## *Geometry of Nacimiento-Gallina fault system, northern New Mexico*


Lee A. Woodward, Michael C. Hultgren, David L. Crouse, and Margaret A. Merrick, 1992, pp. 103-108

*in:*

*San Juan Basin IV*, Lucas, S. G.; Kues, B. S.; Williamson, T. E.; Hunt, A. P.; [eds.], New Mexico Geological Society 43rd Annual Fall Field Conference Guidebook, 411 p.

*This page is intentionally left blank to maintain order of facing pages.*

# GEOMETRY OF NACIMIENTO-GALLINA FAULT SYSTEM, NORTHERN NEW MEXICO

LEE A. WOODWARD[1], MICHAEL C. HULTGREN[2], DAVID L. CROUSE[3] and MARGARET A. MERRICK[4]
[1]Department of Geology, University of New Mexico, Albuquerque, New Mexico 87131-1116; [2]3517 Pilgrim Lane, Plymouth, Minnesota 55441; [3]1036 Whetstone Court, Raleigh, North Carolina 27615; [4]393 Fricke Court, Gardnerville, Nevada 89410

**Abstract**—The Nacimiento-Gallina fault system trends northerly for about 110 km, separating the San Juan Basin and the Colorado Plateau from the Rocky Mountain foreland to the east. From south to north the Pajarito, Nacimiento, Gallina and Tierra Montañosa faults comprise this system. The east-dipping Pajarito and Nacimiento faults bound the west side of the Nacimiento uplift and are characterized mainly by reverse separation. The Gallina and Tierra Montañosa faults are nearly vertical and define the west boundary of the Gallina-Archuleta arch. Movement on the Gallina fault had both dip-slip and strike-slip components and displacement on the Montañosa fault was essentially dip slip. This complicated eastern boundary of the Colorado Plateau has led to markedly different interpretations of its tectonic evolution, mainly because of previous lack of detailed geologic maps. Since the pioneering work of Vincent Kelley in the 1950s there has been general agreement that the Colorado Plateau underwent right shift with respect to the adjacent Rocky Mountain foreland in northern New Mexico prior to the Pajarito and Nacimiento faults rupturing the sedimentary cover. However, there has been considerable debate concerning the amount of right slip (as distinct from shift) along the Nacimiento-Gallina fault system. Right shift in Precambrian basement rocks among the eastern margin of the Colorado Plateau in late Paleocene to mid-Eocene time created northwest-trending echelon folds in the overlying Phanerozoic strata. This was followed by development of a west-facing monocline that was cut by the Pajarito and Nacimiento reverse faults. As the San Juan Basin subsided it was differentially folded relative to the Gallina-Archuleta arch, resulting in a component of strike slip along the Gallina fault. This differential folding resulted in variable offset along the Gallina fault with nonmatching folds on opposite sides of the fault. The axes of the folds do not predate fault movement and therefore cannot be used to determine the amount of strike slip. Lack of piercing points along the Pajarito, Nacimiento and Gallina faults precludes precise calculations of the strike-slip component of movement. These discontinuous faults with relatively short traces suggest that only minor amounts of right slip occurred along them. Thus, right shift of the Colorado Plateau dies out at the north end of the Gallina fault and displacement on the Tierra Montañosa fault is principally dip slip.

## INTRODUCTION

The boundary between the Colorado Plateau and the Rocky Mountain foreland in northern New Mexico is a major tectonic element, and interpretation of its development has important implications concerning the structural evolution of the southern Rocky Mountain region. One problem in interpreting the deformation along this boundary had been the lack of detailed geologic maps.

Reconnaissance maps by Renick (1931) and Wood and Northrop (1946) showed one continuous fault bounding the west side of the Nacimiento uplift (Fig. 1). Wood and Northrop (1946) also indicated that the north end of the Nacimiento uplift contained a west-north-westerly trending, north-dipping, normal fault which they named the San Pedro Mountain fault. This fault played a significant role in later tectonic analyses by Baltz (1967) and Chapin and Cather (1981).

We have completed geologic mapping at 1:24,000 and locally larger scales along the eastern margin of the San Juan Basin where it adjoins the Nacimiento uplift and Gallina-Archuleta arch (Merrick and Woodward, 1982; Crouse, 1985; Hultgren, 1986; Woodward, 1987). This mapping shows that four separate and distinct faults mark the eastern boundary of the San Juan Basin. These faults are collectively called the Nacimiento-Gallina system and are, from south to north, the Pajarito, Nacimiento, Gallina and Tierra Montañosa faults. Also, there clearly is no such structure as the San Pedro Mountain fault (Woodward et al., 1976; Merrick and Woodward, 1982).

