STRUCTURE AND STRATIGRAPHY OF THE ESPAÑOLA BASIN, RIO GRANDE RIFT, NEW MEXICO

by

Kim Manley

Open-File Report 78-667

1978

STRUCTURE AND STRATIGRAPHY OF THE ESPAÑOLA BASIN, RIO GRANDE RIFT, NEW MEXICO

by
Kim Manley

INTRODUCTION

The purpose of the present paper is to bring together and describe what is presently known or can now be deduced of the Cenozoic history of the Española basin and to call attention to areas requiring further study. Much of the basin has received little study until recently. Now, a considerable amount of new data are available that allow for a reasonably accurate reconstruction of the Cenozoic history.

The Española basin is one of a series of north-south alined Cenozoic structural and topographic basins that extend from central Colorado to southern New Mexico (Chapin, 1971; Chapin and Seager, 1975) (fig. 1). These basins constitute the Rio Grande trough, depression, graben, or rift. The Española basin is 40 km long and 65 km wide (fig. 2). Structurally, the basin is separated from the Santa Domingo subbasin to the south by the northwest-trending La Bajada fault which has down to the southwest motion. To the north of the Española basin is the San Luis Valley. The boundary between these basins is difficult to pinpoint but is generally assumed to be along the northern flanks of the Picuris Range and westward to the Ojo Caliente area via an isolated Precambrian exposure known as Cerro Azul. East and west the Española basin is bounded by Precambrian-cored uplifts, the Nacimiento uplift on the west and the Sangre de Cristo Mountains on the east.

The western half of the basin is filled with volcanic rocks of the Jemez Mountains which define the western edge of the topographic basin. The topographic Española basin is only 32 km wide. North and south the topographic basin terminates near basalts of the Servilleta Formation and Cerros del Rio volcanic field, respectively. These basalt flows cap and abut against areas topographically higher than the central basin. Tertiary sedimentary rocks (Galisteo, El Rito, Abiquiu, Picuris and Tesuque Formations and the Chamita Formation of Galusha and Blick, 1974) and several Pliocene/Pleistocene alluvial deposits (including the Ancha and Puye Formations [which are part of the Santa Fe Group of some authors]) are preserved in the central basin. The sedimentary rocks are also exposed in the Abiquiu area north of the Jemez Mountains and in the Picuris embayment which is also the location of the northeast plateau.

PREVIOUS WORK

Several areas in and around the Española basin have been studied in recent years. Cenozoic sediments in the east-central part of the basin have been described by Galusha and Blick (1971), in the northeastern portion by Miller and others (1963) and Manley (1974, 1976a, 1976c), and in the southern portion by Spiegel and Baldwin (1963) and Manley (1976a, 1976b). The Cerros del Rio volcanic field has been studied by Griggs (1964), and the Jemez Mountains by Griggs (1964), Bailey and others (1969), and Smith and others (1970). K-Ar ages for two flows in the Cerros del Rio volcanic field are given by Manley (1976b); additional ages are available in Bachman and Mehnert (1978). Radiometric ages determined by fission-track dating of tephra layers in the Santa Fe Group are in Manley (1976a) and Manley and Naeser (1977).

The geologic history of the Española basin presented in this report is a synthesis of the work done by the above geologists and field work of the author from 1971 to the present.

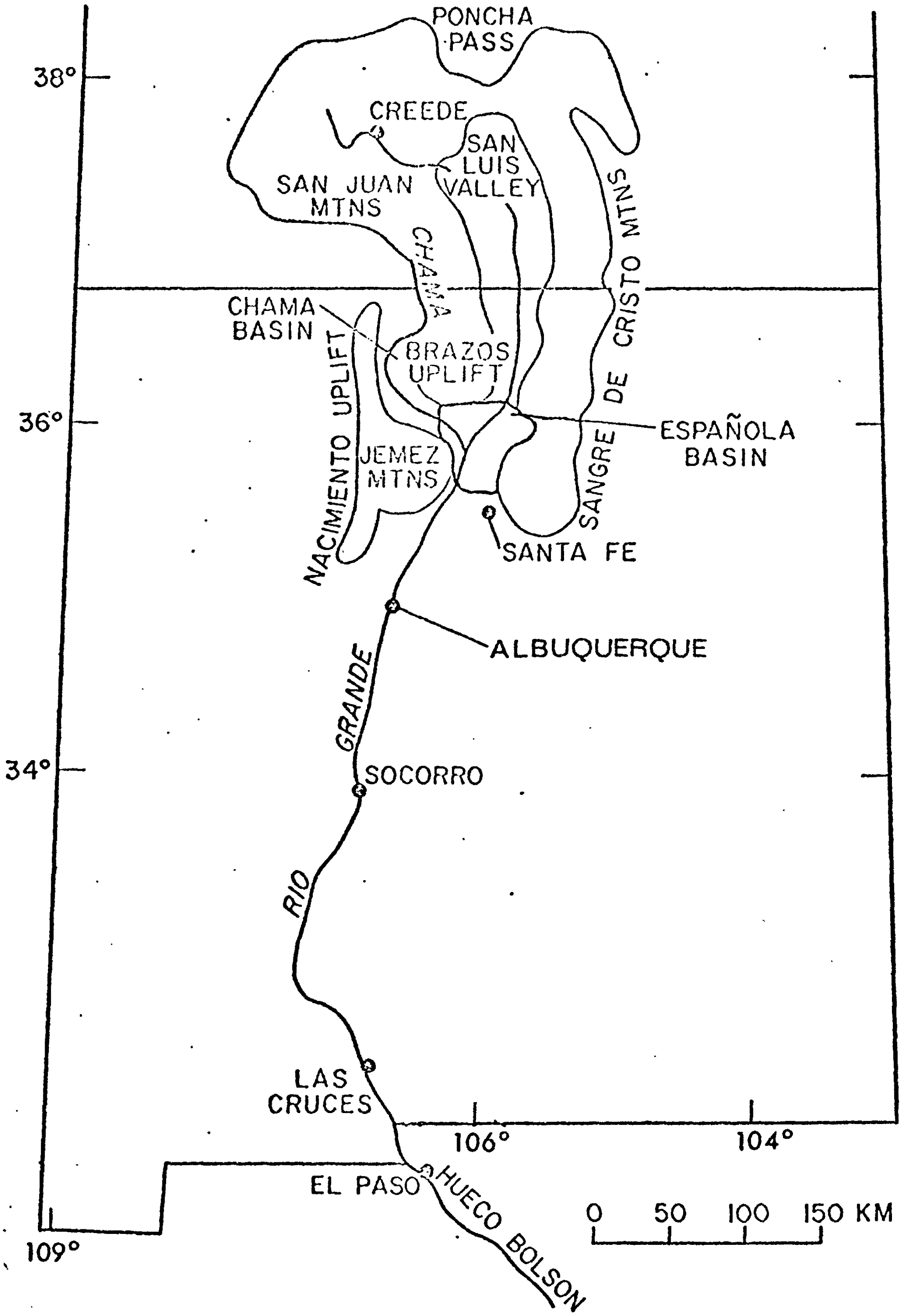
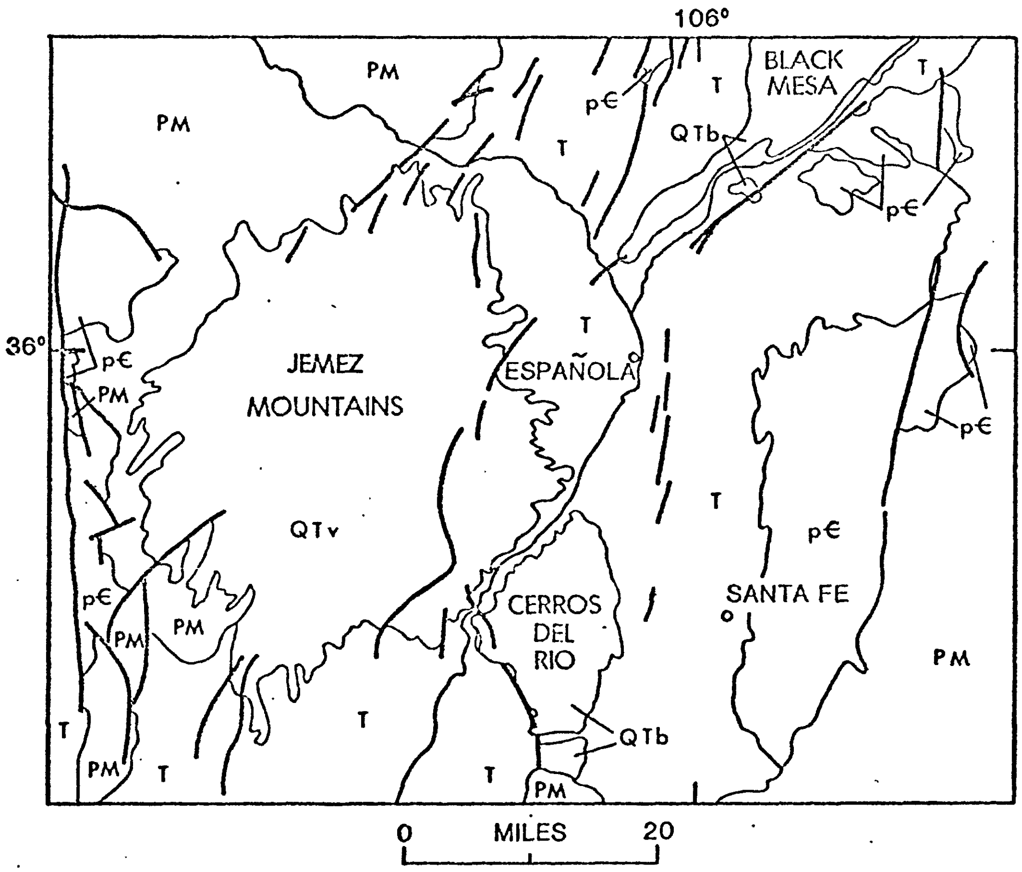


