Phanerozoic tectonic setting of Santa Fe country

Lee A. Woodward and R. V. Ingersoll

1979, pp. 51-57. https://doi.org/10.56577/FFC-30.51

in:

Santa Fe Country, Ingersoll, R. V. ; Woodward, L. A.; James, H. L.; [eds.], New Mexico Geological Society 30 th Annual Fall Field Conference Guidebook, 310 p. https://doi.org/10.56577/FFC-30

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

PHANEROZOIC TECTONIC SETTING OF SANTA FE COUNTRY

LEE A. WOODWARD and RAYMOND V. INGERSOLL
Department of Geology
University of New Mexico
Albuquerque, New Mexico 87131

INTRODUCTION

In the area of this field conference, there have been four main periods of Phanerozoic tectonic activity: late Paleozoic, Laramide (Late Cretaceous-early Tertiary), mid-Tertiary and late Cenozoic. Only the latter three have associated structures expressed in the present physiography of the region. Precambrian tectonics are not considered here.

From Cambrian through Devonian time, this region was stable, being located on the south flank of the transcontinental arch, a mildly positive feature (e.g., Lochman-Balk, 1972). There are no lower Paleozoic rocks in this region. The Mississippian was a time of quiescence also, during which a thin sequence of shelf carbonates accumulated (Armstrong, 1967; Armstrong and Mamet, this guidebook). High-angle faulting and epeirogenic uplift resulted in removal of most of the Mississippian strata prior to deposition of Pennsylvanian rocks.

During late Paleozoic time, the San Luis uplift, part of the larger Uncompahgre uplift (Baltz, 1965), developed near the site of the present Brazos uplift, and the smaller Pefiasco axis (Read and Wood, 1947) developed along the present Nacimiento uplift to the west of the Jemez region; these positive areas shed clastic debris into adjacent basins (e.g., Casey and Scott, this guidebook). The area of the southern Sangre de Cristo uplift was a major basin (Rowe-Mora basin of Read and Wood, 1947) that was to the east of the contemporaneous San Luis uplift. DuChene and others (1977) suggested that shelf deposition of Lower Pennsylvanian sediments on the southern and western sides of the San Luis uplift (Uncompahgre highland) occurred in most of the area southwest of Santa Fe.

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 Permian and Triassic strata, and between Jurassic and Cretaceous strata.

The Brazos and Sangre de Cristo uplifts, and the Raton and Chama basins attained their present structural outlines during Laramide time. The Hagan embayment area was low at this time, as indicated by the presence of the Galisteo Formation of Eocene age (Gorham and Ingersoll, this guidebook). Numerous sills, dikes and laccoliths were emplaced in the northerly trending Ortiz porphyry belt during middle Tertiary time. These igneous bodies are mostly porphyritic laccoliths, and from north to south, comprise the Cerrillos, Ortiz, San Pedro and South Mountain igneous centers.

Late Cenozoic epeirogenic rise of the entire region may have been contemporaneous with development of the Rio Grande rift, an event that is Miocene to Holocene in age. During the later stages of rifting (Pliocene and Quaternary), volcanism occurred along the western margin of the rift to form the Jemez volcanic field. Related flows formed the extensive Cerros del Rio volcanic field southeast of the Jemez area.

All of these complex tectonic events may be understood more completely when viewed in the regional context of plate-tectonic interactions that occurred along both the Pacific and Gulf of Mexico margins through the Phanerozoic. Timing of tectonic events along plate margins closely corresponds with the above-described events although distances to Santa Fe country are large. Thus, tectonic events of global significance can be related to local manifestations.

ROCK UNITS

The basement in Santa Fe country is Precambrian igneous, metasedimentary and metaigneous rocks that have deformed by fracturing; these rocks are exposed in the Sangre de Cristo, Brazos and Sandia uplifts, and in the Monte Largo horst east of the Sandia uplift (fig. 1).

Rocks that are preorogenic with respect to Laramide deformation also include Paleozoic and Mesozoic strata (e.g., Ingersoll and Kelley, this guidebook). Paleozoic limestone and sandstone units are more ductile than the Precambrian rocks, but more competent than the thick mudstone intervals of the Mesozoic. Cretaceous mudstone, in particular, tends to deform plastically.

Synorogenic rocks of Laramide age are represented by the Galisteo Formation and correlative strata (Eocene) to the southwest and west of the Sangre de Cristo uplift (Baltz, 1978; Gorham and Ingersoll, this guidebook). Other synorogenic rocks are present on the east side of the Sangre de Cristo uplift (Woodward and Snyder, 1976), but are outside the area of this field conference.

Volcanic and volcaniclastic rocks (mostly Oligocene and lower Miocene) of the Espinaso, Abiquiu, Zia Sand and Los Pinos formations were deposited in broad, shallow basins that predate formation of the Rio Grande rift proper. Upper Cenozoic sediments of the Santa Fe Group and volcanic rocks that fill the Rio Grande rift or straddle its western margin are contemporaneous with rifting. Rocks older than rifting, Precambrian to mid-Cenozoic, have fractured under the tensional stress field associated with rifting.

