GL00194

COLORADO GEOLOGICAL SURVEY

SPECIAL PUBLICATION 18

A SUMMARY OF THE GEOLOGY OF THE SAN LUIS BASIN, COLORADO-NEW MEXICO WITH EMPHASIS ON THE GEOTHERMAL POTENTIAL FOR THE MONTE VISTA GRABEN

By

Richard L. Burroughs
Consulting Geologist
Alamosa, Colorado

1981

NOTICE

This report has been greatly revised from the original report, "A summary of the geology of the San Luis Basin, Colorado-New Mexico with emphasis on the geothermal potential of the Monte Vista graben," which was funded by the Four Corners Regional Commission, Albuquerque, New Mexico, under FCRC Contract No. 292-399-104-8 entitled Geothermal Agripark Site Demonstration.

DISCLAIMER

NOTICE

NOTICE

CONTENTS

LIST OF FIGURES

LIST OF PLATES

INTRODUCTION

The objective of this report is to review the known geologic data of the San Luis Basin and to relate it to an understanding of the hydrogeothermal potential of the Alamosa-Monte Vista area. The report reviews the physiographic setting of the region; the structural framework of the basin and its influence on the stratigraphic makeup of the rock sequence, which in turn control the occurrence of potential deep water reservoirs. It is here suggested that the San Luis Basin was well-developed by Miocene time; and that although the basin was modified by Neogene faulting, it is essentially a late Laramide event having been produced during the Paleogene. Attention is also given to high heat flow along the Rio Grande Rift and to the geothermal gradient of the San Luis Basin. The "confined" aquifer is then considered in respect to its hydrogeology, water quality, and as to the legal aspects of the system.

PHYSIOGRAPHIC SETTING

The San Luis Basin, an intermontane structural depression, is made up of the San Luis Valley in south-central Colorado and the Taos Plateau in north-central New Mexico. On the east it gives way abruptly along a steep fault scarp to the Sangre de Cristo Range, culminated by 14,363 foot Mt. Blanca. On the west the San Juan Mountains in Colorado and the Tusas Mountain, sometimes referred to as the Brazos Mountains or southern San Juan Mountains, in New Mexico, gradually rise above the valley floor. Upson (1939) subdivided the basin into five physiographic provinces--the Alamosa Basin, the San Luis Hills, the Taos Plateau, the Costilla Plains, and the Culebra Re-entrant--a subdivision generally accepted today (Fig. 1).

STRUCTURE

The San Luis Basin, a complex hinged graben with eastward tilt, is one of a series of enechelon grabens of northerly trend within the Rio Grande Rift--a large extensional feature which trends northward from El Paso, Texas, to Leadville, Colorado. The northern end of the rift began opening about 27 million years ago (m.y.), while the southern end began about 5 m.y. earlier; thus the system tapers northward and pinches out about 12 miles north of Leadville. The grabens making up the rift are arranged northeasterly along the course of the Rio Grande River.

The northern boundary of the San Luis Basin is at Poncha Pass in Colorado and its southern boundary is at the Embudo constriction in New Mexico. The basin is disrupted by an intrarift horst, the San Luis Hills (Fig. 1). These hills consist of a series of upthrown blocks arranged northeasterly across the central part of the basin. They are a physiographic barrier between the San Luis Valley to the north and the Taos Plateau to the south, as well as a structural divide between the northern (Alamosa Basin) and southern (Taos Trough) halves of the San Luis Basin. Extending northward from the San Luis Hills is a buried north-trending fault block with eastward tilt which bifurcates the Alamosa Basin (Fig. 2). The crest of this ridge, the Alamosa horst, is about 5,400 feet beneath the valley floor (Plate 1). It was penetrated by the Amerada Petroleum Corp. No. 1-F State (Sec. 16, T. 39 N., R. 10 E.) which encountered Precambrian rocks at that depth. East of the ridge in the Baca graben the Reserve Oil No. 1-33 NBH Alamosa (Sec. 33, T. 40 N., R. 11 E.) penetrated the Precambrian at 6,880 feet and the Marco - Amoco Production No. 1-32 State (Sec. 32, T. 40 N., R. 12 E.) bottomed at 9,480 feet in Paleocene (?) rocks. At the Marco-Amoco well location, the Precambrian is estimated to be at about 12,000 feet. In the gravity minimum about ten miles north of the Marco-Amoco well the basement is estimated to be about 19,000 feet (Fig. 3). West of the Alamosa horst, in the Monte Vista graben, the Orrin Tucker No. 1 Thomas (Sec. 13 T. 41 N., R. 8 E.) bottomed at 8,023 feet in Eocene (?) rocks and the Tennessee Gas No. 1-B State (Sec. 14 T. 41 N., R. 7 E.) penetrated the Precambrian at 9,920 feet.

When the regional gravity data is considered, it appears that the Tennessee Gas well is near the deepest part of the Monte Vista graben (Fig. 3). The maximum amount of structural relief between the Alamosa horst and the Baca graben is about 13,500 feet. Between the Alamosa horst and the Monte Vista graben the structural relief is about 4,500 feet. Some detailed gravity and seismic data are available for the eastern basin and depth estimates are more accurate there than in the Monte Vista graben, which lacks this type of control. The deepest part of the Monte Vista graben could be 1,000-2,000 feet deeper than that at the Tennessee Gas well location. A well drilled at Monte Vista should penetrate the Precambrian at about 10,000 feet!

The structural and stratigraphic relationships of the Alamosa Basin are shown in Plate 1. The location of the east-west lines of section are plotted on Figure 2. Several important relationships have been illustrated which lead to our understanding of the Alamosa Basin. The relationship between the central horst block (Alamosa horst) and the adjacent structural lows (Baca and Monte Vista grabens) has generally been interpreted as bounded by major normal faults (Fig. 4a). The interpretation is logical when one considers the regional gravity data (Fig. 3) and the depths to the Precambrian at the Tennessee Gas (9,920 feet), Amerada (5,420 feet) and Marco-Amoco (12,000 feet?) well locations. This type of relationship is illustrated in Plate 1 (C-D) between the southward projection of the Tennessee Gas (Monte Vista graben) well and Amerada (Alamosa horst) well.

Figure 4a and 4b

However, between the Amerada well (Alamosa horst) and the Marco-Amoco well (Baca graben) a completely different relationship is shown (Plate 1, A-B). In the latter area some seismic and detailed gravity data are available which greatly aid geologic interpretation (Gries, 1980, personal communication). It is apparent that although pre-Neogene bounding faults are present, along the east side of the Alamosa horst, they do not have several thousand feet of throw. The difference in structural relief from the Alamosa horst to the Baca graben is taken up by additional stratigraphic section of pre-Neogene age. Although doubtful, a similar relationship may exist between the Alamosa horst and the Monte Vista graben. The eastern San Luis Hills with west-facing scarps, consist of a series of uplifted blocks tilted 10-15° southeast (Burroughs, 1971). It is believed that this general relationship also holds true for the major structural elements making up the Alamosa Basin—the deeper basinal features being composed of two pre-Neogene hinged grabens with eastward tilt (Plate 1, A-B; Fig. 4b), at least at this line of section (Fig. 2). Although it is recognized that the terms horst and graben have been defined as structural features bounded by normal faults—and that the subsurface structures of the Alamosa Basin appear to be pre-Neogene tilted fault blocks, bounded by faults on only one side—it does not seem appropriate to discontinue using the terms horst and graben for the features under discussion.

Alamosa Basin—Age of Development

The Oligocene Fish Canyon (27.8 m.y.) (Steven and others, 1974) and Carpenter Ridge ash flow tuffs are believed to have been penetrated at about 2,100 feet in the Tennessee Gas well (Plate 1). These units crop out about six miles to the west where they are seen dipping 5-10° eastward beneath valley fill (Lipman, 1968). Tweto (1979, Fig. 4) pinches these units out between the Tennessee Gas and Tucker wells. However, on the basis of electric log characteristics, a sample description of the Tucker well (Powell, 1958), and a commercial sample log of the Tennessee Gas well, I believe that a good correlation can be established between these wells. One mile east of the Tucker well the Snowden No. 1 Killian (Sec. 14, T. 41 N., R. 9 E.) bottomed in these units at 3,778 feet. This section is also present in the Carr No. 1 Kennedy and Williams well (Sec. 11, T. 41 N., R. 9 E.) four miles east of the Snowden well (Plate 1; Fig. 2). This latter well is located within a downdropped block or paleovalley which crosses the Alamosa horst (Fig. 2). The above correlation of the Fish Canyon-Carpenter Ridge ash flow tuffs is important as it indicates that there has been no significant post-Oligocene displacement along the fault bounding the Monte Vista graben and Alamosa horst. Oligocene (?) volcaniclastics are present in the Monte Vista graben beneath the Fish Canyon-Carpenter Ridge ash flow tuffs. They cannot be presented to any significant extent along the crest of the Alamosa horst. They are not present in the Baca graben, where an angular unconformity marks the boundary between the Miocene-Pliocene Los Pinos-Santa Fe units and underlying Eocene and older rocks (Plate 1) (Gries, 1980, personal communication). This erosion surface is believed to be a buried remnant of the late Eocene erosion surface as described by Epis and Chapin (1975) and Epis and others

(1980). It can be inferred that this surface bounds the Vallejo formation and the overlying Oligocene (?) volcaniclastics in the Monte Vista graben.

Of the 19,000 feet of fill in the Baca graben 75% of this accumulated prior to the development of the late Eocene erosion surface. Of the 10,000 feet of material present in the Monte Vista graben 65% of it is of pre-Miocene age. While the areas of the Baca graben, Alamosa horst, and San Juan volcanic field were undergoing erosion during Oligocene time, Oligocene volcaniclastics were accumulating in the developing Monte Vista graben. Lovejoy and Uphoff, 1980, have noted a similar relationship at the southern end of the Rio Grande Rift near El Paso, Texas. They point out that the Mesilla Basin had begun to develop in Paleocene time and was more than 75% completed by the end of the Oligocene. About 10,000 feet of material accumulated within the Mesilla Basin during Paleogene time (Uphoff and Lovejoy, 1980).

With rifting beginning in Miocene time the upper 5,000 feet of section accumulated within the Alamosa Basin. This Miocene-Pleistocene sequence is of rather uniform thickness above the Baca graben and the Alamosa horst, gradually thinning to zero along the western margin of the basin (Plate 1, A-B).

It therefore appears that there were four major stages in the development of the northern half of the San Luis Basin. The Baca graben began forming along the eastern half of the basin at least as early as Paleocene time---continuing to do so thorough much of the Eocene. This was followed by the development of the late Eocene erosion surface. Deformation then shifted to the western side of the basin with formation of the Monte Vista graben during the Oligocene, ending with eruption of the Fish Canyon-Carpenter Ridge ash flow tuffs. From early Miocene to the present the Alamosa Basin has been subsiding as a single structural unit, in response to the development of the Rio Grande Rift, with the accumulation of an additional 5,000 feet of valley fill.