FIG 1. REGIONAL MAP OF NEW MEXICO AND SOUTHERN COLORADO



QTv	MIOCENE TO QUATERNARY VOLCANIC ROCKS OF THE JEMEZ MTS.	PM	PALEOZOIC AND MESOZOIC ROCKS INCLUDES EARLY TERTIARY ROCKS
QTb	PLIOCENE TO QUATERNARY THOLEIITIC AND ALKALI OLIVINE BASALTS	pЄ	PRECAMBRIAN ROCKS
T	EOCENE TO PLIOCENE SEDIMENTARY ROCKS WITHIN THE ESPANOLA BASIN	(wavy line)	CONTACT
		(solid line)	FAULT

FIG. 2. GEOLOGIC MAP OF ESPAÑOLA BASIN, NEW MEXICO.

STRATIGRAPHY

A discussion of the pertinent aspects of the stratigraphy is presented here to further the understanding of the geologic history (fig 3). Two presumably equivalent formations that are the earliest Tertiary deposits and that were deposited prior to the initiation of rifting exist within the basin; they are the Eocene and Oligocene Galisteo and El Rito Formations. Three units were then deposited in response to volcanism in the area: the Picuris and Abiquiu Tuffs, and the Bishops Lodge Member of the Tesuque Formation. These tuffaceous sediments are overlain by the Tesuque and Chamita Formations of the Santa Fe Group of Galusha and Blick (1971). The youngest basin deposits are the fan-shaped Pliocene Ancha and Puye Formations (which are also part of the Santa Fe Group according to some authors). After their deposition, erosion dominated in the basin. Pleistocene alluvial deposits are confined to erosional-surface gravels, terraces, and dune sands.

Eocene and Oligocene Galisteo and El Rito Formations

The Eocene and Oligocene Galisteo (Stearns, 1943) and El Rito (Smith, 1938) Formations are the oldest Tertiary deposits in the Española basin. They consist of sandstones, shales, and boulder conglomerates with red iron oxide staining. The El Rito Formation is exposed only in the northwest part of the Española basin. The Galisteo is exposed along the southern margin of the basin and in an upthrown block on the southeast edge of the Jemez Mountains (Smith and others, 1970). Both formations unconformably overlie Mesozoic rocks. The El Rito Formation is unconformably overlain by the Abiquiu Tuff; the Galisteo Formation is conformably overlain by the Espinaso Formation.

Stearns (1943) cited the Sangre de Cristo Mountains and the Nacimiento uplift as source areas for the Galisteo Formation. The Precambrian core of the Brazos uplift was the source for much of the El Rito Formation according to Bingler (1968).

Fossils have not been reported for the El Rito Formation but late Eocene mammalian fossils are present in the upper Galisteo Formation (Galusha and Blick, 1971; Disbrow and Stoll, 1957) and early Eocene fossils have been found in the lower Galisteo Formation (Robinson, 1957). The equivalency of these two formations is not yet supported by fossil evidence; it rests solely on lithologic characteristics.

Espinaso Formation

The Espinaso Formation overlies the Galisteo Formation south of the Española basin in the Santo Domingo subbasin. The formation consists of volcaniclastic debris K-Ar dated at 37 m.y. (Weber, 1971). Source areas (Stearns, 1953) have been dated at 46 m.y., 35 m.y. and 32 m.y. (Jaffe

