The southern Rocky Mountains in west-central New Mexico--Laramide structures and their impact on the Rio Grande rift extension

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The southern Rocky Mountains in west-central New Mexico—Laramide structures and their impact on the Rio Grande rift extension

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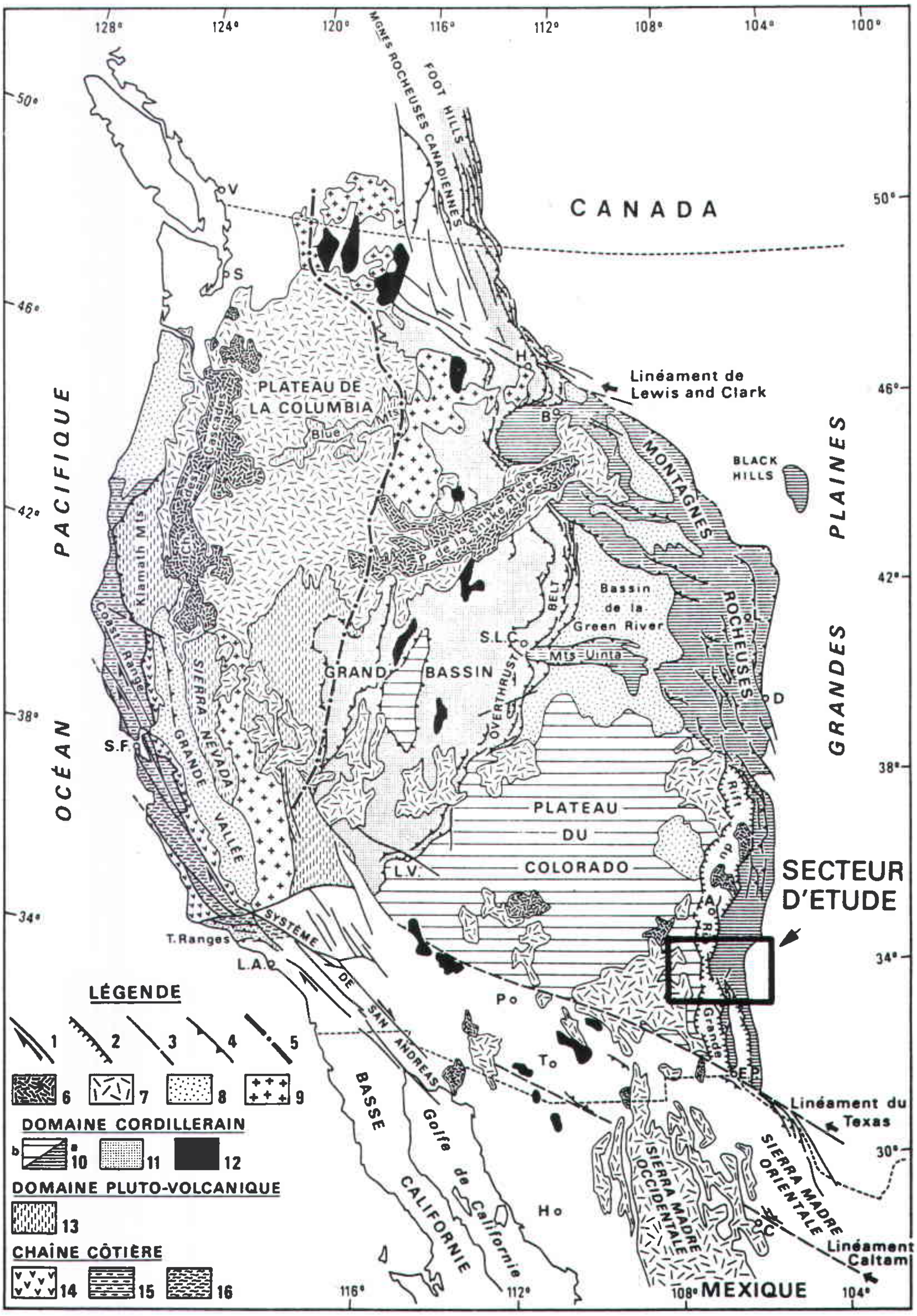

FIGURE 1—Structural map of the western United States Cordillera (modified from Auboin et al., 1986). Legend:
1, transcurrent fault;
2, normal fault;
3, fault undifferentiated;
4, thrust fault;
5, strontium line ($^{87}Sr/^{86}Sr = 0.706$);
6, Quaternary volcanism;
7, Tertiary volcanism;
8, main basins;
9, granites (large batholiths inside and outside the pluto-volcanic axis where small batholiths are not detailed).
10–12, Cordillera area:
10, autochthonous
a, deformed during Laramian orogeny;
b, not deformed;
11, allochthonous;
12, main "metamorphic core complexes."
13, pluto-volcanic area.
14–16, Coast Range:
14, Great Valley units, with ophiolites;
15, Franciscan units;
16, Salinian block.
A, Albuquerque; **B,** Boise; **C,** Chihuahua; **D,** Denver, **EP,** El Paso; **H,** Helena; **H,** Hermosillo; **L,** Laramie, **LA,** Los Angeles, **LV,** Las Vegas; **P,** Phoenix; **S,** Seattle; **SF,** San Francisco; **SLC,** Salt Lake City; **T,** Tucson; **V,** Vancouver.

(Contents on next page)

Pascal Cabezas participated in a long-term "student program" of French doctoral students in the U.S. and Canada from a number of French universities, initiated in 1978 by Société Nationale Elf Aquitaine. The company's American (EAP) and Canadian (ACC) branches supported this program both logistically and technically.

Mapping and field work in the West American Cordillera was carried out during the summer months from 1979 through 1988 by 12 students. Lab work and thesis writing took place during wintertime at the French universities. Participants were supervised by French and American thesis advisors. Students were able to maintain close contact with American universities, scientific organizations, and the USGS. Cooperation and good understanding between French and American scientists were very pleasant byproducts of this "student program."

Pascal Cabezas participated as the ninth student in the program. He carried out extensive field work, including mapping in central New Mexico. He was based in Socorro during three consecutive summers (1985–1987) and was in close contact with the New Mexico Bureau of Mines and Mineral Resources.

Pascal Cabezas received his doctoral degree in 1989 from the University of Nice and Sophia Antipolis (France). He published the main results of his dissertation in the Bulletin Centres de Recherches Exploration–Production Elf Aquitaine, v. 13, no. 2, pp. 229–245, Dec. 4, 1989, Boussens, France, from which the present text has been translated.

Mathis A. Zimmermann
Denver, Colorado
February 25, 1991

This paper is important because it presents a comprehensive synthesis of the Cenozoic tectonic evolution of the Socorro region as seen through "new" eyes. Not everyone will agree with the interpretations and some ideas may not stand the test of time, as is generally true of all geologic investigations. But the ideas, so well illustrated in the maps and cross sections for which the French are famous, should provoke much discussion and a fresh look at the geology of central New Mexico.

Pascal Cabezas accomplished a remarkable amount of mapping and synthesis in three short field seasons, in a strange country, and largely on his own. I was privileged to accompany Pascal and his French advisors during some of their field checks. I was especially impressed with the beautiful sketches they made at nearly every stop. I felt like an amateur as I stood there merely looking at the geologic structures while they industriously sketched them in their field notebooks. And I wondered if I could have accomplished so much had I been assigned a comparable area in a foreign country with three field seasons to get it done.

The student program initiated by Elf Aquitaine is an excellent example of how company participation in the education process can benefit an exploration project and also help assure a future supply of well-trained geologists. Mathis Zimmermann was Resident Manager for Elf Aquitaine during Pascal's project and a member of Pascal's doctoral committee. I wish to acknowledge his contributions here and to thank him for his help in translating the paper. Thanks are also due to Dr. Jacques Renault of the Bureau staff who did the original translation from the French. The maps and cross sections were not relabeled in English because it is quite easy to understand them in French; the figure captions in the original publication were printed in both French and English, so the original English version has been used here. We also thank Elf Aquitaine for permission to reprint the paper.

Charles Chapin
Director and
State Geologist

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INTRODUCTION

The region studied is located in New Mexico in the folded and faulted foreland of the western American Cordilleran system, which extends for more than 4,800 km from Alaska in the north to Mexico in the south.

