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FRACTURE STUDIES IN THE LUCERO UPLIFT,
NEW MEXICO

Final Report

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ABSTRACT

The Lucero Uplift is a transitional tectonic element situated along the boundary of the Colorado Plateau and the Rio Grande graben belt of central New Mexico. The eastern margin of the structure has been complexly faulted during two (or more) periods of Tertiary deformation. Evidence is presented in support of the hypothesis that both stages of tectonic development involved primarily vertical movement along sharp monoclinial flexures possibly emanating from displacement along deep seated fracture zones. The composite fracture pattern developed over the uplift indicates that the faults and joints are essentially parallel and were produced by a common cause. The dominant fracture pattern is regional and indicates primary east-west lateral elongation with secondary north-south stretching of the sediments due to bending of the rock between the primary fractures.

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OBJECTIVES

The purpose of this project was to study in detail the factors controlling the formation of fractures and the fracture pattern actually developed in an area transitional between Colorado Plateau and Basin and Range type structures. In particular, it was desired to establish the nature of the association of faults and joints and the relationship of both to regional tectonic forces. Because fracturing may play a major role in the localization of many of the uranium deposits of the Colorado Plateau, a better understanding of this phenomenon is of direct economic importance. For these reasons, the Lucero Uplift was selected as a subject for this program.

This report is intended, primarily, to summarize the most important data gathered from a field investigation undertaken during six months of 1952 and six weeks in the spring of 1953. As much as possible, the information is recorded in the form of maps, sections and diagrams and the text is largely designed to clarify and explain the data presented in the illustrations.

INTRODUCTION

The Lucero Uplift is situated in Valencia, Socorro and Bernalillo counties in central New Mexico. In a broad sense it encompasses an area of about 2,000 square miles extending between the axis of the McCartys

syncline to the northwest and the Rio Puerco-Rio Grande lowland to the east, and bounded to the south and north respectively by latitudes $34^{\circ}15'$ and $35^{\circ}15'$. This report deals only with the eastern third of this area.

The structure has been commonly termed the "Lucero Anticline" but the definition is somewhat of a misnomer for the western limb of the uplift is as much as 30 miles wide, whereas (with the exception of the north end) the eastern limb is at most one mile wide, and along the southern half of the structure there is no conclusive evidence of any reversal in dip.

In fact, the most outstanding feature of the Lucero Uplift as a whole is the abruptness of its eastern border. For tens of miles to the west, the beds dip westwardly at a low angle -- 10° or less, whereas within an extremely narrow zone, generally less than a half-mile wide, along the eastern margin, the beds dip steeply, attaining verticality or even slight local overturning. Deformation within this belt is severe and complex; the structure contrasts markedly with the simplicity of that which is encountered but a short distance to the west. Along this structural "front", which is also represented by an east-facing topographic scarp, well-cemented limestone and sandstone beds have been shattered or brecciated; more plastic units (gypsum and poorly consolidated shale) have flowed chaotically; dips and strikes vary erratically over distances of a few hundred feet; low- and high-angle, normal and reverse faults abound; horizons stratigraphically thousands of feet apart

have been juxtaposed along remarkably narrow fault slivers; and hot springs, evidently emanating from depth have laid down thick calcareous deposits along most of the belt.

Clearly, the important clues concerning the tectonic history of the Lucero Uplift are to be found in the details of its eastern margin.

Considerable differences in opinion have arisen concerning the relative importance of horizontal compressional movement and of vertical movement in the development of the structure. The variance in ideas is based in part on theoretical considerations (viz., whether or not it is logical or probable that horizontal compression has directly produced much of the structural relief), and in part on actual field relations (viz., whether or not true thrusting or compressional folding can be observed along the Lucero fault zone).

It is the writer's contention that the field evidence does not warrant the conclusion that large scale thrusting as a result of Laramide compression has occurred within the Lucero Uplift, and much space will be devoted to a consideration of this evidence.

It is beyond the scope of this report to discuss regional tectonics in detail; however, a few points might be noted in this regard. The Lucero Uplift is located along the eastern edge of the Colorado Plateau. It is separated from the Great Plains to the east by the downfaulted Albuquerque-Belen Basin, which is part of a great Tertiary graben belt extending along the entire height of the state. Structures east of the basin are not unlike those encountered in the Luceros. The Sandia-Manzano-Los Pinos range forms a compound upfaulted block beyond which the

structure passes eastward into flat lying beds within a very short distance. There is a strong suggestion that the Colorado Plateau, which reacted quite differently from the folded belt of the Southern Rockies to early Tertiary (Laramide) orogeny, may have extended across the present Rio Grande trough in the vicinity of the Albuquerque-Belen Basin.

Darton first mapped the Lucero area in 1928, (scale, 1:250,000) and recognized that the Paleozoic and Mesozoic sediments are separated from Tertiary-Quaternary deposits of the Rio Grande Valley by a major fault. He was noncommittal as to the nature of the faulting -- merely indicating that the eastern block is structurally low and showing the faults as vertical in his cross sections.

Kelley and Wood in 1946, in a much more detailed map (1:62,500), realized that the structure is far more complex than Darton had indicated. The single Lucero fault became a compound fault zone. These workers also noted that individual faults probably differ in age. They recognized, too, strikingly anomalous stratigraphic relations and low-angle faults, which they interpreted as a result of eastward Laramide thrusting within the sediments and modified by later, relaxational normal faulting of the same zone.

In the same year, Wright mapped one of the most critical areas (around Carrizo Arroyo) in still greater detail (1:12,000); but being primarily interested in the Tertiary geology, he completely omitted the aforementioned structural complications which are well developed there. Although not implying a thrust, Wright believed the Lucero Uplift to have been initiated as a compressional anticline during Laramide time and to

have been modified by late Tertiary and Quaternary normal faulting.

The present writer found that even within the deformed belt, uniformity is the exception rather than the rule. Most striking is the difference between areas north and south of Comanche Arroyo (Plate VIII). To the south the stratigraphically oldest rocks crop out (viz., Mississippian (?), Pennsylvanian, and pre-Cambrian); the beds are almost invariably sharply upturned to the east; slump structures are entirely lacking; no Quaternary basalt flows are present; a single, very well exposed low angle westward thrust is present; and finally, small patches of Permian and Triassic red beds are locally present along the eastern edge of the belt.

North of the arroyo, typical structures are vastly different. Stratigraphically younger units are present (Pennsylvanian-Cretaceous); the beds are invariably sharply downflexed to the east as a strongly asymmetric anticlinal fold with progressive younger beds occurring eastward; slump structures occur where very steeply dipping Permian beds are faulted against the Triassic; Quaternary basalt flows cap almost all remnants of the Ortiz (Pleistocene) erosion surface; and finally, no recognizable thrusts are present.

These two provinces will be considered separately with particular reference to the accompanying maps and sections. (See Appendices I and II for a discussion of the methods used in preparing these diagrams, for the reference system employed on the map and for stratigraphic details.)

STRUCTURE

Carrizo Arroyo Area (Plates I-IV)

This area is of primary interest because of the presence of well exposed low-angle faults, stratigraphic inversions, and overturned beds. It includes as well, the north end of Kelley and Wood's Comanche thrust belt.

The main physiographic features are the series of five ridges 400 to 500 feet high, here named Able (MM-114), Baker (HH-98), Charlie (W-74), Dog (M-45), and Easy (K-29), respectively from south to north, for purposes of reference. All of these hills are post-Pleistocene erosional remnants capped by resistant beds of the Glorieta-San Andres formations. Each is bounded on both sides by major faults. West of Able ridge an east-facing resequent fault-line scarp is developed where the resistant Pennsylvanian limestones lie against the soft shale and gypsum of the upper (Los Vallos) member of Yeso formation. Still farther to the west, the Abo formation forms a cuesta extending northward to Carrizo Arroyo. A Pleistocene (Ortiz) erosion surface bevels Pennsylvanian and Permian beds and is capped by Quaternary basalt flows, portions of which are shown in the western and southern parts of the map.

