THE ORIGIN OF THE LINCOLN FOLD BELT, LINCOLN COUNTY, NEW MEXICO

by

Walter Yuras

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ABSTRACT

Large scale disharmonic folds occur within sediments of the middle Permian Yeso Formation near Lincoln, New Mexico. These flexural-slip and flexural-flow folds contrast with the near homoclinal attitude of the conformable overlying San Andres Formation. This unique setting has led to various estimates of the age of fold formation which have ranged from middle Permian to early Recent.

Previous theories of fold origin favored gravitational gliding as the mechanism of deformation. However, the forms of the folds and their kinematic orientation indicate that the Lincoln folds are not consistent with features considered typical of gravity-induced folds.

Investigation into regional structural relationships shows the Lincoln Fold Belt to be most closely related to the development of the Sierra Blanca basin-Mescalero arch trends in south central New Mexico. The high-angle tectonic transport reflected in the folds was brought about by tectonic compression and high pore pressures generated by the late Laramide subsidence of the Sierra Blanca basin.

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INTRODUCTION

The occurrence of folds in ancient sediments has long been the subject of intensive inquiry. As an integral part of structural geology, folds bear witness to periods of intense deformation in the geologic past. Under appropriate circumstances, they allow the investigator to place a date on the age of deformation and thereby provide another clue to the understanding of tectonic processes.

Area of Study

The folds which are the subject of this investigation occur in sediments of the Yeso Formation of Leonardian (middle Permian) age and are exposed in low lying hills northeast of the town of Lincoln, New Mexico (see Figure 1). The hills are separated by north-south trending arroyos which are largely controlled by fold morphology. The arroyos flow southward and drain into the southeastward flowing Rio Bonito.

The best exposures are directly above the floodplain on the north side of the Rio Bonito valley. The fold belt is easily accessible and several important

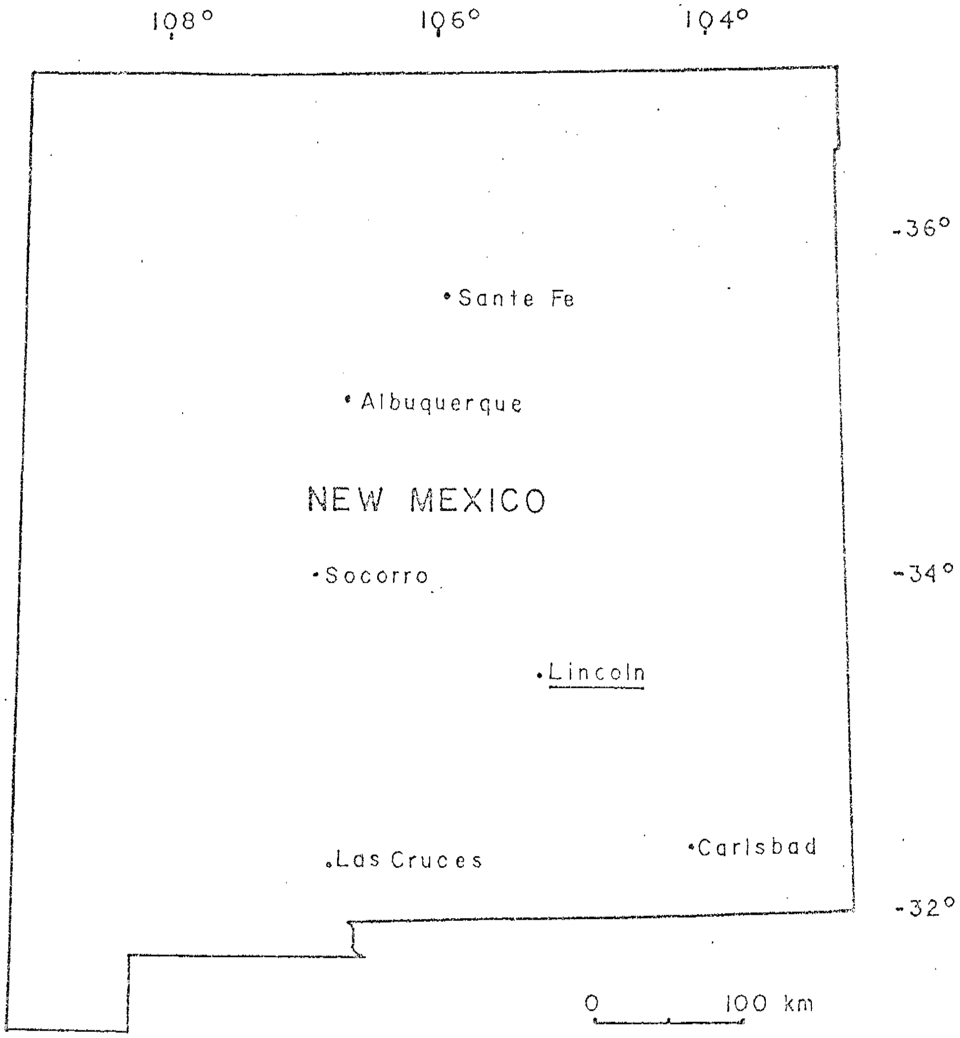

Figure 1. Location map of Lincoln, New Mexico.

outcrops are visible to the north from Highway 380. However, the permission of local landowners should be obtained in order to cross the floodplain of the Rio Bonito, which is the location of numerous orchards and private farmland.

Purpose of Study

The Lincoln Fold Belt is thought by some authors to be part of a regional fold set (Craddock, 1964) and by others (Foley, 1964) to be of only local significance. The style of folding is markedly disharmonic and large scale. The geologic setting of the fold belt is complicated by the presence of conformable, flat lying younger sediments and sills. This unusual setting has led to estimates on the age of fold formation ranging from middle Permian to early Recent. In addition, proposed mechanisms of formation for these folds range from penecontemporaneous soft sediment deformation to doming and gravitational gliding and to pressures exerted by large amounts of glacial outwash.

Following a review of regional stratigraphic and structural relations, several possible mechanisms and ages of fold formation applicable to the Lincoln folds are examined in light of observed fold characteristics together with the regional tectonic setting, in order to determine the age and mechanism of fold formation.

Method of Study

In order to examine the Lincoln Fold Belt in detail, a major portion of this study entailed mapping the folds on a scale of 1:1000. The field area was limited to the best exposures of the folds near Lincoln, New Mexico and encompasses an area of approximately nine square kilometers. Mapped units include 146 meters of the middle and upper portions of the Yeso Formation, 140 meters of San Andres Formation, several Cenozoic sills, and Recent valley fill.

The majority of the field work was accomplished during the months of July and August, 1975. Attitude data from twenty large scale anticlinal folds, intervening synclines, and numerous other structural features were collected for stereographic analysis. Representative rock samples were collected for petrographic analysis. Stratigraphic relationships were examined both in the field and from the literature. The style and scale of folding are classified after the manner described by Ramsay (1967). In addition, these features when compared to the works of others, have been used in an attempt to determine the environment and mechanism of deformation. The origin of the Lincoln Fold Belt, viewed in conjunction with other regional structures, is here linked to the tectonic development of the major structural trends in south central New Mexico.

STRATIGRAPHY

Introduction

Rocks of the middle and upper portions of the Yeso Formation are the oldest that outcrop in the area of Lincoln, New Mexico. These rocks are overlain by the Rio Bonito and Bonney Canyon members of the San Andres Formation (Kelley, 1971). Discontinuous Cenozoic sills occur near the Yeso-San Andres contact.

According to Dunn (1954), the Yeso Formation in this area is separated from the Precambrian basement by about a hundred meters of lower Permian redbeds and locally some Pennsylvanian strata. Approximately twenty kilometers to the south at Pajarito Mountain, Kelley (1968) has shown that the Yeso Formation directly overlies the Precambrian. According to Lloyd (1949), the Yeso Formation lies directly on the Precambrian further to the north. In contrast, Meyer (1966, p. 72) presumes that Wolfcampian strata, mostly upper parts of the Abo Formation, exceeds 300 meters along the top of the buried Pedernal Uplift (see Figure 2). Kelley (1971, p. 5), however, states that the few wells in the area penetrate thicknesses of only 90 to 240 meters and that the existence of greater thicknesses of Abo Formation in the surrounding subsurface seems unlikely. In addition,

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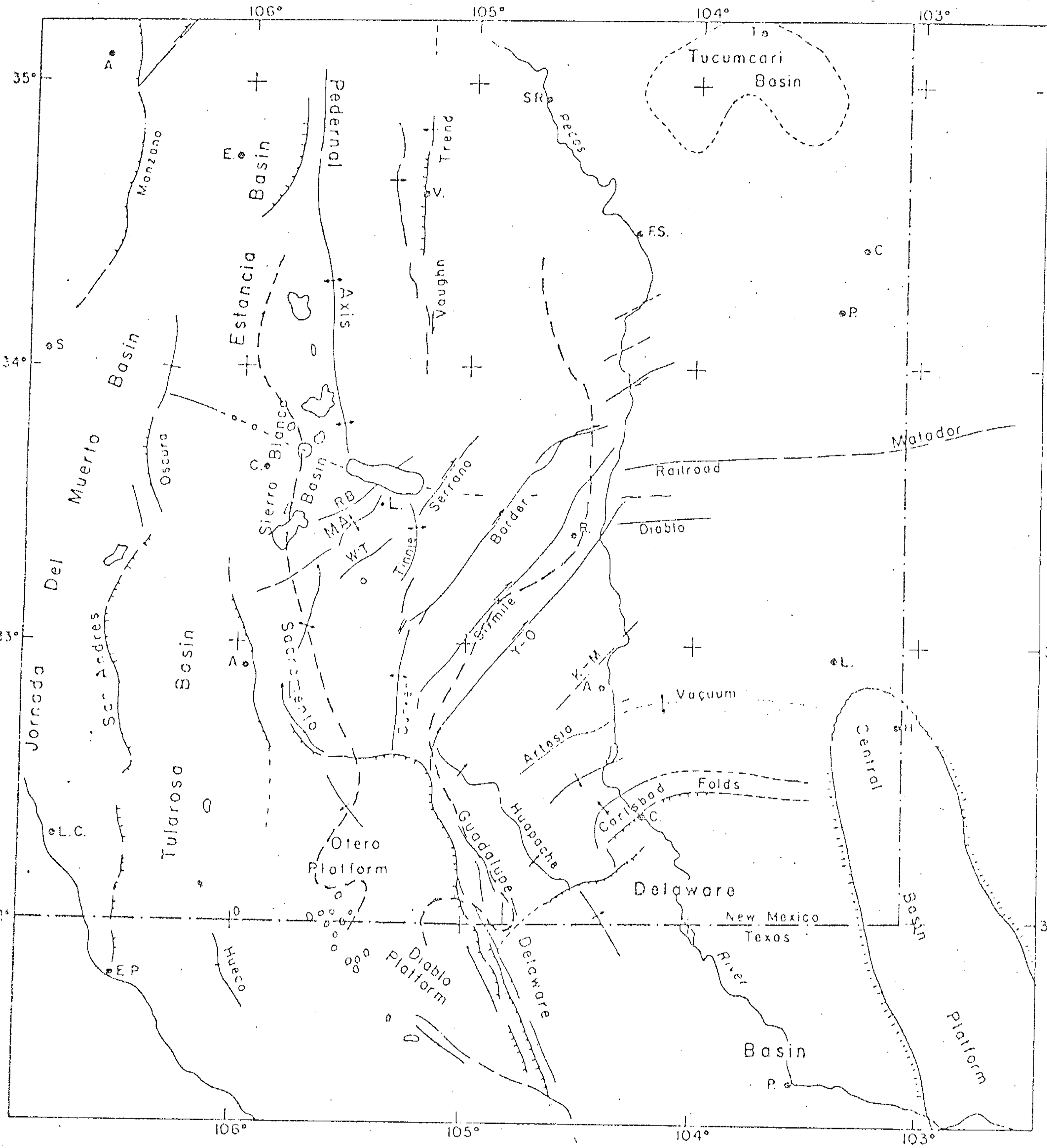


Figure 2. Tectonic map of southeastern New Mexico. RB=Rio Bonito Fault, MA=Mescalero arch, WT=White Tail buckle, dashed line indicates approximate boundary of the Pedernal (after Meyer, 1966). Adapted from Kelley, 1971.

Kelley speculates that west of the Tinnie Fold Belt, the Yeso Formation may directly overlie the Precambrian.

Yeso Formation

The Leonardian Yeso Formation as exposed near Lincoln, New Mexico consists of interbedded limestone, fine grained clastics, and gypsum. A striking feature of different stratigraphic sections in the Yeso Formation is a lack of laterally persistent units. Due to a lack of suitable paleontologic or lithologic marker horizons, and variations in thicknesses and lateral facies changes, stratigraphic correlation within the Yeso Formation presents a problem. Weber and Kottlowski (1959) have defined four members for the Yeso Formation: the basal Meseta Blanca sandstone; the Torres limestone, siltstone, and gypsum member; the Cañas gypsum member; and the upper Joyita sandstone member. The lithologic heterogeneity of the folded interval exposed near Lincoln most closely matches the Torres Member and is also similar to the middle Yeso horizons described by Pray (1961).

Craddock (1964) measured a section of the middle and upper Yeso Formation near Lincoln that totaled 146 meters. A nearly complete section measured by Pray (1961) near Bent, New Mexico, 64 kilometers to the southwest, indicates a thickness of 365 to 548 meters. Kelley (1971, p. 6) states that the Yeso Formation or its stratigraphic equivalents thickens to as much as 731 meters in southeastern New Mexico.

The folded interval is best exposed in the 65 meters of middle Yeso Formation that outcrops along the Rio Bonito floodplain. This stratigraphic interval is described in more detail in Appendix 1. Within the measured section, fine grained clastics comprise 50 percent of the section, limestone 43 percent, and gypsum 7 percent.

Fine grained clastics are dominantly reddish brown to yellow in color. Separate units vary from calcareous to quartzose siltstones. These units outcrop poorly and tend to be indistinctly bedded and internally structureless.

The limestones are quite variable in character and range from silty, vuggy, and unfossiliferous micrites to relatively pure, dense, and fossiliferous biomicrites containing brachiopods, gastropods, molluscs, and forams. Dolomitic horizons are present only locally in discontinuous horizons. The limestone units average eight meters in thickness, are thin to medium bedded, and are interbedded with siltstones. The folds are best exposed by these resistant limestone units which stand out in contrast to the less resistant clastics and evaporites.

The gypsiferous units outcrop poorly, but where exposed appear as discontinuous but massive units with scattered coarsely crystalline horizons. It is possible that greater thicknesses of gypsum or anhydrite occur in the subsurface, but such data for the immediate area is lacking. Water from wells in the area is not salty so it seems unlikely that halite is present in significant amounts. According to Kelley (1971, p. 5) most exposures of gypsum are confined to the upper 30 to 60 meters of the Yeso Formation.