Paleogene_Paleovalleys_(?)

The present relief of the Sangre de Cristo Mountains is the result of Neogene uplift. Concurrent with the uplift were continued development of the San Juan volcanic field and deposition of the Miocene-Pliocene Los Pinos formation and Sante Fe Group in the Alamosa Basin. Oligocene rocks are present throughout much of this area, being remnants of a large volcanic field that occupied much of the Southern Rocky Mountains (Steven and Epis, 1968). Oligocene ash flow tuffs and volcaniclastics crossed the northern end of the Sangre de Cristo's via northeast-trending paleovalleys (Scott, 1975). Oligocene rocks filled old stream channels cut in the late Eocene erosion surface, then covered the surface itself. Scott (1975) notes that the floors of some of these channels contain deposits which correlate with the Echo Park and Huerfano formations (Vallejo formation equivalents). The northern Sangre de Cristo's thus did not exist in Oligocene time.

Within the Alamosa Basin, the buried north-trending Alamosa horst is cut by one and possibly two major paleovalleys and/or downdropped blocks. The regional gravity map (Fig. 3) indicates that a major fault may be present between the Tucker No. 1 Thomas and Carr No. 1 Kennedy and Williams wells. A sample log is not available on the Carr well; however, the correlation between the two wells appears well established on the basis of electric log characteristics. This is particularly true when these two wells are compared with the Tennessee Gas well. A sample description of the Tucker well is available (Powell, 1958); a sample log is available on the Tennessee gas well. Log characteristics do not indicate the presence of a major fault in this area (Plate 1).

The gravity data (Fig. 3) indicates that the Carr No. 1 Kennedy and Williams well and the Amerada well are located along the crest of the Alamosa horst. It also suggests that the depth to the Precambrian should be about the same at both locations. The Amerada well penetrated the Precambrian at 5,410 feet. The Carr well bottomed in Oligocene (?) volcaniclastics at 6,831 feet. This suggests the presence of a buried east-west trending paleovalley and/or down-dropped block along the north-striking Alamosa horst. A similar, but more pronounced feature, is indicated by the gravity data (Fig. 3) to exist in the Alamosa area between the Amerada well to the north and the San Luis Hills horst to the south (Fig. 2). It is interesting to note that both of these areas are associated with positive magnetic anomalies (Fig. 5) (Zietz and Kirby, 1972). The reason for this seemly anomalous relationship is not clear. However, if such paleovalleys and/or downdropped blocks do exist, and if the appropriate reservoir rocks are present in the volcaniclastics, these areas could have excellent geothermal potential. If the buried valleys completely cut the Alamosa horst then they could provide a means whereby deep water (greater than 5,400 feet) could move across the Alamosa horst from the Monte Vista graben into the Baca graben. If the valleys do not completely cut across the Alamosa horst then these possible re-entrants could provide excellent traps for the localization of water. The presence of a buried paleovalley and/or downdropped block in the Alamosa area would make this a most promising location for geothermal exploration. On the other hand, if no such feature exists and the Alamosa horst is found to be present at about 5,400 feet, then the Alamosa area would not appear to have great geothermal potential. It might, however, be possible to tap the eastern wedge of the Fish Canyon-Carpenter Ridge ash flow tuffs, which may extend onto the western edge of the Alamosa horst (Plate 1). This unit appears to be the best aquifer in the Tennessee Gas well and if present in the Alamosa area may provide water in the 150-175°F range (see later discussion). It is apparent that all the answers are not known and that there is need for more information. Prior to drilling a well in the Alamosa area the depth to basement should first be determined through geophysical means. If a paleovalley and/or downdropped block is not present then it would be best to locate the bounding fault between the Alamosa horst and Monte Vista graben and drill west of that fault.

Figure 5

By projecting the geologic features seen in the Tennessee Gas and Tucker wells southward a line of section (C-D) has been constructed, which extends from the city of Monte Vista on the southwest to the Amerada welll on the northeast (Plate 1). On the basis of regional gravity data and differences seen in the stratigraphic units, the bounding fault between the Monte Vista Basin and the Alamosa horst is projected north-south through section 28, T. 29 N., R. 9 E. For a deep hole (10,000 feet) it is necessary to be west of this fault. The projection of a deep hole for the Monte Vista area does not present the problems seen for the Alamosa area. However, as one moves between the basin and the horst the location could be critical. Without detailed gravity and/or seismic or well-control, this boundary relationship cannot be fully understood.

STRATIGRAPHY

In general the stratigraphic section is composed of five or six major rock units. At the top of the section is the Alamosa formation of Pliocene to Holocene age. Underlying this are the Miocene-Pliocene rocks of the Santa Fe Group, which intertongues with the volcaniclastics and volcanic rocks of the uppermost Oligocene to Pliocene Los Pinos formation. Beneath the Los Pinos, Oligocene (?) volcaniclastics are present which in turn overlie the Eocene Vallejo formation (Echo Park). In the Marco-Amoco well, the Santa Fe overlies with angular unconformity the Vallejo (?) formation. The Vallejo (?) in turn is intruded by an Oligocene sill (perhaps at its base) and overlies older volcaniclastic and volcanic rocks. The Vallejo (?) may be thin or absent in the Reserve well.

Alamosa Formation

Siebenthal (1910) described the Alamosa formation as a series of "blue" clays interstratified with water-bearing sands. These beds divide much of the Alamosa Basin into an upper unconfined aquifer, and a lower, confined aquifer (Emery and others, 1971). At Hansen Bluff, the type section of the Alamosa Formation (Sec. 11, T. 36 N., R. 11 E.), Huntley (1976a) described the unit as consisting of green and blue clays interfingering with fine grained, dark sands. He noted that the clays had little lateral continuity and were often interrupted by channel-fill sands. The clays are more numerous and thicker at the northern end of the Alamosa Basin. In the Marco-Amoco well, 2,050 feet of Alamosa formation were logged. The upper 180 feet of the well penetrated loose, well-sorted sand. From 180 to 320 feet, blue-gray fresh water lake clays were present. At 320 feet the lake clays became greenish-gray and were penetrated to a depth of 1,780 feet. From 1,780 to 2,050 feet, a transition zone exists with the greenish-gray clays being mixed with fine to very coarse sand. At 2,050 feet, the pinkish-orange clays and sands of the Santa Fe Group were encountered. The thick clay sequence encountered in the Marco-Amoco well thins westward and intertongues with detrital sands. According to Huntley (1976a), the number and thickness of the clay beds decrease westward. Along much of the western margin of the Alamosa Basin only one blue clay remains; this pinches out against coarse-grained alluvial beds or volcanic flows. The approximate limits of the uppermost confining clay is shown on Figure 2 (also see Emery and others, 1973) (Plate 2). The peripheral area outside the clay limit is the "recharge" area and its waters contribute to both the unconfined and confined aquifers. The exact identification of the clay layer from well cuttings is not always possible, as it varies in color and in thickness, and is one of a series of clays interbedded with the sands and gravels.

Santa_Fe_Group

Rocks of the Santa Fe Group are found beneath the Alamosa formation in the eastern part of the Alamosa Basin. To the west they intertongue with volcanic and volcaniclastic rocks of the Los Pinos formation (Plate 1, A-B). They outcrop locally along the west flank of the Sangre de Cristo Mountains and within the Culebra Re-entrant. In the Costilla Plains and Taos Plateau they are found beneath the Servilleta basalts (Burroughs and McFadden, 1976).

In the Mapco-Amoco well, the Santa Fe Group consists of buff to pinkish-orange clays with interbedded poorly to moderately-sorted silty sands. Locally the sands become well-sorted and make up a major portion of the sample. The sand grains consist generally of quartz, volcanic (VRF), plutonic rock fragments (PRF), and metamorphic rock fragments (MRF). Locally one or the other may become dominant reflecting an influx from their respective source area (VRF's from the San Juan Mountains PRF's and MRF's from the Sangre de Cristo's). The color of the Santa Fe Group and presence of PRF's and MRF's generally serves to distinguish this unit in the subsurface from the volcaniclastic Los Pinos formation.

In the Mapco-Amoco well, the Santa Fe Group is about 2,800 feet thick. Westward it facies with the Los Pinos formation. The intertonguing relationship is shown in the Reserve well (Plate 1, A-B). In the Amerada well the Santa Fe Group is about 700 feet thick and overlies the Los Pinos. In the Tucker well Powell (1958) describes zones of light-orange to buff clays above 3,600 feet. These have been included within the Los Pinos formation, as detailed sample control is not available.

Los_Pinos_Formation

The Los Pinos formation, formerly Los Pinos Gravel (Atwood and Mather, 1932), was named for exposures in the canyon of the Rio de Los Pinos, Tusas Mountains, New Mexico. The Los Pinos formation is one of the most widely distributed and continuous formations of the eastern Tusas Mountains (Butler, 1946, and 1971). In Colorado, the Los Pinos is a widespread eastward-thickening alluvial wedge having developed by coalesing alluvial fans along the eastern flank of the San Juan Mountains. It accumulated concurrently with the eastward tilting of the San Juan volcanic sequence and development of the early Miocene San Luis Basin (Lipman, 1975).

In general, the Los Pinos formation is a fluviatile sandy gravel with poorly indurated volcaniclastic sandstones interbedded with tuffaceous material. Butler (1946) notes that one-fourth of the unit may be made up of tuff and tuffaceous rocks, which are more common near the base than the top of the unit. Individual sand beds are typically one-quarter of an inch to six inches thick, with a few as much as one foot thick. The sandstone grades to tuffaceous siltstone or sandy conglomerate, becoming more poorly sorted toward the mountains. Cobbles and boulders, although widespread, form only a small portion of the unit. These beds have a maximum thickness of 10 feet, but most are about one foot thick. The thicker beds are largely composed of pebbles and cobbles less than four inches in diameter; particles to four feet in diameter also occur. The smaller particles are subangular and less well rounded than the larger ones. The sand grains are generally angular.

Atwood and Mather (1932) considered the Los Pinos Gravels as having been deposited as a great alluvial fan following uplift of the peneplained San Juan Mountains. It has since been noted (Butler, 1946, 1971; Lipman, 1975), however, that lava flows, volcanic breccias, and tuffs are interbedded with the alluvial deposits; that the gravels are petrographically similar to the interbedded and contemporaneous volcanics; and that the pebbles making up the gravel change compositionally from one interbedded layer to another. This type of lithologic control could prove to be of great value in subsurface correlation of the volcaniclastic units. Thus the Los Pinos formation contains rocks of late Oligocene to Pliocene age and are interbedded with various volcanic units dating from 28 m.y. to 5 m.y. The gravels, rather than being mainly eroded from an older volcanic source, formed as alluvial aprons associated with many active volcanic centers over a long interval of time. If any material making up the unit was derived from pre-Los Pinos rocks, then the San Luis Hills, as well as the San Juan Mountains, would be a natural source. From the San Luis Hills detritus could have been transported northward into the developing Monte Vista graben. The San Luis Hills were eroded to a mature topography prior to being flanked along their southern and eastern margin by the Servilleta basalts. Since that time they have undergone further burial and are presently being exhumed (Burroughs, 1971).

