstone beds of the upper part of the Mesilla Valley Formation. Assimilation of the sandstones locally has produced very quartz-rich andesites. Assimilation of the ironstone has produced the high iron content of the andesite, now manifest by the weathered limonitic surface (suggested to me by Stephen Balough). This implies penecontemporaneous intrusions.

Second, $F_{1–9}$ may have been a higher angle (30°), north-dipping, normal fault during early stages of andesite magma emplacement, similar to the Outer fault north of the pluton (fig. 19). The present and smaller northward dip of the fault could be the result of rotation by arching of the south-dipping strata of the dome in the peripheral ring, but the strata at Bowen Gulch dip 60° N. and the Outer fault dips 30° S., hence are at right angles to each other.

The angle between F_1 and beds below F_1 is only 15-25°. Thus the analogy does not hold.

Third, F_1-$_9$ may have been a prefelsite and preandesite tectonic fault arched by the andesite and along which the felsite was emplaced. The felsite sill has been emplaced along two essentially different stratigraphic horizons, only one of which involves this thrusting: west of section 16 the felsite intruded the unfaulted Muleros, and east of 17 it intruded the Boquillas (except between the eastern ends of F_1 and **F_7;** fig. 14). If **F_1-$_9$** was a tectonic thrust, then the Anapra between sections 18 and 19 may be an allochthon intruded by the andesite. However, $F_{1–9}$ is essentially flat. If the andesite has produced the 5-15° dips of the beds beneath **F_1-$_9$** (as seems reasonable), prearching **F_1-$_9$** would have dipped 15-25° N. All thrust faults in the Sierra de Juarez dip southwest (Wacker, 1972; Campuzano, 1973). Thus, F_1-$_9$ was probably not a preandesite and prefelsite thrust.

All of this suggests that F_1-$_9$ was produced by northward emplacement of the felsite, probably during andesite magma emplacement.

36, p. 52—The fact that these low-angle faults and the other complications adjacent to the felsite are at the present erosional front of the felsite indicates that the present front is a special zone of deformation. However, the present front of the felsite zone also is an erosional front. The felsite originally extended north, perhaps over the andesite. Thus, the structural complexity along the present front may also show that this is associated with the felsite wherever the felsite exists, indicating that beneath the felsite there probably also are low-angle thrust faults and high-angle faults.

37, p. 55—No Mexican detailed topographic maps exist for this area and all elevations are estimates only. The Fort Hancock Formation extends across the contact here and locally covers it. The Fort Hancock cover is very close to the elevation of the high-level geomorphic La Mesa surface which caps the Fort Hancock Formation along the flat surface west of the Rio Grande. Therefore, the elevation is no less than 1,250 m (4,100 ft) here (see photo 24).

Appendix 2—New Formation Names in the Cretaceous at Cerro de Cristo Rey, Doña Ana County, New Mexico

by William S. Strain

ABSTRACT

Del Norte, Smeltertown, Muleros, Mesilla Valley Shale. and Anapra Sandstone are new formation names proposed for stratigraphic units previously identified by numbers assigned by Bose in 1910. Previously named units (Finlay Limestone, Del Rio Clay, Buda Limestone, and Boquillas Formation) also are present at Cerro de Cristo Rey and previously identified by Bose's numbers.

INTRODUCTION

Cerro de Cristo Rey (Cerro de Muleros) is approximately 5 miles northwest of the main business district of the city of El Paso, Texas. This peak is on the boundary between the United States and Mexico, partly in Dona Ana County, New Mexico, and partly in Chihuahua, Mexico.

The geology of Cerro de Cristo Rey was studied by Böse in 1910. He identified and briefly described individual units, and assigned each a number, but he did not name the formations. For convenience of correlation and mapping, and to meet the requirements of the American Commission on Stratigraphic Nomenclature, formal names are here proposed for the stratigraphic units that Bose described. New formation names are given to five units and the use of previously established names is suggested for four others.

An andesite intrusion of probable Eocene age formed Cerro de Cristo Rey and deformed the surrounding Cretaceous strata. Sedimentary rocks bound the intrusion on all sides and in general dip away from it. Because of the deformation of the Cretaceous strata, determining the true thickness of most stratigraphic units is difficult.

The locations chosen for the type sections of the various formations are outcrops where the top and bottom of each unit are visible, where there is essentially a continuous exposure, and where deformation is minimal.

To make clear the relations between Böse's numbered beds and the new names, Böse's original descriptions of the petrographic character and thickness of beds are reprinted from the original publication (Böse, 1910).

The part of Cerro de Cristo Rey in the United States is shown on the U.S. Geological Survey 71/2-minute Smeltertown quadrangle, 1955 edition.

PROCEDURES

The thickness of all sections was measured with a Jacob staff and Brunton pocket transit.

Colors used to describe rocks discussed in this paper are those in the Rock-Color Chart published by the National Research Council, Washington, D.C., 1948 (reprinted by Geological Society of America, 1975).

DESCRIPTION OF FORMATIONS (IN ASCENDING ORDER)

DEL NORTE FORMATION

Introduction —

Böse's (1910, p. 20, 21) description of subdivisions 2 and 3 follows:

> 2 Capas con *Schloenbachia bravoensis*
>
> Catheter petrográfico.—En esta subdivisión predominan margas pardas hasta amarillas, á veces apizarradas, y en menor cantidad existen lechos delgados de caliza de color azul obscuro, y areniscas calcáreas en bancos medianos. Las calizas se componen en parte casi ùnicamente de fósiles, son especialmente frecuentes los corales.
>
> Espesor y distribucion.—E1 espesor de estas capas es en lo general de unos 10 á 20 m.
>
> 3 Capas con *Schloenbachia* cfr. *belknapi*
>
> Catheter petrográfico.—En esta subdivision predominan calizas en parte arenosas, en parte compactas de color pardo hasta obscuro; al lado de estas rocas existen areniscas calcáreas y margas pardas; estas ùltimas tienen en ciertas partes bastante potencia en comparacion con el espesor general de este depósito. Las calizas son muy fosiliferas, pero en lo general los fósiles no se desprenden Bien de la roca, cuando se trata de capas margosas; esta es la causa por que la lista de fósiles parece relativamente limitada.
>
> Espesor y distribución.—Estas capas tienen en lo general una potencia de unos 10 m.
>
> *Translation:* 2. Beds with *Schloenbachia bravoensis*
>
> Petrographic character.—Brown to yellow marls predominate in this subdivision; locally there are slaty [laminated] shales; in minor amounts are thin beds of dark-bluish limestone, and calcareous, medium-bedded sandstones. Locally the limestones consist wholly of fossils, among which corals are most abundant.
>
> Thickness and distribution.—The thickness of these strata generally is about 10 to 20 m.
>
> 3. Beds with *Schloenbachia* cf. *belknapi*
>
> Petrographic character.—Limestones predominate in this subdivision. Some are sandy and some are dense, brown to dark colored. Associated are calcareous sandstones and brown marls. The latter, in certain places, are quite thick in comparison with the general thickness of this deposit; the limestones are very fossiliferous, but generally the fossils cannot be broken out of the rock. For this reason the fossil list is rather limited.
>
> Thickness and distribution.—These shales generally are about 10 m thick.

The Del Norte Formation (new) corresponds to subdivisions 2 and 3 of Böse's section. The formation name is derived from Rio Bravo del Norte which is 1) the name originally applied to the Rio Grande, 2) still used in Mexico, and 3) used in Böse's report on the Cerro de Muleros (table 8).

For ease of recognition and convenience in mapping, the writer has designated subdivision 2 as the Lower Clay Member and subdivision 3 as the Upper Calcareous Member of the Del Norte Formation. These are equivalent, respectively, to the Brick Plant Member (below) and the Refinery Member (above) of Strain (1968).

Outcrops of the Del Norte Formation are in the areas between and adjacent to the railroad tracks and just west of the Rio Grande flood-plain. This is in NW% sec. 15, T. 29 S., R. 4 E., Smeltertown 7½-minute quadrangle, Doña Ana County, New Mexico.

TABLE 8—TYPE SECTION OF DEL NORTE FORMATION

Unit	Description	Thickness ft (m)
	Upper Calcareous Member	
3	Sandy, fossiliferous, medium-gray (N5) limestone weathering to very pale orange (10 YR 8/2), interbedded with dark-yellow-brown shale (10 YR 4/2); weathered surface of shale stained with limonite	12.5 (3.81)
	Lower Clay Member	
2	Calcareous, olive-gray (5Y 4/1) shale; interbedded, fossiliferous, nodular layers of medium-gray (N5) sandy limestone in beds up to 20 cm thick, weathering to very light gray (N8). Outcrop stained with limonite; veins of calcite and selenite	39.0 (11.88)
1	Beds up to 7.5 cm thick of fine-grained, pale-yellow-brown (10 YR 6/2) sandstone, weathering to grayish-orange (10 YR 7/4); interbedded with calcareous shale of same color	5.0 (1.52)
	Total	56.5 (17.21)

Lower Clay Member

Definition—A calcareous clay shale with interbedded layers of fine-grained sandstone and nodular limestone. The type section is adjacent to and west of the kilns at the brick plant (fig. 2; map III, sheet 2). This is in the NW% SW% NW% sec. 15 T. 29 S., R. 4 E., Dona Ana County, New Mexico (table 8). The strike of the beds is N. 20° W. and the dip is 10°, S. 70° W. The base of the member is at the top of the Finlay (Limestone) Formation on an east-facing slope. The direction of the traverse is S. 70° W. The top of the member is the base of the first massively bedded, fossiliferous, sandy limestone bed, about 40 cm thick, near the top of the slope. The Lower Clay Member is conformable with the Finlay Limestone below and with the Upper Calcareous Member.

Age—Böse (1910, p. 21) correlated this subdivision with the Early Cretaceous Fredericksburg Group of central Texas. He recorded 19 genera and 26 species of fossils from which the following are listed. *Oxytropidoceras acutocarinatum* (Shumard), *0. bravoensis* (Bose), *Lima bravoensis* Bose, *Texigryphaea navia* Hall, *Texigryphaea corrugata* Say, *Exogyra texana* Roemer, *Pholadomya sancti-sabae* Roemer, and *Turritella bravoensis* Bose.

The writer believes that Böse's correlation is valid and that the Lower Clay Member of the Del Norte Formation is Early Cretaceous in age and corresponds to the middle part of the Albian of the European stages.

Upper Calcareous Member

Definition—A fossiliferous, medium-gray limestone interbedded with dark-yellowish-brown shale. Fossils are abundant in the limestone, but do not weather out readily. This member is conformable with the Lower Clay Member below and the Smeltertown Formation above.

Because the Upper Calcareous Member is poorly exposed at the locality of the measured section of the Lower Clay Member, the type section is offset to a point between the Railroad tracks where there is a better outcrop of the Upper Calcareous Member. Location is in the SW% NW% NW% sec. 15, T. 29 S., R. 4 E. (table 8).

The measured section is on the north side of the arroyo and on the wall of a small excavation where the strata are horizontal. The basal unit in the section is a sandy, fossiliferous limestone about 40 cm thick.

Age—Bose (1910, p. 22) believed that this unit correlated with the base of the Washita Group or possibly more correctly with the top of the Fredericksburg Group (Cretaceous System) of Texas. The following fossils are among the 10 genera and species on which he based his conclusion: *Oxytropidoceras* cf. *belknapi* (Marcou), *Pecten texanus* Roemer, *Ostrea carinata* (Lamarck), *Texigryphaea navia* Hall, *Texigraphaea corrugata* Say, and *Exogyra texana* Roemer. These fossils indicate that the member is Early Cretaceous in age and is near the time boundary between the middle and late Albian of the European stages.

SMELTERTOWN FORMATION

Introduction —

Böse's (1910, p.22) description of subdivision 4 follows:

> 4 Capas con *Schloenbachia nodosa,* n. sp.
>
> Catheter petrográfico.—En esta subdivision predominan pizarras arcillosas negras hasta grises, pero hacia la ladrillera se intercalan margas grises y bancos de caliza. En estas pizarras se encuentra gran cantidad de lechitos delgados de yeso. Las capas están bien descubiertas en el primer corte del Ferrocarril de Bisbee, donde se encuentran abajo principalmente las pizarras negras y arriba las margas con bancos de caliza, sobre las cuales yace en el mismo corte el horizonte con *Schloenbachia trinodosa,* bastante reducido en potencia; á los lados del corte se notan principalmente ya las capas superiores de esta subdivisión, es decir, las de catheter margoso.
>
> Espesor y distribucion.—Estas capas tienen una potencia de 30á 50 m.; es bastante diffcil estimar el espesor por la existencia de numerosos pliegues pequenos en las pizarras obscuras.
>
> *Translation:* 4. Beds with *Schloenbachia nodosa,* n. sp.
>
> Petrographic character.—Black to gray, clayey, slaty shales predominate in this subdivision, but toward the brickworks gray marl and limestone beds are intercalated. In the shales are found numerous thin layers of gypsum. The strata are well exposed in the first cut along the Bisbee Railroad, where near the base black slaty shales predominate and toward the top are marls with limestone beds. Above the latter, in the same cut, is the layer with *Schloenbachia trinodosa,* but considerably reduced in thickness. Away from the sides of the cut the upper manly beds of this subdivision are particularly apparent.
>
> Thickness and distribution.—These beds are 30 to 50 m thick. It is difficult to estimate the thickness because of the numerous small folds in the dark shales.

Definition—

The Smeltertown Formation is subdivision 4 of Bose's (1910) section. It crops out on the eastern side of Cerro de Cristo Rey and the principal exposure is just west of the brick plant.

This formation is named for a small community across the Rio Grande east of Cerro de Cristo Rey. The type section is on the north side of an arroyo trending S. 70° W. from the kilns at the El Paso Brick Company plant. Unit 1 and unit 2 of the section are in the NW% SW% NW% sec. 15, T. 29 S., R. 4 E. Because of an offset in the measured section, unit 3 and unit 4 are in the SE% SE% NE% sec. 16, T. 29 S., R. 4 E. (table 9).