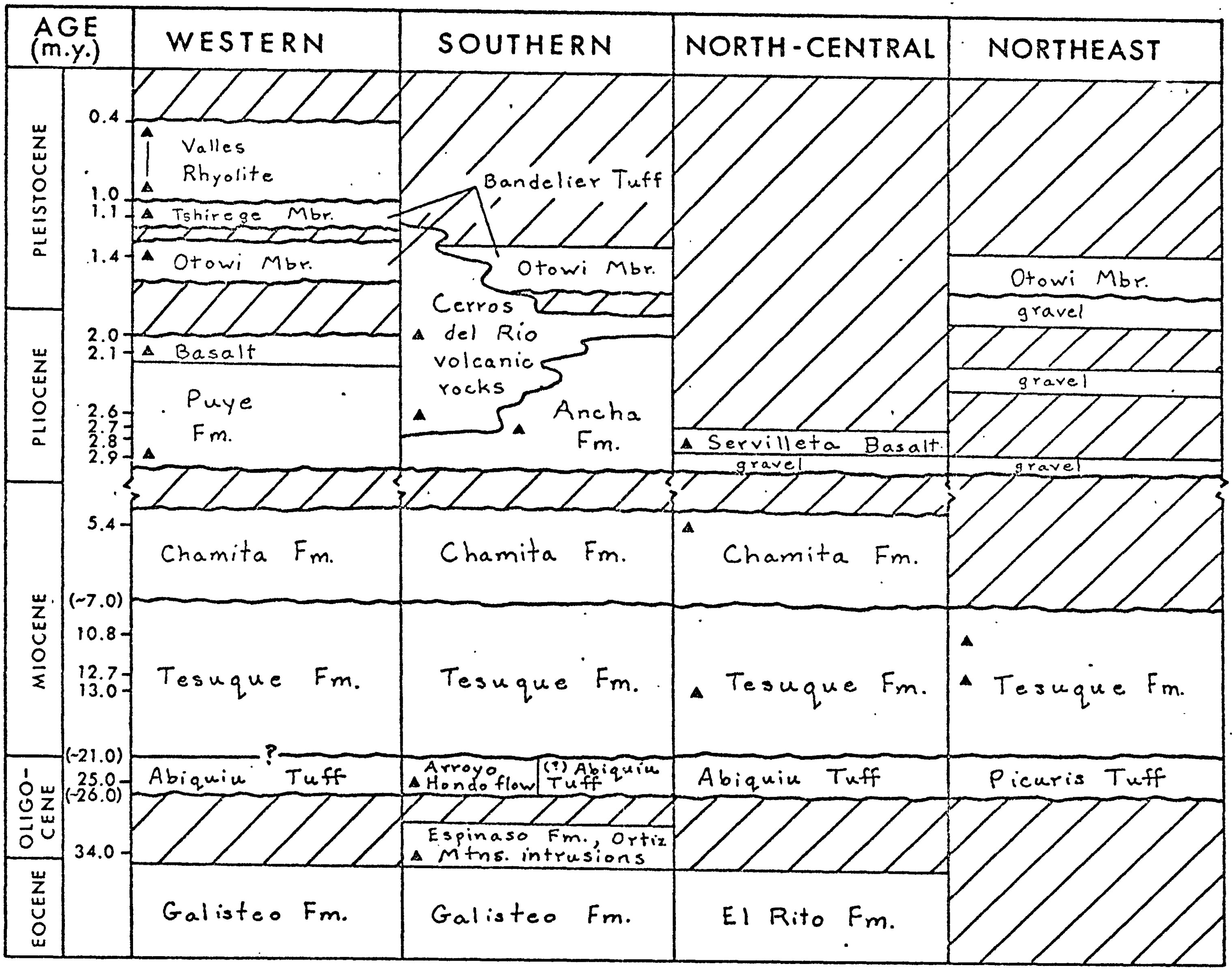


Fig. 3. Stratigraphic correlation chart for the Española Basin, New Mexico.
▲ = radiometric age.

and others, 1959) for the Cerrillos Hills stock and 34 m.y. (Bachman and Mehnert, 1978) for the Ortiz Mountains. These ages provide a minimum age for the Galisteo Formation and a maximum age for possible Abiquiu Tuff deposits in the Cienega area.

Abiquiu and Picuris Tuffs

The Abiquiu Tuff (Smith, 1938) unconformably overlies the El Rito Formation on the western side of the basin. The Abiquiu Tuff, and its probable correlative in the northeast part of the basin, the Picuris Tuff (Cabot, 1938), are tuffaceous sands and gravels containing numerous intermediate volcanic clasts. The probable source areas for these tuffs were the volcanic highlands to the north: the southern San Juan Mountains, the Taos Plateau and the Questa volcanic center. (The Taos Plateau is predominantly Pliocene basalts but these flows have buried older intermediate volcanic rocks [P.W. Lipman 1976, written commun.].)

There are no paleontologic or radiometric ages published for either formation. The ages of the source areas serve as one indication of maximum age for these formations. The Platoro caldera, situated at the northern end of the Brazos uplift was active around 27 to 30 m.y. ago (Lipman and others, 1970). Preliminary ages for early activity on the Taos Plateau range from 26 to 22 m.y. (P. W. Lipman 1975, written commun.) The Questa volcanic center in the Sangre de Cristo Mountains was active about 23 m.y. ago (Laughlin and others, 1969). Additionally, the Abiquiu Tuff and the overlying Chama-el rito Member of the Tesuque Formation of Galusha and Blick (1971) interfinger northward with the lower part of the Los Pinos Formation (S. J. May 1977, written commun.) The Los Pinos Formation was deposited near the eastern Brazos uplift and Taos plateau where it interfingers with 27 to 5 m.y. old flows of the Hinsdale Formation (Lipman and Mehnert, 1975).

Further indications of age come from the southern end of the basin. In the Cienega area, an exposure of possible Abiquiu Tuff overlies the Espinaso Formation (Stearns, 1953) and several intermediate volcanic rocks (Stearns, 1953; Sun and Baldwin, 1958) whose age is probably mid-Oligocene. These rocks are being K-Ar dated by W. S. Baldridge (1977, oral commun.). Near Santa Fe a tuffaceous sand and siltstone with occasional tuff and conglomerate beds is present (Spiegel and Baldwin, 1963). The clasts are highly weathered intermediate volcanic rocks. These deposits were called the Picuris Tuff by Cabot (1938) and Galusha and Blick (1971) and the Bishops Lodge Member of the Tesuque Formation by Spiegel and Baldwin (1963). In Arroyo Hondo, 3 km south of Santa Fe, the Bishops Lodge Member overlies an intermediate flow with an age of 25 m.y. (Bachman and Mehnert, 1978). Perhaps this flow is related to the episode of volcanic activity at La Cienega and, all or part of the Bishops Lodge Member is equivalent to the Abiquiu(?) Formation of Stearns (1953) and the Abiquiu Tuff. Boyer (1959) describes playa deposits in the Bishops Lodge Member of the Tesuque and states the member is disconformably overlain by the upper part of the Tesuque Formation.

Los Pinos Formation

The Los Pinos Formation is exposed in the most northwestern part of the Española basin and northward along the Brazos uplift into the southern San Juan Mountains. It is composed of volcaniclastic sandstones and conglomerates with tuffs and basalts flows. The source area was the southern San Juan Mountains. To simplify terminology, Lipman and Mehnert (1975) have suggested the interbedded basalt flows be considered part of the Hinsdale Formation. These flows range in age from 25 m.y. to 4.4 m.y. (Lipman and Mehnert, 1975). The Los Pinos Formation is therefore late Oligocene to early Pliocene in age and equivalent to the Abiquiu and Picuris Tuffs in its basal part and the Tesuque and Chamita Formations of the Santa Fe Group in its upper part.

The Los Pinos Formation and the Abiquiu and Picuris Tuffs all overlie an erosion surface. Rocks immediately beneath this surface in the southern San Juan Mountains are 30 to 26 m.y. old (Lipman and Mehnert, 1975).

Santa Fe Group of Galusha and Blick

Santa Fe Group sedimentary rocks overlie the Abiquiu and Picuris Tuffs. The Santa Fe Group has been divided into the Tesuque and Chamita Formations by Galusha and Blick (1971). They further subdivide the Tesuque Formation into five members (fig. 4): Nambé, Skull Ridge, Pojoaque, Ojo Caliente Sandstone and Chama-el rito. Galusha and Blick (1971) envision the Pojoaque and Chama-el rito Members to be contemporaneous fans deposited in different areas of the Española basin from separate source areas. The Chama-el rito is exposed in the northwest portion of the basin and is the only member with dominantly volcanic rock clasts. The volcanic detritus in the Chama-el rito Member indicates drainage southward from the Platoro and Questa volcanic centers. The other members contain predominantly granitic clasts derived from the Sangre de Cristo Mountains.

Much additional stratigraphic study of the Santa Fe Group is needed. The members defined by Galusha and Blick (1971) have not been comprehensively described, nor has all of the basin been mapped. There are large areas to the south and northeast not included in the work of Galusha and Blick (1971). Recent mapping of mine in the northeast (Manley, 1977) and northwest portions of the basin has led to the recognition of 1) young faulting (described below) that alters the stratigraphic correlations across the basin (fig. 4); and 2) rocks in the northeast that are volcanic clast rich and possibly equivalent to the Chama-el Rito; and, 3) a major east-west drainage 10 m.y. old (the Cejita Member of the Tesuque Formation [Manley, 1976c and 1977]).