Oligocene_(?)_Volcaniclastics

The Oligocene (?) volcaniclastics, which overlie the Vallejo formation in the Alamosa Basin, appear to be present only within the Monte Vista graben. Our knowledge of them is from one source, the sample log of the Tennessee Gas Well. The upper boundary of these volcaniclastics has been placed at the base of the Fish Canyon-Carpenter Ridge ash flow tuffs. These tuffs are at the base of and are interbedded with the Los Pinos sands (Lipman, 1975). Thus the Oligocene (?) volcaniclastics would have to primarily be the erosional products of the early intermediate-composition rocks (Conejos formation) and older ash flow units (Tuff of Rock Creek and Treasure Mountain Tuff, Lipman, 1975) of the San Juan Mountains. As with the Los Pinos formation, these volcaniclastics could also have been derived, in part, from the San Luis Hills. Although three million years younger, Burroughs (1971), on the basis of lithologic similarity, correlated these pre-rift rocks of the San Luis Hills with those of the Conejos formation. The Conejos is composed of lava flows, flow breccias, explosion breccias which are interbedded with their erosional products, mudflow breccias, conglomerates and tuffaceous sandstones. As noted by Lipman (1975) there is sufficient lithologic variation within the Conejos formation that subdivision of the volcaniclastic facies would be possible. Burroughs (1971) also noted significant petrologic differences in the rocks of the San Luis Hills. The ash flows (Tuff of Rock Creek and Treaure Mountain Tuff) overlying the Conejos formation in the San Juan Mountains are significantly different from that unit. Thus, as with the Los Pinos formation, these lithologic variations could be used to help solve subsurface correlations within the Monte Vista graben.

The Fish Canyon-Carpenter Ridge ash flow tuffs and the Oligocene (?) volcaniclastics should be the main reservoir rocks for geothermal water in the Monte Vista graben. The absence of these units in the Baca graben explains, at least in part, the paucity of water in the Mapco-Amoco well. In that well the only zone tested was below the Santa Fe in the underlying Vallejo formation (?). It would therefore appear that the potential for deep water reservoir (to 10,000 feet) rocks is much greater in the Monte Vista graben than in the Baca graben. The deepest portion of the Baca graben remains an unknown quantity.

Vallejo Formation

Upson (1941) named the Vallejo formation for a red-colored, fluvial clay, sand, and gravel at the base of the Tertiary rocks in the Culebra Re-entrant. He described the unit as being composed of a "fine-grained, unconsolidated, but compact silt and clay with thin lenses of cemented sand and fine gravel, and thick layers of coarse gravel containing rounded cobbles." The sands and gravels are channel deposits of permanent streams flowing on low gradients, and the clay and silt represent the adjacent flood-plain deposits. The Vallejo formation ranges in thickness from zero to 500 feet in the Culebra Re-entrant. It overlies the Precambrian crystalline rocks and underlies the Tertiary volcanic and volcaniclastic rocks. The detrital particles making up the Vallejo formation are therefore noticeable in their lack of VFR's and presence of PRF's and MRF's.

A significant lithologic change occurred at about 4,900 feet in the Mapco-Amoco well. The typical pinkish-orange clays and siltstones of the Santa Fe Group are replaced by a reddish-brown clay and siltstone which, more or less, persists to 8,000 feet, the depth of logging. Also encountered was a higher percentage of PRF's and MRF's and a decreasing amount of VRF's. It appears that this lithologic change marks the top of the Vallejo formation and the angular unconformity between the Santa Fe Group and Vallejo formation. These conclusions are consistent with the age (Paleocene-Eocene) of the palymorphs analyzed by K. A. Newman and reported by Huntley, 1976a.

The K-Ar date of 34.4 + 1.4 m.y. obtained by Amoco Production from cuttings (8,650-8,700 feet) in the Mapco-Amoco well is believed to be that of an Oligocene sill near the base of the Vallejo formation.

The Vallejo formation is about 2,200 feet thick in the Tennessee Gas well; about 1,100 feet thick in the Amerada well; and may be represented by more than 3,600 feet of section in the Marco-Amoco well. It is very thin or absent in the Reserve well (Plate 1).

The channel sands of the Vallejo formation may be considered as a secondary objective for deep geothermal water.

Pre-Vallejo Rocks (?)

The volcanics and volcaniclastics at the bottom of the Reserve and Marco-Amoco wells may be Cretaceous or Paleocene material similar to that noted by Scott (1975) in the Denver Basin and South and Middle Parks. Apparently no rocks of similar age are present in the Tennessee Gas well.

Significance of the Vallejo Formation

The presence or absence of the Vallejo formation in the Alamosa Basin lends great significance to the understanding of the geologic history of this area. Following the Laramide Orogeny, erosion persisted through Paleocene into Eocene time resulting in the development of the late Eocene erosion surface (Epis and Chapin, 1975; Epis and others, 1980). However, in Eocene time fluviatile sediments like that of the Echo Park and Huerfano formations (Thirty-Nine Mile volcanic field and Huerfano Park areas, respectively) were deposited to thicknesses of more than 3,000 feet in developing grabens and basins (Scott, 1975). The Vallejo is believed to be correlative with those units. This suggests that faulting in the Alamosa Basin had taken place as a late phase of the Laramide Orogeny. Thinning of the Vallejo formation over the Alamosa horst and its angular relationship to the overlying Santa Fe Group and Los Pinos formations in the Baca graben (Plate 1) suggests that here is a remnant of the late Eocene erosion surface. Tweto (1979), attributes thinning of the Echo Park (Vallejo) and the overlying volcaniclastics over the horst block to Oligocene movements. He suggests that this faulting could be an early manifestation of the rifting event.

HIGH HEAT FLOW - RIO GRANDE RIFT

Recent studies (Edwards and others, 1978; Reiter and others, 1975, 1978, 1979; Swanberg, 1979) have shown the Rio Grande Rift to be a zone of high heat flow. In spite of this, the rift contains relatively few geothermal springs and only a few have been studied in any detail (Barrett and Pearl, 1978; Trainer and Lyford, 1979). Nevertheless, it is these springs and a few thermal wells that generated the initial interest in the region as one of high heat flow. The lack of numerous springs, and the results of recent studies suggest that there are as yet undiscovered sources of geothermal waters lacking surface expression.

Grose (1974) summarized several characteristics which could indicate that an area may be of interest for geothermal energy. Only a few are noted here. The Rio Grande Rift is of special interest for its geothermal potential for the following reasons: it's a site of recent volcanism and other igneous activity; it has undergone recent tectonic extension resulting in normal faulting, with many faults extending to great depths; it's a site of high heat flow with values greater than 2.0 HFU (Heat Flow Units); it's a site of good reservoir rocks and trapping mechanisms; and it's a known source of water.

Some of the more recent volcanism in the San Luis Basin has taken place within the Taos Plateau (Burroughs, 1974; Lipman and Mehnert, 1979). Lipman and Mehnert (1979) note that at least 35 central-vent volcanic shields and cones are known within the Taos volcanic field. They range in composition from basalt to rhyolite and in age from about 4.5 to 2.0 m.y. All of these young volcanic features are significant in respect to high heat flow studies, as they occur within the rift. Of particular interest are the basalts. The olivine tholeiites of the Servilleta formation occur within the rift, while alkalic basalts flank the rift (Lipman, 1969). Recent crystallization experiments on natural basalts have shown that basalt types are dependent on pressure (depth) conditions, partial melting, fractionation, rate of advance to the surface, and tectonic conditions. Green and Ringwood (1967), and Green and others (1967) suggested that alkalic basalt may form at depths of 35-70 km; high-alumina basalt with either alkalic or tholeiitic affinities at 15-35 km; quartz tholeiite at less than 15 km. It thus appears that the Servilleta basalts developed at depths of 15-35 km, quickly rising to the surface as uncontaminated basalts during the formation of the Rio Grande Rift. The crustal thickness of the southern Rocky Mountains is about 50 km (Jackson and Pakiser, 1965). A movement of the mantle into the rift zone would allow the Servilleta basalt to fractionate at higher crustal levels and would aid in the creation of geothermal heat. This area is characterized by heat flow values greater than 2.5 HFU (Edwards and others, 1978; Reiter and others, 1975, and 1979) (1 HFU = 1 x 106 cal/cm2/s = 41.8 mW/m2; the global average heat flow is about 1.5 HFU).

Many studies have noted that the Rio Grande Rift is tectonically and volcanically active. The presence of shallow magma bodies along the rift have been suggested through heat flow, seismic, geochemical, and gravity studies. Supporting the idea of high subsurface temperatures are recent geomagnetic studies which suggest the presence of anomalously high electrical conductivity beneath the southern part of the rift. Current uplift observed near Socorro, New Mexico, may be related to a proposed magma body at depth (see Reiter and others, 1979, for references). Edwards and others (1978) notes that radioactive decay in the upper crust contributes about 0.38 HFU to the Rio Grande Rift. This implies that heat flow of the rift (2.56 HFU) has been brought about by tectonic and magmatic sources, and not by an anomalously high crustal radioactivity.

Two regions within the Southern Rocky Mountains have heat flow above 2.4 HFU. The San Juan volcanic field has the highest heat flow values (2.85 + 0.65 HFU). The average heat flow value along the Rio Grande Rift is 2.56 + 0.65 HFU. In both instances, values greater than 4.0 HFU were not included in figuring the averages. The large variability (+ 0.65) of heat flow data for both areas suggest the occurrence of groundwater movement in convection of heat (Reiter and others, 1979). Trainer and Lyford (1979), in their study of thermal waters along the rift, suggest that the springs may be a considerable distance from their sources--that those of the Rio Grande Gorge (Taos Plateau) may be supplied by lateral flow through "fractured and rubble zones" between lava flows.

Reiter and others (1975) noted the coincidence of high heat-flow with the western part of the rift. Figure 6, modified from Reiter and others (1975, and 1979), and Edwards and others (1978) is a heat-flow map of northern New Mexico and southern Colorado.

GEOTHERMAL GRADIENT - SAN LUIS BASIN

The geothermal gradient of the San Luis Basin is illustrated in Figure 7. The bottom-hole-temperature (BHT) curve was constructed from BHT's obtained from electric logs for nine wells. Except for the Tusas No. 1 Vaughn, all the wells are located within the Alamosa Basin. The Vaughn well is located near San Luis, Colorado, along the margin of the Costilla Plains and Culebra Re-entrant (Fig. 2). A BHT curve should always be suspect, but especially one using data obtained from old wells. In many instances, these BHT's were calculated temperatures and not measured temperatures! Thus a BHT curve should be supported with other data when available.

