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ORIGIN OF FOLDS IN THE PERMIAN YESO FORMATION, LINCOLN, NEW MEXICO

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Abstract—Large-scale disharmonic folds occur within sediments of the middle Permian Yeso Formation near Lincoln, New Mexico in T2S, R16E. 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 that 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 folds 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 late Laramide subsidence of the Sierra Blanca basin.

INTRODUCTION

Folded sediments of the Yeso Formation of Leonardian (middle Permian) age are exposed in low-lying hills north of the town of Lincoln, New Mexico in T9S, R16E and are visible from US-380. The folded units are overlain by the San Andres Formation. No folds were noted in the San Andres north of Lincoln. The style of folding is disharmonic, large scale and located in an area with a complex tectonic history. Previous estimates of the age of fold formation range from middle Permian to early Recent. Proposed mechanisms of formation include penecontemporaneous soft-sediment deformation, doming with gravitational gliding and mass slumping.

This study was undertaken to define the age and mechanism of deformation in the Yeso Formation in relation to regional tectonic development. Attitude data from 20 large anticlinal folds was collected for stereographic analysis in the 9 km^2 area north of Lincoln. A more complete review of the geology of the area and alternate fold theories can be found in Yuras (1976).

STRATIGRAPHY

Introduction

Rocks of the middle Yeso Formation are the oldest that crop out near Lincoln, New Mexico. Approximately 146 m of the Yeso is exposed, although the folds are best displayed in the 65 m that crop out along the Rio Bonito floodplain. Approximately 310 m of lower Yeso and 90 to 240 m of Abo Formation (Kelley, 1971) separate the folded interval from the Precambrian basement in this area. These rocks are overlain by approximately 140 m of the Rio Bonito and Bonney Canyon Members of the San Andres Formation (Kelley, 1971). Discontinuous Cenozoic sills occur near the Yeso–San Andres contact.

Yeso Formation

The Leonardian Yeso Formation in this area consists of interbedded limestones, fine-grained clastics and gypsum. The lithologies of the folded interval most closely match the Torres Member of Weber and Kottlowski (1959). The folded interval is composed of 50% fine-grained clastics, 43% limestone and 7% gypsum.

Fine-grained clastics are reddish-brown to yellow and calcareous to quartzose siltstones. The folds are best exposed by resistant limestone units which average 8 m in thickness and range from silty, vuggy and unfossiliferous micrites to dense, fossiliferous biomicrites. The gypsum units crop out poorly and appear as discontinuous but massive units with scattered coarsely crystalline horizons. The uppermost Yeso is a red-to-yellow siltstone of variable thickness. No evidence of unconformity at this horizon was found.

San Andres Formation

The basal thick-bedded Rio Bonito and the porous and thin-bedded Bonney Canyon Members of the San Andres overlie the Yeso in the Lincoln area. The Rio Bonito consists of dark-gray limestone beds approximately 1 m thick with interbeds of red siltstone. The Bonney Canyon beds appear light gray in outcrop and consist of fine-grained dolomite and limestone (Kelley, 1971).

Post–San Andres units

The San Andres is the youngest Paleozoic unit exposed in the Lincoln area. Farther west, Mesozoic and younger formations are exposed as a result of the development of the Sierra Blanca basin.

Cenozoic intrusive sills of diabase composition are common along the Yeso–San Andres contact. The sills were probably emplaced during the widespread intrusive period of late Eocene to Oligocene time (Kelley and Thompson, 1964).

Alluvial floodplain deposits may be as much as 30 m thick. 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 may be the result of Recent glacial outwash (Foley, 1964).

REGIONAL STRUCTURAL FEATURES

Tectonic setting

Fifty kilometers west of Lincoln, 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 to the west and descends under the Tertiary volcanics.