East of the main series of ridges, poorly consolidated Tertiary (Santa Fe) beds and Quaternary gravels form the western edge of the Rio Puerco-Rio Grande lowland. A small butte (U-98) of Santa Fe beds protected by cemented gravels represents a probable outlier of the Ortiz erosion surface.

The stratigraphic units employed in the map are described in Appendix II. Fortunately, it is possible to considerably subdivide standard formations in the field; thus permitting a much better understanding of the structure. In particular, the San Andres formation is divisible into lower evaporite, lower limestone, upper evaporite and upper limestone members, respectively. None of these units is purely evaporite or limestone, but rather each consists of interbedded limestone, gypsum, sandstone, and shale in varying proportions. The nature and thickness of the interbeds is one of the most helpful criteria in recognizing the individual units. The overall thickness of each of these members varies widely over the area and this is primarily due to the extensive lateral flow and folding within the gypsum beds.

From Carrizo Arroyo northward, the Glorieta sandstone is divisible into three members, and the uppermost part of the thick (1,000 foot) Los Vallos member of the Yeso formation is distinguishable from the lowermost part. This proved to be of importance in locating several important faults, which are not directly observable when they are wholly contained within the Los Vallos.

Concerning the structure, only the most salient features, having a direct bearing on the tectonic history, will be described here.

General structure and high-angle faulting

Essentially, the structure of the western portion of the area consists of a gentle northwestward dipping homocline, involving beds of the Madera, Abo, and Yeso formations. North of Carrizo Arroyo, a

reversal in dip produces a gentle, asymmetric, northward plunging anticline. Within this entire area the beds are relatively undeformed and unbroken by large faults.

To the east lies a belt, generally about 2,000 feet wide, in which highly deformed east-dipping Permian beds are isolated by major faults. With the exception of the fault separating Dog and Easy ridges, all of the important blocks are downdropped to the east, resulting in a compound fault zone in which is concentrated almost all of the thousands of feet of structural relief between the Rio Puerco-Rio Grande lowland and the complementary upland to the west (Plates I and II).

The steep dips within the intermediate blocks are clearly not a result of drag along the individual faults but rather to the penecontemporaneous or subsequent fragmentation related to the development of a very sharp, narrow flexure whose western limb is nearly horizontal and whose eastern limb is very steep. True drag can be observed along many of the large faults, but its effect is invariably limited to a zone a few scores of feet wide, along which the poorly consolidated beds have been pulled out towards parallelism with the fault and the more massive units have been slightly warped in the direction of movement (Plates I and II). Easy ridge dipping towards the upthrown fault block (Plate II, secs. 3, 4) completely belies the idea of drag producing the present structure.

These points are mentioned here in order to distinguish between the concept of "drag" and that of vertical movement along deep-seated faults producing a flexure in overlying sediments, causing in turn, development of major faults of secondary origin.

The direction and angle of dip of the major fault surfaces can be directly observed at only a few locations, and calculations based on apparent dips are of doubtful reliability because of abrupt changes in strike. (The change in trend of the normal fault at the top of Baker hill (II-97), for example, is almost certainly due to an alteration in strike of a nearly vertical fault rather than to the effect of the topography on a single plane dipping east at a low angle.) Nevertheless, where reliable observations can be made, the planes always dip toward the downthrown block at angles of 50 to 85 degrees (T-73, BB-77, KK-101).

The sharp angularity of the fault pattern (with exceptions noted below) over variable topography further supports a concept of moderate to high-angle faulting, and at no place is there evidence of reverse throw. In particular, the hypothesis that hills Able and Baker are outliers of a thrust sheet demands that the large fault to the west be a root zone of such a thrust. This fault is remarkably linear; just south of the map, it takes an abrupt change in trend; west of the Able ridge (VV-129 to OO-109) the Yeso shales are consistently dragged and indicate a persistent 75 to 80 degree eastward dip of the fault; at the north end of the Madera limestone cuesta (NN-105) it branches into clearly normal faults, at which point a number of high-angle slices have been developed (Plate II, secs. 14-15). These facts suggest that the fault is actually a high-angle normal fault -- a viewpoint further strengthened by independent evidence (see below) that the hills to the east are not true "klippen".

The strike of almost every fault in the mapped area falls within a range of N 25° E and N 25° W, and wherever faults of different trends intersect, the bisectrix of the obtuse angle is aligned in an east-west direction.

The only important exceptions are the short faults to the north (CC-95) and south (MM-103) of Baker hill. Both represent cross breaks arising at points where the total vertical displacement along a single northerly trending fault becomes shared by a pair of such faults. A number of narrow basaltic dikes striking between $N 5^{\circ} E$ and $N 15^{\circ} E$, together with the overall fracture pattern supports a concept that east-west horizontal stretching has produced tension fractures which strike almost due north and conjugate pairs of fractures whose obtuse angle faces the direction of maximum elongation.

The age of most of the faults cannot be precisely determined from field relations alone. The easternmost fault, which involves upper Santa Fe beds but pre-dates the completion of the Ortiz erosion surface, can be established as late Pliocene or early Pleistocene (?) age. From the center of Charlie ridge (T-73) northward, this fault places the Santa Fe beds alternately against the soft purple and red Triassic shales and the drab, fossiliferous Cretaceous shales, which are in turn faulted and strongly dragged against the Permian. Wright (1946) states that the uppermost Santa Fe gravels in this area contain indigenous fragments of Pennsylvanian, Permian, and Triassic beds, as well as of the Tertiary intrusion along Able ridge. This indicates that much of the structural relief of this portion of the Lucero Uplift had been established previously and that erosion had progressed to such an extent that large masses of Cretaceous and Triassic beds could hardly have remained on the high blocks through late Santa Fe time. It appears, then, that the Triassic-Cretaceous fault contact with the Permian (as well as most of the other faults in the area)

is probably older than the "Santa Fe" fault, and that the latter followed almost the identical zone from Charlie ridge northward.

Independent evidence (Wright, 1946; Kelley and Wood, 1946) suggests that the earliest period of deformation occurred in late Cretaceous or very early Tertiary time. There seems, however, little indication that the two (or more) stages of structural development represent completely different tectonic phenomena.

Gypsum flowage; sliding and brecciation of adjacent beds

Along all of Charlie ridge (DD-89 to U-64) a distinct breccia is continuously exposed within the Glorieta. The breccia varies in thickness from 1 to 15 feet; it consists of angular fragments consisting solely of Glorieta sandstone; individual blocks vary in size from a few inches to a few feet; fragments near the center of the zone are commonly jumbled irregularly; frequently, near the edges of the zone, fragments are semi-coherent and, although separated, adjacent blocks can be visually restored to a unit; the zone grades imperceptibly (vertically) into highly jointed but unbrecciated Glorieta sandstone; the matrix consists of aragonite, calcite, and limonite; the breccia follows a single stratigraphic horizon within the Glorieta; and finally, at the north end of the ridge (U-64) the breccia disappears and a wedge-shaped unit of gypsum appears at the same horizon.

Along this ridge a second important breccia band occurs (Y-79 to U-65), differing from the first, only in the presence of mixed fragments of Glorieta sandstone and San Andres limestone. At both the north and

south ends of the zone, a thick gypsum wedge occurs as the dip steepens along the flank of the flexure. Thinner, less conspicuous zones are present at numerous horizons within the San Andres.

Similar breccias occur along Able, Baker and Dog ridges but, to the south, their relation to the gypsum is less clear because the evaporite beds are completely lacking. Along Easy ridge, where dips are low and uniform, the breccias are absent and evaporites are present at the corresponding horizons.

Typically, the breccias are present near the crests of sharp flexures and recrystallized gypsum exhibiting flow structures is present along the flanks -- occurring in notably great thickness where the strike of adjacent beds changes abruptly.

It is clear that extensive lateral movement has occurred within the highly plastic evaporite units, deforming and facilitating down-dip sliding of overlying beds, and attaining its ultimate development in a complete tectonic pinch-out along the crests of sharp flexures. The presence of aragonite as a cement indicates that the movement was initiated when these zones had access to hot solutions arising from below; whereas other factors (discussed below) definitely show that at least part of the movement is of post-Pleistocene age and may even be active at present.