Of the wells shown in Figure 7, temperature survey logs were run on two of them: Tennessee Gas and Marco-Amoco. A company is not required to release these logs to the Colorado Oil and Gas Commission; thus, so far, it has only been possible to obtain the temperature survey log for the Marco-Amoco well. This log covers the upper 8,000 feet of the hole. It was the first of three mechanical logs run when the hole was at 8,000 feet (Amoco took over the hole at this depth). The BHT obtained from the temperature survey log was 192°F, a little lower than expected from the BHT curve. The temperature survey curve departs from the BHT curve at the 7,000-foot level to the surface. This should be expected as the up-hole temperatures would be

Figure 6.

Figure 7

influenced by the BHT conditions. If temperature survey logs from other wells were available, a similar departure would probably be noted. After the temperature survey was completed on the Mapco-Amoco well, a Dual Induction-Laterolog was run. Four hours after the temperature survey was taken, the BHT had increased 18°F to 210°F. With the running of the Formation Density log three hours later, the BHT had increased another 7°F to 217°F. It is apparent that temperature survey logs do not tell all of the story either.

A drill-stem test (DST) was conducted on the Mapco-Amoco well after the above logs were run. For the interval tested (5,304-5,491 feet), the final temperature obtained was 177°F after a period of four hours and five minutes from the time of the initial temperature which was 167°F. The 177°F temperature probably represents the best formation temperature known for any of the wells. Although DST's were run on some of the other wells, the formation temperatures were not reported and probably are not available. The formation temperature curve suggests that at 8,000 feet formation temperatures of about 240°F could be expected. This is consistent with the BHT of 217°F obtained, which could be expected to increase with further stabilization and correction for the cooling effect of the drilling mud. At 10,000 feet, formation temperatures of about 300°F can be expected. It is important to note that Figure 7 suggests that a fairly constant temperature to depth relationship exists throughout the Valley region.

THE CONFINED AQUIFER

The confined aquifer is made up of the volcanic, volcaniclastic, and other rocks below the "clay series". Thus the confined aquifer includes everything below the "clay series" to the "basement" (Precambrian) rocks, which in the Baca graben may be 19,000 feet thick.

Emery and others (1973) limited their study of the confined aquifer to the upper 3,000 feet. They noted that nearly all of the water obtained from the confined aquifer was from the upper 1,500 feet of the aquifer. There was no way their study could include the rest of the stratigraphic section as only a few wells reach "basement," and those that do have been for the exploration of hydrocarbons. They noted that in the southwest part of the Alamosa Basin (T. 37 N., R. 9 E.) that the "clay series" overlapped northwest dipping lava flows and the uppermost lava flow is the principal confining unit. The lava flow is about 600 feet below the surface (Emery and others, 1973, Plate 2). This may be the case for these particular volcanic rocks in the San Luis Basin. Volcanic rocks, like all rocks, are highly variable and complex in their composition, origin, and hydrologic characteristics. Whether the "lava flows" (T. 37 N., R. 9 E.) are truly lava flows, ashflows, ash-falls, laharic breccias, or some other type of volcanic rock, is not known by the author. The important thing to note is that volcanic rocks are not all the same. Unfortunately, because these "lava flows" may indeed be a confining unit, the opinion has prevailed in the San Luis Valley that all volcanics act as aquitards or aquicludes.

Huntley (1967a,b), in his study of the Alamosa Basin north of the Rio Grande River, noted that ground-water recharge to the aquifers of the Baca graben "is primarily from ground water flow in the volcanic aquifers of the San Juan Mountains". He considered intergranular permeability, when compared to fracture permeability, to be insignificant in the volcanic rocks. Intrusive igneous rocks are considered aquicludes. Volcanic rocks lacking in fracture permeability, such as ash-fall tuffs, water-laid tuffs, agglomerates, flow-breccias, and laharic breccias are aquitards, having hydraulic conductivities of about 10-7 cm/sec. The fractured andesite and basalt lava flows are considered aquifers, as are the welded zones of the ash-flow tuffs. Hydraulic conductivity of the andesite flows may be 5(10-4) cm/sec. The welded ash-flows are intensely fractured, highly permeable, having hydrualic conductivities on the order of 5 (10-2) cm/sec. The welded portion of the ash-flow unit is overlain and underlain by less-welded to unwelded, unfractured, ash-flow with low permeability. The unwelded zones may have hydrualic conductivity as low as 10-7 cm/sec. Thus the ash-flow units which have welded interiors have good horizontal permeability. The amount of horizontal permeability is controlled by the intensity of the fracturing, which is closely related to the degree of welding. Primary fracturing is restricted to the ash-flow sheets and to the lava flows. Secondary fracturing is the only significant source of permeability in other types of volcanic rocks. Because of the brittleness of the welded ash-flow tuffs, these zones, like the lava flows, are also the most susceptible to secondary fracturing.

Along the west side of the San Luis Valley are outcrops of the Fish Canyon and Carpenter Ridge ash-flow tuffs of Oligocene age (Fig. 2) (Steven and others, 1974). They dip eastward into the volcaniclastic sequence of the Monte Vista graben. The Fish Canyon is the most widespread (at least 15,000 km2) and voluminous (more than 3,000 km3) of the ash-flow sheets in the San Juan Mountains, and is one of the largest in the world (Lipman, 1975). The Carpenter Ridge ash-flow tuff has a distribution similar to that of the Fish Canyon. According to Huntley (1976c), the conductivity of these units ranges from 2(10-2) to 5(10-2) cm/sec. At Big Springs Picnic Ground (T. 44 N., R. 6 E.), flow from the Fish Canyon is up to 1.5 cfs and the calculated fracture permeability is about 5(10-2) cm/sec, as great as the most permeable alluvium in the San Luis Valley. These units are interlayered with the volcaniclastics of the Los Pinos formation, as are other volcanic units along the eastern slopes of the San Juan Mountains (Lipman, 1975). Older volcanic units are interbedded with the Oligocene (?) volcaniclastics.

Water_Quality_of_the_Confined_Aquifer

Due to the lack of data, not much is known about the water quality from the deeper zones of the confined aquifer. Probably the best information currently available is from tests performed on drill stem samples taken from the Mapco-Amoco well in the Baca graben at depths of 5,304 to 5,491 feet, which might be from within the Vallejo formation (?).

Figure 8 is a nomogram showing the results of the two analyses. Copies of the original data are on file with the Colorado Oil and Gas Commission. The two samples analyzed presumably came from the same test and were taken at the same time. The reason for the difference in dissolved material is not clear, although one analysis was conducted in the field and the other in the laboratory facilities of Yapuncich, Sanderson and Brown. This later laboratory test indicates total dissolved solids concentrations of about 4,000 ppm.

MAPCO Well (Data by Yapuncich, Sanderson & Brown in Billings and Chem. & [illegible] [illegible] Casper)

	YSB	COGC
Na	2123	3614
Ca	198	398
Mg	11	0
S	564	1200
Cl	3100	2800
CO_3	0	1068
HCO_3	270	2330

Figure 8

The chloride concentration is of special interest; the two test results seen in Figure 8 indicate concentrations between 2,200 and 3,500 ppm. Other field testing indicated concentrations possibly as high as 7,500 ppm. The 5,304-5,491-foot DST depth was below the unconformity with the overlying Santa Fe Group, and thus an old erosion surface and soil horizon is present. This might account, at least in part, for the comparatively high chloride content of this formation water.

Emery and others (1973) note that the water quality of the confined aquifer near the edge of the basin is excellent. It has a specific conductance (an index of dissolved-solids concentration) of less than 200 micromhos per centimeter. In the "Closed Basin" area of the Baca graben, the specific conductance is greater than 1,250 micromhos per centimeter. Near the edge of the basin the chemistry of the water reflects that of the recharge water. As the confined water moves downdip into the basin, it changes both physically and chemically. Compositional changes take place more rapidly than do those of concentration. There is an increase in sodium content with a corresponding loss of calcium through ion exchange with clay. Likewise, silicate hydrolysis contributes to the pH and as the water moves to the center of the basin, it becomes a sodium bicarbonate type. The change of water quality from the recharge area eastward through the aquifer is reflective of the chemistry of the host rocks. If Emery's map (Plate 8 in Emerey and others, 1973) reflects the deeper water picture, then the area of the Monte Vista graben is a high water quality region.

For additional data on water quality, the reader is referred to Emery and others (1972).

Log_Analysis_of_the_Tennessee_Gas_Well

Log analysis of the Tennessee Gas well was done from an Induction Electric Log (IES) and a Microlog (ML). The interval considered was from 2,100 feet to total depth, 10,349 feet. The first 2,100-foot section (Alamosa and Los Pinos formations) was not considered, as a microlog tool cannot be used in a cased interval, and is thus not available for the upper part of the hole. The IES and ML with caliper appear to be of good quality. The well was drilled with a fresh-water-based drilling mud and the logs perform well under these conditions. The ML is now seldom used due to the availability of better porosity determining instruments. However, it can still be regarded as an excellent tool when used under the proper conditions. Conditions that cause questions to arise include the bit size, hole size, washed out zones, lithology and tool limitations. In this case, the bit size used to drill the hole 2,106' to 9,201 feet was 12 1/4 inches. Drilling time over this interval was over three months and hole wash out was inevitable. According to caliper measurements, hole size reached a 16-inch diameter, in places, which is maximum for this tool. In large hole diameters, the pad on the ML tool will not conform properly with the wall of the hole and interpretation is difficult or impossible.

Within the Fish Canyon-Carpenter Ridge ash flow tuffs, Oligocene (?)

Volcaniclastics, and Vallejo formations, 39 excellent water-bearing zones are indicated having a cumulative footage of 357 feet. There are, in addition, 79 possible water-bearing zones having a cumulative footage of 481 feet. The zones classified as of excellent quality are mainly within the volcanic horizons of the Fish Canyon-Carpenter Ridge and Oligocene (?) volcaniclastics, and within the sandstone and gravel horizons of the Vallejo formations. The data is summarized below:

	Number of Zones						Number of Feet					
	Excellent	+	Possible	=	Total		Excellent	+	Possible	=	Total
Fish Canyon-Carpenter Ridge	4	+	7	=	11		186	+	56	=	242
Oligocene (?) Volcaniclastics	11	+	63	=	74		39	+	381	=	420
Vallejo Fm.	24	+	9	=	33		132	+	44	=	176
Precambrian	0	+	2	=	2		0	+	4	=	4
Total	39	+	81	=	120		357	+	485	=	842

	Avg. No. Ft/Excellent Zone	Avg. No. Ft/Possible Zone
Fish Canyon-Carpenter Ridge	46.5	8.0
Oligocene (?) Volcaniclastics	3.5	6.0
Vallejo	5.5	4.9
Precambrian	0	2.0

Fish Canyon-Carpenter Ridge and Oligocene (?) Volcaniclastics
Volcanics vs. Volcaniclastics

	Excellent	+	Possible	=	Total
Volcanics					
Number of zones	13	+	16	=	29
Number of feet	186	+	119	=	305
Avg. no. ft/zone	14.3	+	7.4	=	--
Volcaniclastics					
Number of zones	4	+	52	=	56
Number of feet	39	+	318	=	357
Avg. no ft/zone	9.7	+	6.1	=	--

There are no volcanic horizons in the Vallejo formation.

