Tectonics of central-northern New Mexico

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TECTONICS OF CENTRAL-NORTHERN NEW MEXICO

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INTRODUCTION

Central-northern New Mexico is comprised of several diverse tectonic provinces. The San Juan Basin, Gallina-Archuleta arch, and Chama basin are parts of the Colorado Plateau, whereas the Brazos and Nacimiento uplifts (Fig. 1) are generally included with the Southern Rocky Mountains; these tectonic features attained their present structural outlines during the Laramide orogeny of Late Cretaceous and early Tertiary time. Superimposed on Laramide structures is the Rio Grande rift that began to form during the Miocene. Volcanism in the Jemez area began after initial development of the rift with immense volumes of extrusive rocks accumulating along the western margin of the rift contemporaneously with late stages of rifting. These volcanic rocks unconformably overlie the eastern part of the Nacimiento uplift and the southern Chama basin.

Major tectonic features here are dominated by vertical movements. Minor horizontal shift and compressional features occur in parts of the Colorado Plateau and Southern Rocky Mountains structures.

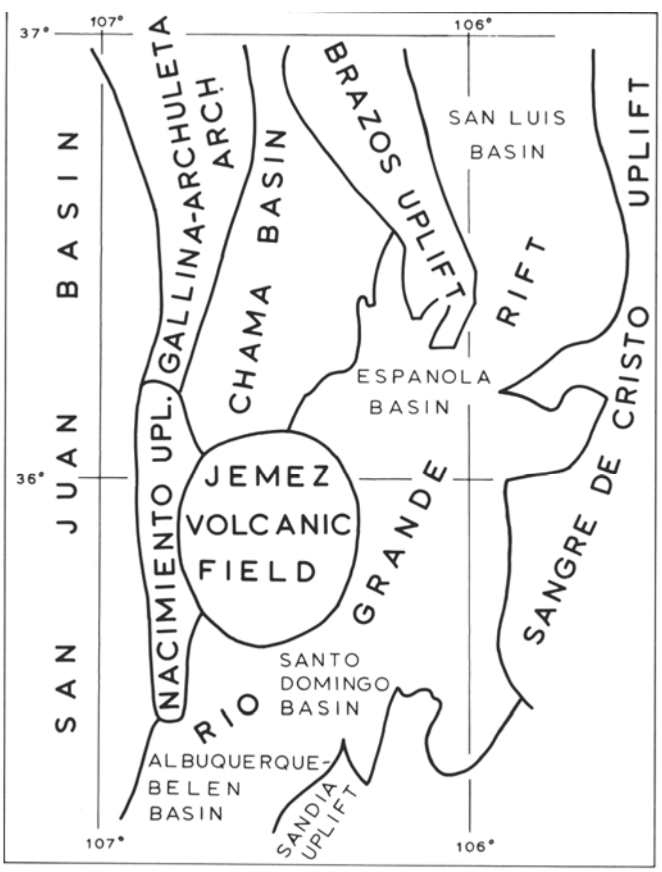

Figure 1. Index map showing major tectonic elements of central-northern New Mexico.

STRUCTURE

Descriptions of the structures of this region (Fig. 2) are based principally on maps by Dane (1948), Kelley (1954, 1955), Kelley and Clinton (1960), Smith and Muehlberger (1960), Smith, Budding, and Pitrat (1961), Lookingbill (1953), Fitter (1958), Muehlberger (1967, 1968), Smith, Bailey, and Ross (1970), Baltz (1967), and Woodward and others (1972b, 1973a, 1973b, 1973c, 1974a, 1974b, 1974c).

Eastern San Juan Basin

Only the eastern part of the San Juan Basin is shown in Figure 2; in its entirety it is nearly circular and about 100 miles in diameter (Kelley, 1957). It is strongly asymmetrical with a steep northern limb and gently dipping southern limb. The axial trace forms an arc that is convex northward and occurs near the northern edge of the basin. In the area of this report the axis trends northwesterly.

The eastern boundary of the San Juan Basin is marked by a monocline along the west side of the Gallina-Archuleta arch and by range-marginal upthrust and reverse faults on the west side of the Nacimiento uplift. A sharp synclinal bend that is locally overturned occurs west of the upthrust and reverse faults. There is at least 10,000 feet of structural relief between the highest part of the Nacimiento uplift and the adjacent part of the San Juan Basin. Structural relief between the basin and the Gallina-Archuleta arch is as much as 8,500 feet in the area shown on Figure 2.

Several northwest-plunging, en echelon, open folds and northeast-trending, high-angle faults of small displacement occur along the eastern margin of the San Juan Basin.

Nacimiento Uplift

The Nacimiento uplift trends north and is about 50 miles long and 6 to 10 miles wide. In general, it consists of an uplifted block that is tilted eastward and is bounded on the west by faults. There is at least 10,000 feet of structural relief between the highest part of the uplift and the adjacent San Juan Basin.