The age of the Santa Fe Group of Galusha and Blick (1971) is fairly well established. Fossil ages for these rocks extend from Hemingfordian to Hemphillian Land Mammal ages (Wood and others, 1941). The

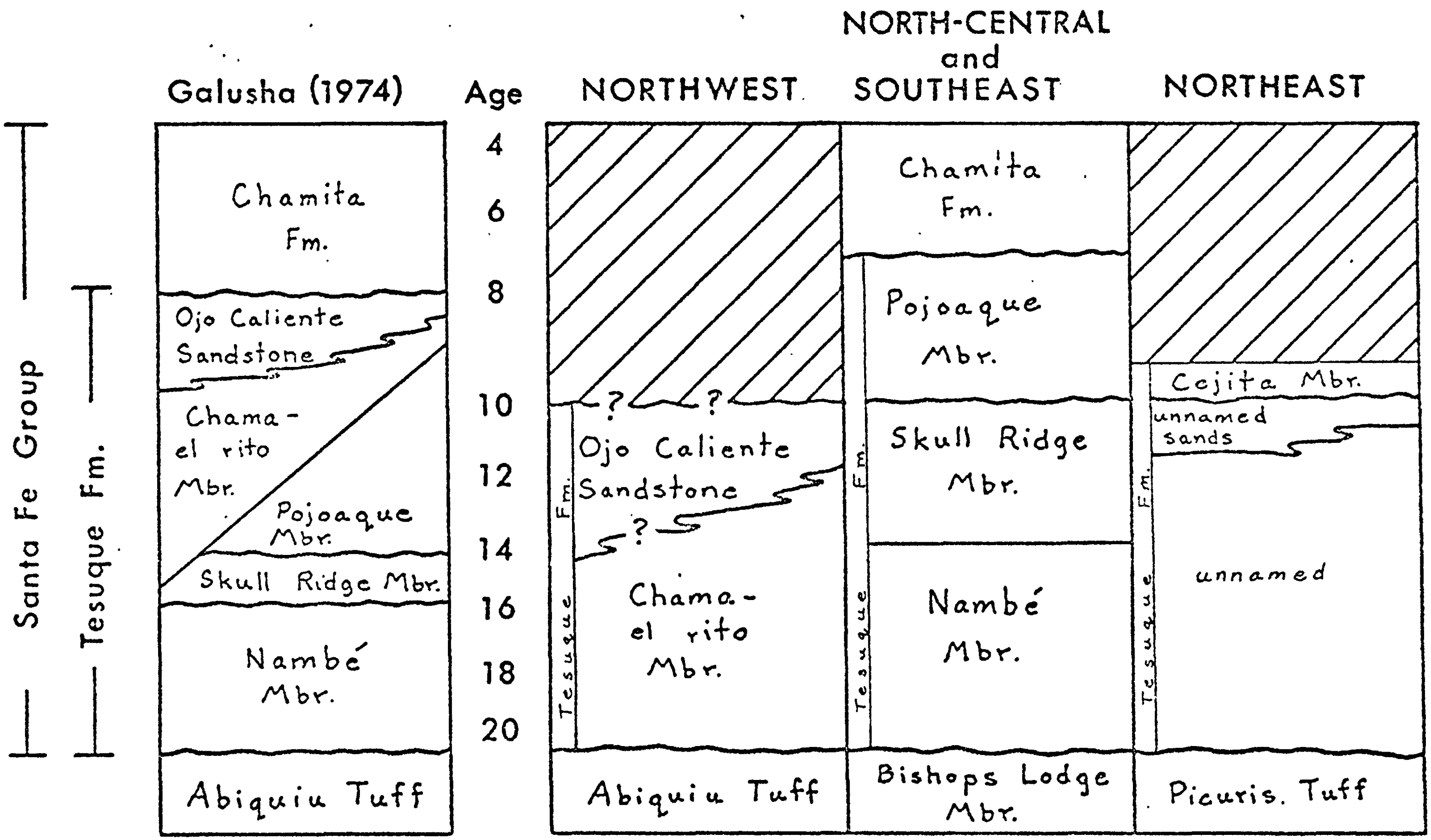


Fig. 4. Comparison of the Santa Fe Group of Galusha (1974) and of this report.

Hemingfordian fauna are considered to have developed nearly 21 m.y. ago (Woodburne and others, 1974; Davis, 1975). Hemphillian fauna are 10 to 3.5 m.y. old (Evernden and Evernden, 1970; Berggren and Van Couvering, 1973). A questionable lead-alpha age of 18 m.y. was obtained by Jaffe and others (1959) for a dacitic ash in the Nambé Member of the Sante Fe Group.

Fission-track ages on zircons in tephra from the Skull Ridge and Pojoaque Members of the Tesuque Formation range from 14 to 9 m.y. (C. W. Naeser and G. A. Izett 1976, written commun.) In this report the Chama-el rito and Ojo Caliente Sandstone Members are assumed to be older than Galusha and Blick (1971) suggested (fig. 3). This assumption is made on the basis of the following points: (1) lithologic similarity between the Chama-el rito and Ojo Caliente Sandstone Members and unnamed Santa Fe Group deposits in the northeast portion of the basin that are >11 m.y. (Manley, 1976a); (2) structural evidence (Manley, 1978); and (3) a >13 m.y. age (H. H. Mehnert 1977, written commun.) from an interbedded basalt in the Chama-el rito Member near El Rito Creek.

Two zircon fission-track ages from the Chamita Formation of Galusha and Blick (1971) give it an age of 5 m.y. (Manley, 1976c; MacFadden and Manley, 1976).

Post-Santa Fe Group formations

A number of different Pliocene and Pleistocene formations overlie the Santa Fe Group of Galusha and Blick (1971) with angular unconformity. These formations include the Puye Formation, (Smith, 1938) the Ancha Formation (Baltz and others, 1952) and the Servilleta Formation (Montgomery, 1953). The Puye and Ancha Formations have been included in the Santa Fe Group by some authors. They are fanglomerates derived from opposite sides of the basin. The Puye Formation, which also contains numerous laharic and pyroclastic deposits was derived from the Jemez Mountains. The Ancha Formation source area was the Precambrian granitic and metamorphic rocks of the Sangre de Cristo Mountains. The two formations interfinger with each other and with the volcanic rocks of the Cerros del Rio field in the south-central part of the basin. The Servilleta Formation consists of olivine tholeiite flows and intervening sediments. It is exposed primarily north of the Española basin.

The Ancha Formation is included in the Santa Fe Group of Spiegel and Baldwin (1963); the Servilleta is not considered to be part of the Santa Fe Group. A terminological difficulty results because in the Española basin these formations are contemporaneous. All are less than 3 m.y. old; zircon fission-track ages from the Puye and Ancha Formations are 2.9 m.y. and 2.7 m.y., respectively (Manley, 1976a); and a basalt flow in the Servilleta Formation capping Black Mesa has a K-Ar age of 2.8 m.y.(Manley, 1976b).

The basaltic rocks of the Cerros del Rio volcanic field, at the southern end of the basin, range in age from 2.6 m.y. (Manley, 1976b) to <1.4 m.y. (Smith and others, 1970). A flow overlying the type area of the Ancha Formation is 2.0 m.y. (Manley, 1976b).

Igneous Rocks of the Jemez Mountains

Volcanism began to create the Jemez Mountains about 12 m.y. ago (Smith and Bailey, 1968). The west side of the Española basin was covered with volcanic rocks deposited first on the south and then to the north. Published K-Ar ages range from 9.1 to 0.43 m.y. (Bailey and others, 1969). Bailey and others (1969) divide these rocks into three groups: Keres, Polvadera, and Tewa.

FAULTS

If one assumes that the Española basin is a rift basin or graben, prominant boundary faults or fault systems should exist at the east and west margins of the basin. Few papers discuss this boundary faulting although several maps indicate boundary faults (Cabot, 1938; Kelley, 1956). Current mapping projects include those of the author on the northeast and west sides of the basin and of E. H. Baltz (U.S. Geological Survey, Denver) along the eastern side.