Drill hole data from near Carrizozo indicates an anomalous drilled thickness of Yeso Formation (1219 m) and a large accumulation of salt interbedded with Yeso sediments, perhaps indicating the presence of a Leonardian evaporite basin (Kottlowski, 1965). This area was probably isolated from typical Yeso depositional trends by the north trending Pedernal axis.

Overlying the folded interval near Lincoln is a red to yellowish siltstone unit that separates the Yeso Formation from the overlying San Andres Formation. Craddock (1964, p. 123) measured seven sections through this interval and found it to vary markedly in thickness from 10 to 68 meters. Unfortunately, this interval and the contact with the overlying San Andres Formation is generally poorly exposed. The upper contact was located in the field at the transition from the slope forming red-yellow siltstone to the dense, thickly bedded, scarp forming limestone units of the lower San Andres Formation.

Where the contact is exposed no evidence for an unconformity could be found.

San Andres Formation

On the basis of extensive work in south-central and southeastern New Mexico, Kelley (1971, p. 7) has subdivided the San Andres Formation into three members: the basal thick bedded Rio Bonito, the porous and thin bedded Bonney Canyon, and the upper Fourmile Draw evaporite member. Kelley has mapped the lower two members in the vicinity of Lincoln, New Mexico. However, the contact between these two members is not obvious and was excluded from the mapping, so that the map (Plate 1, in pocket) shows the San Andres Formation as undivided.

No folds were observed in the nearly flat lying San Andres Formation near Lincoln. Although the attitude of bedding features in the Rio Bonito member are difficult to measure, changes in the elevation of its lower contact indicate a one to two degree dip to the east.

The Rio Bonito Member occupies a stratigraphic position commonly assigned to the Glorieta Formation in other parts of New Mexico. No lithology similar to the quartzose sandstone considered typical of the Glorieta Formation was observed within the mapped area. Kelley (1971, p. 10), however, states that one or two sandstone tongues of the Glorieta Formation occur in the lower Rio Bonito in south-central New Mexico. Further to the north, the Rio Bonito occurs as tongues in the Glorieta Formation. In addition, Kelley states that in an east-west distance of some 56 kilometers across south-central New Mexico, there is no evidence of stratigraphic rise or fall of the Yeso-Rio Bonito contact.

Characteristics of the Rio Bonito and Bonney Canyon members may be summarized as follows: the Rio Bonito consists of dark grey limestone beds one to one-and-one-half meters thick with interbeds of red siltstone less than one half meter in thickness near its base. The Bonney Canyon beds are typically thin bedded, appear light grey in outcrop, and consist of fine grained dolomite and limestone (Kelley, 1971, p. 12). South of T. 15 S. the Rio Bonito thickens gradually while the Bonney Canyon thins. Based on the upper contact of the Yeso Formation, a combined thickness for these two members in the Lincoln area gives a value of approximately 140 meters.

Post San Andres Units

Post San Andres units are not exposed in the Lincoln area. But further west, Mesozoic and younger formations are exposed as a result of the development of the Sierra Blanca basin (see Figure 3). Smith and Budding (1959) have listed the following thicknesses from the eastern half of the Little Black Peak quadrangle:

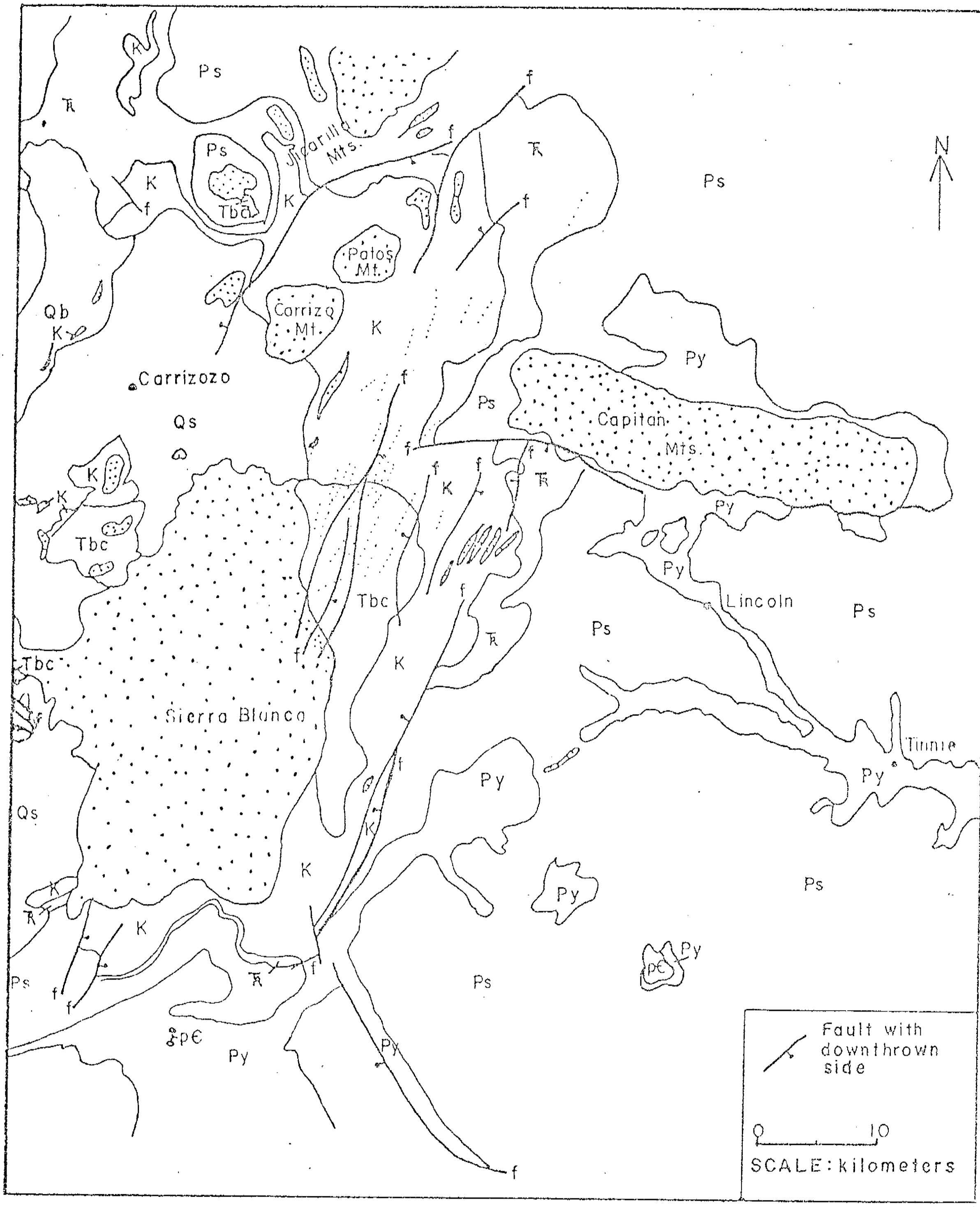


Figure 3. Regional geologic map: Qs=Quaternary sediments, Qb=Quaternary basalts, stipple pattern and dotted lines= Tertiary igneous rocks, Tbc=Tertiary Cub Mountain Formation, K=Cretaceous Dakota, Mancos, and Mesa Verde formations, TR=Triassic Chinle and Santa Rose formations, Ps=Permian Bernal and San Andres formations, Py=Permian Yeso Formation, pЄ=Precambrian (after Dane and Bachman, 1965).

Permian San Andres Formation	183 meters
Bernal Formation	76 meters
Triassic Santa Rosa Sandstone	61 meters
Chinle Formation	122 meters
Cretaceous Dakota Sandstone	46 meters
Mancos Shale	198 meters

In addition, Kelley (1971) lists the following ranges in thickness:

Cretaceous Mesa Verde Formation	152-457 meters
Paleocene Cub Mountain Formation	152-609 meters

Where Permian units are not exposed in the Lincoln area, the surfaces above the floodplain are covered by colluvial slope debris, talus, and soils derived from the Yeso and San Andres formations.

The alluvial floodplain deposit contains some coarse material and may be as much as 30 meters thick. Small deposits of poorly sorted gravel mark the present course of the Rio Bonito.

Extensive lobes of limestone debris of gravel and boulder size have been deposited at the mouths of the arroyos on the north side of the valley. Such deposits are probably the result of Recent glacial outwash (Foley, 1964).

Igneous Rocks

Cenozoic intrusive sills of diabase composition are common along the Yeso-San Andres contact. Although not laterally persistent, some may be quite extensive. The sill mapped in the N.W $\frac{1}{4}$, Section 29, (Plate 1) is 12 meters thick and extends horizontally for a distance of about 55 meters. Most of the sills were probably emplaced during the widespread intrusive period of late Eocene to Oligocene time (Kelley and Thompson, 1964, p. 120). Beds lying adjacent to the sills are undisturbed for the most part but show slight baking alterations near the contact. Faulting has dropped part of a sill and the overlying San Andres Formation into the upper Yeso siltstone (S.E. $\frac{1}{4}$ of Section 31, T.9S., R.16E., Plate 1).

The skyline to the north of Lincoln is dominated by the outline of the Capitan Mountains, an east trending intrusive about 35 kilometers long. The intrusive, although different in trend, is generally associated with the north trending Sierra Blanca-Carizo Mountain lineament further to the west (see Figure 3). According to Thompson (1972) the Sierra Blanca igneous rocks are Oligocene in age and consist of 80 percent volcanic trachyte, andesite, or latite and 20 percent intrusive syenitic stocks.

REGIONAL STRUCTURAL FEATURES

Structural relations in south-central New Mexico are complicated by the presence of Tertiary volcanics and intrusives. Fifty kilometers to the west, the Sierra Blanca volcanic pile occupies a structural depression known as the Sierra Blanca basin. Many normal faults and an associated dike swarm trend northeastward from this center. According to Kelley and Thompson (1964), the basin is a faulted synclinal depression, the eastern flank of which is downfaulted and descends under the Tertiary volcanic pile. At Lincoln, the regional dip of the lower San Andres Formation is about one degree to the east. This implies that between Lincoln and Capitan, New Mexico, there exists the crest of a broad arch. Kelley and Thompson (1964) refer to this as the Mescalero arch, and state that it roughly follows the axis of the buried, north trending Pedernal landmass. The trend of this arch is continuous through south-central New Mexico and can be traced through the crest of the Sacramento Mountains in the south, through the Lincoln area, and to the north of the Capitan Mountains.

However, as can be seen in the tectonic map of Figure 2, the Mescalero arch takes on an added complexity in the Lincoln region. After trending northward through southern New Mexico, the arch in the Lincoln region has swung eastward and trends northeast until it meets the south side of the Capitan Mountains. Kelley and Thompson (1964) indicate that the trend of the arch can be found again on the west end of the Capitan Mountains where it resumes a north to northwest trend. The offset of this axis indicates a left lateral displacement of approximately 14 kilometers accompanied by a vertical displacement, north side down, of about 488 meters. In addition, the outcrops of Triassic and Cretaceous rocks as shown in Figure 3 also illustrates this left shift. Allen and Ferebee (manuscript) have attempted to account for this with low angle, eastward directed thrusting or décollement.

The offset of the Mescalero arch is but one aspect of this westerly trend. Kelley and Thompson (1964) refer to this offset as the Capitan lineament. They link this westerly trend with similar or parallel deflections of the Jornada and Tularosa basins, the northeastward deflection of the San Andres uplift, and with the change in the course of the Rio Grande at this latitude. Also, the Jones Dike and several long dikes east of Roswell are associated with this trend. Figure 4 is a part of a regional gravity map of this west trending zone. Although the presence of this zone may be inferred, the exact nature of this shift is not clear.

Approximately 56 kilometers southwest of Lincoln is the location of several northeast trending structural

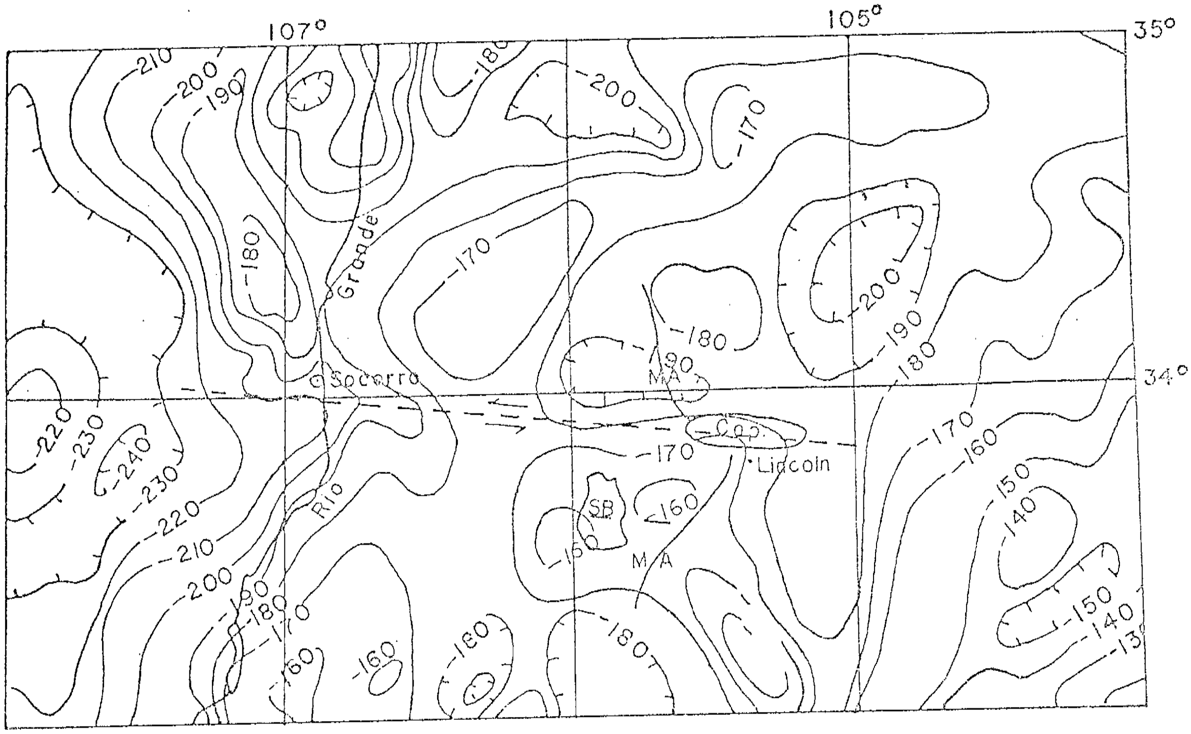


Figure 4. Bouguer gravity map of central New Mexico. SB= Sierra Blanca complex, MA= Mescalero arch. Dashed line indicates approximate trend of the Capitan lineament. Note offset of -160 contour in the Sierra Blanca region. Adapted from Woollard and Joesting, 1964.

zones. Kelley (1971) has examined these features in detail and describes them as upward directed buckles. They include: the Border Hills, the Six-mile, and the Y-O buckles. In addition, Kelley reports that a similar structure, the Serrano Buckle, is present near the east end of the Capitan Mountains. Although these features change their direction of asymmetry along strike, they are laterally continuous for long distances and display a component of right lateral shear.