This folded and faulted foreland (Rocky Mountain foreland) abuts in the east on the Great Plains, a vast region of little deformation, and is bordered on the west by an eastward vergent overthrust belt emplaced during the Late Cretaceous and early Tertiary. Underlain by the Precambrian metamorphic and granitic series of the American craton, the foreland includes two great domains (Fig. 1): 1) the Colorado Plateau, a segment of the American platform cut by large monoclinal folds; 2) the central and southern Rocky Mountains, which form a chain of basement-cored mountains whose large lenticular slices are imbricated by reverse faults. Faulting and folding occurred for the most part during the Late Cretaceous–early Tertiary. From central Colorado through New Mexico, the Rio Grande rift of Miocene to Pliocene age is superposed on the southern Rocky Mountains. This has resulted in a complex tectonic evolution where the geometries of compressional structures have been dismembered by later extension, resulting in discontinuous structures. Nevertheless, the quality of the outcrops and subsurface data (COCORP seismic reflection profiles) permit a tentative reconstruction of its tectonic history.

The field area studied is located in the region of Socorro, between the Colorado Plateau to the west and the Great Plains to the east (Fig. 2). It is bordered on the east by the Manzano–Los Pinos Mountains and the Cerro del Viboro [also known as Loma

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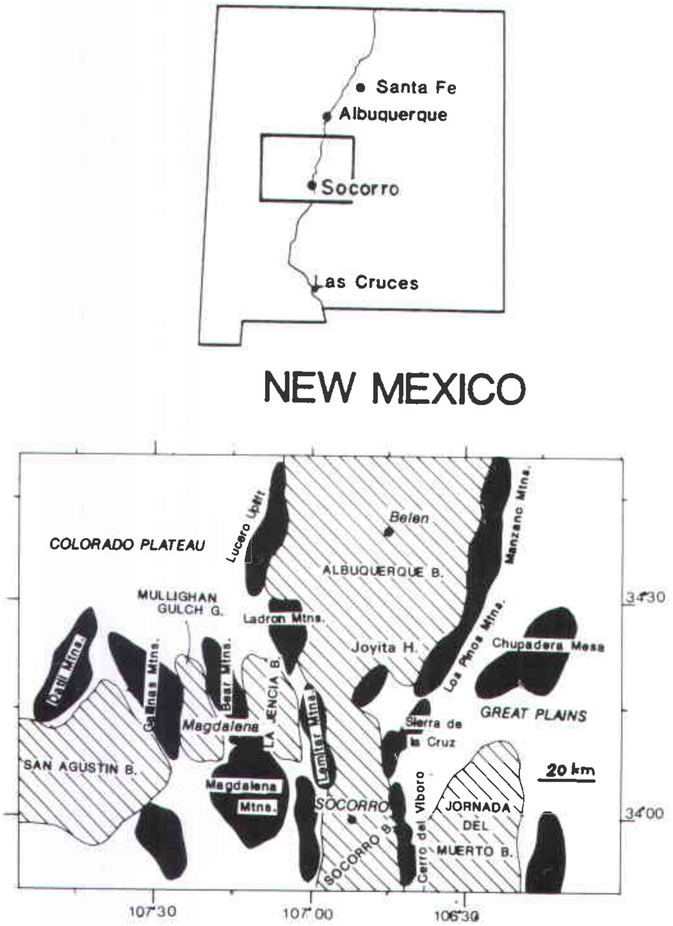

FIGURE 2—The main morpho-structural ensembles of the Socorro region.

de las Cañas–Ed.] and on the west by the Lucero uplift and the Ladron Mountains. In the middle, the Albuquerque and Socorro Basins form part of the Rio Grande rift, and to the southwest the Datil–Mogollon volcanic field (Oligocene to Recent) masks the earlier structures. This is a key area to study the structural evolution of the southern Rocky Mountains and the effect of more recent extension by the Rio Grande rift.

First, the stratigraphy of the region is described briefly, with special emphasis on the syn- and post-orogenic deposits. Main attention is given to the structural geometries and tectonic displacements that were caused first by early Tertiary compression, and then by Neogene extension. In conclusion, a schematic regional tectonic evolution is presented.

STRATIGRAPHY

The studied region contains a very incomplete stratigraphic column ranging from Proterozoic to Recent.

The basement is represented by polymetamorphic rocks (phyllites, schists, and gneisses) intruded by middle Proterozoic granitic and gabbroic bodies (1,660 to 1,380 Ma; Condie, 1981; Bowring et al., 1983). As a result of major unconformities, the overlying Phanerozoic is divided into three stratigraphic assemblages.

Upper Paleozoic to Mesozoic preorogenic deposits

Upper Paleozoic

Because the lower Paleozoic is missing, the oldest sediments lying on the Precambrian basement are locally preserved, massive gray epicontinental carbonates of the Kelly Formation (Mississippian) (Fig. 3) (maximum 30 m). The overlying upper Paleozoic rocks comprise the Magdalena Group (Pennsylvanian to basal Permian) and the Manzano Group (Permian). [Manzano Group was a stratigraphic name used by Lee and Girty (1909); it was abandoned by the U.S. Geological Survey and now is obsolete.–Ed.]

The Magdalena Group (Fig. 3) constitutes a complete cycle of four sedimentary packages. 1) The transgressive Sandia Formation is characterized by coarse-grained, crossbedded quartz sandstones and encrinites alternating with shales and platform limestones. 2) The lower gray limestone member of the Madera Formation is composed of very fossiliferous, massive gray carbonates, typical of platform sedimentation in an open marine environment. 3) These are overlain by platform carbonates and terrigenous sediments of the arkosic limestone member of the Madera Formation. 4) The Bursum Formation is characterized by the appearance of red beds (continental?) alternating with marine carbonates indicating regression. This formation is transitional between the marine carbonates of the Madera Formation and the continental basal rocks of the Manzano Group.

The average thickness of the Magdalena Group is from 600 to 800 m. One of the main characteristics is the presence of reduced and condensed series (0–140 m), indicating the existence of shallow or emergent zones in the Pennsylvanian (Kottlowski and Stewart, 1970).

The Manzano Group (Fig. 3) (see note above) is from 520 to 680 m thick and includes from bottom to top: 1) the dark-red Abo Formation is continental as indicated by the presence of mudcracks and imprints of raindrops and plants. 2) The Yeso Formation is essentially terrigenous; the sandstones of its Meseta Blanca Member mark the beginning of the Permian transgression toward the north that is completed by the carbonates of the Torres Member (McKee, 1967; Kottlowski, 1963). The top of the Yeso Formation (top of the Torres Member and Cañas Member) is rich in evaporites indicating a lagoonal environment. 3) The gray to yellow sandstones of the Glorieta Formation are composed of well-sorted and rounded grains derived from ancient beach sands and enclose an evaporite horizon near Riley. 4) The carbonates of the San Andres Formation were deposited at the maximum extent of the Permian transgression. The presence of evaporites near Socorro indicates, however, a restricted marine environment.

The sea withdrew after deposition of the San Andres Formation. This withdrawal is documented by a karst surface containing pockets filled with sand of the Upper Permian Bernal Formation (Tonking, 1957; Smith and Budding, 1959).

Mesozoic

Only Triassic and Upper Cretaceous strata crop out in the Socorro region (Fig. 3).

The Triassic is represented by alternating shales, sandstones, and red conglomerates (average thickness: 250 m). They are of continental origin as indicated by mudcracks, the red color of the sediments, and the imprints of plants. The pelitic rocks represent deposits of an alluvial plain, and the sandstones and conglomerates are channel deposits.