In the Lincoln area, the regional dip of the lower San Andres Formation is about 1° to the east. This implies a dip reversal between Lincoln and the Sierra Blanca basin. Kelley and Thompson (1964) referred to this as the Mescalero arch and stated that it roughly follows the trend of the buried, north-trending Pedernal uplift. The Mescalero arch is located approximately 4.8 km west of Lincoln. As shown in Fig. 1, the Mescalero arch exhibits a left lateral displacement of approximately 14 km, which is accompanied by a vertical displacement of about 488 m. This has been referred to as the Capitan lineament and has been linked to 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 (Kelley and Thompson, 1964).

The Tinnie fold belt is located 16 km east of Lincoln. This low anticlinorium of north-trending, long, closely spaced folds in the Yeso and San Andres Formations occurs in a 5-km-wide belt. Folds are typically 0.5 to 0.8 km from crest to crest, with as much as 300 m of structural relief on the larger folds (Kelley, 1971). The appearance of these folds in cross section suggests that diapiric forces may have been involved in the deformation.

A series of regional fold/faults known as the Border Hills, Sixmile and Y-O buckles is located approximately 56 km southeast of Lincoln.

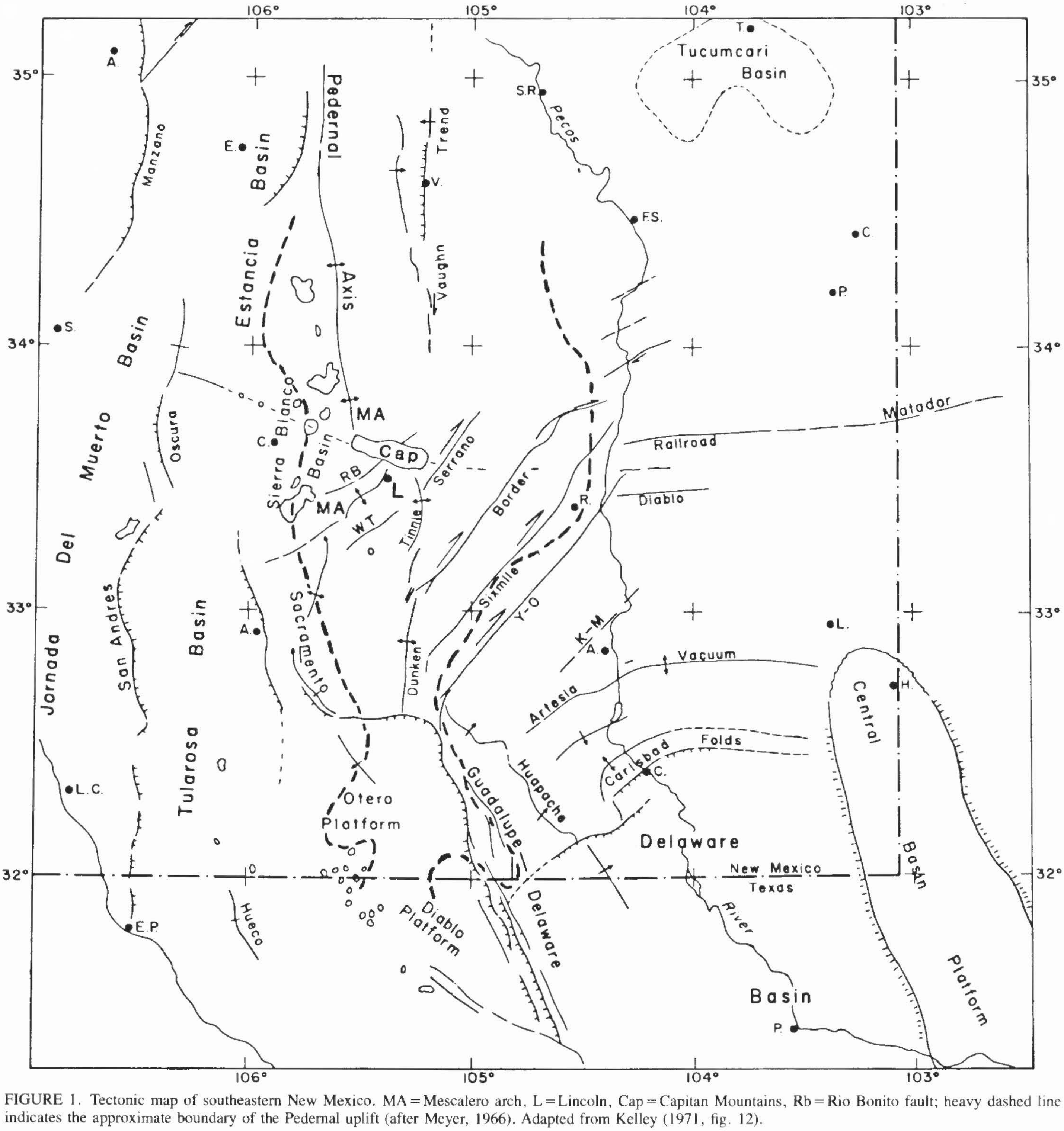

FIGURE 1. Tectonic map of southeastern New Mexico. MA = Mescalero arch, L = Lincoln, Cap = Capitan Mountains, Rb = Rio Bonito fault; heavy dashed line indicates the approximate boundary of the Pedernal uplift (after Meyer, 1966). Adapted from Kelley (1971, fig. 12).

According to Kelley (1971), there is good evidence that these buckles have undergone right lateral displacement as great as 150 m. The region also contains numerous northeast-trending faults of normal displacement which are generally downthrown to the northwest. In addition, Kelley (1971) mapped a northwest-trending fault in the Rio Bonito valley that is downthrown to the southwest.

Tectonic history

The subsurface in this area is dominated by the Pedernal uplift, which according to Kelley (1971), began to rise in late Pennsylvanian time and continued to rise during the Wolfcampian. Kelley and Silver (1952) indicated that Montanan time marked the beginning of Laramide disturbances in this region. This is documented by the unconformity between the Late Cretaceous Mesa Verde and early Tertiary Cub Mountain Formation. According to Kelley (1971) and Kelley and Thompson (1964), Laramide reactivation of the Pedernal trends formed broad, north-trending folds across central New Mexico, including the Mescalero arch, the Sierra Blanca basin, the Claunch-Tularosa sag, the Chupadera–San