East of the range-marginal faults there is locally an anticlinal bend along the western margin of the uplift. The Nacimiento fault, an upthrust that is steep at depth but flattens upward and has westward movement of the hanging wall block over the San Juan Basin (Woodward and others, 1972a), bounds the northern part of the uplift. Farther south a reverse fault dipping steeply to the east bounds the west side of the uplift.

The northern end of the uplift is a broad, faulted anticline that plunges 10° to 20° northward and merges with the Gallina-Archuleta arch. The uplift terminates at the south with

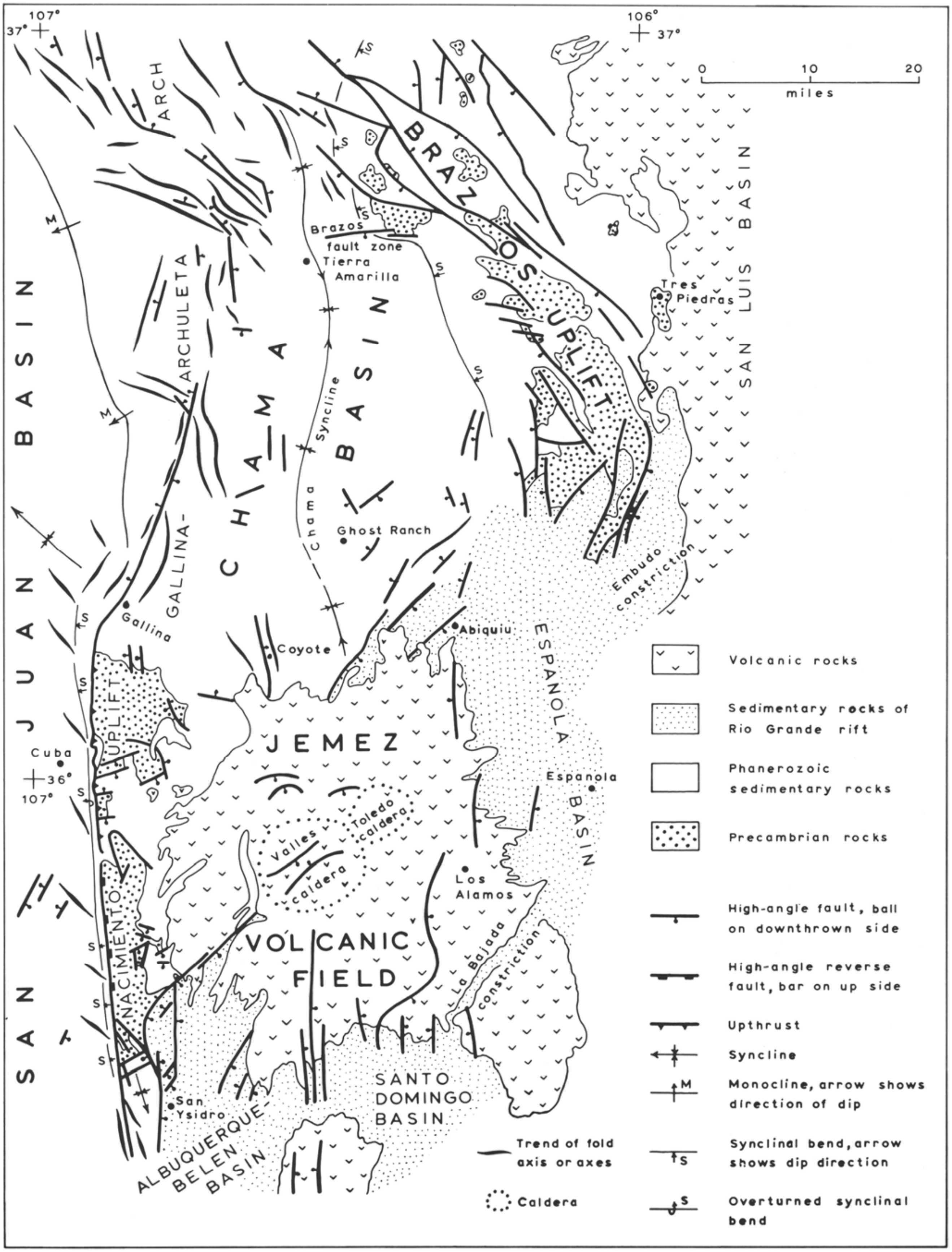

Figure 2. Generalized tectonic map of central-northern New Mexico. Volcanic rocks of the northern Brazos uplift and Chama basin are not shown. Sedimentary rocks of Rio Grande rift include preorogenic strata of Paleozoic and Mesozoic age in addition to synorogenic Cenozoic sediments.

folds that plunge to the south beneath an unconformable cover of Tertiary rocks (Slack, 1973).