Low-angle faulting; rootless masses; "slump" structures

The tops of hills Able and Baker and the southernmost tip of Charlie ridge are rootless masses, bounded at the base by low angle faults. The hypothesis of eastward Laramide thrusting within the sediments, has been

based, in part, upon the interpretation of these rootless bodies as "klippen". The features exposed within these areas will be considered in detail.

Along the eastern side of Charlie ridge, the various members of the San Andres formation have been normally faulted against the plastic Triassic shales. The truncated, resistant east-dipping San Andres beds rise high above the present resequent fault-line scarp and protect the eastern slope of the hill. Within 100 feet of the fault line, the Triassic beds surficially dip very steeply to the east, or more commonly, are slightly overturned towards the west; the evaporite members of the San Andres have interflowed with the Triassic shales along the fault contact; and the two limestone members have slid downward and eastward over the gypsum units so that the front edge of the beds has been steepened into a "toe" which lies on top of the Triassic. (See Plate III-B). Within this area these effects are clearly superficial.

Along the same ridge, the Glorieta sandstone progressively steepens southward. At the extreme end of the hill (FF-90), the formation is cut off by the intersection of two large faults. (The westernmost fault is poorly exposed but well inferred from the absence of about 900 feet of the Los Vallos member.) Within 300 feet of this intersection, the Glorieta is moderately (85° W) to strongly (35° W) overturned and the entire southern tip of the ridge appears to have been rotated in a clockwise sense (looking north), placing Glorieta discordantly on the Yeso along a low-angle break (Plate II, sec. 11). The displacement is slight,

for some of the overturned beds can be traced continuously into the normal, east-dipping hogback a very short distance to the north.

These relations are highly suggestive of minor antithetic faulting and rotation of a block caught between two faults progressively down-thrown to the east. The actual break may well have been initiated in this manner; however, most of the displacement is undoubtedly very recent. A tiny remnant (EE-90) of Quaternary gravels has been preserved, cemented against a Glorieta bedding plane. The attitude of the gravel bedding is far too steep to represent a primary dip and indicates that the now inverted Glorieta was standing nearly vertical at the time of deposition, having been displaced by subsequent slumping on fairly modern topography.

At the top of Baker hill, the Glorieta sandstone and the lower limestone unit of the San Andres rest on the soft gypsiferous shales and silts of the upper Los Vallos. The contact is in part normal and in part discordant.

At the center of the hill (II-97) two blocks of Glorieta have been rotated clockwise (looking north) on well exposed low-angle faults which dip to the northwest at angles of 20 to 30 degrees. This displacement places the truncated eastern edges of Glorieta beds directly against the older Los Vallos (Plate II, sec. 12). As on Charlie ridge, the phenomena may have commenced as antithetic movement associated with the major fault just to the west (II-97).

Above the Glorieta, the lower San Andres limestone member has apparently moved eastward, sliding down-dip on the lower evaporite member, which is no longer present. As a result, a persistent breccia has been produced along the Glorieta-San Andres contact and the truncated eastern edges of the limestone beds have been steepened into a "toe" which now rests discordantly on the Los Vallos (Plate II, sec. 12). (In the process, a sliver of upper Glorieta sandstone also moved eastward in a similar fashion, perhaps sliding on gypsum within the Glorieta. This fault is shown on the map but omitted from the cross sections.)

According to these facts, it seems that a narrow block consisting of Glorieta sandstone and the two lower members of the San Andres was first isolated by large normal faults; subsequently, flowage of the plastic Los Vallos beds widened the space between the faults and resulted in a corresponding east-west lengthening of the overlying section by small rotational faults and sliding on bedding planes lubricated with gypsum. This development is illustrated in Plate III, A, B, C.

Other evidence supports this hypothesis. The Los Vallos beds along the western half of the hill are relatively undeformed except for drag along the fault. On the other hand, the eastern fault is marked by a highly folded vertical zone about 200 feet wide. The fault trace becomes very irregular and assumes the character of a flowage contact wherever San Andres evaporite lies against the Upper Yeso (II-104 to EE-98). It is therefore quite feasible that the original fault was several hundred feet west of its present position and has since been modified by eastward flowage. The striking similarity in shape of the Glorieta (II-97)

and the San Andres (GG-99) blocks capping the hill, while not conclusive, strongly suggests that the two blocks were originally superimposed, with the eastern linear boundary of the Glorieta approximately representing the original position of the fault.

The north end of Able ridge also is capped by truncated Glorieta-San Andres beds lying discordantly upon the older Los Vallos under conditions analogous to those encountered on the hills to the north. The eastern slope is further complicated, however, by the presence of Permian beds lying upon the Triassic.

Typically, a thin veneer (never visibly exceeding 50 feet), consisting of large, more or less coherent blocks of San Andres covers the hillside as a fairly continuous sheet. Progressively younger units occur downslope, associated with a steepening of dip -- and considerable overturning along the edge of the mass. The contact with the Triassic, well exposed at the northeast corner (II-114) and in several gullies to the south, is a very irregular, nearly horizontal surface along the eastern margin but assumes an eastward dip upslope where the San Andres lies exotically on Los Vallos. The main body of this sheet lies discordantly on a wedge of west-dipping, inverted Triassic (JJ-114 to LL-119) which in turn lies discordantly upon west-dipping, upright Triassic sandstones and shales. With this sole exception, the dips of the Triassic in the entire region are to the east -- a fact which strongly suggests that the beds under the Permian sheet may have been depressed locally.

The most important evidence concerning the nature and origin of these unusual features is to be found at the extreme northeast corner of Able hill. At II-109 a large normal fault dipping about 65 degrees east and throwing Triassic against Yeso is well exposed. Within several hundred feet of the fault, the gypsiferous Los Vallos shales and silts have flowed into chaotic folds, and just to the south, the material has been extruded eastward, downslope, over the normal fault and onto the Triassic beds (II-112). The westernmost part of the San Andres sheet, in turn, lies upon this flow mass (JJ-113).

The movement of the gypsum is more recent than the Tertiary igneous intrusion along the hill, for angular fragments of this rock have been incorporated in associated flow breccias within the Los Vallos; it is clearly younger than the major normal fault which it crosses (and which must continue southward beneath the entire exotic sheet): both the gypsum and the San Andres have moved onto a lower, post-Ortiz erosion level developed in the weak Triassic beds; and finally, the recentness of the movement is further attested by the breaking and tilting (up to 45 degrees) of a small post-Ortiz caliche cap at KK-123. It seems inescapable that the allochthonous sheets represent an unusual type of mass gravity movement of fairly recent age.

The development of these peculiar structures is controlled by, and is a direct result of a unique arrangement, in time and place, of several lithologic, structural and geomorphic features.

The Triassic shales in the entire Lucero Uplift are notoriously

conducive to landsliding wherever they underlie resistant beds. On Lucero Mesa and Sierra Lucero, slump blocks have developed under a basalt cap for distances up to a mile or more from the present rim line. The Glorieta-San Andres formations, consisting of massive sandstone and limestone units interbedded with plastic evaporites, readily deform by bending and bedding plane slippage. The thick, homogeneous body of poorly consolidated, gypsiferous beds of the Upper Yeso (Los Vallos member) is very susceptible to plastic flowage en masse.

The complete isolation, by normal faulting, of narrow Permian blocks produces "ready made" units small enough to encourage gravitational movement. The predominantly steep eastward dips within these blocks, together with the downdip fault contact of the laminated Glorieta-San Andres rocks and Triassic shales forms the ideal structure for potential sliding.

With the stage thus set, it remained only for recent erosion to provide the final condition necessary to inaugurate mass gravity movement on a grand scale -- the formation of a Triassic lowland beneath a high, resequent fault-line scarp.