The Gallina and Tierra Montañosa faults were mapped as one fault by Lookingbill (1953). Kelley (1954), however, indicated that the Nacimiento and Gallina faults were separate and not connected. Generalized maps by Hutson (1958) and Fitter (1958) showed the Nacimiento, Gallina and Tierra Montañosa faults as one continuous structure. A tectonic map compiled by Baltz (1967, plate 7) showed the Pajarito, Nacimiento, Gallina and Tierra Montañosa faults as one continuous structure; this map was later used by Chapin and Cather (1981, p. 186) in a tectonic analysis of the region. Chapin (1983, fig. 1) showed a major wrench fault trending northeasterly through the central part of the Nacimiento uplift, but detailed geologic mapping indicates there is no fault of such trend or displacement at that locality (Woodward, 1987).

The purpose of this paper is to present the results of detailed geologic mapping that provides new data for interpreting the deformation along the eastern boundary of the Colorado Plateau in northern New Mexico.

## PREVIOUS TECTONIC INTERPRETATIONS

Since the work of Kelley (1955, p. 66) there has been general agreement that the eastern margin of the Colorado Plateau has undergone

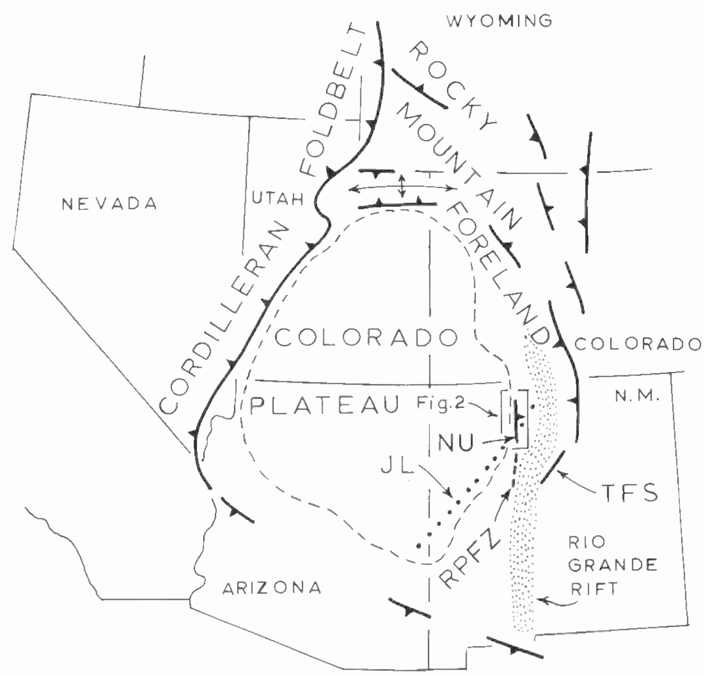


FIGURE 1. Index map showing Colorado Plateau and thrust and reverse faults of Rocky Mountain foreland and Cordilleran foldbelt. JL = Jemez lineament, TFS = Tijeras-Cañoncito fault system, RPFZ = Rio Puerco fault zone.

right shift with respect to the Nacimiento uplift of the Rocky Mountain foreland (Fig. 1). Although Kelley (1955) did not estimate the amount of right shift, he presented compelling evidence in the form of northwest-trending echelon folds along the eastern edge of the San Juan Basin, where it adjoins the Nacimiento uplift. Kelley (1955) also noted echelon folds along the northern margin of the plateau and suggested that these patterns of folds were the results of the plateau being pushed northeast relative to its surroundings. Small, diagonal crossfolds that cause sinuosity of the north-trending Defiance monocline are indicative of right shift within the plateau, which is the same sense of shift as along the eastern edge of the Colorado Plateau (Kelley, 1967). Kelley and Clinton (1960, p. 2) postulated two phases of Laramide (Late Cretaceous–early Tertiary) deformation for the Colorado Plateau. The first phase resulted from a principal regional stress oriented easterly to southeasterly, and the second was caused by a principal regional stress oriented northeasterly. Kelley (1950) suggested that the Laramide deformation consisted mostly of folding, including development of a monocline along the eastern margin of the San Juan Basin, and that the Nacimiento fault formed later in the Tertiary along the site of the monocline.

Baltz (1967, p. 2) inferred that the four faults separating the San Juan Basin from the Nacimiento uplift and Gallina arch were connected and were high-angle reverse faults (his Nacimiento and Gallina faults). The faults were interpreted to have formed as the basin was down-buckled and underwent right lateral motion. Baltz (1967) also suggested that right shift may have been as much as 5 km along the northern part of the Nacimiento uplift during three phases of deformation (late Paleocene, early Eocene and later in the Tertiary). His interpretation of right slip on the northern segment of the Nacimiento-Gallina fault system (Tierra Montañosa fault) was based largely on the assumption that variations in the sense and amount of stratigraphic separation were due to juxtaposition of different folds (Baltz, 1967, p. 75). Use of offset folds is a valid criterion for strike-slip movement only if it can be demonstrated that the folds are older than faulting; there is no unequivocal evidence that the folds at that locality predate the fault.