Eastward dipping Paleozoic rocks on the east side of the uplift are unconformably covered by extrusive rocks of the Jemez volcanic field. The southeastern boundary of the uplift with the Rio Grande rift is defined by high-angle normal faults that are downthrown to the east; the major bounding fault appears to flatten at depth (DuChene, 1973). The northeastern part of the uplift merges with the Chama basin through a broad slope dipping gently to the northeast.

Structures within the uplift include north-trending normal faults that bound second-order, tilted fault-blocks at the north end of the uplift and a graben in the southern part of the uplift. There are also high-angle faults trending east-west, northwest, and northeast; these faults separate differentially uplifted segments within the Nacimiento uplift. A few northwest-trending folds are seen near the south end of the uplift (Reutschilling, 1973). It is possible that folds with similar trends were present elsewhere in the uplift, but stripping of sedimentary strata from most of the uplift has removed any evidence of them.

Gallina-Archuleta Arch

The Gallina-Archuleta arch separates the relatively deep San Juan Basin from the shallower Chama basin. There is at least 8,500 feet of maximum structural relief between the arch and the adjacent part of the San Juan Basin whereas the Chama basin is about 1,500 feet structurally lower than the arch.

In general, the Gallina-Archuleta arch is a north-trending, arcuate anticlinorium that is slightly convex eastward. Previously, the southern part of the arch has been called the French Mesa and Gallina uplifts (Kelley and Clinton, 1960); however, together they are only about 24 miles in length and up to 8 miles wide, and they merge with the Archuleta arch to the north. Thus, they are described as a single tectonic feature in this report.

On the west the arch is bounded by a monocline that dips steeply westward at its southern end, but dips more gently as it is traced northward. The southern part of the arch merges with the shallow Chama basin through a broad, gently dipping slope to the northeast. The eastern margin of the northern part of the arch is arbitrarily placed along the western limb of the Chama syncline.

The southern part of the arch trends north-northeasterly and contains a longitudinal, high-angle fault near the crest and several longitudinal, doubly plunging anticlines.

In the northern part of the Gallina-Archuleta arch there are numerous longitudinal, high-angle faults. Stratigraphic separation on these faults is mostly less than 100 feet although a few may have about 1,000 feet (Dane, 1948). There are numerous open folds with trends parallel to the arch, with the principal exceptions being west-northwesterly trending fold axes west of the Brazos fault zone (Muehlberger, 1967).

Chama Basin

The Chama basin is intermediate in structural height between the San Juan Basin and the Brazos uplift. Also, the basin is shallow with respect to the Gallina-Archuleta arch and thus could be called a platform or structural terrace (Muehlberger, 1967). Structural relief between the deepest part of the Chama basin and the Gallina-Archuleta arch is about 1,500 feet whereas there is a minimum of 7,000 feet of structural relief between the basin and the highest part of the Brazos uplift. The Chama basin trends north and is about 60 miles long. Width of the basin ranges from about 20 miles at the south end to about 4 miles near Chama at the north.

The western boundary of the Chama basin with the Gallina-Archuleta arch and Nacimiento uplift has been described above. At the south end the basin is unconformably covered by extrusive rocks from the Jemez volcanic field. High-angle, northeast-trending faults, mostly downthrown to the east, separate the southeastern part of the Chama basin from the Rio Grande rift. The boundary between the Chama basin and the Brazos uplift is marked by a synclinal bend with locally vertical beds.

Within the basin the principal structure is the broad, open, north-trending Chama syncline. About 3 miles north of Tierra Amarilla, the east-west-trending Brazos fault zone (Muehlberger, 1967, p. 56) crosses the Chama basin. Fold axes are sigmoidally bent as they approach the fault zone. Westward projection of the trend of the fault zone into the Gallina-Archu leta arch encounters west-northwest-trending axial traces, suggesting left shift along the zone and its westward projection. Elsewhere in the Chama basin there are high-angle faults trending north, northeast, and northwest, and having small displacements.

Brazos Uplift

The Brazos uplift trends northwesterly and extends into Colorado. That part of the uplift in New Mexico is about 50 miles long and up to 25 miles wide.

On the west the uplift is bounded by the synclinal bend of the eastern Chama basin. The southern and southeastern edges of the uplift are irregular and serrate in outline because of northeast- and northwest-trending faults that have created horsts of Precambrian rock and intervening grabens of Tertiary strata of the Rio Grande rift. The eastern margin of the uplift is covered by volcanic rock, but, presumably, high-angle faults separate the uplift from the Rio Grande rift near the edge of the volcanics. There is probably about 12,000 feet of structural relief between the uplift and the adjacent part of the rift (Shaffer, 1970).