The folds in the Yeso Formation near Lincoln are but a small portion of a region with numerous folds, mostly within the San Andres Formation. The most prominent of these structures, the north trending Tinnie Fold Belt, is located approximately 16 kilometers to the east of Lincoln. This system of folds will be discussed later in greater detail.

This region also contains numerous northeast trending faults of normal displacement which are generally downthrown to the northwest. The traces of several of these major faults are given in Figure 3. Their alignment seems to define a graben from the area east of Sierra Blanca to the west end of the Capitan Mountains. According to Kelley (1971), some of these are ancient flexures involving the basement that at some time in their history have been reactivated to disrupt younger sediments. Faults through the Ruidoso area downfault the west limb of the Mescalero arch into the Sierra Blanca basin. The Rio Bonito Fault trends northeast from the Sierra Blanca volcanic pile to the south side of the Capitan Mountains and may extend through and past the intrusive (see Figure 2).

Kelley (1971) has mapped a northwest trending fault in the Rio Bonito valley, down to the southwest. Although abundant evidence is lacking, this would account for the lack of fold exposures on the south side of the valley wall.

In addition to the overall northeast trend of the faults and buckles in this region, several other structural aspects stand out in the tectonic map of Figure 2. The trend of the fold belts is of particular interest. The overall trend is north-south but a broadly convex to the east pattern is indicated. Of greater significance is the observation that the trend of most folds is perpendicular to the Capitan lineament. Craddock (1964) also mapped folds in the Yeso Formation north of the Capitan Mountains and includes these in his regional fold system discussion.

TECTONIC HISTORY

The late Paleozoic and Mesozoic stratigraphy of south-central New Mexico has recorded the tectonic activity of the Pedernal Uplift, the southern extension of the ancestral Rockies which dominates the subsurface throughout this region (see Figure 2). According to Kelley (1971), the Pedernal began its rise in late Pennsylvanian time and continued to rise during the Wolfcampian. Locally, shales of the upper part of the Abo Formation were deposited on this landmass. Leonardian sediments of the Yeso Formation were the first to completely bury the Pedernal. Younger Permian sediments indicate broad arching during and following Artesia deposition. This arching was followed by a similar rise during and following Salado time (mid-Ochoan).

The region was a broad peneplain during the late Permian and early Triassic. The intervening period is poorly recorded but regional relations indicate a slight tilt to the north accompanied by widespread stripping from late Jurassic to early Cretaceous. These processes were followed by a regional subsidence to sea level until Montanan time (late Cretaceous). Kelley and Silver (1952) indicate that Montanan time marked the beginning of Laramide disturbances in this region. This period is documented by the unconformity between the Mesa Verde Formation (Montanan) and the late Cretaceous to Paleocene

Cub Mountain Formation. Kelley (1971, p. 60) makes an important point when he states:

> "owing to the involvement of the Paleocene or Eocene Cub Mountain Formation and the noninvolvement of the Oligocene volcanic breccias in the western limb of the Mescalero arch, the arch and the Pecos slope are probably Laramide."

Laramide relations in this region are complicated by large folds involving the basement, the development of the Sierra Blanca basin, and Tertiary volcanics and intrusives. Kelley (1971) and Kelley and Thompson (1964) propose the following sequences of events: during early Laramide, trends of the Pedernal were reactivated and formed broad north trending folds across central New Mexico, including the Mescalero arch, the Claunch-Tularosa sag, the Chupadera-San Andres arch, and the Jornada del Muerto sag during Eocene (?) time. The deep seated plastic shift mentioned earlier is also thought to have occurred during the Eocene disturbances and resulted in the northeastward deflection of the large folds listed above. Included in this interval is the development of the Sierra Blanca basin.

The Sierra Blanca volcanics are Oligocene in age and are essentially flat lying, above sediments that are dipping as a result of earlier orogenic basin development. Thompson (1972) reports that K-Ar dates from the area of Sierra Blanca indicate that volcanism began approximately 35 m.y. ago and continued until about 25 m.y. ago. Dates from the intrusive stocks fall into the same 35 to 25 m.y. range. In addition, Thompson has shown that the intrusives account for only 20 percent of the Tertiary igneous complex.

Chapin (personal communication) estimates that the Capitan stock was coeval with the Sierra Blanca complex and will probably date at about 28 m.y. The sills mapped in the Lincoln area and common throughout the region are probably satellitic to the Capitan stock.

According to Thompson (1972), fractional melting of eclogite or fractional crystallization of andesitic basalt of the lower crust may have generated the Sierra Blanca parent magma. The fault zones along the Capitan and Pedernal lineaments allowed the andesitic and alkalic magmas to penetrate crustal rocks from a depth probably greater than 40 kilometers. Christiansen and Lipman (1970) indicate that the widespread distribution of intermediate volcanic rocks throughout the western United States is a result of active Benioff zone systems during middle Cenozoic time. Thompson suggests that one of these may have extended eastward below the Sierra Blanca area during the Oligocene.

Laramide disturbances and middle Tertiary igneous activity were succeeded by late Tertiary (Miocene-

Pliocene) Basin and Range faulting along the earlier monoclinal flexures of the Sacramento, San Andres, and Oscura uplifts. These long north trending ranges owe the majority of their present relief to this latest stage of normal faulting.

THE LINCOLN FOLDS

Introduction

Folds in the Yeso Formation are common in south-central New Mexico, probably as a result of the incompetent nature of the variable Yeso lithologies. Nowhere are the Yeso folds better exposed than in the valley of the Rio Bonito. Craddock (1964) has mapped folds in the Yeso Formation north and east of the Capitan Mountains and as far south as Green Tree. However, Kelley (1971) states that there are considerable areas of no folding in the Yeso Formation, such as in the Tularosa Canyon country and in the Guadalupe escarpment.

Fold development varies with each location. In some areas folds can be directly related to local forces such as dike emplacement, movements on faults, gravity forces, or collapse due to solution. But, the well-developed folds in the valley of the Rio Bonito are not so easily explained. Following a discussion of the style of deformation of the Lincoln folds, several of the most likely dynamic settings are discussed with respect to kinematic implications.

Attitude data collected while mapping these folds was later plotted as either β or Pi diagrams to determine trends of fold axes after the method outlined in Ragan (1973, p. 110). Because the folds are so well exposed in cross section, one can characterize the cylindrically folded surfaces with a minimum amount of quantitative data. The results of the mapping and of these constructions are the subject of Plate 1 (in pocket). Simplified stereographic projections indicating axial plane orientations and plunge of fold axes have been added to the map to aid in the understanding of fold orientations. In addition, Table 1 summarizes the characteristics of the major anticlinal folds.

Fold Classification

Attempts at classifying these folds as to their style of deformation must reflect the irregular nature of fold development. A morphological classification after Badgley (1965) suggests a parallel and disharmonic style of folding which corresponds in part to the holomorphic style of Beloussov (1960).

The construction of dip isogons on fold cross sections taken from photographs after the method outlined in Ragan (1973, p. 54) reveals a convergent set of isogons. These correspond to Ramsay's (1967) subclass 1B, parallel folds, or Whitten's (1966) flexural slip folds. However, the variable nature of these folds, as seen in Figure 5, suggests that not all constructions would lead to a strictly parallel folding style interpretation, and that

Table 1

Major Anticlines

Fold	Fold axis plunge, trend	Axial plane orientation	Vergence	Kinematic 'a' axis	Comments
a	28°,N30E	N30E,90	-	62°,S32W	symmetry, 50-60° limb dips
b	21°,S37W	N 40E,77E	N	65°,N68E	asymmetric box fold, complexities in crest
c	26°,S31W	N39E,74E	NW	60°,N67E	open, asymmetric, large wavelength
d	10°,N14E	N14E,90	-	80°,S14W	small wavelength, cusp-like core
e	33°,N12W	N12W,90	-	57°,S12E	long wavelength, broad box fold, flat crest
f	24°,S5W	S5W,90	-	66°,N5E	long wavelength, box fold, sag in crest
g	28°,N42E	N30E,68E	NW	54°,S2E	asymmetric, box type, steeper west limb
h	12°,N46E	N46E,90	-	78°,S46W	upright, tight fold, buckle in crest
i	7°,S40W	N42E,80E	NW	80°,N89E	symmetric core, box-like higher up

Table 1 continued

Fold	Fold axis plunge, trend	Axial plane orientation	Vergence	Kinematic 'a' axis	Comments
j	10°,N25E	N26E,85W	SE	80°,S46W	box type, crest dips 10° east with buckle in crest
k	20°,N19E	N19E,90	-	70°,S19W	asymmetric box fold, syncline in crest is the one with clastic dike - fig. 11
l	20°,N6E	N6E,90	W at top	70°,S6W	ax. pl. vert. in core, but dips 30°E at top, asymmetric
m	11°,N	N,90	-	89°,S	tight box fold, vertical limbs, spring in core
n	28°,N45E	N28E,60E	WNW	47°,S11E	asymmetric, steep west limb crestal sag
o	7°,S13W	N13E,90	-	83°,N	asymmetric
p	5°,S39W	N39E,90	-	85°,N39E	upright box fold
q	5°,S11W	N11E,75E	W	75°,N78E	asymmetric box fold
r	12°,N13E	N10E,80E	W	76°,S22E	crest dips 10° east, complex buckles on east limb
s	3°,N37E	N36E,75E	NW	77°,S30E	long wavelength, asymmetric
t	15°,S19E	N17W,78E	W	70°,N16E	symmetric flat crest

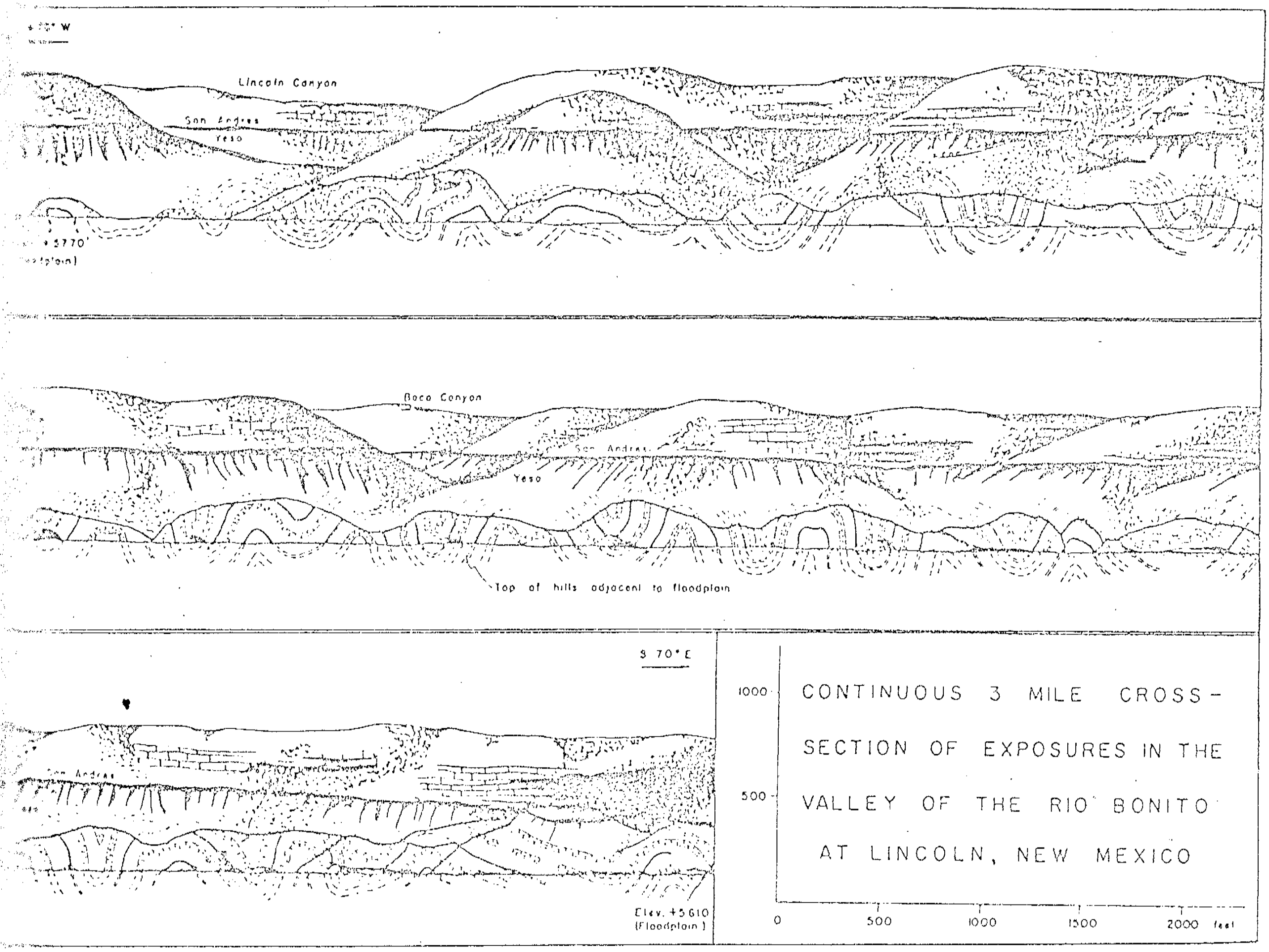


Figure 5. Cross section of the Lincoln Fold Belt, looking NNE from the floodplain of the Rio Bonito (from Craddock, 1964).

some folds would probably fall into Ramsay's subclass 1C. This may suggest that the more competent units were moderately ductile at the time of folding.

A classification based on the mechanism of folding after Donath and Parker (1964) suggests that more than one mechanism may have been operative. The stratigraphic alternation of competent limestones with more incompetent siltstones and mudstones indicates a moderate to high ductility contrast. Folds characterized by layers of fairly constant thickness, i.e. parallel or concentric, could have developed only by flexural slip. However, the lack of consistent geometry within a single fold or between neighboring folds are considered by Donath and Parker (1964, p. 60) to be characteristic of quasi-flexural folding and reflects the irregular flow that has produced the folds. Such folds are characterized by irregular folds within and across layers. This may account in part for some of the numerous small scale features noted in the less competent units.

Size and Orientation

The Lincoln folds are generally not traceable along their axes for more than about 200 meters unless favorably breached by a north trending arroyo. The wavelengths of the major folds range from about 100 to 370 meters. Amplitudes are somewhat more constant and are generally less than 120 meters.

Fold axes trend mostly northeast in the cross-sectional exposures but take on a more northerly trend further up the arroyos. Fold axes were seen to plunge at values ranging non-systematically from 5 to 33 degrees, generally to the north, but also to the south in part. Several sets of folds (of a smaller scale than those shown in Figure 5) trend east-west, and stand out in marked contrast to the general northern trend. Craddock (1964) has mapped several west trending folds northwest of Lincoln.

