TERTIARY SEDIMENTATION AND TECTONICS: SAN JUAN SAG-SAN LUIS BASIN REGION, COLORADO AND NEW MEXICO

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ABSTRACT

The San Juan sag of the San Juan Mountains region of Colorado and the adjacent San Luis Basin of south-central Colorado and north-central New Mexico contain thick sections of Tertiary sedimentary and volcanic rocks. The stratigraphy of these Tertiary basins documents the tectonic development of a significant portion of the Southern Rocky Mountains region. Analysis of borehole data and geophysical surveys, combined with petrologic and sedimentologic study of existing outcrops, reveals distinct stages of development of the region which are related to the Laramide orogeny, Oligocene volcanism, and the development of the Rio Grande rift.

The San Juan sag is a Laramide basin which underwent several stages of development or modification from Late Cretaceous to Eocene. Basin analysis of the Animas (Late Cretaceous-Paleocene) and Blanco Basin (Eocene) formations, reveals the relative timing and mode of development of the San Juan sag and its bounding uplifts. The lower member of the Animas Formation is a volcaniclastic sequence consisting of reddish debris-flow and alluvial deposits derived from a northwestern source, the San Juan uplift. Provenance data, paleocurrents, and areal distribution of the lower member, and possible correlatives such as the McDermott Member (near Durango, Colorado) and Cimarron Ridge Formation (near Montrose, Colorado) suggest that the San Juan uplift was a northeast-trending, Precambrian-cored

uplift which followed the trend of the Colorado Mineral Belt and was uplifted accompanying Late Cretaceous intrusion and volcanism.

The upper member of the Animas Formation is a sandy alluvial plain sequence which was deposited by southwest-flowing braided and meandering streams. It includes green-gray-brown carbonaceous mudstones and pebbly sandstones containing clasts of mudstone, andesite and detritus from Precambrian and Mesozoic rocks exposed in the rising Brazos-San Luis uplift to the east and northeast. By the end of Animas deposition, the San Juan sag (then a north-eastern extension of the San Juan basin) was a broad, southwest-plunging synclinal downwarp bounded by uplifts to the northwest, north, and east. An erosional period followed Animas deposition; the greatest thickness of Animas was preserved along the axis of this synclinal feature.

Renewed subsidence of the San Juan sag in the Eocene is marked by the reddish sandy mudstone and pebbly sand-stone and conglomerate of the Blanco Basin Formation. This proximal braidplain deposit unconformably overlies Precam-brian through Paleocene rocks. Comparison of clast compo-sition between five reference sections shows that composi-tion is strongly dependent upon local sources. Paleo-current data show drainage into the San Juan Basin until rise of the intervening Archuleta anticlinorium.
This Eocene uplift probably accompanied right-lateral slip

along the eastern margin of the San Juan sag which resulted in segmentation of the Brazos-San Luis uplift and formation of the north-northwest trending, narrow, asymmetrical Monte Vista basin. The Monte Vista basin was filled with as much as 696m of Blanco Basin-like Eocene redbeds, including micaceous sandy mudstone and coarse arkosic sandstone containing lithic pebbles derived from granitic basement rock.

A period of volcanism in the early to late Oligocene covered the Laramide basins with several kilometers of volcaniclastic deposits, andesitic lavas, and ash-flow tuffs of the San Juan volcanic field.

Analysis of borehole and reflection seismic data from the Alamosa Basin (northern San Luis Basin) reveals that ash-flow tuffs correlative to 29-27 Ma tuffs of the San Juan volcanic field occur in deep wells across the San Luis Valley and comprise a basin-wide time marker. In the western half of the Alamosa Basin, the tuffs overlie the Conejos Formation (early Oligocene), which in turn covers the Eocene rocks of the earlier-formed Monte Vista basin; evidence that the western half of the younger, rift-related Alamosa Basin is superimposed over the Laramide Monte Vista basin. The tuffs rest directly on denuded Precambrian basement in the eastern half of the San Luis Basin.

Extension related to the Rio Grande rift resulted in eastward-tilting of the entire Alamosa Basin area following emplacement of the ash-flow tuffs. Filling the resulting half-graben is the late Oligocene-Recent Santa Fe Group (as

much as 5.6 km thick) comprised of variegated mudstones and coarse lithic sandstones and conglomerates. Lithic fragments in the Santa Fe Group represent two sources: variable-composition volcanic rocks from the San Juan volcanic field to the west (majority) and plutonic-metamorphic-sedimentary basement-derived rocks from the Sangre de Cristo Range to the east (minority). An angular unconformity within the Santa Fe Group documents strong early tilting due to movement on the Sangre de Cristo fault zone. The rift-related geometry of the crust beneath the Alamosa Basin is that of two east-tilted crustal blocks creating two second-order half-grabens within the basin.

INTRODUCTION

The San Juan sag to San Luis Basin region lies in southern Colorado and adjacent New Mexico ranging from the eastern San Juan Mountains in Colorado (Tusas Mountains in New Mexico), eastward to the San Luis Valley and Sangre de Cristo Range. Collectively, the San Juan sag and San Luis Basin contain a nearly complete section of Tertiary sedimentary and volcanic rocks. Knowledge of the history of the two basins has remained incomplete, however, because much of their strata are not exposed at the surface.

A combination of extensive volcanic and alluvial cover at the surface, rugged topography and heavy vegetation in mountainous parts of the region, and thickness of Tertiary units have discouraged extensive drilling efforts. However, application of improved seismic data collection and processing techniques have made hydrocarbon exploration possible. Despite the obvious drawbacks of deep drilling and limited accessibility, a number of deep stratigraphic tests have been drilled. In addition to subsurface data from these operations, there are scattered key outcrops of most rock units which provide further clues to the identity of basin strata. Therefore, there is sufficient scattered petrologic and geophysical data available to begin reconstruction of the stratigraphy and tectonic development of the basins.

The purpose of this dissertation is to integrate all available subsurface and surface data in a basin analysis approach to determine individual episodes and styles of tectonic development. The research techniques utilized to complete this project were varied, including field exercises such as stratigraphic section measurement and collection of sedimentologic and petrologic data, examination of well samples, petrography of surface and subsurface samples, and interpretation of well logs, seismic lines and gravity survey maps.

The dissertation which follows is divided into three separate, but related parts. Each part contains its own introduction, summary, list of references, and appendix, and was designed to stand alone as a journal article. The first part is a detailed study of the Blanco Basin Formation, an early Tertiary redbed deposit. Equivalents of the Blanco Basin Formation are widely distributed in the subsurface of the region of study. Part 1 integrates field and laboratory techniques to characterize the petrology, stratigraphy and sedimentology of the formation as it occurs in outcrop. Part 1 is intended to be a standard against which similar rocks can be compared, as is done in Parts 2 and 3.

Part 2 is an analysis of the stratigraphy and tectonic development of the San Juan sag, an early Tertiary foreland basin in the San Juan Mountains region. The San Juan sag has been the site of recent wildcat drilling which has established the presence of live hydrocarbons. Part 2 summarizes new subsurface data and field observations of the stratigraphy and sedimentology of outcropping syntectonic basin fill. The purpose of Part 2 is to build upon the foundation of previous work to better define the extent and history of the San Juan sag.

Part 3 describes the Alamosa Basin, a sub-basin of the San Luis Basin of the Rio Grande rift. The Alamosa Basin is a late Tertiary rift basin, the western half of which is superimposed over the proposed early Tertiary Monte Vista basin and eastern half of which is superimposed over part of an eroded early Tertiary uplift. Part 3 begins with an analysis of the stratigraphy of the San Luis Basin, and then applies this information to interpreting seismic lines across the basin. This integrated approach has resulted in a new interpretation of the basin structure and developmental history.

The three parts of this dissertation comprise an updated history of the Tertiary tectonic development of the San Juan sag and San Luis Basin. Although most of the data presented in this dissertation are from locations in south-central Colorado, the interpretations of the data generally apply to the broader region of the Southern Rocky Mountains.

PART 1

THE BLANCO BASIN FORMATION (EOCENE), SAN JUAN MOUNTAINS REGION, COLORADO AND NEW MEXICO

INTRODUCTION

The Eocene Blanco Basin Formation is a coarse, alluvial redbed deposit found in isolated outcrops along the southwestern flanks of the San Juan Mountains in south-central Colorado and adjacent New Mexico. This formation has received little attention in the past, yet it is an important record of a part of the early Tertiary geologic history of the San Juan Mountains region. It was deposited in the San Juan sag, a Laramide foreland basin which lies buried beneath the extensive volcanic pile of the Oligocene San Juan volcanic field. The formation documents the relative timing of uplift events which occurred in the region during the latter part of the Laramide orogeny. Understanding of the timing and style of uplift and basin formation and the general paleogeography of the region are of economic importance because of the recently recognized petroleum potential of the San Juan sag.

Remoteness of outcrops, rarity of complete exposures, and apparent non-existence of economic mineral resources are probably the primary reasons that the Blanco Basin Formation has not seen detailed study in the past. Earlier work was limited to regional reconnaissance of the formation where it was described, mapped, and tentatively correlated with similar formations. This paper refines the definition of the Blanco Basin Formation through analysis of its contacts, thickness, lithofacies associations, conglomerate and sandstone petrology, and paleocurrents. Together, these reveal the stratigraphy, sedimentology, and provenance of the formation.

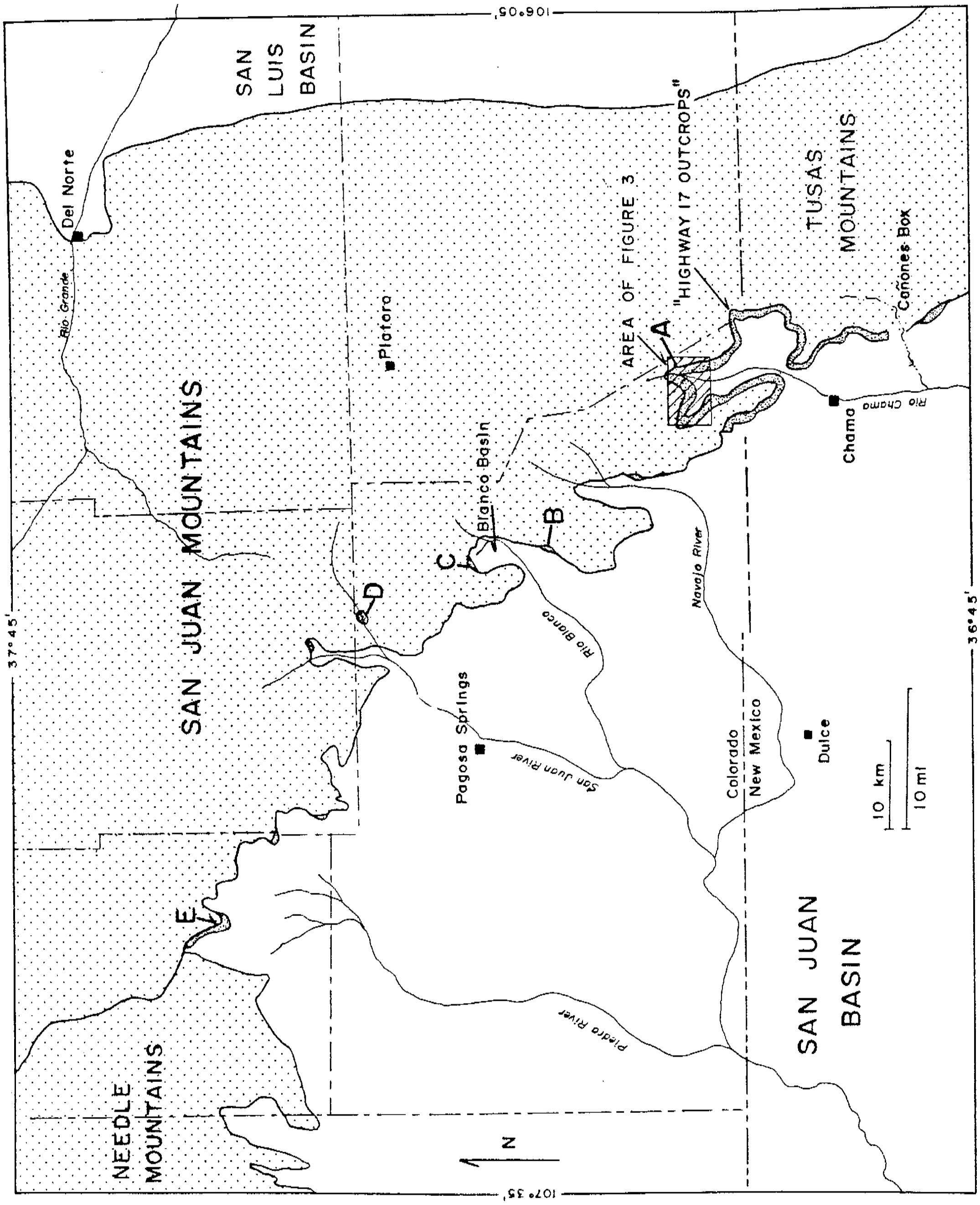
General description

The Blanco Basin Formation (as exposed) is a relatively thin (<200m), Eocene, unconformity-bound braidplain deposit. It is comprised of reddened, oxidized conglomerate, sandstone, and soft mudstone deposited by generally southwest-flowing streams. It is poorly consolidated and friable, with varying amounts of carbonate, hematite and clay making up interstitial material. Clastic material in the formation was derived from a number of different source rock types exposed in nearby active uplifts during the latter part of the Late Cretaceous to Eocene Laramide orogeny.

Location and setting

Outcrops of the Blanco Basin Formation are restricted to a narrow band along the southern flank of the San Juan Mountains in southwestern Colorado and adjacent New Mexico where they are exposed beneath the volcanic units of the San Juan volcanic field (Fig. 1). Heavy vegetation and extensive Holocene landslides cover almost all of the formation. Reference sections discussed in this paper were measured on public lands because access to private lands is

Figure 1: Regional location map. Blanco Basin Formation (dark stippled pattern) crops out at scattered locations along southwestern flank of San Juan Mountains (light stippled pattern). Bold letters (A,B,C,D,E) show locations of reference sections discussed in text.


106°05'
SAN LUIS BASIN
Del Norte
Rio Grande
Platoro
SAN JUAN MOUNTAINS
AREA OF FIGURE 3
"HIGHWAY 17 OUTCROPS"
A
TUSAS MOUNTAINS
Cañones Box
Chama
Rio Chama
Blanco Basin
B
C
D
Navajo River
Rio Blanco
37°45'
36°45'
Pagosa Springs
San Juan River
Colorado
New Mexico
Dulce
10 km
10 mi
E
SAN JUAN BASIN
Piedra River
NEEDLE MOUNTAINS
N
107°35'

strictly controlled and discouraged. Although most outcrops have poor lateral extent, enough widely separated individual exposures exist to enable reconstruction of probable early Eocene paleogeography and depositional environments.

PREVIOUS WORK

The Blanco Basin Formation was first described and named by Cross and Larsen (1935, p.48) for "prominent development about Blanco Basin, in the central part of the Summitville quadrangle". Blanco Basin (once the name of a small village) is a basin-shaped, glaciated valley surrounded on three sides by steep mountains, one of which is an exhumed laccolith weathered to a white ("Blanco") color. Unfortunately, the outcrops of the formation in Blanco Basin are sparse and incomplete; most of the "prominent" outcrops in the area can be demonstrated to be volcaniclastic beds of the Oligocene Conejos Formation.

The type section of the Blanco Basin was described from an unspecified location in the valley of the Rio Chama, in the southeastern corner of Archuleta County, Colorado (Cross and Larsen, 1935). Supplemental sections were described by Larsen and Cross (1956) and Adams (1957; reprinted in Muehlberger, 1967). Other detailed descriptions of the Blanco Basin Formation and its tectonic significance are those by Dunn (1964a, 1964b) and Muehlberger (1967). Many other authors have made brief mention of the Blanco Basin Formation, and where possible, are cited elsewhere in this text.

STRATIGRAPHIC POSITION AND AGE

To date, no macrofossils have been recovered from the Blanco Basin Formation and no lithologies are suitable for radiometric dates. A palynology assemblage from the lower part of the formation indicates a possible late Paleocene-early Eocene age (E.B. Robertson, 1990 written commun.), but the assemblage was sparse, and has not been reproduced (see Appendix 1). The best indication of age of the formation is based upon stratigraphic position and correlation with units of better known age.

The Blanco Basin Formation overlies rocks as high in the stratigraphic section as the upper member of the Animas Formation which has been assigned a Paleocene age based on biostratigraphic criteria (Reeside, 1924; Newman, 1982; R.H. Tschudy in Ryder, 1985, p.99). The lower contact of the Blanco Basin is everywhere unconformable. As exposed, the formation overlies progressively older strata from Paleocene to Triassic towards basin margins. The degree of angular discordance at its lower contact increases towards basin margins (Fig. 2a). In the central part of the San Juan sag, the angularity between the Blanco Basin and Animas Formations may be minor and other criteria such as petrology, lithofacies, color, and abundance of organic matter must be employed to distinguish their contact.

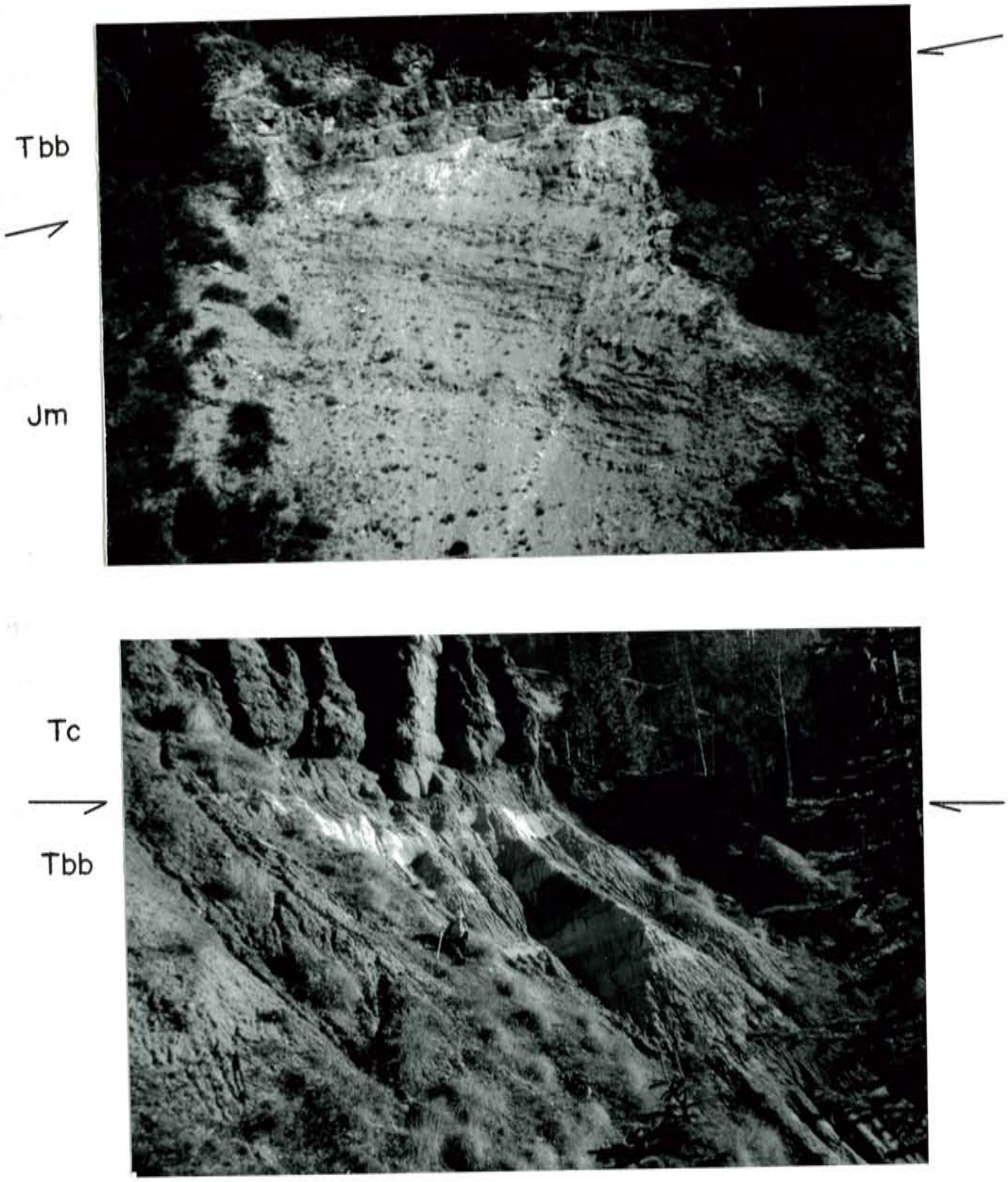


Figure 2: Photographs of upper and lower contacts of the Blanco Basin Formation. 3a) Angular unconformity between Blanco Basin Formation (Tbb) and Morrison Formation (Jm) visible from Highway 17, near state line, north of Chama, New Mexico. 3b) Contact between Blanco Basin Formation and Oligocene Conejos Formation (Tc) at Oil Creek, Colorado (location "C" on Fig. 1).

The Blanco Basin Formation is overlain by the Conejos Formation which has been radiometrically dated to range from 35 to 30 Ma in age (Lipman and others, 1970). Apparent conformity between the two formations at some localities was described by Cross and Larsen (1935), but they also mentioned that it was in places erosionally thinned prior to deposition of overlying units. Later detailed mapping efforts have confirmed an erosion surface of probable latest Eocene age (Steven, 1975). This surface cuts strata as low in the section as the Lewis Shale (upper Cretaceous) along the northeastern flank of the Archuleta anticlinorium. Folding of the Blanco Basin and older strata over the Archuleta anticlinorium occurred in the middle(?) Eocene (Dunn, 1964a, 1964b). Figure 2b illustrates a rare excellent exposure of the upper contact.

Numerous authors have suggested that the Blanco Basin is a piedmont facies of the lower Eocene San Jose Formation (Baltz, 1953, 1967; Barnes, 1954; Van Houten, 1957; Muehlberger, 1967; Dunn, 1964a, 1964b; Lucas, 1984; and others), however, few attempts have been made at direct correlation. Smith (1988) showed that paleocurrent indicators at one outcrop north of Chama, New Mexico, demonstrated southwest flow towards the San Juan Basin. He also demonstrated that the Regina, Llaves, and Tapicitos members of the San Jose Formation were derived from northern and northeastern sources; thus they may correlate with the Blanco Basin, at least in part.

A comparison of sandstone composition between the two formations was reported by Dunn (1964a). Lucas (1984) suggested Dunn's study provided possible criteria for correlation of the Blanco Basin Formation with the Cuba Mesa Member of the San Jose Formation. Such a correlation is tenuous, at best, because Dunn's study was intended only to show similarity between the formations and was not detailed enough to justify correlation of the Blanco Basin with any specific member of the San Jose. However, the similarities between some members of the San Jose and Blanco Basin formations in lithology, stratigraphic position, and general sedimentologic trends indicate that they correlate at least in part.

Other formations to which the Blanco Basin has been correlated are the Telluride Conglomerate and El Rito Formation. The Telluride Conglomerate (Cross and Larsen, 1935) occurs in outcrops along the western margin of the San Juan Mountains. It was was shed westward and northwestward (Steven and Hail, 1989) from the Needle Mountains area (part of the Laramide San Juan uplift) during the Eocene (?) whereas part of the Blanco Basin was derived from the Needle Mountains area but shed south to southeast. The two formations probably reflect sedimentary response to the same uplift event.

The relationship between the Blanco Basin Formation and the El Rito Formation has been the subject of some debate. The El Rito Formation (Smith, 1938) is a coarse, reddened, conglomeratic unit which crops out in the Tusas Mountains and southern Chama Basin (Smith and others, 1961; Bingler, 1968). Logsdon (1981) demonstrated that the El Rito Formation was deposited by southward flowing stream systems headed in the Laramide Brazos and Nacimiento uplifts, and suggested that it is the upstream equivalent of the Eocene Galisteo Formation (Gorham and Ingersoll, 1979). The El Rito Formation at its type locality differs substantially from the Blanco Basin Formation at its type locality, particularly in clast composition, but also in the abundance of some lithofacies types, and destination basins (as determined from paleocurrent studies). Lucas (1984) suggested that the El Rito Formation is younger than the Blanco Basin Formation, based on regional stratigraphic relations, but this has not been confirmed through field studies.

The boundary between the two formations is rather arbitrary, due to the rarity of good exposures on the western flank of the present-day Tusas Mountains which makes detailed analysis difficult. Muehlberger (1968) noted interfingering (suggesting contemporaneity) between the two formations in the vicinity of Cañones Box, southeast of Chama, New Mexico. Muehlberger's study predated Logsdon's (1981) refinement of the El Rito Formation which considers its basin of deposition. Muehlberger's separation of the two formations was based primarily upon provenance-determined criteria which need not be diagnostic of either formation. For example, quartzite clasts tend to dominate in the El Rito drainage basin, but such clasts are also common components of the Blanco Basin at many locations.

No marked interfingering was observed by the author in the vicinity of Cañones Box. The transition from granitic-schistose-quartzitic composition to almost exclusively quartzitic composition appears to be relatively abrupt adjacent to the covered contact inferred between schistose metavolcanic and metaquartzite Precambrian terranes. There appears to be no abrupt change in paleocurrents across this transition; instead, paleocurrents appear to swing gradually southward further north near the state line. Whether or not interfingering can be demonstrated, the outcrops of the El Rito Formation as mapped by Muehlberger (1968) at Cañones Box are here considered to be identical in stratigraphic position to the Blanco Basin Formation. Documentation of the possible transition between the two formations awaits further study of the outcrops between Cañones Box and the El Rito type locality.

REFERENCE SECTIONS

In order to gain a more complete understanding of the range of characteristics of the formation, the author briefly visited most outcrops reported in the literature (exceptions were on some private lands where permission for access was unattainable). Reference sections were measured from the best exposed and accessible outcrops to provide a means of demonstrating vertical and lateral variations of the formation.

Principal reference section

A new principal reference section and locality are proposed here because the description of the location of Cross and Larsen's (1935) type section along the Rio Chama was not detailed enough to determine its exact location. The principal reference section occurs on public land and is easily accessible in good weather via a gravel road (Fig. 3). The principal reference section (Fig. 4; called section "A" in this paper) is the thickest section measured from the formation (194m) and appears to be the most representative single section.

Cross and Larsen (1935, p.48) described three informal members:

> ...an upper cliff-forming white sandstone with some horizontal fluting; a middle member that crops out as broken cliffs and is made up of alternating beds of white sandstone and red shale, giving a general pinkish outcrop; and a lower bright-red member of muddy sandstone and shale that is soft and gives poor exposures.