Slack and Campbell (1976) interpreted northwest-trending echelon folds and northeasterly trending normal faults of the Rio Puerco fault zone to the south of the Nacimiento fault (Fig. 1) as right-lateral wrench structures that formed in late Paleocene to mid-Eocene time, and estimated the amount of right shift as less than 2 km.

Woodward et al. (1972, p. 2394) suggested that there was no conclusive way of determining the amount of right shift near the north end of the Nacimiento uplift and that the geometry of the echelon folds did not warrant as much right shift as the 5 km proposed by Baltz (1967).

Chapin and Cather (1981) recognized two phases of Laramide deformation and estimated that during the second phase (latest Paleocene–earliest Eocene) the Colorado Plateau was moved 60 to 120 km to the north-northeast relative to the crustal block to the east. Their estimate was based on the presumed amount of crustal shortening across thrust and reverse faults to the north of the plateau (in the Wyoming province), and on correlation of the Jemez lineament (expressed mainly by late Cenozoic volcanic features) with the well-defined Tijeras-Cañoncito fault zone (Lisenbee et al., 1979) on the east side of the Rio Grande rift (Fig. 1). They suggested that the decoupling occurred within a zone up to 100 km wide marked by the Nacimiento-Gallina fault system on the west, with some of the strike-slip motion on faults now buried by the sedimentary fill of the Rio Grande rift.

## GEOMETRY OF FAULTS

Four separate and distinct faults bound the east side of the San Juan Basin, separating it from the Nacimiento uplift and the Gallina-Archuleta arch (Fig. 2). These faults are, from south to north, the Pajarito, Nacimiento, Gallina and Tierra Montañosa faults.

### Pajarito fault

The Pajarito fault is poorly exposed at most places, but where it is well exposed it is a vertical to high-angle reverse fault dipping 90° to 76°E. Maximum stratigraphic separation is about 1100 m (Martinez, 1974). This fault grades into a west-facing monocline at its southern end (Woodward and Ruetschilling, 1976). Near the north end of the fault the vertical separation diminishes and ends where the fault abuts a short, high-angle, east-west fault having minor displacement. North of the small cross fault for about 1.5 km there is no fault separating the Nacimiento uplift from the San Juan Basin to the west (Fig. 2), but rather, a synclinal bend separates the uplift and basin (Woodward et al., 1973). The synclinal bend is also present to the west of the Pajarito fault; maximum structural relief between the uplift and basin here is at least 2225 m (Martinez, 1974). Along most of the trace of the fault Precambrian crystalline rocks are to the east and steeply dipping Paleozoic and Mesozoic strata to the west, except at its south end where Mesozoic rocks occur on both sides of the fault (Woodward and Ruetschilling, 1976).

### Nacimiento fault

The Nacimiento fault is an east-dipping reverse and thrust fault along most of its trace on the west side of the Nacimiento uplift. It changes northward to a vertical fault and at its north end is a west-dipping normal fault (Fig. 2) that marks the western boundary of the Gallina-Archuleta arch. Where the Nacimiento fault bounds the Nacimiento uplift it is an upthrust that is steep at deep stratigraphic and structural levels, but flattens upward and has westward movement of the hanging wall block over the San Juan Basin (Woodward et al., 1972). The fault is steep where there is little stratigraphic separation, but dips more gently where there is greater displacement. Erosion has removed the gently dipping or flat-lying part of the fault at most localities; however, there are three places where nearly horizontal segments of the fault are preserved. At these places the youngest preserved rocks (Triassic strata) in the upthrown block are thrust onto steeply dipping Cretaceous beds. The transition from a steeply dipping to a gently dipping fault is also seen at these localities.

The Nacimiento fault curves slightly eastward at its south end where it dips steeply eastward and dies out in Permian rocks. At the north end of the Nacimiento uplift the fault curves north-northeastward (Woodward et al., 1976; Merrick and Woodward, 1982) and separates the Gallina-Archuleta arch from the San Juan Basin to the west (Fig. 2).