Axial planes are near vertical for the most part, especially in the upright symmetrical folds. Asymmetric folds are characterized by axial plane inclinations which exhibit a distinct westward vergence.

The geometry of these folds suggests that their development requires a shearing off horizon or décollement at the base of the folds. A construction to determine the depth to the décollement horizon, after the method outlined in Ragan (1973, p. 68), indicates a depth of about 150 meters below the floodplain of the Rio Bonito. If we infer an approximate total thickness for the Yeso Formation of about 450 meters, (minus the 140 meters exposed near Lincoln) and about 150 meters for the upper Abo Formation, about 460 meters is indicated an an approximate depth to the basement. This suggests a décollement horizon at a considerable distance above the basement contact.

Description

As is readily apparent from reference to Figure 5, the morphology of individual anticlines as they appear in cross section varies considerably. Broad, asymmetric, box-type folds are associated with regularly spaced, more symmetric and concentric buckles. Bedding planes in the cores of the tight synclines dip vertically close to the axial planes.

The broad box-type folds generally display the following features: anticlinal cores are nearly symmetric with vertical axial planes. Higher up, the folds develop horizontal or gently dipping crests with parallel secondary hinges, requiring an axial plane bifurcation outward from the core. The core of one such box fold is pictured in Figure 6. The resistant unit is a thin and evenly bedded silty micrite. The cave in the axial zone exposes siltstone and mudstones, poorly consolidated in part, and a limestone pebble breccia in a well cemented, iron stained, silty calcareous matrix. Although not visible in the photograph, these zones were seen to parallel the bedding of the thin bedded unit. However, vestiges of bedding within the zones are subperpendicular to the bedding planes of the micrite unit. Presumably,

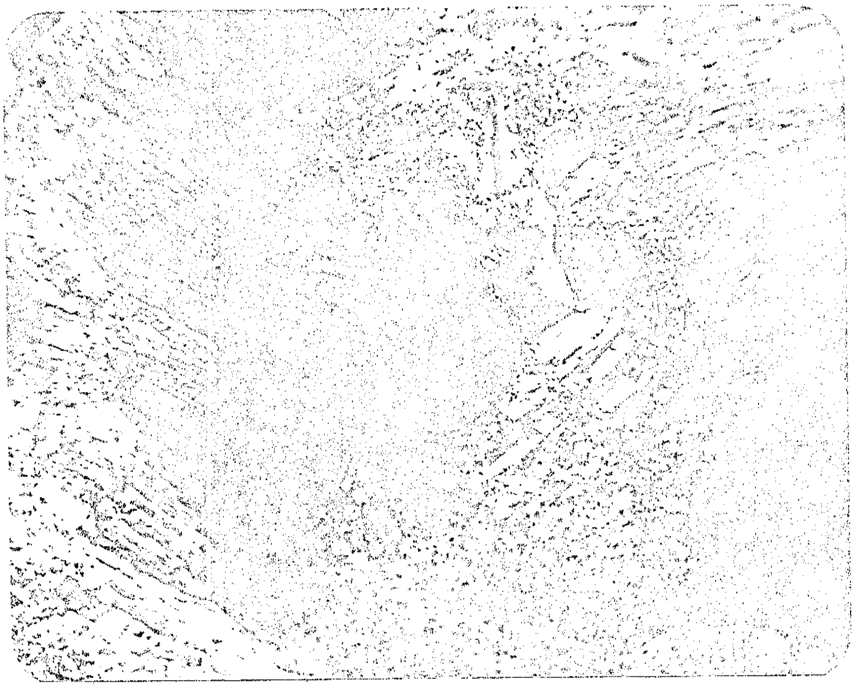
Figure 6. Core region of one of the box-folds. Orientation of anticlinal axis: 14°, N30E. Approximate scale: 0 ——— 30 meters

the breccia filled zones are produced as a result of fracture and flow into cavities produced by the parallel folding. These zones are a maximum of 15 centimeters across and variable but persistent around the core.

Secondary features in the form of right angle flexures and discontinuous buckles commonly modify the crestal regions and flanks of these folds. Figures 7a and 7b illustrate the occurrence of such secondary flexures. Although the axis of the subsidiary flexure is nearly parallel to that of the major fold (both plunge about 11°, N10E), this is usually not the case for the majority of such flexures. Further east, this same unit forms another anticline (10°,N40E) with the axis of secondary buckles, 45°, S45E. On the west flank of this anticline, there are at least three sets of buckles measuring approximately one meter from axis to axis. Axial zones of the secondary flexures indicate limited flowage of material. The axial zones of some of the minor flexures appear to have been subjected to pressure significant enough to obscure any evidence of bedding. The material in the axial zones is dense, dark, and minutely crystalline in contrast to the silty, lighter colored, and well bedded microcrystalline limestone of the major fold.

An example of a chevron-type syncline modifying the crest of an anticline is pictured in Figure 8. The large

7a.



7b.

Figure 7. Secondary flexure in Figure 7b occurs to the left of man in Figure 7a. Axis of both structures: 10°, N10E.

Figure 8. Chevron syncline on crest of anticline. Hammer for scale near center of figure. Looking northeast.

fold plunges 28 degrees in a direction N45E. The axis of the chevron-syncline plunges 37°, N80E. No evidence of flowage in the core of the anticline was observed. The folded unit is a medium bedded, dense, dark grey, sparse biomicrite and exhibits no lithologic changes in the core of the subsidiary syncline.

Several features are indicative of the relative ease with which these sediments were deformed. Figure 9 pictures two small wavelength anticlines and an intervening syncline. The axes of these folds are parallel and plunge 21°, S36W. However, on the crest of the anticline on the left, a younger lithologic unit is buckled into another anticline, the axis of which (12°, N88E) trends obliquely to the axis of the lower syncline. Numerous brachiopods were collected from these units, none of which showed any evidence of macroscopic strain.

Figure 10 illustrates a small scale feature observed on the east flank of a major anticline. Pictured is a small flowage fold (axis perpendicular to photo) in a very fine grained calcareous siltstone. Closely spaced original bedding planes are preserved and have been examined in thin section. The major anticlinal axis plunges 12° and trends N27E, the axis of the flowage fold plunges 40°, N67W.

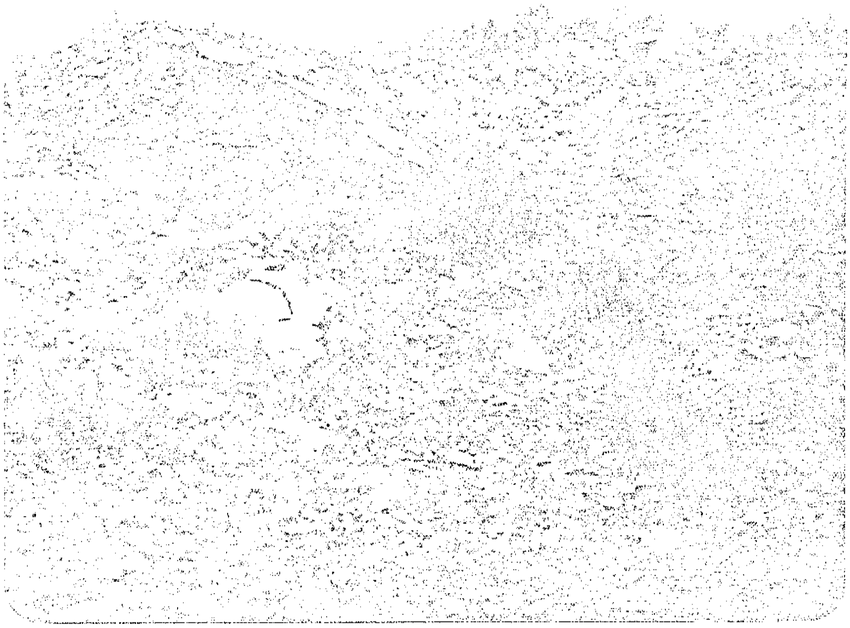


Figure 9. View of north trending anticline and syncline, looking north. Tree in synclinal core is approximately 2 meters tall.

Oblique east trending anticline is located above syncline in center of figure.

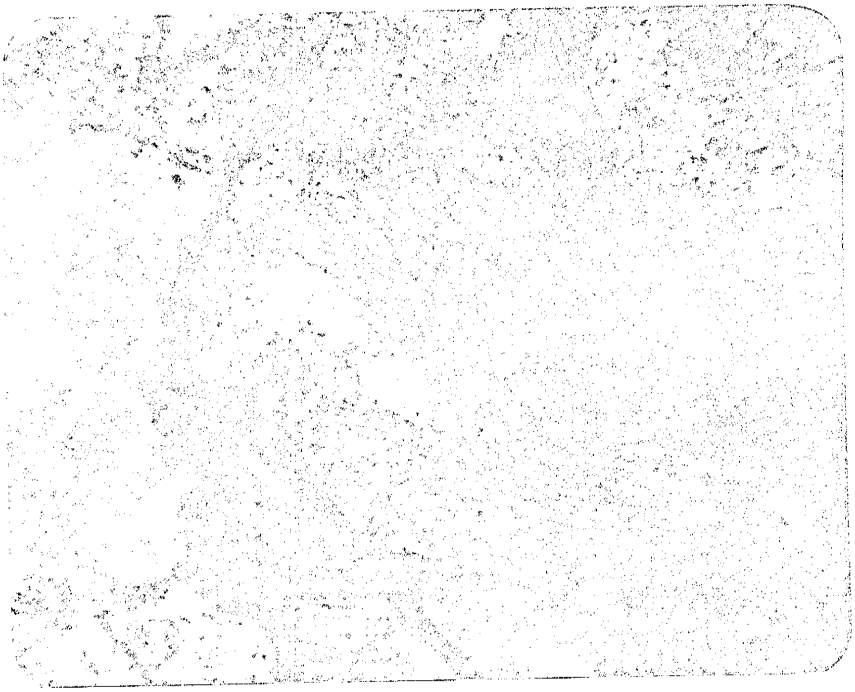


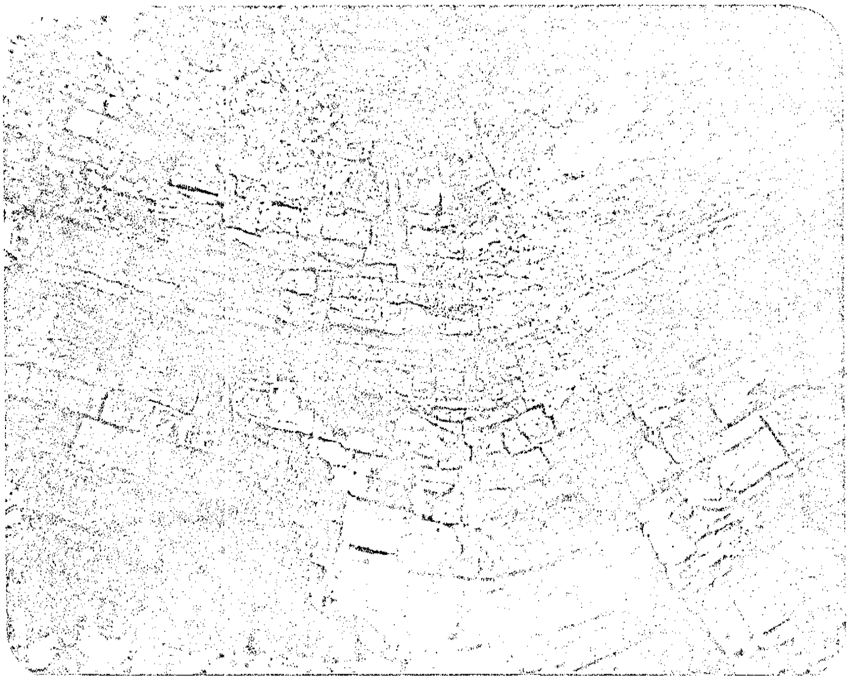
Figure 10. Flowage fold in calcareous siltstone. Pencil is 19cm long, and points to axis of fold which is perpendicular to photograph. Note yellow color of fresh surface in lower left corner of photograph.

Several features such as the zones of flowage in anticlinal cores and the flowage in axial zones of minor flexures support the idea that fold development was accompanied by high pore pressures. In addition, the author noted the formation of several injection type clastic dikes (Figure 11a). The vertical zone is approximately 25 centimeters wide and occurs in the thin bedded unit (Figure 11b) near the axial zone of a gentle syncline which modifies the crest of a major anticline. In addition to a dark and crystalline calcite matrix, the zone contains a chaotic arrangement of angular carbonate blocks. The dips of beds are different on opposite sides of the dike, and the rocks display an extraordinary amount of fracturing and brecciation. Craddock (1964, p. 125) reports several steeply dipping clastic dikes up to 4.5 meters wide occupying small faults or fractures which were probably injected from below during the folding.

Other Folds

The folds discussed in the preceeding section are restricted to the Yeso Formation near Lincoln, New Mexico. However, many regional studies in this area have revealed long wavelength folds in the San Andres Formation which interrupt its regular easterly dip. A short discussion of these folds is warranted. Kelley (1971, plate 1) has mapped such folds west, north, and east of Lincoln.

11a, looking east



11b, looking north

Figure 11. Injection type clastic dike in Figure 11a occurs to the left of synclinal axis pictured in picture 11b.

Craddock (1964) includes the folds to the east as part of his Lincoln Fold System although the latter lack cohesive relationships to the Lincoln folds. Reference to Figure 2 reveals that such folds in the San Andres Formation are continuous for long distances and that the fold axes define a semi-arcuate pattern that is slightly concave to the west. Continuation of the north trending folds to the east and north of the Capitan Mountains suggests that these folds predate the intrusion.

Several kilometers to the north of Lincoln and near the alluvial fan of the Capitan Mountains, Kelley mapped several north trending folds in the San Andres Formation. About 8 kilometers to the west, Kelley mapped three anticlines in the San Andres Formation that trend northwest and are perpendicular to the strike of the Rio Bonito Fault.

Sixteen kilometers to the east and southeast of Lincoln, many north trending folds occur in a 5 kilometer wide belt that Kelley named the Tinnie Fold Belt. These folds consist of closely spaced, long, narrow anticlines and synclines with moderately to steeply dipping limbs. Anticlines are typically 0.5 to 0.8 kilometers from crest to crest. Structural relief on the larger folds may be as as much as 300 meters. Overall, the belt is a low anticlinorium which plunges to the south in the north and plunges slightly to the north in the south. The two structure sections of Figure 12 have been reproduced from Kelley (1971).

These folds stand out in marked contrast to the homoclinal eastward dip of the San Andres Formation. According to Craddock (1964, p. 130) basal beds of the San Andres Formation are locally downfolded into the upper Yeso siltstone with dips as high as 70°. These folds are also parallel, somewhat symmetrical, although some change their direction of asymmetry along strike. Several of these isolated buckles tend to lift the Yeso-San Andres contact above its normal elevation.