Standard petroleum engineering, log interpretation techniques were used to develop a quantitative analysis of two horizons, one in the Fish Canyon-Carpenter Ridge formations, and one in the Vallejo formation:

1. Fish Canyon-Carpenter Ridge formations (2,366-2,535 feet) (ML)
   a. Formation temperature — FT = 115°F
   b. Porosity — Ø = 24%
   c. Water saturation — Sw = 100%
   d. Formation water resistivity — Rw = 1.1 ohm meters @115°F

e. Formation water salinity--equivalent NaCl solution--3,400 ppm

2. Vallejo formation (8,257-8,276 feet) (ML)
   a. Formation temperature FT = 203°F
   b. Porosity Ø = 24%
   c. Water saturation Sw = 100%
   d. Formation resistivity Rw = 0.57 ohm meters @203°F
   e. Formation water salinity--equivalent NaCl solution--3,500 ppm
   f. These calculations will probably apply fairly well to any other zones with excellent porosity from 7,700 to 8,700 feet.

The calculated formation temperature of 115°F for the above interval in the Fish Canyon-Carpenter Ridge formations agrees fairly well with that obtained from the graph (Figure 7) where the BHT is indicated at 85°F and the FT at 103°F. For the Vallejo formation, the calculated temperature of 203°F is close to the BHT of 205°F, but well below the FT of 247°F as indicated in Figure 7.

It is interesting to note the similarity in salinity values for the two intervals calculated in spite of the fact that one interval is about 6,000 feet below the other.

With 25-percent porosity, the calculated reservoirs contain 1,939.5 bbl, or 81,549 gallons of water per acre-foot. For the "excellent" zones in the Fish Canyon-Carpenter Ridge, Oligocene (?) volcaniclastics and Vallejo formations, we should have around 29 million gallons of water per acre within 357 feet of section. It should be noted, however, that the porosity has not been calculated for every zone indicated.

According to Emery and others (1973) of the 21 water wells in the valley at that time that were more than 2,000 feet deep, artesian flowing production rates were in the order of 3,000 gpm.

In summary, this brief "first look" at the logs from the Tennessee Gas well indicate the probability of high production rates of waters to temperatures of 200°F or more is very good. Formation porosities and permeabilities are adequate. Based upon DST shut-in pressures (1,500-1,900 lbs) for zones within the Oligocene (?) volcaniclastics formation pressures appear to be at or above a normal pressure gradient. It would, therefore, appear that all the requisites for good reservoir conditions are present in this well.

SOME LEGAL ASPECTS

Geological nomenclature for the aquifers of the San Luis Valley does not enjoy common usage. However, the more commonly used legally derived designation correlates well with the geologic units. Many of the ideas presented here are the result of conversations with D. H. McFadden (1980, personal communication). The "confining clay" is the Alamosa formation. The sands and gravels above the "confining clay" make up the "unconfined" aquifer, and everything from the "confining clay" to "basement" make up the "confined" aquifer. Therefore, in a legal sense, all of the Santa Fe, Los Pinos, Oligocene (?) volcaniclastics, Vallejo and older volcanics and volcaniclastics are lumped into a single aquifer, the "confined." In a geologic sense, this is not accurate. There are bound to be many separate aquifers with various degrees of hydraulic connection in more than 10,000 feet of stratigraphic section. Recent geothermal activity in the valley has brought the "confined" aquifer under scrutiny as the main source of geothermal water. Eventually questions of a legal nature concerning this aquifer will have to be addressed. The Colorado Division of Water Resources is to make determinations as to the source of underground water, and the surface stream, if any, to which it is tributary. It then advises the Colorado Water Court having jurisdiction in the entering of decrees for underground water rights.

The present designation of aquifers in the San Luis Valley (Water Division 3) is based principally on the presently a accepted legal usage, which in turn was based on studies conducted by the U.S. Geological Survey in the 1960's and reported in Emery, 1970, Emergy and others, 1973, and 1975.

Any project planned in the State of Colorado which requires the use of water must assign a high priority to securing sufficient water rights to meet the project water requirements.

Certain nonconsumptive uses, such as power generation, nonevaporative cooling, or certain geothermal uses where the heat alone is extracted enjoy a special privilege. If water so used is returned, undiminished, to the system from which it is taken within a time frame which causes no injury to any vested rights, such uses are usually decreed by the courts as "nonconsumptive" on a routine basis.

Projects requiring consumptive use of water, which do not return the water to the stream system from which it came or which might in any way deprive others right to the water to which they are entitled, must provide compensation to those injured in order to continue to legally use the water.

Various methods of payment to mitigate injury have been used to satisfy this legal requirement. Without a doubt, the cleanest and most generally satisfactory way is the outright purchase of water, sufficient in amount and priority to offset any possible injury to others. For any project requiring the use of geothermal water should include provision for the legal use of that water.

No legal consideration has been given to the restrictions that may be placed on these various ideas by water quality requirements. However, if heat extraction constitutes the only change in the water, then this does not appear to be a problem.

Any opinion as to the above aspects should be asked of the State Engineer.

SUGGESTIONS FOR FURTHER STUDIES

Introduction

From a legal standpoint, it is necessary that the hydrogeology of the "confined" aquifer be well understood. Well control, seismic and detailed gravity data is minimal. However, there is much that can be done to increase the understanding of this geologically complex system. The lack of detailed knowledge as to the geology of the San Luis Basin leads to the inevitable corollary that little is known about its hydrogeology.

Geophysical

Regional gravity and magnetic surveys have given a clue to the generalized "basement" structure of the San Luis Basin. Scattered segments of seismic and gravity lines in widely separated parts of the San Luis Basin have given more detailed knowledge of specific areas. These surveys, conducted for the most part by energy companies, were undertaken for specific purposes and confined to the investigation of limited areas. Surveys by the Colorado School of Mines have been conducted over the last several summers.

For the immediate future, the available seismic and gravity coverage cannot provide a single continuous cross-section (line) across the basin--either east-west or north-south. As of now, information west of Colorado Highway 17 is essentially not available.

It is imperative that an inventory and evaluation of existing detailed geophysical work of the basin be undertaken and that this work be considered in the recommendations for future studies. A very high priority should be assigned to the completion of an east-west seismic line of acceptable quality which would tie the Mapco-Amoco, Amerada, and Tennessee Gas wells. A gravity profile with the same coverage would most certainly aid in the interpretation of existing gravity data, and the same is probably true of a magnetic profile. Future studies should tie this east-west cross-section to existing deep tests, where competent geophysical and lithologic control is available. Although relatively few in number, information from these wells is invaluable in the interpretation of existing data and to obtain optimum results from future studies. Another high priority item should be seismic and gravity lines in the Alamosa area.

Lithologic Studies

Although commercial sample logs are presently available for three wells (Mapco-Amoco, Amerada and Tennessee Gas) sample studies should be conducted prior to the drilling of another deep test in the basin. Samples are currently available from the Mapco-Amoco, Reserve, Amerada, and Tennessee Gas wells. They may also be available from the Tucker well.

Sample studies will greatly aid the understanding of the hydrogeology of the basin. They will help in the interpretation of the geophysical well logs, and present and future seismic control. They would greatly aid in obtaining the optimum knowledge from any future test. Because of the lithologic relationship between the volcaniclastics and interlayered volcanics (see discussion of the Oligocene (?) volcaniclastics and of the Los Pinos formation), it may be possible to tie the subsurface data to outcrops in the San Juan Mountains.

Any future test should include in its drilling program the obtainment of selected cores. The cores would greatly aid the lithologic studies conducted from cuttings and the lithologic studies would help in selecting the best horizons for coring. The cores can also be used in the determination of porosity and permeability, which in turn would aid in the interpretation of these characteristics from the geophysical logs. Potassium-argon age dates from the volcanics can be more reliably made from cores than from cuttings. The age dates in conjunction with the lithologic studies would help to make more exacting correlations with the outcrops. This in turn will help to better understand the hydrogeologic unit from which production can be obtained. With good correlations, injection, if necessary, can be made into this same unit, but at a shallower depth. If it were eventually decided that injection into the same unit might produce a cooling affect on the producing horizon, then the studies would help us in selecting an alternative horizon for the injection.

Geophysical_Well_Log_Studies

For this report, an analysis of the geophysical logs from the Tennessee Gas well has been made. This study should be extended to include the other deep tests in the basin. It would help in the understanding of the facies relationship between the Los Pinos formation and the Santa Fe Group. This in turn will increase the understanding of the hydrogeology of the "confined" aquifer.

When drilling wildcat and other wells, energy companies generally pool their resources to obtain optimum results. The reason for this is simple. The risks are great and drilling costs are high. Prices are constantly changing but drilling costs can probably figure at $30 to $40 per foot with completion costs pushing the figure to $60 per foot. With the great sums of money involved, it pays to get all the cooperation possible.

During 1980, energy companies have been acquiring oil and gas leases in all of T. 40 N. and the east half of T. 41 N., R. 8 E. The Tucker well is along the eastern edge of the latter township. On a DST at 6,310 feet, with 3,000 feet of water cushion in the hole, the well started flowing gas and distillate. Thus the interest in the area! Leasing has also been going on in the southern part of the Alamosa Basin.

The companies doing the leasing should be interested in proving up their acreage, and thus should cooperate in a joint venture. Through this approach, it might also be possible to acquire the results of their seismic work.

BIBLIOGRAPHY

Atwood, W. W., and Mater, K. F., 1932, Physiography and Quaternary geology of the San Juan Mountains, Colorado: U.S. Geol. Survey Prof. Paper 166, 176 p.

Barrett, J. K., and Pearl, R. H., 1978, Appraisal of Colorado's geothermal resources: Colorado Geol. Survey Bull. 39, 224 p.

Behrendt, J. C., and Bajwa, L. Y., 1974, Bouguer gravity map of Colorado: U.S. Geol. Survey Geophy. Inv. Map GP-895.

Burroughs, R. L., 1971, Geology of the San Luis hills, south-central Colorado: New Mexico Geol. Soc. Guidebook, 22nd Field Conf., p. 277-287.

_______1974, Neogene volcanism in the southern San Luis Basin: New Mexico Geol. Soc. Guidebook, 25th Field Conf., p. 291-294.

Burroughs, R. L., and McFadden, P. H., 1976, Some hydrologic problems in the San Luis Basin, Colorado-New Mexico, in Epis, R. C., and Weimer, R. J., Contr. No. 8, p. 544-549.

Butler, A. P., Jr., 1946, Tertiary and Quaternary geology of the Tusas-Tres Piedras area, New Mexico: Unpub. Ph.D. dissertation, Harvard Univ., 188 p.

_______1971, Tertiary volcanic stratigraphy of eastern Tusas Mountains, southwest of the San Luis Valley, Colorado-New Mexico: New Mexico Geol. Soc. Guidebook, 22nd Field Conf., p. 289-300.