LARAMIDE TECTONICS

Sangre de Cristo Uplift

The Sangre de Cristo uplift is one of the largest positive elements of the Rocky Mountain foreland, as it is nearly 320 km long with an arcuate northerly trend, and is up to 30 km wide. The western margin of the uplift is the eastern edge of the late Cenozoic Rio Grande rift; locally, this contact is marked by normal faults, but elsewhere sedimentary fill of the rift is unconformable on Precambrian basement rocks of the uplift (Kelley, 1978). It is likely that the western margin of the uplift in Laramide time was west of the present margin, as the rift structures are superimposed on the older uplift. The eastern margin of the uplift is characterized by reverse faults (Baltz, 1972; Goodknight, 1973; Prucha and others, 1965; Schowalter, 1968). There are at least 4,725 m of structural relief between the highest part of the southern Sangre de Cristo uplift and the deepest part of the Raton basin just north of Las Vegas. Based on calculations of depth to Precambrian

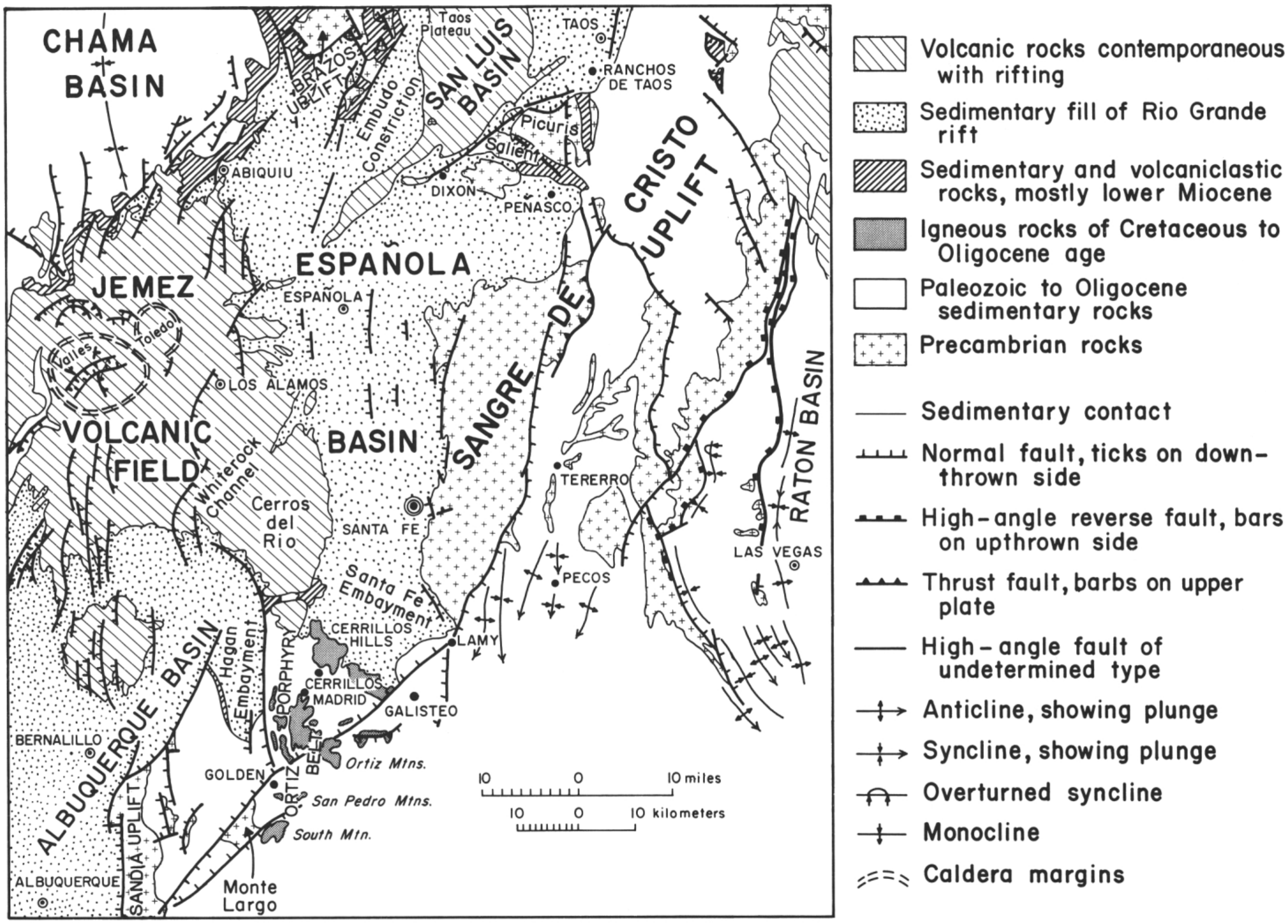

Figure 1. Generalized tectonic map of Santa Fe country.

basement using gravity data for the Rio Grande rift near Española (Cordell, 1976, this guidebook), there are probably about 4,570 m of structural relief on the west side of the uplift.

In the southern part of the uplift, there are several major north-northeast-trending faults that juxtapose Precambrian rocks with sedimentary cover, mostly Pennsylvanian strata. The Picuris salient of the uplift consists of Precambrian rock that juts westward into the Espahola basin of the Rio Grande rift. At the south end, the uplift dies out with gentle, south- and southeast-plunging, open, upright anticlines and synclines (fig. 1).