This sub-division applies well to those outcrops along the Rio Chama in the principal reference locality (Fig. 5), but has less application to most other outcrops of the formation away from the Rio Chama area. For this reason, these members are not extended to other areas. The general trend of coarsening upward of sandstone and conglomerate units and upward-decreasing abundance of mudstone units implied in Cross and Larsen's three members, however, is a common feature in most complete sections of the formation in outcrop.

Other reference sections

Measured sections B and C (Fig. 6) were erosionally thinned prior to deposition of the Conejos Formation but are included here because their upper and lower contacts are exposed, and because of sedimentologic and petrographic differences from section A. Section D (Fig. 7) shows the greatest contrast with section A in lithofacies types. Section E (Fig. 7) demonstrates paleodrainage from a different uplift source. Sections B and C are best accessed by foot travel, whereas D and E are easily visited by passenger car.

Figure 3: Simplified geologic map of principal reference locality showing paleocurrent rose directions for Blanco Basin Formation. Formation contacts dashed where covered and inferred. Base map from U.S. Geological Survey 7.5' topographic map series, Archuleta Creek quadrangle, Colorado.

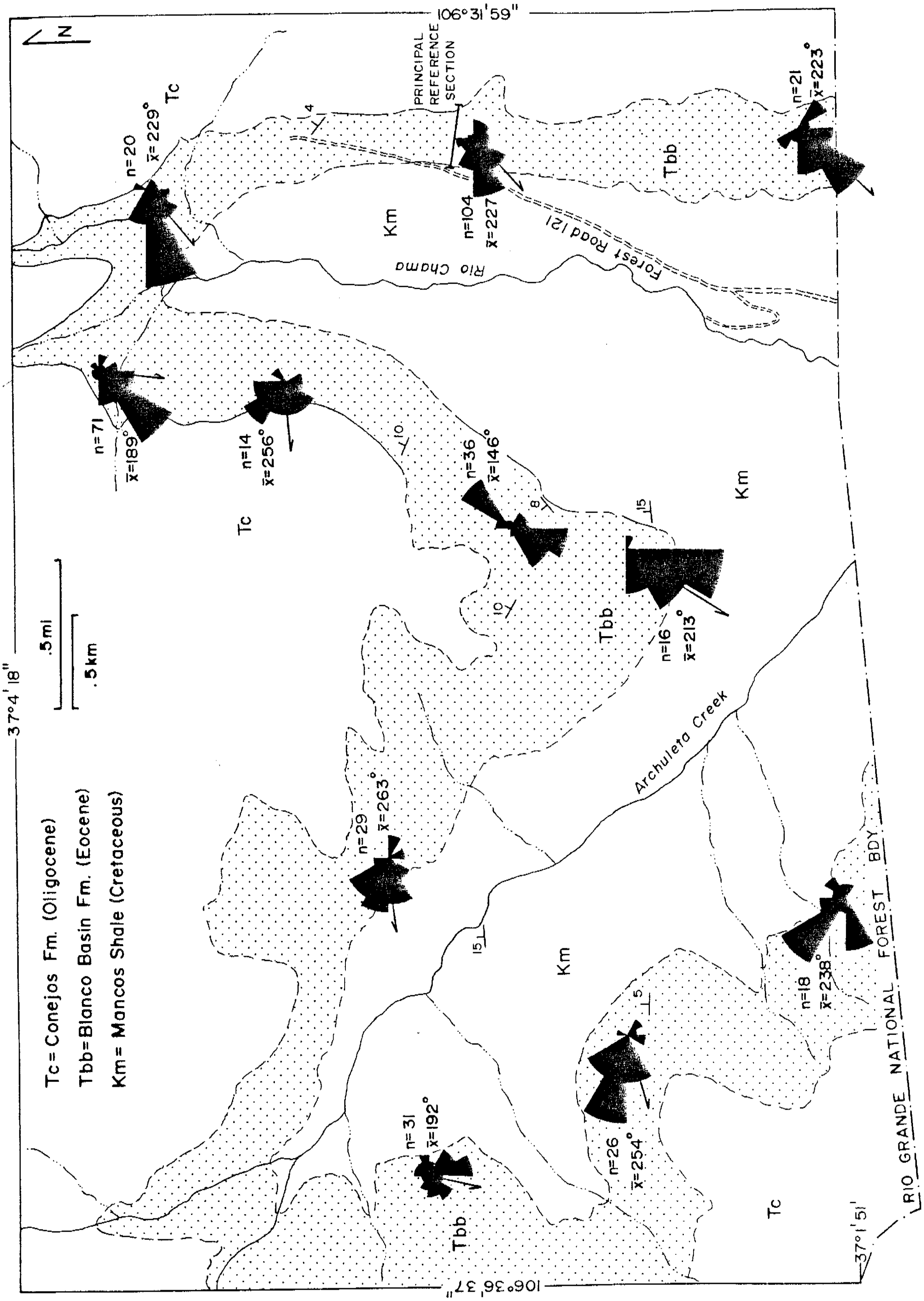
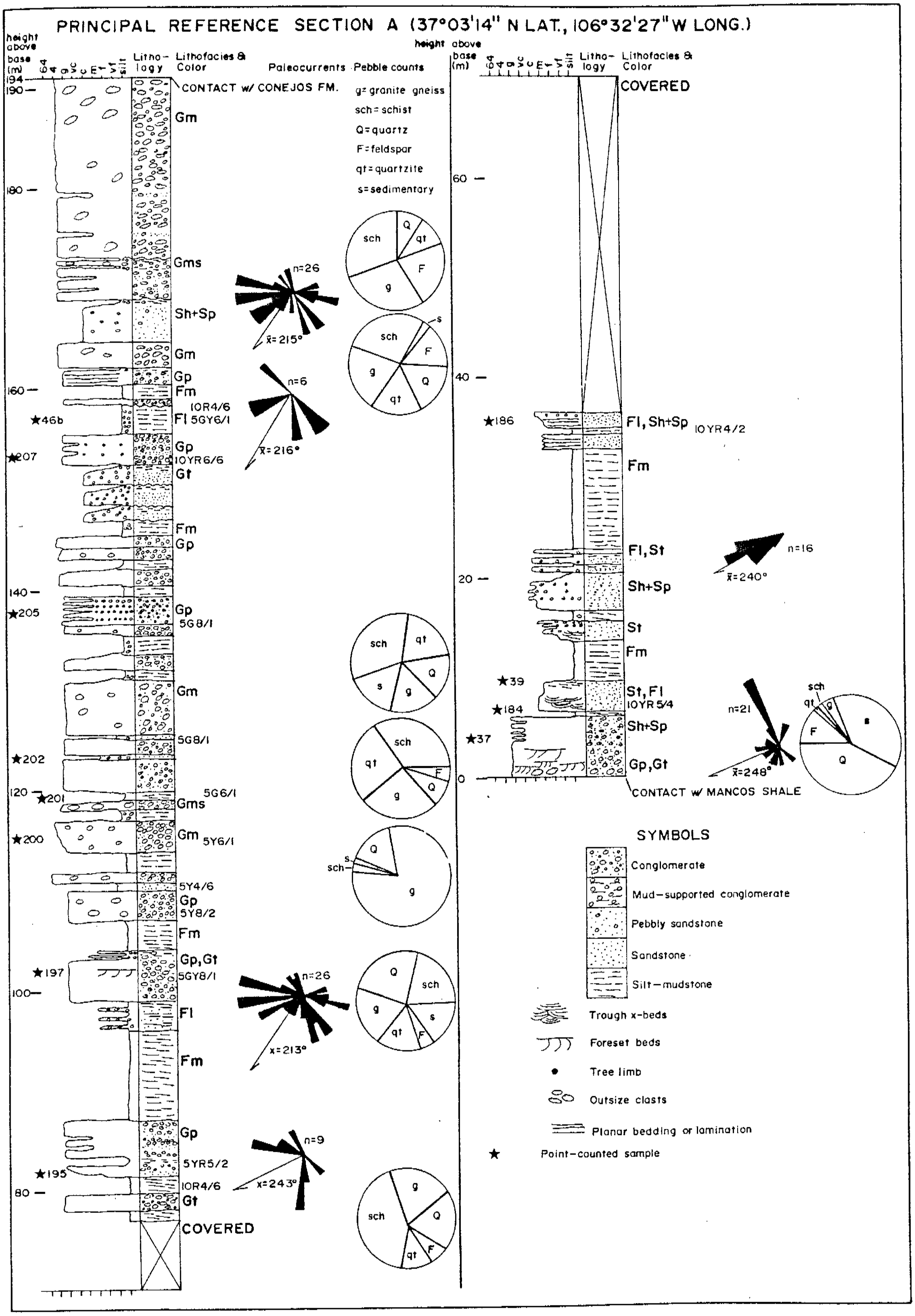

106°31'59"
N
PRINCIPAL REFERENCE SECTION
Tc
n=20
x̄=229°
n=104
x̄=227
n=21
x̄=223°
Tbb
Km
Rio Chama
Forest Road 121
n=71
x̄=189°
n=14
x̄=256°
n=36
x̄=146°
n=16
x̄=213°
Tc
Km
Tbb
.5mi
.5km
37°4'18"
Tc = Conejos Fm. (Oligocene)
Tbb=Blanco Basin Fm. (Eocene)
Km= Mancos Shale (Cretaceous)
n=29
x̄=263°
Archuleta Creek
Km
n=18
x̄=238°
n=31
x̄=192°
n=26
x̄=254°
Tbb
Tc
RIO GRANDE NATIONAL FOREST BDY
37°1'51"
106°36'37"

Figure 4: Measured section for the Blanco Basin Formation; principal reference locality, Rio Chama, Archuleta County.


PRINCIPAL REFERENCE SECTION A (37°03'14" N LAT., 106°32'27" W LONG.)
height above base (m)
Litho-logy
Lithofacies & Color
Paleocurrents
Pebble counts
CONTACT w/ CONEJOS FM.
g= granite gneiss
sch= schist
Q= quartz
F= feldspar
qt= quartzite
s= sedimentary
COVERED
CONTACT w/ MANCOS SHALE
SYMBOLS
Conglomerate
Mud-supported conglomerate
Pebbly sandstone
Sandstone
Silt-mudstone
Trough x-beds
Foreset beds
Tree limb
Outsize clasts
Planar bedding or lamination
Point-counted sample

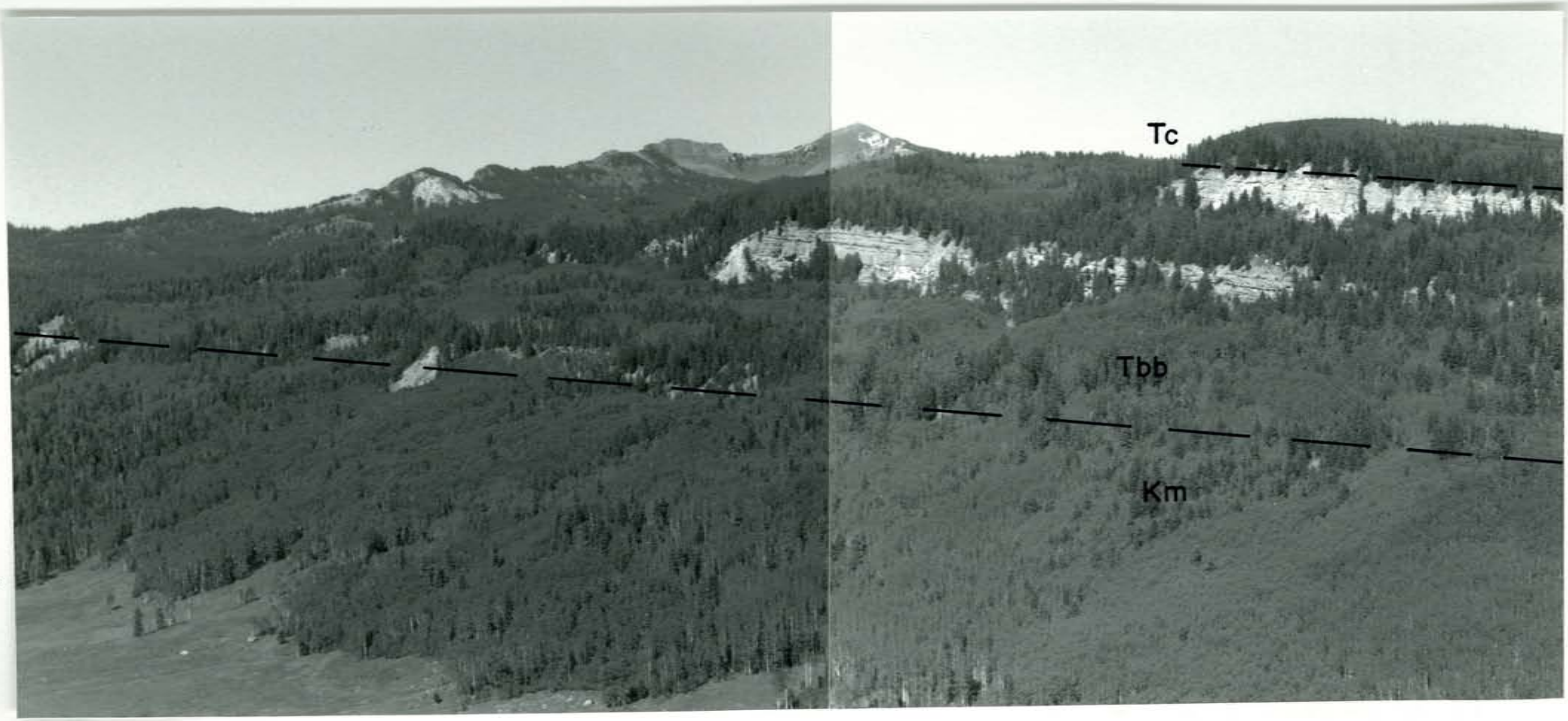


Figure 5: Photograph of Blanco Basin Formation (Tbb) outcrops in the vicinity of the prinicpal reference section, valley of Rio Chama, Colorado. Tc = Conejos Formation; Km = Mancos Shale.

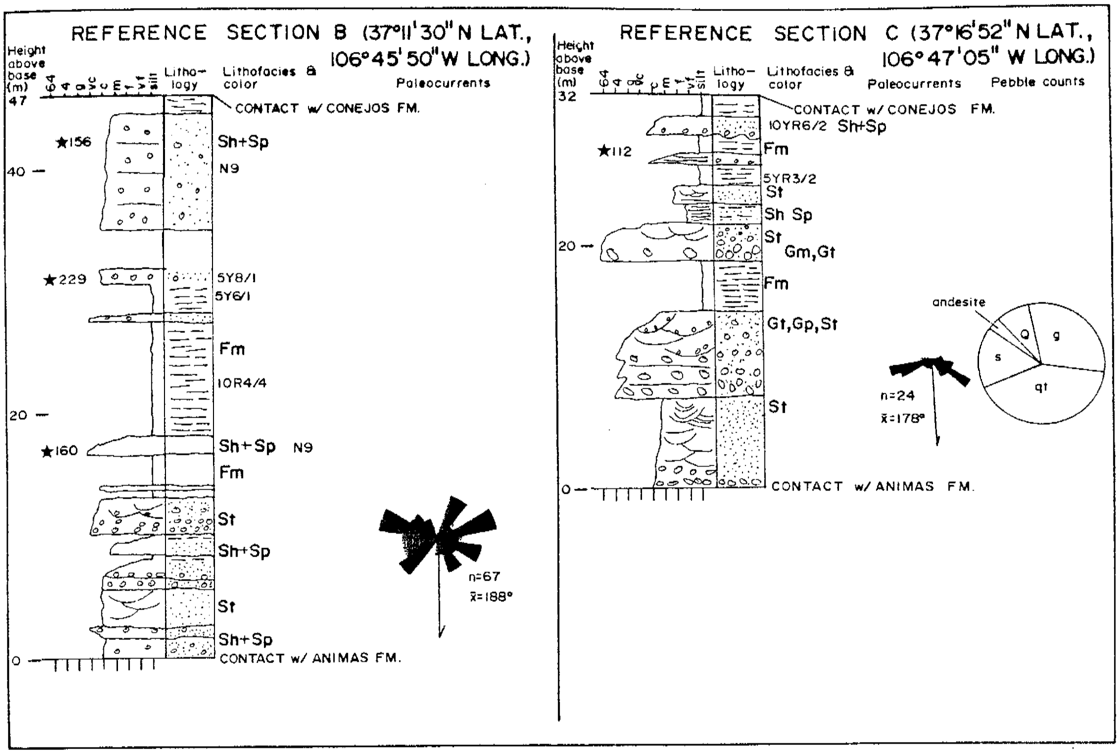
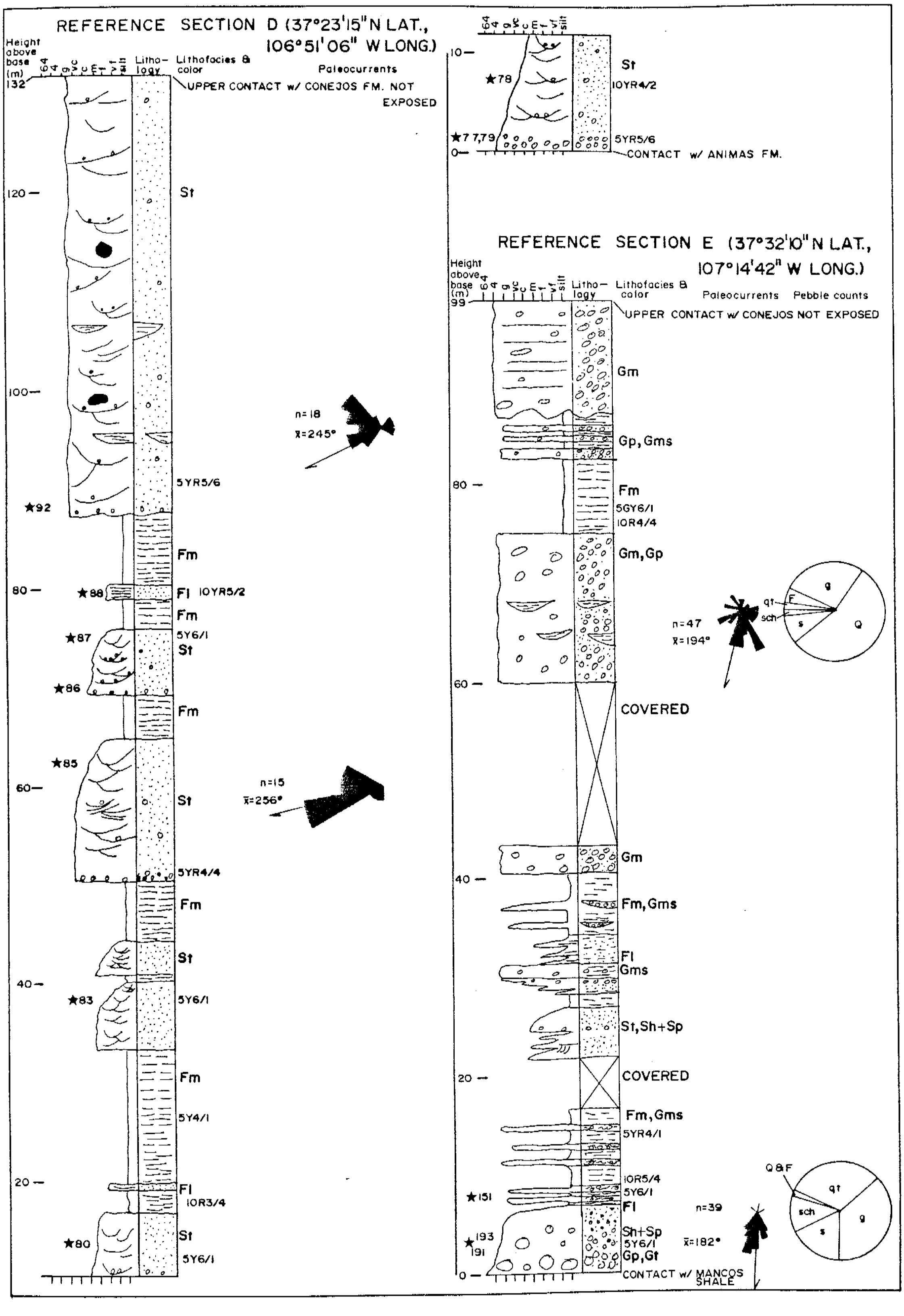


Figure 6: Reference sections B and C for the Blanco Basin Formation. Symbols explained in Figure 4.

Figure 7: Reference sections D and E for the Blanco Basin Formation.
See figure 4 for key to symbols.


REFERENCE SECTION D (37°23'15"N LAT., 106°51'06" W LONG.)
Height above base (m)
Litho-logy
Lithofacies & color
Paleocurrents
UPPER CONTACT w/ CONEJOS FM. NOT EXPOSED
St
5YR5/6
n=18
x̄=245°
Fm
Fl 10YR5/2
5Y6/1
n=15
x̄=256°
5YR4/4
5Y4/1
10R3/4
CONTACT w/ ANIMAS FM.
10YR4/2
REFERENCE SECTION E (37°32'10"N LAT., 107°14'42" W LONG.)
Pebble counts
UPPER CONTACT w/ CONEJOS NOT EXPOSED
Gm
Gp, Gms
5GY6/1
10R4/4
Gm, Gp
n=47
x̄=194°
COVERED
Fm, Gms
Fl
Gms
St, Sh+Sp
5YR4/1
10R5/4
Sh+Sp
Gp, Gt
n=39
x̄=182°
CONTACT w/ MANCOS SHALE

LITHOFACIES TYPES

Lithofacies of the Blanco Basin are highly variable within, and between, individual outcrops. The types of lithofacies present were dependent upon distance between sources and depositional sites, and specific environments of deposition, at least two of which are recognized. In general, facies are similar to those typical of humid subaerial alluvial fans and braidplain deposits. Descriptive terminology in common usage for such facies is that of Miall (1977; 1978; 1984), Rust (1978), and Rust and Koster (1984). This terminology has been modified slightly in the following discussion to group various lithofacies types recognized from the Blanco Basin Formation.

Lithofacies *Gms* (matrix-supported gravel)

This lithofacies is composed of matrix-supported sedimentary breccias and pebbly mudstones generally devoid of current-produced sedimentary structures. Clasts are angular to round pebbles with random orientation; matrix is sandy, red mudstone. These deposits are typically ungraded and only rarely contain outsized clasts (ie. boulders). Lithofacies *Gms* is apparently localized to areas proximal to uplift boundaries, thus transport distance was minimal. The transport mechanism envisioned for these deposits is similar to that described by Nilsen (1968) from the Devonian of western Norway where slopewash colluvium at the toes of talus fans was remobilized and transported as debris flows spreading out in a sheet over an alluvial fan surface. *Gms* facies of the Blanco Basin appear to be similar unconfined mass-flow deposits.

Local faulting is the most likely origin for the fragmental material near basin margins. North of Chama, New Mexico, at the site of Figure 2b, the Blanco Basin Formation lies atop Mesozoic sandstones and shales which are cut by a series of north-trending minor-displacement reverse faults. These faults are interpreted as part of a fault zone marking the western edge of the Brazos uplift at this location. At this and other locations proximal to the Laramide Brazos uplift, a sedimentary basal breccia (defined by Laznicka, 1988) occurs, and similar breccias are interbedded with coarse braided-stream facies throughout the section. Such a facies association is interpreted to reflect episodic local input of unconfined mudflows associated with recurrent fault activity. This phenomenon has been described from the Echo Park basin in Colorado by Chapin and Cather (1981) and Chapin and others (1983). These authors attribute mass-flow processes such as sheet-wash of weathered regolith, mudflow, and debris flow as directly related to seismic events on active wrench-faults.

Lithofacies *Gm* (massive gravel)

This lithofacies is composed of thick sheets of massive to crudely stratified, clast-supported, pebble to cobble conglomerate (Fig. 8). Clast arrangement ranges

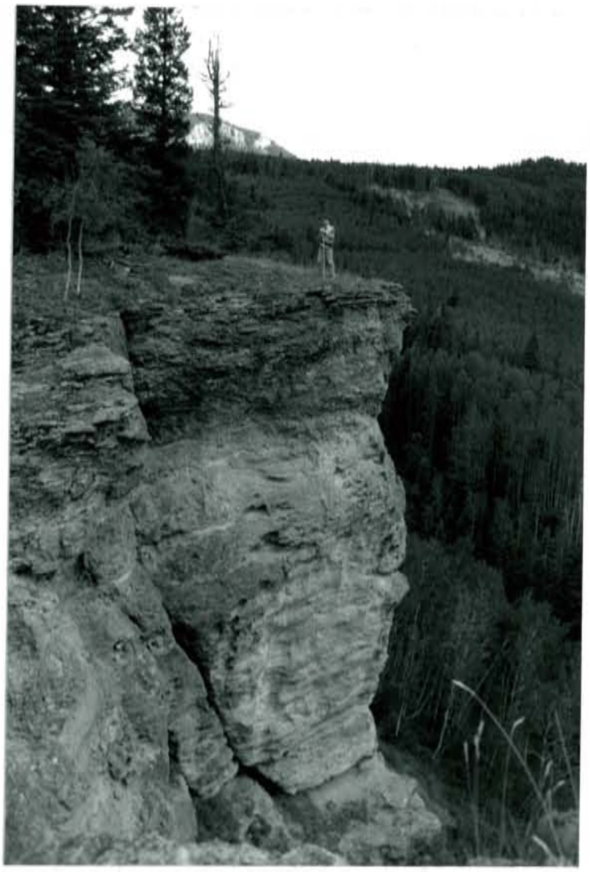


Figure 8: Massive to horizontally stratified conglomerate (lithofacies *Gm*), uppermost pebble-cobble conglomerate, in vicinity of principal reference section "A" at the Rio Chama. Weathering enhances stratification.

from non-imbricated to well imbricated. Some beds may be uniform in grain-size, but most tend to fine upward. Sorting is moderate with a dearth of large clasts. Matrix is medium to granular sand which infiltrated during waning stages of floods. The matrix tends to decrease in grain size near the top of single flood units, as would be expected during waning transport energy. Lower bounding surfaces are scoured and may be planar or undulatory.

Transport mechanisms of similar clast-supported high flow regime deposits range from dilute, turbulent stream flow to viscous, nonturbulent clast-rich mass-flows (Nemec and Steele, 1984; Smith, 1986). Considering such a spectrum, the majority of conglomerates in the Blanco Basin Formation closely resemble deposits of the braided stream end-member, with gravels transported as traction load and deposited in longitudinal braid-bars. Climatic factors (weathering and soil development), topographic gradient, and grain-size of source rocks was such that most mass-flow deposits in the Blanco Basin are matrix-rich and may be classified as lithofacies *Gms*.