After a long hiatus of erosion and peneplanation, New Mexico was covered again by an epicontinental sea in the Late Cretaceous, resulting in deposition of 560 to 600 m of terrigenous epicontinental deposits interstratified with more typically marine horizons. Two sedimentary cycles are recognized (Hook, 1983; Hook et al., 1983): 1) The Greenhorn cycle (Cenomanian to middle Turonian; Fig. 3) begins with sands of the Dakota Formation and is followed by the lower part of the Mancos Shale (dark marine pelites). The regression is represented by the coastal sands of the Atarque Member of the Tres Hermanos Formation and terminates with deposition of continental deposits (lacustrine and fluvial) of the Carthage Member (Landis et al., 1973). 2) The Carlile cycle (upper Turonian through Coniacian; Fig. 3) begins with coastal sandstones of the Fite Ranch Member. The sea transgressed toward the east–southeast and attained its maximum extent during

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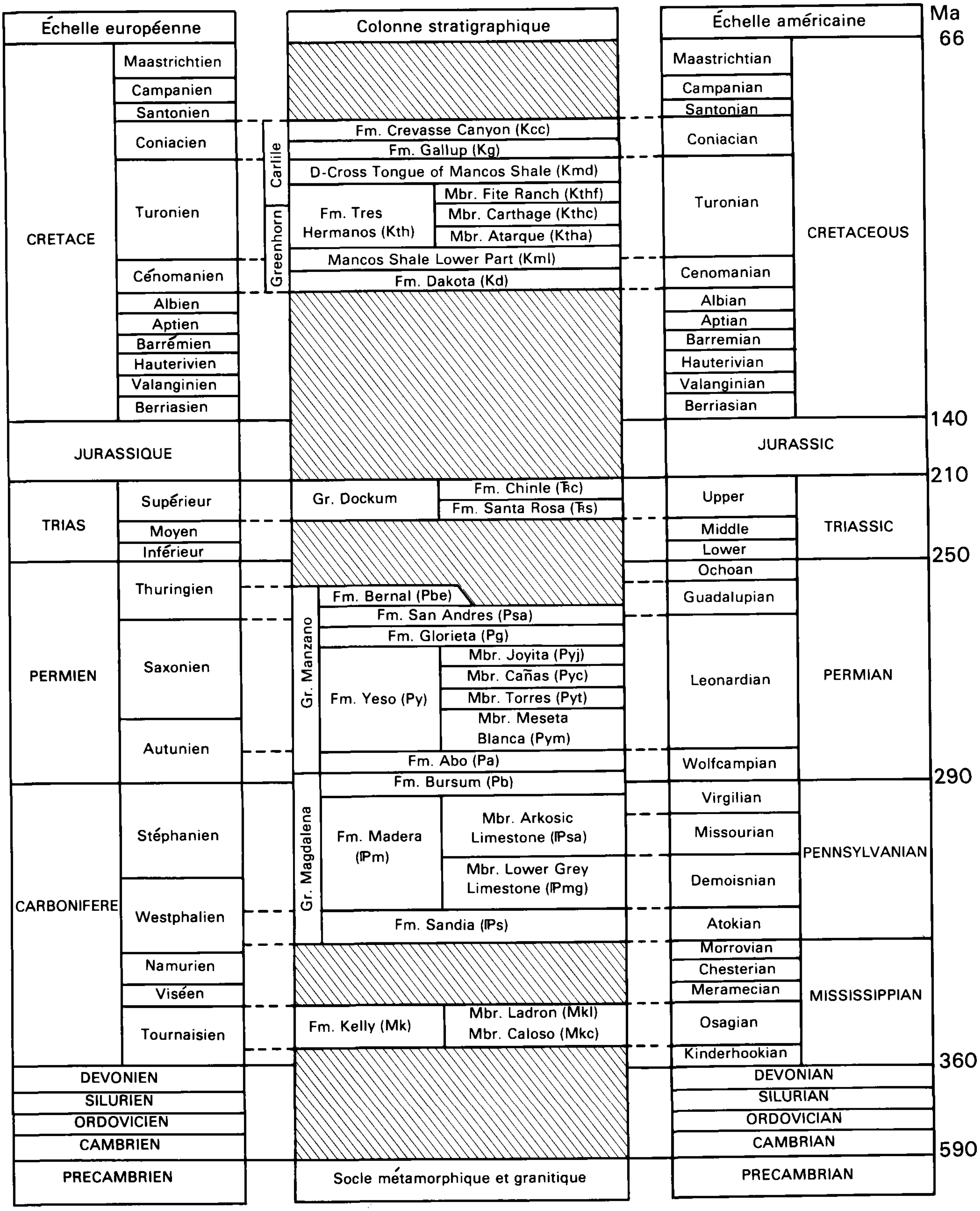

FIGURE 3—Precambrian to Mesozoic stratigraphic chart for the Socorro region.

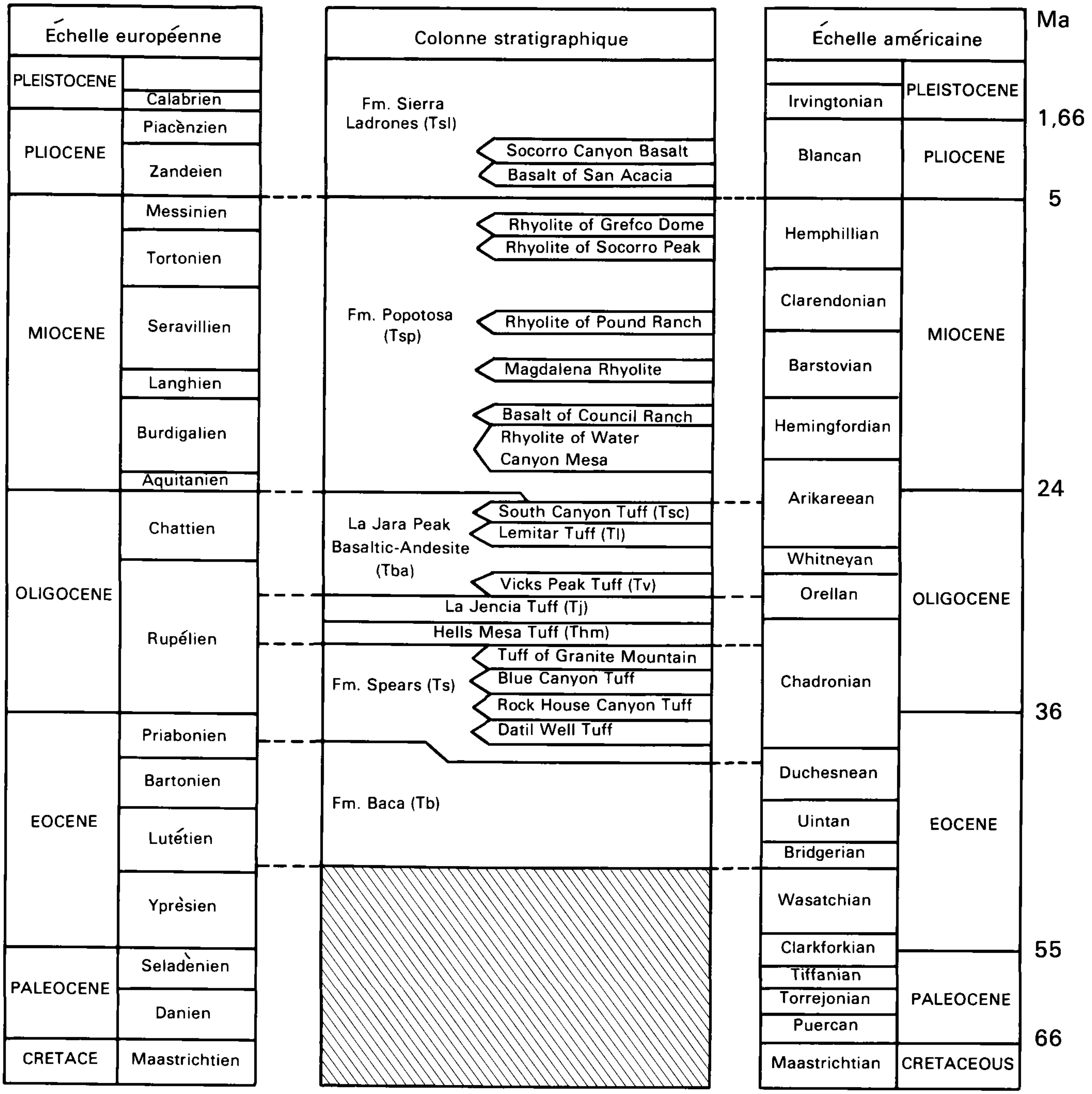

FIGURE 4—Cenozoic stratigraphic chart for the Socorro region.

deposition of marine shale deposits of the D-Cross Tongue. The sandstones of the Gallup Formation mark the beginning of regression. The Crevasse Canyon Formation, composed of shales and sands grading into carbonaceous material (sedimentation in a deltaic or lagoonal environment, Johansen, 1983), ends the cycle.

Middle Eocene to Oligocene

After uplift of the Rocky Mountains and before opening of the Rio Grande rift, the following strata were emplaced. At the base, the Baca Formation, a post-tectonic molasse, caps the structures of the Rocky Mountains (Cather, 1983) with unconformity. At the top is a thick volcanic and volcaniclastic assemblage (or pile) comprising the Spears Formation and basaltic andesite flows and interstratified tuff horizons.