During the Eocene, a basin in the vicinity of Lamy and the Hagan embayment accumulated up to 1,300 m of terrestrial strata of the Galisteo Formation, probably in part derived from the adjacent Sangre de Cristo uplift as well as more westerly uplifts (Gorham and Ingersoll, this guidebook; Stearns, 1943, 1953). The Espinaso Formation was deposited in the same basin without any apparent break in deposition, and is presumed to be derived from nearby volcanic centers, accompanied by the formation of broad, north-plunging, faulted folds (Stearns, 1953). The original outline of the sedimentary basin is obscure, as the basin has been modified severely by younger events, including intrusion of the Ortiz and related igneous bodies, formation of the Rio Grande rift and Sandia uplift, and extensive late Cenozoic erosion.

Raton Basin

Bounding the east side of the Sangre de Cristo uplift, the Raton basin is about 300 km long and up to 100 km wide. The basin is strongly asymmetric, with a steep western limb and a gentle eastern limb. Only the westernmost part of the southern end of the basin, the Las Vegas sub-basin, is shown on Figure 1. Cretaceous rocks are exposed in the central part of the basin near Las Vegas; to the north are extensive Cenozoic volcanics, mostly basaltic. The Raton basin was covered by the 1976 guidebook of the New Mexico Geological Society, and therefore, is not described further here.

Brazos Uplift

Only the south end of the Brazos uplift is shown on Figure 1. Overall, the uplift trends northwesterly and extends into Colorado; the part of the uplift in New Mexico is about 80 km long and up to 40 km 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 late Cenozoic, northeast- and northwest-trending faults that have created horsts of Precambrian rock and intervening graben of Tertiary strata of the Rio Grande rift. The eastern margin of the uplift is overlain unconformably by volcanics and sediments deposited contemporaneously with rifting. There are at least 2,130 m of structural relief between the highest part of the uplift and the deepest part of the Chama basin to the west; in the area shown on Figure 1, there are about 1,300 m of structural relief. Between the southern end of the uplift and the deepest part of the Espanola basin to the south, there are probably about 3,050 m of structural relief.

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 involved eastward downthrow during Laramide time and westward downthrow during the late Tertiary (Muehlberger, 1960). Stratigraphic separation may be as much as 500 m on some of these faults (Muehlberger, 1960). Faults trending south and northeast are also present, but tend to be less numerous and have shorter traces than those trending northwest. Late Cenozoic eastward tilting of the uplift imparted dips of 3° to 5° to Tertiary sediments (Bingler, 1968).

Chama Basin

The Chama basin trends north, is about 100 km long, and ranges from about 32 km wide at the south end to about 6 km at the north end. The boundary between the basin and the Brazos uplift is a synclinal bend with locally vertical beds. At the south end, the basin is covered unconformably by extrusive rocks of the Jemez volcanic field. High-angle, northeast-trending faults, that involved eastward downdropping, truncate the southeastern part of the basin and separate it from the Rio Grande rift.

Within the basin, the principal structure is the broad, open, north-trending Chama syncline. In the southern part of the basin, shown on Figure 1, there are high-angle, north- and northeast-trending faults with small displacements.

MID-TERTIARY TECTONICS

The structures of mid-Tertiary age that are expressed topographically are igneous centers, mostly laccolithic, of the Cerrillos, Ortiz, San Pedro and South Mountain areas. Bachman and Mehnert (1978) report K-Ar dates of 34.0 ± 2.2 m.y. for a latite sill on the west side of the Ortiz Mountains and 47.1 ± 3.2 m.y. for a latite intrusion in the Cerrillos Hills. These igneous rocks are intrusive into strata ranging in age from Pennsylvanian to Tertiary and have resulted in domes, presumably laccolithic. There is a general north or north-northeast trend to these intrusions. Kelley (1978) referred to these collectively as the Cerrillos uplift; however, the doming is localized around the intrusions and the overall geometry is too irregular to be an uplift in the ordinary sense. Therefore, we refer to them as the Ortiz porphyry belt.

LATE CENOZOIC TECTONICS

Rio Grande Rift

The Rio Grande rift is comprised of a series of north-trending graben (arranged en echelon north-northeasterly) occurring for a distance of at least 725 km in New Mexico and Colorado (Kelley, 1952). Antithetic and synthetic faults occur within the major graben, forming step faults as well as second-order graben and horsts. The major graben, usually referred to as basins, are described from north to south; those basins in the area covered by Figure 1 are discussed in more detail than the others.

The Upper Arkansas valley in Colorado is the northernmost graben of the Rio Grande rift (Chapin, 1971). This basin extends to the Continental Divide north of Leadville and is linked with the San Luis valley to the south by a structural constriction containing upper Cenozoic sediments. The basin is about 100 km long and narrows to a point at its north end where the graben dies out.

The San Luis basin is about 240 km long and up to 90 km wide. The northern part of the basin consists of a central, north-trending horst flanked by graben, with the greatest structural relief along the east side (Tweto, 1978). To the south, in New Mexico, the basin appears to be tilted mostly toward the east. In addition to upper Cenozoic sediments, extensive volcanic rocks of the Taos Plateau occur within the basin and extend into the northern Espanola basin. These volcanic rocks are 4.5 to 2.0 m.y. old and are mostly tholeiitic basalt, but they also include andesite, rhyodacite and rhyolite (Lipman and Mehnert, 1979). The San Luis basin merges with the Espanola basin to the south at the Embudo constriction, where there is an intragraben horst of Precambrian rock between the Picuris salient of the Sangre de Cristo uplift and the south end of the Brazos uplift (fig. 1) (Muehlberger, this guidebook).