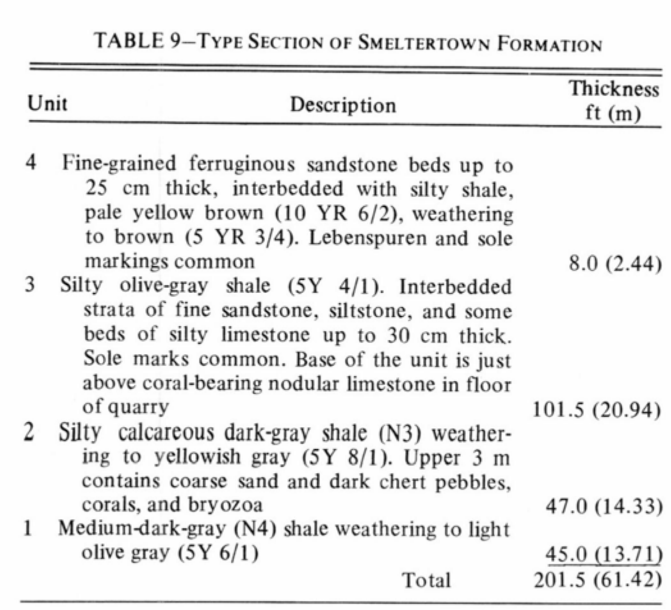

TABLE 9—TYPE SECTION OF SMELTERTOWN FORMATION

Unit	Description	Thickness ft (m)
4	Fine-grained ferruginous sandstone beds up to 25 cm thick, interbedded with silty shale, pale yellow brown (10 YR 6/2), weathering to brown (5 YR 3/4). Lebenspuren and sole markings common	8.0 (2.44)
3	Silty olive-gray shale (5Y 4/1). Interbedded strata of fine sandstone, siltstone, and some beds of silty limestone up to 30 cm thick. Sole marks common. Base of the unit is just above coral-bearing nodular limestone in floor of quarry	101.5 (20.94)
2	Silty calcareous dark-gray shale (N3) weathering to yellowish gray (5Y 8/1). Upper 3 m contains coarse sand and dark chert pebbles, corals, and bryozoa	47.0 (14.33)
1	Medium-dark-gray (N4) shale weathering to light olive gray (5Y 6/1)	45.0 (13.71)
	Total	201.5 (61.42)

The Smeltertown Formation is conformable with the Del Norte Formation below and the Muleros Formation above. The base of the measured section is on the west limb of a southeasterly plunging anticline and in a small tributary arroyo about 15 m south of the railroad carrying eastbound traffic (table 9). The strike is N. 20° W. and the average dip of the first three units is 15° S. 70° W. The dip of unit 4 is 25° in the same direction as the other three units. The base of the section is just above a sandy limestone stratum at the top of the Del Norte Formation (table 9). The line of traverse of the measured section is S. 70° W. At the top of unit two, the section is offset 120 m south to a small quarry. From that point the line of the section parallels the original line of measurement. Much of unit 3 along this traverse is covered with colluvium, but it is well exposed to the north on the opposite side of the hill.

Age—

Bose suggested that the Smeltertown Formation was a transitional bed between the Washita Group and the Fredericksburg Group of the Texas section. He recorded the following fossils: *Oxytropidoceras* cf. *belknapi* (Marcou), *Prohysteroceras whitei* (Bose), *Mortoniceras nodosa* (Bose), *Mortoniceras trinidosa* (Bose), *Pecten texanus* Roemer, *Ostrea carinata* (Lamarck), *Ostrea marcoui* (Böse), *Texigryphaea navia* Hall, *Homomya aff. ligeriensis* d'Orbigny.

Although Bose did not mention them, several species of algae and colonial corals occur near the top of unit two, and can be used as a horizon marker.

Fossils are not abundant in this formation; strong evidence on which to base a precise age determination is lacking. Fossils do indicate that it lies near the boundary between the Fredericksburg Group and the Washita Group of the Texas section. Fossils in the formations below are typical Fredericksburg forms and the fossils in the formations above the Smeltertown are characteristic of the Washita Group.

The Smeltertown Formation is equivalent to the European late Albian Stage of Early Cretaceous age and may be correlative with the Duck Creek Formation of northeast Texas.

MULEROS FORMATION

Introduction-

Bose's (1910, p. 23) description of subdivision 5 follows:

> 5 Capas con *Schloenbachia trinodosa* n. sp.
>
> Catheter petrográfico.—La mayor parte de este horizonte se compone de margas grises hasta azuladas, que en estado de alteracion toman un color gris blanquizco; entre estas margas están intercalados bancos de caliza.
>
> Espesor y distribucion.—El espesor de estas capas cambia entre 30 y 50 metros.
>
> *Translation:* 5. Beds with *Schloenbachia trinodosa* n. sp.
>
> Petrographic character.—Most of these beds consist of gray to bluish marls, which, where altered, are grayish white; interbedded with the marls are limestone beds.
>
> Thickness and distribution.—The thickness of these beds ranges from 30 to 50 m.

Definition—

The Muleros Formation, subdivision 5 of Böse's stratigraphic section, crops out at numerous places around the intrusion. The best exposures are on the north and east sides of the mountain. In addition to the type section (table 10), a good exposure of this section can be seen in the first railroad cut west of the Rio Grande along the tracks which carry eastbound traffic.

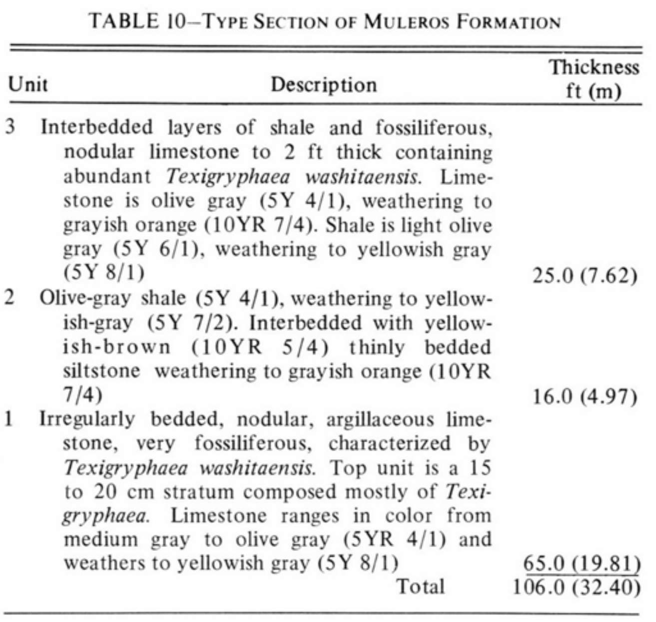

TABLE 10—TYPE SECTION OF MULEROS FORMATION

Unit	Description	Thickness ft (m)
3	Interbedded layers of shale and fossiliferous, nodular limestone to 2 ft thick containing abundant *Texigryphaea washitaensis*. Limestone is olive gray (5Y 4/1), weathering to grayish orange (10YR 7/4). Shale is light olive gray (5Y 6/1), weathering to yellowish gray (5Y 8/1)	25.0 (7.62)
2	Olive-gray shale (5Y 4/1), weathering to yellowish-gray (5Y 7/2). Interbedded with yellowish-brown (10YR 5/4) thinly bedded siltstone weathering to grayish orange (10YR 7/4)	16.0 (4.97)
1	Irregularly bedded, nodular, argillaceous limestone, very fossiliferous, characterized by *Texigryphaea washitaensis*. Top unit is a 15 to 20 cm stratum composed mostly of *Texigryphaea*. Limestone ranges in color from medium gray to olive gray (5YR 4/1) and weathers to yellowish gray (5Y 8/1)	65.0 (19.81)
	Total	106.0 (32.40)

The Muleros Formation is named for Cerro de Muleros which is the original name for Cerro de Cristo Rey. The type section is in the arroyo trending S. 70° W. from the kiln area of the El Paso Brick Company plant and was measured on the north side near the head of the arroyo (table 10). Here the strike is N. 10° W. and the dip ranges from 34 to 52° S. 80° W. An average dip of 43° was used in measuring the section.

This locality is in the SE¼SE¼NE¼ sec. 16, T. 29 S., R. 4 E., Doña Ana County, New Mexico.

The base of the section is at the top of the sandstone member of the Smeltertown Formation and the top is the last limestone stratum containing large numbers of *Texigryphaea washitaensis*. The Muleros Formation is conformable with the Smeltertown Formation below and with the Mesilla Valley Shale above. At the base of the Muleros the lithologic distinction between it and the formation below is clear, but at the top of the Muleros there is a gradational change to the Mesilla Valley Shale. The top of the Muleros Formation is arbitrarily chosen as the last limestone layer containing great numbers of *Texigryphaea.* The occurrence of abundant *Texigryphaea* in banklike layers is a distinguishing feature of the Muleros Formation.

Age—

This formation contains numerous fossils. Bose identified 21 genera and 27 species of which the following are useful in correlation: *Lima wacoensis* Roemer, *Ostrea carinata* Lamarck, *Texigryphaea washitaensis* Hill, *Pholadomya shattucki* Bose, and *Ampullina collina* (Conrad). He also described *Prohysteroceras burkhardti* (Böse) and *Mortoniceras nodosa* (Bose) from this formation, but they are extremely difficult to find and for that reason are not readily usable as index fossils.

Bose believed the fossils clearly indicated that this subdivision was correlative with the Washita Group of Texas and his conclusion is valid. The Muleros Formation is Early Cretaceous in age and belongs in the European late Albian stage.

MESILLA VALLEY SHALE

Introduction-

Böse's (1910, p. 25) description of subdivision 6 follows:

> 6 Capas con *Ostrea quadriplicata* (Shum.), White
>
> Carácter petrográfico.—La mayoria de esta subdivision se compone de margas grises hasta pardas, pero existen intercalaciones de una arenisca Tina en lechos delgados y de bancos de caliza, en parte bastante considerables.
>
> Espesor y distribucion.—E1 espesor de estas capas cambia bastante, mientras que en algunos lugares como p. e. en el S. E. del cerro llega apenas á 10 m., tienen las mismas capas arriba del Monumento Inicial más de 20 m. de potencia; en otras partes en el Oeste y el Norte de la montana probablemente todavia más, solo que el plegamiento de las capas hace diffcil una estimación.
>
> *Translation:* 6. Beds with *Ostrea quadriplicata* (Shum.), White
>
> Petrographic character.—Most of this subdivision consists of gray to brown marls, but there are interbeds of fine-grained sandstone in thin layers and of limestone beds; locally the limestone is abundant.
>
> Thickness and distribution.—The thickness of these beds shows a considerable range. For example in some places southeast of Cerro de Muleros the thickness barely reaches 10 m. At the First Monument, the thickness is more than 20 m. In the west and north of the Cerro the thickness probably is greater, but there is a problem in measurement because of the folds.

Definition—

The Mesilla Valley Shale is subdivision 6 of Böse's stratigraphic section. It crops out widely about the intrusion, but the best exposures are on the north and east sides. The formation is named for the Mesilla Valley, an agricultural area on the Rio Grande flood plain north of Cerro de Cristo Rey and in Dona Ana County, New Mexico. The formation is principally clay shale with thin beds of siltstone and calcareous strata containing numerous fossils. Near the top of the formation the shale grades into thinly bedded ferruginous sandstone. In the lower part of the unit the shale is carbonaceous and has a shiny luster.

The formation is conformable with the Muleros Formation below and the Anapra Sandstone above (see table 11). The base of the stratigraphic unit is chosen as the top of the highest *Texigryphaea* bank of the Muleros Formation and the top is the base of the first 1-ft-thick sandstone stratum in the Anapra Sandstone.

The type locality is on the north side of the largest railroad cut in which east-bound traffic passes (table 11). The base of the section is 30 m north of the metal conduit crossing the railroad and in a small arroyo where the top of the Muleros Formation is exposed. This is in the NW¼NW¼NE¼ sec. 16, T. 29 S., R. 4 E., Doña Ana County, New Mexico. The strike is N. 35° W. and the dip is 30° N. 55° E. The direction of the section was measured parallel with the direction of the dip.

CHART SHOWING EVOLUTION OF STRATIGRAPHIC NOMENCLATURE IN

Series	Provincial Series	Central Texas Groups	European Stages		Böse, 1910 and C. Burckhardt, 1930-31		Stanton and Vaughn, 1896		University of Texas Bull. 3232, Sellards, Adkins and Plummer, 1932	
Upper Cretaceous	Gulfian	Eagle Ford	Cenomanian		Turonian	Eagle Ford Horizon à *Inoceramus labiatus*	10(7) Sandstone White, yellow, brown		11 Eagle Ford 10 Woodbine Ss. *Felsite not sandstone*	Cenomanian Stage
Lower Cretaceous	Comanchean	Washita			Cenomanian Superior	10 Woodbine Grès clair *This bed is felsite not sandstone* 9, 8 Horizon à *Hemiaster calvini* Buda (Upper Washita)	9(8) Clay shale 8(9) Hard limestone *Failed to recognize overturning of upper 3 beds*		9 Buda 8 Del Rio 7 Main Street	
			Albian	Upper	Cenomanian Inferior	Gres rouge à 7 *Exogyra whitneyi* Del Rio (Upper Washita) 6, 5, 4 Horizon à *Schloenbachia trinodosa* (Middle and Lower Washita)	7 Sandstone White or brown 6 Clay shale and sandy flagstone 5 Flaggy argillaceous limestone with shale 4 Clay shale, calcareous bands	Washita	6 Weno-Pawpaw 5 Fort Worth-Denton 4 Duck Creek 3, 2 Kiamichi	Albian Stage
		Fredericksburg		Middle	Vraconian	3, 2, 1 Horizon à *Exogyratexana* (Fredericksburg)	3 Ledges of hard limestone 2 Alternations of clay and soft argillaceous limestone ledges 1 Argillaceous limestone in thick ledges, weathering to nodular masses surrounded by clay	Fredericksburg	1 Edwards	

TABLE 11—TYPE SECTION OF MESILLA VALLEY SHALE

Unit	Description	Thickness ft (m)
2	Thinly bedded ferruginous sandstone and siliceous shale	15.0 (4.57)
1	Olive-gray clay shale (5Y 4/1), weathering to pale yellowish brown (10YR 6/2). A few limestone and siltstone beds up to 30 cm thick. *Texigryphaea* and *Cribrotina* abundant in limestone and siltstone layers.	195.0 (59.43)
	Total	210.0 (64.00)

Age—

Bose listed 20 genera and 23 species of fossils from the Mesilla Valley Shale. Following is a list of these most commonly found: *Lima wacoensis* Roemer, *Lima mexicana* Bose, *Pecten texanus* var. *elongatus* Bose, *Pecten subalpinus* Bose, *Plicatula incongrua* Conrad, *Ostrea quadriplicata* (Shumard), *Texigryphaea washitaensis* *Trigonia emery'* Conrad, *Helicocryptus mexicanus* Bose, *Turritella granulata* Sowerby var. *cenomanensis* d'Orbigny, *Heteraster bravoensis* (Bose), and *Cribrotina texana* (Conrad).

Bose stated that all of the fossils examined from this subdivision occur in the Washita Group in the Texas section. Based on the fossil evidence, the Mesilla Valley Shale is Early Cretaceous in age and is correlative with the European late Albian stage.