Faults within the basin have been mapped by H. T. U. Smith (1938), Smith and others (1970), Galusha and Blick (1971), and Manley (1977, and current mapping).

Basin boundary faults

The eastern margin of the Española basin appears to lack a graben-style border fault. A right-lateral, strike-slip fault, the Pecos-Picuris fault, which formed the eastern margin of the Uncompahgre highland in late Paleozoic time (Sutherland, 1972) has been considered by some to be a boundary fault and is shown as such in many papers. There is, however, evidence that the Pecos-Picuris fault had right-lateral strike-slip motion followed by down-to-the-east motion (Miller, and others, 1963). There is also no good evidence for an eastern border fault west of the Pecos-Picuris fault. Faults mapped north of Santa Fe by Cabot (1938) and Spiegel and Baldwin (1963) do not involve the Santa Fe Group and are pre-Santa Fe Group in age according to Galusha and Blick (1971, p. 104). Post-Tesuque Formation faults are present along the eastern margin but their displacements are small and frequently down to the east (Manley, unpublished mapping; E. H. Baltz 1976, oral commun.). Further mapping in this area should clarify the fault history.

In many locations the Santa Fe Group sediments are in depositional contact with Precambrian or Pennsylvanian rocks which suggests an onlap relationship; there is no thick deposit of Tertiary sediments abutting the Precambrian block. The Bouguer gravity anomaly map of Cordell (1976) shows a much gentler gradient for this border compared to the eastern border of the Albuquerque-Belen basin. Thus it appears that either the eastern border is a series of step-faults or is not a fault controlled border. In the latter case, the contact might be a tilted onlap relationship. The present western slope of the Sangre de Cristo Mountains from a mile north of Sierra Mosca to the beginning of the Santa Fe Group gives many indications of being a stripped surface. Its dip is approximately 73 m/km which would allow for 1,212 m of sedimentary rocks beneath Española. This figure coupled with at least 330 m of downdropping in the central Velarde graben (discussed below) gives a figure of roughly 1,550 m of fill compared to the 2,150 m suggested by Cordell's calculated basement elevation map (1976, p. 67).

The western margin of the Española basin is defined by a zone of down-to-the-east faulting largely concealed by the volcanic rocks of the Jemez Mountains. North and south of the Jemez Mountains, the Santa Fe Group rocks are faulted against Mesozoic rocks (Smith and others, 1970). Within this zone, however, are eastward-tilted blocks of Santa Fe Group rocks. The western boundary fault zone can be especially well observed in the Cañones quadrangle. The zone trends northeast-southwest toward El Rito. Faults in this area offset deposits Permian to Quaternary in age. It is unknown when the greatest motion occurred. (See further discussion under Geologic History.)

Intra-basin faults

Numerous high-angle, normal faults cut the Santa Fe Group in the eastern half of the basin. Most are of limited extent (less than 3.2 km) and displacement is generally less than 91 m (Galusha and Blick, 1971, p. 101). "The faults with east side down are more numerous, but those with west side down are usually larger" (Galusha and Blick, 1971, p. 101). Faults strike northward, subparallel to the strike of the Santa Fe Group.

Near the western margin of the basin the faults begin to parallel the northeast-southwest trend of the boundary fault zone. To the north, this zone intersects the northwest-southeast faults that bound the Precambrian uplifts near La Madera and form the northern margin of the basin.

The Velarde graben

Several important high-angle normal faults have recently been mapped in the Española basin (Manley, 1976c, 1977, and 1978) (fig.4). One prominent fault, the Velarde fault, extends along the western margin of the northeast plateau parallel to the Rio Grande flood plain near the town of Velarde; a probable fault parallels this one 0.8 km to the northwest. Stratigraphic relationships indicate a combined west-down total displacement on both faults of >300 m. A third fault crosscuts the basalt of La Mesita (northeast of Velarde) and the basalt cap is dropped down to the west about 60 m. Smaller faults and folding can be observed in the Santa Fe Group northeast of Velarde. All of these faults are a continuation southward of the fault zone on the northwest side of the Picuris Range (Miller and others, 1963) and they form the east boundary of the Velarde graben.

The western boundary of the Velarde graben is defined by a second set of faults that exist beneath Black Mesa. The major fault extends southward from near the southern end of Black Mesa. It is a high-angle, east-down, normal fault that places the Chamita Formation next to the Ojo Caliente Sandstone Member of the Tesuque Formation. These relationships suggest a displacement of 330 m.

The faulting near Velarde and beneath Black Mesa have created a graben (the Velarde graben) roughly 8 km wide. The course of the Rio Grande from Velarde to Española parallels the eastern margin of this graben. Large slump blocks of basalt-capped Chamita Formation that flank the eastern side of Black Mesa are probably in part a reflection of the underlying graben structure.

Another major zone of faulting is present northwest of Black Mesa, west of and subparallel to the Rio Ojo Caliente. Although the major fault of this zone shows a west-down displacement (Galusha and Blick, 1971), the eastern block is rotated downward to the east. This motion may have been a response to the formation of the Velarde graben. The north-south trend of this fault zone is subparallel to those beneath Black Mesa and within the central part of the basin.

As the Velarde graben continues southward, the western margin passes across the Pajarito Plateau as the Pajarito fault zone. At the southern end of this fault zone the offset has placed the Pleistocene Bandelier Tuff against the Eocene and Oligocene Galisteo Formation. These western margin faults are shown by Galusha and Blick (1971) and Smith and others (1970).

The eastern boundary of the Velarde graben south of Española is obscured by the broad flood plains of the Rio Grande, Santa Cruz River and Pojoaque River. Prominent north-south faults are present in this part of the basin but the amount of displacement along them has not yet been determined. The eastern edge of the graben here may be a series of small faults and rotated blocks as is characteristic of a tensional environment. Such faults are shown by Galusha and Blick (1971) and have been observed by the author.

The Cerros del Rio volcanic field lies across the southern end of the Española basin and obscures the structural relationships within the Santa Fe Group of Galusha and Blick (1971). However, there is evidence that the Velarde graben is present. Along the Rio Grande, in White Rock Canyon, the interfingering Pliocene Puye and Ancha Formations are exposed above the Chamita Formation. The contact is near river level. Near the eastern edge of the Cerros del Rio volcanic field, Spiegel and Baldwin (1963) map a rather abrupt, and in one case, faulted, contact between the Tesuque and Ancha Formations and mention other high-angle, north-trending faults which could not be traced any distance due to poor exposures (Spiegel and Baldwin, 1963, p. 76). The Ancha Formation rapidly thickens westward from this contact toward the Rio Grande. Also present in the area is an anomalous exposure of north-east trending Pennsylvanian(?) quartzite blocks (Spiegel and Baldwin, 1963, p. 77-78). An inference can be made from these observations that this is the eastern boundary of the Velarde graben. The area beneath the Cerros del Rio volcanic field and the Pajarito Plateau as far west as the Pajarito fault is the southern end of the Velarde graben, and the graben here would be approximately 30 km wide. Within it the greatest thickness of post-Tesuque Formation deposits in the basin is preserved. An implication of the presence of the Velarde graben through the Española basin is that the upper part of the Pojoaque Member (Galusha and Blick, 1971) of the Tesuque Formation mapped in the central part of the basin, could be within the graben structure and therefore younger than previously assumed. These rocks may be equivalent to the Chamita Formation and this possibility is supported by recent stratigraphic studies (Manley, unpub. data).