The Espanola basin, 65 to 80 km long and 30 to 65 km wide, is tilted mainly to the west, where it is bounded by high-angle faults near Abiquiu. These faults are covered by extrusive rocks of the Jemez volcanic field to the south, but reappear on the south side of the volcanics along Jemez Creek. Kelley (1978) shows normal faults in addition to sedimentary contacts between Cenozoic basin fill and Precambrian rocks of the Sangre de Cristo uplift on the east side of the basin. The southeastern end of the basin is the Santa Fe embayment (Kelley, 1978), where the sediments filling the rift rest unconformably on Mesozoic and Paleogene rocks.

The Santo Domingo and Albuquerque-Belen basins (Kelley, 1952) are considered as one tectonic feature in the present report. This feature, about 145 km long and 48 km wide, hereafter is called the Albuquerque basin. The northern end of this basin is asymmetric, with the deepest part on the east side where the depth to Precambrian rocks may be approximately 5,500 m below sea level (Black and Hiss, 1974), giving maximum structural relief of approximately 8,500 m against the eastward-tilted Sandia uplift. The Hagan embayment, an eastward-tilted half-graben marking the northeastern edge of the Albuquerque basin and merging southward through a broad slope with the Sandia uplift, contains upper Cenozoic sediments deposited contemporaneously with rifting. Upper Cenozoic volcanics, mainly basaltic (Kelley and Kudo, 1978), occur within the Albuquerque basin. To the south of the area shown on Figure 1, the Albuquerque basin becomes more symmetrical, and in the vicinity of Socorro, may bifurcate (Woodward and others, 1978), with an arm extending toward the San Augustin Plains to the southwest and the main part continuing to the south.

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. Volcanics of the Jemez field unconformably overlie rocks of the Nacimiento uplift to the west, the Chama basin to the north, and to the south, east and northeast, sediments filling the Rio Grande rift.

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). 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).

PLATE-TECTONIC SETTINGS

Introduction

Plate tectonics offers new insight to the evolution of sedimentary basins, uplifts, deformation and igneous activity along continental margins as well as far inland (Dickinson, 1974). Plate tectonics primarily deals with horizontal motions, but these motions, in turn, induce significant vertical motions which form sedimentary basins, deform the crust, and cause igneous and metamorphic activity. Therefore, a knowledge of plate-tectonic processes occurring along adjacent continental margins increases our understanding of the tectonics of inland regions.

Santa Fe country is approximately equidistant from the Pacific and Gulf of Mexico continental margins (fig. 2). Therefore, we must look to plate-tectonic events along both margins to evaluate their relative significance. New Mexico is relatively unique in that there is ample evidence of repeated tectonic and igneous activity through the Phanerozoic, and yet two, or maybe three, potential plate margins are equally distant in opposing directions. In order to apply plate-tectonic principles to the interpretation of events in Santa Fe country, it is necessary to call on transmission of stresses and deformation across major continental blocks. This idea is consistent with observed modern deformation far from plate boundaries (e.g., Molnar and Tapponnier, 1975, 1978).

The purpose in presenting the paleotectonic-paleogeographic maps shown in Figure 2 is to outline the regional influence on tectonic development of Santa Fe country. We do not suppose to understand all of the effects that plate-tectonic events have had on New Mexico, nor to understand all of the mechanisms by which these effects occurred. Our intentions are threefold: (1) to identify the correspondence in time and space of local with regional events, (2) to identify the types of events occurring along adjacent plate margins and what effects these have had on Santa Fe country, and (3) to point out the types of questions that need to be asked in order to understand these relationships. The tectonic evolution described below "can be viewed as the result of a succession of discrete plate-tectonic settings and plate interactions whose effects blend into a continuum of development" (Dickinson, 1974, p. 1).

Early Paleozoic

The latest Precambrian-Cambrian history of North America may have involved the formation of rifted continental margins along all of the present margins (e.g., Bird and Dewey, 1970; King, 1975; Stewart, 1972). Santa Fe country lay equidistant from the Cordilleran and Ouachita rifted margins (fig. 2). The transcontinental arch was a mildly positive area through much of the early Paleozoic, although shallow-marine deposition occurred along the margins of the arch as seas transgressed across the slowly subsiding continental margins. The Anadarko-Ardmore aulocogen formed as an elongate basin at a high angle to the Ouachita margin (Ham and others, 1964). Conditions in Santa Fe country were cratonal during the early Paleozoic.