Also applicable to this discussion is the occurrence of the well known Border Hills, Six Mile, and Y-O buckles. Kelley (1971) has mapped similar northeast trending features, the Serrano and White Tail buckles, near the east end of the Capitan Mountains. Several of these buckles have been included in Figure 2. Kelley refers to these structures as buckles because although they are exposed for 60 to 130 kilometers northeast along strike, their surface expressions are sometimes folds, sometimes faults, or combinations. There is also good evidence indicating that these buckles have undergone right lateral displacements as great as 150 meters (Kelley, 1971). Although many authors consider these buckles to be the result of movement on basement faults, the precise cause of these buckles is not yet clear.

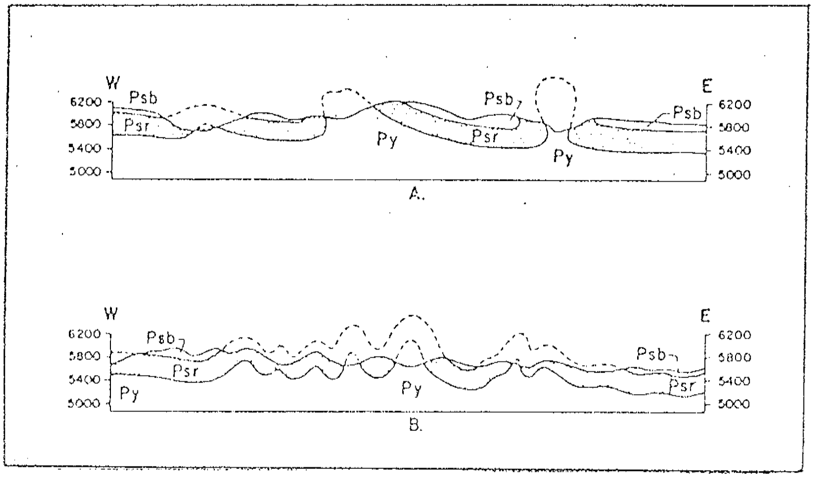


Figure 12

STRUCTURE SECTIONS OF THE TINNIE FOLD BELT

Horizontal scale not specified (from Kelley, 1971).

ASPECTS OF FOLD FORMATION

Introduction

In order to arrive at an understanding of the mechanics of deformation responsible for the Lincoln folds, it is necessary to approach the problem from two different aspects. First, we must consider the shape of the folds together with the observable characteristics within the folds which may indicate the magnitude of the strains. Secondly, we will examine the folds from a theoretical viewpoint, which calls for an inference to be made about the physical properties of the rocks at the time of deformation. Although the latter has long been a subject of much dispute, it is the author's opinion that as long as the results of such theory are regarded only as approximations to the actual situation, their use outweighs their omission.

Strain Indicators

At the onset of this study, it was hoped that a means of estimating the finite strain within these folds would become obvious during the field work. However, in the course of the field work, it was the absence of such features that was noted most often. As indicated earlier, examination of numerous brachiopods from folded fossiliferous units revealed no evidence of macroscopic strain. In addition to the brachiopods, two types of cephalopods were collected from the flank of a major fold near the east end of the section. Not only is the circular nature of the coiled ammonite preserved, but the linearity of orthoconic cephalopods is also unaltered. This lack of fossil straining may be partly accounted for by the box-like appearance of these folds. According to Ramsay (1967, p. 393), the structure which gives the least strain over the largest area is that of the box fold.

The development of schistosity and/or fan cleavage in folded rocks has long been considered indicative of compressive forces. Again, the development of regular fracture or fan cleavage planes is absent in the Lincoln folds. The rocks are however highly jointed. Several prominent directions of jointing commonly occur and it would be difficult if not impossible to suggest that these formed prior to the folding. The arrangement of joint sets fits the orientations described by figure 4-3 in Badgley (1965, p. 100). This diagram is reproduced in Figure 14 with the addition of kinematic fold axes after Whitten (1966, p. 109). Joints include the development of longitudinal or ab sets, cross or ac sets, diagonal, and strike joint sets. Billings (1972) refers to the ab set as release joints which may form due to the

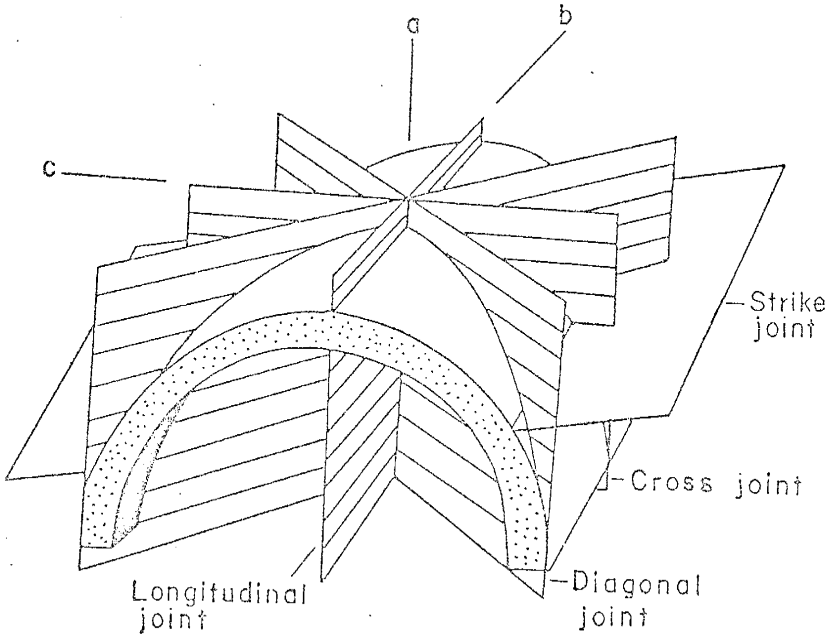


Figure 13. Geometric orientation of strike, cross, diagonal, and longitudinal joint sets relative to the orientation of kinematic axes for a flexural slip fold (after Badgley, 1965, and Billings, 1972, and Whitten, 1966).

release of the principal stress where it is considered to be perpendicular to the b or fold axis. The ac joints are referred to as extension joints and are related to slight elongation parallel to the b direction. Calcite commonly fills these joint planes and was observed most often in the ac joints. However, calcite filling the diagonal joint sets is often preserved as only a thin layer on the joint surface. This thin calcite layer is also commonly striated, suggestive of slickensides parallel to the plane of jointing. These features suggest that the diagonal joints may be shear fractures which formed during the folding, at angles of approximately 30 degrees to the principal stress direction. Billings (1972, p. 168), however, states that such slickensides may form later as a result of tensional stresses.

Due to a lack of suitable strain indicators, we are left only with the concept of percent shortening and thickening of the folded units to describe the magnitude of the deformation. If the folds are considered to be parallel or flexural slip folds, then according to Ramsay (1967, p. 397) the amount of layer shortening may be determined by measuring along the length of any lithologic unit. Such a measurement across the Lincoln folds indicates a 30±5 percent apparent lateral shortening. However, according to Kehle (1970, p. 1655), if the folds are a part of a décollement zone, estimates of original bed length cannot be made by simply straightening the beds and that this unfolding will erroneously attribute considerable lateral shortening to a décollement zone when, in fact, there is none. Craddock (1964, p. 132) estimated a minimum value of 12 kilometers lateral shortening in the Yeso Formation which contrasts with a 3 kilometers shortening in the San Andres Formation elsewhere. It should be mentioned here that variations in member thicknesses are apparent only in separate stratigraphic sections. The competent limestone units maintain a nearly constant thickness throughout the folds while the less competent units may exhibit as much as 20 percent variation in thickness. In any case, attenuation of the limbs of folds is not well developed.

Viscosity Indicators

In order to be able to make some inferences about the behavior of the Yeso sediments during folding, we must first establish a descriptive viscosity contrast between the deforming units. That the limestones were more competent and deformed differently than the clastic siltstones and mudstones has been discussed previously, and we may infer that their viscosities differed by at least an order of magnitude. The Yeso Formation near Lincoln would best be described an an enclosed multilayer, so that any relations between the strut units and the medium must be considered in terms of multilayer theory. Biot (1964) has investigated the properties of a model consisting of 'n' alternating layers with viscosities 'u_1' and 'u_2' and each with a constant thickness 't', confined between two straight and rigid boundaries. He was concerned with determining a dominant wavelength 'W_d' and found that this increased as the number of layers in the multilayer was increased, but that it was sensitive to changes in the viscosity contrast between the two types of layers. These relations are shown in Figure 14.

The wavelengths of the Lincoln folds are variable but most are between 150 and 300 meters. If we consider one of the competent limestone units in the Yeso Formation as a strut unit 9 meters thick (see Figure 19 in Appendix 1), and we apply the simple relation of Currie, Patnode, and Trump (1962) which relates fold wavelength to member thickness by the equation

$$L = 27t$$

in which 'L' is the wavelength and 't' is thickness, we obtain a value of 243 meters which is a good approximation to an average wavelength for the Lincoln folds.

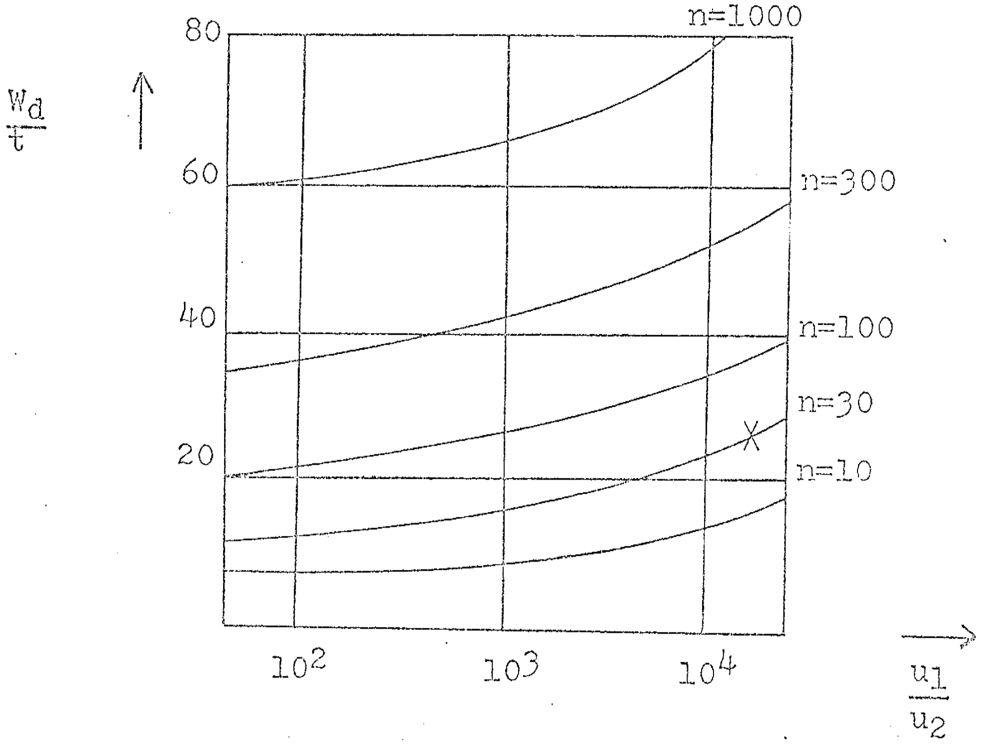


Figure 14. Dominant wavelength/thickness plotted against viscosity contrasts. Curves represent different values for 'n', the number of layers within the multilayer. 'X' indicates plot for the Lincoln folds (after Biot, 1964).

If we adopt this as a dominant wavelength value and a value of 9 meters for 't', we arrive at a 'W_d/t' value of about 27 which plots along the y-axis in Figure 14. The number of layers in the multilayer is given by the thickness of the folded part of the Yeso Formation (approximately 200 meters), divided by a thickness of 9. The 'n' value of 22 is approximated by the '$n = 30$' curve in Figure 14, and indicates after plotting that the viscosity contrast 'u_1/u_2' must have been on the order of 10^3 or 10^4.

According to Biot (1964, p. 656), the horizontal portions of the curves on the left side of the diagrams are approximated by the expression

$$W_d = 1.9t\sqrt{n}$$

and is obtained by neglecting interstitial flow. Applied to the Lincoln folds, this relation yields a value of 80 meters for the dominant wavelength. However, the ascending portions of the curves on the right of the chart, where the Lincoln folds plot, correspond to large amounts of interstitial flow and are approximated by the formula

$$W_d/t = 1.66n^{1/3}\,(u_1/u_2)^{1/6}.$$

When applied to the Lincoln folds, this expression indicates a value of 285 meters for the dominant wavelength. Although not precise, this expression does give a result of the right order of magnitude and points to an important process during the deformation.

Craddock (1964) has applied the formula of Currie, Patnode, and Trump (1962) for the buckling of a competent layer embedded in a yielding homogenous medium to the Lincoln folds. His results indicate that the prediction of an initial wavelength approximated the wavelengths of the Lincoln folds only when the ratio of Youngs moduli of the competent layer to the medium approaches unity. This has led him to suppose that a passive mechanism of deformation may have been operative and that viscosity contrasts were not great. However, the stratigraphy of the Lincoln folds requires that any folding analysis be considered in terms of multilayer theory only.

The results of the application of Biot's dominant wavelength approximations suggest that interstitial flow was important during folding but it does not indicate that the folding was particularly passive. According to DeCaprariis (1974), such calculations are linear and misleading, because, as the amount of non-Newtonian behavior increases, the dominant wavelength can develop only in a relatively thick layer. Therefore, these results should be regarded only as approximations.

Fold Morphology

Even though we cannot make any quantitative statements about the way these folds formed, we can make several generalizations based on fold morphology and unit viscosity. According to Ramsay (1967, p. 417), if competent layers are of about the same viscosity and thickness, harmonic folds are set up and folds have the same wavelength. The variability of wavelength and style in the Lincoln folds suggests that the units differed both in thickness and viscosity. This is related to another observation by Ramsay; when thicknesses or viscosities of the competent layers are variable, the folds show a compound wavelength of two or more orders of size. In addition, if the layers have a resistance, they will buckle and generally produce a complex mass of small crumples in the core of the structure. Both of these statements are applicable to the Lincoln folds.

As we have seen, the expression $W_d = 27t$ gives a good approximation to the wavelength of the Lincoln folds. The application of this relationship to the Tinnie Fold Belt does not yield realistic values for the wavelength expected for a thick and massive unit such as the San Andres Formation. This may indicate that the two fold systems do not fit the structural lithic unit concept of Currie, Patnode, and Trump (1962) as described in Figure 15.