ANAPRA SANDSTONE

Introduction-

Bose's (1910, p. 26) description of subdivision 7 follows: 7

> Areniscas con *Exogyra ponderosa,* Roemer
>
> Catheter petrográfico.—Esta subdivisión se compone ùnicamente de una arenisca cuarzosa de grano grueso hasta mediano, de color rojo con bancos blanquizcos hasta amarillentos; la arenisca forma bancos bastante gruesos.
>
> Espesor y distribución.—E1 espesor de estas capas cambia bastante; á veces tiene como en el S. E. y en el N. apenas 20 m., otras veces tiene una potencia de hasta 100 m.
>
> *Translation:* 7. Sandstones with *Exogyra ponderosa,* Roemer
>
> Petrographic character.—This subdivision consists solely of medium- to fine-grained quartzose sandstone, red in color, with whitish to yellowish beds; the sandstone occurs in rather thick beds.
>
> Thickness and distribution.—The thickness is quite variable. In places, as in the southeast and north, it scarcely reaches 20 m; in other places it has a thickness up to 100 m.

Definition—

The Anapra Sandstone is subdivision 7 in Böse's stratigraphic section. Outcrops of the formation are principally on the north, east, and west sides of the intrusion. The rock is resistant to weathering and forms the highest ridges in the sedimentary section around the intrusion. The formation is named for the small community of Anapra, New Mexico, which is on the west side of the mountain near its base.

The Anapra Sandstone is thin to massively bedded quartz sandstone with interlaminations of siliceous shale. It is conformable with the Mesilla Valley Shale below and with the Del Rio Clay above. The base of the Anapra is the lowest sandstone stratum 30 cm thick or more just above the thinly bedded sandstone beds at the top of the Mesilla Valley Shale.

The type locality is on the east side of the road to Cerro de Cristo Rey and just east of the abandoned site of Bowen, New Mexico (table 12). Bowen was a siding along the railroad carrying eastbound traffic. This area is in the SW¼SE¼SW¼ sec. 9, T. 29 S., R. 4 E., Dona Aria County, New Mexico.

The base of the section is on the north side of the private road trending easterly from Bowen and the top is at the base of the overlying Del Rio Clay. The strike is N. 80° W. and the average dip is 42° N. 10° E. The direction of the measured section parallels the dip (table 12).

ERRO DE CRISTO REY AREA (Numbers are Böse Subdivisions)

Imlay, 1944	Kottlowski, and others, 1956	Strain, 1968	Cordoba and Rodriguez, 1970 (mapped only in Mexico)	Cordoba and Rodriguez, 1970 proposed nomenclature for northeastern Chihuahua	Strain, this paper
11 Eagle Ford (or Colorado Shale) 10 Woodbine Ss. *Felsite not sandstone*	11 Eagle Ford group 10 Woodbine Ss. *Felsite not sandstone* Gulf Series	10 Boquillas *Bed 10=bed 11 of Böse*	La Mina Fm.	La Mina Ojinaga Turonian	10 Boquillas Fm. *Bed 10=bed 11 of Böse* Cenomanian
9 Buda 8 Del Rio 7 Main Street 6 Pawpaw-Weno equivalents 5 Denton-Fort Worth equivalents 4 Duck Creek equivalents 3 Kiamichi 2 Edwards (Finlay limestone) 1 Sandstone, Unnamed	9 Buda 8 Grayson or Del Rio 7 Main Street 6b Pawpaw 6a Weno 5 Denton 4 Duck Creek 3 Kiamichi 2 Goodland 1 Sandstone Comanche Series	9 Buda 8 Del Rio 7 Anapra 6 Mesilla Valley 5 Muleros 4 Smeltertown 3, 2 Del Norte 1 Courchesne	Juarez Fm. Arroyo Colorado Fm.	Buda Del Rio Anapra Mesilla Valley Muleros Cenomanian Smeltertown Del Norte Vraconian Courchesne Albian	9 Buda Ls. 8 Del Rio Clay 7 Anapra Ss. 6 Mesilla Valley Sh. 5 Muleros Fm. 4 Smeltertown Fm. 3, 2 Del Norte Fm. 1 Finlay Ls. Albian

TYPE 12—TYPE SECTION OF ANAPRA SANDSTONE

Unit	Description	Thickness ft (m)
4	Interbedded layers of massive-bedded, mottled, ferruginous, medium- to fine-grained, quartz sandstone and siliceous shale. Sandstone layers up to 3 m thick form ridges. Sandstone is moderate reddish orange (10R 6/6), weathering to pale reddish brown (10R 5/4) or grayish orange pink (5YR 7/2). Siliceous shale is dusky brown (5YR 2/2)	50.0 (15.24)
3	Massive-bedded, medium-grained, quartz sandstone, very pale orange (10YR 8/2), weathering to moderate yellowish brown (10YR 5/4). Numerous limonite concretionary masses ranging in diameter from 2 mm to 1.5 cm	12.5 (3.81)
2	Pale yellowish-brown arenaceous shale (10YR 6/2) with interbedded layers of sandstone up to 0.45 m thick. Sandstone layers are dark yellowish orange (10YR 6/6)	45.0 (13.70)
1	Thin- to massive-bedded, fine- to medium-grained, ferruginous sandstone. Very pale orange (10YR 8/2) weathering to various shades of brown	65.0 (19.81)
	Total	172.5 (52.56)

Age—

Fossils are not abundant in this stratigraphic unit, but numerous specimens of *Exogyra whitneyi* Bose occur in the upper 2-3 m of the formation. This species is not as diagnostic as many fossils in the Cretaceous section of Texas; moreover, this species does occur in the Del Rio Clay in the Big Bend area (Maxwell and others, 1967, p. 52). It also occurs with *Enallaster calvini* (Clark) in the Del Rio Clay at Cerro de Cristo Rey.

The Anapra Sandstone may be equivalent to the lower part of the Del Rio Clay, but because of the scarcity of fossils, positive evidence for correlation is lacking. Adkins (1928, p. 110) implied that the Anapra was correlative with the Main Street Formation of the northeast Texas section. In the Cerro de Cristo Rey section, the Anapra is below the Del Rio Clay and in the position of the Main Street of the Texas sequence.

The Anapra Sandstone is Cenomanian in age, and the base of the Cenomanian Stage is here placed at the base of the Anapra.

OTHER FORMATIONS AT CERRO DE CRISTO REY

Four of Bose's subdivisions (1, 8, 9, and 11) are recognized as being formations previously described, but at localities other than Cerro de Cristo Rey. Subdivision 1 is the Finlay Formation; subdivision 8 is the Del Rio Clay; subdivision 9 is the Buda Limestone. All three are Early Cretaceous in age. Subdivision 11 is the Boquillas Formation which is Late Cretaceous in age.

These exposures are isolated outcrops of the various formations. The nearest outcrop of any of these units is 100 km (60 mi) or more to the east, but lithology, fossil content, and stratigraphic position are so similar to typical exposures in the Big Bend region of Texas that the correlation is believed valid.

Some liberties are taken in this interpretation, but I believe using established names already in the geological literature is preferable to introducing new names.

Bed 10 of Bose's stratigraphic section is felsite, not sandstone as reported by him and some later workers. There is a Limited outcrop of this pluton which forms a small sill in the Muleros Formation on the New Mexico side at the international boundary. Base's bed 10 is thus absent in the normal stratigraphic section in New Mexico and his bed 11 (bed 10, Boquillas of this paper) lies unconformably on the Buda Limestone (bed 9).

In 1968 Strain proposed Boquillas Formation be used for bed 11 rather than Eagle Ford as Bose suggested. Future research may show that it would be more appropriate to use Ojinaga Formation or possibly Chispa Summit Formation instead of Boquillas. Both formations are in about the same stratigraphic position as the Boquillas and are Late Cretaceous in age. Both the Ojinaga and the Chispa Summit crop out in the Big Bend area southeast of Sierra de Cristo Rey.

Recent study (W. A. Cobban and Stephen C. Hook, personal communication) of fossils from the Boquillas at Sierra de Cristo Rey suggests that the base of the Boquillas lies in the Zone of *Acanthoceras alvaradoense* and that neither Woodbine nor Dakota formation equivalents are present. Other fossils in addition to *Acanthoceras alvaradoense* Moreman tending to support this zonation are *Ostrea beloiti* Logan, *Desmoceras aff. . D. japonicum* Yabe, *Turrilites* cf. *T. acutus americanus* Cobban and Scott, *Tarrantoceras rotatile* Stephenson, and *Inoceramus arvanus* Stephenson.

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Index in 8 pt. Press Roman, leaded one-point
Display heads in 24 pt. Times Roman, letterspaced

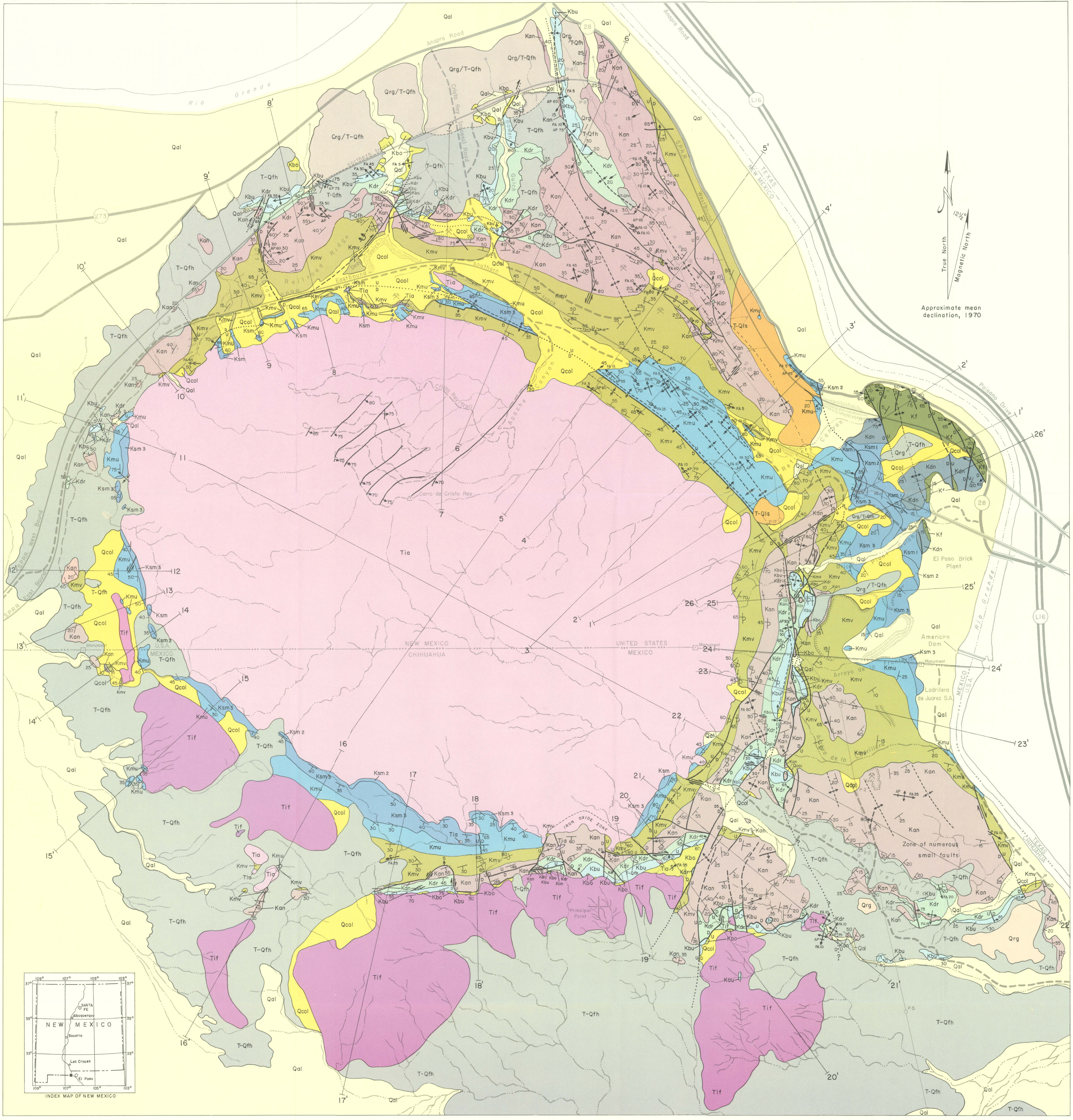
Presswork: Miehle Single Color Offset

Binding: Sewn with softbound cover

Paper: Cover on 17 pt. Permalin
Text on 70 lb. *White Matte*

NEW MEXICO BUREAU OF MINES & MINERAL RESOURCES   A DIVISION OF NEW MEXICO INSTITUTE OF MINING & TECHNOLOGY

MEMOIR 31   SHEET 1   MAP 1



Cartography by Margaret Hoenig and Steve Balough, 1973

EXPLANATION

SEDIMENTARY ROCKS

Qcol
Colluvium
Regolith from subjacent or upslope rock. Around pluton may include paleo-colluvium of Fort Hancock Formation. Fill included

Qal
Alluvium
Stream deposits and river deposits of post-Wisconsinan age

Qrg / **Qrg/T-Qfh**
River gravels
Well-rounded quartzite, and fine-grained igneous rocks up to cobble size. **Qrg/T-Qfh**, *locally thin gravels on Fort Hancock Formation*

T-Qls
Landslide
Andesite rubble between 1-1′ and 2-2′, Anapra rubble between 2-2′ and 4-4′

T-Qfh
Fort Hancock Formation
Interbedded quartz sands and clays; basal conglomerate, mainly andesite clasts and grus

EROSIONAL UNCONFORMITY

Kbo
Boquillas Formation
Calcareous shales and very thin bedded limestone

EROSIONAL UNCONFORMITY

Kbu
Buda Formation
Medium to massive fine grained limestone, abundant gastropods

Kdr
Del Rio Formation
Shale, calcareous shale, thin nodular limestone beds, Exogyra *near base*

Kan
Anapra Formation
Quartzose sandstone and siltstone; three massive coarse-grained sandstone members separated by two thin-bedded purple siltstone members

Kmv
Mesilla Valley Formation
Dark-gray shale; some ironstone and fine-grained sandstone near top and black shale and a few limestone beds in lower part

Kmu
Muleros Formation
An upper, thin-bedded Gryphaea *packstone; a middle shale and siltstone member; a lower medium bedded* Gryphaea*-rich limestone*

Ksm 3 2 1
Smeltertown Formation
(3) Fine-grained sandstone at the top of the upper shale; (2) middle nodular limestone-interbedded shale; (1) lower shale

Kdn
Del Norte Formation
Upper limestone, fossiliferous (Refinery member) lower calcareous shale, fossiliferous (Brick Plant member)

Kf
Finlay Formation
Massive and nodular fine-grained limestone

Kl
Lagrima Formation
Interbedded shale and limestone

QUATERNARY
TERTIARY
U. CRETACEOUS
LOWER CRETACEOUS
European Stages (for Cretaceous)
GULFIAN
COMANCHEAN
Cenomanian
Albian
Washita Group
Fredricksburg Group
Trinity Group

IGNEOUS ROCKS

Tif
Loma Blanca Felsite
Cream-colored, aphanitic, no identifiable minerals

Tia
Muleros Andesite
Plagioclase and hornblende porphyry

MIDDLE EOCENE
TERTIARY

STRUCTURE

Contact
Depositional or intrusive

35 65
Bedding
Strike and dip of bedding (left symbol), strike of vertical bedding (center symbol), strike and dip of overturned bedding (right symbol)