Late Paleozoic

The ancestral Rocky Mountain uplifts and basins of Pennsylvanian age have been an enigma. The geologic evidence for their existence is clear, but their plate-tectonic setting has been unclear. Cordilleran deformations preceded (Antler orogeny of Devonian-Mississippian age) or succeeded (Sonoma orogeny of Permian-Triassic age) ancestral Rocky Mountain deformation. Coney (1978a) and Dickinson (personal commun., 1979) suggest that timing of continental collision in the Ouachita-Marathon orogen (Graham and others, 1975) corresponds exactly with timing of ancestral Rocky Mountain deformation. The geometry of Pennsylvanian uplifts and basins (fig. 2) suggests that deformation was concentrated along zones extending from parts of the Ouachita foldbelt experiencing the most structural telescoping (Ouachita and Marathon areas). Areas of previously developed weaknesses (most notably the Anadarko-Ardmore basin) were especially prone to deformation during the continental collision. Some of these zones of weakness probably propagated into the craton as deformation progressed. Thus, the tectonic setting of New Mexico during the Pennsylvanian and Early Permian can be viewed as being roughly analogous to that of modern central Asia north of Tibet, where collision-related deformation occurs many hundreds of kilometers from the suture belt (Molnar and Tapponnier, 1975, 1978). The precise mechanisms by which these stresses and strains are transmitted through the continental crust and the types of deformation to result should be the subjects of future research (W. R. Dickinson, personal commun., 1979).

Mesozoic

Following the assemblage of Pangea by the end of the Paleozoic (e.g., Dott and Batten, 1976), opening of the modern Atlantic Ocean and Gulf of Mexico began in the early Mesozoic. The "Gulf depression" was subsiding actively along the margins of the modern Gulf of Mexico by the Cretaceous, but the exact nature of the broad basin in southern Arizona and northern Mexico (fig. 2) is unclear, although evidence for extensional tectonics and basin filling is good (Bilodeau, 1978; Coney, 1978b). Following complex early Mesozoic events in the Cordilleran region (Coney, 1978b; Dickinson, 1976), an Andean-type arc-trench system was established and was the dominant tectonic control of orogenesis and basin formation into the Cenozoic. Figure 2 shows the major components of the arc-trench system during the Cretaceous. A thick sedimentary sequence accumulated in the forearc basin between the trench and the magmatic arc (Ingersoll, 1978). In a retroarc setting, eastward-directed thrusting and folding occurred in the Sevier belt (Armstrong, 1968) (fig. 2). A foredeep developed east of the foldbelt, and Dickinson (1976) has suggested that this formed due to structural telescoping that resulted in the downbowing of the crust. Santa Fe country was on the edge of this broad basin and relatively thin Cre-