Baca Formation

The Baca Formation is composed of coarse-grained sands and boulder conglomerates (35 to 230 m thick) characterized by the presence of Precambrian granite boulders and by the absence of volcanic clasts. The formation lies with angular unconformity on a peneplaned surface of Pennsylvanian, Permian, Triassic, or Upper Cretaceous strata. It contains reworked clasts of all these rocks indicating tectonic uplift subsequent to the Coniacian and prior to its deposition. In west-central New Mexico, the Baca Formation includes vertebrate fragments of middle to late Eocene age (Snyder, 1970; Schiebout and Schrodt, 1981; Lucas et al., 1981; Lucas, 1982). It is covered by the volcaniclastic Spears Formation. Radiometric dates on andesite clasts taken from the basal Spears

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indicate K/Ar ages of 39.6 ± 1.5 Ma and 38.6 ± 1.5 Ma (Osburn and Chapin, 1983) giving a late Eocene age as an upper limit to the Baca Formation.

Late Eocene–Oligocene volcanism

Beginning in the late Eocene a large volcanic area, the Mogollon–Datil volcanic field, manifested itself in southwestern New Mexico with the development of calderas, some as large as 30 km in diameter. This volcanism possesses calc-alkaline affinities (Chapin and Seager, 1975; Elston and Bornhorst, 1979; Morgan et al., 1986). These authors recognize two periods of activity. The first, from 40 Ma to 36 Ma (late Eocene), is characterized by potassic calc-alkaline volcanism with emplacement of lahars and andesitic flows that form the base of the Spears Formation (Chapin and Seager, 1975; Osburn and Chapin, 1983; Cather, 1986; Morgan et al., 1986; Chapin et al., 1987). The second, between 36 Ma and 30 Ma (early Oligocene), is marked by the regional emplacement of the first rhyolitic and rhyodacitic tuffs intercalated in volcaniclastic horizons at the top of the Spears Formation (Chapin and Seager, 1975; Osburn and Chapin, 1983; Cather, 1986; Morgan et al., 1986).

Oligocene to Recent opening of the Rio Grande rift

In the region of Socorro, most authors place the opening of the rift around 29 to 31 Ma (bracketed by late Oligocene to early Miocene; Chapin and Seager, 1975; Chapin, 1979; Chamberlin, 1983; Chapin et al., 1987; Morgan et al., 1986) and distinguish two periods of deformation recorded in the sedimentation.

The first, from late Oligocene to early Miocene (Fig. 4), is recognized by epigene dikes and sills dated between 31.3 and 24.3 Ma (late Oligocene; Aldrich et al., 1986) in the region of the Rio Salado and by basalt flows and basaltic andesites dated between 30 and 24 Ma (Chapin and Seager, 1975; Elston, 1984; Morgan et al., 1986) displaying calc-alkaline affinities. This volcanic activity is related to the initial extension of the late Oligocene to Miocene basins of the rift, which are filled by as much as 2,500 m of continental terrigenous deposits (Popotosa Formation) lying unconformably on older formations (Machette, 1978).

The second period of deformation ranges from late Miocene to early Pliocene (Fig. 4) and was accompanied by basaltic volcanism with tholeiitic or alkaline affinities dated between 8.3 ± 0.2 and 0.5 ± 0.02 Ma (late Miocene to Holocene; Bachman and Mehnert, 1978; Baldridge et al., 1987). The modern basins of the rift opened during this period and were filled with up to 900 m of continental deposits of the Sierra Ladrones Formation (Pliocene).

TECTONICS

One of the main features of the Socorro region is the Rio Grande rift, a great structural depression extending for more than 1,000 km from Leadville, Colorado, to El Paso, Texas. It is marked by elongated north–south basins separated by mountainous massifs, which have undergone commonly more than a kilometer of erosion. In the study area, the rift is broken into asymmetric north–south-trending basins (Albuquerque, Socorro, La Jencia, Jornada del Muerto, and Mulligan Gulch Basins) separated by tilted horst blocks of the same orientation (Lemitar, Magdalena, Bear, and Gallinas Mountains).

The rift and its fill masks, in large part, older structures that tend to be overlooked. Before its opening, two periods of structural deformation are observed: one in the early Pennsylvanian to early Permian, then a major one from late Paleocene to middle Eocene that was connected with the uplift of the Rocky Mountains.

Late Paleozoic tectonism

Arguments in favor of a tectonic event in the late Paleozoic are, in this region, mainly stratigraphic. They depend on evidence of a north–south paleotopographic high (Armstrong et al., 1979), which is covered by a reduced and condensed Pennsylvanian to Lower Permian section and, in turn, overlain by the Abo Formation (Lower Permian) whose basal contact is an erosion surface. Even though the tectonic uplift causing this paleotopography has not been documented structurally in the field, the absence of an angular unconformity at the base of the Abo Formation and the notable differences in deformation style between the Pennsylvanian and the Permian argue in favor of extensional tectonics. This uplift ceases to exist at the base of the Permian because the Abo Formation (Lower Permian) buries the paleotopography; the time of its inception remains to be determined in this area.

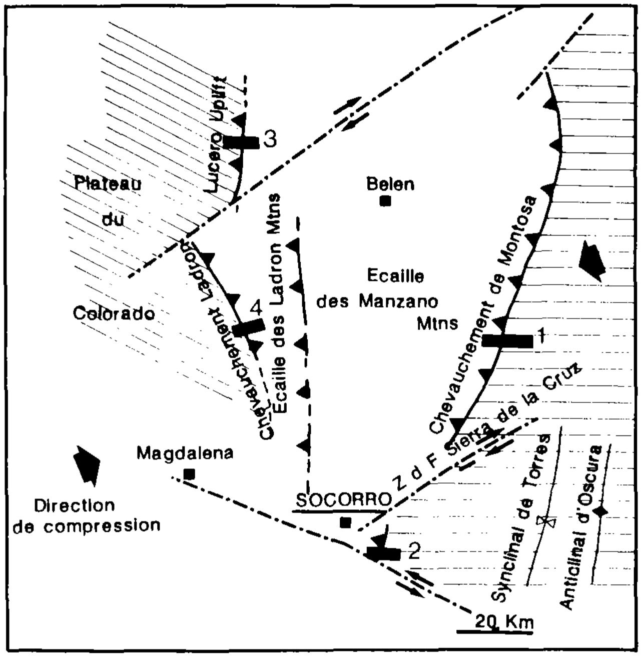

FIGURE 5—The main structural ensembles of the southern Rocky Mountains. [1–4, cross section lines for Figs. 6 and 7.–Ed.]

Compressive tectonism of the Rocky Mountains (Laramide orogeny)

Field studies, complemented by analysis of COCORP (Consortium for Continental Reflection Profiling) seismic profiles, show that compressive tectonism can be subdivided into two phases: 1) a major east–west compression resulting in the imbrication of north–south-oriented crustal slices with eastward vergence; 2) transpression of less importance marked by right-lateral displacements of north–south orientation on the eastern border of the Colorado Plateau.

In the region of Socorro, the Baca Formation conceals most compressive structures of the Rocky Mountains. In the absence of Upper Cretaceous sediments and Paleocene or lower Eocene sediments, the exact age of the beginning of compressive tectonic movement could not be established. The work of Baltz (1967) in northwestern New Mexico suggests a latest Paleocene to early Eocene age for the compressive phase and a middle to late Eocene age for the transpressive phase.