The sequence of events producing these "slump" structures is illustrated (somewhat diagrammatically) in Plate III. Although primarily designed to show the relations on Able hill, the figures also roughly apply to Baker and Charlie ridges, for the latter represent less extreme stages of the same process. The simplest result of post-Ortiz erosion (Plate III-B) is marked by partial removal of the Triassic "buttress",

causing down-dip sliding of San Andres beds along gypsum layers, surficial steepening or overturning of the older normal fault and of nearby beds. Charlie ridge is at this stage today.

The steepening of the older fault widens the section horizontally and results in lateral movement of the Los Vallos against and along the original fault plane, causing a complete separation of the Glorieta-San Andres from its original contact with the Triassic (Plate III-B, C). Overlying beds adjust by small west-dipping antithetic faults to the rotational effect of horizontal stretching combined with downslope eastward movement (Plate III-B, C). Baker and Able hills show these features.

Ultimately (Plate III-D), as on Able hill, the surficial Triassic beds are completely inverted and faulted off. Los Vallos gypsum flows out over this sheet, carrying with it jostled and semi-coherent remnants of higher beds.

North of Charlie ridge, no similar structural complications are encountered along the entire Lucero fault zone, either within or beyond the area shown on the map. South of the mapped area, however, these features persist for about one-half mile and are illustrated in great detail in Plate IV, which is an extension of the map.

At the south end of Able hill (PP-128) a small patch of Upper San Andres limestone is in contact with Triassic shales. The nature of the contact at this location is obscure but it has been indicated as a "slump" fault, for as one walks south a few hundred yards he comes to a series of exposures which show without doubt that the limestones are lying discordantly upon the Triassic along a flat lying surface. (Plate III, secs. 4, 5, 6, 8)

As on northeast Able hill, the limestones are present as a thin veneer in which beds are steepened (or slightly inverted) to form a "toe" along the eastern margin. To the west a basic intrusion (the "Major Stock" of Wright) is capped by remnants of east dipping Glorieta-San Andres beds and forms a hill several hundred feet high. It is entirely feasible that the limestone sheet was derived from there and moved downward onto the Triassic in a manner similar to that farther north.

Far more puzzling, however, is the presence of tiny remnants of Triassic red sandstones, shales and chert-pebble conglomerates lying directly on top of Los Vallos beds. (Plate IV, secs. 2, 4, 5). The outcrop pattern on the hillsides and in gullies ascertains that the contact is very nearly horizontal. Meager evidence in the form of drag (Plate IV, secs. 3, 5) suggests that the main mass of Triassic to the east is in place, and is separated from Los Vallos by a large normal fault. The anomalous patches of Triassic on the hillside to the west are today at higher elevations than the fault contact. If they were emplaced by "slump", the blocks would have to have been derived either from an obsequent fault line scarp to the east or from above the intrusion to the west, and deposited on an erosion surface which was slightly higher (50 to 70 feet) than today. Neither of these explanations is entirely satisfactory. It is very doubtful that Triassic beds were still present above the intrusion at so recent a period in the erosion cycle. On the other hand, the Triassic in the region normally does not form high scarps. In this particular area there is a large

percentage of well cemented sandstone in the Triassic section and it is feasible that a low Triassic ridge was present east of a subsequent valley developed in the very weak Los Vallos silts and gypsum. Such a difference in elevation might have been sufficient to account for the exotic blocks (which are ridiculously small in areal extent) as due to "slump".

Alternative explanations fail completely. The possibility that the Los Vallos gypsum beds have produced piercement-type structures such as occur on Able ridge is belied by the lack of deformation within that unit. The bedding is undisturbed except for gentle folds normally found in such lithologies. The hypothesis that the Los Vallos has been thrust onto the Triassic completely fails to account for the presence of Triassic upon the Los Vallos.

Summary

Along two and one half miles of the Lucero fault zone near Carrizo Arroyo, structures are present which suggest low angle overthrusting. This is the only area along the entire thirty miles of the Lucero front where there is direct field evidence which might support a concept of thrusting (high or low angle). This same area is the only one in which a unique series of lithologic, structural and geomorphic relations has combined to form conditions highly conducive to mass gravity ("landslip") movements. Considerable other evidence supports the latter hypothesis: (1) All of the exotic rocks are indigenous (i.e., they would normally be present at higher elevations on fault line scarps);

(2) displacements on low angle faults are small; (3) as commonly as not, younger beds lie discordantly upon older ones; (4) much of the movement is definitely connected with the present erosion cycle (post-Pleistocene); (5) various localities illustrate the succession of stages in the history of these features.

North of the Carrizo Arroyo area to New Mexico highway 6 and south to Comanche Arroyo, the larger structural features are similar to those found around Carrizo Arroyo -- that is, the gentle regional westwardly dip of the beds abruptly reverses along a narrow north-trending fragmented flexure. Beyond the highway, a strong northward plunge exposes progressively younger beds; the flexure zone becomes broader and gentler, and its eastern edge changes trend from north to north-northeast, continuing along that direction for many miles as the Ignacio Monocline. The latter change is reflected in the pattern of both faults and joints (see below). As the flexure widens, the total vertical displacement between the highest and lowest parts of the structure is distributed among a large number of relatively small faults rather than being concentrated along a few very large faults as in the Carrizo area.

It is the writer's opinion that the flexures are an expression of differential movement of adjacent blocks along sharply defined fracture zones at depth, and that the sedimentary faulting is only secondarily related (through the folding) to the basement fractures, particularly in the higher beds where the folds are less severe. Whether or not this hypothesis be correct, the important feature of this region is that the

beds are down-flexed from the uplift towards the down-dropped Rio Grande graben belt. Farther south we shall see that a remarkably different set of structural relations prevails along the eastern edge of the Lucero Uplift.

Gray Mesa Area (Plates V, VIII, X)

For 15 miles from Comanche Arroyo south to the Ladron Mountains, the boundary between the Lucero Uplift and the Rio Puerco-Rio Grande Valley follows a rather sinuous line. (Plate VIII) West of this line a continuous belt of hills and cuestras is developed in Pennsylvanian and older rocks, whereas to the east valley fill and plates of Quaternary hot spring deposits lap up over the base of the hills. At widely separated locations, tiny patches of Permian red beds are exposed beneath the Quaternary cover, and are lying so near to the Pennsylvanian as to demand the existence of at least one fault of large throw along the entire zone. The main fault itself is almost completely under cover and the writer found that actual exposures are even more limited than had been previously supposed, for a number of small red bed outcrops along the south and east sides of Gray Mesa reported to be Permian proved upon close examination to be red sands interbedded with gravels containing large angular fragments of indigenous rocks (Madera limestone, Sandia quartzite and pre-Cambrian granite). These probably represent old (Tertiary (?)) alluvial deposits and are, at least locally, unfaulted and overlain unconformably by Quaternary travertine.

Even where beds on either side of the border fault are exposed, as at Red Tanks and Salt Creek Arroyos, the nature of the fault itself is obscure and is best inferred by examining adjacent structures. For these reasons a number of closely spaced traverses were made across the base of Gray Mesa where the structure relations are similar to those farther south and at the same time exposures are more continuous here than in any other critical area. These are reconstructed in the large scale sections shown in Plate V. The sections are largely self explanatory and only a few salient features will be emphasized here.

The Pennsylvanian limestones and claystones of the Madera formation are the main beds involved in the deformation along the front. These form a thick sedimentary unit notably deficient in marker horizons, so that any interpretation of structural relations must be based almost entirely on the change in dip and strike of the beds and the relation of the Madera limestone to rocks of other age (wherever the latter make their rare appearance). Moreover, where the sediments are sharply flexed the limestone beds are commonly so badly shattered that a careful examination is required to distinguish bedding from jointing, and the possibility of finding primary sedimentary features suitable for identifying the top of the beds is everywhere practically nil.