Andres arch, and the Jornada del Muerto sag during Eocene(?) time. The left-lateral displacement along the Capitan lineament is also thought to have taken place during the Eocene and followed the development of these regional structures.

The Sierra Blanca volcanics are Oligocene in age and postdate the regional structuring. Thompson (1972) reported that K-Ar dates from the Sierra Blanca area indicate volcanism dates between 35 and 25 Ma. Middle Tertiary igneous activity was followed by late Tertiary Basin-and-Range faulting.

THE LINCOLN FOLDS

Introduction

Folds in the Yeso Formation are common in south-central New Mexico. Craddock (1964) has mapped folds in the Yeso Formation north and east of the Capitan Mountains and as far south as Ruidoso Downs, as well as in the Lincoln area. Kelley (1971), however, stated that there are considerable areas of nonfolding in the Yeso, such as in the Tularosa Canyon region and in the Guadalupe escarpment.

Fold classification

The Lincoln folds are classified as flexural-slip folds after Whitten (1966), based on the construction of dip isogons on fold cross sections after the method outlined in Ragan (1973, p. 54). The appearance of the folds in cross section (Fig. 2), suggests a disharmonic style after Badgley (1965). The folds may also be classified as quasi-flexural after Donath and Parker (1964) because of a lack of consistent geometry between neighboring folds.

Size and orientation

The Lincoln folds are generally traceable for about 200 m along their axes. The wavelength of the major folds ranges from 100 to 370 m; amplitudes are generally less than 120 m. Fold axes trend mostly north and northeast, and plunge at 5 to 33°, generally to the north, but also to the south, in part. Axial planes are near-vertical for the most part, especially in the upright symmetrical folds. Folds with east- or southeast-dipping axial planes and asymmetric folds are characterized by axial plane inclinations exhibiting a distinct westward vergence, as shown in Fig. 3.