Maximum stratigraphic separation on the Nacimiento fault is about 1200 m, but structural relief between the Nacimiento uplift and the San Juan Basin is at least 3400 m because of an anticlinal bend east of the fault and a synclinal bend to the west. The synclinal bend is locally overturned and the eastern, overturned limb dips as gently as 45°E. East of the fault the beds are not overturned and commonly dip 5° to 15°W, but locally are steeper. Maximum observed thrust component of slip on the fault is approximately 750 m where the fault is nearly horizontal and has gently dipping Triassic beds resting on steeply dipping to overturned Cretaceous strata.

At the north end of the Nacimiento uplift, the fault appears to be a very steep reverse fault dipping east; northward the fault changes to a normal fault dipping 65° to 75°W and ultimately dies out northward after overlapping the Gallina fault for about 8 km (Fig. 2). Stratigraphic separation is about 215 m near the north end of the Nacimiento uplift (Woodward et al., 1976) where Mesozoic strata are juxtaposed.

It is not possible to construct a longitudinal structure section east of the Nacimiento fault to show the amount of crustal shortening parallel to the fault due to folding because the stratified rocks have been eroded from most of the Nacimiento uplift. Therefore, a precise comparison of the amount of crustal shortening on each side of the fault cannot be made and piercing points are not available to precisely calculate slip. Baltz (1967, p. 70) suggested that folds in the San Juan Basin (Fig. 2, locations 1A, 2A) might correspond with the topographically high part of the Nacimiento uplift (Fig. 2, location 1B) and a transverse graben within the uplift (Fig. 2, location 2B), respectively, giving a maximum of 5 km of right slip along the Nacimiento fault.

### Gallina fault

The Gallina fault is nearly vertical and trends north-northeasterly, parallel to and west of the northern part of the Nacimiento fault (Fig.