20 25 D U
Normal fault
Showing dip, bearing and plunge of slickensides, and relative movement (D, downthrown side; U, upthrown side), ▹▹ breccia

U D
Fault
Projected beneath mapped units

AP 70 FA 20
Anticline
Showing bearing and plunge of fold axis (FA); strike and dip of axial plane (AP)

Syncline
Showing trace of major fold axis, dashed where approximate, dotted where concealed

Overturned anticline

Small folds
Axial trend of small anticline (left symbol) and syncline (right symbol)

AP FA 10
Folds too small to plot individually
Showing bearing and plunge of fold axis; vertical axial plane shown

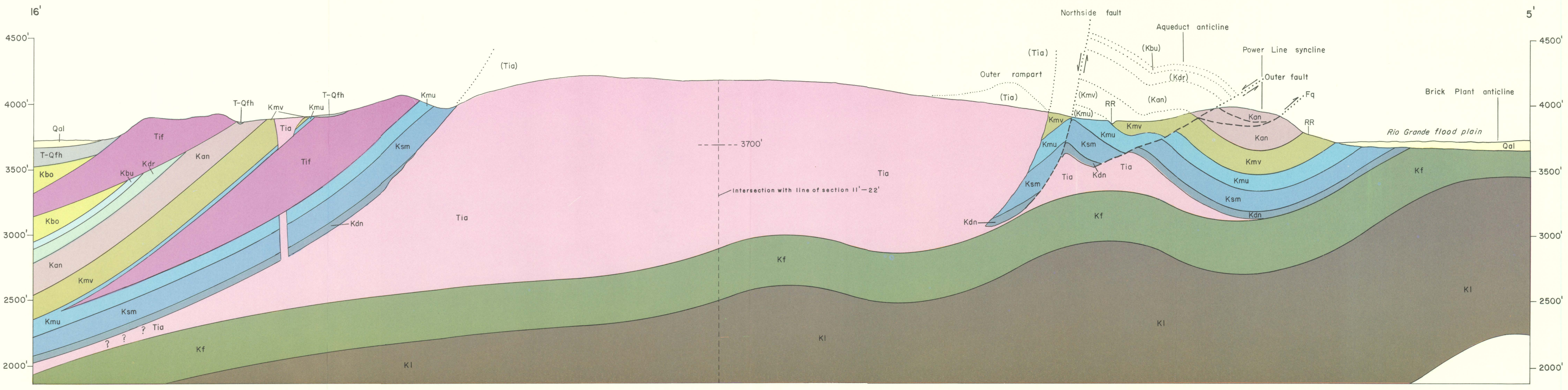
CULTURE

P·19
Power line
Showing numbered pole

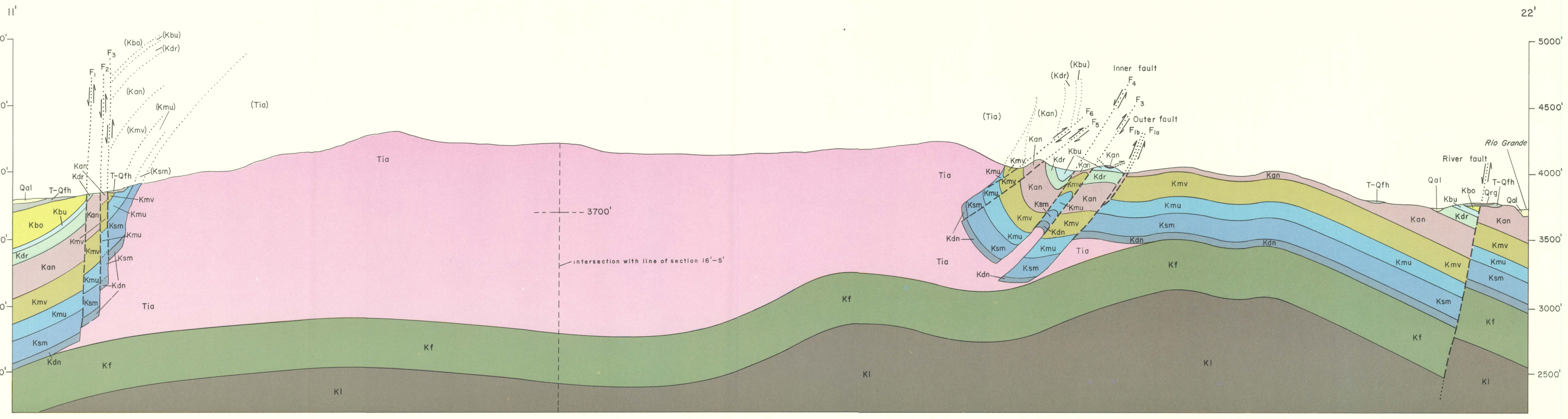
Monument
International boundary

State boundary

Quarry



SECTION 16′–5′



SECTION 11′–22′

GEOLOGIC MAP AND SECTIONS OF CERRO DE CRISTO REY UPLIFT CHIHUAHUA, MEXICO AND NEW MEXICO, UNITED STATES

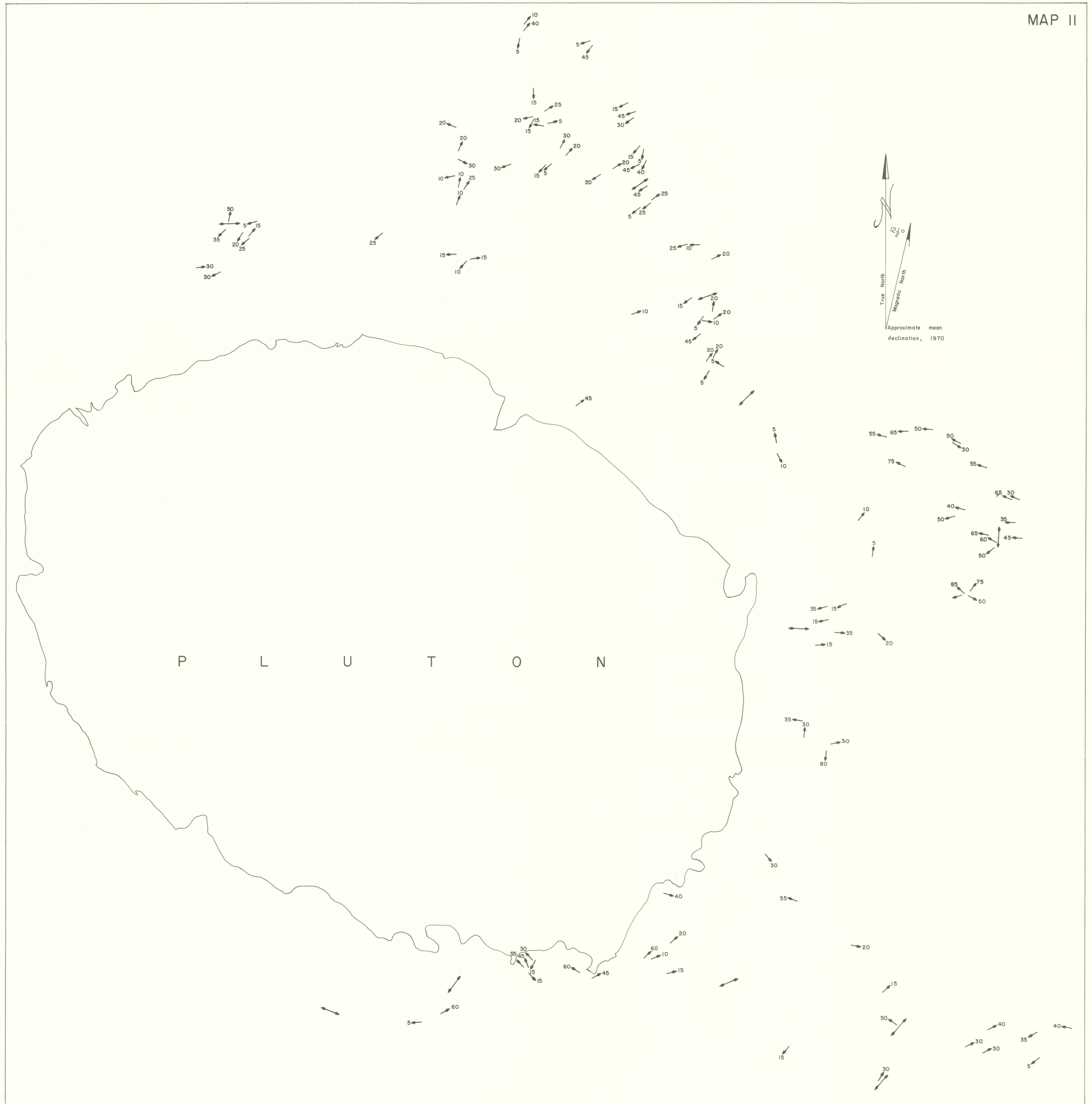
by Earl M.P. Lovejoy

.25 Mile 0 500 1,000 1,500 Feet

.25 Kilometer 0 250 Meters

Vertical and horizontal

1976

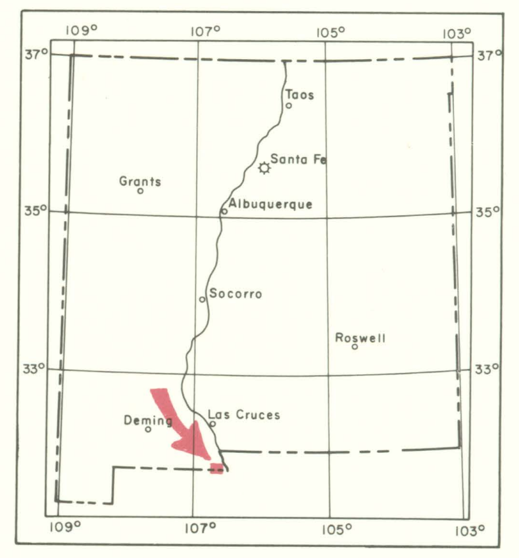


SLICKENSIDES IN CERRO DE CRISTO REY UPLIFT

by Earl M.P. Lovejoy

.25 Mile 0 500 1,000 1,500 Feet

.25 Kilometer 0 250 Meters



E X P L A N A T I O N

Paved road

Unpaved road

Path

Quarry

Intermittent stream

International boundary

State boundary

Power line
Showing numbered pole

Railroad
Showing bridge

Contact

Slickensides
Showing bearing and plunge

Fault
Showing dip and relative movement (D, downthrown side, U, upthrown side), dotted where projected beneath mapped units

Monocline

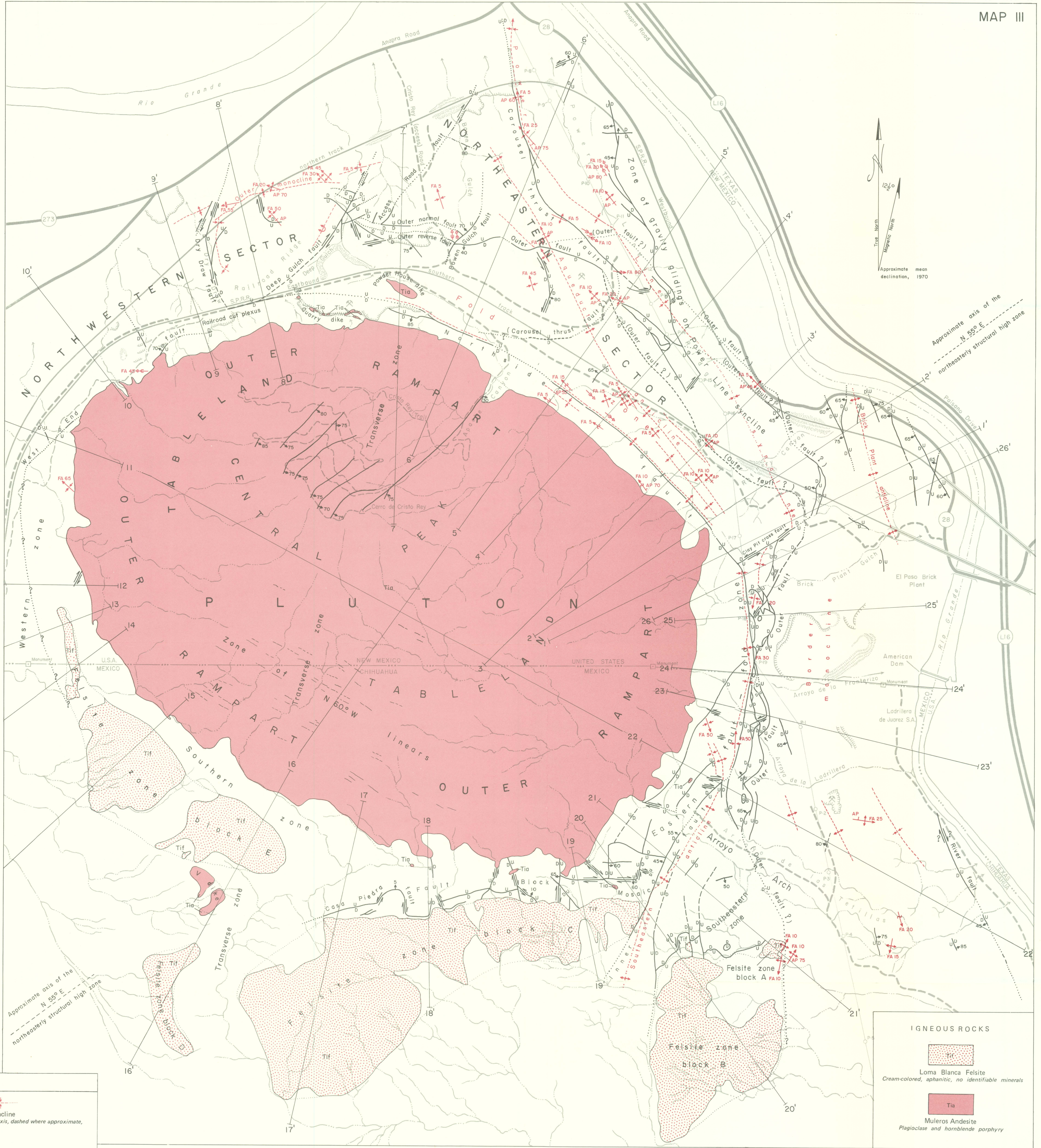
Anticline
Showing bearing and plunge of fold axis (FA); strike and dip of axial plane (AP)

Syncline
Showing trace of major fold axis, dashed where approximate, dotted where concealed

Overturned anticline

Small folds
Axial trend of small anticline (left symbol); syncline (right symbol)

Folds too small to plot individually
Showing bearing and plunge of fold axis; vertical axial plane shown