Fold geometry suggests a shear horizon or decollement at the base of the folds. A construction to determine the depth to the decollement, after the method outlined in Ragan (1973, p. 68) indicates a depth of 150 m below the floodplain of the Rio Bonito. This places the decollement within the lower Yeso and approximately 300 m above the basement.

Description

Broad, asymmetric, box-type folds are associated with regularly spaced, more symmetric and concentric folds. The appearance of folds in cross section varies considerably. Bedding planes in the cores of tight synclines dip vertically close to the axial planes. Box-type folds exhibit

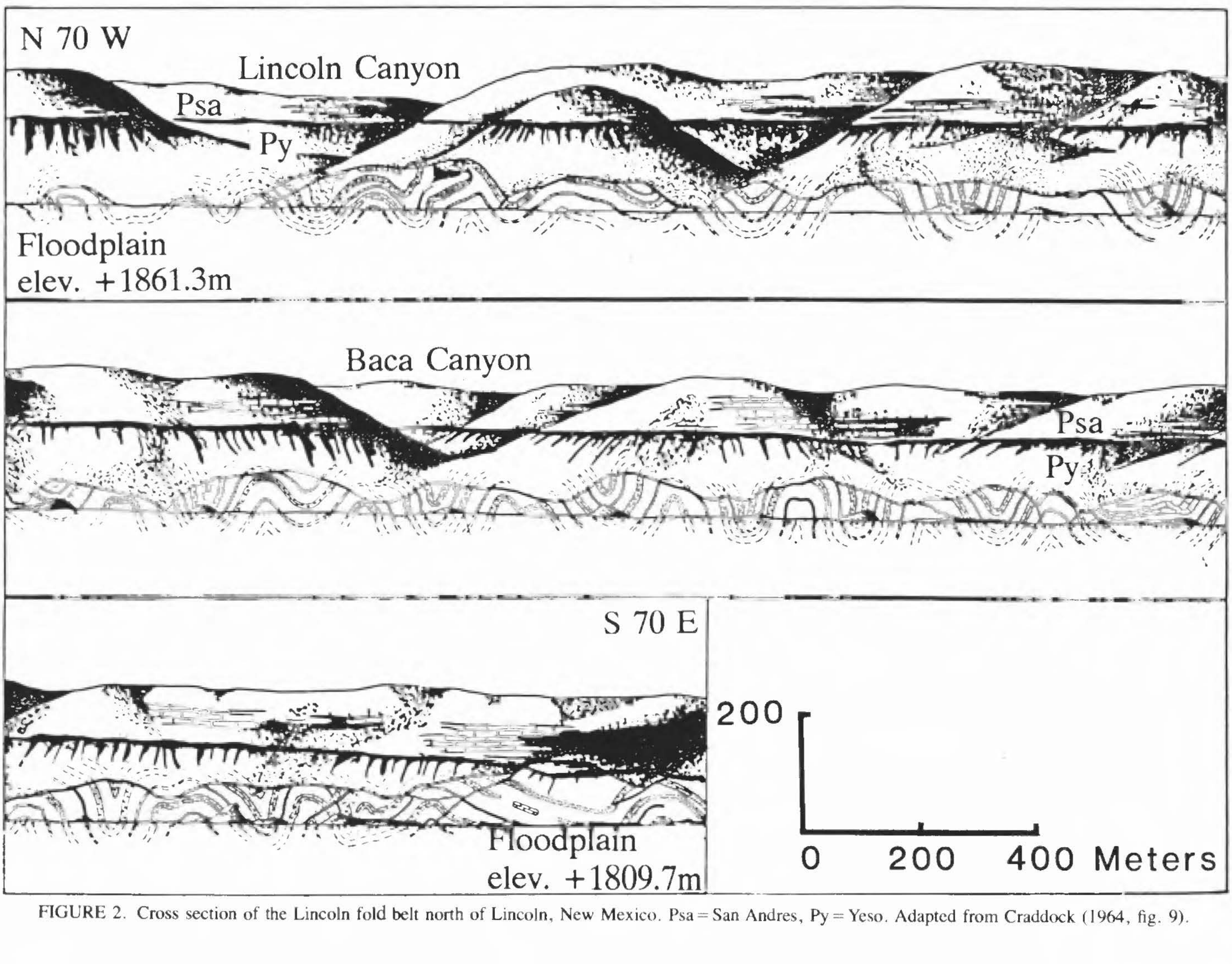

FIGURE 2. Cross section of the Lincoln fold belt north of Lincoln, New Mexico. Psa = San Andres, Py = Yeso. Adapted from Craddock (1964, fig. 9).