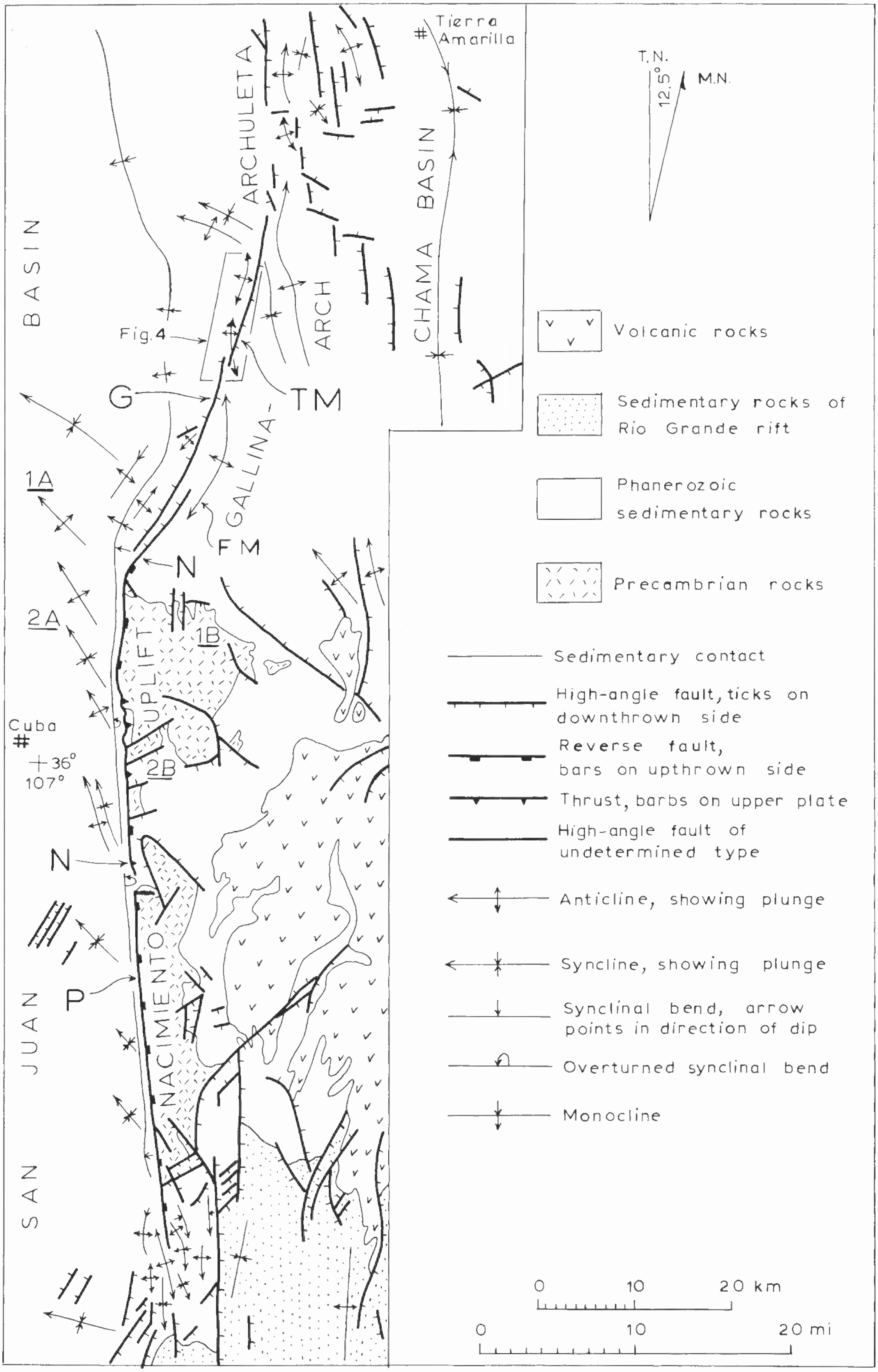


FIGURE 2. Generalized tectonic map of eastern margin of San Juan Basin and adjacent part of southern Rocky Mountain foreland. P = Pajarito fault, N = Nacimiento fault, G = Gallina fault, TM = Tierra Montañosa fault and FM = French Mesa anticline. Modified from Woodward et al. (1975). Numbered localities discussed in text.

2). There is variable offset along the Gallina fault (Fig. 3). At most localities the fault is downthrown on the west side with maximum stratigraphic separation of about 490 m where a syncline on the west side is juxtaposed with a poorly defined northwest-trending anticline on the east side (Fig. 3). At one locality the fault is downthrown to the east with about 30 m of stratigraphic separation where Triassic and Permian strata are juxtaposed. About 3 km from the northern terminus of the Gallina fault there is 365 m of left separation of Jurassic strata where the fault cuts the western limb of the French Mesa anticline. The fault terminates near the southern end of the Rio Gallina anticline (Fig. 4) where it offsets gently west-dipping Mesozoic beds on the western limb of the Rio Gallina anticline, with about 250 m of right separation.

There are no readily correlated piercing points along the Gallina fault that would enable precise calculation of slip.

### Tierra Montañosa fault

The Tierra Montañosa fault is not well exposed, but judging from its trace is nearly vertical. It trends north-northeasterly and nearly parallels the axial traces of the Gallina and Rio Gallina anticlines (Fig. 4). The southern termination of the fault is near the southern end of the Rio Gallina anticline, to the east of the Gallina fault. There, the two faults bound a small horst of Jurassic strata (Fig. 4). The Tierra Montañosa fault offsets Pennsylvanian, Permian, Triassic and Jurassic strata with the east side downthrown, having a maximum of approximately 550 m of stratigraphic separation. Jurassic Entrada Sandstone has right-lateral separation on the northern ends and left-lateral separation on the southern ends of the doubly plunging Gallina and Rio Gallina anticlines (Fig. 4), suggesting dominantly dip slip on the Tierra Montañosa fault. The fault may die out approximately 1 km north of the Gallina anticline, as Landis and Dane (1967) did not show the fault continuing northward into the adjacent Tierra Amarilla quadrangle. The doubly plunging anticlines along the Tierra Montañosa fault (Fig. 4) are readily explained by dip-slip movement on the fault, and to invoke strike-slip movement with juxtaposition of different fold axes across the fault is untenable. There are only two folds along the fault and there is clearly no strike separation of fold axes.

## DISCUSSION

Deformation along the west side of the Nacimiento uplift began with right slip in Precambrian basement rocks, creating northwest-trending echelon folds in overlying Phanerozoic strata (Kelley, 1955; Kelley and

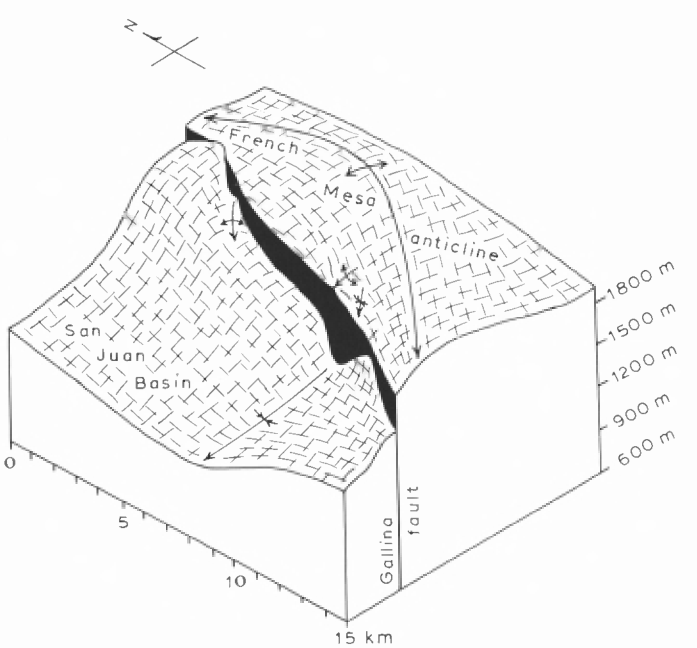


FIGURE 3. Generalized block diagram showing configuration of top of Permian strata along the Gallina fault. Elevations are above sea level.