Lithofacies *Gp* (planar bedded gravel)

This lithofacies includes both planar cross-stratified and horizontal planar bedded (bedding is distinct), clast-supported conglomerate (Figure 9a). Clasts tend to be small pebbles with occasional larger pebbles or cobbles. Clasts are often imbricated, and matrix is typically

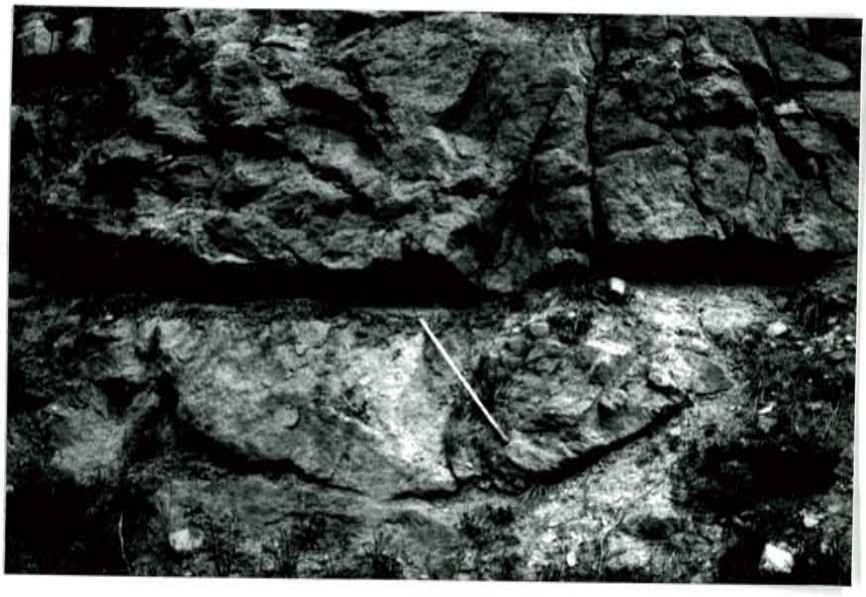


Figure 9: a) typical well-stratified small-pebble conglomerate at reference section "E"; b) trough-shaped scour-fill conglomerate near base of principal reference section "A".

granular sand. Units are multistoried, sheet-like bodies with irregular, undulatory scoured bases. Large-scale planar cross-beds are typically oblique to the paleocurrent transport direction measured from other indicators such as imbrication, thus indicating lateral accretion of transverse bars. The nature of such braided channels implies deposition on relatively steep gradients characteristic of mid- to proximal settings (Atkinson, 1986).

Lithofacies *Gt* (trough cross-stratified gravel)

This lithofacies is characterized by trough cross-bedded conglomerates. Both sheet-like bodies and ribbon-like bodies (isolated laterally by finer-grained facies) comprise this lithofacies. Sheets are formed where troughs step laterally or where they are stacked. Other trough cross-stratified units occur as fills of erosional scour channels (Fig. 9b). Clasts are generally well-rounded, self-supporting, and well sorted. Overall, individual troughs and channel fills tend to fine upward, both in coarse clasts and sand matrix. Where this lithofacies occurs over bedrock, erosional channel fills may have basal sand-matrix sedimentary breccias. In such cases, bedrock makes up the majority of clasts. Where this facies occurs as discreet erosional channel fills, it grades laterally into facies *Sh* and *Fm*.

Lithofacies *Sh+Sp* (horizontal bedded and planar cross-stratified sand)

This common sandstone lithofacies is composed of massive, horizontal planar-bedded, and planar cross-bedded sandstone. This lithofacies tends to be medium to coarse grained, pebbly sandstone deposited under conditions of the upper flow regime in planar bed flow or at sandy parts of braid-bars during floods, in less proximal areas of the Blanco Basin's depositional basin. Individual flood units are often floored by imbricated pebbles, thus distinguishing beds in massive-bedded units. These beds occasionally exhibit parting lineation.

Lithofacies *St* (trough cross-bedded sand)

This lithofacies contains medium grained to granular sandstones in multistoried sheets that contain solitary (theta) and, more commonly, grouped (pi) trough x-beds. This lithofacies is indicative of lower flow regime conditions of stream flow (Miall, 1978). Trough size is in large part dependent upon grain size and thickness of sand bodies, ultimately related to flow regime of the stream system. This is seen in section D where troughs in coarse, thick, mud-free, (6.5-43m) sandstone sheets range up to several meters across and deep (Fig. 10). Where fine grained, however, troughs are small (on the order of centimeters) and somewhat muddy. Paleocurrents from several localities were determined, in part, from 3-D trough orientations in this lithofacies. Pebbles may occur

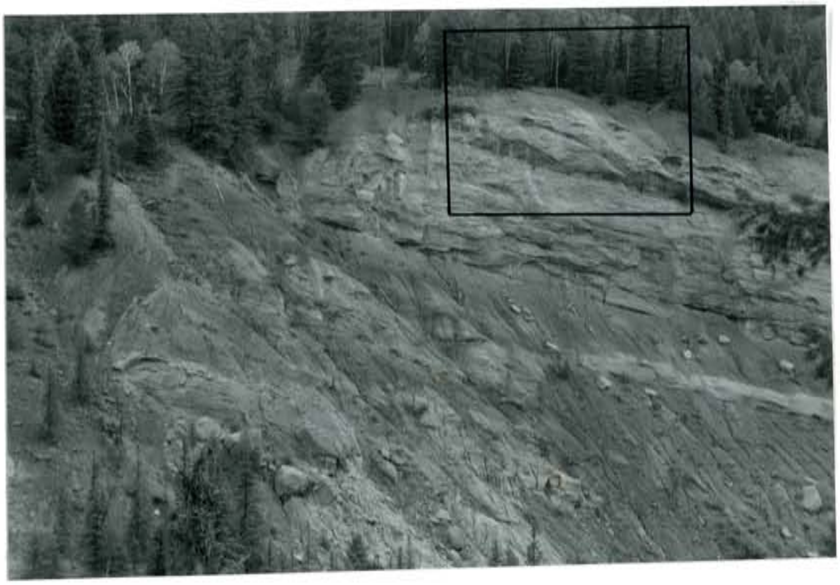


Figure 10: a) 110 m exposure of Blanco Basin Formation at reference section "D", East Fork of the San Juan River. Box indicates area of Figure 9b; b) Lithofacies *St*, individual troughs in sandstone are on the order of 2 m high and 4 m across.

at base of individual troughs.

Lithofacies *Fl* (horizontally laminated fines)

This lithofacies is the least common facies in the formation. It is comprised of horizontally laminated, flaggy, fine-grained sandstone to siltstone which is interbedded with lithofacies *Fm* near the base of section A. These beds are planar laminated to faintly rippled. Horizontal and oblique burrows and sole marks are sometimes present. This lithofacies typifies over-bank or waning flood deposits (Miall, 1978), and occurs laterally from ribbon-like channel sand bodies. *Fl* can be traced laterally for only short distances (tens of meters) due to the poor quality of outcrops, but may extend laterally to a much greater extent.

Lithofacies *Fm* (massive fines)

This lithofacies of the Blanco Basin is common in most outcrops of the formation excluding the most proximal occurrences. It is distinguished by massive red to gray mudstones and siltstones which are sandy, and strongly oxidized (generally devoid of organic matter/pollen spores; gray vitrinite is evidence of extensive oxidization, E.B. Robertson, written communication). Individual units tend to be gray green at top and base, associated with post-depositional reduction by ground waters containing H_2S derived from decaying organic matter. According to Smith (1987) red coloration in the San Jose Formation ('downstream' correlative to Blanco Basin) is due to hematite formed in oxidizing environments, this is probably due to excellent drainage (percolation to a low water table) in these deposits rather than to red source rocks as suggested by Dunn (1964a) and Muehlberger (1967). Conglomerates conglomerates containing intraformational mudclasts often fill channels scoured into the upper parts of lithofacies *Fm*.

Laminated, mudstones are lacking, perhaps due to extensive bioturbation and pedogenic modification. No detailed study was made to determine the degree of pedogenesis in the formation, however, well-preserved soil horizons are not common. The most obvious paleoweathering is at the base of the formation wherever it overlies Cretaceous shales and older rocks near basin margins where reddening or bleaching and kaolinitization of these rocks is seen. Transported kaolinite clasts in conglomeratic facies were probably derived from similar paleoweathering zones. Such paleoweathering zones develop at major stratigraphic breaks and may represent long periods of pedogenesis (Wright, 1986).

Interpretation of lithofacies associations

The depositional environments of the Blanco Basin Formation are best discussed considering their lithofacies associations. Lithofacies in the following four associations are listed in order of relative abundance:

Gm, Gms: This facies association is only found north and east of Chama, New Mexico, mostly east of Highway 17. It appears to be limited to proximal areas subject to occasional muddy debris-flow deposition caused by high storm runoff. Streams originating in adjacent low mountainous areas constantly reworked debris, thus facies *Gm* predominates. No point-sources (canyons at head of fan) for alluvial fans have been recognized from the existing deposits. This association is identical to the Trollheim-type model of braided stream deposits (Miall, 1978). The limited contribution of *Gms* to this lithofacies association needs emphasis because general statements made by Dunn (1964a, 1964b) about the formation may be misconstrued as indicating that mudflow facies are volumetrically important in the formation as it is exposed at the surface. Recent drilling efforts along the eastern margin of the San Juan sag have discovered that in some areas, the Blanco Basin may contain more extensive *Gms*-type facies.

Gm, Gp, Gt, Fm: This association is common in the upper parts of reference sections A and E and characterizes proximal braided-river deposits. Even though this association is found close to basin margins, mean paleocurrent indicators at the principal reference locality (Fig. 3) reflect nearly unidirectional flow, indicating that either alluvial fans do not extend any distance from basin margins, or that fans are very broad with extremely low gradient, and thus there is not a distinct boundary between the fans and adjacent braidplains. This association is similar to the Scott-type model of modern braided rivers (Miall, 1977).

***Fm, Gt, Gp, Fl, St, Sh+Sp*:** This lithofacies association is characteristic of the lower portion of sections A and E, and sections B and C (upper parts of these sections have been removed by erosion) and grades upward into the lithofacies association discussed above. Its finer-grained nature could be a criterion for interpreting it as a more distal association than that above; however, grain size may also reflect high rates of local tectonically-induced subsidence, or fine-grained source rocks, or both. The basal part of section A contains significant amounts of reworked sedimentary material and much of the fine material in this section may come from erosional beveling of the thick Mesozoic shaly formations (i.e., Mancos Shale, Morrison Formation) at basin margins. In sections B and C, which are interpreted to be more geographically distal sections, this association lacks significant thicknesses of gravelly lithofacies. This braidplain lithofacies association is similar to the Donjek-type model of Miall (1977).

***St, Sh+Sp, Fm, Fl*:** This is the most distal lithofacies association of the Blanco Basin Formation. It is found at reference section D and is interpreted as a coarse, sand-dominated, braided trunk stream system draining the interior of the depositional basin (San Juan sag). This lithofacies is dominated by lithofacies St and is lacking in gravel facies. This lithofacies association is similar to the South Saskatchewan-type model of sandy braided rivers of Miall (1978).

PALEOCURRENTS

Paleocurrent rose diagrams shown in Figure 11 were derived primarily from pebble imbrications, with lesser contributions from parting step lineations, cross-beds, and trough orientations (data listed in Appendix 1). Several general observations can be made from Figure 11. First, mean paleocurrent directions appear to converge obliquely towards a central axis that trends towards the San Juan Basin, confirming Smith's (1988) observation that one or more major trunk streams drained into the San Juan Basin from the San Juan sag region. This paleodrainage pattern indicated is important evidence supporting correlation of the Blanco Basin Formation with the San Jose Formation of the San Juan Basin and shows that the Archuleta anticlinorium was not an emergent uplift feature during Blanco Basin deposition.

Secondly, paleocurrents near basin margins appear to be oriented obliquely to the margins (as opposed to perpendicular) and vary little within sections at individual localities. Therefore, extensive high-gradient alluvial fans are not interpreted from this data. This is supported by the overall distribution of lithofacies associations discussed above.

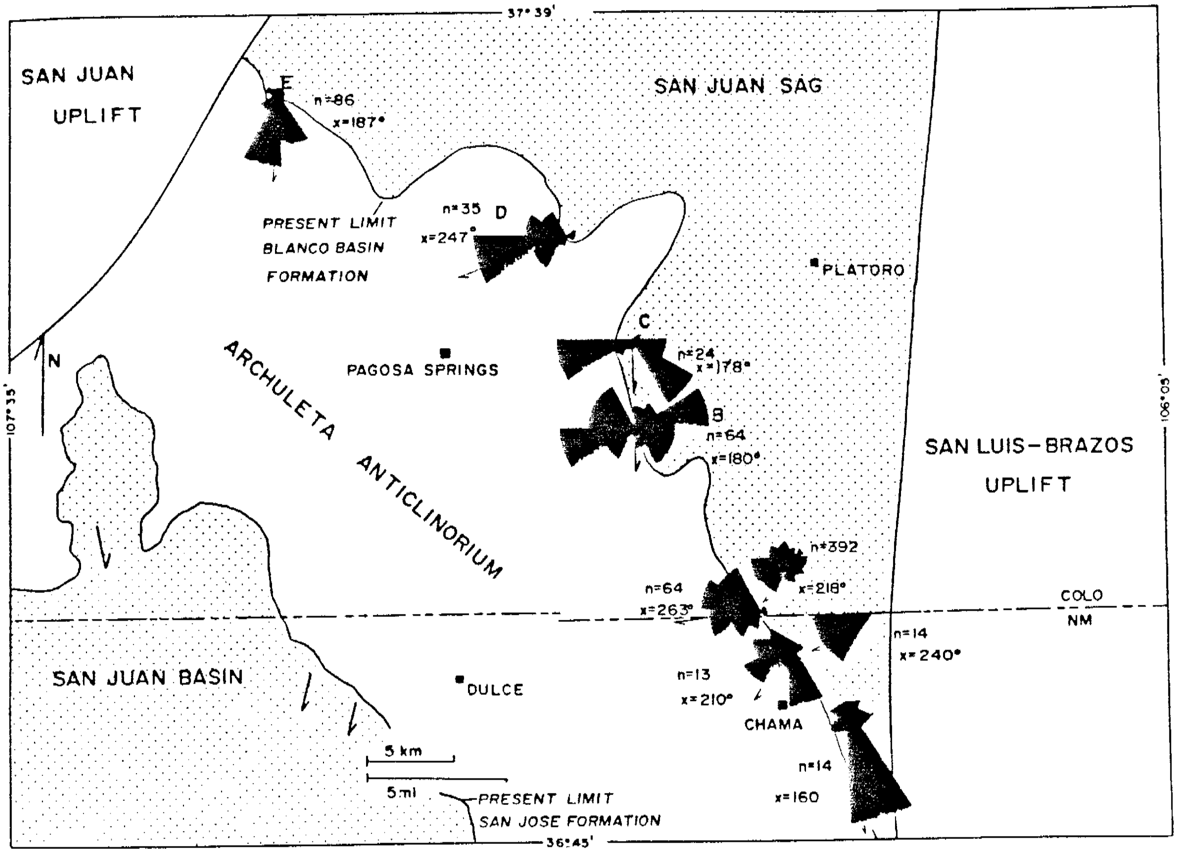


Figure 11: Regional tectonic elements and paleocurrent patterns. Blanco Basin Formation is stippled pattern in San Juan sag; San Jose Formation is stippled pattern in San Juan Basin. Paleocurrent means for San Jose Formation from Smith (1988).

Third, exposures of the formation along the eastern side of the basin and recent drilling data (discussed in Part 2) demonstrate the presence of an uplifted area east of the San Juan sag. Paleocurrents support provenance data that suggest that the present Needle Mountains area was another uplifted area on the western side of the basin.

CLAST COMPOSITION AND PROVENANCE

Detritus in the Blanco Basin Formation is mainly arkosic. Common minerals (in decreasing abundance) are: quartz in a variety of monocrystalline and polycrystalline types, orthoclase, microcline, biotite, sodic plagioclase, muscovite, heavy minerals (particularly opaques), and perthitic intergrowths of plagioclase and K-feldspar. Most of these minerals owe their origin to the plutonic and metamorphic rocks in basement-cored uplifts which were present along the eastern and western margins of the San Juan sag. Lithic fragments from these terranes plus sedimentary and volcanic lithic fragments from Mesozoic and lower Tertiary sources are also important constituents. On average, clay, cement, and alteration and replacement minerals make up approximately 28% of the sandstones examined. Clay occurs as both authigenic and detrital material and calcite is the most common cement, followed by hematite.

Conglomerate and sandstone clast compositions examined from a number of outcrops during reconnaissance were found to vary significantly, but in a predictable fashion, both laterally between outcrops, and vertically within measured sections. Therefore, study of clast compositions in the Blanco Basin Formation and comparison with other formations for correlation purposes must consider such variation. Point-counts of sandstones (mostly medium-grain size) were carried out to document these compositional changes.

Twenty-nine samples were examined from the measured sections illustrated in Figures 4, 6 and 7. The samples were point-counted using the parameters explained in Table 1 which were tailored to maximize provenance data. More than 500 total points (bulk sample) were counted such that important constituents in low abundance (matrix, cement, rare rock fragments) could be compared between samples and so that approximately 500 sand-sized detrital grains could be counted from each sample. According to Van der Plas and Tobi (1965), the reliability of point-counted results of 500 points is such that with a 95% confidence, twice the standard deviation will be 4.5% or less. For the purpose of this paper, which is to examine general trends in sample variation, such reliability of results is adequate. Table 2 lists resultant values of the various point-count parameters.

Figure 12 illustrates the compositional characteristics of the formation at the principal reference section. Overall, the samples reflect a strong input of local Precambrian detritus, both in feldspars from granitic sources and in dominance of quartzitic and schistose rock

Table 1: Point-count parameters defined.

Qt = total quartz = Qm + Qp
  Qm = total monocrystalline quartz = Qc + Qu + Qrf
    Qc = monocrystalline common quartz, may be slightly undulose
    Qu = monocrystalline quartz, strongly undulose.
    Qrf = Qc or Qu in in coarse granitic rock fragment
  Qp = total polycrystalline quartz = Qpc +Qite
    Qpc = silt-clay size or cryptocrystalline, commonly chert
    Qite = sand size crystals and pure SiO_2, mostly quartzite

Ft = total feldspar = Fp + Fk + Fi
  Fp = total plagioclase = Fps + Fprf
    Fps = single plagioclase grain
    Fprf = plagioclase in coarse granitic rock fragment
  Fk = total k-feldspar = Fu + Fm
    Fu = total untwinned K-feldspar (mostly orthoclase) = Fus + Furf
      Fus = single untwinned K-feldspar
      Furf = untwinned K-feldspar in coarse granitic rock fragment
    Fm = total twinned microcline = Fms + Fmrf
      Fms = single twinned microcline
      Fmrf = twinned microcline in coarse granitic rock fragment
  Fi = total intergrown plagioclase and k-feldspar = Fis + Firf
      Fis = single intergrown plagioclase and k-feldspar
      Firf = intergrown plagioclase and k-feldspar in coarse granitic rock fragment

Lt = total lithic fragments and polycrystalline quartz = L + Qp
L = total lithic fragments = Lv + Ls + Lm
  Lv = total volcanic rock fragments (unmetamorphosed)
  Lm = total schistose rock fragments
  Ls = total sedimentary rock fragments
    Ls1 = mudclasts or kaolin grains (interpreted as not *in situ*)
    Ls2 = sandstone rock fragments
    Ls3 = limestone rock fragments

M = phyllosilicates = Mb + Mm
  Mb = biotite
  Mm = muscovite

H = heavy minerals

clay = clay non-detrital and detrital
C/R = cements and replacement minerals
  silc = silica
  carb = carbonate
  hem = hematite

Table 2: Point-count data; nc=not counted, tr=trace (continued on pages 44-46

Framework (sand-sized detrital) material (% of framework grains)

Sample#	195	197	200	201	202	205	207	46B	184	39	37	186	160
Qt	62	55	51	56	48	50	48	59	90	89	84	91	53
Qm	59	42	42	48	43	38	41	52	82	74	74	87	50
Qc	55	34	27	41	35	33	21	51	75	69	61	80	46
Qu	3	5	7	5	3	2	4	tr	7	5	12	7	3
Qrf	1	3	8	2	5	3	16	1	tr	-	1	-	1
Qp	3	13	9	8	5	12	7	7	8	15	10	4	3
Qpc	-	2	nc	2	2	4	-	nc	1	14	1	1	-
Qite	3	11	nc	6	3	8	7	nc	7	1	9	3	3
Ft	26	22	44	23	34	38	47	27	8	9	9	8	38
Fp	3	1	7	3	3	7	4	5	tr	tr	-	tr	3
Fps	2	tr	5	3	2	7	2	5	tr	tr	-	tr	3
Fprf	tr	tr	2	tr	1	tr	2	tr	-	-	-	-	-
Fk	22	21	33	20	31	29	40	22	7	8	9	7	34
Fu	21	16	30	15	22	21	23	20	6	7	4	5	22
Fus	19	14	18	14	17	17	14	19	6	7	4	5	22
Furf	2	2	12	1	5	4	9	1	tr	-	tr	-	-
Fm	1	5	3	5	9	8	17	2	1	1	5	2	12
Fms	1	4	2	4	6	7	11	2	1	1	5	2	12
Fmrf	tr	1	1	1	3	1	6	tr	tr	-	tr	-	tr
Fi	1	tr	4	tr	tr	2	3	tr	tr	tr	-	tr	1
Fis	tr	tr	3	tr	tr	2	3	tr	tr	tr	-	tr	1
Firf	tr	-	1	-	tr	tr	tr	tr	-	-	-	-	-
Lt	7	23	11	12	11	17	10	7	8	16	17	4	11
L	4	10	2	4	6	5	3	tr	-	1	7	tr	8
Lv	tr	tr	tr	-	-	tr	-	-	-	tr	-	tr	8
Lm	1	9	tr	4	5	3	2	tr	-	tr	1	tr	-
Ls	3	1	1	tr	tr	1	1	-	-	-	6	tr	tr
Ls1	nc	1	nc	tr	nc	1	nc	-	-	-	4	tr	tr
Ls2	nc	-	nc	-	nc	-	nc	-	-	-	-	-	-
Ls3	nc	-	nc	-	nc	-	nc	-	-	-	2	-	-
M	7	8	2	12	8	6	2	10	tr	tr	-	tr	1
Mb	5	5	tr	7	4	3	1	8	-	-	-	tr	tr
Mm	2	3	1	5	4	3	1	2	tr	tr	-	tr	tr
H	1	5	1	5	4	1	tr	4	2	tr	tr	tr	-
Total	721	500	999	500	494	500	500	505	499	510	503	500	500

Fine-grained detrital and nondetrital material (% of total points)

	195	197	200	201	202	205	207	46B	184	39	37	186	160
Total%	37	62	28	38	31	32	22	50	44	48	35	30	14
%Matrix	24	62	18	36	30	31	8	50	tr	3	-	11	14
%C/R	13	-	10	2	1	1	13	-	44	45	35	19	-
%silc	-	-	2	-	-	tr	4	-	-	-	-	-	-
%carb	13	-	3	2	1	tr	9	-	42	45	35	8	-
%hem	-	-	5	-	-	-	-	-	2	-	-	11	-

156	229	112	92	88	87	86	85	83	80	79	78	77	151	191	193
46	51	54	46	49	45	56	21	48	39	45	43	26	56	84	73
45	49	48	43	45	40	54	19	43	38	37	38	22	54	76	67
39	44	32	33	43	39	50	17	34	35	22	30	19	41	74	60
5	5	10	3	1	1	3	1	6	2	5	6	2	5	2	6
1	tr	6	7	1	-	tr	tr	3	1	10	2	1	8	-	1
1	2	6	3	4	5	2	2	5	1	8	5	4	2	8	4
-	tr	-	tr	4	1	-	tr	-	tr	-	-	tr	1	7	1
1	2	6	3	tr	4	2	1	5	1	8	5	4	1	1	3
39	36	41	49	35	33	38	36	44	31	28	51	30	39	13	23
5	7	4	9	3	6	4	8	6	5	3	7	3	10	1	7
5	7	4	9	3	6	4	8	6	5	1	6	3	9	1	7
tr	-	tr	tr	-	-	tr	-	tr	-	2	1	tr	1	-	-
31	25	36	38	32	26	33	27	37	25	25	43	27	26	12	16
26	20	17	27	26	22	23	24	29	20	14	25	15	14	12	9
25	20	13	24	25	21	23	23	28	20	10	22	1	13	12	9
1	-	4	3	tr	1	tr	1	1	tr	4	3	14	1	-	tr
5	5	19	11	6	4	10	3	8	5	11	18	12	12	tr	7
5	5	18	9	6	4	9	3	8	5	8	15	11	10	tr	7
tr	-	1	2	-	tr	tr	-	tr	tr	3	3	1	2	-	tr
3	4	1	2	tr	1	1	1	1	tr	-	1	tr	3	-	-
3	4	1	2	tr	1	1	1	1	tr	-	1	-	2	-	-
-	-	-	tr	-	-	-	-	-	-	-	-	tr	tr	-	-
16	15	11	7	14	23	7	40	12	28	33	10	47	4	9	5
15	13	5	4	10	18	5	38	7	27	25	5	43	2	tr	1
13	12	5	2	6	12	4	28	5	21	23	4	27	tr	tr	tr
-	-	-	tr	tr	1	tr	4	1	tr	tr	-	tr	1	-	-
2	1	-	1	3	5	tr	6	tr	5	2	1	16	tr	tr	1
2	1	-	tr	3	5	tr	4	tr	5	2	1	14	-	tr	1
tr	-	-	1	tr	tr	tr	2	tr	tr	-	tr	2	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
tr	tr	-	tr	2	tr	tr	4	1	1	tr	1	tr	3	tr	2
tr	-	-	tr	1	tr	-	4	1	1	tr	tr	tr	3	-	2
-	tr	-	tr	tr	-	tr	tr	tr	-	-	tr	-	tr	tr	tr
tr	-	-	-	4	4	1	1	-	2	2	-	tr	tr	2	tr
500	500	498	500	500	500	500	500	500	500	500	499	507	500	500	500

18	17	8	17	26	32	8	35	19	32	10	11	8	28	44	27
18	17	2	tr	6	tr	tr	tr	-	tr	9	3	2	8	15	8
-	-	6	17	20	32	7	34	19	32	tr	8	6	20	29	19
-	-	tr	3	1	4	tr	-	-	-	tr	-	-	2	tr	-
-	-	6	tr	19	28	5	34	18	32	-	7	-	18	28	19
-	-	-	14	tr	tr	2	-	tr	-	-	tr	6	-	-	-

Table 2 (continued)