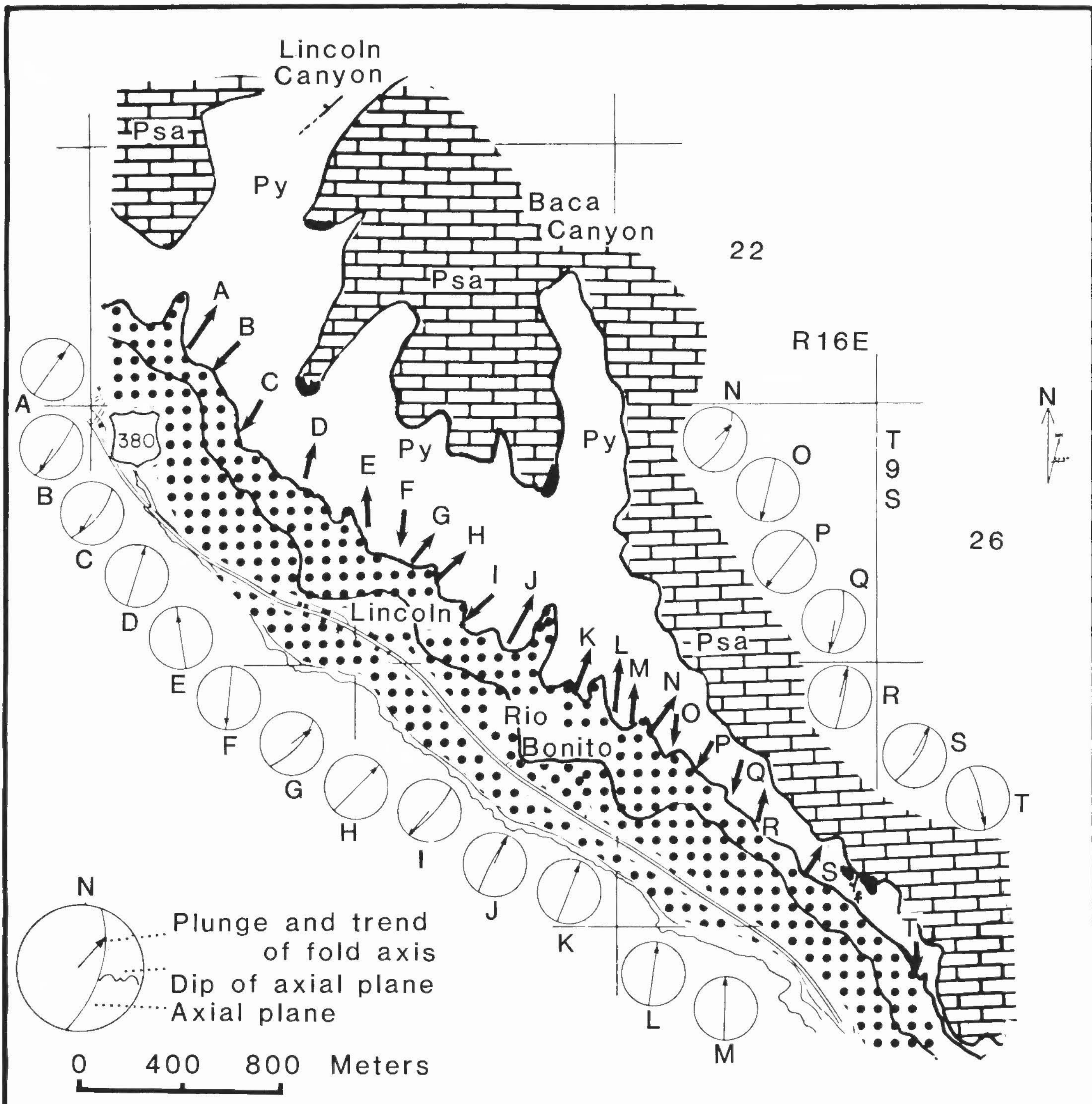

FIGURE 3. Tectonic and geologic map of the Lincoln fold belt. Block pattern = San Andres Formation (Psa); unpatterned with anticlinal axes = Yeso Formation (Py); dot pattern = Quaternary deposits; solid pattern = Cenozoic sills. Fold axis and axial-plane orientation of each of the 20 major anticlines is plotted stereographically, lower hemisphere projection. Adapted from Yuras (1976).

symmetric anticlinal cores with near-vertical axial planes. Secondary features in the form of right-angle flexures and discontinuous buckles modify the crestal regions and flanks of many of the folds.

Numerous brachiopods and cephalopods from folded fossiliferous units were examined and revealed no evidence of macroscopic strain. Also lacking is the development of regular fracture or fan cleavage planes. The folds are highly jointed and exhibit longitudinal, cross, diagonal and strike joint sets. Attenuation of the fold limbs is not well developed within the competent limestone units, whereas the less-competent zones may exhibit up to 20% thickness variation. The folds exhibit approximately 30% lateral shortening across the outcrop belt.

The presence of high pore-fluid pressures during folding is indicated by numerous breccia-filled zones of flowage and injected-type clastic dikes in the axial zones of some folds. Injected-type clastic dikes up to 4.5 m wide were noted by Craddock (1964).

Kinematic analysis

In flexural-slip folds, the dominant slip has occurred along original bedding surfaces, and the B-kinematic axis is parallel to the fold axis, according to Whitten (1966). Many of the Lincoln folds are upright and trend north or northeast. A smaller number are asymmetric and display a westward vergence. None of the Lincoln folds are recumbent.

The slip-line direction concept used here is patterned after Davis (1975), corresponds to the "a" direction of Whitten (1966), and is often referred to as the direction of tectonic transport. The slip-line is oriented 90° from the "b" or fold axis. The orientations of the slip-line directions for the 20 major anticlines have been plotted stereographically in Fig. 4. The direction of tectonic transport for 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.