Structures vary markedly within a few hundred feet; however, most typically a traverse from west to east reveals a progressive and remarkably sudden increase in dip. Within 300 to 500 feet the Madera limestones, dipping 5 to 15 degrees west along the cliff face of the Gray Mesa cuesta,

are abruptly upturned to the point of standing vertical (Plate V, secs. 10, and 16-27). Locally, as in sections 22, 24, and 25, the easternmost beds dip steeply to the east and the uninterrupted progression of dips from 80° W to 90° to 80° E suggests very strongly that the east dipping beds are slightly overturned. An alternative explanation, offered by Kelley and Wood (1946, section HH'), is that the east dipping beds are not inverted but represent the east limb of a very sharp anticline developed in conjunction with eastward thrusting of Pennsylvanian rocks over the Permian. This interpretation should not be taken lightly, for anyone who has worked in the area will understand the uncertainties that are involved. Nevertheless, this writer cannot accept this hypothesis for a number of reasons: (1) The abrupt and progressive upturning of the sediments is identical with that encountered just west of Ladron Peak (Plate VIII) where an almost vertical fault is excellently exposed over almost 1,000 feet of topographic relief. Here, the basal Carboniferous rocks stand steeply against the up-faulted pre-Cambrian crystallines to the east. (2) Between sections 10 and 11 (Plate V) the continuous eastward increase in dip of the Madera limestones becomes discontinuous along a fault developed somewhere between the two sections. The vertical displacement along the fault must be small at this point, and the relations in section 10 indicate that the eastern block (having steeper dips) was down dropped from the nearly vertical flank of a fold upturned to the east. The same fault can be traced almost continuously southward to section 16 where a fair exposure shows a nearly vertical dip of the fault

plane. (3) In sections 10, 11, and 12, progressively older rocks occur eastward (Sandia quartzite and pre-Cambrian granite). Although the rocks are infaulted there is no evidence that the faults involve very great displacement. If it be postulated that the entire structure resulted from the development of a sharp monocline, whose eastern side was up-thrown and whose vertical and slightly overturned flank was fragmented, these rocks would occur in their logical sequence, whereas the assumption of an anticlinal flexure demands that these rocks be infaulted in a completely independent earlier period of deformation. (4) In sections 12 to 16 (Plate V) the infaulted block of Madera limestone dips moderately or steeply to the east. In sections 14 to 16 both edges lie against gently dipping beds of the same formation.

The writer believes that the most satisfactory explanation of all these phenomena lies in the hypothesis that during an early period of deformation (possibly late Cretaceous or early Tertiary) a very sharp monocline developed along intersecting trends from the south edge of Gray Mesa to the Ladrons. Both the eastern and western limbs of this flexure were very nearly horizontal and the intervening flank was nearly vertical or, locally, slightly overturned towards the west. Possibly the flexure was the expression in the sediments of displacement along major crustal fractures emanating from below with the eastern block moving up. Penecontemporaneous fracturing of the steep flank and subsequent foundering of the east block primarily along the same zone of weakness during a second period of deformation accounts not only for the presence of infaulted pre-

Cambrian rocks, but also for the presence of the Permian. These stages in the structural history are illustrated (somewhat diagrammatically) in Plate X. The sections in Plate X are most directly applicable to section 10 in Plate V. Most of the other Gray Mesa sections are less complex and the essential similarities to the type of structures shown in Plate X should be apparent.

Between sections 9 and 10 at the easternmost point along Gray Mesa (Plate V) the strike of the beds abruptly changes from about N 40° E to N 30° W. To the north a clearly exposed low angle, westward thrust is developed in the transition zone between the vastly different types of structures developed in the north and south halves of the Lucero Uplift.

FRACTURING

The joint pattern of the Lucero Uplift is shown in Plate VII. The symbols at each location summarize 40 to 250 joint readings taken in the field. At most points, one hundred measurements were made. To avoid subjective selection, every measurable joint within a small area was recorded. These data were then plotted on a Schmidt equal area net and contoured with ellipses which enclose 1% of the total area of the net, according to a method proposed by Strand (1944). This method is somewhat more accurate than the conventional methods of contouring and it was used with the purpose of determining whether the distribution of joint orientations around a center of concentration is entirely random (normal distribution) or whether

there might, for example, be greater variations in strike than dip (skewed distribution). In general the results indicate no extreme deviations from a normal frequency distribution.

In the field, it was found that the characteristics of the joints are quite different in various formations and it was expected that the contour diagrams might also be useful as a pictorial representation of the physical behavior of different lithologic units -- applicable not only to the immediate vicinity but to wherever similar lithologies are encountered. To a limited extent this proved to be true; the diagrams for some formations have unique features that are frequently (but not invariably) present and seem to be related indirectly to the rocks' physical properties (notably denseness and grain size).

The maximum percentage at a center of concentration depends, in part, upon the number of joint sets at the particular locality. If only one set is present the maximum percentage could theoretically reach 100, whereas, if two equally developed sets exist, the maximum could not exceed 50 percent at each center. The peak values are also a reflection of the variability of the joint trends -- being very high where most of the joints are planar and parallel; being low where the joint surfaces are irregular and have less distinct trends.

These characteristics are illustrated by a few typical plots shown in Plate VI. The well-cemented, fine-grained Abo sandstones are invariably fractured by long, sub-parallel, clean-cut joints. This is reflected in the contour diagrams by very high maxima. A few joints varying from the major trends by as much as 25° , typically produce an

"apron" in the low percentage field around the centers of concentration. The dip of the joint planes rarely deviates more than a few degrees from perpendicularity with bedding and results in a slightly flattened distribution. The plots for the Carboniferous limestones also commonly exhibit very high concentrations about particular trends, and usually the contour lines are more nearly circular than for the Abo -- indicating a slightly greater variation in dip. The medium grained, friable to moderately well cemented Glorieta-San Andres sandstones show much lower concentrations than the previous formations, and the diagrams are usually marked by a low percentage "girdle" of joints perpendicular to the bedding. Although the dominant trends are quite distinct, the girdle reflects the presence of a fair number of joints having random strikes. At many locations these same beds contain a very few low angle joints related to cross-bedding (see below). Similar lithologic units in the Cretaceous show patterns quite similar to those from the Glorieta-San Andres. A number of locations in Quaternary bedded caliche and travertine deposits all give identical results which show only very weak trends. In the field these joints are extremely irregular breaks -- rarely running more than a few feet in a straight line and apparently having no strongly preferred orientation other than being at right angles to the bedding. Two samples were taken from the pre-Cambrian crystalline rocks in the Ladron Mts. These are the only rocks in which low angle joints are common. A large variability in the fracture orientation accounts for the type of pattern shown in the illustration.

At almost every location, certain joints are dominant over others; that is, one or more sets of joints are developed along persistent, plane surfaces which divide the bed into long strips or polygons, whereas other fractures ("cross joints") break up these blocks but rarely or never cross the major joints. The "cross joints" without exception have more irregular surfaces, are wider spaced, are more variable in trend and are obviously penecontemporaneous or later than the dominant fractures. The variability results in low concentrations in the contour diagrams so that almost all of the very short lines on the map represent cross joints. (The length of the joint symbols on the map is proportional to the largest percent of joints occurring at each maximum on the contour diagrams -- see Appendix III). Commonly two sets of joints are equally well developed, crossing each other indiscriminately. Unlike veins, the mere crossing of unfilled fractures is not a criterion for judging the chronologic sequence, and field evidence is rarely sufficient to establish whether such sets are contemporaneous or not. Other features, however, justify calling them conjugate joint sets. These usually appear on the map as lines of sub-equal length.

Except for the crystalline rocks and two cases apparently related to peculiar lithologic characteristics, all of the jointing throughout the uplift is essentially perpendicular to the attitude of the beds. Only occasionally does one encounter joints at a low angle to the bedding and where they do occur they never exceed 3 to 4% of the total number. The nature and occurrence of these joints is of interest, for they are

almost exclusively confined to cross-bedded sandstones in the Glorieta-San Andres formations, and most of them actually developed along the planes of cross-bedding. Typical beds are 3 to 5 feet thick with the cross-bedding sweeping across the whole thickness of the unit with a dip of 15 to 25 degrees. The sandstones are sufficiently well cemented so that fissility along both the true and false bedding is not pronounced; and the low angle joints have, here and there, (usually scores of feet apart) followed a plane of weakness which would not have opened without the imposition of tectonic forces. It is particularly striking that wherever such joints were noted, the strike of the cross-bedding is essentially parallel to the strike of one dominant set of vertical joints; and, moreover, the slickensliding, which is rarely absent from these joints, indicates, without exception, that the upper block has moved down dip elongating the bed horizontally. This is a clear-reflection of horizontal stretching within the beds being accomplished not only by means of purely secondary fractures (vertical joints), but also by the utilization of primary weaknesses wherever the latter are suitably oriented.