Three major compressional regions (Fig. 5)

The western border of the Great Plains—In the east of the study area, the frontalmost compressional structures mark the boundary with the Great Plains. This zone is characterized by

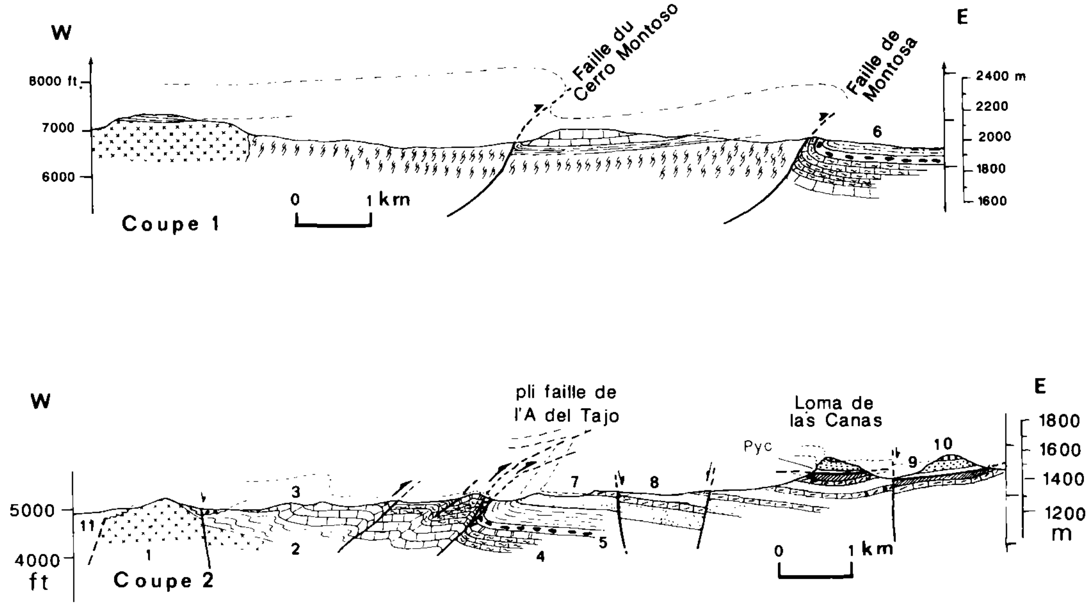

FIGURE 6—Two geologic cross sections of the southern Rocky Mountains front (location on Fig. 5). **1**, Precambrian; **2**, Sandia Fm.; **3**, lower grey limestone mbr.; **4**, arkosic limestone mbr.; **5**, Bursum Fm.; **6**, Abo Fm.; **7**, Meseta Blanca Mbr.; **8**, Torres Mbr.; **9**, Glorieta Fm.; **10**, San Andres Fm.; **11**, Sierra Ladrones Fm.

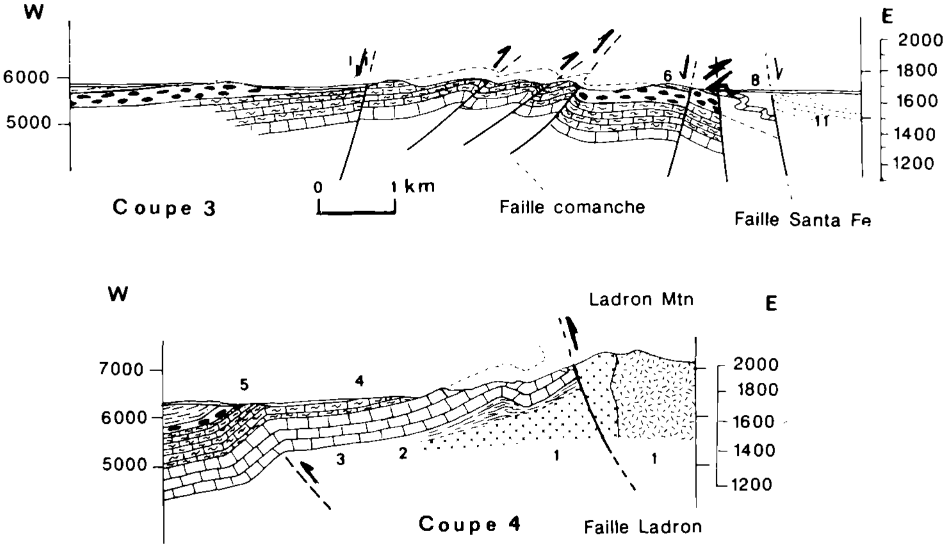

FIGURE 7—Two geologic cross sections of the western boundary of the southern Rocky Mountains (location on Fig. 5; same legend as Fig. 6).

tight, overturned, north–south-striking, east-vergent folds ahead of the thrust front that pass eastward into broad, open, widely spaced (>10 km) folds. The tight folds developed above two levels of detachment observed in the field. The shales of the Sandia Formation (Lower Pennsylvanian) give rise to intense disharmonic folding (Arroyo de los Pinos and Arroyo del Tajo; Cabezas, 1989, p. 150). Another set of widespread spectacular folds developed above evaporites of the Yeso Formation (Upper Permian) that contain subhorizontal detachment surfaces with local lateral ramps marked by tectonic solution breccias up to 20 m thick (Baker Hill; Cabezas, 1989, p. 158, fig. 100). The displacement on these surfaces is accompanied locally by tectonic removal of the gypsiferous interval of the Yeso Formation, of all or part of the Glorieta Formation, and sometimes of part of the San Andres Formation (Fig. 6). These detachments, even if they are spectacular, in no case imply important displacements; the restored cross section indicates a shortening of only 3% (Cabezas, 1989).

The southern Rocky Mountains—The central zone, which is masked in large part by the basin fill of the Rio Grande rift, corresponds to the southern Rocky Mountains sensu strictu.

The overthrust front (Fig. 6) is located at the base of the Manzano–Los Pinos Mountains slice and extends for more than 60 km along the east flank of the Manzano Mountains southward to Arroyo de las Cañas, where it disappears against a more recent normal fault. It can be divided into three segments: 1) to the north,

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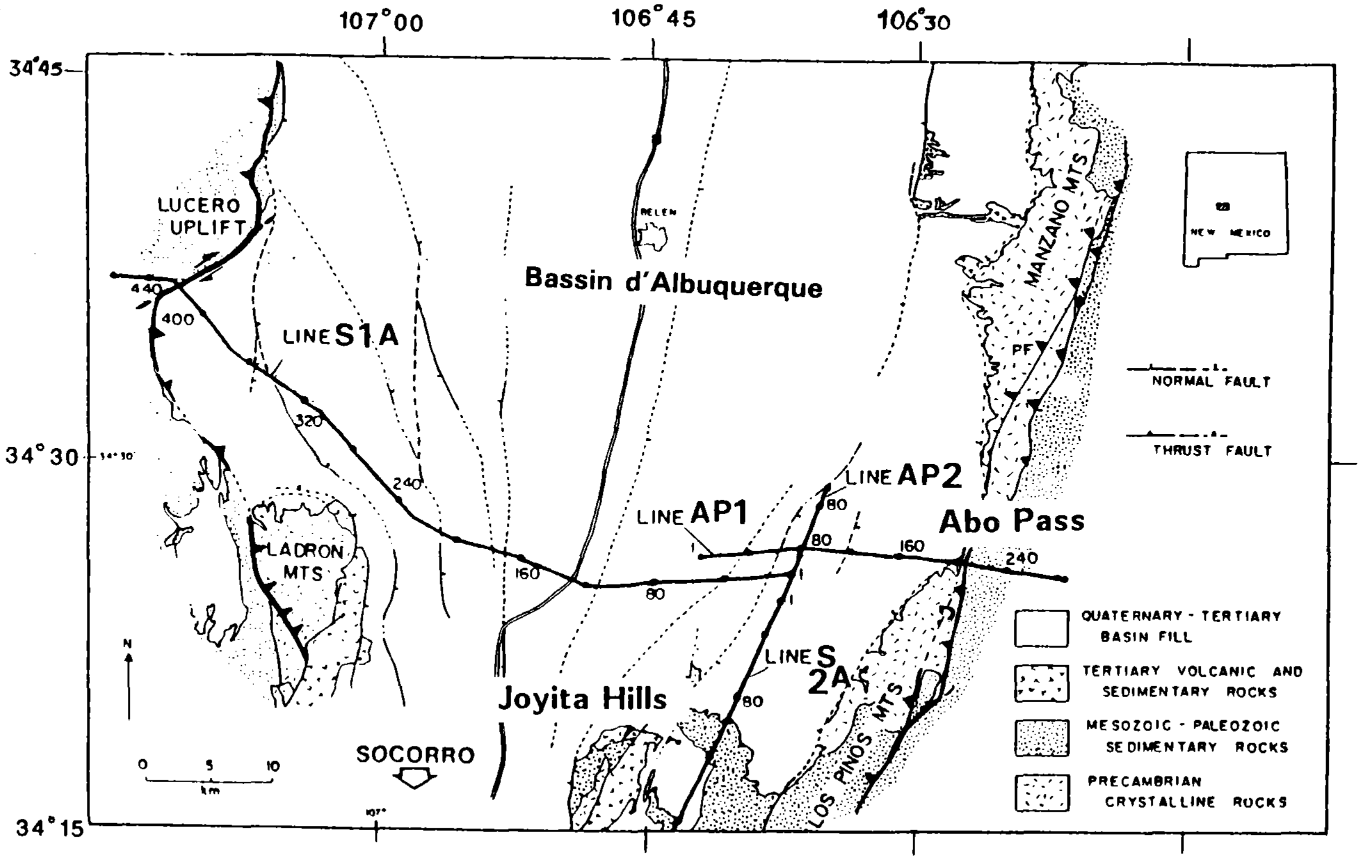

FIGURE 8—Location map of the COCORP line (in Cape et al., 1983).