The central graben of the Española basin can be recognized geophysically. It is present on the Bouguer anomaly gravity map of Cordell (1976). This map also supports the presence of a similar, though wider, structure in the Santo Domingo subbasin. Gravity surveys done by Gaca and Karig (1966) suggest a continuation of the Velarde graben to the north through the San Luis Valley.

In conclusion, the Española basin contains a narrow, central graben at the northern end of the basin. This Velarde graben appears to continue southwestward to the southern end of the basin and controls the position of the Rio Grande.

GEOLOGIC HISTORY

Laramide orogeny resulted in the uplift of the Precambrian-cored ranges of north-central New Mexico (Woodward, 1974). Both the Nacimiento uplift and Sangre de Cristo Mountains became positive areas. During the Paleocene and early Eocene they were partially stripped of Mesozoic rocks. Low areas to the east and south of these uplifts were filled with the Galisteo and El Rito Formations; however, the basins were not the same configuration as the later rift basins (Stearns, 1953). Paleocurrent and provenance studies would contribute greatly to the understanding of these formations and their depositional basins. Near the close of the Eocene, the area was probably one of low relief with a broad erosion surface similar to that described for southern Colorado by Scott (1975). Probable remnants of this erosion surface have been observed in the Sangre de Cristo and Tusas Mountains by the author. The interval of erosion may correlate with that observed by Stearns (1953) as preceding deposition of his Abiquiu(?) Formation at the southern end of the Española basin.

There ensued, in early Oligocene, a period of intermediate volcanism in and around the basin, for example, at the Cerrillos Hills and Ortiz Mountains and in the southern San Juan Mountains. The latter rocks were tilted eastward and beveled prior to deposition of the Los Pinos Formation (Lipman and Mehnert, 1975) which began in late Oligocene time.

The Rio Grande rift began to form in the late Oligocene. Direct evidence is not available from the Española basin, but the Abiquiu and Picuris Tuffs, if considered deposited early in the rifting history can be presumably traced to source areas with ages from 22 m.y. to 30 m.y. Work by other geologists north and south of the basin support this time of initial rifting: regional extension began about 29 m.y. ago in the Socorro-Magdalena area (Chapin and Seager, 1975); rifting was in progress by 26 m.y. in southern New Mexico (Seager and Clemons, 1975) and in southern Colorado (Lipman and Mehnert, 1975).

The Los Pinos Formation and Abiquiu and Picuris Tuffs were deposited on an erosion surface about 26 m.y. old. The lower parts of the formations appear to be contemporaneous. The area of deposition was not the present Española basin; the Abiquiu Tuff is found west of the present rift margin on the eastern flank of the Nacimiento uplift. Relief was probably still low (Denny, 1940; Stearns, 1953; Church and Hack, 1939) although basal gravels in the Abiquiu Tuff indicate a Precambrian source area to the north or west. These angular, poorly sorted gravels could reflect the earliest tilting and fragmentation resulting from extension in the Española basin area. During this time the Jemez Mountains were not in existence. A seasonal lake occupied an area near the southern margin of the basin (Stearns, 1953) and drainage directions were generally southward at the northern end of the basin but paleodrainage networks have not been fully studied.

During the early Miocene, with the Sangre de Cristo Mountains emerging as a source area, the Nambé Member of the Tesuque Formation was deposited to the southeast, sedimentary rocks were deposited in the northeast (near Embudo), and the Chama-el rito Member was deposited on the northwest. These deposits are primarily conformable on the older tuffaceous units but do show unconformable contacts in local areas of deformation, especially near developing margins of the Española basin.

On the west, the Chama-el rito Member extended beyond the present rift boundary although perhaps not as far as the Abiquiu Tuff. Both units have been faulted by western boundary faults. A capping flow of Lobato Basalt (uppermost Miocene) is offset as much as 320 m near Cañones. There are no coarse fanglomerate deposits in the Chama-el rito here, so there is no evidence that the boundary faults were in existence yet as an active fault system.

As this early Miocene interval of deposition progressed, the intermediate volcanic detritus entering the basin from north and south decreased. The decrease was earliest and most pronounced at the southern end of the basin. To the north, volcanic clasts mixed with Paleozoic and Precambrian clasts. Further north, the interfingering Los Pinos Formation continued to be predominantly volcaniclastic. The interfingering relationships of these formations near Ojo Caliente has been mapped by S. J. May (1977, written commun.)

In mid-Miocene, basaltic volcanism occurred within the basin along north-south faults north of the present Jemez Mountains. Flows interbedded with the Chama-el rito Member and dikes crosscutting the Abiquiu Tuff range from 13 to 9 m.y. in age (H. H. Mehnert 1977, written commun.). These eruptions indicate the onset of volcanism that culminated in the accumulation of the Jemez Mountains volcanic pile. They may also be an indication of the initiation of faulting which produced the present western rift boundary in the Española basin.

Also in mid-Miocene a major stream became established in the northern part of the basin (Manley, 1974; 1976c). This mid-Miocene stream flowed westward from the Sangre de Cristo Mountains through the Picuris embayment. Coarse, well-rounded gravel of Precambrian and Paleozoic clasts implies considerable positive relief within the Sangre de Cristo Mountains. The stream may have terminated in a closed-basin lake, whose deposits are as yet unrecognized, or it may have exited the basin by an unknown route in which case the most plausible route would have been into the San Juan basin. There are no deposits of the appropriate age exposed in either the Santo Domingo or San Juan basins. In the Albuquerque-Belen basin, correlative deposits (lower part of Cochiti Formation) give no indication of a major stream.

The upper Miocene Chamita Formation of Galusha and Blick (1971) was deposited by westward flowing streams (Manley, 1976c); however, the major stream established in the mid-Miocene had become less competent and more braided and the axis of the basin appears to have been shifting eastward as the basin filled. Playa deposits, present in probable correlative beds, imply a closed basin at this time. In none of the Chamita Formation exposures is there an indication of through-going drainage.

The Velarde graben formed in early Pliocene. Motion along its boundary faults may have begun in the late Miocene but the greatest amount of deformation occurred in the short interval between 5 and

3 m.y.; the Chamita Formation was displaced at least 300 m. Thereafter the entire basin underwent a period of erosion that removed the Chamita Formation from the surrounding highlands and left it preserved primarily within the graben.

Renewed tectonism and volcanism in the late Pliocene is implied by the deposition of the Puye and Ancha Formations, and the eruption of basalts at Black Mesa and in the Cerros del Rio volcanic field. Continued downdropping of the Velarde graben resulted in thick accumulations of the Puye and Ancha Formations within the graben. Outside the graben these formations were subject to continual regrading. Periodic damming of the Rio Grande by flows in the Cerros del Rio field caused changes in the river's course and, at least once, created a large lake that filled much of the basin. A basalt flow that entered the lake has an age of 2.1 m.y. (R. L. Smith 1974, written commun.).

In the Pleistocene, erosion dominated the history of the basin with the exception of the eruption of the Bandelier Tuff. The basin was excavated to its present configuration with only a few standstills that allowed for the formation of minor surfaces. Velarde graben faults were still active: the Pajarito fault offset the 1.1 m.y. Tshirege Member of the Bandelier Tuff (Smith and others, 1970; Doell and others, 1968) and several earthquake epicenters have been plotted near the Pajarito fault in the last decade (Jiracek, 1974).

Age of the Rio Grande

The Rio Grande follows the rift from the San Luis basin in southern Colorado to the southern edge of the state of New Mexico. It serves to connect the structural basins that comprise the rift, therefore its inception as a through-going drainage is significant to rift development.