The core of the uplift consists of Precambrian rocks overlain by a thin veneer of Tertiary volcanic and continental clastic rocks. Dominant structures within the uplift are northwest-trending faults, some of which were downthrown to the east during Laramide time and were later downthrown to the west during the late Tertiary (Muehlberger, 1960). Stratigraphic separation is mostly a few hundred feet on these faults, but may be as much as 1,600 feet (Muehlberger, 1960). Faults trending north and northeast are also present, but tend to be less numerous and have shorter traces than those trending northwest. Late Tertiary eastward tilting of the uplift has imparted dips of 3° to 5° to Tertiary sediments (Bingler, 1968).

Rio Grande Rift

The Rio Grande rift is comprised of a series of north-trending grabens that are arranged en echelon north-northeasterly in New Mexico and Colorado for a distance of at least 450 miles (Kelley, 1952) and perhaps 600 miles (Chapin, 1971a). Antithetic and synthetic faults occur within the major grabens, forming step faults as well as second-order grabens and horsts. The major grabens are usually referred to as basins; they are described from north to south.

The San Luis basin is about 150 miles long and up to 55 miles wide. The southern part of the basin, within New Mexico, is nearly 50 miles long. There is probably about 12,000 feet of structural relief between this part of the basin and the Brazos uplift to the west. In addition to sediments of late Cenozoic age, there are volcanic rocks within the basin.

The Espanola basin, 40 to 50 miles long and 18 to 40 miles wide, is connected with the San Luis basin by the Embudo constriction. To the west, near Abiquiu, the Espanola basin is bounded by high-angle faults that are mostly downthrown to the east. These faults disappear beneath extrusive rocks of the Jemez volcanic field about 5 miles southeast of Coyote. To the south the western margin of the rift is covered by volcanic rocks to the vicinity of Battleship Rock along Jemez Creek. High-angle faults offset the volcanics at many localities, indicating continued graben development during and after volcanism.

The Santo Domingo basin and Albuquerque-Belen basin (Kelley, 1952) are considered as one tectonic feature in this report inasmuch as the boundary between them is poorly defined in the area considered here. This feature is called the Albuquerque basin, and, as defined here, is about 90 miles long and 30 miles wide. Extrusive rocks of the Jemez field cover the north end of the Albuquerque basin; however, the volcanic rocks are offset by some of the faults defining the graben. Several normal faults which dip east and have a maximum of 2,250 feet of stratigraphic separation mark the western margin of the basin with the Nacimiento uplift. The depth to Precambrian rocks in the Albuquerque basin may be greater than 10,000 feet below sea level (Joesting and others, 1961), giving a structural relief of over 19,000 feet between the southern part of the Nacimiento uplift and the Rio Grande rift.

Jemez Volcanic Field

The Jemez volcanic field straddles the western margin of the Rio Grande rift and consists of a thick pile of Pliocene and Quaternary extrusive rocks. Present elevation of the Jemez Mountains is due to accumulation of volcanic rocks rather than to structural uplift. Rocks of the Jemez field unconformably overlie rocks of the Nacimiento uplift to the west and the Chama basin to the north. To the south, east, and northeast the sediments filling the Rio Grande rift are unconformably overlain by the Jemez volcanics.

Volcanism began after initial development of the Rio Grande rift and continued contemporaneously with later stages of rifting. Early eruptions of basalt were followed by extrusion of andesite, dacite, quartz latite, rhyolite, and rhyolitic ash flows (Ross and others, 1961).

Major structures within the Jemez field are the Toledo and Valles calderas (Smith and others, 1970) which formed by collapse after extrusion of tremendous volumes of Bandelier Tuff (Ross and others, 1961). Within the Valles caldera is a resurgent dome, Redondo Peak, that has about 3,000 feet of structural relief and is cut by a northeast-trending graben. High-angle faults in the southern and eastern parts of the Jemez field that are related to rifting were active during and after volcanism, resulting in eastward thickening of the volcanic pile (Ross and others, 1961).

PALEOTECTON IC SETTING

From Cambrian through Devonian time this region was stable, being located on the south flank of the Transcontinental arch, a mildly positive feature. There are no lower Paleozoic rocks in this region. The Mississippian was a time of quiescence also when a thin sequence of shelf carbonates accumulated (Armstrong, 1967).

High-angle faulting and epeirogenic uplift resulted in removal of most of the Mississippian strata prior to deposition of Pennsylvanian rocks. During Pennsylvanian time the approximate sites of the Brazos and Nacimiento uplifts were positive areas shedding elastic debris into adjacent areas. These positive tendencies continued into Permian time.

Mesozoic strata were deposited throughout the region except for the Brazos area which underwent several episodes of uplift (Muehlberger, 1967). Epeirogenic uplift resulted in regional unconformities between the Permian and Triassic and between the Jurassic and Cretaceous strata.

Structural development of the present-day Brazos and Nacimiento uplifts was initiated during the Laramide orogeny; further uplift of these areas occurred during the late Tertiary. Thus, the present tectonic features shown on Figure 2 are principally of Cenozoic age.