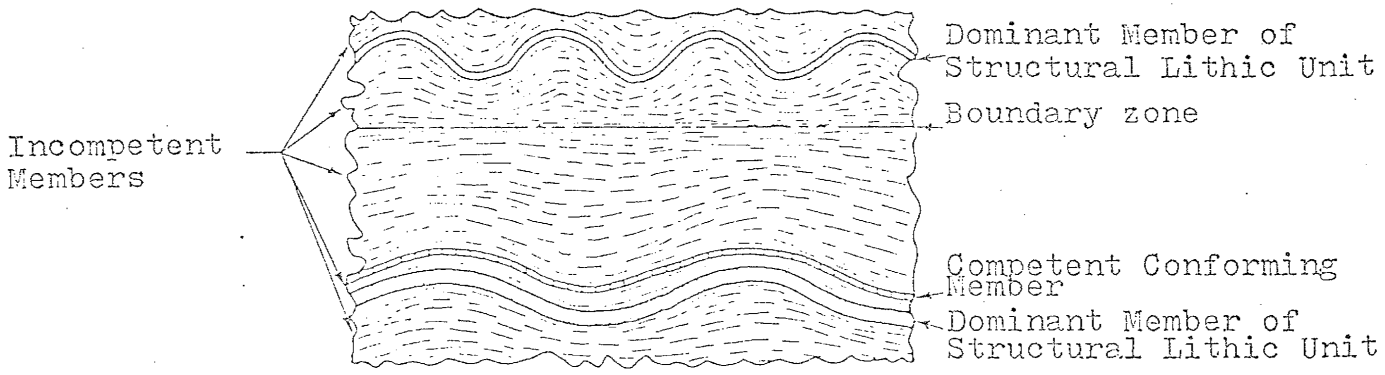


Figure 15. Structural lithic unit concept (from Currie, Patnode, and Trump, 1962).

The many irregularities which characterize the fold limbs and crests have been discussed earlier, but the overall appearance of these folds in cross section also merits discussion. The fold belt is best described as a length of buckles that incorporates tightly squeezed synclines separated by broad anticlines similar to the "dejective style" first described by Stille (Goguel, 1952). Bedding planes in the core of the synclines approach vertical. Such tight folds may indicate that folding took place under substantial cover.

The broad anticlines are box-like in appearance and according to Gzovskii (1965), such box folds may result from the action of both vertical and horizontal forces. When the concept of vertical forces is considered in relation to the effect of high pore pressures on a thick sequence of shales, the action of diapiric forces within unstable density stratifications becomes possible.

Reference to the cross sections of the Tinnie Fold Belt in Figure 12 indicates that the folds in the San Andres Formation are not similar in style to the Lincoln Fold Belt and that several of the folds appear to be related to a buoyant piercement effect of the underlying Yeso Formation.

The non-systematic orientation of fold axes and axial plane vergence of the Lincoln folds, together with the variability of fold wavelength suggest that more than one mechanism of deformation may have been operative at the time of folding. In addition, on the basis of fold morphology and style, the Lincoln folds and the Tinnie Fold Belt do not appear related.

Kinematic Analysis

In attempting to define a direction of tectonic transport for the sheath of deformed Yeso sediments, it is necessary to investigate the kinematic or movement picture involved in the development of the Lincoln folds. Because the Lincoln folds have been classified as ranging from true flexural slip folds to quasi-flexural folds, a certain amount of flowage of material is inferred. Stratigraphic thickening must have been accomplished by flow within layers. The absence of axial plane cleavage and the influence of layering on the morphology of the folds, would, according to the characteristics described by Donath and Parker (1964), lead to a flexural-slip and flexural-flow kinematic classification.

According to Whitten (1966, p. 131), in flexural-slip folds, the dominant slip has occurred along original S_0 or bedding surfaces, and the B-kinematic axis is parallel to the fold axis. In addition, the S surfaces are kinematically active during the folding. Although the Lincoln folds are not entirely uniform in development, at least three different orientation characteristics are prominent: (1) many folds are upright and may be tight, close, or open folds (i.e., interlimb angles are less than or equal to 90^{o}), (2) a smaller number of folds are asymmetric and display a westward vergence, (3) a still smaller number of folds are east trending with either vertical or north dipping axial planes. These different fold orientations imply differences in the orientations of the kinematic axes.

If slip occurred primarily along bedding planes the direction of tectonic transport was parallel to the inclination of the fold limbs. Because the axial plane may be defined as the bisector of the interlimb angle we may infer that the line of relative movement within an individual fold was contained in the axial surface and oriented perpendicular to the fold axis.

As seen in Plate 1, the orientations of fold axes vary widely, but may be generally described as north trending, at least for the major folds. If we accept an overall northern trend for the Lincoln folds (which may link them to the Tinnie Fold Belt) and apply the considerations described above, we may approximate the trends of slip-line directions for the Lincoln folds, similar to the methods used by Davis (1975) to determine slip-line directions for several sets of folds in southeastern Arizona. The slip-line direction concept used here corresponds to the 'a' direction of Whitten (1966) and is often referred to as the direction of tectonic transport, oriented 90° from the 'b' or fold axis.

The application of the above considerations to the three prominent orientations within the Lincoln folds results in three possible directions for major tectonic transport. The direction of tectonic transport in the upright folds suggests a nearly vertical direction for the 'a' axis. Slip-line inferences for the folds with a westward vergence indicate a near vertical transport direction to the west. The direction of tectonic transport for the east trending folds displaying a southern vergence is correspondingly near vertical to the south. It should be mentioned here that none of the Lincoln folds are recumbent folds. The orientations of inferred slip-line directions have been plotted stereographically in Figure 16. The importance of the above factors and their implications will become obvious when the results are viewed in conjunction with the dynamic forces responsible for the deformation in the discussion of fold origin.

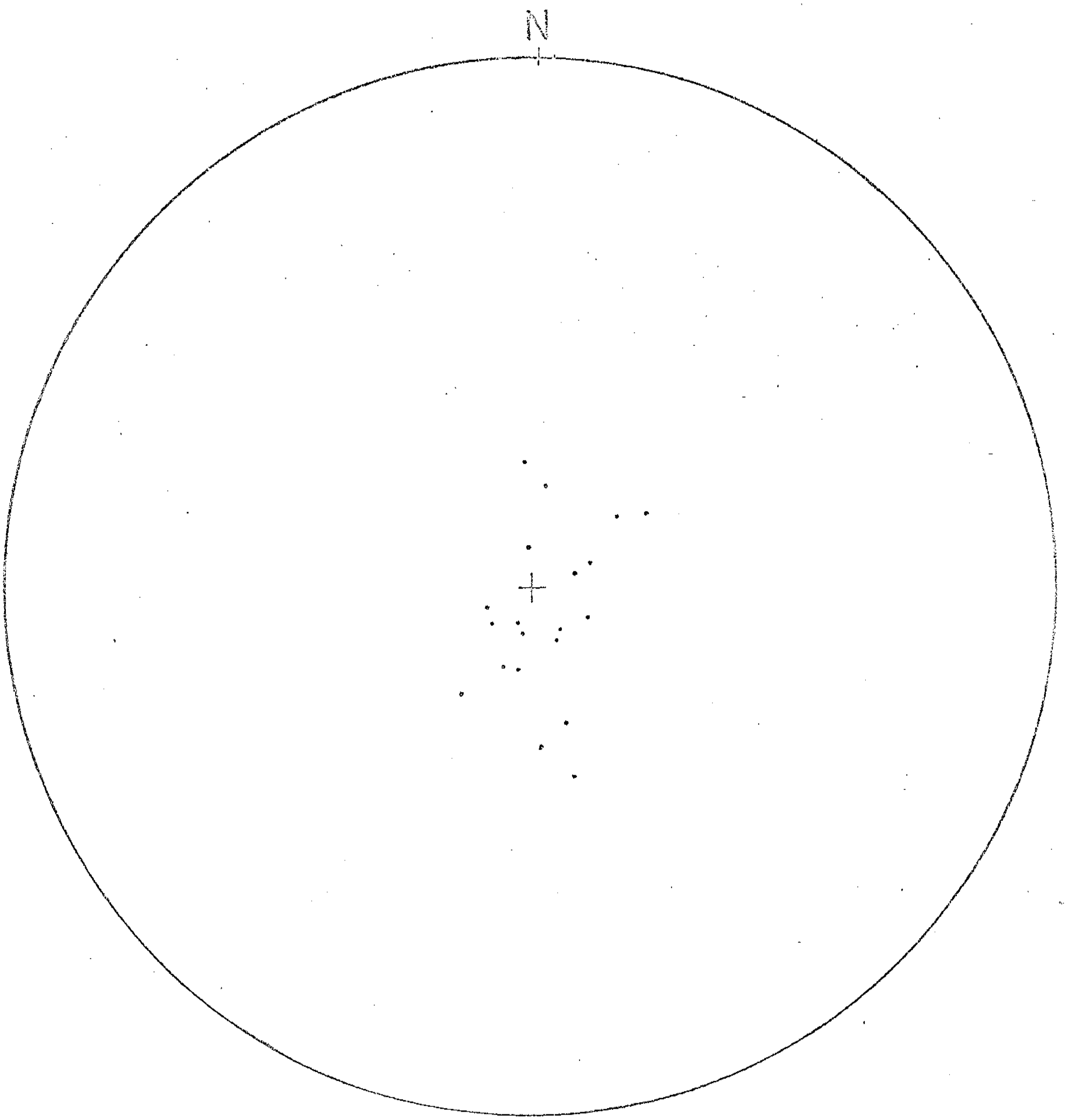


Figure 16. Stereo plot of the twenty kinematic 'a' axes for the major anticlines within the Lincoln Fold Belt. Lower hemisphere projection.

ORIGIN OF THE LINCOLN FOLDS

Introduction

The following discussion centers around the time of formation of the Lincoln Fold Belt. Several times of origin of the folds will be considered together with the arguments for a particular time and mode of origin.

In this connection it is important to note that in Kelley's opinion (1971), most of the Yeso folds in southeastern New Mexico are erratic in form and distribution and could have formed at almost any time from shortly after Yeso deposition to the present. However, the characteristics of the Lincoln folds suggest that it should be possible to assign an approximate date and probable origin to these folds.

The possible ages for the Lincoln folds may be grouped into five time intervals: middle Permian, i.e., shortly after deposition; late Permian through middle Cretaceous; late Cretaceous to early Tertiary or Laramide time; during the middle Tertiary period of igneous activity; and middle Tertiary through Recent. Each of these time intervals will be discussed in terms of their regional and local significance in relation to the development of the Lincoln folds.

Middle Permian

A cursory examination of the structural relationship of the Permian beds in the vicinity of Lincoln, New Mexico, would indicate a penecontemporaneous or Leonardian age for the deformation. Intensely deformed Leonardian sediments are overlain by the nearly flat-lying Guadalupian San Andres Formation. However, no evidence for an unconformity between these two formations could be found. The youngest folded beds outcrop below a red or yellow siltstone unit which occupies the stratigraphic horizon between the folds and the overlying San Andres Formation. This horizon also contains isolated lenses of massive gypsum, which may correspond to the Cañas Member elsewhere in New Mexico.

In the Guadalupe Mountains, 108 kilometers to the southeast, the Bone Spring Flexure has been mapped by King (1948), who has assigned a Leonardian age to the deformation. However, this structure is considered by most authors to be only a restricted local feature. The entire northwestern shelf of the Permian Basin is considered to have been quite stable and lacking in local tectonism throughout the late Paleozoic and most of the Mesozoic.

In addition, the Permian sediments near Lincoln, although severely deformed, still display a certain unit coherence. They lack the chaotic features and near horizontal axial planes generally considered typical of penecontemporaneous deformation or the formation of olistostromes as discussed by Elter and Trevisan (1973). For these reasons along with the general lack of similar Permian age features on other portions of the northwestern shelf, a middle-Permian age for the formation of the Lincoln folds is not considered likely.

Late Permian through Middle Cretaceous

A review of the tectonic development of the area under study was outlined in Chapter 3. This time interval was characterized by the deposition of both marine and continental sediments of regional extent. Tectonic events during this period include repeated reactivation of the by now buried Pedernal landmass and a slight regional tilting to the north.

According to Kelley (1971, p. 60), evidence for a renewed rise of the Pedernal in post-Triassic to pre-Dakota time is shown by the pinch-out of the Triassic beneath the Cretaceous Dakota in T.13 S. and T.11 S.

Although Jurassic rocks are missing, Kelley states that the gradual overstepping of the Cretaceous Dakota beds down through Triassic to Permian beds in T.14 S. indicates an expansive slight tilt to the north during late Jurassic to early Cretaceous time, accompanied by widespread stripping.

It does not appear likely that the Yeso sediments underwent a great deal of deformation during this period. However, as mentioned previously, the Mesozoic record in this area is poor. If the folds owe their origin to tectonism during this interval, geologic relations to corroborate this viewpoint are lacking.

Late Cretaceous through Early Tertiary

Although tectonic developments during this time interval have been modified by late Cenozoic faulting, certain structures have been assigned a Laramide age. According to Eardley (1962), the Laramide belt of deformation in New Mexico was a narrow one through the central part of the state, which is characterized by large asymmetrical anticlines, some with gravity slide thrusting on the steep flanks. Certain of these structures such as the Oscura and San Andres ranges expose Precambrian rocks along their margins. Kelley and Thompson (1964) describe Laramide disturbances in central New Mexico as broad north trending folds or upwarps and sags.

According to Kelley (1971), the unconformity between the late Cretaceous-Paleocene Cub Mountain Formation and the older Cretaceous formations in the Sierra Blanca basin indicate an early Laramide reactivation of the Pedernal and the beginning of subsidence of the Sierra Blanca basin. Principal basin development came after or during deposition of the Cub

Mountain and before eruption of the Sierra Blanca volcanics. This later basin development was aided by north and northeast trending normal faults, which according to Kelley (1971), are probably late Laramide in age, although they may have undergone a later Tertiary movement as well. The deep seated left shift along the Capitan lineament is thought by Kelley to have taken place during Eocene time, and postdates arch and basin development.