I G N E O U S R O C K S

Tif — Loma Blanca Felsite
Cream-colored, aphanitic, no identifiable minerals

Tia — Muleros Andesite
Plagioclase and hornblende porphyry

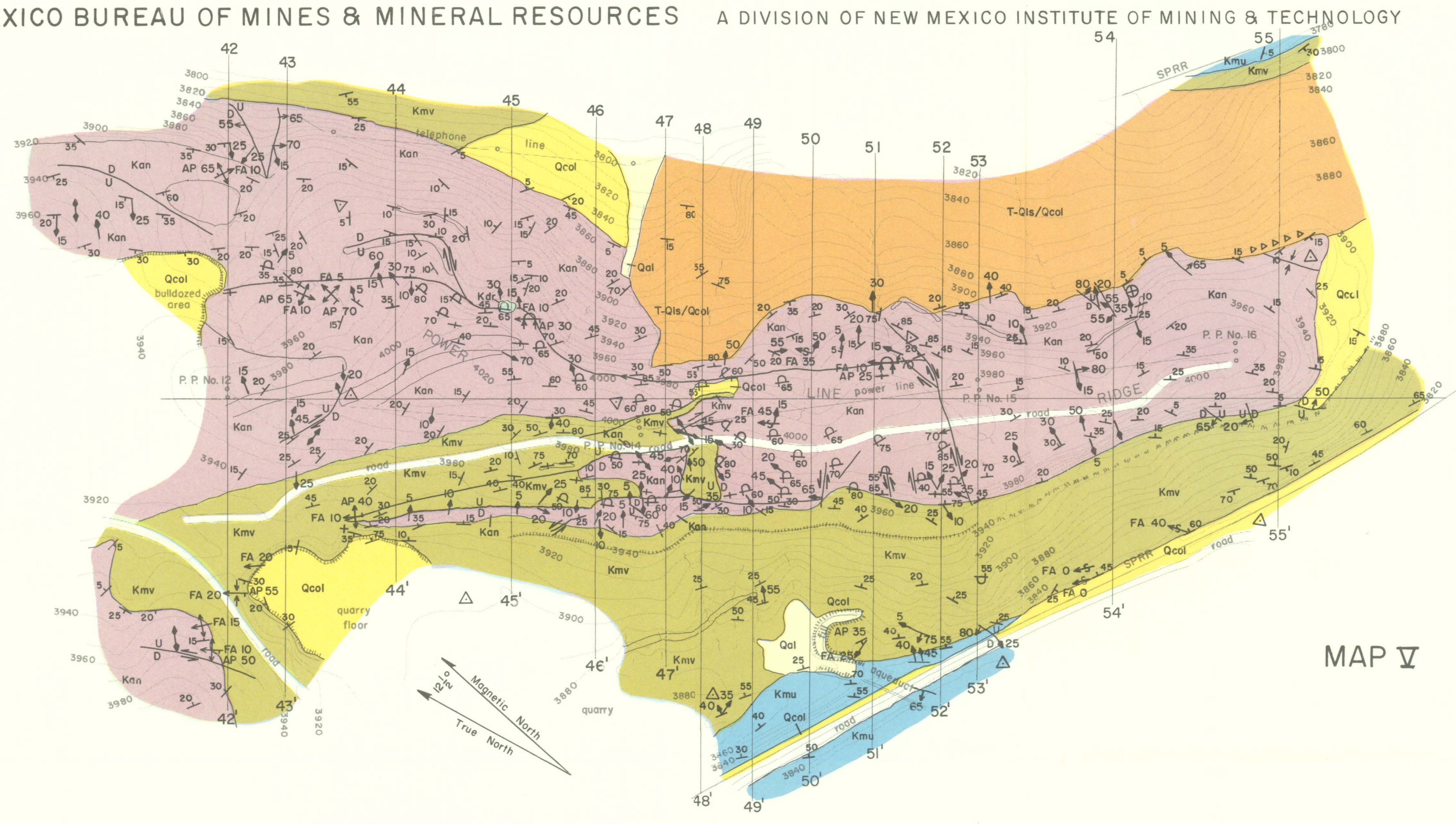
Cartography by Steve Balough, 1973

INTERPRETIVE STRUCTURAL GEOLOGIC MAP OF CERRO DE CRISTO REY UPLIFT CHIHUAHUA, MEXICO AND NEW MEXICO, UNITED STATES

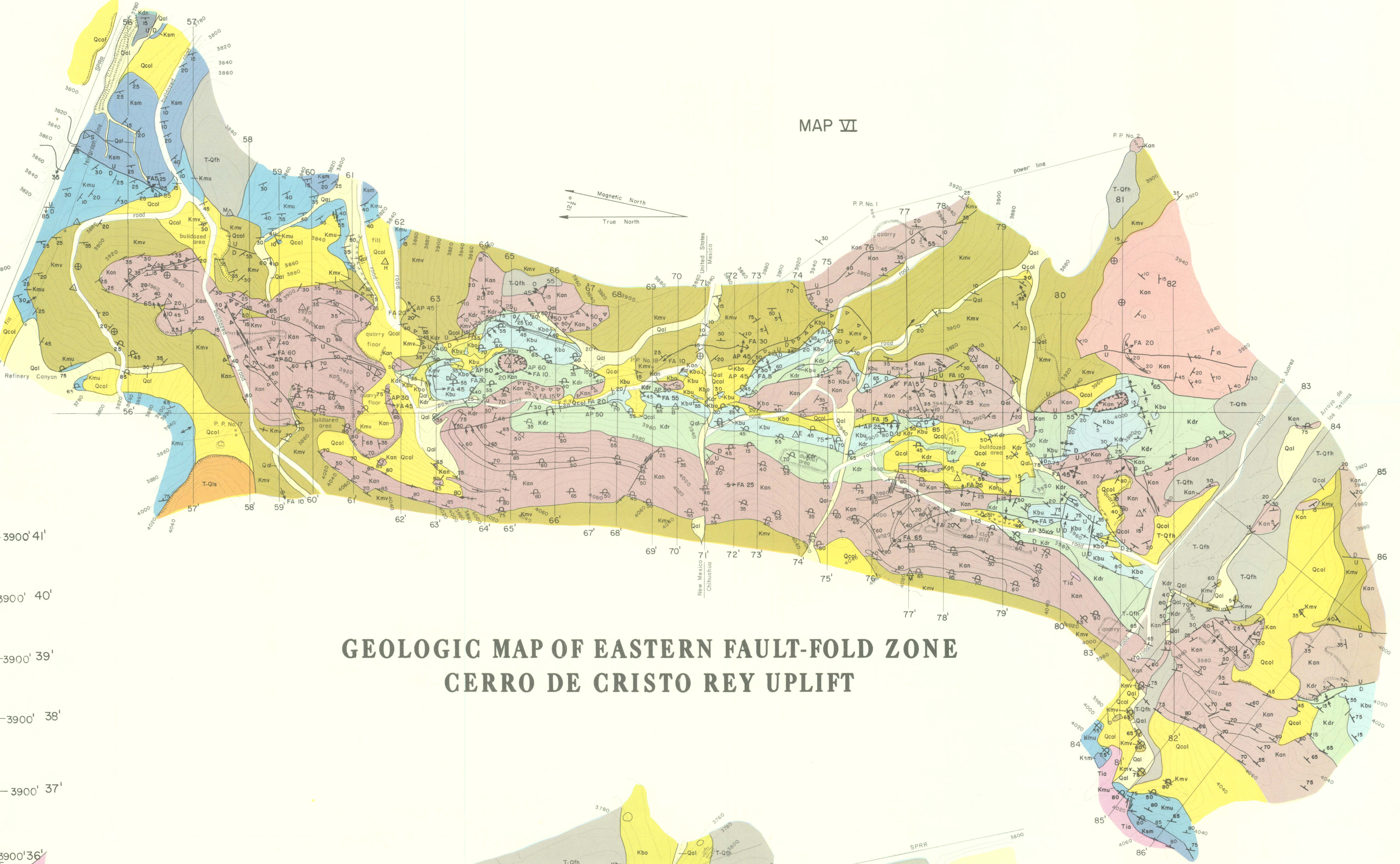
by Earl M.P. Lovejoy
1976

.25 Mile 0 500 1,000 1,500 Feet

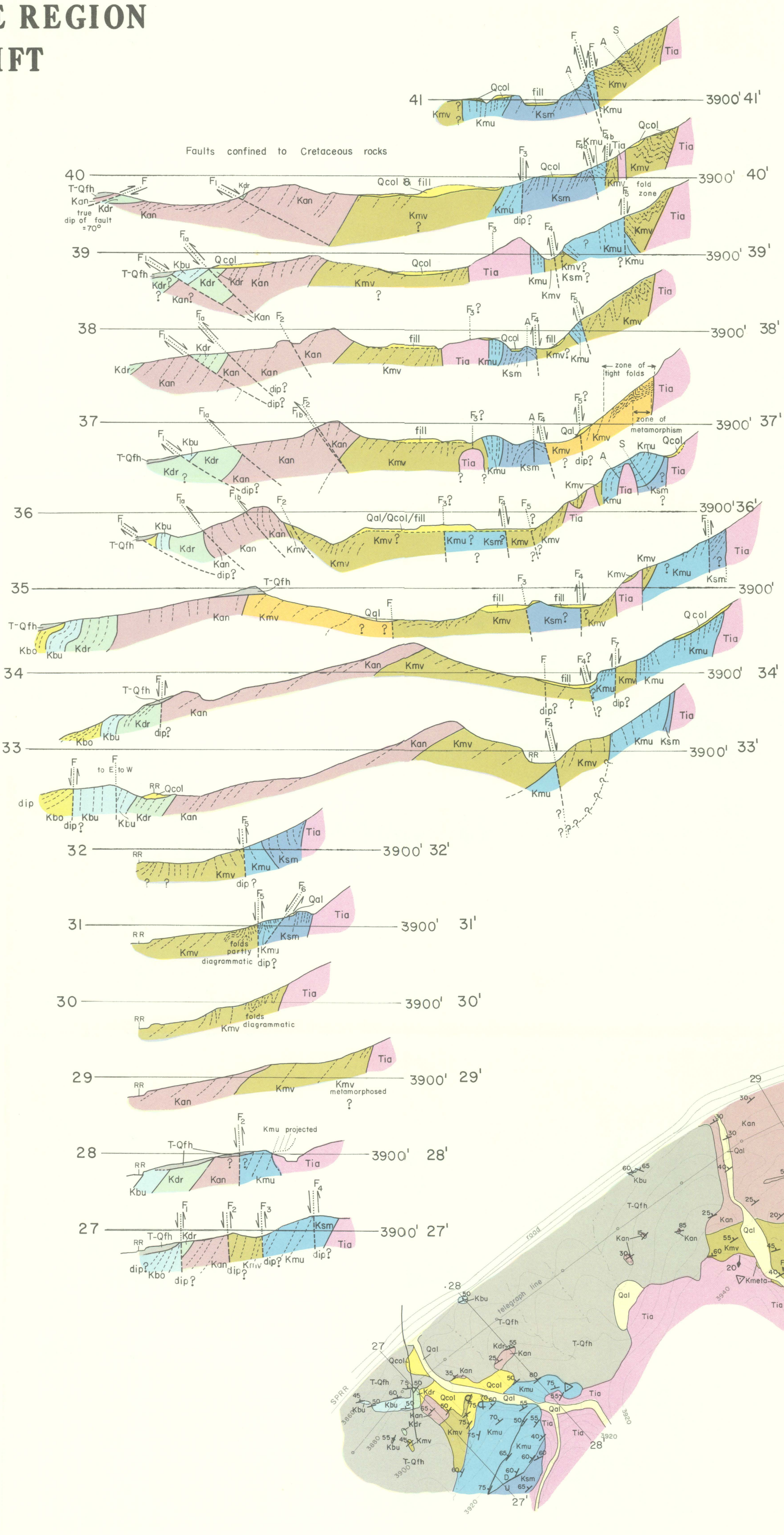
.25 Kilometer 250 Meters

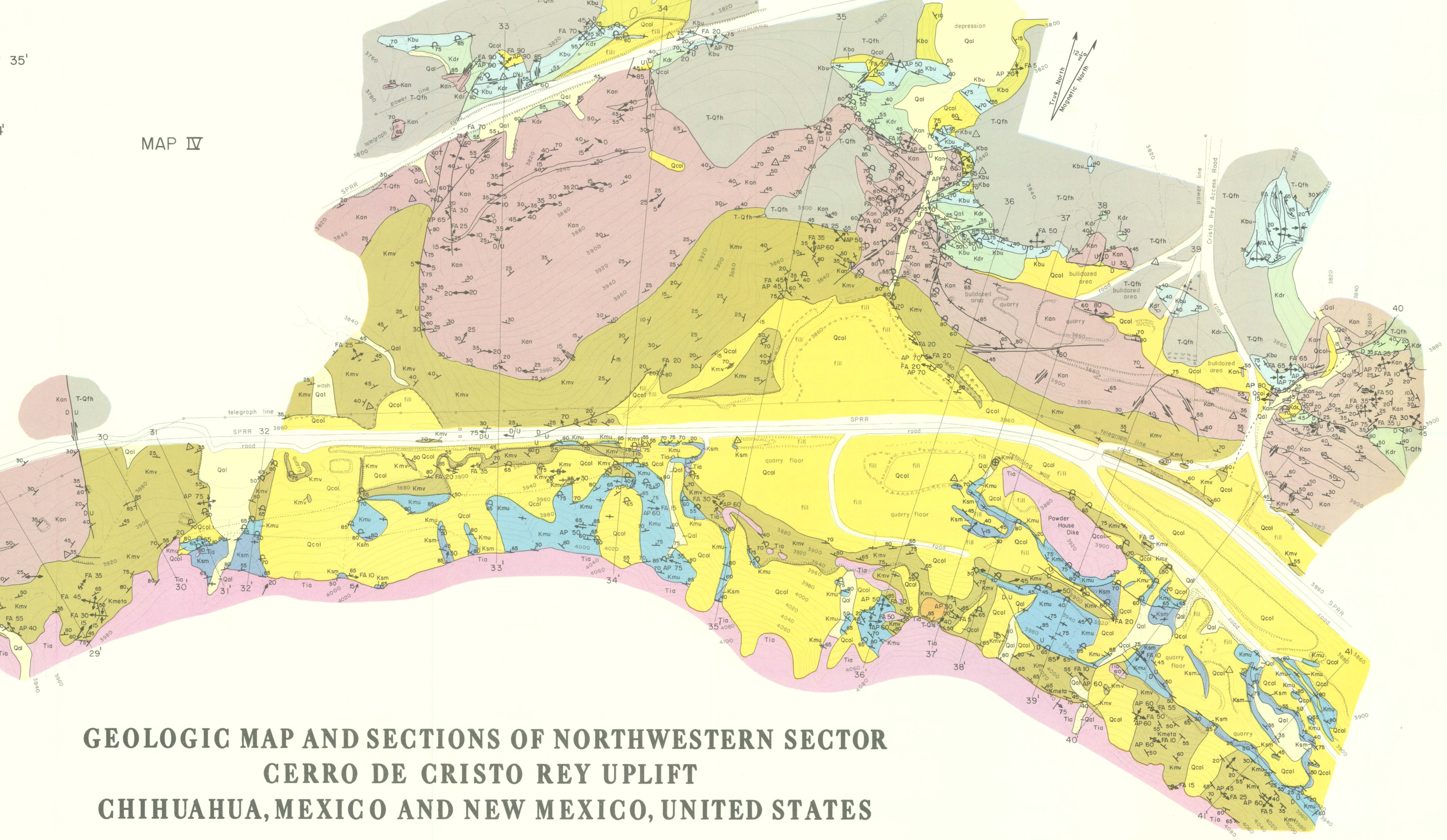


GEOLOGIC MAP OF GRAVITY-GLIDE REGION
CERRO DE CRISTO REY UPLIFT



GEOLOGIC MAP OF EASTERN FAULT-FOLD ZONE
CERRO DE CRISTO REY UPLIFT





GEOLOGIC MAP AND SECTIONS OF NORTHWESTERN SECTOR
CERRO DE CRISTO REY UPLIFT
CHIHUAHUA, MEXICO AND NEW MEXICO, UNITED STATES