Preorogenic rocks range in age from Precambrian to early Tertiary, whereas the San Jose Formation (Eocene) of the San Juan Basin is synorogenic with respect to Laramide deformation. The crystalline Precambrian basement rocks are brittle and tend to deform by fracturing; overlying sedimentary strata are mostly flexible and the thick sequence of shale of Mesozoic age tends to behave plastically.

Late Cenozoic sediments (Santa Fe Group) and volcanic rocks that fill the Rio Grande depression are synorogenic with respect to rifting. Preorogenic rocks of Precambrian to mid-Cenozoic age have fractured under the tensional stress field associated with rifting.

TECTONIC EVOLUTION

Two principal episodes of deformation are evident in this region, the Laramide orogeny of Late Cretaceous and early Tertiary age, and development of the Rio Grande rift during late Cenozoic time. Some of the Laramide structures were rejuvenated or further developed during the time of rifting.

The San Juan Basin, Gallina-Archuleta arch, Chama basin, Brazos uplift, and Nacimiento uplift attained their present structural outlines during Laramide time. The Colorado Plateau structural block was pushed toward the northeast as a result of east-west compression in the Nevada and Utah segment of the Cordilleran foldbelt and nearly north-south compression in the foldbelt in New Mexico and Arizona (Fig. 3).

Northeastward yielding of the Colorado Plateau structural block resulted in right shift on the eastern margin of the plateau, forming the northwest-trending, en echelon folds on the east side of the San Juan Basin (Fig. 2). The Brazos fault zone probably represents a conjugate shear having left-lateral movement during this time (Fig. 4). This fault zone may be localized because of anisotropy in the Precambrian basement (Muehlberger, 1967).

Laramide deformation continued with development of monoclines bounding the west sides of the Nacimiento and Brazos uplifts, and with formation of the San Juan and Chama

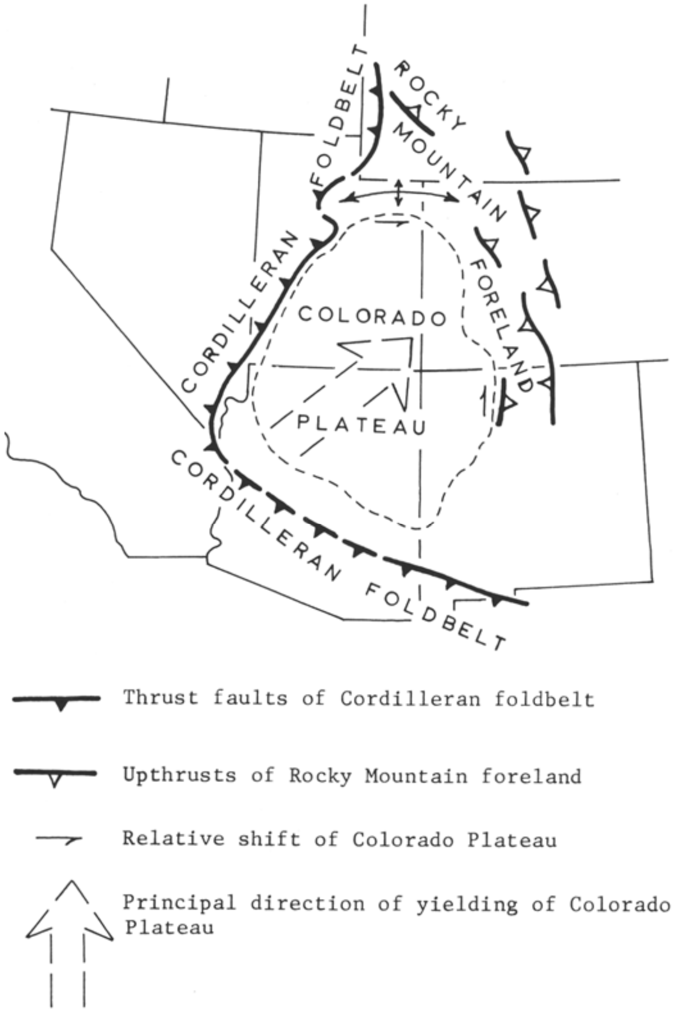

Figure 3. Regional tectonic sketch map showing Cordilleran foldbelt, Colorado Plateau, and Rocky Mountain foreland.

basins and the intervening Gallina-Archuleta arch. Northwest-trending faults in the Brazos uplift and the longitudinal faults and folds in the Gallina-Archuleta arch probably formed during this episode of deformation.

Thus, the dominant Laramide movements were vertical, although it is likely that the crystalline crust was undergoing horizontal compression in response to westward drift of the North American plate over an eastward-dipping subduction zone, or possibly imbricate subduction zones (Lipman and others, 1972), along the eastern edge of the oceanic Farallon plate (Atwater, 1970). Lateral movement of large amounts of sialic crustal material by metamorphic flowage from the west to beneath the Colorado Plateau (Gilluly, 1963, 1973) and the Southern Rocky Mountains may have occurred during this time. This may account for the fact that the sialic crust beneath the Colorado Plateau and Southern Rockies is now much thicker than beneath the Basin and Range province to the west (Pakiser, 1963; Jackson and Pakiser, 1965).