Edwards, C. L., Reiter, M., Shearer, C., and Young, W., 1978, Terrestrial heat flow and crustal radioactivity in northeastern New Mexico and southeastern Colorado: Geol. Soc. Am. Bull., v. 89, p. 1341-1350.

Emery, P. A., 1970, Electric analog model evaluation of a water-salvage plan, San Luis Valley, South-Central Colorado: Colo. Water Conserv. Board, Circ. 14, 11 p.

Emery, P. A., Boettcher, A. J., Snipes, R. J., and McIntyre, H. J., Jr., 1971, Hydrology of the San Luis Valley, south-central Colorado: U.S. Geol. Survey Hydrol. Inv. Atlas HA-381.

Emery, P. A., Snipes, R. J., and Dymeyer, J. M., 1972, Hydrologic data for the San Luis Valley, Colorado: Colo. Water Conserv. Board Basic-Data Release 22, 146 p.

Emery, P. A., Snipes, R. J., Dymeyer, J. M., and Klein, J. M., 1973, Water in the San Luis Valley, south-central Colorado: Colo. Water Conserv. Board, Circ. no. 18, 26 p.

Emery, P. A., Patten, E. P., Jr., and Moore, J. E., 1975, Analog model study of the hydrology of the San Luis Valley, south-central Colorado: Colo. Water Conserv. Board, Circ. no. 29, 21 p.

Epis, R. C., and Chapin, C. E., 1975, Geomorphic and tectonic implications of the Post-Laramide, Late Eocene erosion surface in the southern Rocky Mountains, in Curtis, B., ed., Cenozoic history of the southern Rocky Mountains: Geol. Soc. Am. Memb. 144, p. 45-74.

Epis, R. C., Scott, G. R., Taylor, R. B., and Chapin, C. E., 1980, Summary of Cenozoic geomorphic, volcanic and tectonic features of central Colorado and adjoining areas, in Kent, H. C., and Porter, K. W., eds., Colorado Geology: Rocky Mtn. Assoc. Geol., p. 135-156.

Green, D. H., and Ringwood, A. E., 1967, The genesis of basaltic magmas: Contr. Mineralogy and Petrology, v. 15, p. 103-190.

Gries, Robbie, 1980, personal communication.

Grose, L. T., 1974, Summary of the geology of Colorado related to geothermal energy potential, in Pearl, R. H., eds., Proceedings of a symposium on geothermal energy in Colorado: Colo. Geol. Survey Bull. 35, p. 11-29.

Guyod, Hubert, 1951, Principles of microlog interpretation: The Oil and Gas Jour., Dec. 6.

Huntley, David, 1976a, Ground water recharge to the aquifers of northern San Luis Valley, Colorado: a remote sensing investigation: Unpub. Ph.D. dissertation, Colo. Sch. Mines, 240 p.

______1976b, Hydrology of northern San Luis Valley, Colorado, in Epis, R. C., and Weimer, R. J., eds., Studies in Colorado field geology: Colo. Sch. Mines Prof. Contr. No. 8, p. 539-543.

______1976c, Field trip northern San Luis Valley, Colorado, in Epis, R. C., and Weimer, R. J., eds., Studies in Colorado field geology: Colo. Sch. Mines Prof. Contr. No. 8, p. 520-531.

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

Lipman, P. W., 1968, Geology of Summer Coon volcanic center, eastern San Juan Mountains, Colorado, in Epis, R. C., ed., Cenozoic volcanism in the southern Rocky Mountains: Colo. Sch. Mines Quart., v. 63, no. 3, p. 211-236.

______1969, Alkalic and tholeiitic basalt volcanism related to the Rio Grande Depression, southern Colorado and northern New Mexico: Geol. Soc. Am. Bull., v. 80, p. 1343-1354.

______1975, Evolution of the Platora Caldera complex and related volcanic rocks southeastern San Juan Mountains, Colorado: U.S. Geol.

Survey Prof. Paper 852, 128 p.

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: Am. Geophy. Union, p. 289-311.

Lovejoy, E., and Uphoff, T., 1980, A reinterpretation of the time of Hueco Basin block faulting and its implications for the age of Rio Grande rift and/or Basin and Range faulting near El Paso, in Lovejoy, E., ed., Sierra de Juarez Chihuahua Mexico Structure and Stratigraphy: El Paso Geol. Soc., p. 53-54.

McFadden, D. H., Jr., 1980, personal communication.

Powell, W. J., 1958, Ground water resources of the San Luis Valley, Colorado: U.S. Geol. Survey Water Supply Paper 1379, 284 p.

Reiter, M., Edwards, C. L., Hartman, H., and Weidman, C., 1975, Terrestrial heat flow along the Rio Grande Rift, New Mexico and southern Colorado: Geol. Soc. Am. Bull., v. 86, p. 811-818.

Reiter, M., Shearer, C., and Edwards, C. L., 1978, Geothermal anomalies along the Rio Grande Rift in New Mexico: Geology, v. 6, p. 85-88.

Reiter, M., Mansure, A. J., and Shearer, C., 1979, Geothermal characteristics of the Rio Grande Rift within the southern Rocky Mountain complex, in Riecker, R. E., eds., Rio Grande Rift: tectonics and magmatism:. Am. Geophy. Union, p. 253-267.

Scott, G. R., 1975, Cenozoic surfaces and deposits in the southern Rocky Mountains, in Curtis, B., ed., Cenozoic history of the southern Rocky Mountains: Geol. Soc. Am. Mem. 144, p. 227-248.

Siebenthal, C. E., 1910, Geology and water resources of the San Luis Valley, Colorado: U.S. Geol. Survey Water-Supply Paper 240, p. 241-260.

Steven, T. A., and Epis, R. C., 1968, Oligocene volcanism in south-central Colorado: Colo. Sch. Mines Quart., v. 63, no. 3, p. 241-260.

Steven, T. A., Lipman, P. W., Hail, W. J., Jr., Barker, F., and Luedke, R. G., 1974, Geologic map of the Durango Quadrangle, southwestern Colorado: U.S. Geol. Survey Misc. Geol. Inv. Map I-764.

Swanberg, C. A., 1979, Chemistry of thermal and nonthermal ground waters in the Rio Grande Rift and adjacent tectonic provinces, in Riecker, R. E., ed., Rio Grande Rift: tectonics and magmatism: Am. Geophy. Union, p. 279-288.

Trainer, F. W., and Lyford, F. P., 1979, Geothermal hydrology in the Rio Grande Rift, north-central New Mexico: New Mexico Geol. Soc. Guidebook, 30th Field Conf., p. 299-306.

Tweto, O., 1978, Tectonic map of the Rio Grande Rift system in Colorado:

New Mexico Bur. Mines and Min. Resources: Circ. no. 163, Sheet 1.

______1979, The Rio Grande rift system in Colorado, in Riecker, R. E., ed., Rio Grande Rift: tectonics and magmatism: Am. Geophy. Union, p. 33-56.

Uphoff, T., and Lovejoy, E., 1980, The structural geology and timing of faulting of the basin blocks adjacent to the Sierra de Juarez, in Lovejoy, E., ed., Sierra de Juarez Chicuahua Mexico Structure and Stratigraphy: El Paso Geol. Soc., p. 47-51.

Upson, J. E., 1939, Physiographic subdivisions of the San Luis Valley southern Colorado: Jour. Geology, v. 47, no. 7, p. 721-736.

______1941, The Vallejo Formation: new early Tertiary red-beds in southern Colorado: Am. Jour. Sci., v. 239, no. 8, p. 577-589.

Zietz, I., and Kirby, J. R., Jr., 1972, Aeromagnetic map of Colorado: U.S. Geol. Survey Geophy. Inv. Map GP-836.

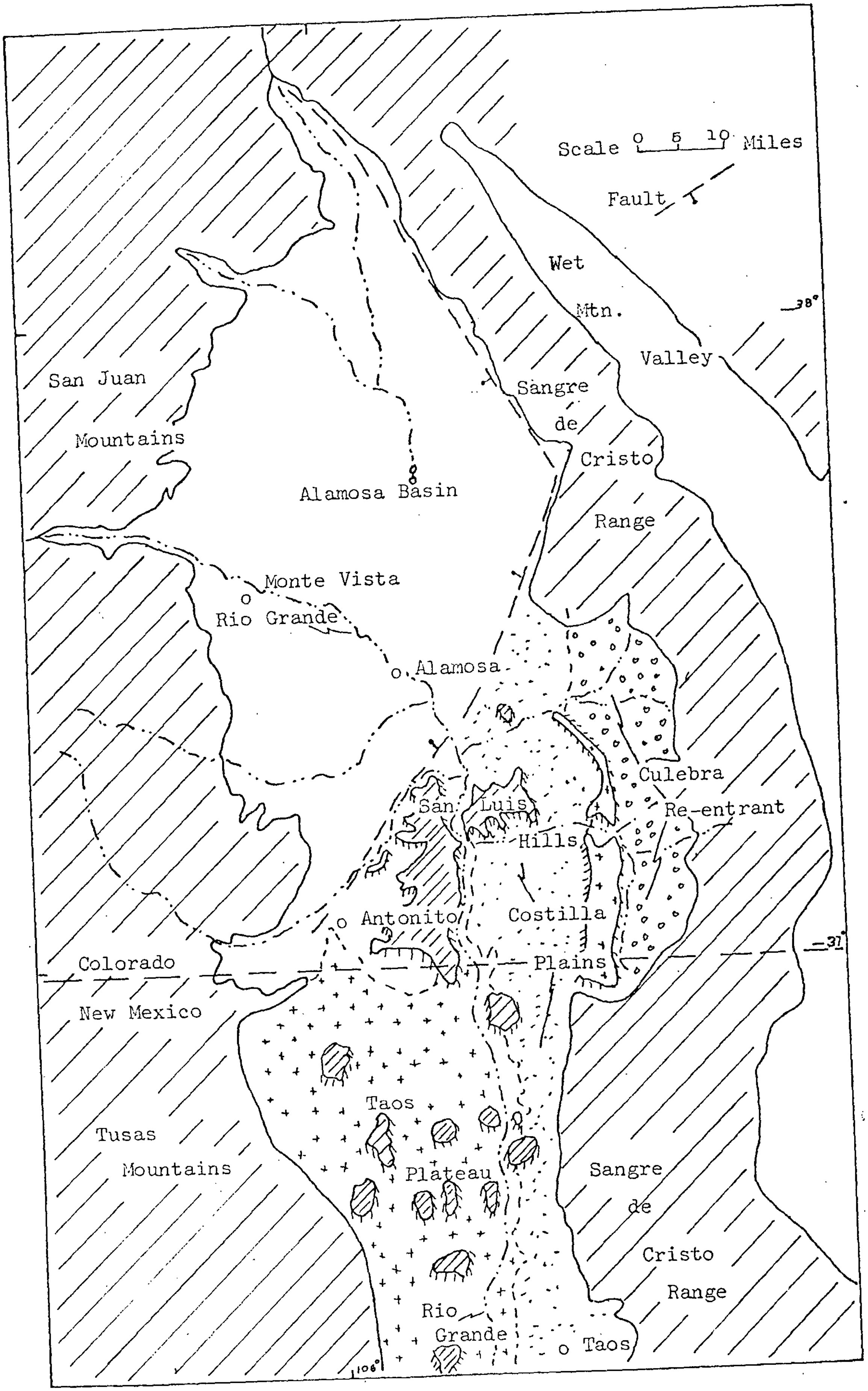

Figure 1. Physiographic subdivisions San Luis basin (modified after Upson, 1939).