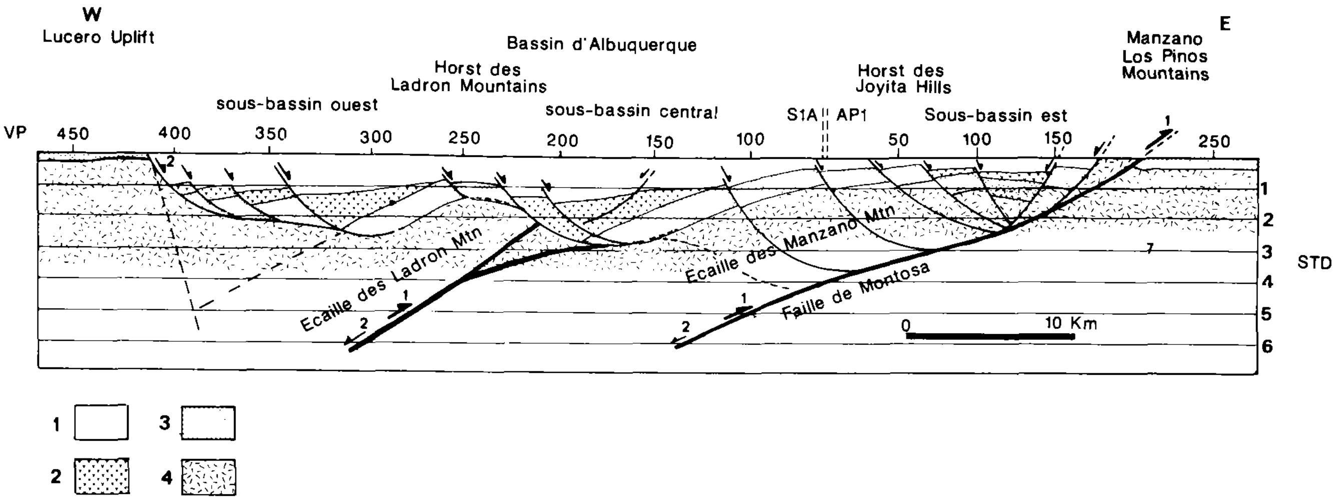

FIGURE 9—Synthetic cross section of the Albuquerque Basin from COCORP data. (Heavy lines are Rocky Mountains thrust faults; thin lines are rift faults.) Legend: **1**, Miocene and Pliocene; **2**, upper Eocene and Oligocene; **3**, Paleozoic and Mesozoic; **4**, Precambrian.

on the east flank of the Manzano and Los Pinos Mountains, it is represented by the Montosa and Cerro Montoso faults, two east-vergent reverse basement structures oriented N15°E. The Paleozoic cover is deformed into large monoclinal east-facing folds. 2) Toward the south, in the area of Sierra de la Cruz and Arroyo Tinajas, the reverse basement faults are intersected by two right-lateral transpressive faults oriented N40°E, the Sierra de la Cruz fault zone and the del Curto fault. The shortening is taken up by north–south-oriented, en echelon folds. 3) Farther to the south, the overriding front reappears in the region of Arroyo del Tajo–Arroyo de las Cañas, where the folds and overthrusts of the cover are oriented N20°W to N20°E. A beautiful example is the faulted fold of Arroyo del Tajo, where the detachment of the cover occurs in the shaly rocks of the Sandia Formation.

The boundary between the southern Rocky Mountains and Colorado Plateau (Fig. 7)—The Comanche overthrust in the Lucero uplift and the Ladron overthrust on the western flank of the Ladron Mountains are the westernmost fractures of Rocky Mountain style observed in the Socorro region. They are considered as marking the border between the Colorado Plateau and the Rocky Mountains. The north–south-trending Comanche overthrust affects rocks of the sedimentary cover (Pennsylvanian and Permian), which are deformed into tight east-vergent folds. The overthrust is cut on the south by the Mesa Aparejo fault, a N45°E transpressive dextral strike-slip fault.

To the south, on the west flank of the Ladron Mountains, the Precambrian basement overrides the Pennsylvanian toward the west along the Ladron overthrust to which are associated monoclinal west-vergent folds. Toward the north, the Ladron thrust can be projected to the Mesa Aparejo fault by the presence of west-vergent monoclinal folds in the prolongation of the Ladron overthrust.

A diagrammatic east–west cross section across the Albuquerque Basin can be drawn by interpreting the combined COCORP seismic lines AP1 (Abo Pass 1) and S1A (Socorro 1A) (Fig. 8) to show the deep geometry of structures under the rift. Two large basement slices of Laramide origin can be observed (Fig. 9): to the east, that of the Manzano and Los Pinos Mountains overlying the Montoso fault (dipping 20° to 40° westward), which is a basement overthrust of easterly vergence; to the west (concealed under the rift fill) that of the Ladron Mountains, underlain by an overthrust dipping 40° to 50° westward. The arching, which expresses itself in the sedimentary cover in the horst of the Ladron Mountains, is associated no doubt with compression.

North of the Ladron Mountains horst the COCORP profile is subparallel to the structures making interpretations inconclusive.

The Colorado Plateau—The western part of the study area belongs to the Colorado Plateau, which is a vast, little-deformed zone characterized by broad folds. In outcrop, these folds involve the Triassic and the Upper Cretaceous, notably in the Riley area north of Magdalena.

The dextral transpressive structures

The north–south-trending Charlie Hill fault (Fig. 10) in the Lucero uplift is a dextral strike-slip fault confirmed by the presence of very steeply plunging, Z-shaped folds associated with nearly horizontal striations in the plane of the fault. This fault cuts folds and overthrusts formed during the major compressive phase. In addition, the Charlie Hill fault cannot be related to rift opening that gave birth to north–south-striking normal faults. Similar right-lateral wrench faults have been described along the eastern border of the Colorado Plateau. For instance, north of the Lucero uplift, the Rio Puerco fault zone was described by Slack and Campbell (1976) as the type pull-apart favored in right-lateral north–south-striking wrench faults. Likewise, Baltz (1967) envisaged a right-lateral wrench fault in the Nacimiento uplift (Fig. 10) and dated it middle to late Eocene.

This wrenching phase is poorly displayed in the Socorro region because of the absence of folds or overthrusts.

Extensional tectonics of the Rio Grande rift

The structural history and magmatic evolution of the Rio Grande rift have been the subject of many investigations (Chapin and Seager, 1975; Chamberlin, 1983; Aldrich et al., 1986; Morgan et al., 1986). New observations in the Lemitar Mountains north of Socorro have allowed the establishment of a tectonic evolution in four stages that is consistent with what is known elsewhere. The chronological evidence for each stage and its deformational characteristics are discussed briefly in the following paragraphs. The subsurface geometry of the rift basins is then examined with special attention to the influence of previous deformations (notably the Laramide structures of the Rocky Mountains) on the extensional geometries.

Tectonic history

Oligocene to early Miocene (Fig. 11–1)—The principal elements that permit dating the beginning of the Rio Grande rift extension in the Rio Salado area are: the emplacement of numerous upper Oligocene (31.3 to 24.3 Ma, Aldrich et al., 1986) basaltic andesite sills and dikes; the angular unconformity of the Popotosa Formation (Miocene) on the Oligocene volcanic formations, especially the South Canyon Tuff, which is dated at 26.3 Ma (Osburn and Chapin, 1983) [since dated at 27.36 ± 0.07 Ma by $^{40}Ar/^{39}Ar$, McIntosh et al., 1990–Ed.]. The dikes of the Rio Salado zone are emplaced along north–south-striking, steeply dipping, normal faults with small displacements (several tens of meters). The method of dihedral angles of Angelier and Mechler (1977) to determine stress orientation at the time of faulting was applied to measurements at four fault sites. The results show that the minimum principal stress σ_3 is subhorizontal and oriented from east–west to N50°W. This direction does not correspond to the one (N70°E) proposed by other authors (Aldrich et al., 1986). It is likely that the results obtained in the Rio Salado zone have only local importance; therefore, it is important to extend these measurements to other areas to determine more reliable regional paleostress orientation. This extension is accompanied by an initial block-tilting stage displayed in the angular unconformity (20° on average) at the base of the Popotosa Formation.