With the data that are currently available it is not possible to definitively state the forces that were responsible for the vertical movements that formed the Laramide basins and uplifts. Among the possibilities to be considered are: 1) horizontal compression in the deeper part of thick, competent crystalline crust with secondary vertical stress fields near the surface; 2) injection of thick sills or laccoliths in the deep crust beneath uplifts with their resultant rise; 3) mineralogical phase changes in the upper mantle or lower crust with volume increase or decrease to bring about subsidence of basins and (or) rise of uplifts.

I favor the last hypothesis involving phase changes triggered by changes in the horizontal stress field for the following reasons.

Horizontal compression alone seems unable to bring about the Laramide vertical movements that are dominated by basin subsidence; relative to sea level, the structural relief of Laramide time was created mainly by basin subsidence rather than rise of the uplifts. Because of the room problem, crustal compression alone should result in upward yielding (rise of uplifts) rather than depression of basins. Also, circular and elliptical basins seem incompatible with the linear structures commonly associated with horizontal compression.

Hydraulic lifting by sills or laccoliths in the deep crust seems unlikely because of the lack of intrusive and volcanic rocks associated with rise of many uplifts, including the Nacimiento. Also, the problem appears to require basin subsidence, not rise of uplifts.

Thus, the geometry and kinematics of basin development seem to require deep crustal or upper mantle volume changes that can best be explained by phase changes. It is also clear that minor horizontal shift and compression occurred during the Laramide. Therefore, a causal relation between crustal stress and phase changes is suggested.

When the subduction zone in the mantle beneath the Southern Rocky Mountains and Colorado Plateau was dissipated after overriding of the East Pacific rise, the thick sialic crust that had been formed by lateral transfer from the west was free to rise isostatically. Thus, the Cenozoic epeirogenic uplift of this region was probably an isostatic adjustment of the thick sialic crust that was derived during the compressional deformation of the Laramide orogeny.

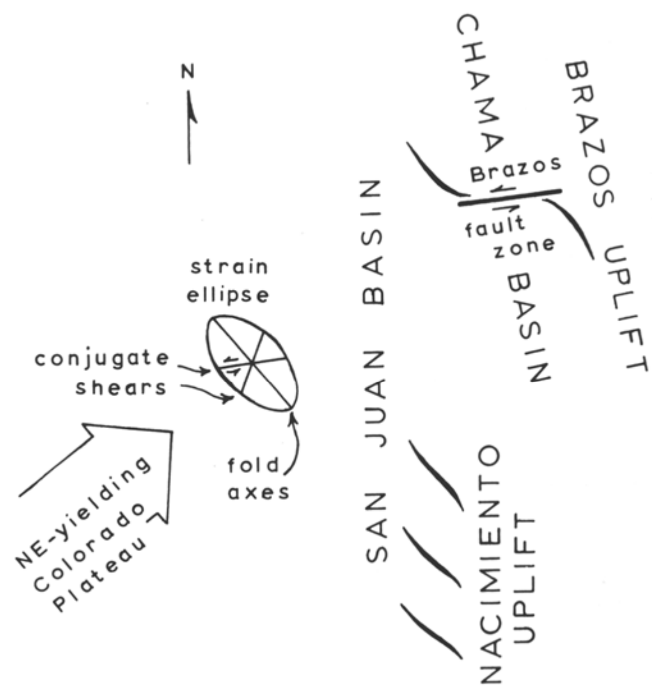

Figure 4. Early Laramide stress field, strain ellipse, and resultant structures.

The Rio Grande rift is a late Cenozoic tensional feature (Chapin, 1971b) that has been superimposed on the Laramide structures, apparently truncating the southeast end of the Brazos uplift. Both the Brazos and Nacimiento uplifts underwent additional development during rifting, with Laramide faults in the Brazos uplift being renewed and high-angle reverse and upthrust faults forming on the west side of the Nacimiento uplift. Stratigraphic and radiometric data indicate that the Rio Grande rift was initiated during the Miocene (Chapin, 1971a).

An area of high heat flow and an associated upward bulge of the mantle beneath the rift have been proposed by Lipman (1969) on the basis of tholeiitic basalts that occur within the rift and partly contemporaneous alkalic basalts that are present in adjacent areas. A subsequent heat flow study by Reiter and others (1973) suggests that the rift is associated with a regional geothermal high. Chapin (1971b) suggested that the crust west of the rift is drifting westward faster than the crust that is east of the rift, thus creating a tensional zone above the mantle bulge.