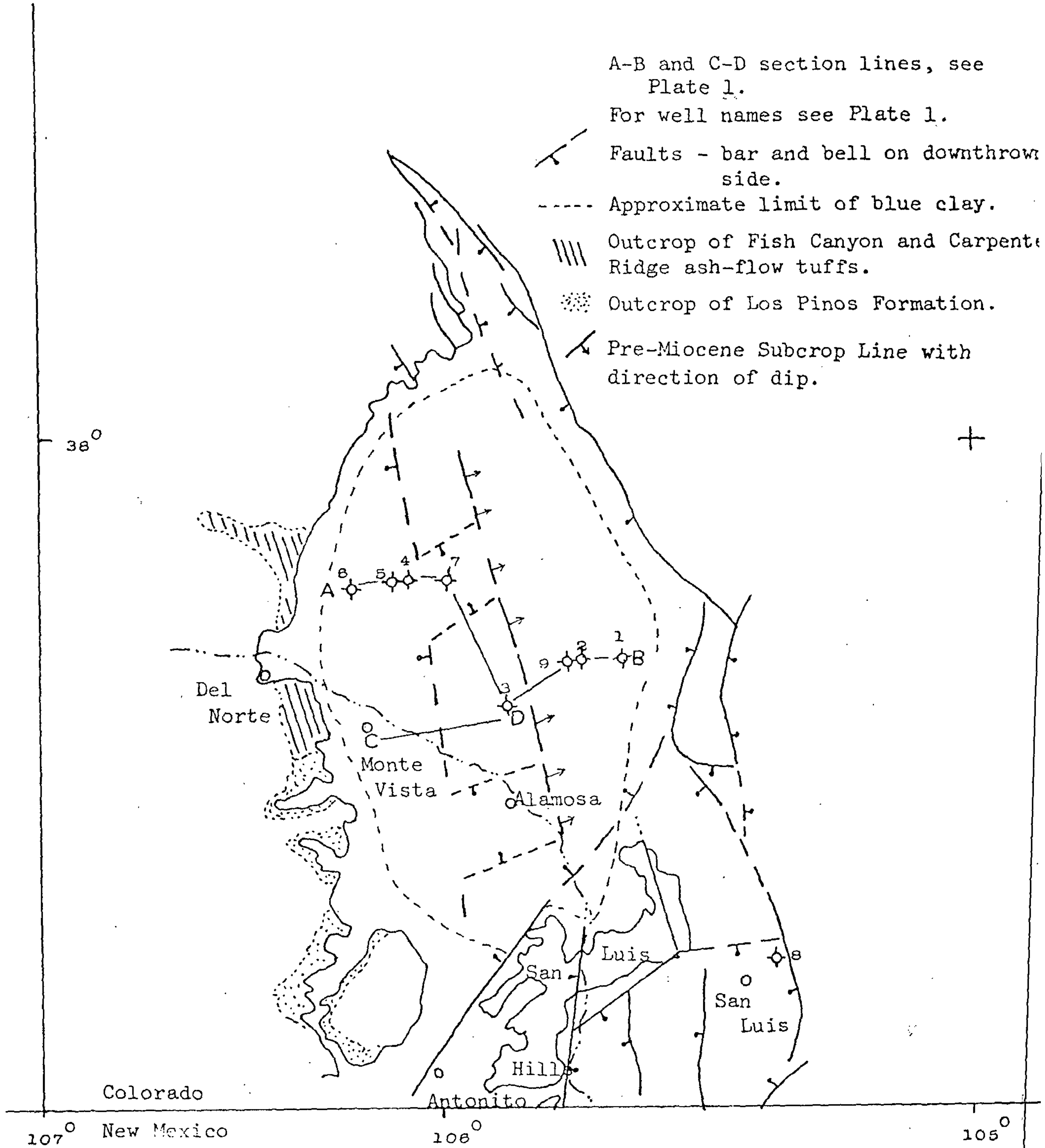

Figure 2. Major structural features of northern San Luis basin, Colorado (modified after Tweto, 1978).

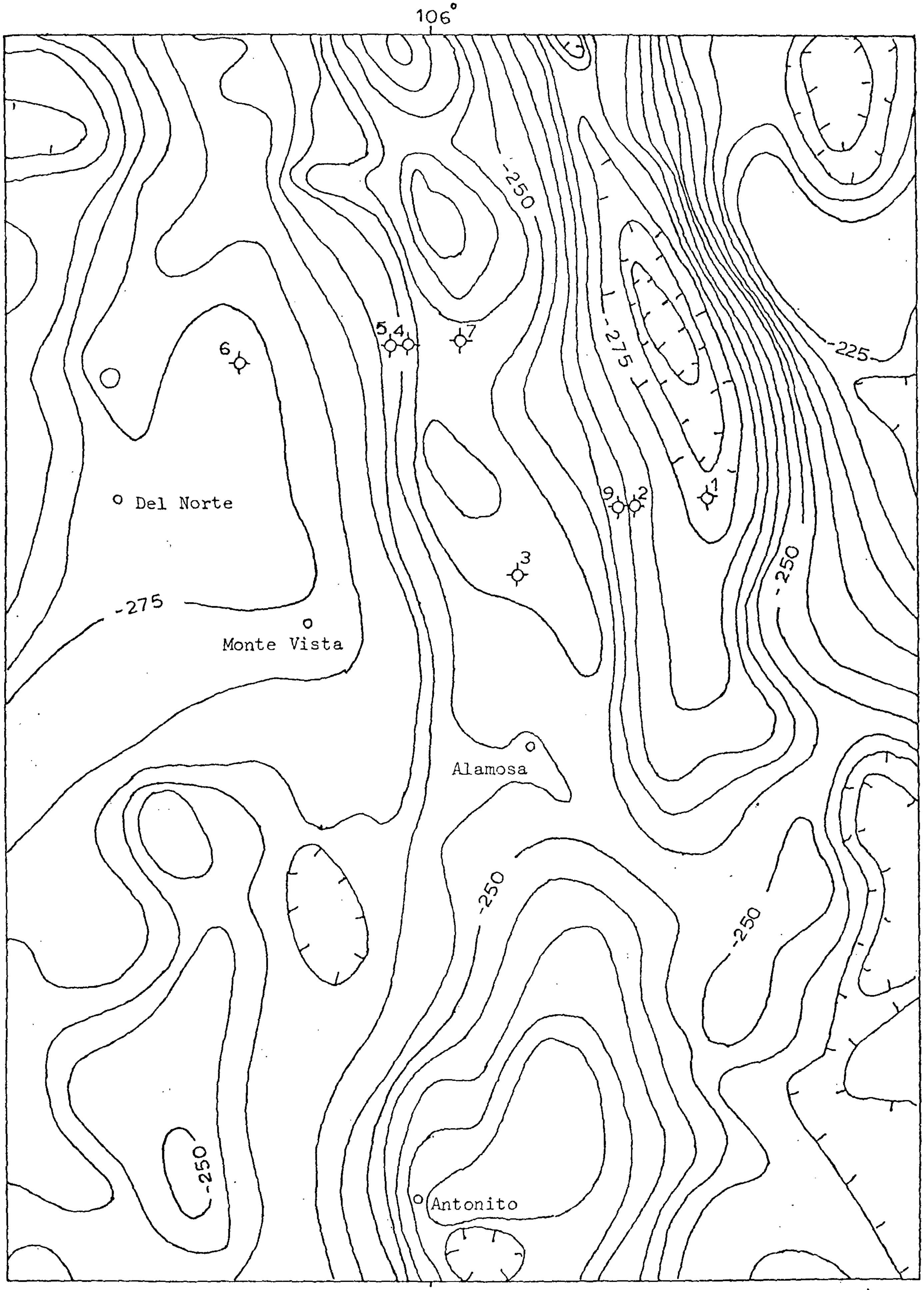

Figure 3. Bouguer gravity map of Alamosa basin, Colorado (C.I = 5 milligals). For well names see Plate 1 (after Behrendt and Bajwa, 1974).

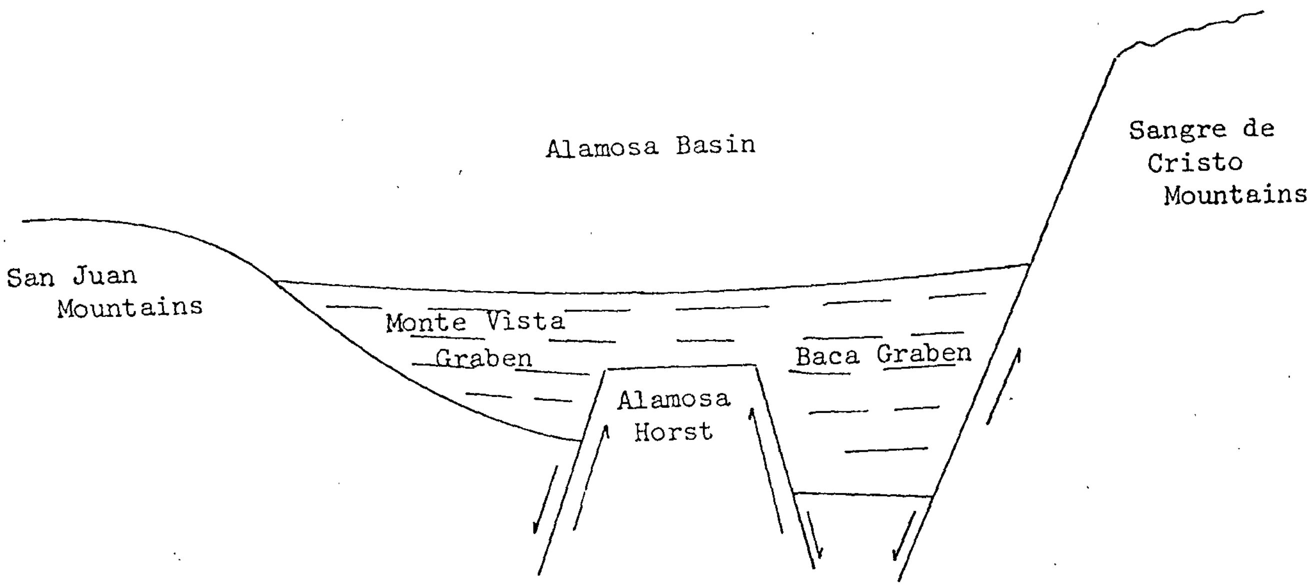

Figure 4a. Sketch showing typical structural interpretation of the Alamosa basin.