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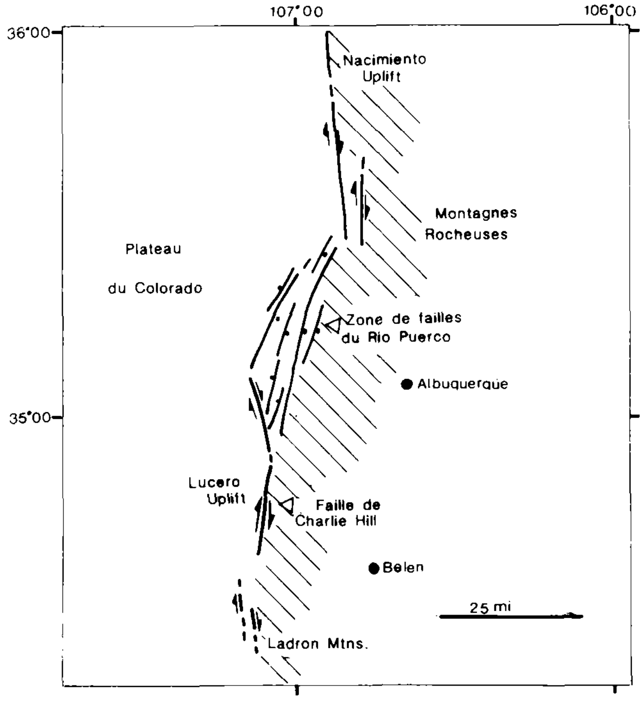

FIGURE 10—Middle to late Eocene wrench faults along the eastern border of the Colorado Plateau (after Baltz, 1978; Slack and Campbell, 1976; and Cabezas, 1989).

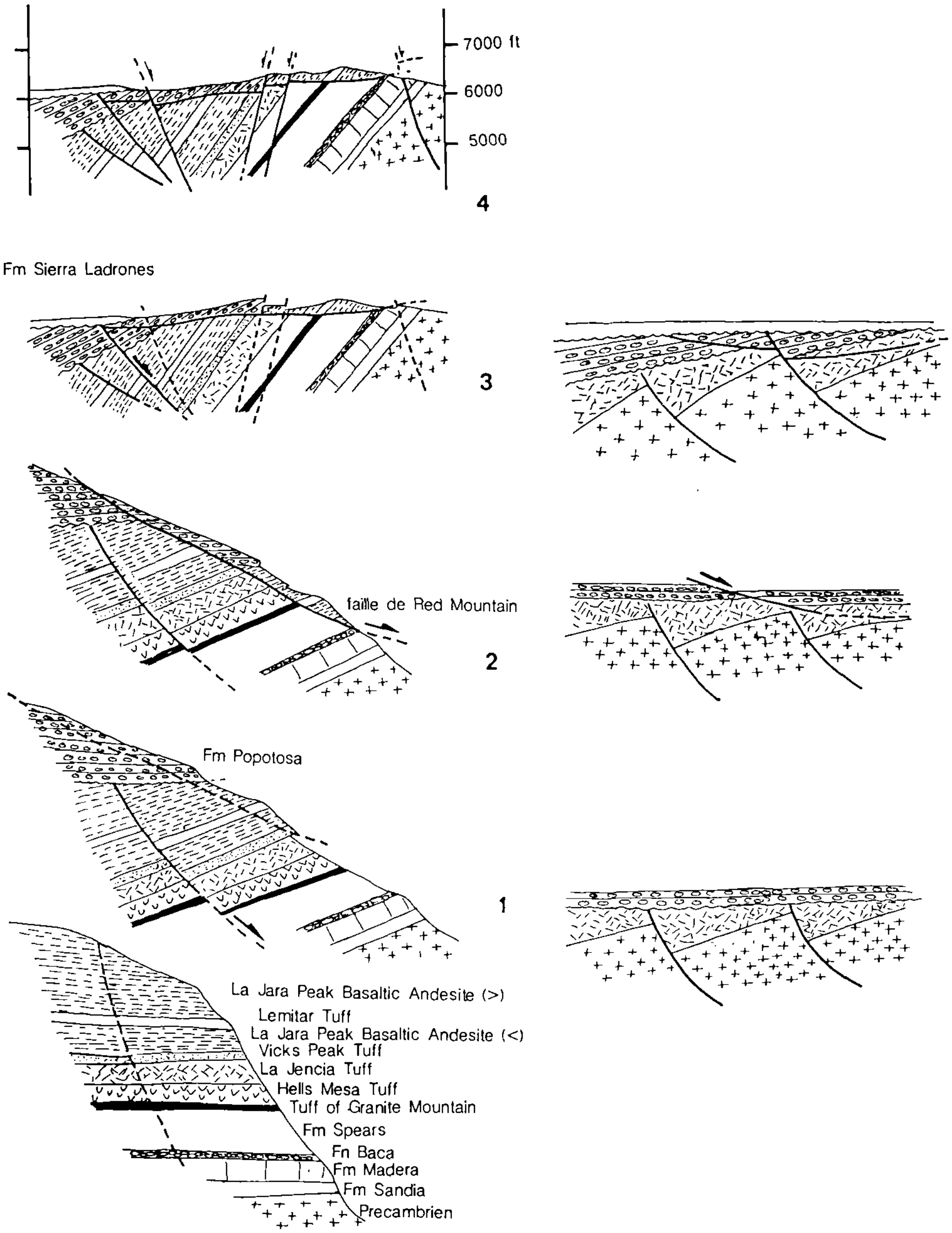

FIGURE 11—Retrotectonic cross sections of the Lemitar Mountains.

Miocene(?) (Fig. 11–2)—A further period of extension (intra-Miocene) caused the associated faults to cut the Popotosa Formation. These faults are themselves cut by younger faults of the third period. A more precise age for these movements depends on a better understanding of the age of the Popotosa Formation in the Lemitar Mountains. In this period falls the displacement of near-surface faults (e.g., Red Mountain fault), which occurs without further tilting of the fault blocks.

Late Miocene to early Pliocene (Fig. 11–3)—An unconformity at the base of the Sierra Ladrones Formation (Pliocene) on the Popotosa Formation (Miocene) marks the beginning of Miocene–Pliocene extension. Eventually, extension continues into the Pliocene as certain faults that affect one part of the Sierra Ladrones Formation are concealed in turn by younger basalts dated by Baldridge et al. (1987) at 3.7 ± 0.4 Ma. A fault with such a history is the Santa Fe fault bounding the Lucero uplift.

This faulting period fixes the geometry of the modern rift basins by normal faults that are either steeply dipping (e.g. Santa Fe fault) or listric (Bustos Well fault east of Socorro), and whose displacements can attain several thousand meters. Paleostress determinations made by the author at seven sites on the border of the rift give consistent results: σ_3 was subhorizontal and oriented east–west, a direction identical to that proposed by other authors (Aldrich et al., 1986). The faulting caused renewed tilting of blocks, notably in the Lemitar Mountains where the angular discordance between the Sierra Ladrones and Popotosa Formations attains 30°.

Late Pliocene to the present (Fig. 11–4)—Extension during this most recent time is the cause of faults affecting the upper Pliocene and Quaternary and of recent active seismicity. Of north–south orientation, the faults are located principally in the rift basins. They are few in number, have small displacements, and have been cataloged by Callender et al. (1983).