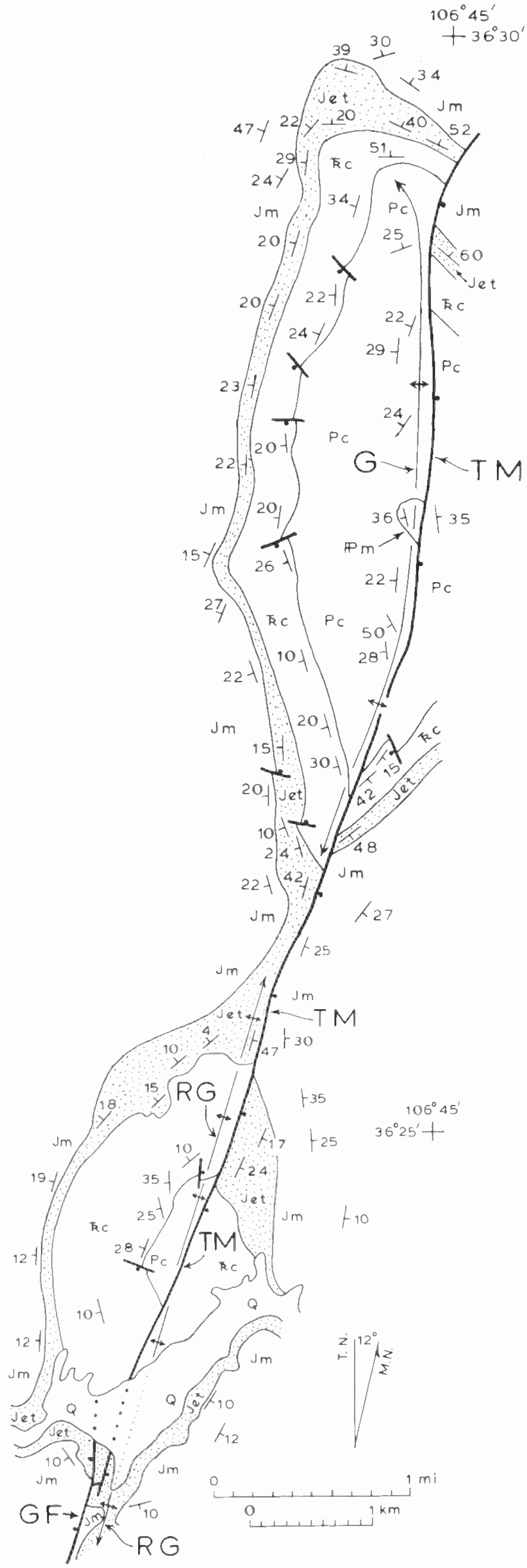


FIGURE 4. Geologic map of Gallina and Rio Gallina anticlines and Tierra Montañosa fault (modified from Hultgren, 1986). ₽m = Pennsylvanian Madera Formation; Pc = Permian Cutler Formation; ₸c = Triassic Chinle Formation; Jet = Jurassic Entrada and Todilto Formations; Jm = Jurassic Morrison Formation; G = Gallina anticline; GF = Gallina fault; RG = Rio Gallina anticline; TM = Tierra Montañosa fault. Ball on downthrown side of fault.

Clinton, 1960). Baltz (1967) presented stratigraphic evidence that these folds formed in late Paleocene and Eocene time, with possible initiation in the Late Cretaceous. Distributed shearing in the basement rocks probably occurred in a north-trending zone up to 5 km wide, judging from the lengths and orientations of the folds (Fig. 2). Baltz (1967, p. 70) assumed that the echelon folds formed in response to right slip on the Nacimiento fault alone, but this is unlikely because at the north end of the Nacimiento uplift the zone of echelon folds continues northward, whereas the Nacimiento and Gallina faults bend to the northeast (Baltz, 1967, plate 7). The echelon folds are refolded by a north-trending, locally overturned synclinal bend west of the Nacimiento fault. Kelley (1950) suggested that the Laramide deformation consisted mostly of folding, including development of a monocline on the east side of the San Juan Basin, and that the Nacimiento fault formed later in the Tertiary when the Rio Grande rift developed. Initiation of the main episode of rise of the Nacimiento uplift is marked by a major unconformity between the Nacimiento Formation (Paleocene) and the San Jose Formation (early Eocene). Presence of the Pedernal chert member of the Abiquiu Formation (Miocene) on the highest part of the Nacimiento uplift supports the idea that some of the rise of the uplift occurred after deposition of the chert and therefore is post-Laramide.