Recalculated parameters

Sample#	195	197	200	201	202	205	207	46B	184	39	37	186	160
	5	6	7	8	9	10	11	12	2	3	1	4	
Section	A	A	A	A	A	A	A	A	A	A	A	A	B
Total# Points	1500	810	1500	689	666	664	624	1000	725	740	684	714	570
Qm/Ft/Lt													
%Qm	64	48	43	58	49	41	41	61	84	75	74	88	51
%Ft	28	26	46	27	38	41	48	32	8	9	9	8	38
%Lt	8	26	11	15	13	18	11	7	8	16	17	4	11
Total#	662	434	968	416	436	464	485	435	489	505	502	495	494
Qt/Ft/L													
%Qt	68	63	52	67	54	54	49	68	92	90	84	92	53
%Ft	28	26	46	27	38	41	48	32	8	9	9	8	38
%L	4	11	2	6	8	5	3	tr	-	1	7	tr	9
Total#	662	434	968	416	436	464	485	435	489	505	502	495	494
Lm+Qp/Lv/Ls													
%Lm+Qp	61	94	87	95	96	90	87	100	100	98	67	95	21
%Lv	4	-	1	-	-	4	-	-	-	2	-	-	72
%Ls	35	6	12	5	4	6	13	-	-	-	33	5	7
Total#	52	114	110	62	46	83	52	33	41	83	84	21	53
Qm/Fp/Fk													
%Qm	70	66	51	68	56	51	48	66	92	90	89	92	58
%Fp	3	2	8	4	4	9	5	7	tr	tr	-	tr	3
%Fk	27	32	41	28	40	40	47	27	8	10	11	8	39
Total#	604	318	813	352	381	369	418	399	447	420	417	473	437

156	229	112	92	88	87	86	85	83	80	79	78	77	151	191	193
B	B	C	D	D	D	D	D	D	D	D	D	D	E	E	E
592	585	541	585	631	662	538	673	593	661	550	554	551	636	720	639
46	49	48	43	47	42	54	20	43	39	38	38	23	55	78	70
39	36	41	50	38	34	39	38	45	32	29	51	30	41	13	24
15	15	11	7	15	24	7	42	12	29	33	11	47	4	9	6
498	499	498	498	470	480	493	473	495	486	489	495	504	482	488	488
46	51	54	47	52	47	56	22	49	41	46	44	27	58	86	75
39	36	41	50	38	34	39	38	45	32	29	51	30	40	13	24
15	13	5	3	10	19	5	40	6	27	25	5	43	2	1	1
498	499	498	498	470	480	493	473	495	486	489	495	504	482	488	488
4	11	55	52	31	25	37	15	48	8	25	51	9	90	94	79
85	79	45	31	45	52	54	71	45	74	69	40	57	5	1	7
11	10	-	17	24	23	9	14	7	18	6	9	34	5	5	14
78	72	58	35	70	114	35	198	60	141	164	55	236	20	46	28
56	60	54	48	56	55	59	35	50	55	57	43	43	59	85	75
6	9	5	10	4	9	5	15	7	8	5	8	7	12	1	7
38	31	41	42	40	36	36	50	43	37	38	49	50	29	14	18
406	409	440	452	398	362	452	271	431	343	325	435	267	450	442	460

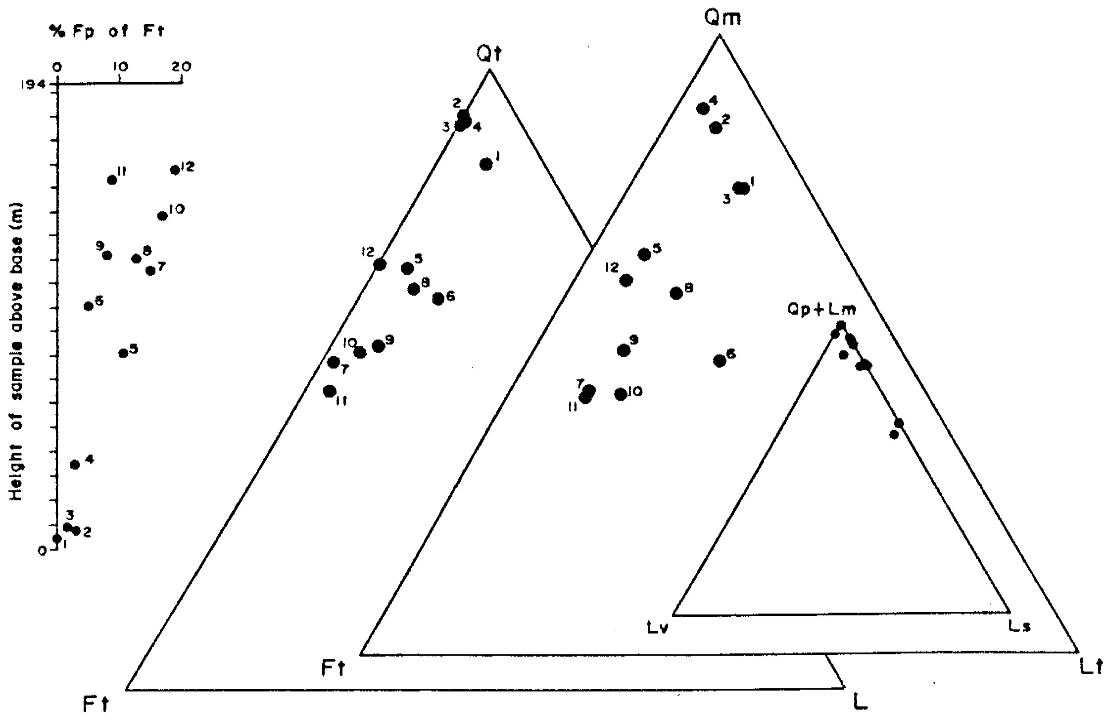


Figure 12: Ternary diagrams illustrating compositional variation of formation at principal reference section A.

fragments in relation to sedimentary or volcanic sources.

Section A is near the eastern margin of the San Juan sag and adjacent to the Laramide Brazos uplift. This section overlies Cretaceous Mancos Shale, but the Blanco Basin Formation oversteps progressively older Mesozoic formations closer to the uplift. Correspondingly, the lowermost conglomerates (see pebble counts, Fig. 4) contain recycled mollusc shell fragments (from Mancos Shale), and sandstone clasts originating from the Cretaceous Dakota Sandstone and Burro Canyon Formation and the Jurassic Morrison Formation and Entrada Sandstone. Similarly, sandstones near the base of the section contain recycled, well-rounded quartz grains from these same Mesozoic sources as seen in enrichment in quartz in ternary plots on Figure 12.

Once the Mesozoic rocks were onlapped and became partially covered by a blanket of the Blanco Basin Formation, they became less important contributors of Blanco Basin detritus. Sandstones low in the Mesozoic section, however, must have been continuously re-exposed at faults along the basin margin near the principal reference section because they are identified in minor amounts throughout most of the section.

Another vertical compositional variation is the upsection increase of plagioclase feldspar in relation to total feldspar. Plagioclase is most common in granite-gneiss rock fragments in the formation. The overall arkosic composition of most samples shows the dominance of granitic detritus when compared against all other inputs, so perhaps the increase in plagioclase represents increasing input of a granitic source enriched in plagioclase relative to other granitic sources.

A few volcanic clasts were observed at section A. These differ greatly in appearance from those found at other sections in that they are highly sericitized and are recognizable only by ghost phenocrysts. They are interpreted to come from the Precambrian Moppin complex (Bauer and Williams, 1989) metavolanic source because of their degree of alteration, their presence in a few samples scattered throughout the measured section, and the presence of metavolcanic rocks exposed nearby in the Tusas Mountains.

Metaquartzite, schist, gneiss and granite are present in different, widely spaced Precambrian terranes in the present Tusas Mountains east and southeast of the principal reference section (e.g. Muehlberger, 1967; Wobus, 1985; Bauer and Williams, 1989). However, there is no indication from paleocurrents (Fig. 4) that section A was the site of coalescing drainages. Because similar mixed-clast compositions can be observed in outcrops directly adjacent to the inferred margin of the uplift, mixing of these clasts must have occurred in areas upon the uplift. This may constrain the uplift as one of low relief with an extensive drainage network atop it, as supported by observations discussed above from paleocurrents and lithofacies distributions.

Figure 13 shows samples from all five measured sections plotted on ternary compositional diagrams. On Qt:Ft:L and Qm:Ft:Lt diagrams, most samples are tightly grouped and are dominated by arkosic detritus from adjacent Precambrian-cored uplift areas. Exceptions are samples from the lower part of section A and from section D. As previously discussed, the lower samples from section A show influence from recycled Mesozoic sandstone sources. Samples from section D, plot toward lithic poles on the diagrams due to presence of volcanic and sedimentary lithic fragments. Sedimentary clasts in this section are primarily mudclasts and the volcanic fragments are strongly weathered volcanic clasts. In the volcanic clasts, most mafic minerals and many feldspars have been removed, altered to clay, or replaced by secondary minerals causing the clasts to take on a more felsic appearance. These clast types probably reflect recycling of andesitic-dacitic detritus from the Animas Formation which this section is interpreted to overlie.

The Qp+Lm:Lv:Ls plot illustrates compositional differences with distance from surrounding uplifts. Samples from sections A and E which lie near plutonic-metamorphic-cored uplifts show predominance of metamorphic clasts. Where sections lie closer to the basin axis, these clasts are overshadowed by reworking of the volcaniclastic rocks from the Animas Formation and destruction of schistose

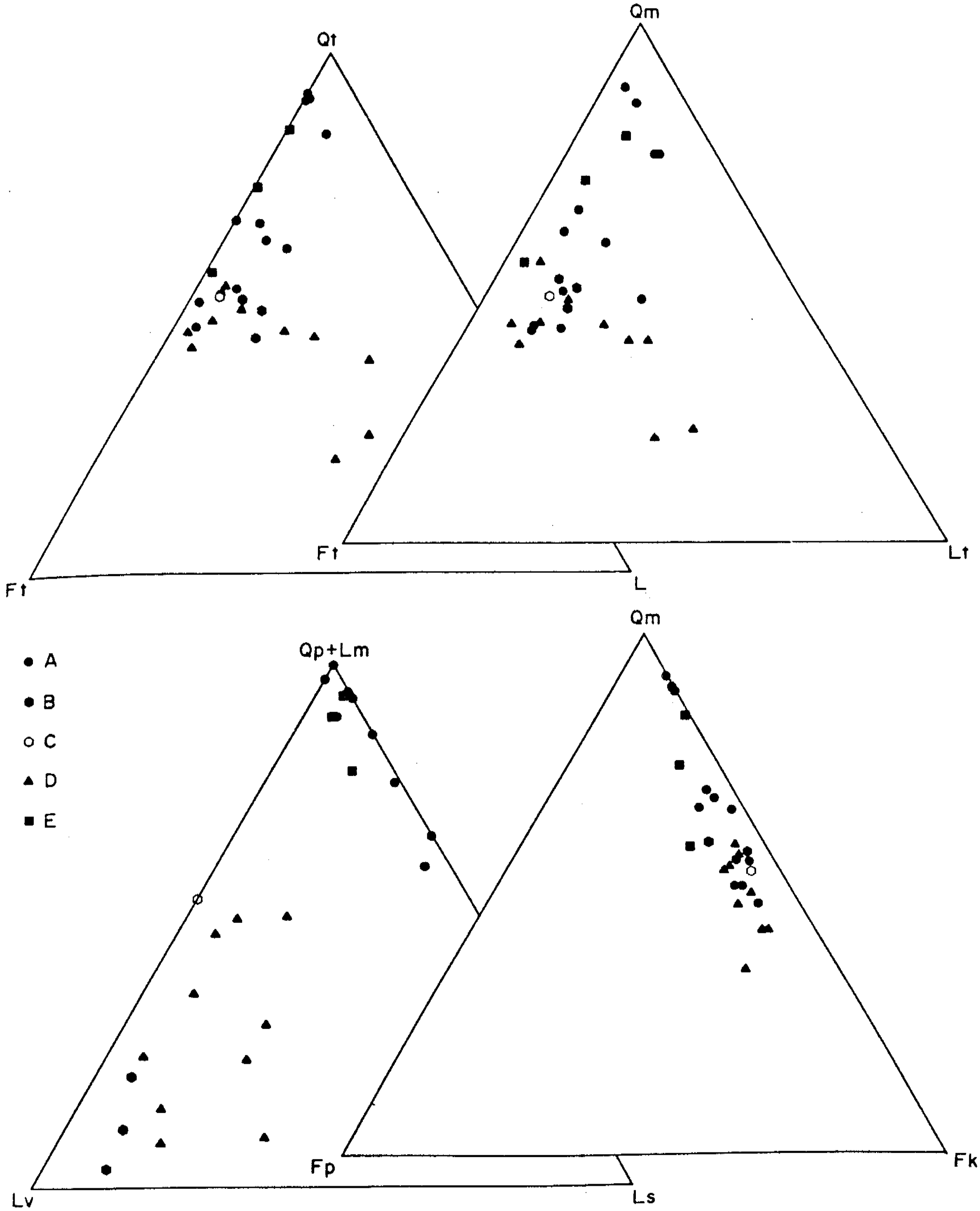


Figure 13: Ternary diagrams illustrating lateral compositional range of Blanco Basin Formation.

clasts during the longer transport.

The Qm:Fp:Fk ternary diagram shows that quartz and alkali feldspar clearly dominate over plagioclase. Note that samples containing volcanic lithic grains are not enriched in plagioclase feldspar; thus volcanic sources contribute little to the overall feldspar content of the rock.

The presence of volcanic rock fragments in sections B,C, and D requires some discussion. Dunn (1964a, p.36) stated "volcanic detritus is notably lacking" from the formation but described volcanic rock fragments reworked from the Animas Formation as minor constituents in his thin section descriptions. Figure 13 confirms their presence and relative importance as minor constituents. Volcanic pebbles in the formation are rare and generally concentrated near the base of the formation. They are most abundant in section B where they occur as small, white, clayey pebbles which when thin sectioned are revealed to be rhyolite with rare phenocrysts of quartz and alkali feldspar.

TECTONIC IMPLICATIONS

The tectonic implications of the Blanco Basin Formation have been previously discussed by Muehlberger and others (1960), Dunn (1964a, 1964b), and Muehlberger (1967), and more conjectural implications are discussed in Part 2 of this dissertation. The most important tectonic implications deal with timing of Laramide tectonic events. Due to the scarcity of excellent, complete exposures of the formation, the following observations are necessarily derived from a few key outcrops.

The unconformity at the base of the Blanco Basin Formation represents a time of regional degradation accompanying renewed uplift of the San Juan sag region. This period of uplift marks the beginning of what may have been the strongest pulse of Laramide tectonism in the Southern Rocky Mountain region as described by Chapin and Cather (1981). Once subsidence of the San Juan sag was able to outpace regional uplift, the Blanco Basin Formation onlapped the unconformable surface (Muehlberger, 1967) in the same manner that the San Jose Formation onlapped progressively older, tilted strata along the margins of the San Juan Basin (Baltz, 1967). This implies that the beginning of Blanco Basin deposition was diachronous and thus the lower parts of the formation along the axis of the San Juan sag and towards its southwestern connection with the San Juan Basin are probably older than near its other margins. It is also likely that while deposition was going on at one site, erosion was going on in areas more proximal to uplift areas. It follows then that the youngest basal deposits of the formation would be nearest basin margins. This may have important implications when attempting correlation with the San Jose Formation. Onlap of the unconformable surface through time is supported by compositional data from section A indicating "shutting off" (near the base) of marginward sources through time, or, in other words, eventual blanketing of sources.

Eventual onlapping of the uplift margins is depicted in Figure 14. This cartoon was designed from outcrop relationships along Highway 17 north of Chama, New Mexico (see Fig. 2a for related photograph). Note that the uppermost and coarsest facies are interpreted to transgress faults which truncate older Blanco Basin strata. In general, it is the younger (upper) beds (interpreted here to post-date earlier fault movement) that can be traced southward to Cañones Box where confusion over the Blanco Basin-El Rito transition occurs.

Lithofacies associations, paleocurrents, and apparent mixing of clasts in drainage nets prior to entering the basin of deposition are all evidence of low to moderate topographic gradient over the uplift areas. Perhaps the western flank of the Brazos uplift during Blanco Basin time should be thought of as an elevated, deeply eroded, but not deeply incised, foothills region.

The pattern of overall coarsening upwards and gradual upwards decrease in abundance of fine-grained deposits requires explanation. Such apparent basinward progradation of more proximal facies could be interpreted as a result of increasing energy due to increased basin subsidence or climatic changes, or greater reworking of deposits in migrating channels accompanying decreasing rates of basin subsidence and sediment accumulation, a process described by Allen (1978). Although onlapping of the Blanco Basin over its basal unconformable surface suggests increased basin subsidence, this onlapping is demonstrated only in its lowest parts where fine-grained deposits are volumetrically important. According to Allen (1978), when subsidence and sediment accumulation are rapid, alluvial suites will be dominated by fine-grained overbank deposits with single or weakly multistorey sand bodies, which is the case at section A. However, when subsidence and sediment accumulation are slow, thick and laterally extensive sand bodies can develop (Allen, 1978). This greater degree of reworking removes finer-grained material to more distal areas and leaves behind the coarse, redistributed material such as that in the upper part of the formation. The uppermost gravels depicted in Figure 14 are interpreted to be essentially post-tectonic and thus mark the end of local subsidence.

The cause for a decrease in basin subsidence and eventual end to aggradation was probably related to the emergence of the Archuleta anticlinorium, a middle (?) Eocene tectonic element which isolated the San Juan sag from the San Juan Basin. As demonstrated by Dunn (1964a), the Blanco Basin Formation is folded to a similar degree as older strata within the anticlinorium; also no ponding of Blanco Basin sediments is indicated by paleocurrent data, therefore the end of subsidence predated or accompanied this tectonic event.

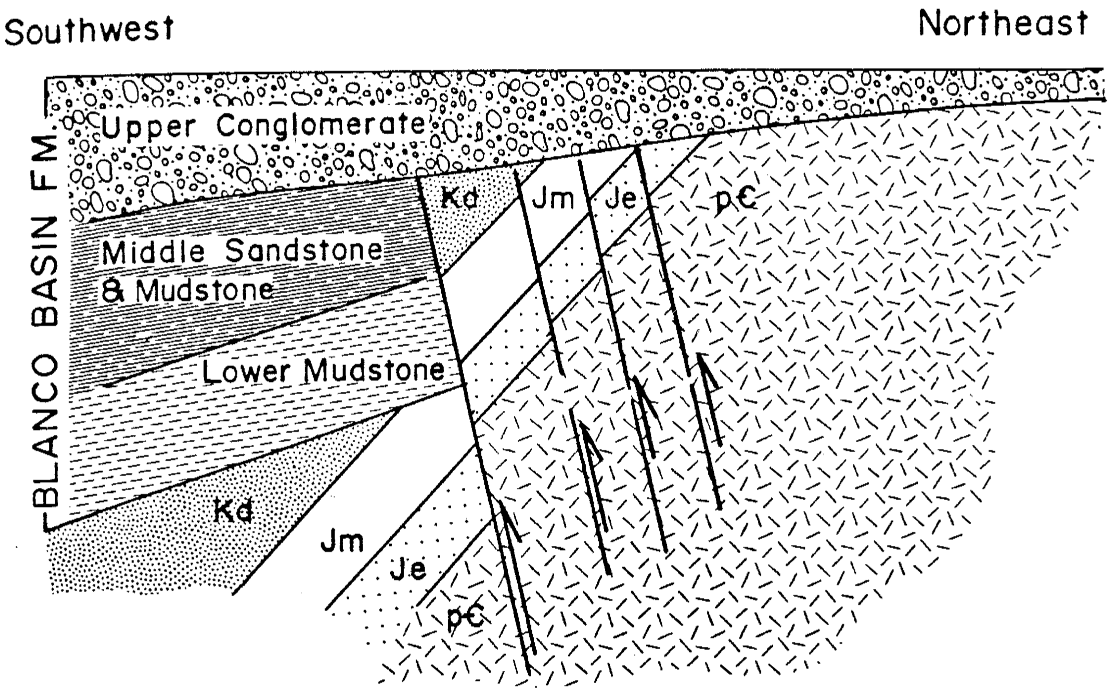


Figure 14: Schematic cross-section of inferred relationship between the Blanco Basin Formation and syndepositional faults at basin margin, "Highway 17 outcrops" Figure 1. Lateral and vertical dimensions not drawn to scale. Kd = Dakota Sandstone, Jm = Morrison Formation, Je = Entrada Sandstone.

An intriguing possible effect of the rise of the Archuleta anticlinorium was that it may have been ultimately responsible for initiation of deposition of the Blanco Basin as well as the cause of the demise of its depositional system. If the anticlinorium began to rise in latest Paleocene at the same time as, and at about the same rate as subsidence of the San Juan sag, it may have caused rivers to drop their loads upstream of this barrier rather than carry their loads over the barrier. If such a case were true, then the tectonic activity in the region during the Eocene may have been more of a continuum than previously recognized.

SUMMARY

This paper is the first detailed examination of the Blanco Basin Formation in more than twenty years, and is the most definitive paper on the formation to date. It contributes to knowledge of the formation in several ways:

1) A principal reference section is proposed and four supplementary measured sections are described.

2) The general types and variations in lithofacies are described and depositional environments interpreted.

3) New paleocurrent data is presented which is useful in interpreting paleodrainage systems and is criteria for correlating the Blanco Basin with the San Jose Formation.

4) The composition of sandstones and conglomerates are examined and typical compositional trends are illustrated

and interpreted.

Considering the current interest in petroleum exploration in the San Juan Mountains region, perhaps the most useful contributions of studying Tertiary units like the Blanco Basin are those which help establish timing and mechanisms of basin formation. Future work should focus upon more detailed correlations between the Blanco Basin and similar units such as the San Jose and El Rito formations and Blanco Basin-like units in the subsurface in the San Juan sag.

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PART 2

LARAMIDE SEDIMENTATION AND TECTONICS OF A BURIED FORELAND BASIN: SAN JUAN SAG, SOUTHWESTERN COLORADO

INTRODUCTION

The Oligocene San Juan volcanic field blankets some 25,000 km^2 in southwest Colorado and adjacent New Mexico (Lipman, 1989) concealing a Laramide foreland basin known as the San Juan sag. During most of the Late Cretaceous to Eocene Laramide orogeny in the San Juan region (Tweto, 1975), the San Juan sag was a northeastern embayment of the San Juan Basin. It was surrounded on three sides by uplifts, and provided a primary pathway for drainage into the San Juan Basin. Preserved within the San Juan sag are Jurassic through Eocene strata equivalent to those of the San Juan Basin, including petroleum source rocks and favorable reservoir lithologies. The syntectonic Late Cretaceous-Eocene sediments provide clues to timing and styles of structural development of the sag and surrounding uplifts. A knowledge of the Laramide tectonic development of the San Juan sag region is essential to predicting petroleum occurrences and contributes to understanding of the sequence of events which produced the eastern margin of the Colorado Plateau and the Southern Rocky Mountains.

The San Juan sag (or simply "sag") was postulated by Kelley (1955) as a synclinal depression between uplifts in the San Juan Mountains region (Fig.1). The San Juan sag connects with the Chama Basin at its southeastern end and

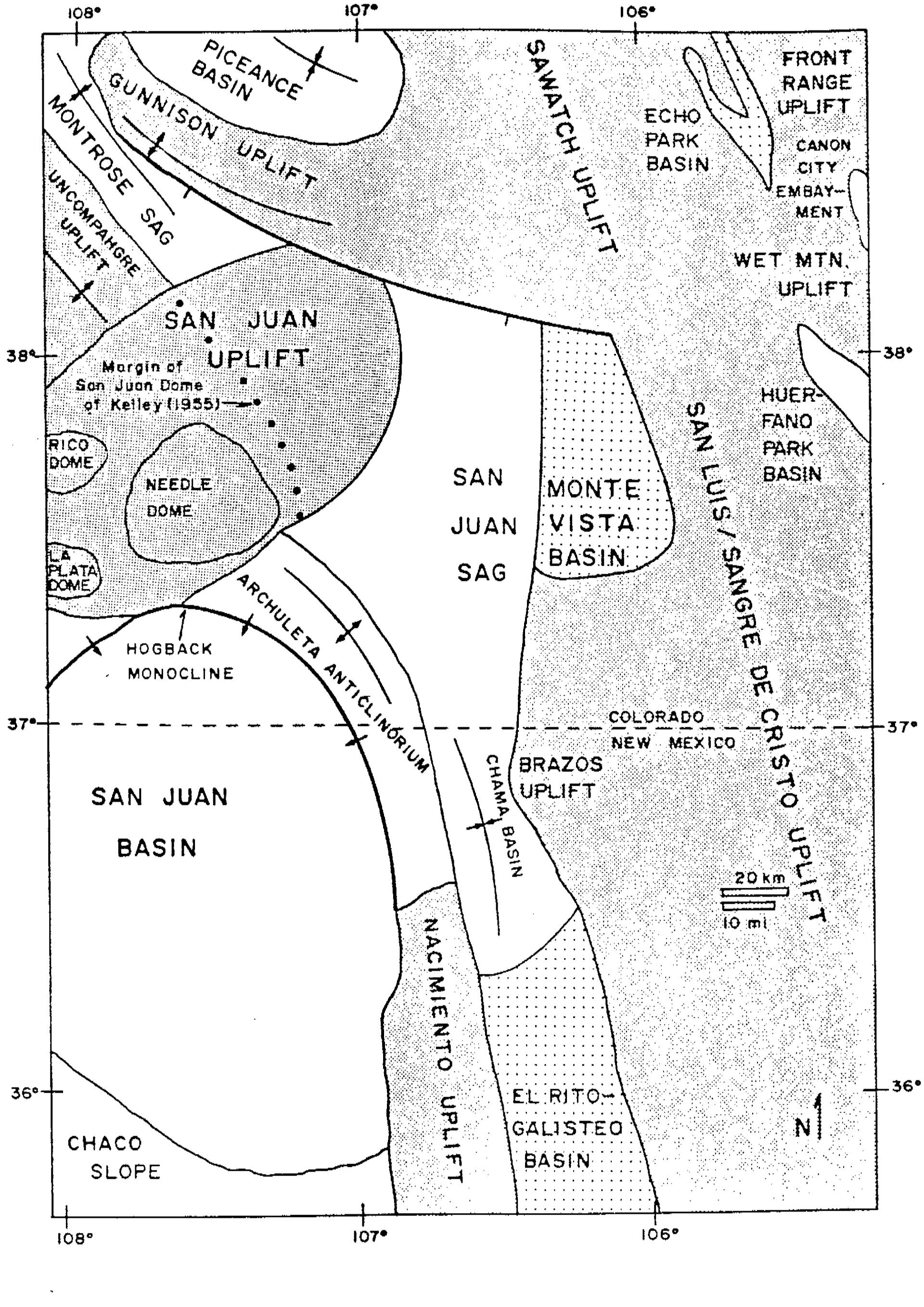


Figure 1: Laramide tectonic elements of southwestern Colorado and northwestern New Mexico. Shaded areas indicate Laramide uplifts. Early Tertiary sediments were deposited over unshaded areas throughout most of the Laramide orogeny. Lightly stippled basin areas contain only Eocene sediments. Figure adapted from Kelley (1955) and Chapin and Cather (1981).