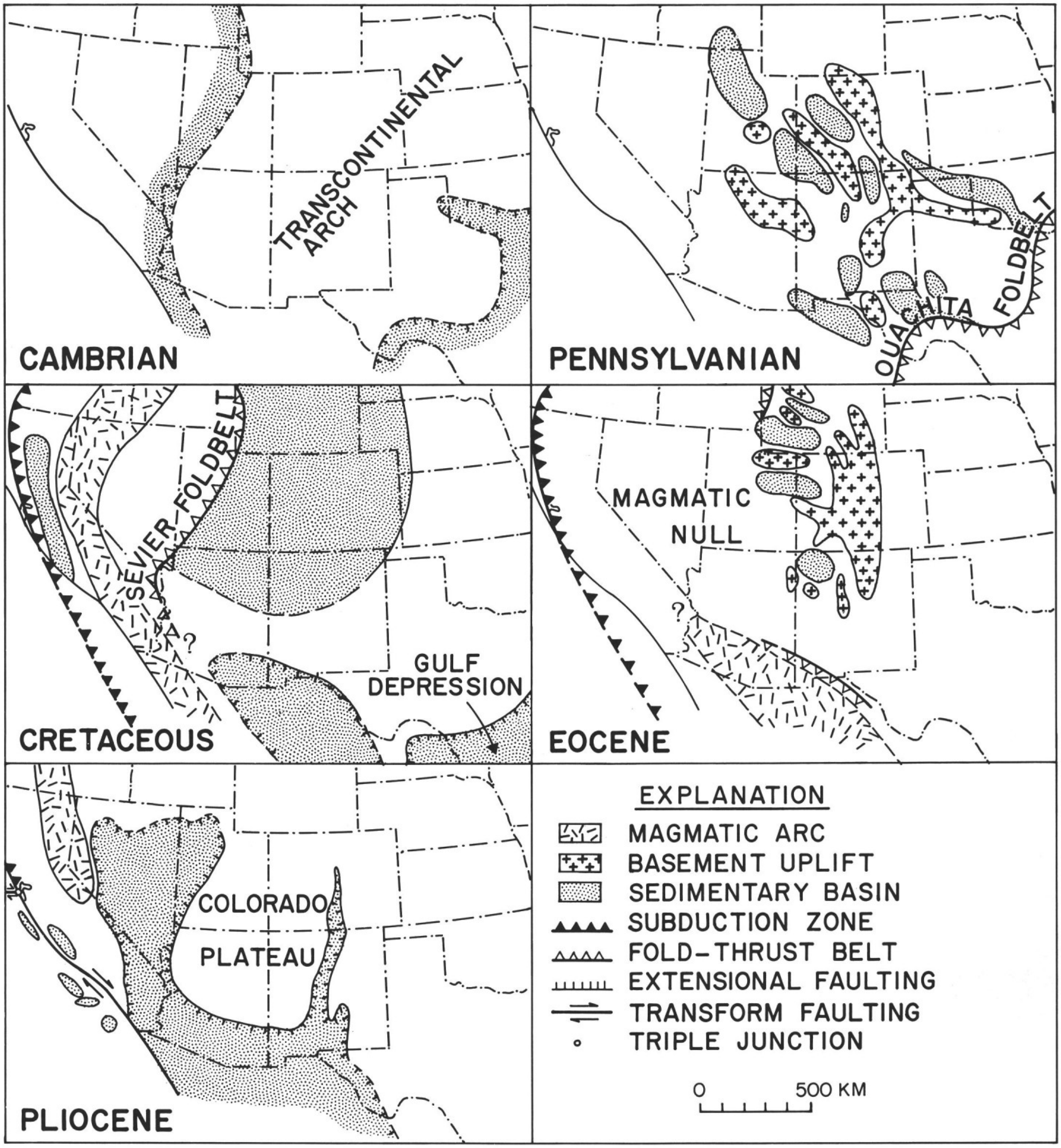

Figure 2. Schematic paleotectonic-paleogeographic maps of the western U.S., showing active plate-tectonic influences affecting New Mexico during selected times in the Phanerozoic. The maps are not palinspastic. See text for discussion. Sources of information include the following: Atwater (1970), Baltz (1978), Bilodeau (1978), Chapin and Seager (1975), Coney (1976, 1978b), Corbitt and Woodward (1973), Dickinson (1976, 1979), Dickinson and Snyder (1978), Dott and Batten (1976), King (1969), Lochman-Balk (1972), Mallory (1972), McDonald (1972), McGookey and others (1972), Robinson (1972), and Stearn and others (1979).

taceous deposits accumulated between this basin and the Gulf depression to the south (fig. 2). Thus, tectonic activity in Santa Fe country mostly consisted of gradual subsidence due to subduction-related deformation to the west during the Cretaceous.

Paleogene

The Laramide orogeny of latest Cretaceous and early Tertiary age has been difficult to explain in terms of the most common types of subduction-related deformation (Woodward, 1974). Amagmatic deformation in the form of basement uplift within the former craton far inland of the subduction zone was characteristic. Coney and Reynolds (1977) and Dickinson and Snyder (1978) suggest that this style of deformation can be explained in terms of a gently dipping subducted slab (Lowell, 1974a,b) analogous to modern amagmatic parts of the Andes (Barazangi and (sacks, 1976). Coney (1976) suggested that flattening of the subducted slab may have been caused in part by increased westward movement of North America. These hypotheses do not explain adequately the detailed mechanics of foreland deformation, but whatever the details of the mechanisms of deformation, it is irrefutable that basement uplift within the former craton is related temporally and spatially to a null of magmatic-arc activity to the west (fig. 2). Contemporaneously, more normal magmatic activity and retroarc thrusting occurred to the north and south of the Rocky Mountain area of the U.S. (e.g., Coney, 1976, 1978b; Corbitt and Woodward, 1973; Dickinson, 1976, 1979). Many of the Laramide structures formed by reactivation of crustal components that were weakened during the Pennsylvanian-Permian deformation (Chapin and Seager, 1975). The end of the Laramide orogeny coincided with a steepening of the subducted slab, and the renewal of magmatism west of the Rocky Mountains (Coney and Reynolds, 1977; Dickinson, 1979).

Neogene

The modern Pacific plate first began interacting with the North American plate soon after 30 m.y. B.P. (Atwater, 1970; Atwater and Molnar, 1973). Regional extension within the Basin and Range province, and in the Rio Grande rift has been related to the geometry of triple junctions (Atwater, 1970; Dickinson and Snyder, 1979a), the lack of a subducted slab (Dickinson and Snyder, 1979b), and dextral shear (Atwater, 1970; Livacarri, 1979). In Santa Fe country, as well as in the Basin and Range province, inherited structures were important influences in determining how and where the crust would respond to this regional extension (Chapin and Seager, 1975) (compare areas of deformation through time on Figure 2).

ACKNOWLEDGMENTS

We thank W. R. Dickinson for use of his unpublished paleotectonic maps of the southwest U.S. and for sharing his thoughts on the plate-tectonic settings of New Mexico as a Sandia Colloquium speaker at the University of New Mexico. J. F. Callender, P. J. Coney and W. R. Dickinson reviewed the manuscript. Acknowledgment is made by Ingersoll to the donors of the Petroleum Research Fund, administered by the American Chemical Society, for partial support of this research.

REFERENCES

Armstrong, A. K., 1967, Biostratigraphy and carbonate facies of the Mississippian Arroyo Pefiasco Formation, north-central New Mexico: New Mexico Bureau of Mines and Mineral Resources Memoir 20, 80 P.

Armstrong, R. L., 1968, Sevier orogenic belt in Nevada and Utah: Geological Society of America Bulletin, v. 79, p. 429-458.

Atwater, T., 1970, Implications of plate tectonics for the Cenozoic tectonic evolution of western North America: Geological Society of America Bulletin, v. 81, p. 3513-3536.

Atwater, T. and Molnar, P., 1973, Relative motion of the Pacific and North American plates deduced from sea-floor spreading in the Atlantic, Indian, and south Pacific oceans: Stanford University Publications in the Geological Sciences, v. 13, p. 136-148.

Bachman, G. 0. and Mehnert, H. H., 1978, New K-Ar dates and the late Pliocene to Holocene geomorphic history of the central Rio Grande region, New Mexico: Geological Society of America Bulletin, v. 89, p. 283-292.

Baltz, E. H., 1965, Stratigraphy and history of Raton basin and notes on San Luis basin, Colorado-New Mexico: American Association of Petroleum Geologists Bulletin, v. 49, p. 2041-2075.