ORIGIN OF THE LINCOLN FOLDS

Previous investigations of the Lincoln folds have proposed ages for fold formation ranging from middle Permian to early Recent, and modes of origin that include soft-sediment deformation, gravitational gliding and mass slumping. Several of these are considered below, together with the arguments for a particular time and mode of origin.

A penecontemporaneous origin for these folds is dismissed because of fold morphology. The folds lack the chaotic features and near-horizontal axial planes that are typical in soft-sediment deformation or in the formation of olistostromes.

The northern trend of the Lincoln folds suggests that horizontal stresses generated by the intrusion of the Sierra Blanca igneous complex 20 km west could be related to folding. Thompson (1972), however, has shown that the igneous complex is 80% volcanic and only 20% intrusive. Intrusion of the nearby Capitan Mountain stock would have resulted in the formation of west-trending folds at Lincoln, rather than the north-trending folds that are observed.

A gravitational gliding origin for the folds (proposed by Craddock, 1964) calls for a temporary doming in the Sierra Blanca region, followed by an eastward gliding of the Yeso and San Andres Formations, resulting in the formation of the Lincoln and Tinnie fold belts. Kelley and Thompson (1964) reported no early doming or early intrusion that could produce the required tilt. According to Davis (1975), gravity-induced folds exhibit axial planes that dip toward the source area and are asymmetric in the direction of gliding. These considerations applied to the Lincoln folds suggest that the westward vergence and the westward asymmetry of some of the folds indicate a direction of transport to the west, rather than east as proposed by Craddock (1964).