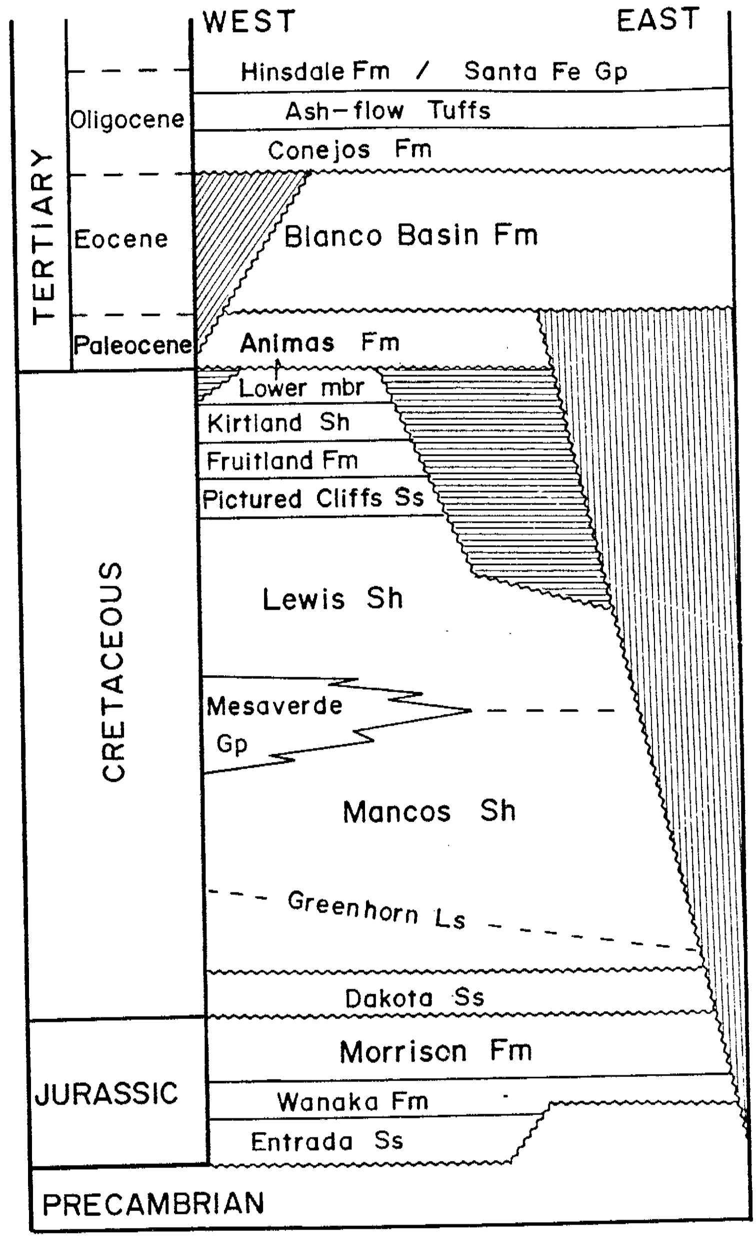


Figure 2: Stratigraphic column for the San Juan sag and vicinity. Time axis not to scale.

elsewhere is surrounded by areas of uplift. Larsen and Cross (1956) mapped Cretaceous strata dipping into the San Juan sag from the Needle Mountains and Archuleta anticlinorium. Baltz (1967, p.84) postulated downfaulting of the southeastern edge of the sag against the Brazos uplift. Ryder (1985) interpreted the attitude of Cretaceous rocks north of the Archuleta anticlinorium as delineating a syncline, trending north and paralleling the Brazos uplift. Investigations of the petroleum potential of the area, have demonstrated the presence of both source and reservoir rocks (Gries, 1985, 1989; Clayton and Gries, 1989; Gries and Clayton, 1989). Interest in the petroleum potential of the San Juan sag has led to the drilling of more than a dozen exploration wells which have helped to establish the eastern margin of the sag, define its stratigraphy (Fig.2), confirm the presence of source and reservoir rocks, and extend the known distribution of early Tertiary synorogenic sediments.

This paper summarizes results from a detailed study of late Laramide deposits in outcrop (Part 1), analysis of cuttings and geophysical logs of boreholes in the San Juan sag region (Appendix 2), and reconnaissance of early Laramide syntectonic sedimentary units. Preliminary observations were reported by Brister (1989). The purpose of this paper is to: 1) describe the internal structure and boundaries of the basin and its relationship to surrounding tectonic features; 2) discuss the distribution, characteristics and implications of synorogenic sediments; and 3) suggest timing of, and mechanisms for, episodes of uplift and basin subsidence.

BASIN BOUNDARIES

The present boundaries of the San Juan sag, as depicted on Figure 1, show that the sag is a structural downwarp bounded on several sides by Laramide uplifts. It is important to note that this structure is the cumulative result of a series of tectonic events. The timing of these events and specific characteristics of the basin margins have not previously been discussed and are important topics discussed in following sections.

Figure 3 is a simplified geologic map of the part of the San Juan Mountains region containing the San Juan sag. Along its northern border, isolated Mesozoic rock outcrops dip generally southward into the sag from the Sawatch and Gunnison uplifts (Fig.1). The boundary between these uplifts and the Montrose sag and San Juan sag is an eroded, faulted monocline, now mostly buried beneath volcanic cover. This boundary is presently marked by exposures of the Cimarron fault. Subsurface evidence suggests that this fault zone extends southeast to the vicinity of Saguache, Colorado, as depicted on the cross-sections in Figures 4 and 5.

There is little control on the northwestern boundary, as it is buried beneath younger volcanic rocks for most of

Figure 3: Simplified geologic map of the San Juan sag region. Calderas in San Juan volcanic field are from Lipman (1989). Dashed pattern in San Luis Basin = late Oligocene-Recent volcanic and sedimentary rift fill; unpatterned area = Oligocene San Juan volcanic field; stippled pattern = Laramide sedimentary rocks; MZ = Mesozoic formations; Pz = Paleozoic formations; p€ = Precambrian basement. Cross-sections A-A', B-B', and C-C' are figures 4,5, and 6. Numbered wells are explained in Table 1.

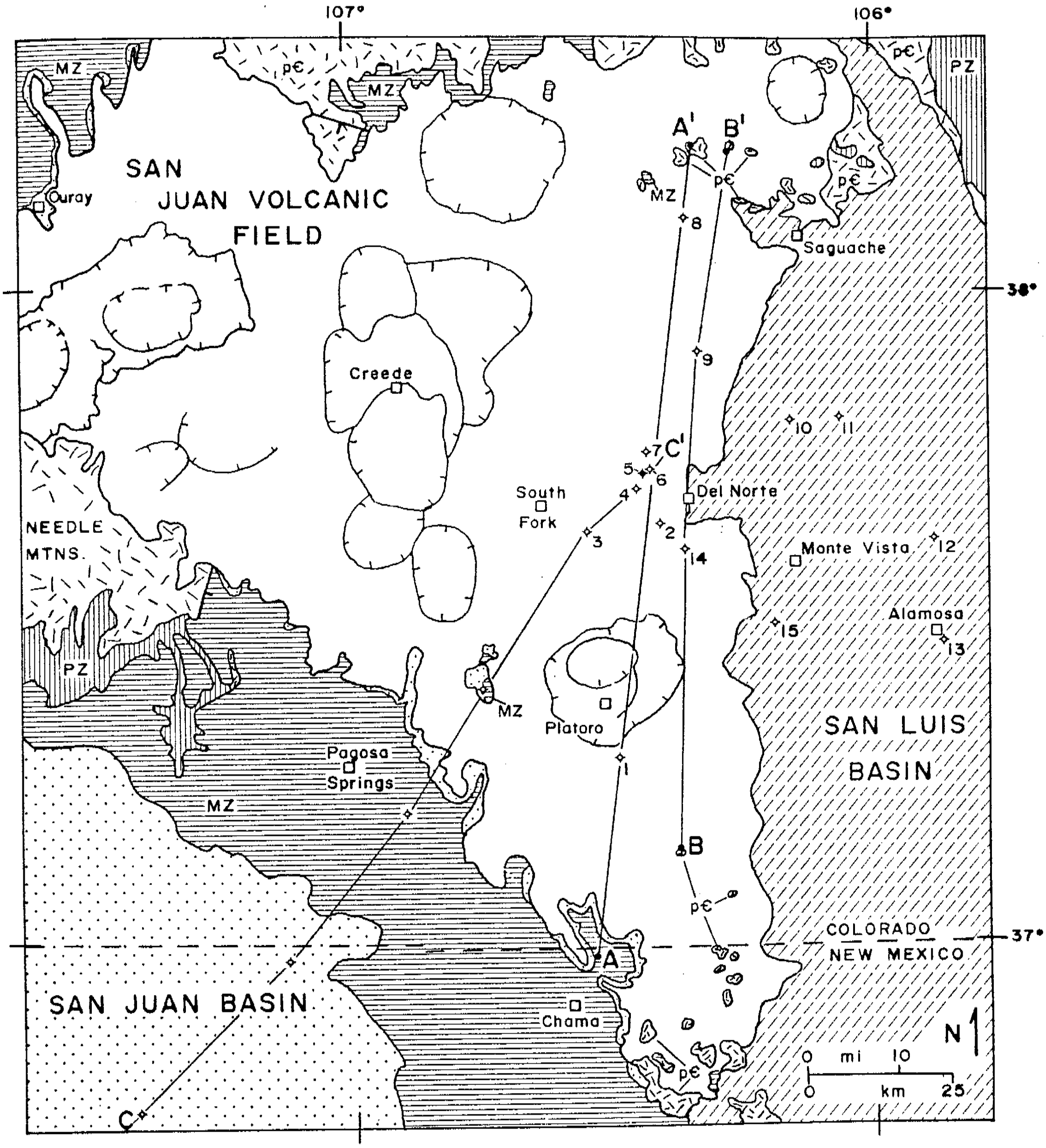

107°
106°
38°
37°
MZ
pЄ
PZ
SAN
JUAN VOLCANIC
FIELD
Ouray
A'
B'
8
Saguache
Creede
9
10
11
7
C'
5
6
4
South
Fork
Del Norte
3
2
14
NEEDLE
MTNS.
Monte Vista
12
Alamosa
15
13
Platoro
SAN LUIS
BASIN
Pagosa
Springs
1
B
COLORADO
NEW MEXICO
A
SAN JUAN BASIN
Chama
N
0 mi 10
0 km 25
C

Table 1: Selected drill hole data from San Juan sag and Monte Vista basin. G.R.=well site elevation; K.B.=kelly bushing; Tbb=Blanco Basin Formation; Tka=Animas Formation; K= Cretaceous formations; Kd=Dakota Formation; Jm=Morrison Formation; pЄ=Precambrian basement; T.D.=total depth of well. "Tops" are depths in feet from K.B.

Well No.	Well Name & Operator	Date	Location S T R	G.R.	K.B.	Top Tbb	Top TKa	Top K	Top Kd	Top pЄ	Total Depth	T.D. Fm.
1	Champlin Pet. 1 Fed. 34A-13	1985	13 35N 4E SW SE	9436	9463	2815	----	2970	4400	6200	6751	pЄ
2	Waggoner-Baldr. 1-10 Federal	1990	10 39N 5E NE SE	8320	8334	5770	----	5810	6615	7275	7361	pЄ
3	Meridian Oil S.Fork Fed.23-17	1988	17 39N 4E NW SE	10066	10086	5865	6590	9010	13330	----	13586	Jm
4	Milestone Pet. 1 AMF	1984	20 40N 5E NW SE	7987	8014	3450	4230	6240	9200	----	9447	Jm
5	Kirby Pet. Jynnifer 1-9	1985	9 40N 5E SW NE SE	8165	8193	4580	5180	5900	8150	????	9264	pЄ
6	Waggoner-Baldr. Shelley 1-10	1985	10 40N 5E NW SW	8161	8178	4450	5150	5970	8000	8550	9008	pЄ
7	Needham-Medford Need.-Med. 1-33	1985	33 41N 5E SW NE	8180	8197	3950	4370	5155	7720	8460	8821	pЄ
8	Champlin Pet. 1 Fed. 24-A1	1985	1 44N 5E	8923	8950	2230	----	2630	2730	3130	3266	pЄ
9	Triton/WECO/UPRC 1 Hellgate21-8	1988	8 42N 6E NE NW	9950	9978	7490	----	----	----	11690	11996	pЄ
10	Tennessee Gas 1 State B	1959	14 41N 7E SW SE	7661	7675	7810	----	----	----	9920	10350	pЄ
11	Orrin Tucker 1 Thomas	1951	13 41N 8E NE NE NE	7600	7605	7920	----	----	----	----	8023	Tbb
12	Amerada Pet. 1-F State	1959	16 39N 10E	7554	7569	4310	----	----	----	4640	6072	pЄ
13	Energy Service 1 Alamosa (Geothermal)	1981	15 37N 10E	N/A	N/A	6370	----	----	----	6780	7125	pЄ
14	Waggoner-Baldr. SanFranc.Cr.1-19	1986	19 39N 6E NW SW	8535	8562	4990	----	----	----	5790	5873	pЄ
15	Heartland O&G La Escondido Uno	1989	3 37N 7E SW	7929	7941	6949	----	----	----	7110	8120	pЄ

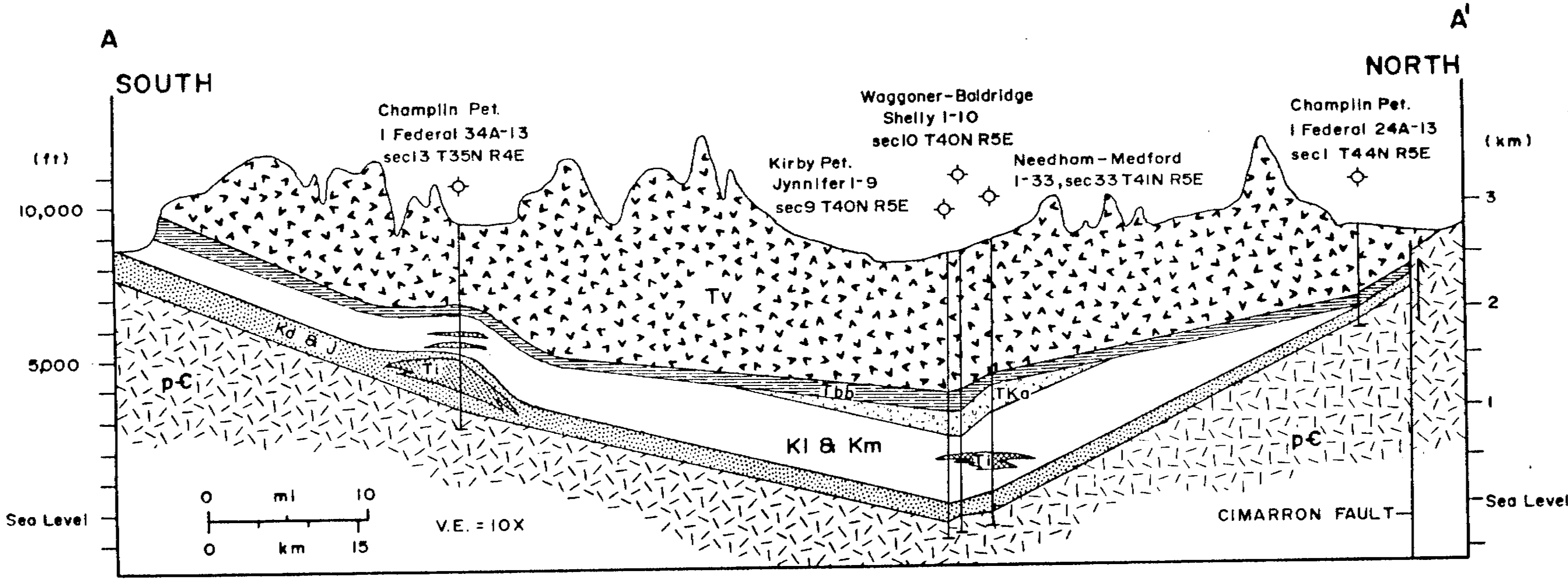


Figure 4: North-south cross-section A-A' of the San Juan sag parallel to its eastern boundary. Ti=Tertiary intrusion; Tv=Oligocene volcanic units; Tbb=Blanco Basin Formation (Eocene); TKa=Animas Formation (Late Cretaceous-Paleocene); Kl=Lewis Shale; Km=Mancos Shale; Kd=Dakota Formation; J=Morrison and Wanakah formations and Entrada Sandstone; p€=Precambrian basement.

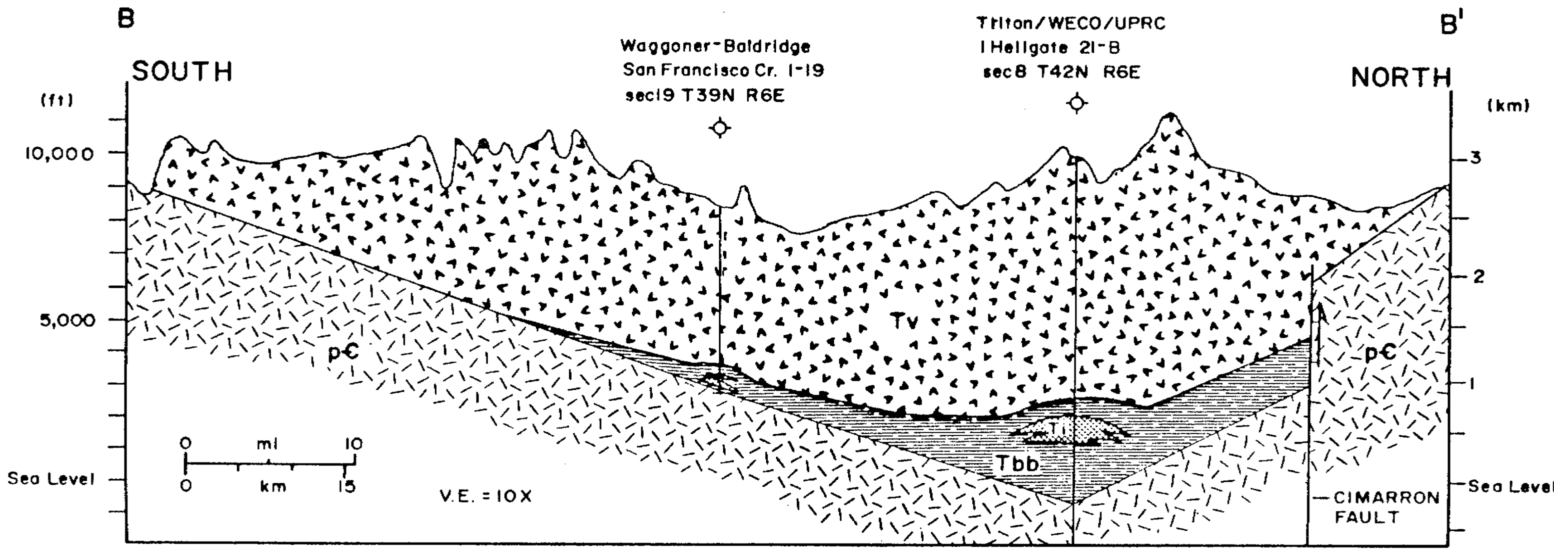


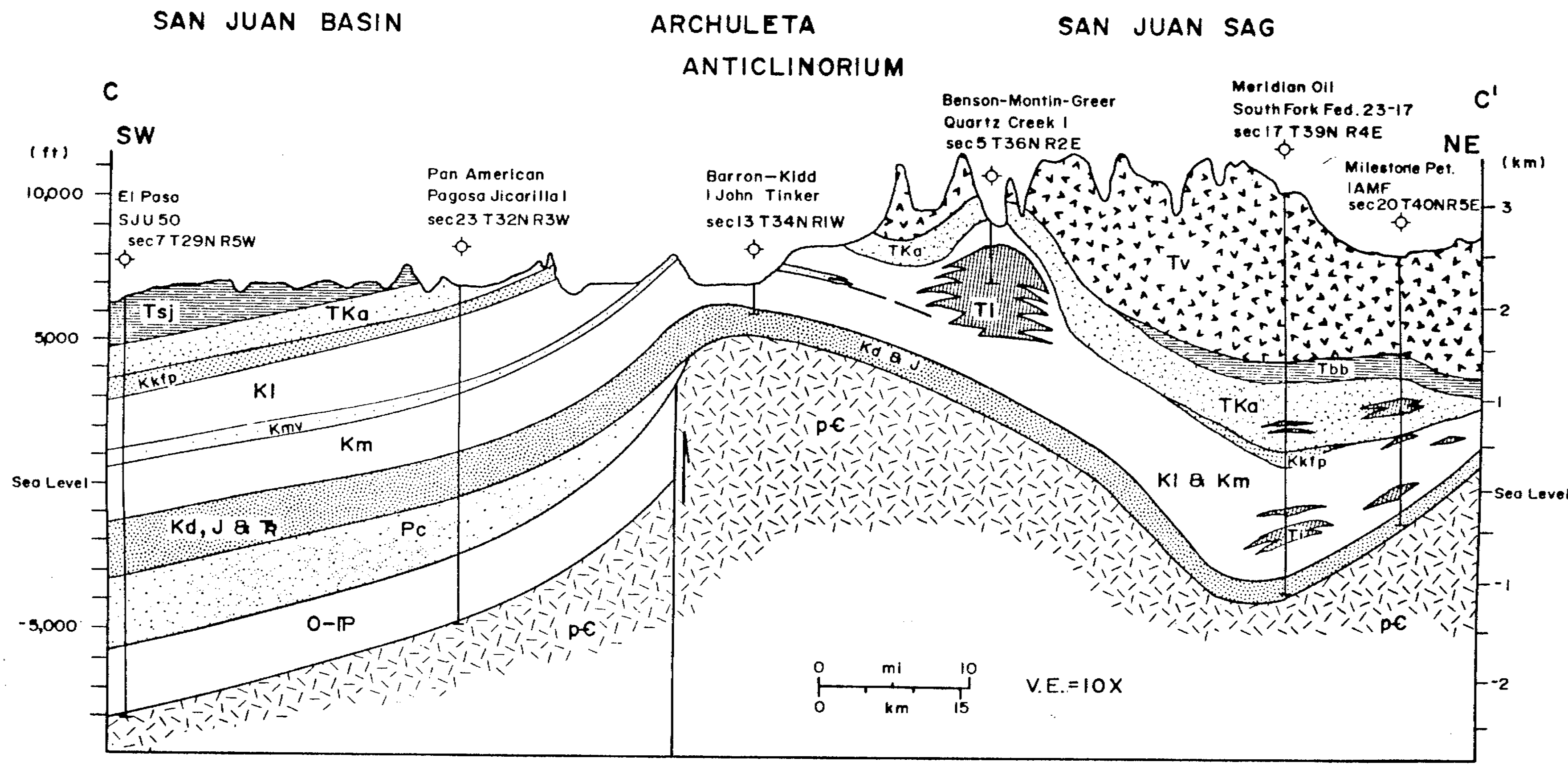
Figure 5: North-south cross-section B-B' of the Monte Vista basin parallel to its western boundary. Ti=Tertiary intrusion (Oligocene); Tv=Oligocene volcanic units; Tbb=Blanco Basin Formation equivalent rocks (Eocene); pЄ=Precambrian basement. The single intrusion drawn through the Triton/WECO/UPRC well is a composite of 33 intrusions in the Tbb unit.

its length. Two scenarios are possible. Mesozoic rocks may continue northwest beneath the volcanic cover to the Montrose sag as originally envisioned by Kelley (1955). This would indicate that the San Juan uplift was limited during the Laramide to its presently exposed extent. The other possibility is that Mesozoic rocks dip southeast or east away from a now-buried northern extension of the Needle dome. Scarce sedimentologic evidence, discussed below, supports the latter scenario. For this reason, the Laramide San Juan uplift is depicted as having a north-northeastern (now buried) extension as depicted in figures in this paper.

The Archuleta anticlinorium (Wood and others, 1948) structurally separates the San Juan sag from the San Juan Basin (Fig. 6). The southeastern corner of the San Juan sag merges with the Chama Basin. The boundary between the two basins is the Salado-Cumbres discontinuity (Baltz, 1967), an ill-defined, but important zone of structural transition which will be discussed below.

The eastern margin of the San Juan sag lies beneath the eastern part of the San Juan volcanic field. Mesozoic rocks drilled west of this boundary dip generally westward (interpreted from dipmeter logs and seismic lines) away from the Precambrian-cored Laramide San Luis uplift, now buried by volcano-sedimentary fill of the late Oligocene-Recent Rio Grande rift. Mesozoic rocks cropping out near Chama, New Mexico, dip south to southwestward away from the

Figure 6: Cross-section C-C' from the San Juan Basin to the San Juan sag. Ti=Tertiary intrusions (Oligocene); Tv=Tertiary volcanics (Oligocene); Tsj and Tbb=Eocene redbeds of the San Jose and Blanco Basin formations; TKa=Animas Formation (Paleocene) and equivalents; Kkfp=Kirtland and Fruitland formations and Pictured Cliffs Sandstone; Kl=Lewis Shale; Kmv=Mesaverde Formation (pinches out to northeast); Km=Mancos Shale; Kd=Dakota Formation; J=Morrison and Wanakah formations and Entrada Sandstone; TR=Chinle Formation; Pc=Cutler Formation; O-P=pre-Permian Paleozoic sediments; pЄ=Precambrian basement.