Almost all the joints in the uplift are coated or filled with some sort of mineralization. Typically, joints in the Carboniferous limestones are filled with crystalline calcite and limonite, and joints in the Glorieta and Cretaceous sandstones often exhibit a limonite coating. The latter, frequently also contain jarosite. Amorphous calcitic material (caliche) is ubiquitous in all formations. Rarely, as north of the Rio San Jose where Jurassic claystones overlie Todilto gypsum, fractures in

the softer beds are filled with selenite. No evidence of uranium mineralization was noted in any part of the area studied.

Areal Fracture Pattern

Throughout this section the reader should refer to Plates VII, VIII, and IX, which are prepared on the same base map to facilitate comparison. The first shows the joints; the second, the faults, dikes and structure contours. Plate IX is somewhat interpretive; it represents an interpolation of joint trends between locations at which readings were taken and also shows, roughly, the relative importance of various joint sets in different areas. The spacing of the trend lines has no significance, but the direction of the lines is the direction of the strike to be expected at any point in the area provided that a continuous fracture pattern exists over the entire structure. This map brings out subtle but progressive point to point changes in trends, which are not at all obvious on the joint map but are striking when individual joint sets are viewed separately.

Certain general features of the fracture pattern are immediately apparent. Foremost among these is the strong northerly component of the strike of almost all the dominant joints. This is particularly noticeable in the central part of the area where, most commonly, only a single set is well developed, with a strike rarely deviating more than 8° from $N\ 5^{\circ}\ E$. From the head of Breach Canyon northward this single set almost entirely

disappears and is replaced by conjugate joints usually striking about N 12° W and N 25° E. The acute bisectrix of these paired joint sets trends N 7° E and thus almost exactly coincides with the direction of the dominant joints farther to the south. The three most easterly locations in the Cretaceous sandstones show a progressive increase in the size of the acute angle (up to 65°) and a notable northeastward shift in the trend of its bisector. Throughout all of this area, joints with a strong easterly component of strike are either wholly absent or else are present only as a very weak and irregular cross set.

Usually the conjugate joint sets are sub-equally developed but one of the two may assume much greater importance if the location is in the proximity of a larger structural feature having the same trends. This is well illustrated at the three San Andres locations south of South Garcia where a sudden change in the axial strike of the flexure just to the west is marked by a corresponding shift in dominance from one conjugate joint set to the other -- the stronger set in each case being parallel to the fold. This does not imply that the joints here are related solely to the flexure, for both sets of conjugate joints are present at each location, although one is entirely unrelated to the fold itself. Rather, both the flexure (which is actually a pair of incipient faults) and the joints are part of a tectonic pattern that covers a much larger region. Movement along the flexure has merely created additional joints, parallel to its axis, and thus increased the relative importance of one of the two sets. A similar case occurs at

one Dakota location just north of the Rio San Jose where the very strong dominance of a single joint trend reflects the presence, nearby, of a large fault having an identical strike. Other examples can be cited, but from all indications this effect, viz., preferred joint concentration along one of two equivalent sets, is extremely local and is limited to distances less than one-quarter mile or so from the larger, causative structural element.

In the southern part of the uplift the joint pattern is more complex. The strong north-south "grain" of the fracture trends is much less evident than to the north because of increased variability in strike and the presence of additional joints having easterly trends. The latter occur either as a single set or as a conjugate pair and become very pronounced in two distinct areas. Near the southwestern corner of the structure (from the Socorro County line south), these trends are well developed in the higher stratigraphic units. In fact, at three locations in Yeso limestones, the north-south fractures assume the minor role of cross joints, or are absent altogether. From point to point, gradual changes of strike occur in all the joints and when the trends are interpolated, the striking radial and concentric pattern shown in Plate IX is seen to exist.

The joints in this area are clearly related to the abrupt termination of the south end of the structure: The 90° change in strike of the beds at the southwest corner (Plate VIII) must inevitably result in considerable stretching parallel to the strike, especially along the flanks,

where the change is most acute. Adjustment has been accomplished largely by the formation of radial joints converging towards an area south of Monte de Belen, around which the structural relief is greater than almost any other part of the uplift except along the eastern fault zone. As is to be expected, near the center of this structural "crest" where the curving (i.e., stretching) of the beds around the southwest corner is less severe (Plate VIII), easterly trending radial joints practically die out. In the same area the structure is truncated by a large fault east of Monte de Belen (east block down) and its southward continuation as a north-trending syncline separating this end of the Lucero Uplift from the Ladron Uplift. (See sections in Kelley and Wood, 1946.) Here the dominant joints reassume their regional northerly strike and swarms of small basaltic dikes and numerous faults with similar, but somewhat more variable trends appear as well.

The second zone in which joints with a large easterly component of strike assume a major role extends from the base of Monte de Belen southeast to the Ladron Mts. In the Carboniferous limestones, a joint set striking between $N 30^{\circ} E$ and $N 70^{\circ} E$ is developed here, with a persistence encountered nowhere else in the region. These joints are curious and somewhat puzzling. They may be connected solely with the Ladron Uplift which has experienced a somewhat different tectonic history than the Lucero Uplift as a whole. It should be noted, however, that a similar joint direction is present in the pre-Cambrian rocks of the Ladrons. If the latter is truly a pre-Carboniferous fracture system, it is quite possible that subsequent stresses might have caused movement along these

pre-existing trends and imposed similar fractures in the beds directly above. Some evidence supports the second hypothesis: The two easternmost locations on Monte de Belen and all of those to the southeast are in horizons near the base of the Carboniferous section (i.e., near to the crystalline rocks), whereas the Madera limestone locations farther to the west (which lack this anomalous joint trend) are considerably higher in the stratigraphic section.

At one location in this belt (one and a half miles south of Red Tank Arroyo) the mineralization in the joints describes an interesting sequence of events. Three sets of joints are present, striking N 70° E, N 29° W, and N 12° E. All three contain crystalline calcite, but the latter two contain, in addition, limonite which crosses the filling of the N 70° E set. Although not even the relative age of the various sets can be established, it is clear that all three had been opened and resealed when a second period of movement reopened only the north trending sets. Quite probably the later event was connected with the development of the large fault to the east.

SUMMARY

The fracture pattern of the Lucero Uplift is dominated by a strong north-south "grain" with easterly trending fractures largely reduced to the secondary role of cross breaks. Major faulting is limited to the eastern (graben) border, where large displacement occurs along a few faults in a narrow zone; and the north and south ends of the structure where dis-

placement is distributed over numerous smaller faults.

The trend and importance of the various sets of joints and faults are essentially the same, with the exception of the border fault running from the south side of Gray Mesa to the Ladrons, which is apparently of independent origin and cuts markedly across the regional trends.

Both the primary and secondary fractures occur either as a single set of tension cracks or as a double set of equivalent fractures whose acute angle is bisected by the trend of the tension cracks. The size of the angle between conjugate fracture sets varies from point to point and in many areas this change is progressive, so that the paired fractures eventually emerge into a single set.

The writer has previously discussed the evidence which led him to believe that the eastern border of the Lucero Uplift is not bounded by a thrust and whereas it would be circular reasoning to use this structural interpretation to explain the fracture pattern and at the same time employ the fracture pattern to justify the absence of a thrust, it should be emphasized that the two are in complete harmony. Although the mechanics of fracturing is still incompletely understood, a great deal of field and laboratory evidence supports the contention that rocks may respond to tectonic forces by breaking either along a single set of fractures perpendicular to the direction of maximum stretching or along two sets of planes whose obtuse angle faces the direction of greatest elongation. In particular, the recent work of the late Arthur Gilkey (1953) indicates that these ideas are sound and that the anticipated dominance of transverse joints on elongate compressional structures and

longitudinal jointing on elongate tensional structures actually does occur.