The Pajarito and Nacimiento are principally steeply dipping reverse faults. Locally, the Nacimiento fault flattens at high structural and stratigraphic levels, probably as a result of its being unconstrained on the west and free to expand over the San Juan Basin. Also, the Nacimiento fault changes to a west-dipping normal fault at its north end where it bends to the northeast. Lack of piercing points along the Pajarito and Nacimiento faults precludes precise calculations of strike slip along these faults. The relatively short traces of these two unconnected faults suggests that the right-slip component of movement was minor.

The Gallina fault is nearly vertical and is characterized by variable stratigraphic separation (Fig. 3), supporting the interpretation by Baltz (1967) that the San Juan Basin was downbuckled and differentially folded relative to the Gallina-Archuleta arch to the east. Folds on the west side of the Gallina fault therefore appear to be coeval with faulting, and the axes of these folds cannot be used as piercing points correlative with fold axes on the east side of the fault. Adjacent to the Gallina and Tierra Montañosa faults, the fold axes are mostly about parallel to the faults, in contrast to the echelon pattern of folds west of the Nacimiento uplift (Fig. 2). This suggests that there was little or no right shift along the Gallina and Tierra Montañosa faults prior to their rupturing the sedimentary strata. The steep Tierra Montañosa fault underwent mainly dip-slip movement, having a maximum of about 550 m of stratigraphic separation with the east side downthrown, as indicated by the geometries of the Gallina and Rio Gallina anticlines (Fig. 4). Cordell and Keller (1984, p. 22) noted that it is difficult to accommodate much strike-slip offset to the north of the Nacimiento-Gallina fault system because continuous gravity anomalies and structural features trend northwesterly from the Rio Grande rift and cross the projected trend of the faults.

Also, there is no such structure as the San Pedro Mountain fault, which Baltz (1967) and Chapin and Cather (1981) described as a north-dipping normal fault bounding the north end of the Nacimiento uplift. They proposed that their San Pedro Mountain fault marked a transtensional zone due to a northeastward bend in the trend of the Nacimiento fault. In the absence of their nonexistent San Pedro Mountain fault it is not necessary to invoke a wrench fault-related origin for the termination of the north end of the Nacimiento uplift.

Thus, right shift of the Colorado Plateau with respect to the adjacent Rocky Mountain foreland in northern New Mexico decreases northward and dies out north of the Nacimiento uplift, and displacement on the Tierra Montañosa fault, the northernmost fault of the Nacimiento-Gallina system, is principally dip slip. Right shift probably does not exceed 2 km along the southern part of the Nacimiento-Gallina fault system. Detailed mapping and careful analysis of well-exposed structures in Mesozoic strata along the Rio Puerco fault zone, the southward extension of the Nacimiento-Gallina fault system (Fig. 2), by Slack and Campbell (1976) led them to calculate the total amount of right shift there as probably less than 2 km.

## ACKNOWLEDGMENTS

We thank J. Leroy Schutz, Michael S. Fulp, Stephen R. Maynard and Steven Ristorcelli for reviewing the manuscript. The New Mexico Bureau of Mines and Mineral Resources supported much of the geologic mapping that provides the basic data for this paper. Chevron Resources provided partial funding for Merrick, ARCO Oil and Gas Company and Getty Oil Company partially supported funding for Crouse, and Southern Union Exploration and Benson-Montin-Greer Drilling Company provided financial support for Hultgren. We thank these organizations for their generous support.

## REFERENCES

Baltz, E. H. Jr., 1967, Stratigraphy and regional tectonic implications of part of Upper Cretaceous and Tertiary rocks, east-central San Juan Basin, New Mexico: U.S. Geological Survey, Professional Paper 552, 101 p.

Chapin, C. E., 1983, An overview of Laramide wrench faulting in the southern Rocky Mountains with emphasis on petroleum exploration: Rocky Mountain Association of Geologists, Rocky Mountain Foreland Basins and Uplifts Guidebook, p. 169–179.

Chapin, C. E. and Cather, S. M., 1981, Eocene tectonics and sedimentation in the Colorado Plateau–Rocky Mountain area: Arizona Geological Society Digest, v. 14, p. 173–198.

Cordell, L. and Keller, G. R., 1984, Regional structural trends inferred from gravity and aeromagnetic data in the New Mexico–Colorado border region, New Mexico Geological Society, Guidebook 35, p. 21–23.