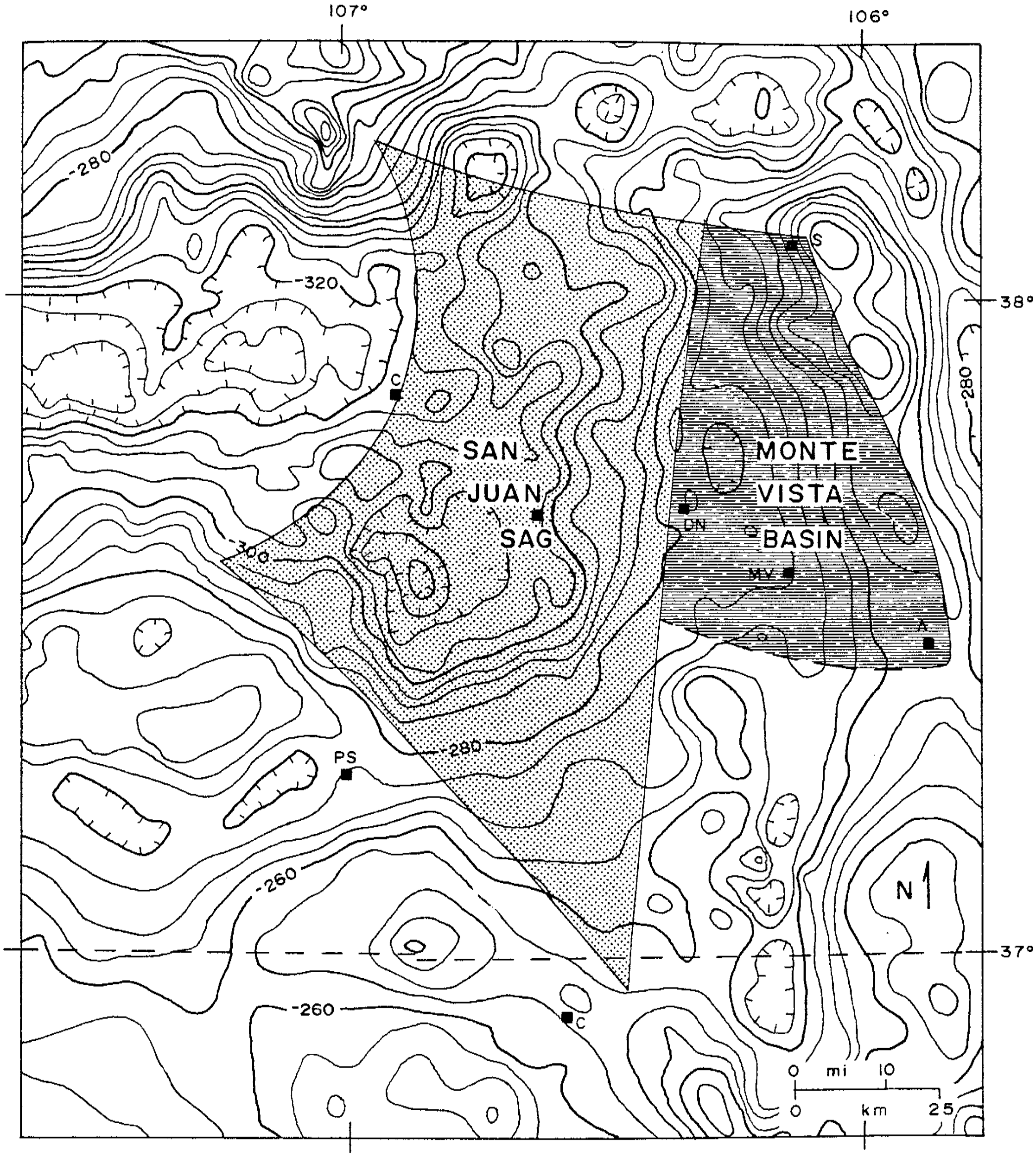


SAN JUAN BASIN
ARCHULETA ANTICLINORIUM
SAN JUAN SAG
C
C'
SW
NE
(ft)
10,000
5000
Sea Level
-5,000
(km)
3
2
1
Sea Level
-1
-2
El Paso SJU 50 sec7 T29N R5W
Pan American Pagosa Jicarilla I sec23 T32N R3W
Barron-Kidd I John Tinker sec13 T34N R1W
Benson-Montin-Greer Quartz Creek I sec5 T36N R2E
Meridian Oil South Fork Fed. 23-17 sec17 T39N R4E
Milestone Pet. IAMF sec20 T40N R5E
Tsj
TKa
Kkfp
Kl
Kmv
Km
Kd, J & TR
Pc
O-IP
pC
Kd & J
Tl
Tv
Tbb
Kl & Km
0 mi 10
0 km 15
V.E.=10X

volcanic-covered, Precambrian-cored, Laramide Brazos uplift. As demonstrated in Figures 3,4, and 5, the north-trending eastern margin of the San Juan sag is a narrow linear zone. West of this zone Laramide synorogenic strata lie upon Mesozoic strata, whereas east of this zone the Mesozoic section is missing and denuded Precambrian basement is overlain by early Tertiary or younger strata.

The San Juan sag as outlined above includes some 11500 km^2 of volcanic-covered, potential petroleum-bearing strata which have been relatively untested by drilling. No published geophysical studies have delineated the full areal extent of the San Juan sag. Anomalies on gravity and magnetic surveys tend to correlate with Oligocene calderas and related intrusions (Plouff and Pakiser, 1972; Gries, 1985; 1989). However, both the southwestern and southeastern boundaries of the San Juan sag can be identified on the Bouguer gravity anomaly map of Figure 7 where gravity "highs" correlate with uplifted basin-bounding structures. These features are similarly seen on residual gravity anomaly maps of the region by Cordell and Keller (1984), Keller and others (1984), and Jenkins and Keller (1989). Reflection seismic lines shot in the vicinity of the eastern margin of the sag near Del Norte, Colorado, by the Colorado School of Mines and petroleum companies have helped to define the structure of the eastern margin of the San Juan sag in that area (Phillips, 1985; Durrenberger, 1986; Covarrubias, 1988; Gries, 1989).

Figure 7: Bouguer gravity anomaly map of San Juan sag region from Cordell and others (1982). Buried Laramide basins are superimposed over gravity contours (milligals). Lighter shaded pattern is the San Juan sag, darker pattern is late Laramide Monte Vista basin. Basin boundaries were determined independently from gravity data and are based primarily upon borehole data and outcrop patterns. Contour interval 5 milligals. Scale and area same as in Figure 3. Towns shown on Figure 3 located by solid squares and letter abbreviations.


107°
106°
38°
37°
-280
-320
-300
-280
-260
-260
-280
SAN
JUAN
SAG
MONTE
VISTA
BASIN
C
S
DN
MV
A
PS
C
N
0 mi 10
0 km 25

PRE-LARAMIDE SETTING

Precambrian rocks in the Southern Rocky Mountains region can be divided into a number of metasedimentary, metavolcanic, and plutonic terranes (Hedge and others, 1986) which are geochemically distinct (Condie, 1986) and "recognizable by differences in lithology, age and/or metamorphic grade." (Grambling and others, 1988, p.724). These terranes are in contact at shear zones and are intruded by plutons ranging in age from 1,684 to 1,450 Ma (Bauer, 1989). Precambrian tectonic activity created north-northwest and west-northwest fault trends and northeast-trending shear zones (Tweto, 1980) which underwent recurrent movement during Phanerozoic tectonic events (Tweto, 1980; Weimer, 1980).

During the Late Paleozoic Ancestral Rocky Mountains orogeny, the area encompassing the present-day San Juan and Tusas mountains, San Luis Basin, and western Sangre de Cristo Range was part of the Uncompahgre-San Luis highland. This broad uplift was stripped of earlier-deposited Phanerozoic sediments. Upper Paleozoic synorogenic rocks and older strata were preserved north, east, and southwest of the range. Its southwestern boundary was located at about the position of the present Archuleta anticlinorium as Paleozoic rocks thicken dramatically southwestward from this feature (Fig. 6). The present northwest trend of the Archuleta anticlinorium is inherited from this uplift margin.

Mesozoic sedimentary rocks progressively onlapped the Late Paleozoic uplift so that by the Middle to Late Jurassic, the Junction Creek Sandstone (member of Wanakah Formation) and Morrison Formation blanketed much of the Late Paleozoic highland. Initial transgression of the Cretaceous sea from the northeast is indicated by the marine upper part of the Dakota Sandstone. The overlying Mancos Shale, Mesaverde Group, Lewis Shale, and Pictured Cliffs Sandstone represent transgression-regression cycles with final northeastward regression of the Cretaceous sea marked by the Pictured Cliffs Sandstone. These sequences are capped by the terrestrial Fruitland Formation and Kirtland Shale. Surviving sections of these Mesozoic formations indicate that the basement was covered by as much as 1400 m of sedimentary rocks at onset of the Laramide orogeny.

LATE CRETACEOUS VOLCANISM AND UPLIFT

The first phase of Laramide uplift to affect the San Juan sag/northern San Juan Basin region began in the Late Cretaceous. This episode was associated with intrusion of laccoliths and emergence of the Laramide San Juan uplift along the northeast-trending Colorado Mineral Belt (of Tweto and Sims, 1963). Reported ages of three intrusions in the region of the Laramide San Juan uplift are: 61.3 Ma for the Rico dome and 65 Ma for the La Plata dome laccoliths (Armstrong, 1969), and 68.5 for intrusions in the Ouray, Colorado, area (Dickinson and others, 1968; age recalculated to 1977 I.U.G.S. decay constants by Hon and Mehnert, 1983).

The first effects of the Laramide San Juan uplift upon sedimentation in the region have been summarized by Klute (1986). Before appreciable volcanism, burgeoning uplift resulted in thicker deposition of Fruitland and Kirtland strata along the downwarping northwestern margin of the San Juan Basin (area of "Hogback monocline" in Fig. 1). Meandering-stream paleocurrent directions reflect a change in source area from the southwest and west for the lower Kirtland Shale (Dilworth, 1960) to a northward source for the upper Kirtland Shale (Powell, 1972). Klute (1986) documents input of volcanic-lithic fragments in the upper Kirtland Shale, marking the first influx of volcanic lithic detritus from the San Juan uplift during the Maastrichtian. Therefore, the upper Kirtland Shale marks the beginning of Laramide sedimentation in the region.

The Cimarron Ridge Formation on the northwest flank of the present-day San Juan Mountains near Ouray, Colorado, (Dickinson and others, 1968) is the only documented surviving occurrence of extrusive volcanic rocks attributable to the early Laramide volcanic event. Extrusive rhyodacite from this formation gave a biotite K-Ar age of 71.3 $\pm$ 2.1 Ma (Dickinson and others, 1968; age recalculated according to I.U.G.S. 1977 decay constants by Hon and Mehnert, 1983). Dickinson and others (1968) concluded that the Cimarron

Ridge Formation overlies folded Kirtland Shale and older formations, thus the Laramide San Juan uplift became emergent and underwent erosion along its monoclinal northwestern edge prior to local volcanism.

The McDermott Member of the Animas Formation was deposited on the southeast margin of the San Juan uplift following deposition of the upper Kirtland Shale with no intervening unconformity (Reeside, 1924). The McDermott Member near Durango, Colorado, is Maastrichtian in age based on palynomorphs (Newman, 1982). It was deposited as a coarse volcaniclastic apron shed southeastward from the La Plata Dome area (Shoemaker, 1956). It is made up of tuffaceous purple sandstones, shales, and coarse andesitic conglomerates (Reeside, 1924). Distinctive red-to-purple muddy debris flows containing volcanic detritus are well preserved near its base in outcrops on the Animas River in Colorado. Well-rounded quartz, chert, and quartzite pebbles and cobbles have been reported both in a thin zone at the base (Zapp, 1949) and at the top of the McDermott Member (Reeside, 1924; Fassett, 1985). These clasts probably had their origin in exposed Dakota or older formations, indicating that significant uplift and erosion accompanied the Late Cretaceous volcanism.

"Lower member", Animas Formation, San Juan sag

The McDermott Member of the Animas Formation thins eastward in outcrops away from its source in the La Plata

Mountains and has not been previously mapped in the San Juan sag area. However, beds which may be equivalent to those of the McDermott Member have been found on the southwest margin of the San Juan sag near Pagosa Springs, Colorado, in the canyon of Oil Creek (37°16'26" N Lat., 106°46'39" W long.). These beds have not been successfully dated, but they are interpreted to be equivalent to the McDermott Member (Maastrichtian) because they share similar stratigraphic positions, source uplifts (San Juan uplift region), lithologies, composition, and color. In this paper, they are informally referred to as the lower member of the Animas Formation, limited in usage to the San Juan sag.

The lower member lies unconformably beneath the upper member of the Animas Formation and is composed of a variety of sedimentary units dominated by muddy debris flow-deposits (Figure 8), and fluvial channel sandstone and conglomerate. The lower member is similar in composition to the upper member in that it contains detritus from Precambrian basement, Mesozoic sedimentary sources, and volcanic sources. The volcanic component of these units ranges in composition from andesite to rhyolite with dacite-rhyolite clasts dominating. No volcanic extrusive units were recognized, but presence of ghosts of fragile glass shards and relatively fresh welded-tuff fragments in thin sections argue against extensive recycling of these materials. Organic matter is rare and colors of many units

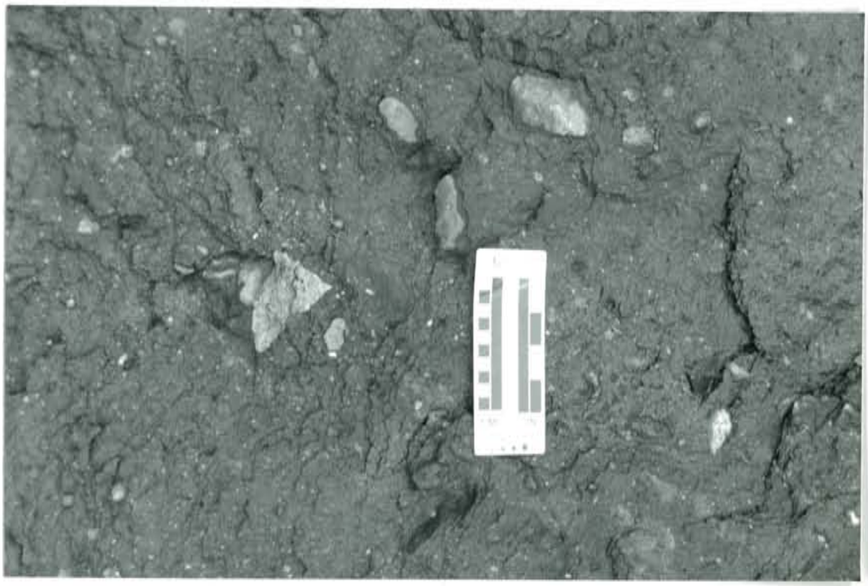


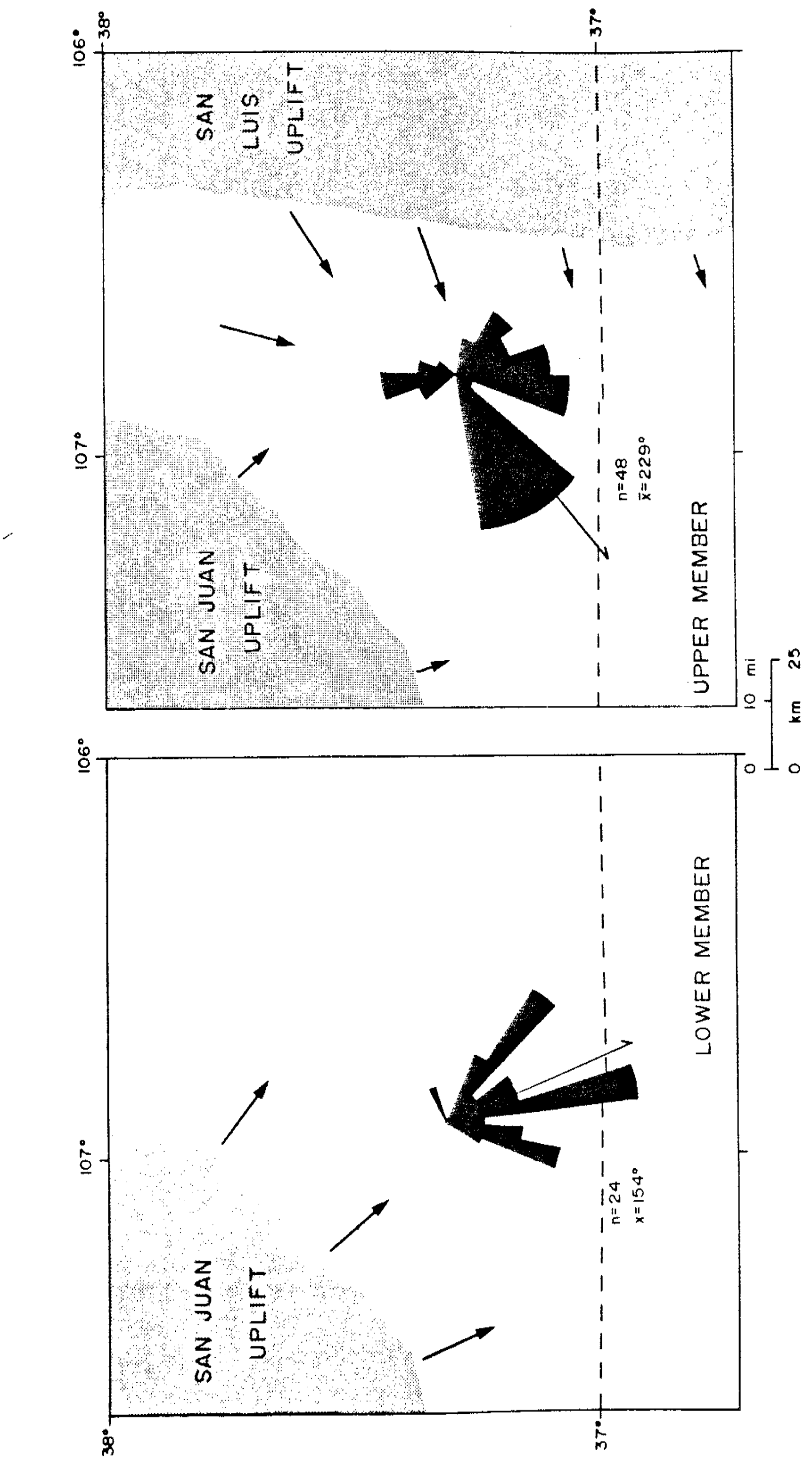
Figure 8: Photographs of debris-flow deposits in lower member of Animas Formation near Pagosa Springs, Colorado, at Oil Creek (location specified in text). a) atypical boulder of volcaniclastic sandstone in mud-matrix debris flow, 1.5 m staff for scale; 8b) typical muddy debris-flow deposit in lower member.

indicate oxidation has occurred. This is in contrast with the overlying reduced upper member of the Animas Formation which contains abundant organic matter and is characterized by drab coloration. The base of the lower member at Oil Creek is not exposed, having been intruded by an Oligocene laccolith, but its contact with the upper member is distinctive, marked by changes in color, lithofacies, and composition. Minimum thickness of the lower member measured at Oil Creek is 73 m.

Exposures of the Animas Formation are generally poor in the San Juan Mountains due to heavy vegetative cover and Quaternary landsliding, therefore it is unknown if the lower member was preserved in other areas. The lower member was not present in the 6 wells which were drilled through the Animas Formation in the vicinity of Del Norte, Colorado, (5 of those listed in Table 1), nor is it present at several locations where the upper member overlies Kirtland Shale and older strata in angular unconformity. Based on this information, it must be assumed that the lower member at Oil Creek represents an isolated preservation of rocks which were elsewhere eroded prior to deposition of the upper member.

Paleocurrent indicators from the lower member suggest a paleodrainage from the north-northwest as opposed to the east-northeast paleodrainage demonstrated in the upper member (Fig. 9). Drainage from the north and west is one line of evidence suggesting the large areal extent of the

Figure 9: Paleogeography of the San Juan sag region during deposition of the Animas Formation. Paleocurrent roses are summaries of the direction of paleostream flow measured from outcrops. Arrows indicate inferred sediment transport directions. 9a) lower Animas paleogeography 9b) upper Animas paleogeography.


106°
38°
37°
107°
SAN LUIS UPLIFT
SAN JUAN UPLIFT
n=48
x̄=229°
UPPER MEMBER
0 10 mi
0 km 25
106°
107°
SAN JUAN UPLIFT
n=24
x=154°
LOWER MEMBER
38°
37°

San Juan uplift beneath younger volcanic cover. As depicted in Figure 1, the San Juan uplift probably followed the northeast trend of the Colorado Mineral Belt, and connected with the eastern margin of the Gunnison uplift. It is postulated that Late Cretaceous volcanic centers in the uplift spread a volcanic-alluvial blanket over the region of the San Juan sag. The blanket would have extended as far southeast as Oil Creek, but was removed by erosion from all but the lowest places prior to deposition of the upper member of the Animas Formation. As in the case of the McDermott Member, the Mesozoic and Precambrian detritus in the Oil Creek outcrops suggest considerable uplift associated with volcanism, enough such that erosion could expose the core of the uplifted region.

The Cimarron Ridge Formation, McDermott Member of the Animas Formation, and the lower member of the Animas Formation in the San Juan sag are small remnants of what was probably a thin, but widespread volcanic-alluvial apron surrounding the Laramide San Juan uplift. The latest Cretaceous landscape in the southern Rocky Mountains region therefore might be thought of as a relatively widespread low-relief surface, blanketed by volcanic debris, and dotted by volcanic-related uplifts following the trend of the Colorado Mineral Belt.

PALEOCENE UPLIFT AND SEDIMENTATION

An erosional episode followed deposition of the upper Cretaceous volcaniclastic rocks in the San Juan sag. During this time, the lower member of the Animas Formation and older rocks such as the Kirtland Shale and Fruitland Formation were eroded from the San Juan sag except for isolated remnants (e.g., the Oil Creek outcrops mentioned above). The region probably experienced upwarping due to the initial rise of the Sawatch, San Luis, Brazos, and southern Sangre de Cristo chain of uplifts to the north, east and southeast. These north-south trending uplifts were the result of east to east-northeast directed compression. In the case of the San Luis-Brazos-Sangre de Cristo uplifted region, this broad uplift was asymmetrical with a thrusted eastern margin (Burbank and Goddard, 1937) and probable faulted monoclinal western margin.

While an erosional episode was occurring in the San Juan sag, deposition was occurring in the San Juan Basin. Sedimentation had shifted from around the margins of the San Juan uplift to the newly subsiding San Juan Basin as marked by deposition in that basin of the early Paleocene Ojo Alamo Sandstone. The Ojo Alamo was deposited by south-east flowing streams draining the San Juan uplift (Klute, 1986) and the San Juan sag area east of the San Juan uplift (Sikkink, 1983). Once the margins of the major uplifts of the Laramide southern Rocky Mountains gained definition and were faulted and/or upwarped against the San Juan sag, the sag experienced a new period of net aggradation marked by deposition of the upper member of the Animas Formation.

Upper member, Animas Formation

The upper member of the Animas Formation in the San Juan sag is correlative with the upper member in the San Juan Basin where it is considered to be Paleocene in age (Reeside, 1924; Newman, 1982). Ryder (1985, p.99) reported a Paleocene palynomorph assemblage at one locality in the San Juan sag. Both lower and upper contacts are unconformable (angular near uplift margins) in the San Juan sag. It disconformably overlies Cretaceous rocks as low in the stratigraphic section as the Lewis Shale and as high in the section as the lower member of the Animas Formation; it is disconformably overlain by the Blanco Basin Formation, and in some locations, by the Conejos Formation.

The upper member in outcrop east and south of Pagosa Springs, Colorado, was deposited by southwest flowing, braided and meandering streams and is characterized by a mix of floodplain lithofacies dominated by sheetlike and ribbonlike sand bodies, and overbank massive mudstone deposits (Figure 10). It lacks both the debris flow deposits of the lower member and the coarse conglomerate common to the overlying Blanco Basin Formation.

The upper member of the Animas Formation is characterized by drab colors indicative of reducing conditions. Overbank mudstones and claystones are brown,

Figure 10: Photograph of overbank deposits, upper member, Animas Formation near Pagosa Springs, Colorado, at Coal Creek (37°19' N lat., 106°53'18" W long.).

olive green, black and gray. These rocks are often chloritic and tend to swell when wet. Organic matter is a common constituent and occurs in several forms. Lignitic coal seams up to several centimeters thick occur at some outcrops and are also evidenced in drill cuttings. Disseminated carbonized leaf matter is common in mudstones and claystones. Sandstones may have carbonized or silicified tree limbs and pebbles of harder coal, the latter presumably recycled from the Cretaceous Fruitland Formation.

Sandstones and pebbly sandstones are common, but true conglomerates are generally rare in outcrops. Colors of sandstones vary depending upon composition, but gray/green, olive, and brown are common. Yellow and reddish colors are less common, and in many cases are a surface phenomenon where pyritic nodules are being oxidized. Where pebbles are present, the majority are andesitic volcanic rocks fragments which are usually small, well rounded, and strongly weathered, calcitized, sericitized, and may be altered to clay. Also common are mudclasts from Cretaceous rocks and pebbles derived from Precambrian basement such as granite, quartzite, feldspar and quartz. In addition to these compositions, sand-sized clasts contain a variety of sedimentary clasts from Cretaceous sources and euhedral feldspars from volcanic sources.

Although no detailed petrographic study of the Animas Formation in the San Juan Sag has been carried out, preliminary field and petrographic observations indicate that the composition of the upper member of the Animas Formation reflects unroofing of the surrounding highlands. This is demonstrated by a general trend from volcanic-dominated to arkosic-dominated composition upwards within the member.

Another trend that has been noted from well samples is that the upper Animas appears to contain less volcanic detritus eastward from the San Juan uplift. This suggests that the San Juan uplift was the ultimate source for much of this detritus and argues against substantial early Laramide volcanism in the area of the eastern San Juan sag or San Luis uplift.

Dunn (1964) and Fassett (1985) postulated a period of Paleocene volcanism responsible for the volcanic detritus in the Animas Formation. There is little evidence to prove or disprove their hypothesis, because the postulated source areas for the Animas Formation would now lie buried beneath Oligocene volcanic rocks. Observations made from the San Juan sag do not support widespread Paleocene volcanism. The volcanic lithic fragments in the upper Animas tend to be small and strongly weathered, indicating recycling. Also, no local primary evidence of Paleocene volcanism exists (intrusive or extrusive) and volcanic detritus appears to be similar in composition to material from the lower member as discussed above; thus this material was probably derived from the upper Cretaceous volcanic rocks. As mentioned above, the abundance of volcanic detritus decreases vertically in many stratigraphic sections, indicating that unroofing of the nearby uplifts reduced the amount of volcanic material available in the source areas.

The thickness of the upper member of the Animas Formation is variable due to post-Animas erosion. The thickest section drilled has been 737m near Del Norte, Colorado (Meridian well, see Table 1). Typical thickness of the formation east of Pagosa Springs, Colorado, where it has an eroded top, is about 300m. The formation has been reported by Smith and others (1985) to be as thick as 815m at an unspecified location near Pagosa Springs.

The San Juan sag was a large intermontane embayment of the San Juan Basin during upper Animas deposition. The Nacimiento Formation of the San Juan Basin is the fine-grained distal equivalent of the upper member of the Animas Formation (Baltz, 1967). Figure 9b depicts the regional paleogeography and paleocurrent directions of the upper Animas sediment-distribution system. It is apparent that deposition across the present area of the Archuleta anticlinorium was continuous and thus either the anticlinorium was not an uplifted feature during deposition of the Animas Formation, or it was not prominent enough to influence sedimentation.