EXPLANATION

SEDIMENTARY ROCKS

QUATERNARY

Qcol Colluvium
Regolith from subjacent or upslope rock; around pluton may include paleo-colluvium of Fort Hancock Formation. Fill included

Qal Alluvium
Stream deposits and river deposits of post-Wisconsinan age

TERTIARY

T-Qls Landslide
Andesite rubble or Anapra rubble

T-Qfh Fort Hancock Formation
Interbedded quartz sands and clays, basal conglomerate, mainly andesite clasts and grus

EROSIONAL UNCONFORMITY

UPPER CRETACEOUS

Kbo Boquillas Formation
Calcareous shales and very thin bedded clayey limestone

EROSIONAL UNCONFORMITY

LOWER CRETACEOUS

Kbu Buda Formation
Medium to massive, fine-grained limestone, abundant gastropods

Kdr Del Rio Formation
Shale, calcareous shale, thin nodular limestone beds, Exogyra *near base*

Kan Anapra Formation
Quartzose sandstone and siltstone; three massive coarse-grained sandstone members separated by two thin-bedded purple siltstone members

Kmv Mesilla Valley Formation
Dark-gray shale; some ironstone and fine-grained sandstone near top; black shale and a few limestone beds in lower part

Kmu Muleros Formation
Consists of upper, thin-bedded Gryphaea *packstone; middle shale and siltstone member; lower medium-bedded* Gryphaea*-rich limestone*

Ksm Smeltertown Formation
Consists of upper fine-grained sandstone; middle nodular limestone-interbedded shale; lower shale member

Kdn Del Norte Formation
Consists of upper limestone, fossiliferous (Refinery member); lower calcareous shale, fossiliferous (Brick Plant member)

IGNEOUS ROCKS

TERTIARY

Tia Muleros Andesite
Plagioclase and hornblende porphyry

METAMORPHIC ROCKS

Kmeta
Refers to the zone of contact metamorphism

Marker beds are locally indicated on the cross sections — particularly in the Anapra and Buda Formations

STRUCTURE

Contact
Intrusive or depositional, locally dotted where concealed

35 ⊕ 45
Bedding
Symbols left to right: strike and dip of beds, strike of vertical beds, strike and dip of overturned beds, horizontal beds

U D
Fault
Showing relative movement

Thrust fault

20
Slickensides
Showing bearing and plunge of slickensides

AP 70 FA 35
Anticline
Showing bearing and plunge of fold axis (FA), strike and dip of axial plane (AP)

Syncline

Overturned syncline

FA 10
Folds too small to plot individually

▷ ▷ ▷ ▷
Breccia zone

3800
3820
Contours

CULTURE

Intermittent stream

Dirt road

SPRR
Railroad

P.P. No. 8
Power line showing pole number
Or telegraph-telephone line

U.S.
MEXICO
International boundary

Quarry

Prospect pit

□
Building foundation

Fill

△
Plane table station

CROSS SECTIONS

F_2
Fault
Dotted where projected above ground, arrows show relative movement

Contact

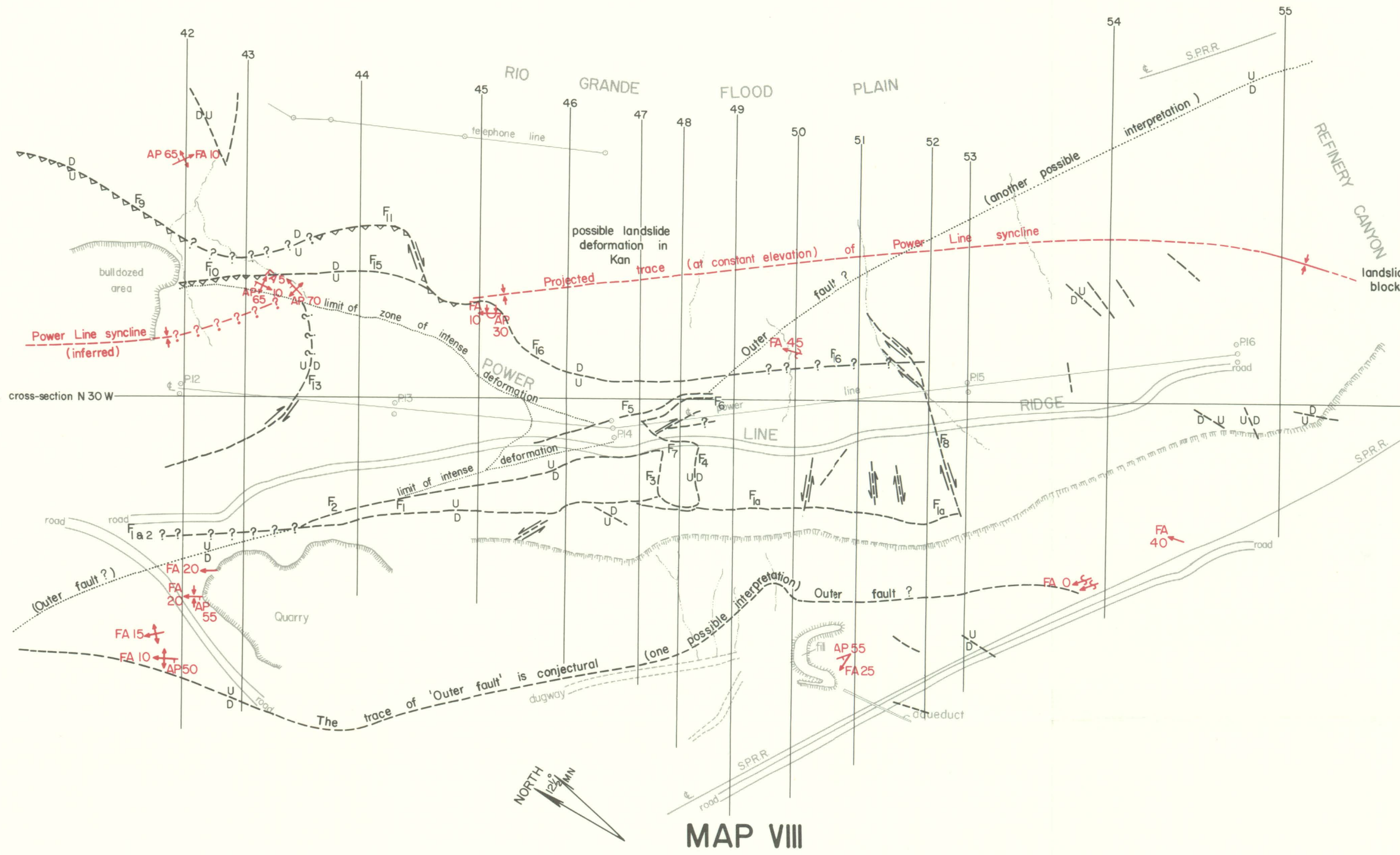
Bedding planes

S A
Syncline, Anticline

300 0 100 200 300 ft
100 0 50 100 Meters
Vertical and horizontal

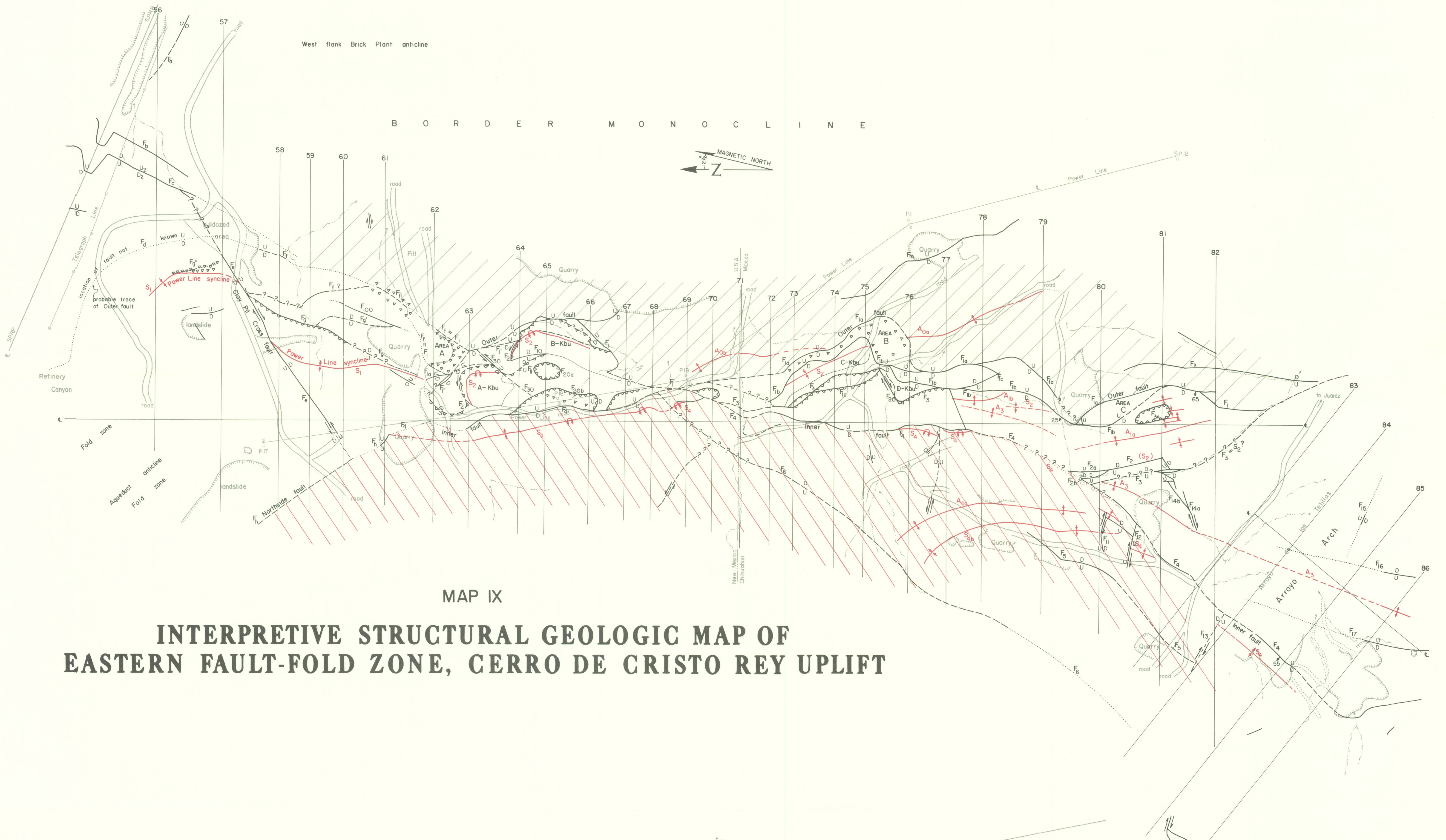
by Earl M.P. Lovejoy
1976

Cartography by Margaret Hoenig, 1973



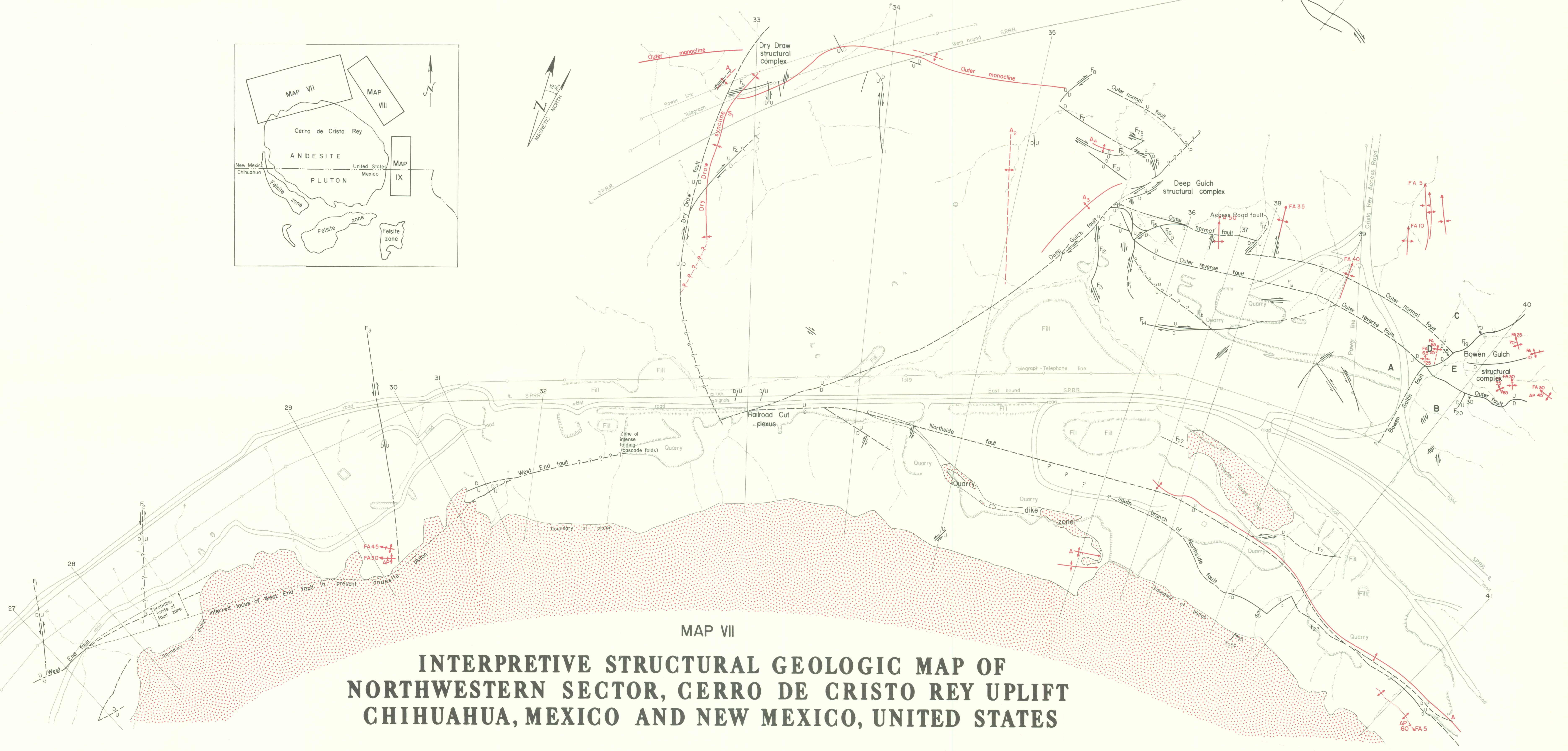
MAP VIII

INTERPRETIVE STRUCTURAL GEOLOGIC MAP OF CERRO DE CRISTO REY UPLIFT GRAVITY-GLIDE REGION, POWER LINE SYNCLINE



MAP IX

INTERPRETIVE STRUCTURAL GEOLOGIC MAP OF EASTERN FAULT-FOLD ZONE, CERRO DE CRISTO REY UPLIFT



MAP VII

INTERPRETIVE STRUCTURAL GEOLOGIC MAP OF NORTHWESTERN SECTOR, CERRO DE CRISTO REY UPLIFT CHIHUAHUA, MEXICO AND NEW MEXICO, UNITED STATES