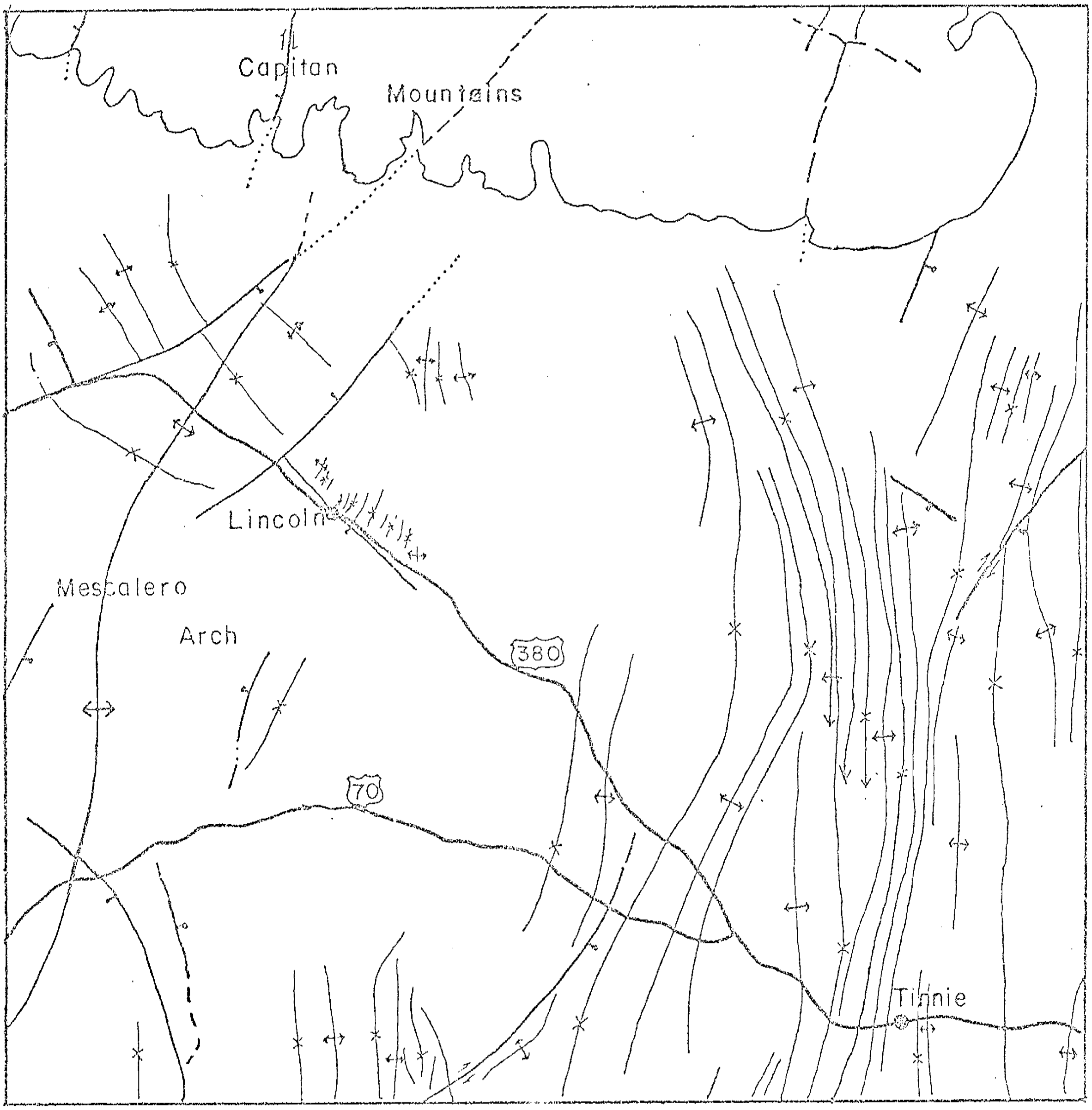
Several aspects of the Lincoln folds relate directly to the development of the Mescalero arch and the Sierra Blanca basin:

1. The arch and the basin trend and plunge north and northeast as do many of the Lincoln folds.
2. Limbs of the Mescalero arch dip gently to the east and more steeply to the west. The Lincoln folds are asymmetrical to the west in part.
3. The fault through Lincoln Canyon (Plate 1) appears to postdate the Lincoln folds, and parallels the Mescalero arch and other faults which are probably Laramide in age.
4. Folds in the Yeso Formation are common in the Lincoln area, but are not common on the eastern slopes of the Sacramento Mountains to the south. The difference

between these two domains of the Mescalero arch is likely related to the occurrence of the Sierra Blanca basin.

Reference to Figure 17 indicates that the axis of the Mescalero arch is offset approximately 16 kilometers to the east on the south side of the Capitan Mountains as a result of the Eocene (?) shift along the Capitan lineament. The effect of such a transverse offset on a previously formed fold (Mescalero arch) would result in the formation of secondary folds with axes oriented at approximately 90° to the axis of the primary fold, as indicated in Figure 18. The effect in the Lincoln area then would have been the formation of northwest trending folds since the Mescalero arch trends northeast. This results in a kinematic elimination of the left shift as a causal mechanism for the Lincoln folds. However, several northwest trending anticlines in the San Andres Formation, northwest of Lincoln, appear directly related in this manner to this left shift (see Figure 17).

In conclusion, this interval is not lacking in either vertically or horizontally directed tectonic stresses. This leaves the possibility that the Lincoln folds are the result of tectonism during this interval.



Syncline

Anticline

Fault with downthrown side

One inch equals 3 miles or 4.8 km.

Figure 17. Tectonic map of the region around Lincoln, New Mexico. (Adapted from Kelley, 1971 and Kelley and Thompson, 1964)

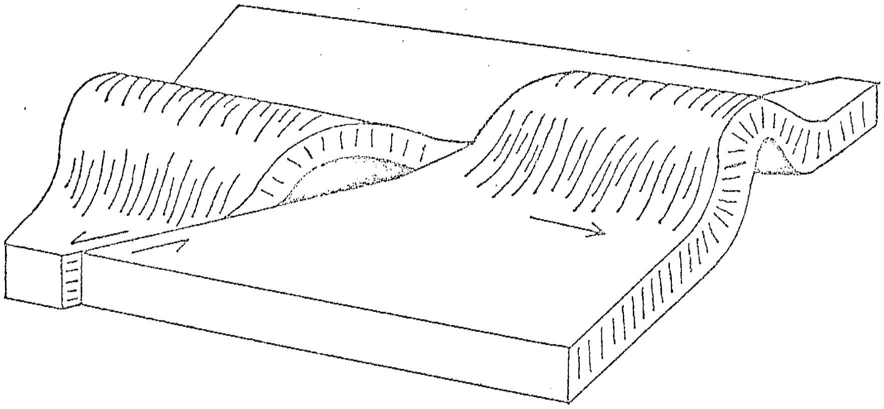


Figure 18. Formation of secondary folds resulting from the transverse offset of a previously formed fold (redrawn from Goguel, 1952).

Middle Tertiary Igneous Events

The cluster of intrusive centers associated with the northern end of the Sierra Blanca basin and the Jicarilla Mountains form a north trending lineament with the Sierra Blanca igneous complex as seen in Figure 3. According to Kelley (1971), two ages of porphyry intrusion are indicated by the late Laramide laccolith at Lone Mountain and the middle Tertiary stocks at Sierra Blanca. The stocks and volcanics at Sierra Blanca have been dated by Thompson (1972) as Oligocene.

The northern trend of the Lincoln folds suggests that the orientation of the folds would be compatible with horizontal stresses generated by intrusion along this lineament. Although a few of these intrusives may have caused local doming, a direct relationship between the intrusive and the folds (at least 20 kilometers away) is lacking. In addition, Thompson (1972) has shown that only 20 percent of the Sierra Blanca igneous complex is intrusive in nature and that the remaining 80 percent is volcanic. The trend of the fold axes is also compatible with what one would expect if the folding was the result of gravity gliding due to doming in the Sierra Blanca region. This subject is further discussed on pages 72 through 74.

Kelley (1971), in describing the numerous dikes which trend north and northeast from Ruidoso to Patos Mountain, estimates that the amount of total cross-section emplacement would be more than 0.8 kilometers. Although the dikes are favorably aligned with respect to the Lincoln folds, it does not seem likely that this amount of emplacement could account for the large amount of apparent lateral shortening within the folds.

Compressional or vertical forces due to the emplacement of the Capitan stock would result in the formation of folds with west-trending 'b' or fold axes. Although their relationship to the Capitan Mountains is not direct, the oblique west trending folds (as discussed on page 36) in the Lincoln area may owe their origin to this intrusive. If that is the case, then the northern trend of the major folds probably predates the emplacement of the Capitan Mountains stock.

Diabase sills are common along the Yeso-San Andres contact in the Lincoln area, but do not appear to have taken part in the folding. Permian beds that outcrop adjacent to the Cenozoic sills remain nearly flat lying.

The possibility that the Lincoln folds owe their origin to Tertiary igneous activity is enhanced by their alignment with the north trending intrusive lineament. However, the proximity of the Capitan Mountains stock suggests that compressive stresses due to intrusion would have resulted in the formation of west-trending folds. If the folds are the result of late Laramide intrusions further west, the connection is not apparent.

Middle Tertiary through Recent

Some of the faults in the Sierra Blanca region are considered by Kelley (1971) to be associated with the igneous disturbances, and therefore are probably Oligocene in age. Monoclinal flexing of the San Andres, Oscura, and Sacramento uplifts began in the Miocene and developed into Basin and Range type faults during the Pliocene. Budding (1963) has shown that sediments of the Pliocene Ogallala Formation in the Jicarilla Mountains overlie superficial gravity glide structures and date the deformation as pre-Pliocene.

Continued erosion, deposition, and fault block movement characterize the remainder of the Pliocene and Quaternary. In addition, limited glaciation occurred during the Quaternary on Sierra Blanca peak.

In relation to this glaciation, Foley (1964) considers the Lincoln folds of only local significance and the result of mass slumping due to the effects of large amounts of glacial outwash during early Recent time. However, the glaciation of Sierra Blanca Peak is considered to have been relatively minor and located at a considerable distance to the west of Lincoln. For these reasons along with the lack of similar features in other more heavily glaciated areas, this explanation is not acceptable.

In summary, this time interval is characterized by vertical movements associated with normal faulting. Kelley and Thompson (1964, p. 120) state that the probable time of maximum development of Lincoln-type folds occurred during the Miocene, associated with faulting and an increase in the tilt of the Pecos slope. However, Kelley (1971, p. 60) states that the Pecos slope is probably Laramide in age. With the possible exception of surficial gravity effects it does not appear likely that the Lincoln folds are the result of late Tertiary or Quaternary tectonics.

Mechanism of Deformation

On the basis of regional and structural relationships explained above, the Lincoln folds appear to be Tertiary in age and predate certain regional features. Their mechanism of formation, however, has yet to be satisfactorily explained. Explanations such as subsurface evaporite solution in the Yeso Formation, dike emplacement during middle Tertiary time, and mass slumping during the Quaternary do not seem adequate in light of previous discussions. Other explanations, such as gravitational gliding, the effects of high pore pressures on shale, and basin subsidence will be discussed below.

If the Lincoln folds owe their origin to one of the above mechanisms, then certain aspects of the folds should be diagnostic of one of these mechanisms and allow us to date the deformation more precisely.

Gravity Gliding

To invoke the principles of gravitational gliding one necessarily implies the consideration of certain parameters. According to Lemoine (1973), the theory must be tested from two points of view: 1) the mechanical properties of the rocks involved and 2) the presence of a suitable slope existing at the time of deformation. In addition, de Sitter (1954), provides a discussion of attributes characteristic of gravity-induced folds.

The obvious presence of high pore fluid pressures as evidenced by the injection type clastic dikes discussed on page 39 , suggests that the rocks may have been in a condition suitable to deformation by gravitational gliding.

Although the present regional dip is about one degree to the east this fact does not preclude the possibility that slopes in the geologic past were different than at present. Perhaps the greatest advocate of gravitational gliding for the origin of the Lincoln folds is Craddock (1964). His discussion of the regional distribution of these folds and their relation to those at Lincoln is interesting, but his mechanism for fold formation requires certain geologic events which, in all likelihood, did not occur.

Craddock calls for a phase of temporary doming to the west in the Sierra Blanca region, followed by an eastward gliding of the Yeso and San Andres formations. This gliding supposedly accounts for the arcuate fold pattern which he states is convex about the center of the Sierra Blanca complex. However, Kelley and Thompson (1964) report no early doming or early intrusions to result in the eastward tilt. They explain the convexity of the fold belt by its concentric relationship to the northeastern edge of the Sierra Blanca basin, and state that the convex pattern may be the result of basin encroachment to the east.

According to Davis (1975), the cross sections in de Sitter (1954) connote that gravity-induced fold structures are, for the most part, characterized by (1) axial planes that dip toward the source area for the glide sheets and (2) asymmetry in the direction of gliding. The application of the above considerations to the Lincoln folds would suggest that (1) the westward vergence of some axial planes indicate a source area to the east (rather than west), and (2) the westward asymmetry of the Lincoln folds, if the result of gravitational gliding, indicates that the direction of transport was to the west, not east. In addition, the forms of the Lincoln folds are not in accord with the characteristics of gravity folds as outlined by de Sitter (1954).

Although the author has not examined the Tinnie Fold Belt in detail (see Figure 12), the cross sections provided by Kelley (1971) suggest that these folds may not have been produced by gravitational gliding either.

In conclusion, we may state that there is little evidence within the Lincoln folds to support an origin exclusively by gravitational gliding.

High Pore Pressures and Shale

The combination of high pore fluid pressures within a thick sequence of shaly units overlain by more dense units produces a diapiric effect due to gravitational instability, identical in mechanics to the forces responsible for salt diapirism. Several lines of evidence suggest that similar forces may have been significant in the development of the Lincoln folds: (1) the stratigraphic location of the folds indicates that they are separated from the basement by lower Yeso clastics and upper Abo shales only, (2) the occurrence of injection type clastic dikes, and (3) the morphology of the folds suggests the effect of both vertical and horizontal stresses. The fact that the Lincoln folds occur near the crest of the buried Pedernal landmass is also significant, as is the continued reactivation of this trend throughout geologic time.

The work of Hubbert and Rubey (1959) has been instrumental in shaping modern concepts of abnormal pore pressures. They suggest that fluid pressure buildup is greatest in geosynclinal tracts, particularly in shales. An increase in interstitial-fluid pressure results in a buoyancy effect or flotation of the overburden, which reduces both the shear stress and the angle of slope required to move the overburden. Ancient abnormal fluid pressures are not without modern analogues, which may help explain the mechanics of overthrust faulting. In addition, several authors have applied the importance of high pore pressures and density contrasts to fold development. Certain aspects of these discussions may be applicable to the development of the Lincoln folds.

In his discussion of folding and diapirism in the Kerch-Taman region of Russia, Lebedeva (1965) details the following processes: during the growth of the main folds, the crests were modified by second order folds. During the development of these second order folds, the main role was played by the displacements of the underlying Maikop Formation. The density and pressure differences between the anticlines and synclines led to the squeezing out of the Maikop clays from beneath the synclines and contributed to their flow toward zones of lower pressure, *i.e.*, toward the crests of the anticlines.

Lisenbee (1976) reports that several domes associated with the Galisteo syncline in northern New Mexico are the result of shale diapirism. Diapirism is attributed to a combination of directed stress and buoyancy of the shale, which is aided in transport by a deep seated fault system. Shale piercement reaches values between 300 and 600 meters and has caused local subsidence.

According to Berry (1973), high pore fluid pressures are associated with anticlinal folds. By making direct fluid-pressure measurements within the Great Valley section of the Sacramento Valley in California, Berry has demonstrated the existence of high fluid potentials. He attributes the origin of folds in the Great Valley to dynamic tectonic compression caused by active deep seated linear diapirism of Great Valley mudstones and related rocks that possess near perfect plastic properties by virtue of their near-lithostatic fluid pressures. The origin of the anomalous fluid pressures adjacent to the San Andres fault is attributed to compression between the granitic Sierran-Klamath and Salinas blocks. In addition, he relates the Kettleman folds, which are long, linear, and non-uniformly asymmetrical to the effects of diapirism along a postulated buried fault zone.