LATE PALEOCENE-EARLY EOCENE TECTONISM

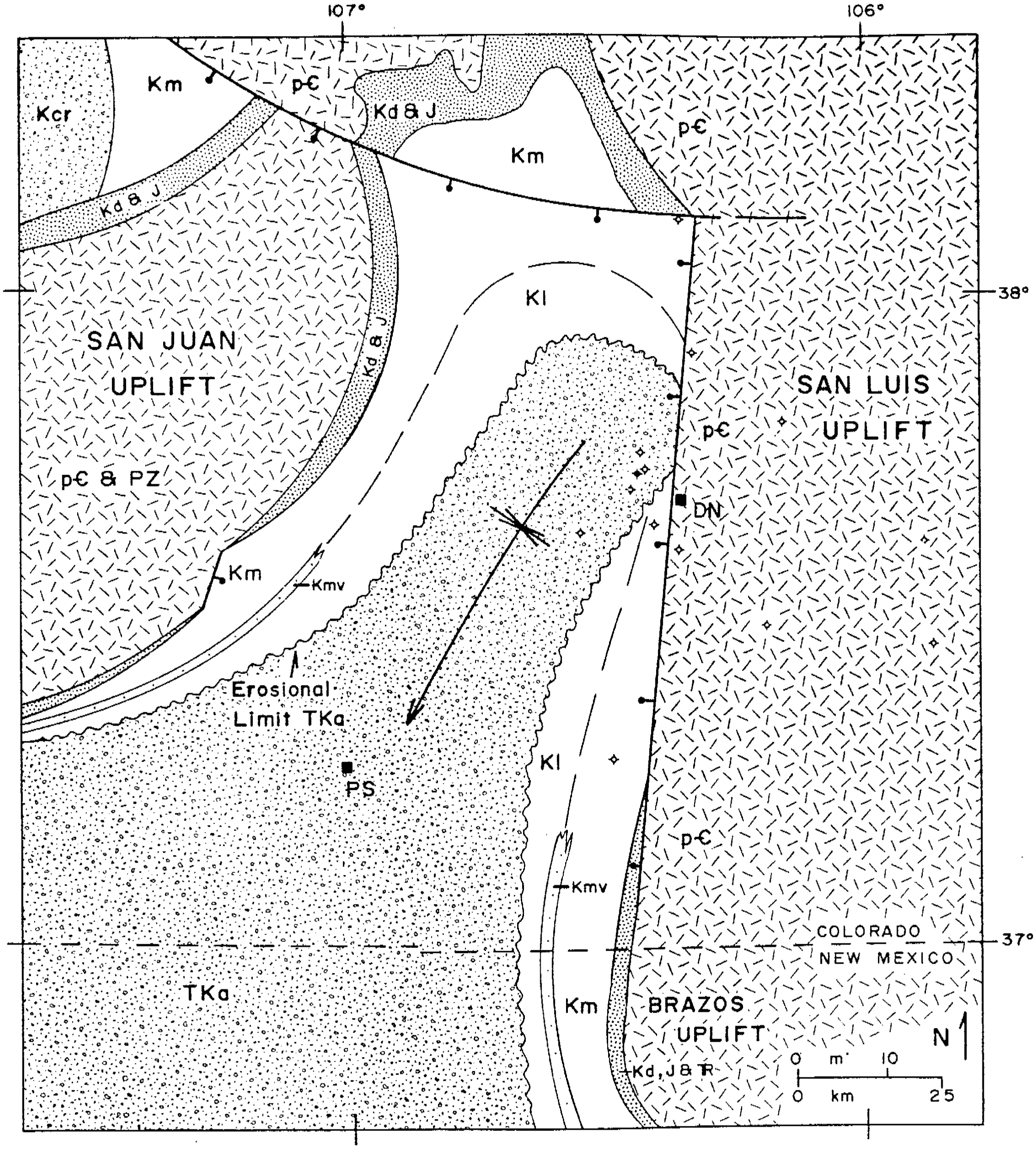
Following deposition of the Animas Formation, the entire San Juan region from the San Juan uplift to the San

Luis-Brazos uplift (including the San Juan sag) was again uplifted and eroded during what was the beginning of the strongest pulse of tectonism during the Laramide (Chapin and Cather, 1981). During this time, basin margins were upwarped and beveled and the Animas Formation was removed from areas marginal to the central axis area of the basin. This episode resulted in development of an erosional surface over the Animas Formation in the central part of the San Juan sag, and on progressively older formations toward the basin's margins, indicating that downfaulting along these margins was not keeping pace with changing base levels. This episode corresponds to a basinward shift (to San Juan Basin) in coarse sedimentation as marked by deposition of sandstones of the Cuba Mesa and Regina members of the San Jose Formation. The Cuba Mesa and Regina members conformably overlie the fine-grained Nacimiento Formation (distal Animas Formation equivalent) along the axis of the San Juan Basin (Smith, 1988). Along the margins of the San Juan Basin, however, the members of the San Jose Formation overlie older rocks in angular unconformity (Baltz, 1967). Figure 11 illustrates the paleogeology of the San Juan sag immediately prior to Eocene sedimentation.

Blanco Basin Formation

The late Paleocene-early Eocene pulse of mountain building culminated in the Eocene with reactivation of the

Figure 11: Paleogeologic map (Eocene subcrop) of the San Juan sag region prior to deposition of Blanco Basin Formation and equivalent units. TKa = Animas Formation (upper + lower members); Kcr = Cimarron Ridge Formation of Montrose sag area; Kl = Lewis Shale; Kmv = Mesaverde Group (pinches out in northeasterly direction); Km = Mancos Shale; Kd & J = Dakota Sandstone and Jurassic Formations; pЄ (also pЄ & PZ) = basement rock.


107°
106°
38°
37°
Kcr
Km
pC
Kd & J
Km
Kd & J
Kl
SAN JUAN
UPLIFT
Kd & J
pC & PZ
Km
Kmv
Erosional
Limit TKa
PS
SAN LUIS
UPLIFT
pC
DN
Kl
pC
Kmv
COLORADO
NEW MEXICO
TKa
Km
BRAZOS
UPLIFT
Kd, J & TR
N
0 m 10
0 km 25

margins of the San Juan sag, causing a new period of net aggradation atop the late Paleocene (?) unconformable surface, which resulted in deposition of the Blanco Basin Formation of Cross and Larsen (1935). The Blanco Basin Formation occurs in isolated outcrops along the southwest margin of the San Juan sag and represents renewed sedimentation during the Eocene following late Paleocene-early Eocene regional uplift. Its precise age is unknown because it has not yielded fossils or other dateable material, however, it probably correlates with the San Jose Formation of the San Juan Basin (e.g. Smith and others, 1985; and many others) and thus is considered to have an early Eocene age (Lucas, 1984).

The Blanco Basin Formation in outcrop is bounded by unconformable surfaces. Angular discordance with underlying strata increases toward the margins of the San Juan sag where these strata are turned up against the bounding uplifts. The maximum measured thickness of the formation in outcrop is 194 m near its type section north of Chama, New Mexico (see Part 1). The thickest section drilled in the San Juan sag was in the Milestone #1 AMF well (Table 1) where it measured 238m. Similar Eocene units in wells in the Monte Vista basin to the east range up to 700 m thick; these are discussed later with the Monte Vista basin.

The Blanco Basin Formation in the San Juan sag differs from the Animas Formation in several ways. It is coarser grained and contains pebble and cobble conglomerate dominated by Precambrian basement-derived detritus. Mesozoic sedimentary detritus may occur near the base of the formation and volcanic detritus is notably lacking in most outcrops. Where present, volcanic detritus is sand-sized, strongly altered and presumably recycled from the Animas Formation (Dunn, 1964).

Blanco Basin Formation mudstones are typically oxidized to bright reddish colors (10R4/6 to 10R5/4) with lesser amounts of green-gray coloration. Sandstone and conglomerate units are red, yellow, gray, or white depending upon composition, thickness and grain size; these colors generally contrast with those of the Animas Formation. Organic matter is sparse in the Blanco Basin Formation, in direct contrast with the upper Animas Formation. Carbonized wood occurs as clasts in one locality (37°23'14" N.lat., 106°51'06" W.long.) but is otherwise absent from the formation.

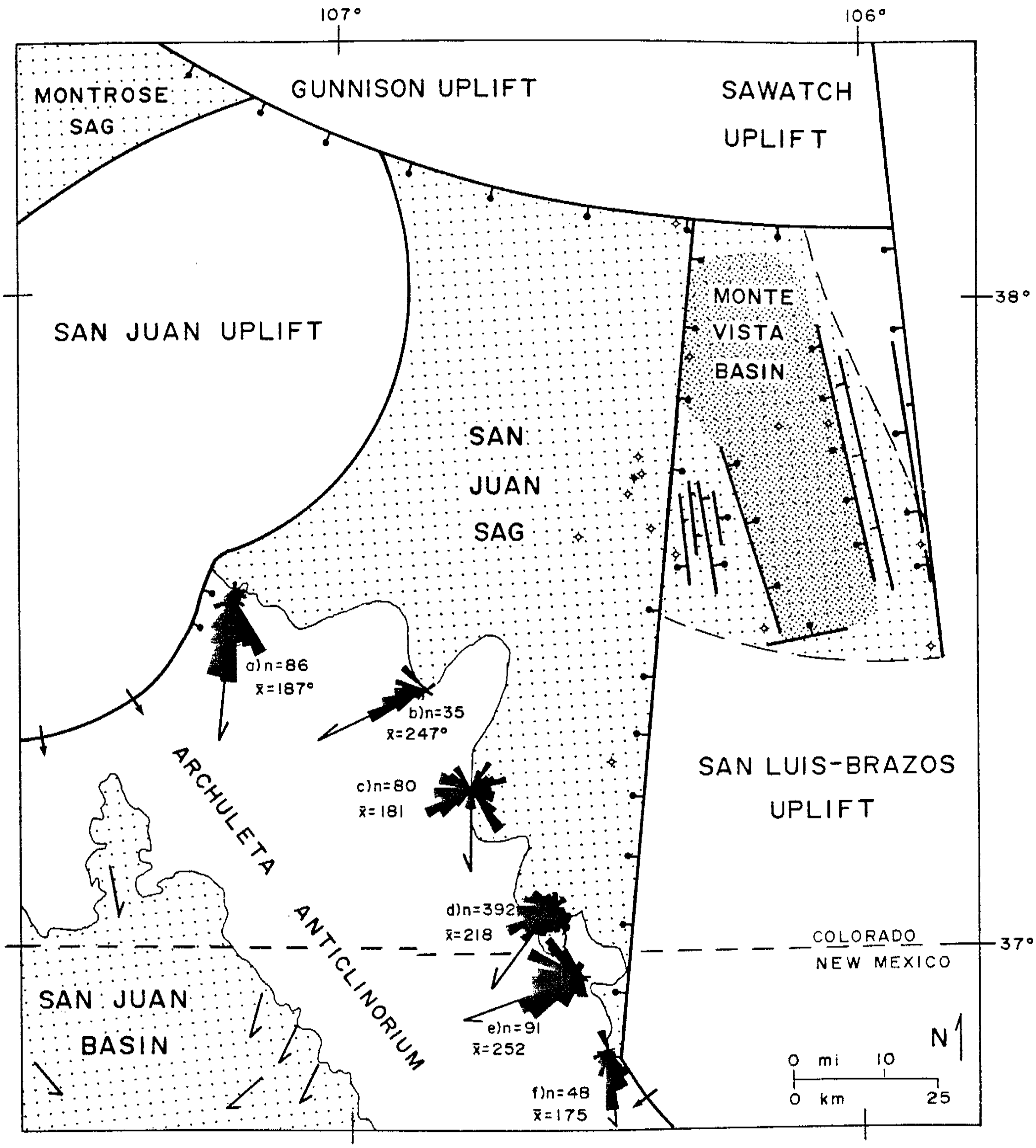
Lithofacies associations of the Blanco Basin Formation indicate that it was deposited primarily by braided streams in a humid alluvial fan-braidplain complex. The formation coarsens toward the margins of the basin where proximal lithofacies such as debris-flow deposits and coarse (boulder/cobble) braided-stream deposits occur. It becomes finer-grained away from the uplifted margins of the basin where overbank mudstones and sandy, braided-channel deposits predominate in a sandy braidplain environment.

Paleocurrents measured from Blanco Basin outcrops indicate that margins established during earlier Laramide events were reactivated during at least early Eocene time (Fig. 12). Paleocurrents of stream systems and the composition of their loads indicate that both the Needle Mountains area and Brazos uplift were being stripped of sediments. Other evidence for uplift of the Needle Mountains area is the Telluride Conglomerate which was shed west and northwest from the Needle Mountains (Steven and Hail, 1989), and the Ditch Canyon Member of the San Jose Formation shed southeastward into the San Juan Basin (Smith, 1988). The Regina, Llaves and Tapicitos members of the San Jose Formation in the San Juan Basin were derived from areas to the north, northeast and east during this time and may be in part the downstream equivalents of the preserved remnants of the Blanco Basin Formation. Figure 12 supports earlier workers' arguments that the Blanco Basin Formation correlates at least in part with the San Jose Formation in the San Juan Basin.

RISE OF ARCHULETA ANTICLINORIUM

The Archuleta anticlinorium is a broad, northwest-trending basement-cored arch which is complexly folded and faulted (Wood and others, 1948; Baltz, 1967). Dunn (1964) noted that it was not involved as a part of earlier uplifts (Brazos and San Juan uplifts) and did not become an uplifted feature until after deposition of the Blanco Basin

Figure 12: Eocene paleogeography of the San Juan sag. Stippled areas indicate the present distribution of Eocene sedimentary deposits. Mean paleocurrent vectors for the San Jose Formation in the San Juan Basin (arrows) are from Smith (1988). Paleocurrent rosettes (Arrows show mean directions) for the Blanco Basin Formation in the San Juan sag are summarized from Part 1. Eocene deposits in the Montrose sag make up the Telluride conglomerate. The dark patterned area in the Monte Vista basin shows where Eocene sediments reach thicknesses between 200 and 700 meters.


107°
106°
38°
37°
MONTROSE SAG
GUNNISON UPLIFT
SAWATCH UPLIFT
SAN JUAN UPLIFT
MONTE VISTA BASIN
SAN JUAN SAG
a)n=86
x̄=187°
b)n=35
x̄=247°
c)n=80
x̄=181
ARCHULETA ANTICLINORIUM
SAN LUIS-BRAZOS UPLIFT
d)n=392
x̄=218
e)n=91
x̄=252
f)n=48
x̄=175
COLORADO
NEW MEXICO
SAN JUAN BASIN
N
0 mi 10
0 km 25

Formation (as presently exposed). As demonstrated in Figure 12, paleocurrents in the Blanco Basin Formation stream systems indicate stream-flow across the anticlinorium; also no ponding of sediments against the anticlinorium can be demonstrated in existing outcrops. Dunn (1964, p.61-63) demonstrated that the Blanco Basin Formation was folded along with older strata within the anticlinorium. The anticlinorium predated late Eocene erosion which, in turn, preceded deposition of the Conejos Formation (early Oligocene).

The Archuleta anticlinorium is one of the structures emplaced during a fundamental change in the stress distribution and structural style of the region. The emergence of the Archuleta anticlinorium during the middle(?) Eocene was probably the result of two factors which acted to reactivate the northwest-trending structural grain in the basement. The first was loading and subsidence in the adjacent San Juan Basin. The second was a change in the regional stress field in the latter part of the Laramide orogeny from east-northeast to northeast-directed compression (Chapin and Cather, 1981). The change in stress fields during the latter part of the Laramide orogeny was accompanied by right-lateral wrench faulting along the eastern margin of the Colorado Plateau as the Colorado Plateau microplate became decoupled from the North American craton and was translated northward (Chapin and Cather, 1981; Chapin, 1983).

Emergence of the Archuleta anticlinorium probably occurred simultaneously with a late episode of wrench fault modification of the Nacimiento and Gallina fault zones in New Mexico and downwarping of the Chama Basin (Baltz, 1967). Wrench-fault reactivation of the eastern margin of the San Juan sag and formation of the late Laramide Monte Vista basin probably also occurred at this time.

MONTE VISTA BASIN

During middle(?) Eocene, the fault zone bounding the eastern side of the San Juan sag was reactivated along part of its length with an opposite sense of movement to earlier faulting episodes. This resulted in the formation of the late-Laramide Monte Vista basin east of the San Juan sag in what is now the northwestern San Luis Basin (Figs. 1,3, 12). The term "Monte Vista basin" is proposed here as an informal term to distinguish this Laramide basin from the later rift-related Monte Vista graben of the San Luis Basin (Burroughs, 1981).

Because of the uncertainties in timing of basin formation and the similarities between the sediments in this basin and the Blanco Basin Formation in the San Juan sag, these deposits are distinguished only in that their thickness in the Monte Vista basin is about four-fold that of the San Juan sag. If the two deposits are the same age (in whole or part), then the rate of subsidence of the Monte Vista basin was low enough that it did not capture the paleodrainage of the entire San Juan sag during deposition of the Blanco Basin Formation (as it occurs in outcrop). On the other hand, if the sediments in the Monte Vista basin are somewhat younger than the Blanco Basin Formation (where it occurs in outcrop in the sag), then this might indicate that the rise of the Archuleta anticlinorium and simultaneous wrench-fault modification of the eastern margin of the San Juan sag (and creation of the Monte Vista basin) isolated the San Juan sag from the San Juan Basin, and diverted drainage towards the downwarping Monte Vista basin.

Redbeds in the Monte Vista basin compare favorably in color, lithologies, and stratigraphic position with redbeds in the subsurface of the San Juan sag and with Blanco Basin Formation outcrops. Besides thickness differences, deposits in the Monte Vista basin differ slightly from those in the San Juan sag in two other regards: grain size and composition.

Grain size trends calculated from borehole geophysical logs suggest that the Monte Vista basin had a higher percentage of mudstone deposited within it than the San Juan sag. The average sand:shale ratio for wells in the Monte Vista basin is 1:1.2 as opposed to the 1.7:1 average for the San Juan sag (surface and subsurface). Close examination of well samples in the Monte Vista basin, however, show that even though muddy facies are common, these appear to be pebbly (mass-flow type deposits) and the "sands" appear to be coarse sandstone and conglomerate, thus the deposits are probably proximal and locally derived. Differences in sand:shale ratio in this case may reflect differences in lithofacies types or provenance. Also, the utility of sand:shale ratios is limited in the San Juan sag region because of sampling bias. Most wells were drilled directly adjacent to basin margins, thus biasing well data toward more proximal alluvial lithofacies.

Compositional differences are only slight between the redbeds in the two basins, primarily in that Mesozoic rocks available to contribute detritus to redbeds of the San Juan sag were removed from the area of the Monte Vista basin prior to its formation. As depicted in Figure 12, the Monte Vista basin was developed within the western half of the Laramide San Luis uplift which was denuded of all post-Precambrian strata prior to Eocene deposition.

The Monte Vista basin, unlike the San Juan sag, did not exist until the time of Eocene redbed deposition. This constraint on timing, in addition to the following criteria, suggests that it is an Echo Park-type basin using terminology of Chapin and Cather (1981). Echo Park-type basins in the Southern Rocky Mountians tend to be north to north-northwest-trending, elongate, between the North American stable craton and the Colorado Plateau, narrow in an east-west direction, and bounded on several sides by high-angle fault zones.

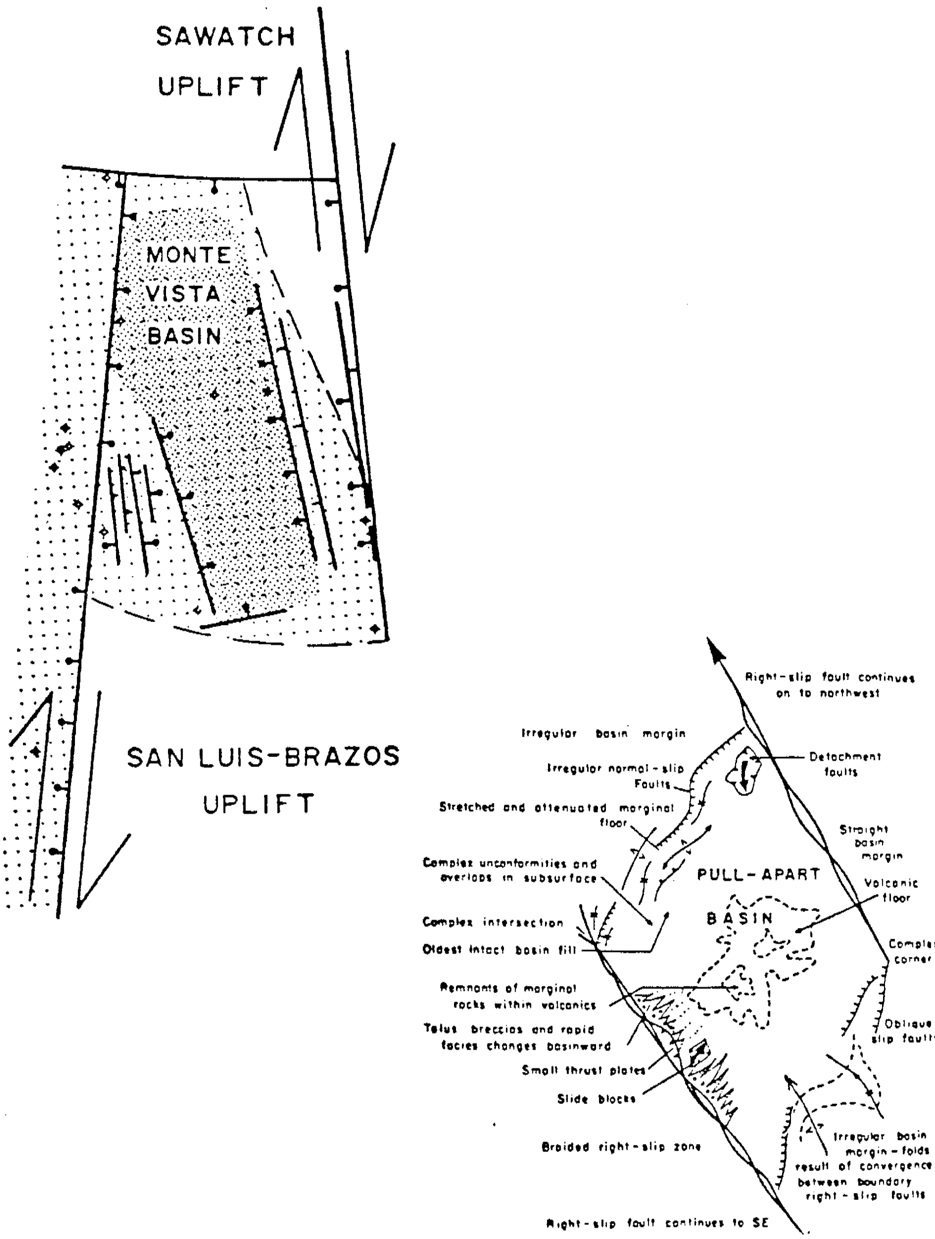


Figure 13: The late Laramide Monte Vista basin (a) compared with model of right-stepping, right-lateral, pull-apart basin (b). Model from Crowell (1974).

Figure 13 compares the Monte Vista basin with models of basins produced by right-stepping *en echelon* right-lateral strike-slip faults (releasing overstep pull-apart basins of Harding and others, 1985). The basin also compares favorably with the model of Rogers (1980) where the separation of bounding en-echelon faults equals about 1/2 the overlap of the faults. Based on seismic interpretation and drilling data, the Monte Vista basin is west-tilted, with thickest sections of Eocene redbeds occurring along its western boundary. It is bounded on the east and west by fault zones that splay (perhaps horsetail splays using terminology of Biddle and Christie-Blick, 1985), diverging southward for the western boundary and northward for the eastern zone. The northern bounding fault zone is postulated in Figures 4 and 5 but has not been verified by reflection seismic, so its structure is not known. The southern boundary of the basin is ill-defined and imperfectly known. A gravity low in Figure 7 extends southward from the basin, but it may be associated with post-Laramide episodes of faulting and so is tentatively not included within the Monte Vista basin. Absence of drilling within this gravity low prevents an age determination for this sub-basin.

SALADO-CUMBRES DISCONTINUITY

The linear, narrow fault zone bounding the eastern margin of the San Juan sag is interpreted to have been a right-lateral wrench fault during at least the latter part of the Laramide orogeny from the following criteria:

1) well control and proprietary seismic data (Gries, 1990, written comm.) constrain the east margin to be a north-trending, narrow fault zone;

2) changes in sense of motion of the fault along its length occur as shown in Figure 12;

3) bounding faults dip at high angles as interpreted from seismic lines (see Part 3, Figure 5).

4) syntectonic sediments were deposited in a narrow, deep, asymmetric basin adjacent to the zone (Monte Vista basin);

5) numerous north to northwest-trending (en-echelon?) structures have been interpreted from seismic and gravity adjacent to, and west of, the wrench-fault zone (R. Gries, 1989, oral and written communication).

6) timing and orientation of the zone in relation to other wrench-related features of the Southern Rocky Mountains suggests a similar origin for the eastern margin of the San Juan sag.

The zone is interpreted to be an extension of the "Salado-Cumbres discontinuity" of Baltz (1967) which is a dextral structural discontinuity along the eastern margin of the Colorado Plateau (Fig. 14). The discontinuity was described by Baltz (1967) as extending possibly as far north as the Conejos River in Colorado (approximately lat. 37° 4' 30''), but is demonstrated here to extend as far north as Saguache, Colorado (approximately lat. 38° 6').

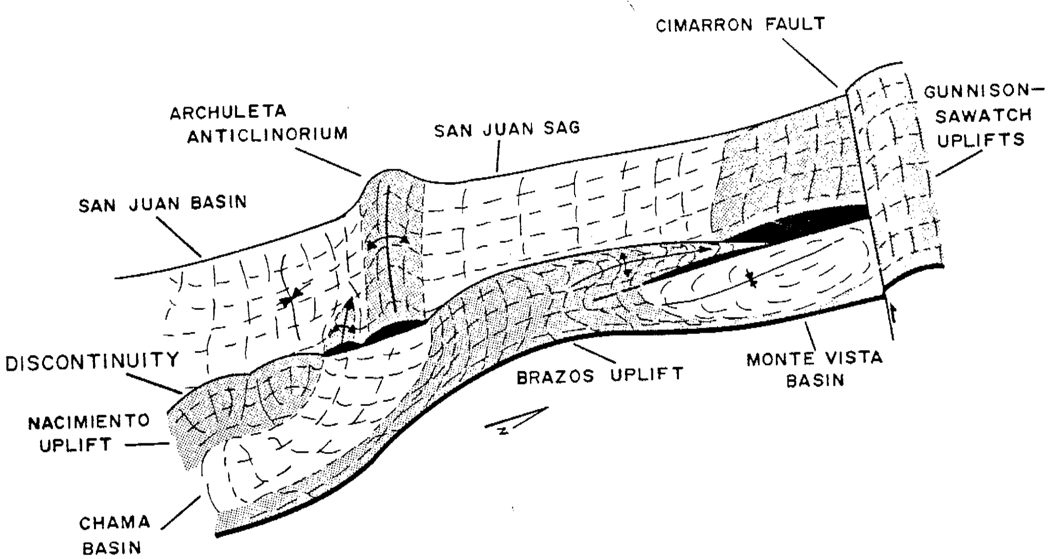


Figure 14: Three dimensional diagram of the sub-Eocene surface in late Eocene in the region of the Salado-Cumbres discontinuity. Figure modified from Baltz (1967).