The vertical movement and associated minor element of compression seen on the west side of the Nacimiento uplift may be caused by westward and upward pushing of the proposed mantle bulge. Thus, the tension in the rift and contemporaneous uplift and minor compression to the west may be the manifestations of the same driving mechanism.

Eruptive centers of the Jemez volcanic field are above the projected border faults of the Rio Grande rift, suggesting that the faults served as deep conduits for the volcanics. Volcanism began after deposition of the lower part of the sedimentary fill in the rift (Ross and others, 1961, p. 142) and continued synchronously with rifting, resulting in thickening of the volcanic pile toward the east. Catastrophic eruptions of large quantities of ash flows in the Quaternary caused collapse to form the Toledo and Valles calderas.

In summary, the following model for the tectonic evolution of this region is proposed:

1. Northeast shift of the Colorado Plateau structural block occurred as the North American plate drifted westward over an eastward-dipping subduction zone in Laramide time. Immediately following and perhaps contemporaneously with the lateral shift, vertical movements caused monoclines to form on the east side of the plateau as a result of lower crust or upper mantle phase changes related to the compressional stress field. Arches and basins within the plateau also formed at this time. Lateral eastward transfer of sialic crust occurred through metamorphic flowage as the subduction zones were overridden.

2. Epeirogenic uplift of the region in Cenozoic time was a result of isostatic rise of the thickened sialic crust after dissipation of the overridden subduction zone.

3. The Rio Grande lift was initiated in late Cenozoic time. Westward and upward push of a proposed mantle bulge beneath the rift renewed development of the Brazos and Nacimiento uplifts. Thus, the uplifts on the east side of the Colorado Plateau are only partly related to the forces that created the internal structures within the plateau; final development of the uplifts is directly related to the evolution of the Rio Grande rift.

REFERENCES

Armstrong, A. K., 1967, Biostratigraphy and carbonate facies of the Mississippian Arroyo Penasco Formation, north-central New Mexico: New Mex. Bur. Mines and Min. Res. Mem. 20, 80 p.

Atwater, Tanya, 1970, Implications of plate tectonics for the Cenozoic tectonic evolution of western North America: Geol. Soc. America Bull., v. 81, p. 3513-3536.

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

Bingler, E. C., 1968, Geology and mineral resources of Rio Arriba County, New Mexico: New Mex. Bur. Mines and Min. Res. Bull. 91, 158 p.

Budding, A. J., C. W. Pitrat, and C. T. Smith, 1960, Geology of the south-eastern part of the Chama basin: New Mex. Geol. Soc. 11th Field Conf., Guidebook of Rio Chama Country, p. 78-92.

Chapin, C. E., 1971a, The Rio Grande rift, part I: modifications and additions: New Mex. Geol. Soc. 22nd Field Conf., San Luis basin, p. 191-201.

– 1971b, A symmetry of the Rio Grande rift: tectonic implications: Geol. Soc. America Abstracts with Programs, v. 3, no. 7, p. 765-767.

Dane, C. H., 1948, Geologic map of part of eastern San Juan Basin, Rio Arriba County, New Mexico: U.S. Geol. Survey Oil and Gas Invest. Prelim. Map. 78.

DuChene, H. R., 1973, Structure and stratigraphy of Guadalupe Box and vicinity, Sandoval County, New Mexico: unpub. M.S. thesis, Univ. New Mex., 100 p.

Gilluly, James, 1963, The tectonic evolution of the western United States: Quart. Jour. Geol. Soc. London, v. 119, p. 133-174.

----, 1973, Steady plate motion and episodic orogeny and magmatism: Geol. Soc. America Bull., v.84, p. 499-514.

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

Jackson, W. H., and L. C. Pakiser, 1965, Seismic study of crustal structure in the Southern Rocky Mountains: U.S. Geol. Survey Prof. Paper 525-D, p. D85-D92.

Joesting, H. R., Case, J. E., and Cordell, L. E.,1961, The Rio Grande trough near Albuquerque, New Mexico: New Mex. Geol. Soc. 12th Field Conf., Albuquerque Country, p. 148-150.

Kelley, V. C., 1952, Tectonics of the Rio Grande depression of central New Mexico: New Mex. Geol. Soc. 3rd Field Conf., Rio Grande Country, p. 93-105.

----, 1954, Tectonic map of a part of the upper Rio Grande area, New Mexico: U.S. Geol. Survey Oil and Gas Invest. Map 0M-157.

----, 1955, Regional tectonics of the Colorado Plateau and relationship to the origin and distribution of uranium: Univ. New Mex. Pub. Geol., no. 5, 120 p.

----, 1956, Tectonics of the Colorado Plateau: Geological Record of Rocky Mtn. Sec. of Am. Assoc. Petroleum Geologists, p. 99-108.

----, 1957, Tectonics of the San Juan Basin and surrounding areas: Four Corners Geol. Soc. 2nd Field Conf. Guidebook, p. 44-52.