There is no doubt that the Luceros have experienced a complex tectonic development commencing in the late Cretaceous or early Tertiary and continuing at least until the early Quaternary. There is structural, geomorphic and sedimentary evidence too, indicating that the geologic history was not the same over all parts of the structure. Nevertheless, if the postulate be accepted that most of the structural relief arose from east-west Laramide compression, then such movement has failed to leave its impression on the fracture pattern. Strong sets of vertical joints with large east-west components of strike or conjugate sets of low-angle joints whose acute angles face east-west, either of which are to be expected in this case, are notably absent. Rather, the impressive feature is the dominance and regularity of the north-south trends which are so persistent in the mapped area, that it is not too hazardous to surmise that a similar fracture pattern continues for many miles in the plateau to the west. In themselves, the joints and faults of the Lucero Uplift are an expression of strong lateral east-west stretching accompanied by much weaker horizontal elongation towards the north and south.

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MAPS

Geologic Map of New Mexico (1928). Scale 1:500,000.

Tectonic Map of the United States, (1944, 1947). Scale 1:2,500,000.

Amer. Assoc. Petrol. Geologists.

APPENDIX I.

Description of Plates I and II

Plate I was constructed from U.S. Soil Conservation Service aerial mosaics on a scale of 1 inch equals one-half mile. The base map was enlarged four times in the field. Topographic contours for the southern two-thirds of the map were established by taking alidade sights to distinct points on the photographs. Horizontal distances were taken from the photographs. Elevations were established by resection to U.S. Geological Survey bench marks and unrecorded elevation markers off the limits of the map. It was expected that this crude procedure would lead to serious errors in elevations (caused by distortions in the mosaics). However, checks from three independent reference marks indicated that the elevations are accurate to ± 15 feet (an error within one contour interval). The elevations for the northern one-third of the map were established by a controlled altimeter survey (2 barometers) and are probably accurate to within ± 5 feet (relatively). The absolute elevations of this part of the map, however, may be in error by as much as ± 50 feet, since the base points were connected with secondary points of the alidade survey and not with established bench marks.

Points on the map, referred to in the text, can be located by pivoting the accompanying reference guide, on the encircled cross marks, aligning the edge against the letters at the borders of the map, and reading off the corresponding number on the guide. (Reference guide printed on bottom of Plate VII.)

Plate II represents east-west serial cross sections constructed from the Carrizo Arroyo map (Plate I). The positions of the sections are as follows: Sections 1 through 10 are at the reference letters A,C, E,G,I,K,M,O,Q, and R respectively on the map; section 11 is halfway between S and T; sections 12 through 18 are at W,X,Z,AA,BB,CC and EE respectively. The stratigraphic nomenclature is the same as that used on the map.

APPENDIX II.

Description of stratigraphic units employed in Plates I-IV

The stratigraphic units employed in the map are identical with those described by Kelley and Wood (1946) with the following subdivisions and additions. The subdivisions are useful only for local mapping and cannot, in general, be extended regionally.

- K (Cretaceous) Mancos shale: 100 feet plus; locally infaulted; total thickness not exposed; drab olive-green to drab yellow fossiliferous silts and muds; unconsolidated; contains Gryphea Newberryi.
- P₈(Permian) Upper San Andres limestone member: About 150 feet thick; consists almost exclusively of dense dark gray limestone beds 3 to 5 feet thick; interbedded with bright yellow unconsolidated shale; shale content decreases southward; locally a few thin, white, friable sandstone beds about 20 feet from top; sandstone content very minor; normal contact with Triassic is commonly marked by 1 to 3 feet of greenish-white cross-bedded siltstone.
- P₇(Permian) Upper San Andres evaporite member: 50 feet (highly variable); yellow, silty gypsum; occasionally marked by thin dark red zone near base; recrystallized to white crystalline gypsum in deformed zones.

- P₆(Permian) Lower San Andres limestone member: 100 to 150 feet (highly variable); limestone and sandstone beds 1 to 4 feet thick, interbedded with gypsiferous silts; basal portion consists mostly of limestone and uppermost part contains mostly friable white, medium grained sandstone; evaporite interbeds usually lacking in deformed areas and adjacent beds may form mixed limestone-sandstone breccias.
- P₅(Permian) Lower San Andres evaporite member: 50 feet (highly variable); gray to yellow silty gypsum; a few thin limestone interbeds 6 inches to 2 feet thick; evaporite recrystallized to white crystalline gypsum or completely pinched out in deformed zones.
- P_{4c}(Permian) Upper Glorieta sandstone member: 50 to 75 feet; thin bedded, spheroidal weathering, white to pale buff, friable sandstones; interbedded with thin shaley gypsum units; no limestone interbeds.
- P_{4b}(Permian) Middle Glorieta evaporite member: 50 to 75 feet (highly variable); interbedded gypsum and friable, white, medium-grained sandstone; completely transitional with (and usually not distinguishable from) Upper Glorieta sandstone; no limestone interbeds.

- P_{4a} (Permian) Lower Glorieta sandstone member: 200 feet;
massive, blocky, well-cemented buff sandstone;
contains some very blocky beds 1 to 4 feet thick
which weather to dark brown rust color due to
staining on joints; no limestone interbeds; little
or no shale interbeds.
- P_{3b} (Permian) Upper Los Vallos member of Yeso formation: 55
feet; this unit is not everywhere distinguishable;
marked at base by 5 foot limestone; upper part
massive and blocky - lower part thinbedded with
shaley partings; overlain by about 50 feet of
orange red silt and soft sands with one prominent
white gypsum band in center.
- P_{3a} (Permian) Lower Los Vallos member of Yeso formation: 3 to
5 feet; gray-green dense limestone; directly over-
lies Meseta Blanca sandstone and is a reliable
indicator of basal Los Vallos. This is the only
prominent marker between the base of Los Vallos
and the Upper Los Vallos member (about 900 feet).
- C_{3b} (Pennsylvanian) Upper Red Tanks member of Madera limestone: 170 to
200 feet; dark gray-green shale with thin, dense
limestone and clastic limestone beds.
- C_{3a} (Pennsylvanian) Lower Red Tanks member of Madera limestone: 100
feet; dominantly red and white, coarse grained
quartzites, sand, limestone-pebble conglomerates;
top is marked by first appearance of gray-green
shale and limestone.

APPENDIX III.

Description of Plate VII (Joint Map)

The length of the joint lines is proportional to the largest percentage of joints per one percent area at each center of concentration on Schmidt net plots. One inch represents 25% except in the outlined region around Carrizo Arroyo where the joint lines are drawn to one-half that scale. The direction of the lines is that of the strike of the joints in the field except for some localities along the eastern border of the structure where it represents the strikes after rotating steeply dipping beds back to horizontal. The restoration of bedding is warranted by the fact that the joints are perpendicular to the bedding and probably developed when the beds were nearly horizontal.

Dotted lines indicate vague trends in Quaternary bedded travertine and caliche.

Dashed lines together with solid lines indicate alternative joint patterns developed in adjacent beds of a single formation at a single locality.

The stratigraphic symbols are as follows:

Qc	Quaternary caliche
Qs	Quaternary spring deposits
Kmv	(Cretaceous) Mesa Verde formation
Kd	(Cretaceous) Dakota sandstone
Jm	(Jurassic) Morrison formation
Jt	(Jurassic) Todilto limestone

Tr (Triassic) Chinle formation, Shinarump formation
 and Correo sandstone

Ps (Permian) Glorieta-San Andres formations

Py (Permian) Yeso formation

Pa (Permian) Abo formation

Cm (Carboniferous) Madera limestone

p-C Pre-Cambrian crystalline rocks.