EXPLANATION

STRUCTURE

Contact
Intrusive or depositional, dotted where concealed

Fault
Showing trace and dip of fault, relative movement, (U, upthrown side, D, downthrown side), dashed where approximate

Fault
Fault trace, dotted where concealed or projected, question marked where uncertain

Thrust fault
Teeth on overthrust block

AP 30 FA 35
Anticline
Showing bearing and plunge of fold axis (FA), strike and dip of axial plane (AP), dashed where approximate

Syncline

Overturned syncline

Small folds

Brecciated beds

CULTURE

road
Dirt road

S.P.R.R.
Railroad

P.12
Power line showing pole number
Or telegraph-telephone line

Center line

International boundary

Quarry

Fill

Building foundation

BM
Bench mark

IGNEOUS ROCK

▨ Andesite

0 100 200 500 1,000 ft

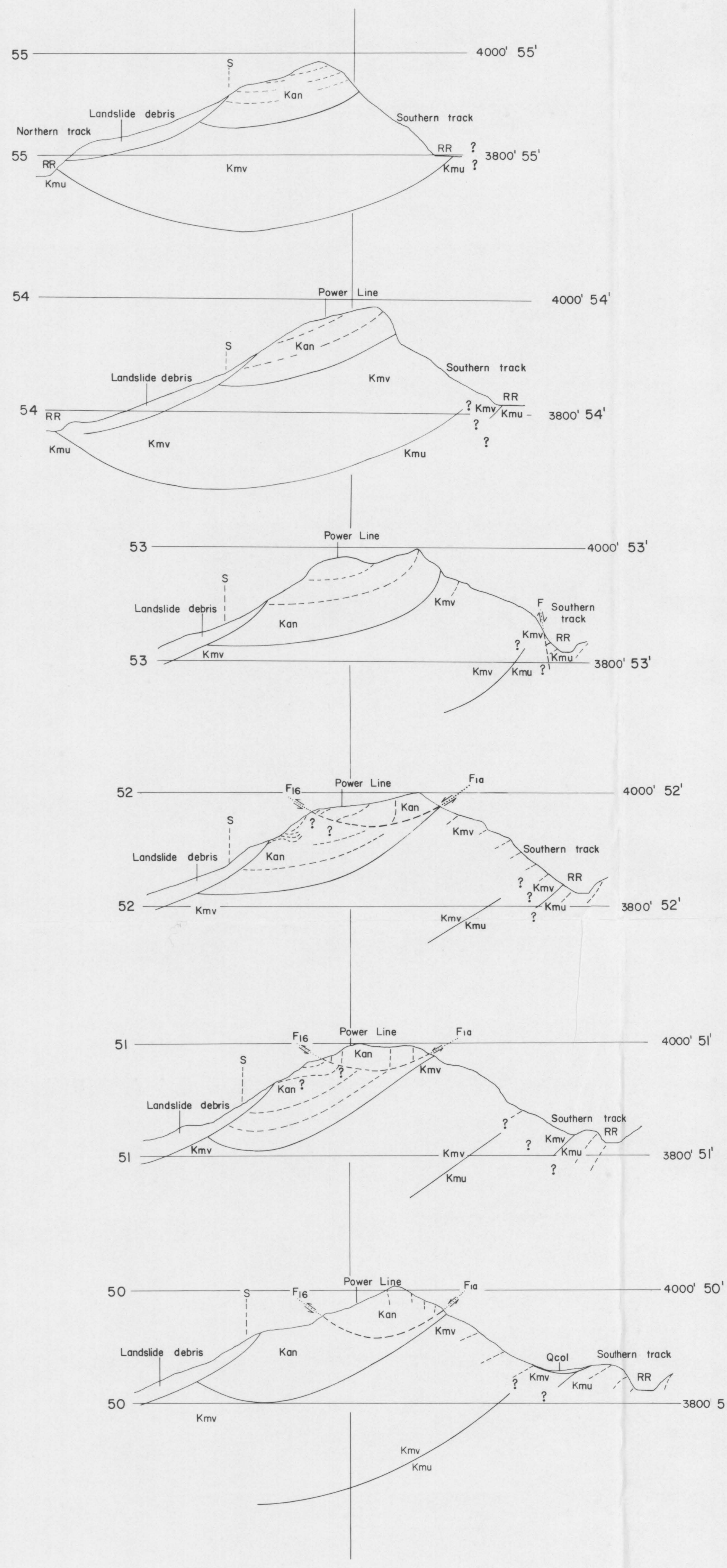
0 100 200 Meters

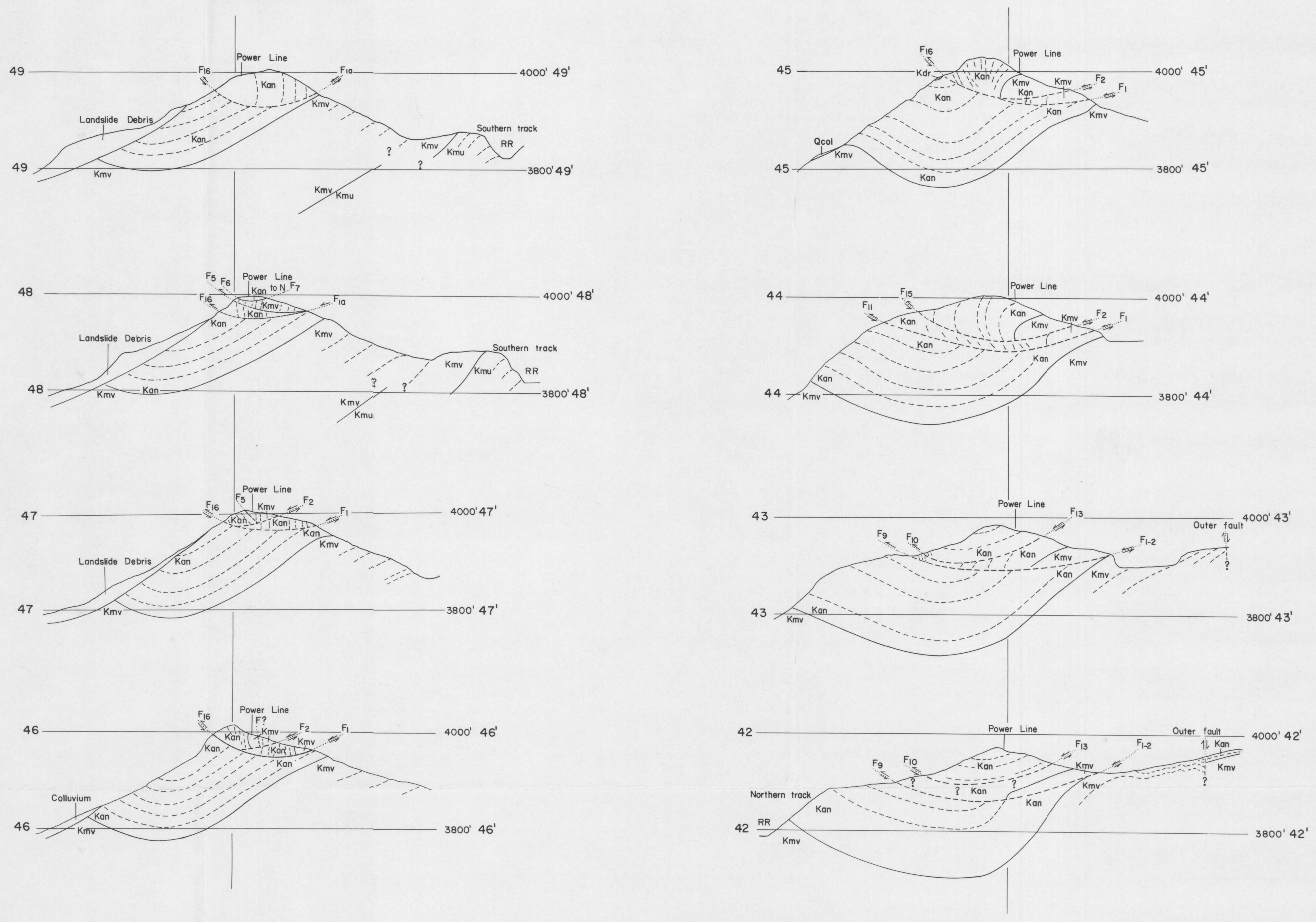
by Earl M.P. Lovejoy

1976

Cartography by Thomas Lau, 1973

CROSS SECTIONS X



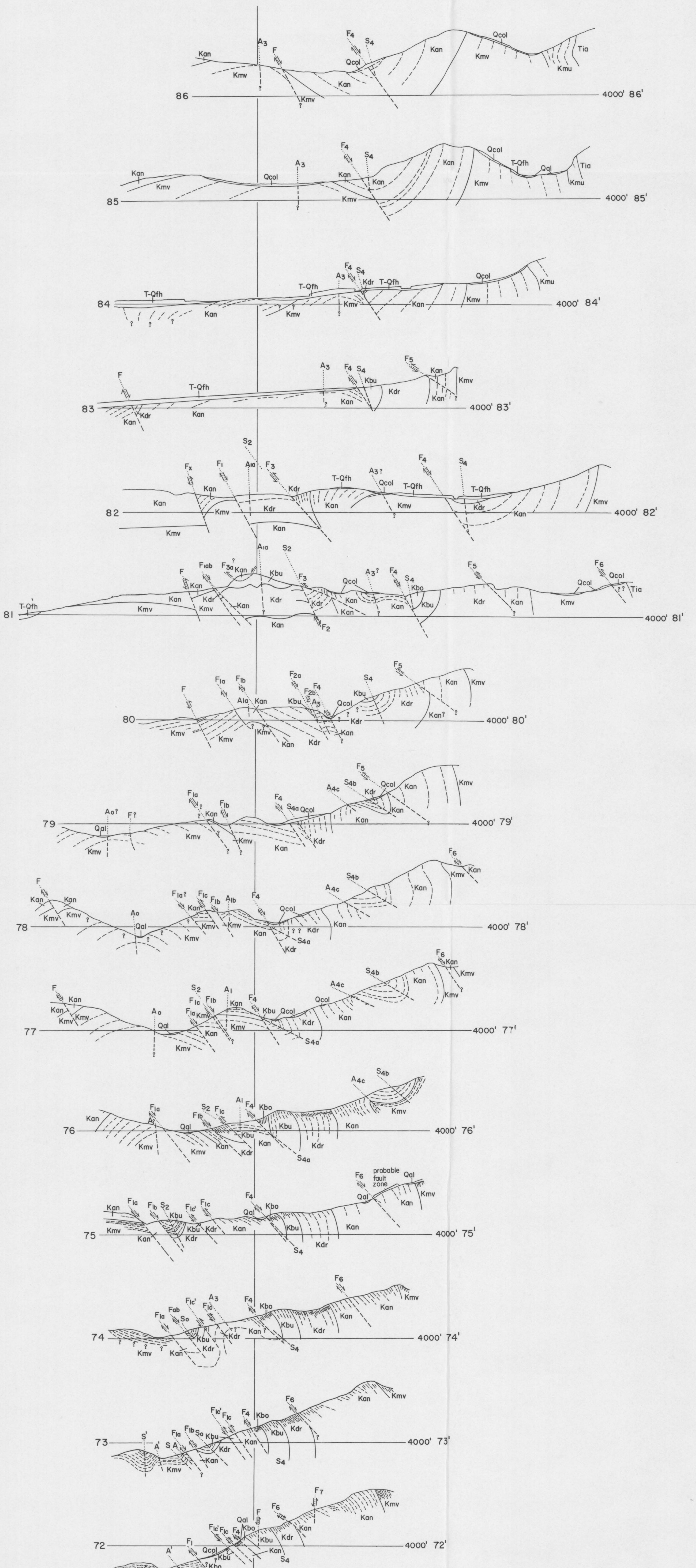


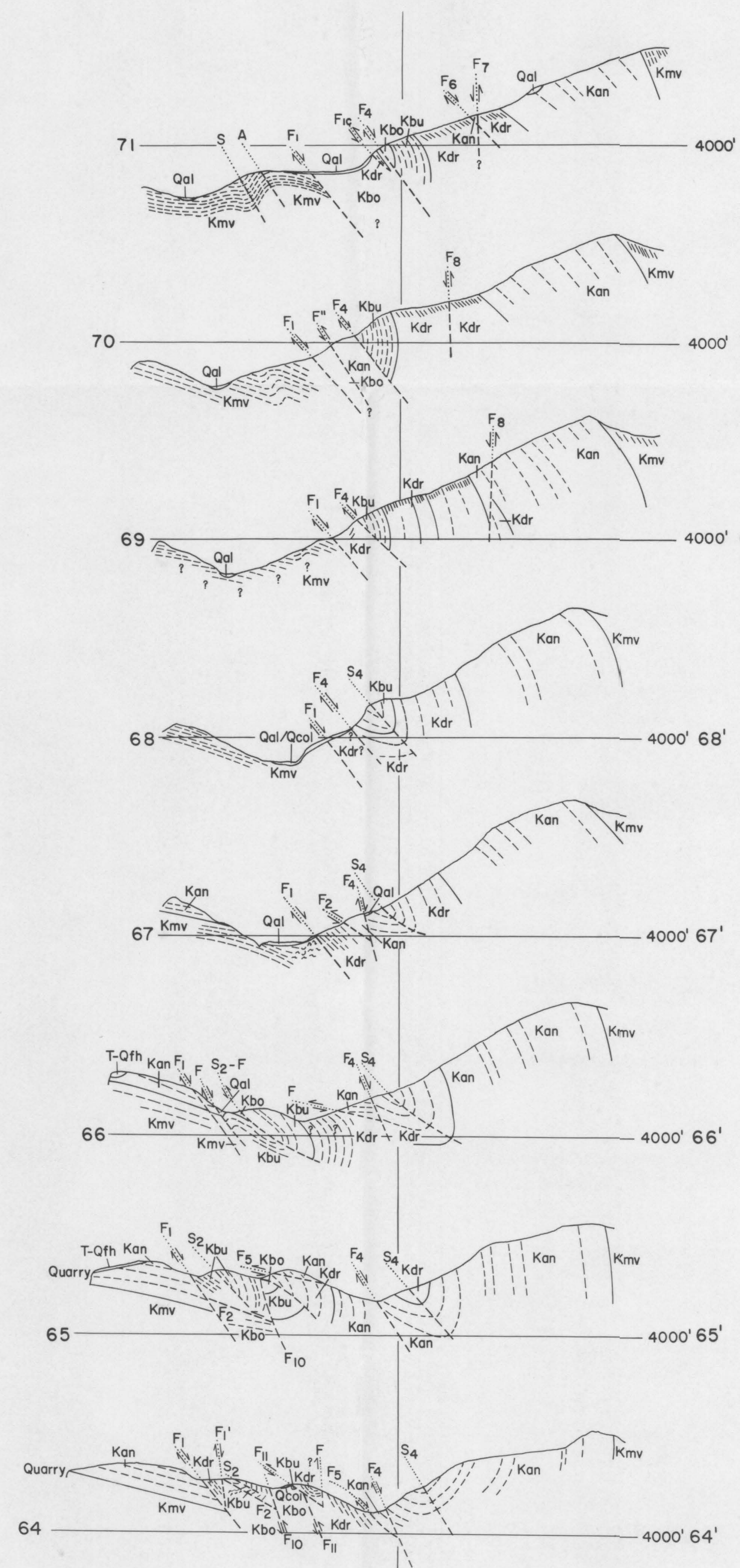
INTERPRETIVE CROSS SECTIONS OF GRAVITY-GLIDE REGION
POWER LINE SYNCLINE
CERRO DE CRISTO REY UPLIFT

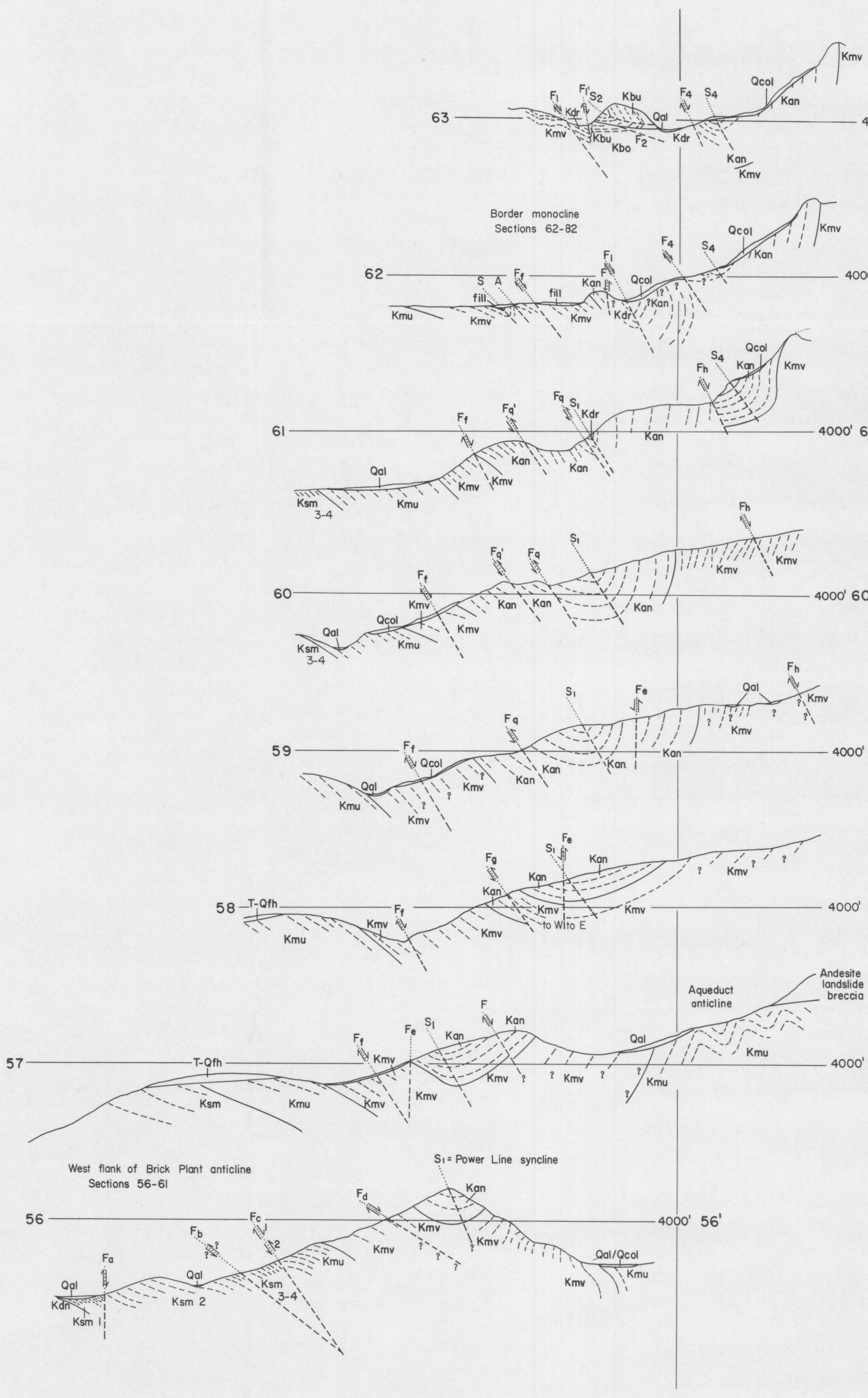
Bearing of all Cross Sections — N 60° E
Bearing of Section Center Line — N 30° W
View looking south

by Earl M.P. Lovejoy

CROSS SECTIONS XI







INTERPRETIVE CROSS SECTIONS OF EASTERN FAULT-FOLD ZONE
CERRO DE CRISTO REY UPLIFT
CHIHUAHUA, MEXICO AND NEW MEXICO, UNITED STATES

View looking south
by Earl M.P. Lovejoy

300 0 100 200 300 ft

100 0 50 100 Meters

Vertical and horizontal
1:2,400

1976

EXPLANATION

SEDIMENTARY ROCKS		
Quaternary	Qal	Alluvium
	Qcol	Colluvium
Tertiary	T-Qfh	Fort Hancock Formation