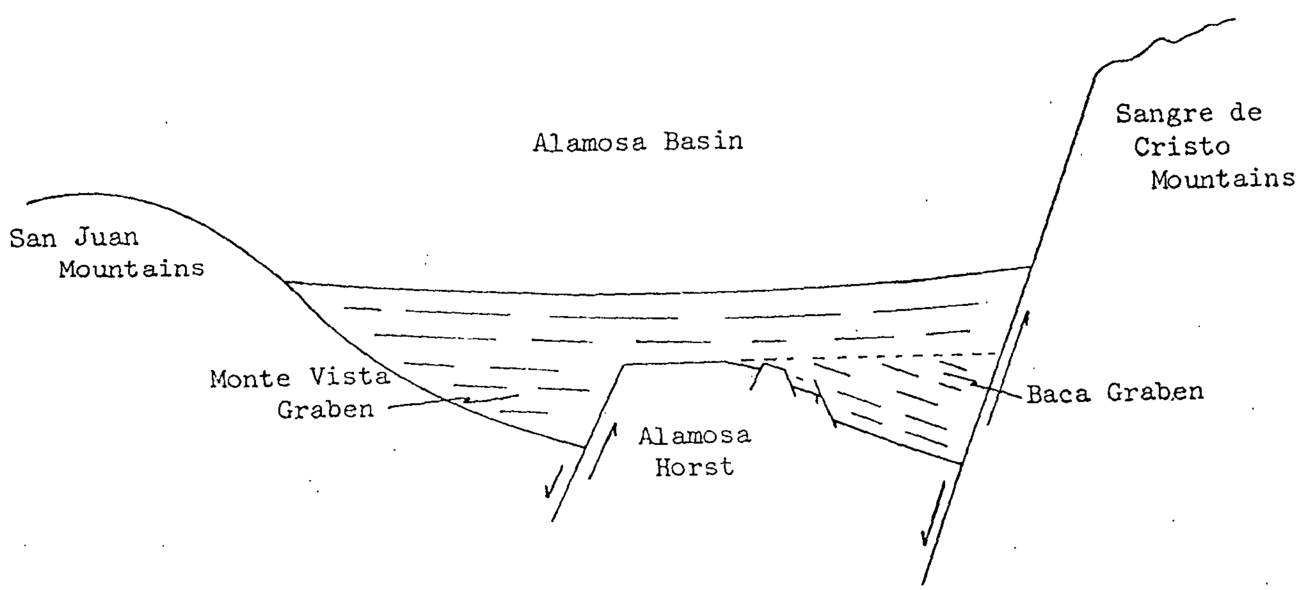

Figure 4b. Sketch of Alamosa basin showing two possible hinged grabens with eastward tilt.

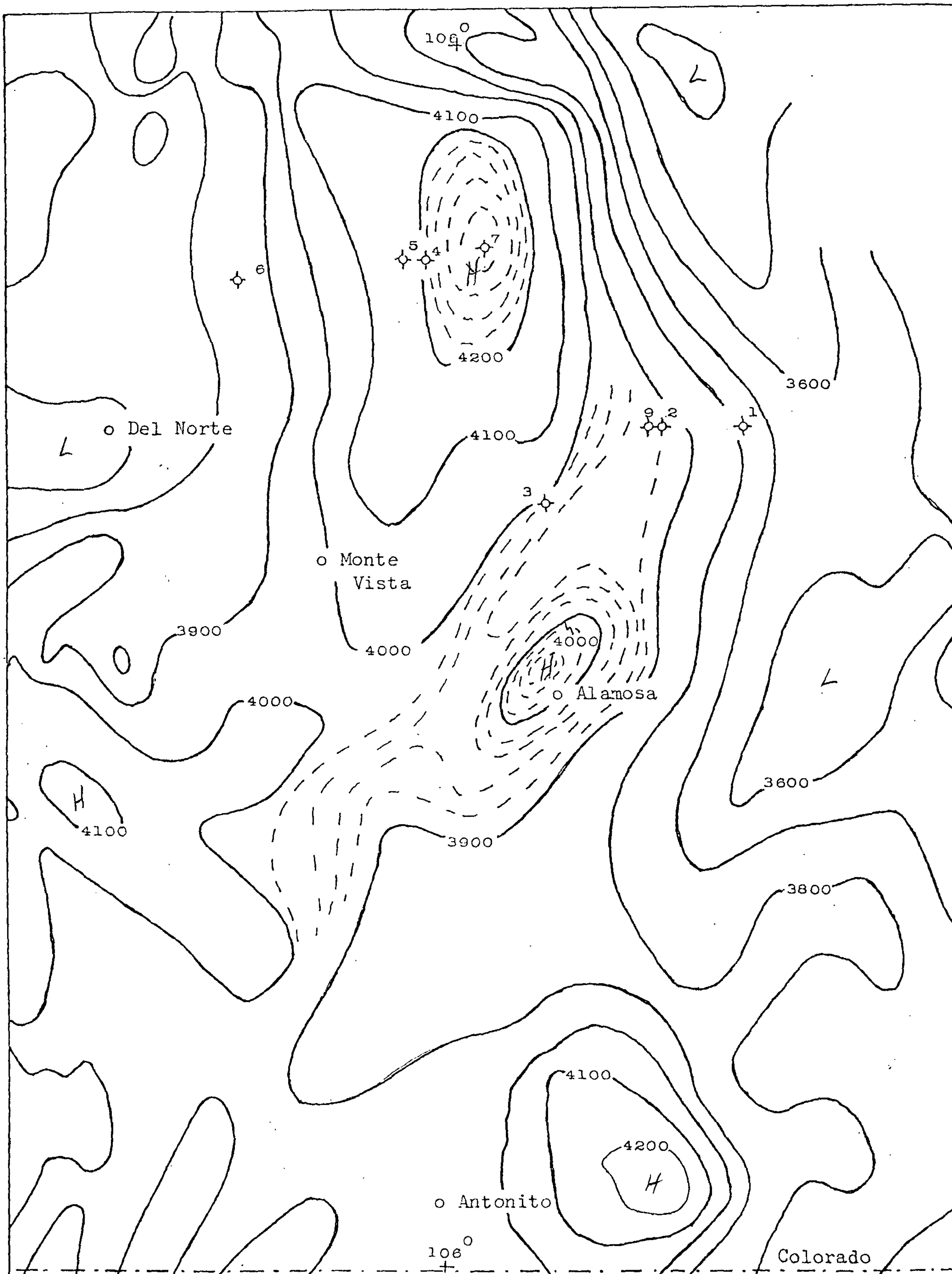

Figure 5. Aeromagnetic map of Alamosa basin, Colorado (C.I. 20 and 100 Gammas) After Zietz and Kirby, 1972. For well names see Plate 1.

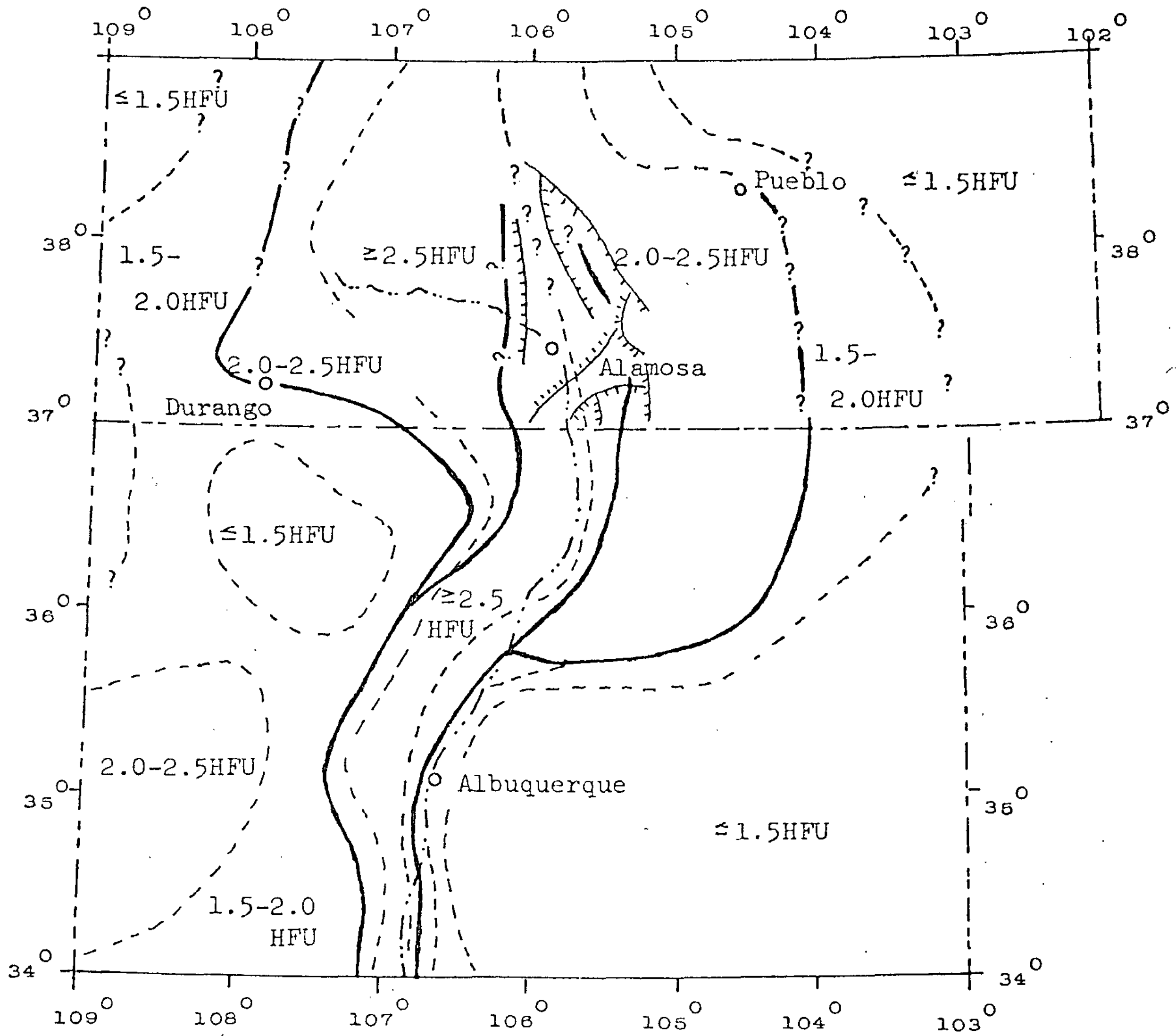

Figure 6. Terrestrial heat-flow map of northern New Mexico and southern Colorado (HFU = Heat Flow Unit)(modified after Reiter and others, 1975, 1979; and Edwards and others, 1979).

High heat-flow envelope believe to be associated with Rio Grande rift.

Normal faults of San Luis basin, hachures on downthrown side.