In the Española basin there is substantial evidence for the age of the Rio Grande. In neither the Tesuque nor the Chamita Formation are there coarse, well-rounded gravels with lithologies from outside the basin. A gravel of this nature is found in the Totavi Lentil at the base of the Puye Formation (Griggs, 1964). These gravels overlie, with angular unconformity, the Chamita Formation. Equally coarse, well-rounded gravel also underlies the Servilleta Formation flow on Black Mesa and unconformably overlies the Chamita Formation. A zircon fission-track age from a pumice bed immediately above the Totavi Lentil is 2.9 m.y. (Manley, 1976a) and the Servilleta flow has a K-Ar age of 2.8 m.y. (Manley 1976b). The Chamita Formation ages of 5 m.y. provide a maximum age control. Thus the Rio Grande became established in the Española basin in conjunction with the mid-Pliocene basin-wide interval of erosion.

RELATIONSHIPS TO OTHER RIFT BASINS

The symmetry of the Española basin differs from adjacent basins to the north and south. Both the San Luis Valley and the Albuquerque-Belen basin have prominent faults along their eastern margins. These faults have a vertical stratigraphic separation of perhaps 1 km and possibly as much as 10 km (Kelley and Northrop, 1975; Gaca and Karig, 1966). Drainage directions in Santa Fe Group deposits in these basins suggest both basins developed from eastward tilting of structural blocks in contrast to the westward tilting in the Española basin. The reasons for this observed difference are unclear but may be related to the presence of individual crustal blocks which have responded to a tensional environment with rotational motion combined with downdropping rather than simple vertical displacement.

The number of radiometric ages available in New Mexico has dramatically increased in the last few years. With these ages it is possible to compare the histories of different areas along the rift.

The chronologies of events from southern Colorado to southern New Mexico show some interesting similarities. Intermediate volcanism was occurring in the early Oligocene (37 to 30 m.y.) in the Las Cruces area (Clemons and Seager, 1973), the Socorro area (Chapin and Seager, 1975), the Santo Domingo subbasin (Bachman and Mehnert, 1978; Weber, 1971; Jaffe and others, 1959), and in the San Juan Mountains (Lipman and others, 1970). These volcanic events are the first in the area following the formation of the late Eocene erosion surface. Near the close of the early Oligocene a period of volcanism extensional faulting began. Suggested ages are 29 m.y. in the Socorro area (Chapin and Seager, 1975) and 28 m.y. in the southern San Juans (Lipman and Mehnert, 1975).

Upper Oligocene volcanic rocks were deposited following another erosional period. At this time basins were partially developed and being filled with volcaniclastic debris: the lower part of the Los Pinos Formation, the Abiquiu and Picuris Tuffs, and the lower part of the Popotosa Formation. Ages for the onset of deposition cluster at 26 m.y. (Lipman and Mehnert, 1975; Bachman and Mehnert, 1978; Manley, unpublished data; Machette, 1978; Lipman and Mehnert, 1978, written commun.; Clemons and Seager, 1973). Chapin and Seager (1975) state that the volcanism between 26 and 20 m.y. in the Socorro area was basaltic andesites. In the Cienega and Arroyo Hondo areas, latites, monzonite, andesite, and basalt were erupted (Sun and Baldwin, 1958). Basalts and rhyolites become more common in the southern San Juans (Lipman and others, 1970).

Throughout the Miocene there were several comparable events from northern and southern ends of the rift. The period of quiescence that is recognized for southern New Mexico (Chapin and Seager, 1975) between 20 and 14 m.y. is not yet documented for the Española basin but may be reflected in the nontuffaceous portion of the Nambé Member of the

Tesuque Formation. Beginning about 14 to 12 m.y. ago, volcanic activity increased. Rhyolites were erupted in the Socorró area (Magdalena Peak, Strawberry Peak, and Socorro Peak) and the Jemez Mountains were initiated as a volcanic field. Somewhat after 9 m.y. deformation increased markedly. The Socorro area was block faulted, the Rincon Valley Formation, containing the 9-m.y.-old Selden basalt flow (Chapin and Seager, 1975), was tilted and beveled, and the Popotosa Formation, containing a 9-m.y.-old basalt in its upper part (Machette, 1978) was tilted and beveled. This time of deformation and erosion could correspond to the erosional period between the Tesuque and Chamita Formations in the Española basin.

In latest Miocene major deformation again occurred or was continuing. Paleobasins in the southern part of the state were disrupted (Chapin and Seager, 1975) and the Velarde graben formed. A subsequent erosional period from roughly 4 to 3 m.y. affected the entire rift. After this erosional period, a number of formations and basalt flows were deposited including the Camp Rice, Sierra Ladrones, Puye, Ancha, and Servilleta Formations and the flows of Mesa Prieta, Santa Ana Mesa (Armstrong and others, 1976), Isleta volcano and Canjilon Hill (Kudo and others, 1977), Chivato Mesa (Lipman and Mehnert, 1978, written commun.), and the Cerros del Rio field (Manley, 1976b; Bachman and Mehnert, 1978).

The initiation of the Rio Grande as a through drainage in the Española basin is established as late Pliocene. Evidence from other basins supports a similar age. River gravels are present beneath Santa Ana Mesa and interfinger with Cerros del Rio flows. The oldest age control at present is provided by a 4 m.y. old basalt (Bachman and Mehnert, 1978) in the Sierra Ladrones Formation. The basalt overlies gravels of the Rio Grande.

REFERENCES

Armstrong, R. L., Speed, R. C., Graustein, W. C., and Young, A. Y., 1976, K-Ar dates from Arizona, Montana, Nevada, Utah, and Wyoming: Isochron/West, no. 16, p. 1-5.

Bachman, G. O. 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.

Bailey, R. A., Smith, R. L. and Ross, C. S., 1969, Stratigraphic nomenclature of volcanic rocks in the Jemez Mountains, New Mexico: U.S. Geological Survey Bulletin 1274-P, 19 p.

Baltz, E. H., Jr., Dixon, G. H., Griggs, R. L., Johnson, R. B., Spiegel, Zane, and Wood, G. H., 1952, First day's road log: New Mexico Geological Society Guidebook 3, p. 12-33.

Berggren, W. A., and Van Couvering, John, 1973, Late Neogene chronostratigraphy, biostratigraphy, biochronology, and paleoclimatology: Woods Hole Oceanographic Institution Technical Report WHOl-73-40: Massachusetts, Woods Hole, 352 p.

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

Boyer, W. W., 1959, Playa deposit in the Bishop's Lodge Member of the Tesuque Formation, Santa Fe County, New Mexico: Journal of Sedimentary Petrology, v. 29, no. 1, p. 64-72.

Cabot, E. C., 1938, Fault border of the Sangre de Cristo Mountains north of Santa Fe, New Mexico: Journal of Geology, v. 46, p. 88-105.

Chapin, C. E., 1971, The Rio Grande rift; Part 1, 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.

Church, F., and Hack, J. T., 1939, An exhumed erosion surface in the Jemez Mountains, New Mexico: Journal of Geology, v. 47, p. 613-629.

Clemons, R. E., and Seager, W. R., 1973, Geology of Souse Springs quadrangle, New Mexico: New Mexico Bureau of Mines and Mineral Resources Bulletin 100, 31 p.

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

Davis, A. M., 1975, Tertiary Faunas: American Elsevier Publishing Company, New York, 447 p.

Denny, C. S., 1940, Santa Fe Formation in the Espanola Valley, New Mexico: Geological Society of America Bulletin 51, p. 677-694.

Disbrow, A. E., and Stoll, W. C., 1957, Geology of the Cerrillos area, Santa Fe County, New Mexico: New Mexico Bureau of Mines and Mineral Resources, v. 48, 73 p.

Doell, R. R., Dalrymple, G. B., Smith, R. L., and Bailey, R. A., 1968, Paleomagnetism, Potassium-Argon ages, and geology of rhyolites and associated rocks of the Valles Caldera, New Mexico, in Studies in volcanology, A memoir in honor of Howell Williams: Geological Society of America Memoir 116, p. 211-248.