Upper Cretaceous	Kbo	Boquillas Formation
Lower Cretaceous	Kbu	Buda Formation
	Kdr	Del Rio Formation
	Kan	Anapra Formation
	Kmv	Mesilla Valley Formation
	Kmu	Muleros Formation
	Ksm	Smeltertown Formation

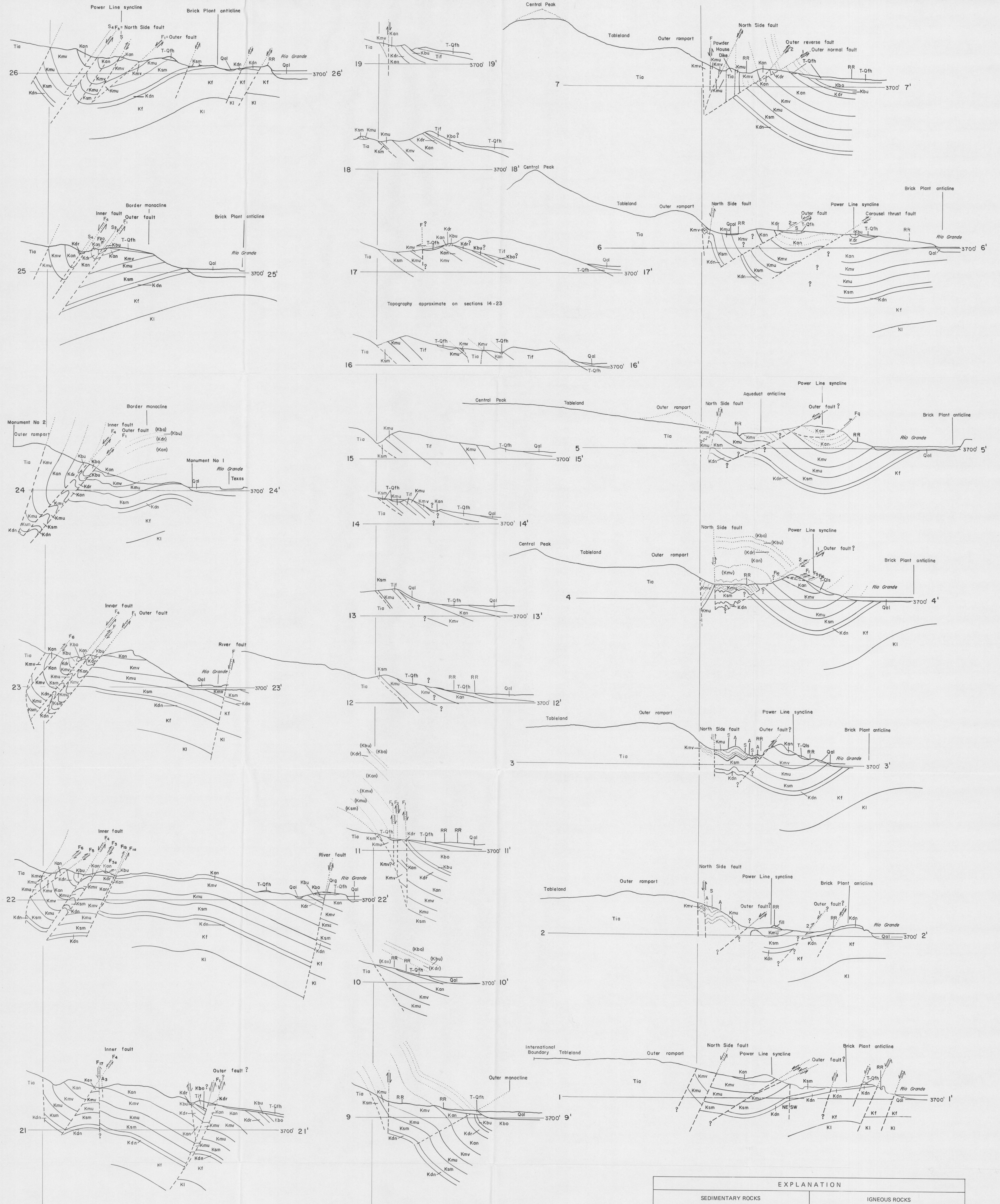
IGNEOUS ROCKS		
Tertiary	Tia	Muleros Andesite

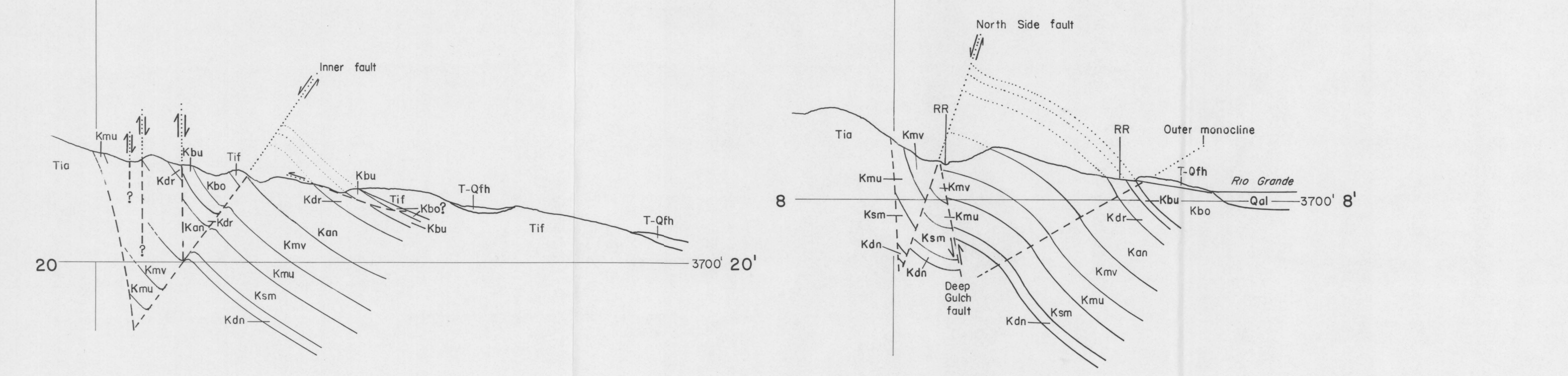
STRUCTURE	
Kan Kmv	Contact
	Bedding Planes
F	Fault (dotted where projected above ground). Arrows show relative movement
S	Syncline
A	Anticline

Cartography by Margaret Hoenig, 1973

NEW MEXICO BUREAU OF MINES & MINERAL RESOURCES A DIVISION OF NEW MEXICO INSTITUTE OF MINING & TECHNOLOGY

MEMOIR 31 SHEET 6 CROSS SECTION XII





EXPLANATION

SEDIMENTARY ROCKS			IGNEOUS ROCKS		
Quaternary	Qal	Alluvium	Tertiary	Tia	Muleros Andesite
	Qrg	River Gravel		Tif	Loma Blanca Felsite
Tertiary	T-Qls	Landslide	**STRUCTURE**		
	T-Qfh	Fort Hancock Formation	Kan / Kmv		Contact (dotted where projected above ground)
Upper Cretaceous	Kbo	Boquillas Formation	F		Fault (dotted where projected above ground). Arrows show relative movement
Lower Cretaceous	Kbu	Buda Formation	Tia		Intrusive contact
	Kdr	Del Rio Formation	S		Syncline
	Kan	Anapra Formation	A		Anticline
	Kmv	Mesilla Valley Formation			
	Kmu	Muleros Formation			
	Ksm	Smeltertown Formation			
	Kdn	Del Norte Formation			
	Kf	Finlay Formation			
	Kl	Lagrima Formation			

Cartography by Margaret Hoenig, 1973

For Geologic Map of Cerro de Cristo Rey see Sheet I Map I

INTERPRETIVE RADIAL CROSS SECTIONS OF THE ANNULUS, CERRO DE CRISTO REY UPLIFT CHIHUAHUA, MEXICO AND NEW MEXICO, UNITED STATES

by Earl M.P. Lovejoy

SCALE

.25 Mile 0 500 1,000 1,500 Feet

.50 Kilometer 0 500 Meters

Vertical and horizontal

1976