Foley (1964) considered the Lincoln folds to be of only local significance and the result of mass slumping due to large amounts of glacial outwash from Sierra Blanca peak during early Recent time. This explanation is considered unlikely because of the large scale of the folds and the lack of similar features in more heavily glaciated areas.

The Lincoln folds are best explained by considering fold morphology, orientation, kinematics and pore-fluid pressures in relation to the regional tectonic development. The broad box-folds described earlier may result from the action of vertical and horizontal forces (Gzovskii, 1965). When the concept of vertical forces is considered in relation to the effect of high pore pressures, indicated by the presence of injected clastic dikes and flowage features, the action of diapiric forces must be considered. Although the Lincoln folds do not exhibit piercement, the buoyancy effect of the pore-fluid pressures was probably instrumental in the folding process. According to Hubbert and Rubey (1959), 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.

Most of the folds at Lincoln exhibit near-vertical axial planes. Some folds, however, indicate a westward vergence and others indicate a westward asymmetry. According to Davis (1975), this indicates a direction of tectonic transport to the west.

The Lincoln folds and the Tinnie folds are both oriented predominantly north, parallel to the axis of the Sierra Blanca basin. According to Woodward (1976), large-scale disharmonic folding parallel to the basin axis is associated with basin subsidence when the axis of a large and elongate basin subsides more than the basin margins. The Tinnie fold axes are convex to the center of the Sierra Blanca basin; Kelley and Thompson (1964) explained this concentric relationship to be related to eastward encroachment of the basin.

The northern orientation of the Lincoln and Tinnie folds does not coincide with the predicted fold orientation for primary folds due to left-lateral displacement along the east-southeast-trending Capitan lineament based on Harding (1976, fig. 1). The northeast-trending Border, Sixmile and Y-O buckles, which indicate right-lateral displacement, exhibit the predicted orientation for strike-slip faults antithetic to the Capitan lineament displacement.

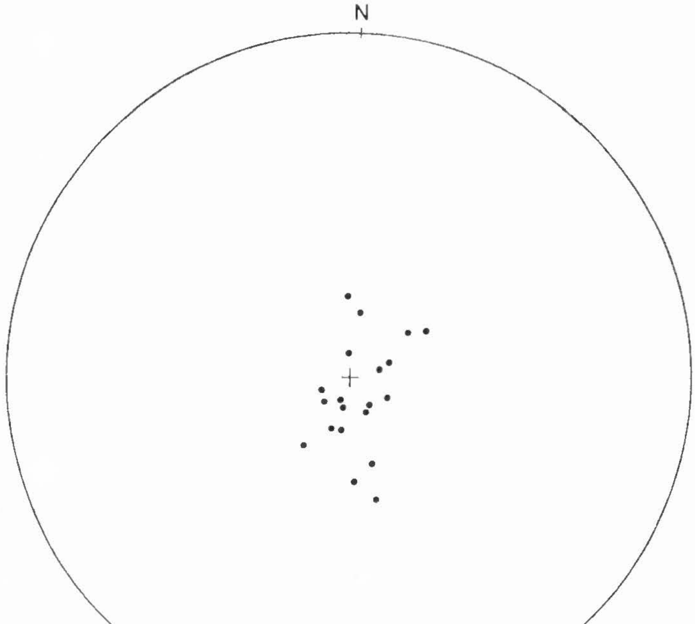

FIGURE 4. Stereographic plot of kinematic "a" axes for 20 major anticlines within the Lincoln fold belt. From Yuras (1976).

CONCLUSION

The formation of the Lincoln fold belt is interpreted to have taken place during the late Laramide (Eocene?) period of structural development and to coincide with maximum subsidence of the Sierra Blanca basin. The Lincoln folds may be coeval with the Tinnie folds, but predate the movement along the Capitan lineament and the formation of the Border, Sixmile and Y-O buckles. Deformation of Yeso sediments was caused by compressional forces associated with the subsidence of the Sierra Blanca basin and was aided by the effects of elevated pore-fluid pressure.