In summary, it appears that the Lincoln folds and their geologic setting bear certain similarities to other instances in which high pore fluid pressures and shale diapirism are the driving mechanisms of deformation. However, the Lincoln folds do not qualify as true diapir folds, due to the fact that they do not exhibit piercement. If high pore pressures and flowage were crucial to fold development, the effect of the overlying, thick and massive San Andres Formation may have been to direct these forces horizontally, rather than permit piercement.

Basin Subsidence

As discussed on pages 64 and 65, the occurrence of the Lincoln folds may be related to the development of the Mescalero arch and the subsidence of the Sierra Blanca basin. It must be borne in mind, however, that basin development was accomplished in two stages: an initial stage associated with early Laramide compression and a later stage prior to but possibly associated with middle Tertiary igneous activity.

According to Woodward (1976), large scale disharmonic folding associated with basin subsidence may result in two kinds of patterns. Radial folds form in response to greater subsidence in the center of the basin than along the margins; the strata along the basin margin are forced to occupy a smaller circumference as strata are depressed and pulled toward the center of the basin. A similar situation exists when the axis of a large and elongate basin subsides more than the basin margins. Because the chord of an arc is shorter than the arc itself, as the center of the arc subsides and approaches the chord, the strata undergo compression resulting in folds parallel to the axis of the basin.

Because the trend of the Lincoln folds parallels the axis of the elongate Sierra Blanca basin rather than radiating from it, the second explanation is more acceptable and may directly relate the folds to basin subsidence. Kelley (1971) states that the principal formation of the Sierra Blanca basin was late Laramide. Therefore, folding related to subsidence was probably associated with the second stage of basin development.

CONCLUSION

The north trending Lincoln folds present a problem of structural deformation related to regional tectonic development. In a region characterized by large persistent folds, widespread igneous activity, and many large displacement normal faults, the significance of the Lincoln folds appears slight. But when viewed in relation to regional structural elements, the Lincoln folds provide an insight into the sequence and mechanisms of regional tectonic evolution.

Stratigraphic correlation of the horizon represented by the Lincoln folds indicates that the folds may be separated from the basement by as much as 450 meters of fine grained clastics and shales. The interval between the folds and the overlying San Andres Formation, though typically occupied by gypsum and sandstone members elsewhere in New Mexico, is represented in the Lincoln area by a sandstone unit of variable thickness containing discontinuous lenses of massive gypsum. Although the San Andres Formation is nearly flat-lying in the Lincoln area, the Tinnie Fold Belt occurs 16 kilometers to the east of Lincoln and several northeast trending linear buckles occur still further to the southeast. These structural features can not be directly related except on the basis of trend, but they may record different aspects of the same deforming forces.

The morphology of the folds suggests that they may have resulted from the action of both vertical and horizontal stresses, and that folding probably took place under substantial cover. The variability of fold wavelength and trend and the lack of axial plane cleavage suggests that the folds were not subject to severe lateral compression and that they were moderately to highly ductile during folding. Various considerations indicate that these folds should be classified as parallel or flexural slip folds, and as quasi-flexural folds in part. The geometry and occurrence of the folds requires an upper and lower detachment surface, one near their contact with the San Andres Formation and one in the shallow subsurface.

Certain aspects of fold formation, such as the presence of injected clastic dikes and the stratigraphic location of the folds, attest to the importance of high pore fluid pressures and buoyancy effects during the deformation.

A review of the characteristics of gravity-induced folds indicates that the Lincoln folds are not due exclusively to the effects of gravitational gliding as suggested by Craddock (1964). Cross sections of the Tinnie folds do not support a gravitational origin either. They may indicate a buoyancy of and piercement by the underlying Yeso Formation.

The discussion of high fluid potentials and shale diapirism indicates that the Lincoln folds are not true diapiric folds, and that although dissimilar in style, they may have been subject to similar forces. Berry's (1973) description of the Kettleman folds may have direct implications for the origin of the northeast trending buckles.

External characteristics such as plunge, trend, and asymmetry associate folding with basin-arch development more closely than with any other regional structural elements. This relationship is enhanced by the discussion of folding which accompanies the subsidence of the axis of an elongate basin, after Woodward (1976).

Maximum fold development is interpreted to have been coincident with the late Laramide subsidence of the Sierra Blanca basin and the development of the Mescalero arch. Later Cenozoic events such as the basement shift, faulting, and widespread volcanism complicate the regional picture and postdate the folding. The similarity in trend between the basin axis and the intrusive lineament may be more than a coincidence if basin subsidence was as great as is suggested by fold development.

The presence of injected clastic dikes indicates the existence of high pore fluid pressures during folding. These abnormal pressures and compressive stresses generated by basin subsidence are believed to have been responsible for the formation of the Lincoln folds.

APPENDIX 1

Stratigraphic section and petrographic descriptions

The stratigraphic interval under discussion outcrops directly above the floodplain of the Rio Bonito near Lincoln, New Mexico. The measured section is located in the NW¼, NE¼, Section 29, T.9S., R.16E. Because the beds are folded at this location, thickness values from tape measurements were later corrected for attitude variations.

The columnar section shown in Figure 19 and described on the following pages is restricted to the stratigraphic interval in which the major folds are prominent, but does not include the entire section of Yeso Formation. At least 90 meters of overlying Yeso sediments are excluded. This interval outcrops poorly and includes red and yellow siltstones, lenses of massive gypsum, diabase sills, and several folded limestone beds.

The numerals on the right side of Figure 19 separate the section into intervals to facilitate description. The letters on the left side of the columnar section refer to thin section descriptions which are representative of the adjacent stratigraphic interval. These descriptions follow the stratigraphic descriptions.

INTERVAL	DESCRIPTION	THICKNESS (meters)
V.	Siltstone, reddish brown, indistinctly bedded, slope former	>5

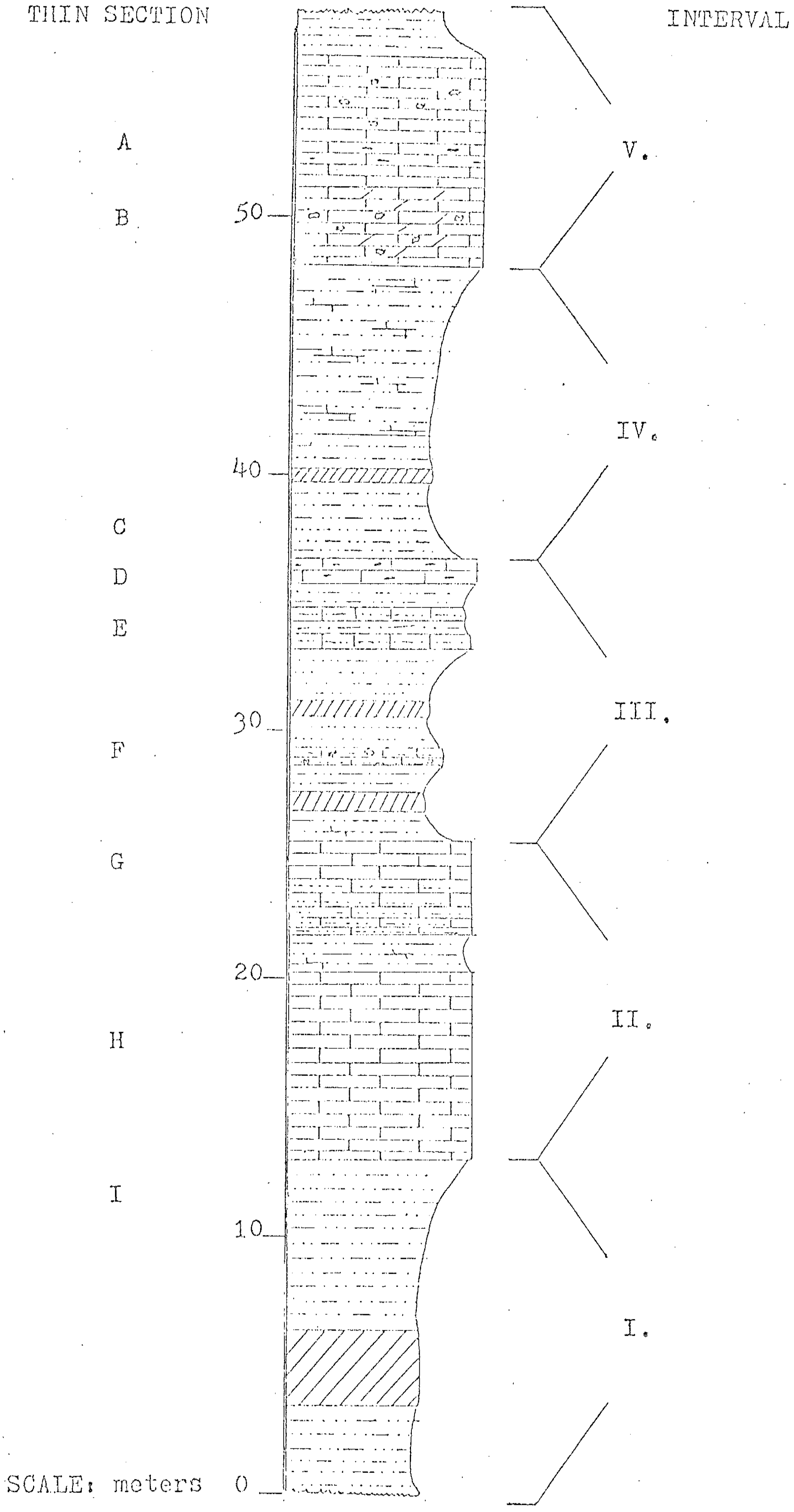


Figure 19. Stratigraphic column.

INTERVAL	DESCRIPTION	THICKNESS (meters)
	Limestone, thin bedded, medium grey, dense, finely crystalline	3
	Limestone, thin bedded, light grey, dolomitic in part, brachiopods, chert nodules	2.6
	Limestone, medium to thick bedded silty, vuggy, dense, brachiopods, cephalopods, few chert nodules and iron concretions, several thin interbeds of yellow siltstone	2.5
IV.	Siltstone, yellow, calcareous, very thin interbeds of silty limestone: lower part is greyish green, noncalcareous siltstone	7.6
	Gypsum, light grey, coarsely crystalline	0.6
	Siltstone, reddish brown to yellow, calcareous, thinly laminated, friable	2.8
III.	Limestone, medium bedded, dark grey, chert nodules	1.0
	Siltstone, reddish, partly calcareous, laminated	0.9
	Limestone, thin bedded, dark grey, very silty, interbed of reddish brown siltstone	1.5
	Siltstone, greenish grey, crops out poorly	1.9
	Gypsum, light grey, massive, silty	0.5
	Siltstone, reddish brown, very thinly bedded, fissile	1.1
	Limestone, thin bedded, grey-brown, very silty, vuggy, coarsely crystalline	0.7

INTERVAL	DESCRIPTION	THICKNESS (meters)
	Siltstone, reddish, calcareous gypsiferous in part, crops out poorly	1.0
	Gypsum, light grey, coarsely crystalline	0.8
	Siltstone, reddish brown, calcareous in part, structureless	1.0
II.	Limestone, thick bedded, medium grey, dense, brachiopods, gastropods, numerous fossil fragments, thin interbedded shale layers	1.6
	Limestone, thin bedded and thinly laminated in part, grey-brown, silty, coarse weathering texture	2.1
	Siltstone, yellowish brown, calcareous, structureless	1.9
	Limestone, medium bedded, dark grey, fossil fragments, finely crystalline, calcite veinlets	6.7
I.	Siltstone, thin bedded, yellow, friable, calcareous in part, reddish brown near gypsum contact	6.4
	Gypsum, light grey, massive, finely crystalline	2.9
	Siltstone, structureless, yellow, partly calcareous, reddish-brown near gypsum contact	3.5

PETROGRAPHIC CHARACTERISTICS

Table 2 summarizes the petrographic characteristics of representative thin sections of the carbonates from the stratigraphic interval discussed in the previous section. Descriptions of the two siltstone thin sections follow the table.

Percent compositions were determined by visual estimates. The carbonates are classified according to the general classification of Folk given in Blatt, Middleton, and Murray (1972, p. 472). The column of diagenetic effects is intended to call attention to only the principal processes observed. The following abbreviations are used in Table 2:

tr=trace
dis=dissolution
ppt=precipitation
inc=incomplete
neom=neomorphism
ext=extensive
mic=micrite
f=forams
g=gastropods
b=brachiopods
m=molloscs
frac=fracturing

TABLE 2

CARBONATE CHARACTERISTICS

Thin Section	Micrite	Microspar and Pseudospar	Sparite	Intraclasts	Pelloids	Skeletal	Terrig. Debris	Porosity	Diagenetic Effects	Rock Name
A	52	10	29	-	-	-	5	4	dis & inc ppt	sandy micrite locally sparite
B	35	12	15	-	-	25 f,g	10	3	dis & ppt	sandy, sparse biomicrite
D	40	30	10	-	-	15 f,b	-	5	ext neom & dis	sparse biomicrite
E	52	45	-	-	-	tr	tr	3	ext neom	micrite
F	40	45	10	-	-	-	tr	5	ext neom	micrite
G	45	37	-	tr	-	10	5	3	neom & dis	sparse biomicrite
H	16	8	15	6	8	40 f,b, m	5	2	neom, dis, frac & inc ppt	foraminiferal biomicrite

SILTSTONES

Thin Section: C

45%	Quartz grains; well sorted, subrounded, slightly embayed, monocrystalline, average apparent diameter: 0.1mm.
40	Carbonate; grain boundaries absent, no precipitated textures observed.
15	Porosity; includes large voids and intergranular pores.

Thin Section: I

59	Quartz grains, poor to moderate sorting, moderately rounded, monocrystalline, average apparent diameter: 0.5mm.
3	Potassium feldspar; appears relatively fresh and unaltered
tr	Plagioclase feldspar
tr	White mica
32	Carbonate; no grain boundaries or precipitated textures observed.
6	Porosity

CENOZOIC SILLS

Samples from different sills within the map area are similar compositionally but variable in constituent percentages. All exhibit ophitic textures and a large percentage of magnetite and iron staining. Differences are associated with the plagioclase/pyroxene ratio and the amount of sericitization. The following analysis is representative of the diabase sills in the Lincoln area:

55%	Plagioclase feldspar, labradorite, albite and Carsbad twins, zonation, and sericitization.
35	Clinopyroxene, augite, neutral in plane light, second order interference colors, maximum extinction angle: 42°
4	Biotite, second order yellowish brown interference colors
6	Magnetite

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This thesis is accepted on behalf of the faculty of the Institute by the following committee:

A. J. Budding

Allan R. Sanford

John R. MacMillan

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