Crouse, D. L., 1985, Structure and stratigraphy of part of the French Mesa quadrangle, Rio Arriba County, New Mexico [M.S. thesis]: Albuquerque, University of New Mexico, 91 p.

Fitter, F. L., 1958, Stratigraphy and structure of the French Mesa area, Rio Arriba County, New Mexico [M.S. thesis]: Albuquerque, University of New Mexico, 66 p.

Hultgren, M. C., 1986, Tectonics and stratigraphy of part of the southern Gallina-Archuleta arch, French Mesa and Llaves quadrangles, Rio Arriba County, New Mexico [M.S. thesis]: Albuquerque, University of New Mexico, 123 p.

Hutson, O. C., 1958, Geology of the northern end of San Pedro Mountain, Rio Arriba and Sandoval Counties, New Mexico [M.S. thesis]: Albuquerque, University of New Mexico, 55 p.

Kelley, V. C., 1950, Tectonics of the San Juan Basin: New Mexico Geological Society, Guidebook 2, p. 124–131.

Kelley, V. C., 1954, Tectonic map of a part of the upper Rio Grande area, New Mexico: U.S. Geological Survey, Oil and Gas Investigations Map 157, scale 1:190,000.

Kelley, V. C., 1955, Regional tectonics of the Colorado Plateau and relationship to the origin and distribution of uranium: University of New Mexico Publications in Geology, no. 5, 120 p.

Kelley, V. C., 1967, Tectonics of the Zuni-Defiance region, New Mexico and Arizona: New Mexico Geological Society, Guidebook 18, p. 28–31.

Kelley, V. C. and Clinton, N. J., 1960, Fracture systems and tectonic elements of the Colorado Plateau: University of New Mexico Publications in Geology, no. 6, 104 p.

Landis, E. R. and Dane, C. H., 1967, Geologic map of the Tierra Amarilla quadrangle, Rio Arriba County, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Geologic Map 19, scale 1:62,500.

Lisenbee, A. L., Woodward, L. A. and Connolly, J. R., 1979, Tijeras-Cañoncito fault system—a major zone of recurrent movement in north-central New Mexico: New Mexico Geological Society, Guidebook 30, p. 89–99.

Lookingbill, J. L., 1953, Stratigraphy and structure of the Gallina uplift, Rio Arriba County, New Mexico [M.S. thesis]: Albuquerque, University of New Mexico, 118 p.

Martinez, Ruben, 1974, Geology of the Pajarito Peak area, Sandoval County, New Mexico [M.S. thesis]: Albuquerque, University of New Mexico, 72 p.

Merrick, M. A. and Woodward, L. A., 1982, Geology of Regina quadrangle, Rio Arriba and Sandoval Counties, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Geologic Map 46, scale 1:24,000.

Renick, B. C., 1931, Geology and ground-water resources of western Sandoval County, New Mexico: U.S. Geological Survey, Water-Supply Paper 620, 117 p.

Slack, P. B. and Campbell, J. A., 1976, Structural geology of the Rio Puerco fault zone and its relationship to central New Mexico tectonics: New Mexico Geological Society, Special Publication No. 6, p. 46–52.

Wood, G. H. Jr. and Northrop, S. A., 1946, Geology of the Nacimiento Mountains, San Pedro Mountain, and adjacent plateaus in parts of Sandoval and Rio Arriba Counties, New Mexico: U.S. Geological Survey, Oil and Gas Investigation Preliminary Map 57, scale 1:95,040.

Woodward, L. A., 1987, Geology and mineral resources of Sierra Nacimiento and vicinity, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Memoir 42, 84 p.

Woodward, L. A. and Ruetschilling, R. L., 1976, Geology of San Ysidro quadrangle, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Geologic Map 37, scale 1:24,000.

Woodward, L. A., Kaufman, W. H. and Anderson, J. B., 1972, Nacimiento fault and related structures, northern New Mexico: Geological Society of America Bulletin, v. 83, p. 2383–2396.

Woodward, L. A., Anderson, J. B., Kaufman, W. H. and Reed, R. K., 1973, Geologic map and sections of San Pablo quadrangle, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Geologic Map 26, scale 1:24,000.

Woodward, L. A., Callender, J. F. and Zilinski, R. E., 1975, Tectonic map of the Rio Grande rift, New Mexico: Geological Society of America, Map and Chart Series #MC-11, scale 1:500,000.

Woodward, L. A., Gibson, G. G. and McLelland, D., 1976, Geology of Gallina quadrangle, Rio Arriba County, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Geologic Map 39, scale 1:24,000.