Evernden, J. F. and Evernden, R. K. S., 1970, The Cenozoic time scale: Geological Society of America Special Paper 124, p. 71-90.

Gaca, J. R., and Karig, D. E., 1966, Gravity survey of the San Luis Valley area, Colorado: U.S. Geological Survey Open-File Report.

Galusha, Ted, 1974, Dating rocks of the Santa Fe Group: programs and problems: New Mexico Geological Society Guidebook 25, p. 283-286.

Galusha, Ted and Blick, J. C., 1971, Stratigraphy of the Santa Fe Group, New Mexico: American Museum of Natural History Bulletin v. 144, no. 1, 127 p.

Griggs, R. L., 1964, Geology and ground-water resources of the Los Alamos area, New Mexico: U.S. Geological Survey Water-Supply Paper 1753, 107 p.

Jaffe, H. W., Gottfried, David, Waring, C. L., and Worthing, H. W., 1959, Lead-alpha age determinatios of accesory minerals of igneous rocks (1953-1957): U.S. Geological Survey Bulletin 1097-B, p. 65-148.

Jiracek, G. R., 1974, Geophysical studies in the Jemez Mountains region, New Mexico: New Mexico Geological Society Guidebook 25, p. 137-144.

Kelley, V. C., 1956, The Rio Grande depression from Taos to Santa Fe: New Mexico Geological Society Guidebook 7, p. 109-114.

Kelley, V. C., and Northrop, S. A., 1975, Geology of Sandia Mountains and vicinity, New Mexico: New Mexico Bureau of Mines and Mineral Resources Memoir 29, 136 p.

Kudo, A. M., Kelley, V. C., Damon, P. E., Shafiqullah, M., 1977, K-Ar ages of basalt flows at Canjilon Hill, Isleta volcano, and the Cat Hills volcanic field, Albuquerque-Belen Basin, central New Mexico: Isochron/West, no. 18, p. 15-16.

Laughlin, A. W., Rehrig, W. A., and Mauger, R. L., 1969, K-Ar chronology and sulfur and strontium isotope ratios at the Questa Mine, New Mexico: Economic Geology, v. 64, p. 903-909.

Lipman, P. W., Steven, T. A., and Mehnert, H. H., 1970, Volcanic history of the San Juan Mountains, Colorado, as indicated by K/Ar dating: Geological Society of America Bulletin 81, p. 2329-2352.

Lipman, P. W., and Mehnert, H. H., 1975, Late Cenozoic basalt volcanism and development of the Rio Grande depression in the Southern Rocky Mountains: Geological Society of America Memoir 116, p. 119-154.

MacFadden, B. J., and Manley, Kim, 1976, Magnetic stratigraphy, tephrochronology, and mammalian biostratigraphy of the type Chamita Formation, north-central New Mexico: Geological Society of America, Abstracts with Programs, v. 8, no. 5, p. 605.

Machette, M. N., 1978, Geologic map of the San Acacia quadrangle, Socorro County, New Mexico: U.S. Geological Survey Geological Quadrangle Map, GQ-1415.

Manley, Kim, 1974, Late Cenozoic history of the Espanola Basin, New Mexico: Geological Society of America, Abstracts with Programs, v. 6, no. 3, p. 213.

_____1976a, Tephrochronology of the Tesuque, Ancha, and Puye Formations of the Santa Fe Group, Espanola Basin, New Mexico: Geological Society of America Abstracts with Programs v. 8, no. 5, p. 606-607.

_____1976b, K-Ar age determinations on Pliocene basalts from the Espanola Basin, New Mexico: Isochron/West, no. 16, p. 29-30.

_____1976c, The late Cenozoic history of the Espanola Basin, New Mexico: Ph D. dissertation, University of Colorado, 171 p.

_____1977, Geologic map of the Cejita Member (new name) of the Tesuque Formation, Espanola basin, New Mexico: U.S. Geological Survey Miscellaneous Field Studies Map, MF-877.

_____ 1978, Pliocene deformation along the Rio Grande rift in the Española basin, New Mexico: Geological Society of America Abstracts with Programs, v. 10, no. 5, p. 233.

Manley, Kim and Naeser, C. W., 1977, Fission-track ages for tephra layers in upper Cenozoic rocks, Espanola Basin, New Mexico: Isochron/West, no. 18, p. 13-14.

Miller, J. P., Montgomery, A. and Sutherland, P. K., 1963, Geology of part of the southern Sangre de Cristo Mountains, New Mexico: New Mexico Bureau of Mines and Mineral Resources Memoir 11, 106 p.

Montgomery, A., 1953, Precambrian geology of the Picuris Range, north-central New Mexico: New Mexico Bureau of Mines and Mineral Resources Bulletin 30, 89 p.

Robinson, Peter, 1957, Age of Galisteo Formation, Santa Fe County, New Mexico: American Association of Petroleum Geologists Bulletin, v. 4, p. 757.

Scott, G. R., 1975, Cenozoic surfaces and deposits in the southern Rocky Mountains, in Cenozoic History of the Southern Rocky Mountains: Geological Society of America Memoir 144, p. 227-248.

Seager, W. R., and Clemons, R. E., 1975, Geology of the Cedar Hills-Selden Hills, Dona Ana County, New Mexico: New Mexico Bureau of Mines and Mineral Resources Circular 133, 23 p.

Smith, H. T. U., 1938, Tertiary Geology of the Abiquiu quadrangle, New Mexico: Journal of Geology, v. 46, no. 7, p. 933-965.

Smith, R. L., and Bailey, R. A., 1968, Stratigraphy, structure, and volcanic evolution of the Jemez Mountains, New Mexico (abst.), in Cenozoic Volcanism in the Southern Rocky Mountains: Quarterly of the Colorado School of Mines, v. 63, no. 3, p. 259-260.

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

Spiegel, Z., and Baldwin, Brewster, 1963, Geology and water resources of the Santa Fe area, New Mexico: U.S. Geological Survey Water-Supply Paper 1525, 258 p.

Stearns, C. E., 1943, The Galisteo Formation of north-central New Mexico: Journal of Geology, v. 51, p. 301-319.

_____ 1953, Tertiary geology of the Galisteo-Tongue area, New Mexico: Geological Society of America Bulletin, v. 64, no. 4, p. 459-508.

Sun, Ming-Shan, and Baldwin, Brewster, 1958, Volcanic rocks of the Cienega area, Santa Fe County, New Mexico: New Mexico Bureau of Mines and Mineral Resources Bulletin 54, 80 p.

Sutherland, P. K., 1972, Pennsylvanian stratigraphy, southern Sangre de Cristo Mountains, New Mexico, in Mallory, W. W., ed., Geologic Atlas of the Rocky Mountain Region, p. 139-142.

Weber, R. H., 1971, K-Ar ages of Tertiary igneous rocks in central and western New Mexico: Isochron/West, v. 71, no. 1, p. 33-45.

Wood, H. E., II, Chaney, R. W., Clark, John, Colbert, E. H., Jepsen, G. L., Reeside, J. B., Jr., and Stock, Chester, 1941, Nomenclature and correlation of the North American continental Tertiary: Geological Society of America Bulletin, v. 52, p. 1-48.

Woodburne, M. O., Tedford, R. H., Stevens, M. S., and Taylor, B. E., 1974, Early Miocene mammalian faunas, Mojave Desert, California: Journal of Paleontology, v. 48, no. 1, p. 6-26.

Woodward, L. A., 1974, Tectonics of central-northern New Mexico: New Mexico Geological Society Guidebook 25, p. 123-129.