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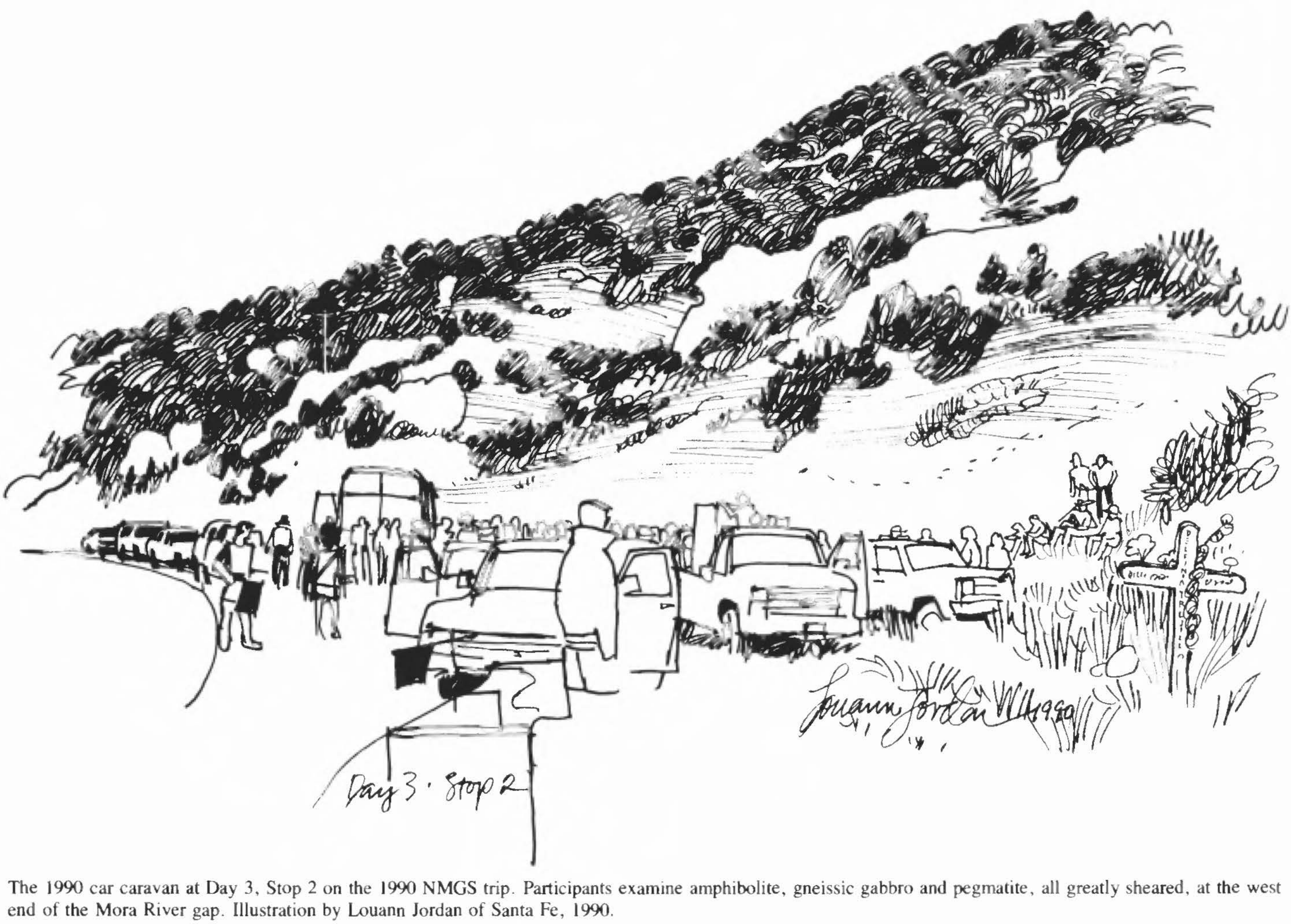

The 1990 car caravan at Day 3, Stop 2 on the 1990 NMGS trip. Participants examine amphibolite, gneissic gabbro and pegmatite, all greatly sheared, at the west end of the Mora River gap. Illustration by Louann Jordan of Santa Fe, 1990.