----, 1972, Geologic map and cross sections of the Gallinas Creek area, Sangre de Cristo Mountains, San Miguel County, New Mexico: U.S. Geological Survey Miscellaneous Geologic Investigations Map 1-673.

----, 1978, Resume of Rio Grande depression in north-central New Mexico: New Mexico Bureau of Mines and Mineral Resources Circular 163, p. 210-228.

Barazangi, M. and [sacks, B. L., 1976, Spatial distribution of earthquakes and subduction of the Nazca plate beneath South America: Geology, v. 4, p. 686-692.

Bilodeau, W. L., 1978, The Glance Conglomerate, a Lower Cretaceous syntectonic deposit in southeastern Arizona: New Mexico Geological Society Guidebook 29, p. 209-214.

Bingler, E. C., 1968, Geology and mineral resources of Rio Arriba County, New Mexico: New Mexico Bureau of Mines and Mineral Resources Bulletin 91, 158 p.

Bird, J. M. and Dewey, J. F., 1970, Lithosphere plate-continental margin tectonics and the evolution of the Appalachian orogen: Geological Society of America Bulletin, v. 81, p. 1031-1059.

Black, B. A. and Hiss, W. L., 1974, Structure and stratigraphy in the vicinity of the Shell Oil Co. Santa Fe Pacific no. 1 test well, southern Sandoval County, New Mexico: New Mexico Geological Society Guidebook 25, p. 365-370.

Chapin, C. E., 1971, The Rio Grande rift, part I: modifications and additions: New Mexico Geological Society Guidebook 22, p. 191-201.

Chapin, C. E. and Seager, W. R., 1975, Evolution of the Rio Grande rift in the Socorro and Las Cruces areas: New Mexico Geological Society Guidebook 26, p. 297-321.

Coney, P. J., 1976, Plate tectonics and the Laramide orogeny: New Mexico Geological Society Special Publication 6, p. 5-10.

----, 1978a, Mesozoic-Cenozoic Cordilleran plate tectonics: Geological Society of America Memoir 152, p. 33-50.

1978b, The plate tectonic setting of southeastern Arizona: New Mexico Geological Society Guidebook 29, p. 285-290.

Coney, P. J. and Reynolds, S. J., 1977, Cordilleran Benioff zones: Nature, v. 270, p. 403-406.

Corbitt, L. L. and Woodward, L. A., 1973, Tectonic framework of Cordilleran foldbelt in southwestern New Mexico: American Association of Petroleum Geologists Bulletin, v. 57, p. 2207-2216.

Cordell, L., 1976, Aeromagnetic and gravity studies of the Rio Grande graben in New Mexico between Belen and Pilar: New Mexico Geological Society Special Publication 6, p. 62-70.

Dickinson, W. R., 1974, Plate tectonics and sedimentation: Society of Economic Paleontologists and Mineralogists Special Publication 22, p. 1-27.

----, 1976, Sedimentary basins developed during evolution of Mesozoic-Cenozoic arc-trench system in western North America: Canadian Journal of Earth Sciences, v. 13, p. 1268-1287.

----, 1979, Cenozoic plate tectonic setting of the Cordilleran region in the United States, *in* Armentrout, J. M., Cole, M. R. and TerBest, H., Jr., eds., Cenozoic paleogeography of the western United States: Pacific Section, Society of Economic Paleontologists and Mineralogists Pacific Coast Paleogeography Symposium 3, p. 1-13.

Dickinson, W. R. and Snyder, W. S., 1978, Plate tectonics of the Laramide orogeny: Geological Society of America Memoir 151, p. 355-366.

----, 1979a, Geometry of triple junctions related to San Andreas transform: Journal of Geophysical Research, v. 84, in press.

– 1979b, Geometry of subducted slabs related to San Andreas transform: Journal of Geology, v. 87, in press.

Dott, R. H., Jr. and Batten, R. L., 1976, Evolution of the Earth: McGraw-Hill, New York, 504 p.

DuChene, H. R., Kues, B. S. and Woodward, L. A., 1977, Osha Canyon Formation (Pennsylvanian), new Morrowan unit in north-central New Mexico: American Association of Petroleum Geologists Bulletin, v. 61, p. 1513-1522.

Goodknight, C. S., 1973, Structure and stratigraphy of the central Cimarron Range, Colfax County, New Mexico (M.S. thesis): University of New Mexico, Albuquerque, 85 p.

Graham, S. A., Dickinson, W. R. and Ingersoll, R. V., 1975, Himalayan-Bengal model for flysch dispersal in the Appalachian-Ouachita system: Geological Society of America Bulletin, v. 86, p. 273-286.

Ham, W. E., Denison, R. E. and Merritt, C. A., 1964, Basement rocks and structural evolution of southern Oklahoma: Oklahoma Geological Survey Bulletin 95, 302 p.

Ingersoll, R. V., 1978, Paleogeography and paleotectonics of the late Mesozoic forearc basin of northern and central California, *in* Howell, D. G. and McDougall, K., eds., Mesozoic paleogeography of the western United States: Pacific Section, Society of Economic Paleontologists and Mineralogists Pacific Coast Paleogeography Symposium 2, p. 471-482.