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NORTH SECTION PLATE I

GEOLOGIC AND TOPOGRAPHIC MAP
OF CARRIZO ARROYO AREA

LEGEND STRATIGRAPHIC COLUMN

Quat.		Quaternary spring deposits	
		Quaternary basalt	
Tert.		Santa Fe formation	
		Tertiary intrusive	
K		Mancos shale	
		Chinle formation	
Permian		Upper limestone member of San Andres formation	
		Upper evaporite member of San Andres formation	
		Lower limestone member of San Andres formation	
		Lower evaporite member of San Andres formation	
		Upper sandstone member of Glorieta formation	
		Middle evaporite member of Glorieta formation	
		Lower sandstone member of Glorieta formation	
		Upper Los Vallos member of Yeso formation	
		Lower Los Vallos member of Yeso formation	
		Mesa Blanca sandstone member of Yeso formation	
		Abo formation	
	Penn.		Upper Red Tanks member of Madera limestone formation
			Lower Red Tanks member of Madera limestone formation
			Atrasado member of Madera limestone formation
		Undifferentiated, silicified beds of Yeso, Glorieta and San Andres formations	

SYMBOLS

	Boundaries of exposures
	Exposed stratigraphic contact
	Covered stratigraphic contact
	Dip and strike of bedding
	Exposed high-angle fault (dot on downthrown side)
	Covered high-angle fault
	Poorly exposed fault; exact position and trend unknown
	Exposed low-angle fault or flowage contact
	Inferred low-angle fault or flowage contact
	Tectonic breccia

Scale: 1:7,920 (1 inch = 1/8 mile)

0 1/8 1/4 3/8 1/2 MILE

contour interval 50'

PLATE II

STRUCTURE SECTIONS OF CARRIZO ARROYO AREA

LEGEND

- STRATIGRAPHIC CONTACT
 — ATTITUDE OF BEDDING
 — OBSERVED FAULT
 — INFERRED FAULT
 — FAULT MODIFIED BY SUBSEQUENT FLOWAGE
 — TECTONIC BRECCIA
 SMALL FAULTS AND INTRUSIONS OMITTED
 HORIZONTAL SCALE = VERTICAL SCALE = 1:17,200 (1 INCH = 1/4 MILE)
 SPACING BETWEEN CROSS SECTIONS = 1:15,840 (1 INCH = 1/4 MILE)

- Q { Qb QUATERNARY BASALT
 TERT. { T TERTIARY INTRUSIVE
 K { K SANTA FE FM.
 K { K MANCOS SHALE
 K { K CHINLE FM.
 P { P1 SAN ANDRES FM., UPPER LIMESTONE MEMBER
 P { P2 SAN ANDRES FM., UPPER EVAPORITE MEMBER
 P { P3 SAN ANDRES FM., LOWER LIMESTONE MEMBER
 P { P4 SAN ANDRES FM., LOWER EVAPORITE MEMBER
 P { P5 GLORIETA FM., UPPER SANDSTONE MEMBER
 P { P6 GLORIETA FM., EVAPORITE MEMBER
 P { P7 GLORIETA FM., LOWER SANDSTONE MEMBER
 P { P8 YESO FM., LOS VALLOS MEMBER
 P { P9 YESO FM., MESETA BLANCA SANDSTONE MEMBER
 P { P10 ABO FORMATION
 PENN. { C1 MADERA LIMESTONE, REDTANKS MEMBER
 PENN. { C2 MADERA LIMESTONE, ATRASADO MEMBER

SOUTH SECTION PLATE I

GEOLOGIC AND TOPOGRAPHIC MAP
OF CARRIZO ARROYO AREA

LEGEND STRATIGRAPHIC COLUMN

Quat.		Quaternary spring deposits	
		Quaternary basalt	
Tert.		Santa Fe formation	
		Tertiary intrusive	
K		Mancos shale	
		Chinle formation	
Permian		Upper limestone member of San Andres formation	
		Upper evaporite member of San Andres formation	
		Lower limestone member of San Andres formation	
		Lower evaporite member of San Andres formation	
		Upper sandstone member of Glorieta formation	
		Middle evaporite member of Glorieta formation	
		Lower sandstone member of Glorieta formation	
		Upper Los Vallos member of Yeso formation	
		Lower Los Vallos member of Yeso formation	
		Meseta Blanca sandstone member of Yeso formation	
		Abo formation	
	Permian		Upper Red Tanks member of Madera limestone formation
			Lower Red Tanks member of Madera limestone formation
			Atrasado member of Madera limestone formation
		Undifferentiated, silicified beds of Yeso, Glorieta and San Andres formations	

SYMBOLS

	Boundaries of exposures
	Exposed stratigraphic contact
	Covered stratigraphic contact
	Dip and strike of bedding
	Exposed high-angle fault (dot on downthrown side)
	Covered high-angle fault
	Poorly exposed fault; exact position and trend unknown
	Exposed low-angle fault or flowage contact
	Inferred low-angle fault or flowage contact
	Tectonic breccia

Scale: 1:7,920 (1 inch = 1/8 mile)

0 1/8 1/4 3/8 1/2 MILE

contour interval 50'

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DEVELOPMENT OF "SLUMP" STRUCTURES IN CARRIZO ARROYO AREA

WEST

EAST

SYMBOLS ARE EXPLAINED IN PLATE I

PLATE IV

STRUCTURAL RELATIONS EAST OF THE MAJOR INTRUSION

LEGEND

TI		TERTIARY INTRUSIVE
T		TRIASSIC SANDSTONE, SHALE, CHERT PEBBLE CONGLOMERATE
P		UNDIFFERENTIATED SS. AND LS. OF GLORIETA AND SAN ANDRES FMS. (PERMIAN)
P _s		SAN ANDRES FM. (PERMIAN); UPPER LIMESTONE MEMBER
P _l		YESO FM. (PERMIAN); LOS VALLOS MEMBER; SILTSTONE, GYPSUM, LIMESTONE
		OBSERVED FAULTS
		INFERRED FAULTS

CONTACTS ON UPPER SURFACE ARE PROJECTED UNDER COVER
 BLANK AREAS IN CROSS SECTIONS REPRESENT COVER

VERTICAL SCALE = HORIZONTAL SCALE
 SCALE IN SECTION 4 IS ABOUT 1:2640 (1 INCH = 1/4 MILE)

SERIAL SECTIONS ACROSS THE EAST SIDE OF GRAY MESA

PLATE V

PLATE VII

JOINT MAP OF THE
LUCERO UPLIFT,
NEW MEXICO

0 1/2 1 2 3
MILES

FOR EXPLANATION OF SYMBOLS SEE
THE ACCOMPANYING TEXT

REFERENCE GUIDE FOR PLATE I—CUT OUT, JOIN TOGETHER AND PIVOT ON CIRCLED MARKS
(SEE DESCRIPTION OF PLATES I AND II ON PAGE 43)

PLATE VIII

STRUCTURAL FEATURES OF THE LUCERO UPLIFT, N.M.

After Kelley and Wood (1946) and Hunt (1936)
with modifications and additions

- Exposed faults
- Probable or inferred faults
- Igneous dikes (mapped only locally)
- Prominent fold axes
- Areas shown in other plates
- Structure contours on top of Atrasado member of Madera limestone; contour interval 500'; datum, mean sea level

PLATE IX
JOINT PATTERN OF
THE LUCERO UPLIFT,
NEW MEXICO

- Strongly developed joint trends
- - - Poorly developed joint trends
- - - Interpolated trends between widely separated locations

Trend lines based on data shown in Plate VII

PLATE X

POSSIBLE STAGES IN THE DEVELOPMENT OF STRUCTURES ALONG
THE EAST SIDE OF GRAY MESA

REPRESENTATIVE JOINT DIAGRAMS

ABO SANDSTONE

MADERA LIMESTONE

GLORIETA SANDSTONE

QUATERNARY CALICHE

PRE-CAMBRIAN GRANITE

PLATE VI

Poles of joint planes contoured on upper hemisphere of Schmidt equal area projection. Solid lines at intervals of 8%. Dashed lines at intervals of 4%.

A. Development of steep monocline and incipient fracturing of flank

B. Fragmentation of flank of monocline and foundering of east block

Area within dotted lines in right-hand diagrams is shown in much greater detail at left. Dotted profile in lower left diagram represents present topography.