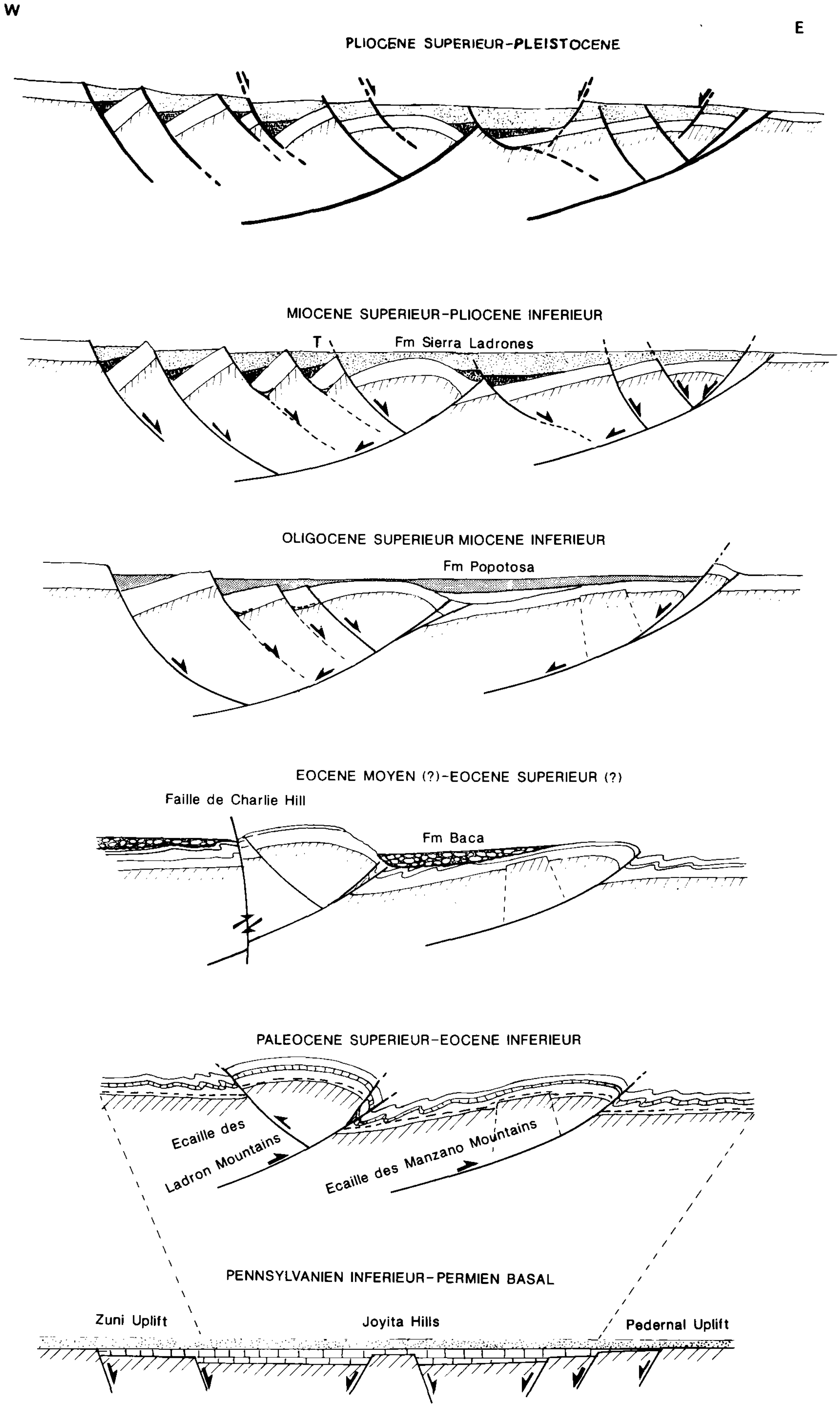

FIGURE 12—Tectonic timing for the Socorro region. (Discussion on p. 36.)

The COCORP seismic profile

The interpretation of the COCORP profile (Fig. 9, the normal faults of the rift are drawn in fine lines) has been discussed on pages 32 and 33. From a morphostructural point of view, the southern Albuquerque Basin is subdivided into three subbasins (east, central, and west) separated by two horsts (Ladron Mountains and Joyita Hills). The west and central subbasins are asymmetric and tilted toward the west and their Miocene–Pliocene sedimentary fill attains 1.5 seconds two-way travel time [approximately 3.5 km–Ed.].

Geometry of the normal faults—At the west end of the profile, the tectonic system is dominated by east-dipping listric faults. They affect the entire sedimentary sequence and often the Precambrian basement. The best example is the east-dipping fault bordering the central subbasin on the west. Between VP 230 and VP 180, at the contact between the Precambrian basement of the Ladron Mountains horst and the Tertiary volcanics, the fault dips steeply to the east. It flattens toward the east to a nearly horizontal attitude between VP 180 and VP 150 in the Paleozoic and Mesozoic cover; east of VP 150 the fault disappears in the Precambrian basement before merging with the Montosa fault.

Faults observed in the west subbasin also seem to be listric and appear to flatten at the basement–sediment contact. It is important to note that this part of the profile is not perpendicular to the directions of faulting. The apparent dip is thus less than the true dip.

Farther east on the profile, on the western flank of the Joyita Hills horst and in the eastern subbasin, dip of the faults varies from moderate to steep. Normal faults merge with the reverse Montosa fault at depths from 2 to 4 seconds two-way travel time [approximately 6 to 12 km–Ed.] without ever cutting it (de Voogd et al., 1986).

Discussion of the COCORP profile interpretation—The normal faults on the east side of the rift, the faults of the Joyita Hills horst and those of the eastern subbasin, do not seem to project very deeply into the crust but abut on, or merge with, the reverse basement faults of Laramide age. This crucial observation implies that these large crustal discontinuities, formed during the Rocky Mountain compression, have been reactivated by the extension with an opposite sense of displacement. Comparable relationships have been observed in the Basin and Range province (Allmendinger et al., 1983).

The models of normal faulting associated with zones of detachment (a zone of weak resistance to shearing such as a basement–sedimentary cover contact, a layer of salt, or a pre-existing fault zone) show that structural evolution can be divided into two stages (Faure and Seguret, 1988): 1) displacement of the upper block along the detachment creates potentially empty space; 2) its collapse causes a rollover or a compensation graben with antithetic normal faults. Structures in the eastern part of the COCORP profile compare favorably with experimental models. In this case, there is at once a compensation graben and a rollover.

In the western part of the Albuquerque Basin, extensional tectonics is dominated by east-dipping listric faults; their dip, approximately 50° near the surface, is close to horizontal at the base of the sedimentary cover. This flattening can be explained by the presence of a horizon of weak resistance to shearing, such as the evaporites of the Yeso Formation or the shales of the Sandia Formation.

In conclusion, it seems that reactivation of Laramide basement faults with an opposite sense of displacement played an important role in the mechanism of extension. It explains the subsidence of the rift basins. The newly formed normal faults are either antithetic faults related to formation of a compensation graben or listric faults flattening in the sedimentary cover.

CONCLUSIONS: TECTONIC EVOLUTION (Fig.12)

Late Paleozoic tectonics (ancestral Rocky Mountains)

In the Pennsylvanian and Early Permian, the North American platform was broken into north–south-trending horsts and grabens mantled by the Lower Permian (Abo Formation). The uplifts (horsts) are characterized by a reduced and condensed sedimentary column.

Compressional tectonics of the Rocky Mountains (Laramide orogeny)

From late Paleocene to early Eocene, compression led to differentiation of the Colorado Plateau, the Rocky Mountains, and the Great Plains. This is principally a compressional basement tectonic style characterized by crustal slices of north–south strike and east vergence being imbricated along reverse faults of shallow dip (Manzano–Los Pinos Mountains plate, Ladron Mountains). The deformation of the sedimentary cover is controlled by the basement blocks and by several levels of detachment. Transverse faults of N45°E orientation with dextral strike slip cut the basement slices (Tijeras–Mesa Aparejo fault, Santa Cruz fault).

By middle late Eocene, dextral north–south wrench faults developed on the eastern border of the Colorado Plateau. This transpressive phase is poorly documented in the Socorro region because of the absence of folds and thrusts. These dextral wrench faults may indicate a displacement of the Colorado Plateau toward the north at the end of the compressive episode of the Rocky Mountains (Chapin and Cather, 1981).

Rio Grande rift

We have discussed above the preponderance of reverse basement faults of Laramide age that represent zones of weakness to shearing reactivated in the opposite sense during extension; this reactivation is sufficient to explain subsidence of the rift basins. As for the recent faults, they are antithetic and related to the formation of a compensation graben or listric flattening in the sedimentary cover.

In the late Oligocene and early Miocene, the beginning of extensional opening is well dated, notably in the area of the Rio Salado northwest of Socorro, by the emplacement of dikes dated as late Oligocene. Basins opening in the course of this phase are filled by the Popotosa Formation of Miocene age, which lies unconformably on Oligocene volcanic and volcaniclastic rocks in the Lemitar Mountains.

The shallow listric faults in the middle Miocene(?) of the Lemitar Mountains are local and do not seem to be associated with this breakup.

From late Miocene(?) to early Pliocene, the second episode of extension resulted in formation of the present rift basins. It is accompanied by a second tilting, producing the angular unconformity of the Sierra Ladrones Formation (Pliocene) that covers the Popotosa Formation (Miocene) and fills the newly opened basins.

From late Pliocene to the present, continued extensional faulting has cut upper Pliocene rocks and Quaternary pediments. This is accompanied by important seismic activity in the region of Socorro and north to Albuquerque.

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