Kelley, V. C., 1952, Tectonics of the Rio Grande depression of central New Mexico: New Mexico Geological Society Guidebook 3, p. 93-105.

----, 1978, Geology of Espanola Basin, New Mexico: New Mexico Bureau of Mines and Mineral Resources Geologic Map 48.

Kelley, V. C. and Kudo, A. M., 1978, Volcanoes and related basalts of Albuquerque Basin, New Mexico: New Mexico Bureau of Mines and Mineral Resources Circular 156, 30 p.

King, P. B., 1969, Tectonic map of North America: U.S. Geological Survey, 1:5,000,000.

– ---, 1975, Ancient southern margin of North America: Geology, v. 3, p. 732-734.

Lipman, P. W. and Mehnert, H. H., 1979, The Taos Plateau volcanic field, northern Rio Grande rift, New Mexico, *in* Riecker, R. E., ed., Rio Grande rift: tectonics and magmatism: American Geophysical Union, Washington, p. 289-311.

Livaccari, R. F., 1979, Late Cenozoic tectonic evolution of the western United States: Geology, v. 7, p. 72-75.

Lochman-Balk, C., 1972, Cambrian System, *in* Mallory, W. W. and others, eds., Geologic atlas of the Rocky Mountain region: Rocky Mountain Association of Geologists, Denver, p. 60-75.

Lowell, J. D., 1974a, Plate tectonics and foreland basement deformation: Geology, v. 2, p. 275-278.

– 1974b, Plate tectonics and foreland basement deformation: reply: Geology, v. 2, p. 571.

Mallory, W. W., 1972, Regional synthesis of the Pennsylvanian System, *in* Mallory, W. W. and others, eds., Geologic atlas of the Rocky Mountain region: Rocky Mountain Association of Geologists, Denver, p. 111-127.

McDonald, R. E., 1972, Eocene and Paleocene rocks of the southern and central basins, *in* Mallory, W. W. and others, eds., Geologic atlas of the Rocky Mountain region: Rocky Mountain Association of Geologists, Denver, p. 243-256.

McGookey, D. P. and others, 1972, Cretaceous System, *in* Mallory, W. W. and others, eds., Geologic atlas of the Rocky Mountain region: Rocky Mountain Association of Geologists, Denver, p. 190-228.

Molnar, P. and Tapponnier, P., 1975, Cenozoic tectonics of Asia: effects of a continental collision: Science, v. 189, p. 419-426.

----, 1978, Active tectonics of Tibet: Journal of Geophysical Research, v. 83, p. 5361-5375.

Muehlberger, W. R., 1960, Structure of the central Chama platform, northern Rio Arriba County, New Mexico: New Mexico Geological Society Guidebook 11, p. 103-109.

----, 1967, Geology of Chama quadrangle, New Mexico: New Mexico Bureau of Mines and Mineral Resources Bulletin 89, 114 p.

Prucha, J. J., Graham, J. A. and Nickelsen, R. P., 1965, Basement-controlled deformation in Wyoming province of Rocky Mountains foreland: American Association of Petroleum Geologists Bulletin, v. 49, p. 966-992.

Read, C. B. and Wood, G. H., Jr., 1947, Distribution and correlation of Pennsylvanian rocks in late Paleozoic sedimentary basins of northern New Mexico: Journal of Geology, v. 55, p. 220-236.

Robinson, P., 1972, Tertiary history, *in* Mallory, W. W. and others, eds., Geologic atlas of the Rocky Mountain region: Rocky Mountain Association of Geologists, Denver, p. 233-242.

Ross, C. S., Smith, R. L. and Bailey, R. A., 1961, Outline of the geology of the Jemez Mountains, New Mexico: New Mexico Geological Society Guidebook 12, p. 139-143.

Schowalter, T. T., 1968, Geology of part of the Creston Range, Mora County, New Mexico (M.S. thesis): University of New Mexico, Albuquerque, 70 p.

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

Stearn, C. W., Carroll, R. L. and Clark, T. H., 1979, Geological evolution of North America: John Wiley and Sons, New York, 566 p.

Stearns, C. E., 1943, The Galisteo Formation of north-central New Mexico: Journal of Geology, v. 51, p. 302-319.

----, 1953, Tertiary geology of the Galisteo-Tonque area, New Mexico: Geological Society of America Bulletin, v. 64, p. 459-508.

Stewart, J. H., 1972, Initial deposits in the Cordilleran geosyncline: evidence of a late Precambrian (< 850 m.y.) continental separation: Geological Society of America Bulletin, v. 83, p. 1345-1360.

Tweto, 0., 1978, Tectonic map of the Rio Grande rift system in Colorado: New Mexico Bureau of Mines and Mineral Resources Circular 163, in pocket.

Woodward, L. A., 1974, Plate tectonics and foreland basement deformation: comment: Geology, v. 2, p. 570.

Woodward, LA. and Snyder, D. 0., 1976, Structural framework of the southern Raton basin, New Mexico: New Mexico Geological Society Guidebook 27, p. 125-127.

Woodward, L. A., Callender, J. F., Seager, W. R., Chapin, C. E., Gries, J. C., Shaffer, W. L. and Zilinski, R. E., 1978, Tectonic map of the Rio Grande rift region in New Mexico, Chihuahua and Texas: New Mexico Bureau of Mines and Mineral Resources Circular 163, in pocket.