Kelley, V. C., and Clinton, N. J., 1960, Fracture systems and tectonic elements of the Colorado Plateau: Univ. New Mex. Pub. Geol., no. 6, 104 p.

Lipman, P. W., 1969, Alkalic and tholeiitic basaltic volcanism related to the Rio Grande depression, southern Colorado and northern New Mexico: Geol. Soc. America Bull., v.80, p. 1343-1354.

Lipman, P. W., Prostka, H. J., and Christiansen, R. L., 1972, Cenozoic volcanism and plate-tectonic evolution of the western United States. 1. Early and middle Cenozoic: Phil. Trans. Roy. Soc. London, v. 271, p. 217-248.

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

Muehlberger, W. R., 1960, Structure of the central Chama platform, northern Rio Arriba County, New Mexico: New Mex. Geol. Soc. 11th Field Conf., Guidebook of Rio Chama Country, p. 103-109.

----, 1967, Geology of Chama quadrangle, New Mexico: New Mex. Bur. Mines and Min. Res. Bull. 89, 114 p.

Pakiser, L. C., 1963, Structure of the crust and upper mantle in the western United States: Jour. Geophys. Res., v. 68, p. 5747-5756.

Reiter, M. E., Edwards, C. L., and Weidman, Charles, 1973, Heat flow studies in New Mexico and neighboring areas of the southwestern United States: Geol. Soc. America Abstracts with Programs, v. 5, no. 7, p. 779.

Ross, C. S., Smith, R. L., and Bailey, R. A., 1961, Outline of the geology of the Jemez Mountains, New Mexico: New Mex. Geol. Soc. 12th Field Conf., Guidebook of Albuquerque Country, p. 139-143.

Ruetschilling, R. L., 1973, Structure and stratigraphy of the San Ysidro quadrangle, Sandoval County, New Mexico: unpub. M.S. thesis, Univ. New Mexico, 79 p.

Shaffer, W. L., 1970, Tectonics of the Rio Grande depression, New Mexico: unpub. open-file report, Univ. New Mex., 18 p.

Slack, P. B., 1973, Structural geology of the northeast part of the Rio Puerco fault zone, Sandoval County, New Mexico: unpub. M.S. thesis, Univ. New Mexico, 74 p.

Smith, C. T., Budding, A. J., and Pitrat, C. W., 1961, Geology of the southeastern part of the Chama basin: New Mex. Bur. Mines and Min. Res. Bull. 75,57 p.

Smith, C. T., and Muehlberger, W. R., 1960, Geologic map of the Rio Chama country: New Mex. Geol. Soc. 11th Field Conf., Guidebook of Rio Chama Country, in pocket.

Smith, R. L., Bailey, R. A., and Ross, C. S., 1970, Geologic map of the Jemez Mountains, New Mexico: U.S. Geol. Survey Misc. Geol. Inv. Map 1-571.

Wood, G. H., Kelley, V. C., and McAlpin, A. J., 1948, Geology of southern part of Archuleta County, Colorado: U.S. Geol. Survey Oil and Gas Invest. Prelim. Map 81,

Woodward, L. A., Kaufman, W. H., and Anderson, J. B., 1972a, Nacimiento fault and related structures, northern New Mexico: Geol. Soc. America Bull., v. 83, p. 2383-2396.

Woodward, L. A., Anderson, J. B., McLelland, D. H., and Kaufman, W. H., 1972b, Geologic map and section of the Cuba quadrangle, New Mexico: New Mex. Bur. Mines and Min. Res. Geol. Map 25.

Woodward, L. A., Kaufman, W. H., Anderson, J. B., and Reed, R. K., 1973a, Geologic map and sections of the San Pablo quadrangle, New Mexico: New Mex. Bur. Mines and Min. Res. Geol. Map 26.

Woodward, L. A., Kaufman, W. H., and Reed, R. K., 1973b, Geologic map and section of the Rancho del Chaparral quadrangle, New Mexico: New Mex. Bur. Mines and Min. Res. Geol. Map 27.

Woodward, L. A., and Schumacher, O. L., 1973c, Geologic map and sections of La Ventana quadrangle, New Mexico: New Mex. Bur. Mines and Min. Res. Geol. Map 28.

Woodward, L. A., and Martinez, Ruben, 1974a, Geologic map and sections of the Holy Ghost Spring quadrangle, New Mexico: New Mex. Bur. Mines and Min. Res. Geol. Map (in press).

Woodward, L. A., McLelland, D. H., and Kaufman, W. H., 1974b, Geologic map and sections of the Nacimiento Peak quadrangle, New Mexico: New Mex. Bur. Mines and Min. Res. Geol. Map (in press).

Woodward, L. A., and DuChene, H. R., 1974c, Geologic map and sections of the San Miguel Mountain quadrangle, New Mexico: New Mex. Bur. Mines and Min. Res. Geol. Map (in press).