Evidence for right slip along the trend of this discontinuity in New Mexico as far south as the Rio Puerco fault zone is summarized in Chapin and Cather (1981).

Figure 14, depicts an interpretation of the sub-Eocene surface in the region of the Salado-Cumbres discontinuity during the latest Eocene, following subsidence of the Monte Vista basin. Note that the "Del Norte High" of Gries (1989) is apparently a north-plunging feature and possible northern extension of the Brazos uplift as it existed in the Eocene. This high was part of the western edge of the larger San Luis uplift prior to Eocene strike-slip modification of the fault zone.

EOCENE EROSION SURFACE

By the latest Eocene, a wide-ranging, low-relief geomorphic surface had been developed over the San Juan region (Steven, 1975; "late Eocene erosion surface" of Epis and Chapin, 1975). The highlands surrounding the Laramide basins of the region had been subdued by Eocene erosion and basins were filled with sediments. It was upon this surface that the Conejos Formation (35-30 Ma; Lipman and others, 1970) was deposited. The erosion surface extended over much of the region, and is best exposed along the northeastern margin of the Archuleta anticlinorium where the Conejos overlies the Blanco Basin and Animas formations and the Lewis Shale in angular unconformity. Erosion accompanied or followed the rise of the Archuleta anticlinorium resulting in partial or total removal of the Blanco Basin and Animas formations from the structure.

Although the topography of the region by the latest Eocene was generally of low relief, some remnant uplifts and basins persisted into the Oligocene. The Gunnison-Sawatch uplift north of the San Juan sag remained high during deposition of the Conejos Formation (Steven and Hail, 1989) and the Monte Vista basin continued to subside into the early Oligocene (discussed in Part 3). In the San Juan sag, the contact between the Conejos Formation and the Blanco Basin Formation as seen on seismic lines appears to lack angular discordance, thus the older beds were not significantly tilted prior to early Oligocene volcaniclastic deposition. This indicates that the Laramide tectonic event had ended prior to the Oligocene.

IMPLICATIONS FOR PETROLEUM EXPLORATION

Deep targets, remote drilling sites, unpredictable results of geophysical surveys over a complex volcanic terrane, and a limited knowledge of the full extent and characteristics of the basin are drawbacks to exploration in the San Juan sag. However, the San Juan sag remains a potential wildcat drilling play for a number of reasons. It contains Jurassic through Eocene strata correlative to the San Juan Basin, and as described in this paper, was simply an embayment of the San Juan Basin throughout most of the Laramide orogeny. This means that the post-Triassic stratigraphy and general history of development are familiar to those exploring in the San Juan Basin region. Synorogenic Tertiary strata in the San Juan sag were not deposited as thickly as in the San Juan Basin, but hundreds of meters of volcanic rock cover petroleum source rocks in the sag. Increased burial depth associated with the mid-Tertiary volcanic episode also aided in maturing hydrocarbons in these rocks (Gries and Clayton, 1989).

Multiple episodes of uplift around the basin margins resulted in complexly folded and faulted margins, creating potential structural traps for hydrocarbons. Structures produced during early Laramide tectonism are monoclinal folds around the basin margins, complicated by faulting as the surrounding mountainous areas rose. Potential late Laramide transpression-related structures range from folds in sedimentary rocks over basement shear zones (possible examples discussed by Baltz, 1967), to en-echelon northwest-oriented folds and faults adjacent to the wrench-faulted eastern margin of the basin. Where transpression was pronounced along the eastern wrench-fault zone, potential exists for positive flower structures or reverse-fault overlap of sedimentary strata by Precambrian basement.

Faulted folds along the trend of the Archuleta anticlinorium have produced hydrocarbons (i.e., Gramps field; Waldschmidt, 1948) and similar structures could occur beneath the volcanic cover of the San Juan sag. Other favorable targets include fractured Cretaceous shales (as in Chromo field; Wengerd and Gill, 1952) and post-Laramide fractured igneous intrusions (as in Del Norte field; Gries, 1985, 1989). Most drilling in the past decade has concentrated upon the eastern margin of the sag; continued exploration efforts in the area should seriously consider interpretations of structures which are compatible with right-lateral wrench faulting.

SUMMARY

--The San Juan sag, during most of the Laramide orogeny was an embayment (reentrant) of the San Juan Basin between the San Juan uplift and the San Luis-Brazos-Sangre de Cristo uplift. --Late Cretaceous intrusion, volcanism, doming and erosion in the San Juan uplift along the trend of the Colorado Mineral Belt was responsible for, and the source of, the lower member of the Animas Formation which was shed southeastward into the San Juan sag.

--A strong pulse of regional east-northeast directed compression and uplift occurred in early (?) Paleocene creating the Sawatch-San Luis-Brazos-Sangre de Cristo mountain chain. Resultant synorogenic deposits make up the upper member of the Animas Formation which was derived from these mountains to the northeast and east of the San Juan sag.

--Another strong pulse of uplift, this time with a more northeasterly compressive stress orientation, started in the late Paleocene to Eocene, eventually resulting in the

development of right-lateral wrench-related structures. The Blanco Basin Formation and correlative (perhaps slightly younger in part) redbeds in the subsurface of the San Juan sag and Monte Vista basin were deposited in response to this episode of tectonism.

--Right-lateral wrench faulting formed the Monte Vista basin adjacent to the eastern margin of the San Juan sag.

--By latest Eocene, active tectonism waned and a low-relief erosion surface developed across the San Juan sag upon which the Oligocene Conejos Formation was deposited.

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PART 3

TERTIARY STRATIGRAPHY AND TECTONIC DEVELOPMENT OF THE ALAMOSA BASIN, RIO GRANDE RIFT, SOUTH-CENTRAL COLORADO

INTRODUCTION

The Alamosa Basin is a sub-basin of the San Luis Basin of south-central Colorado and north-central New Mexico. The San Luis Basin is but one of a series of similar features in the Rio Grande rift (Fig.1), a north-trending intra-continental rift which extends from north of Leadville, Colorado, to as far south as El Paso, Texas, and beyond (Chapin, 1971). The San Luis Basin is more than 200 km long from north to south. Physiographically, its northern limit is at Poncha Pass, Colorado (Upson, 1939), and its southern limit is near the Embudo constriction in New Mexico (Kelley, 1956). The San Luis Basin is bordered by the San Juan and Tusas mountains on the west and the Sangre de Cristo Range on the east. At the latitude of Alamosa, Colorado, it is about 70 km across. This paper examines a 5520 km^2 area in the San Luis Basin, north of the San Luis Hills, called the Alamosa Basin. The Alamosa Basin contains a more complete record of Tertiary stratigraphy than any other portion of the San Luis Basin. Its stratigraphy, structure, and tectonic history is interpreted from subsurface data, including borehole samples and geophysical surveys.

The Alamosa Basin has had a complex history, the region having been recurrently uplifted and down-dropped

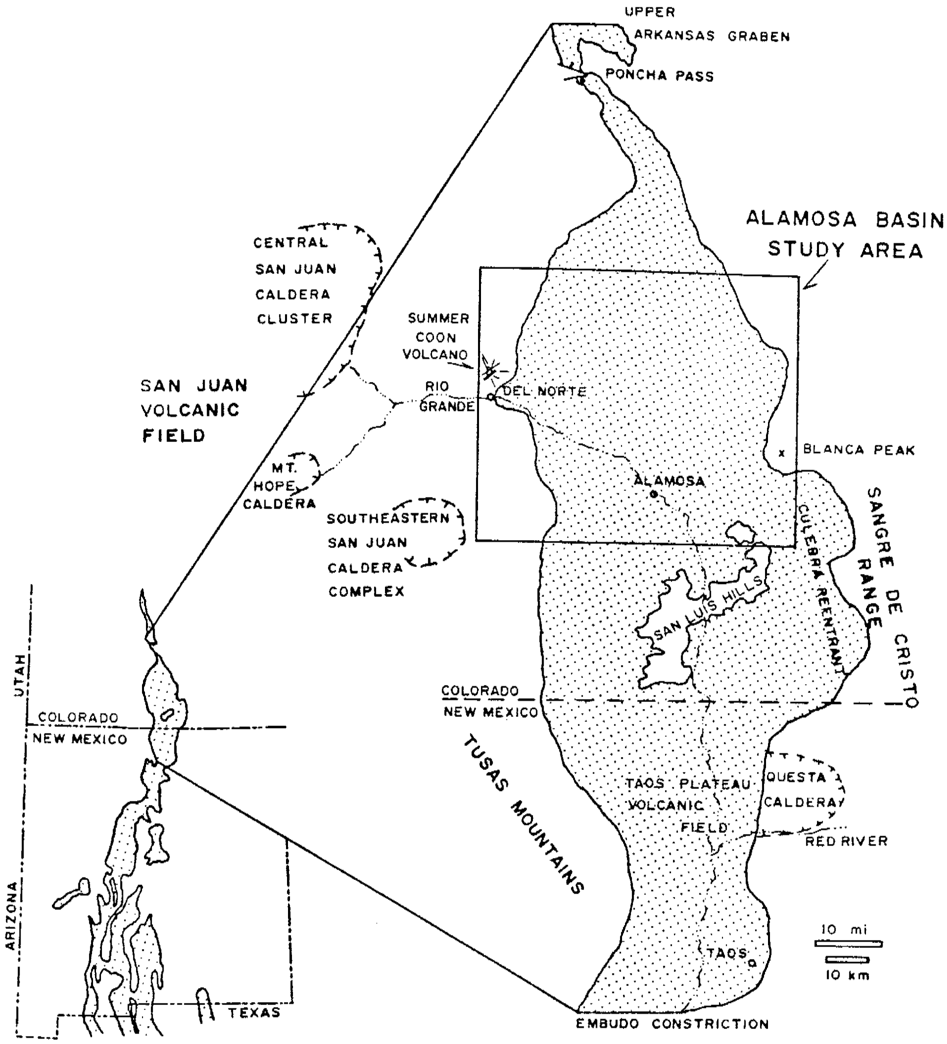


Figure 1: Location map showing Alamosa Basin study area, San Luis Basin, Rio Grande rift, and geographic features discussed in text. Stippled pattern denotes rift-basin fill.

during several tectonic events. As a Rio Grande rift basin, the Alamosa Basin today takes the form of an asymmetric, first-order half-graben with stratigraphic units tilted eastward from their pre-rift positions (Fig. 2). This half-graben is bounded along the Sangre de Cristo Range by the Sangre de Cristo fault zone (Personius and Machette, 1984, p.87). The basin is divided into western and eastern halves by a basement high termed the "Alamosa horst" (Burroughs, 1981). The western half of the basin is referred to as the Monte Vista graben and the eastern half the Baca graben. Both the Monte Vista and Baca grabens are second-order half-grabens, but the Baca graben was the site of the greatest degree of tilting and thickest sedimentary infilling during rifting due to its proximity to the Sangre de Cristo fault zone.

The purpose of this paper is to present an interpretation of the tectonic development of the Alamosa Basin based on new insight into the stratigraphy of the basin fill. This paper begins with a discussion of the physical characteristics of the basin stratigraphy as defined from petrologic analysis of subsurface samples. Once defined, the lithostratigraphic units are correlated using reflection seismic lines. This is followed by a discussion of basin geometry. The combined stratigraphic and structural information is then applied to interpreting the timing of episodes of basin development. The resulting conclusions differ from those of earlier studies, but are

Figure 2: Interpretive cross-section A-A' across the San Luis Basin; location of section indicated in Figure 3. Symbols: TQa & Qal = Alamosa Formation (Plio-Pleistocene) and Quaternary alluvium, Tsfl = lower Santa Fe Group (Mio-Pliocene), Tt = ash-flow tuffs of San Juan volcanic field (Oligocene), Tc = Conejos Formation and equivalents (Oligocene), Tbb = Blanco Basin Formation (Eocene), pC = granite-gneiss basement (Precambrian). Figure modified from Gries and Brister (1989).

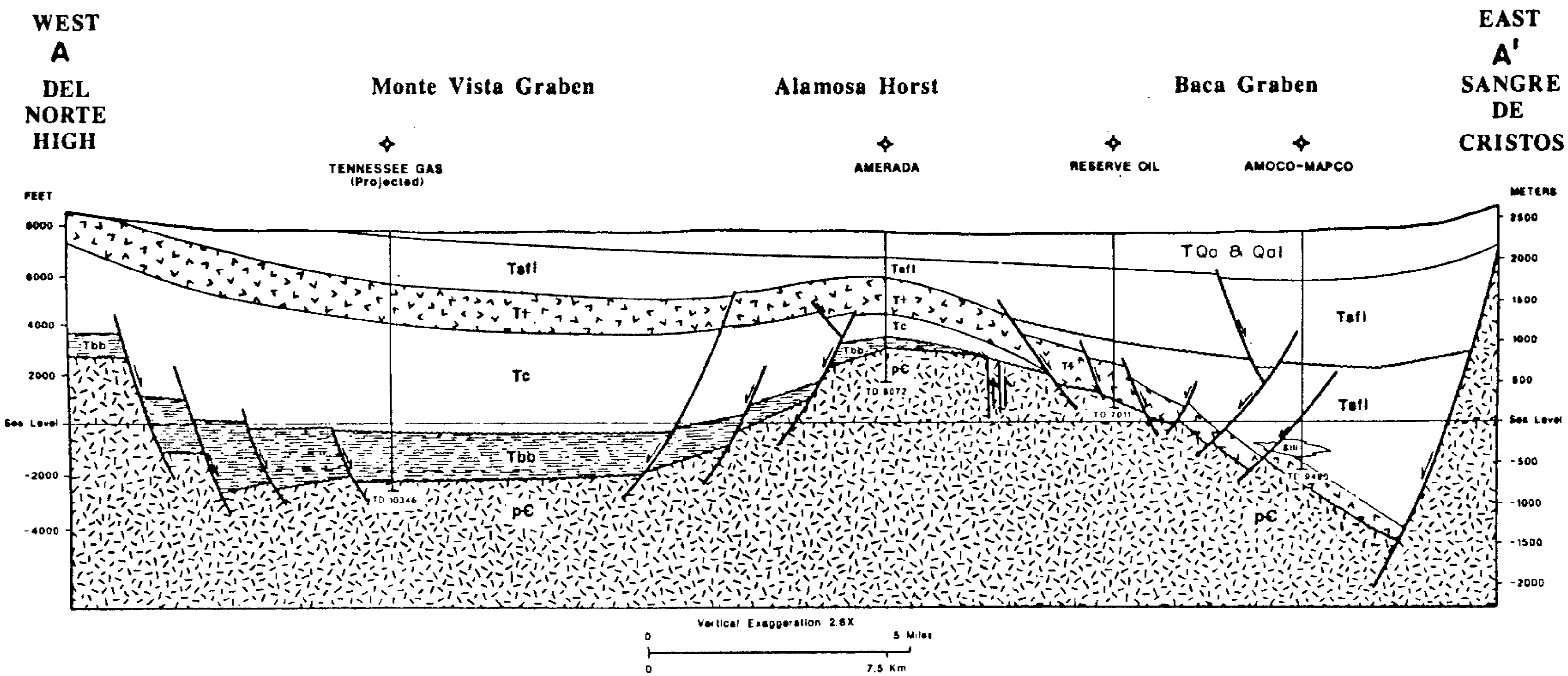
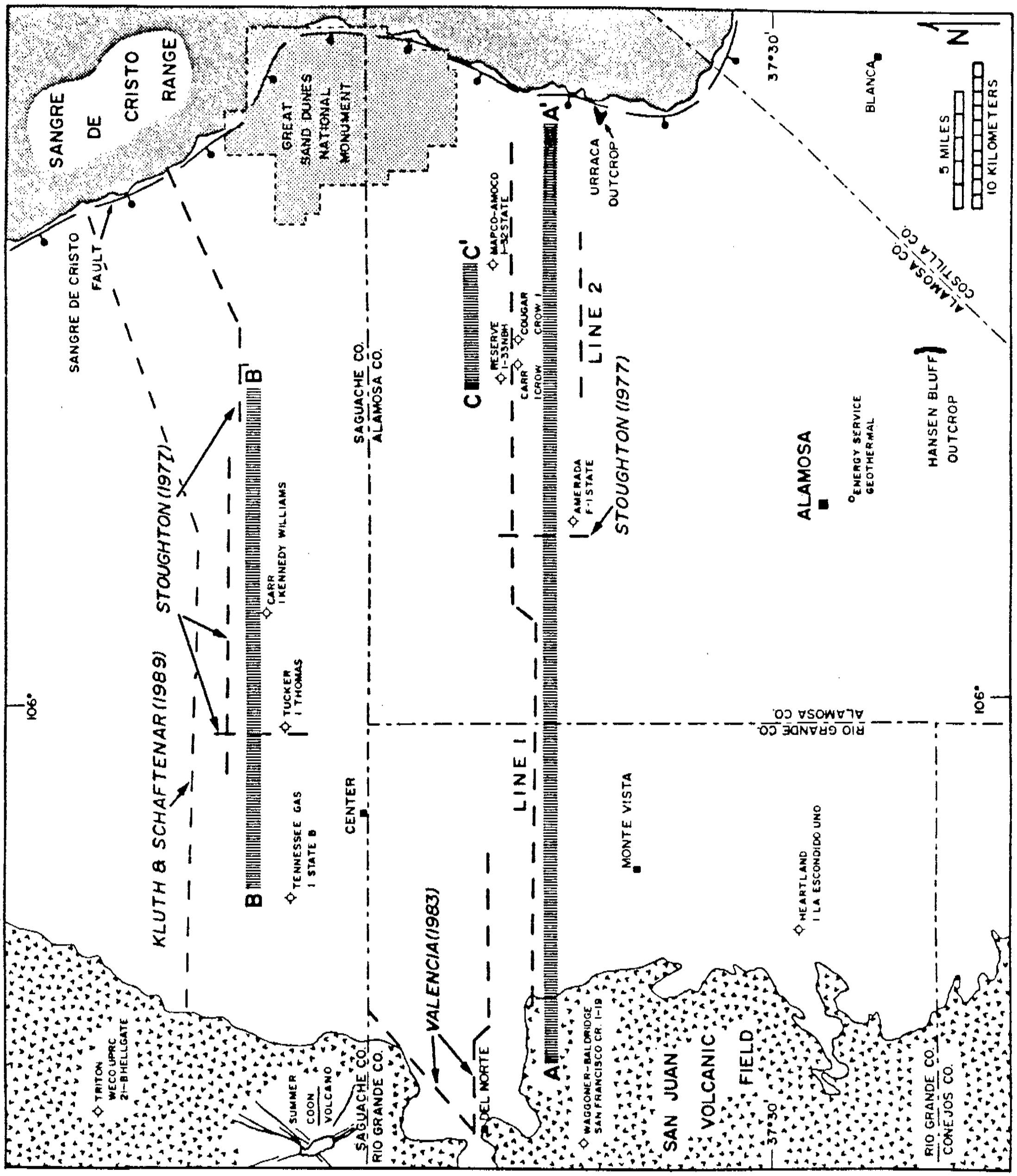

WEST
A
DEL NORTE HIGH
Monte Vista Graben
Alamosa Horst
Baca Graben
EAST
A'
SANGRE DE CRISTOS
TENNESSEE GAS (Projected)
AMERADA
RESERVE OIL
AMOCO-MAPCO
FEET
8000
6000
4000
2000
Sea Level
-2000
-4000
METERS
2500
2000
1500
1000
500
-500
-1000
-1500
-2000
Tsfl
Tt
Tc
Tbb
pC
TQa & Qal
TD 10346
TD 8072
TD 7011
Vertical Exaggeration 2.8X
0
5 Miles
7.5 Km

Figure 3: Map of the Alamosa Basin study area showing oil and gas drilling, seismic lines illustrated or discussed in this paper, and cross-sections A-A', B-B', C-C'.


SANGRE DE CRISTO RANGE
GREAT SAND DUNES NATIONAL MONUMENT
SANGRE DE CRISTO FAULT
STOUGHTON (1977)
KLUTH & SCHAFTENAR (1989)
VALENCIA (1983)
B
B'
C
C'
A
A'
LINE 1
LINE 2
SAGUACHE CO.
ALAMOSA CO.
RIO GRANDE CO.
ALAMOSA CO.
CENTER
MONTE VISTA
DEL NORTE
ALAMOSA
BLANCA
URRACA OUTCROP
HANSEN BLUFF OUTCROP
ENERGY SERVICE GEOTHERMAL
AMERADA F-1 STATE
CARR 1 KENNEDY WILLIAMS
TUCKER 1 THOMAS
TENNESSEE GAS 1 STATE B
MAPCO-AMOCO 1-32 STATE
RESERVE 1-35NBH
CARR 1 CROW
COUGAR CROW 1
HEARTLAND 1 LA ESCONDIDO UNO
WAGGONER-BALDRIDGE SAN FRANCISCO CR. 1-19
TRITON WECO UPRC 21-8 HELLGATE
SUMMER COON VOLCANO
SAN JUAN VOLCANIC FIELD
RIO GRANDE CO.
CONEJOS CO.
COSTILLA CO.
ALAMOSA CO.
106°
37°30'
5 MILES
10 KILOMETERS
N

in better conformance with regional stratigraphy and tectonic history.

Previous work

Many papers have mentioned the San Luis Basin in some capacity. The classic references on the location and physiographic setting of the basin are Siebenthal (1910b) and Upson (1939). Overviews which discuss the relation of the San Luis Basin to the Rio Grande rift are Chapin (1971, 1979, 1988), Cordell (1978), Hawley (1978), Keller and others (1984), and Tweto (1979). Notable geophysical investigations of the study area are Cordell (1978), Gries (1985a), Keller and others (1984), and Stoughton (1977).

Published studies of the subsurface stratigraphic units in the Alamosa Basin have been few. Huntley (1979) was the first to publish a correlation of stratigraphic units between boreholes suggesting that the basin fill was entirely of Tertiary age. Burroughs (1981) studied the western half of the basin in greater detail, making the important discovery that some of the more wide-ranging volcanic units of the region could be readily identified and correlated in borehole geophysical logs.

Reflection seismic lines published by Gries (1985a) were of high quality, but insufficient petrologic and stratigraphic data existed to explain the various features visible on the lines. Attempts to resolve this problem by obtaining radiometric and palynological age determinations failed due to the unreliability of these techniques when applied to contaminated rotary drill cuttings. This paper reports the results of a new detailed petrologic study of borehole samples. Preliminary results were discussed in Gries and Brister (1989) and Brister (1989b).

Subsurface data

Figure 3 is a map of the Alamosa Basin depicting sources of subsurface information utilized in this paper. Most of the subsurface petrologic data comes from rotary drill cuttings. Some published and commercial well-sample description logs were used in addition to new composite-interpretive logs compiled during cutting examination (Appendix 3).

STRATIGRAPHY

The sequence of lithostratigraphic units in the Alamosa Basin varies greatly depending upon location within the basin. In general, the sequence of tectonic events that formed the western half was different from that which formed the eastern half and so the two halves have significantly different stratigraphic sections. The stratigraphy is best illustrated by a west-to-east cross-section (Fig. 2). Petrologic studies of samples from the depicted units are the physical basis for the interpreted stratigraphy of the basin in the discussion to follow.

Precambrian basement (pC)

The stratigraphically lowest unit is Precambrian basement. Several oil and gas test wells in the study area have bottomed in basement rocks and were drilled through several tens of meters of them, presumably unintentionally. These rocks drill fast and, at first glance, cuttings have the appearance of arkosic sandstone or "granite wash". In general, the basement rocks are granitic in composition but have a gneissic texture. The gneisses are layered, as cuttings from 10 ft intervals show alternating concentrations of light and dark minerals. The basement rocks have high electrical resistivity (often from 100-2000 ohmms) and densities typical of granitic rocks (greater than 2.6 gm/cc). Cuttings are often stained orange by hematite, especially along grain boundaries. This may indicate oxidation resulting from weathering when the basement was exposed subaerially during the Ancestral Rocky Mountain and Laramide orogenic events.

Mineralogically, the basement rocks contain quartz, orthoclase, microcline, perthite, plagioclase, muscovite, biotite, and amphibole. Alignment of micas is common in most samples. Most quartz grains are strained, monocrystalline types which reflect a probable metamorphic origin. Some quartz grains are coarsely polycrystalline with nonsutured boundaries. Although these grains would usually be expected to come from metaquartzites, they may also be found in finer grained granites and schists (Folk, 1974).

A wide range of metamorphic rock types have been described from exposures in the nearby Sangre de Cristo Range (Johnson, 1969), including granites, gneisses of various compositions, amphibolites, and metasediments. Such variation probably also occurs beneath the Alamosa Basin, but has not been found by drilling. The top of the Precambrian basement is an unconformable surface of erosion, upon which Tertiary units were deposited.

Blanco Basin Formation (Tbb)

The Blanco Basin Formation (Eocene) consists of non-volcanic, alluvial red-beds unconformably overlying the Precambrian basement in wells in the western half of the Alamosa Basin (Monte Vista graben). Total thickness varies across the Basin from 0 to 696 m. The Blanco Basin Formation is composed of sandy, micaceous mudstone and coarse arkosic sandstone and conglomerate.

The mineral composition of the coarser sedimentary rocks is identical to that of the Precambrian basement and indicates that basement rocks were their primary source. Sandstones in some wells also contain a small percentage of sedimentary rock fragments of Paleozoic and/or Mesozoic provenance. Rarely, fine-to-medium grained, frosted, rounded quartz grains occur in the samples, perhaps eroded from Mesozoic rocks in the region such as the Junction

Creek Formation, an eolian deposit of Jurassic age. In Figure 4, the composition of the Blanco Basin Formation is compared with younger Tertiary sandstones in the basin.

Those units sampled which are "sands" in geophysical logs are arkosic, coarse, pebbly sandstones and conglomerates containing granitic pebbles. The log characteristics of these bodies are variable, but individual sand bodies tend to be cylinder shaped (terminology of Rider, 1986) with lesser occurrence of bell and funnel shapes. Contacts against surrounding mudstones range from abrupt to gradational.

Blanco Basin mudstones are generally reddish brown (Hue 10R, saturation 4 to 6, value 3 to 4) but may vary to red, green, gray, maroon, and purple. Often a single cutting chip may display mottling of two or more of these colors suggesting that coloration may be dependent upon diagenesis. Organic matter is sparse in the mudstones, perhaps due to oxidizing conditions in their alluvial environment of deposition; therefore they have no real potential for generating hydrocarbons. The mudstones are barren of fossils and pollen, and thus the exact age of the formation is unknown and has been the subject of some controversy.

Justification for age and name: The formation here termed Blanco Basin Formation in the western part of the the Alamosa Basin has been considered to be Eocene in age by other workers based on its color, degree of

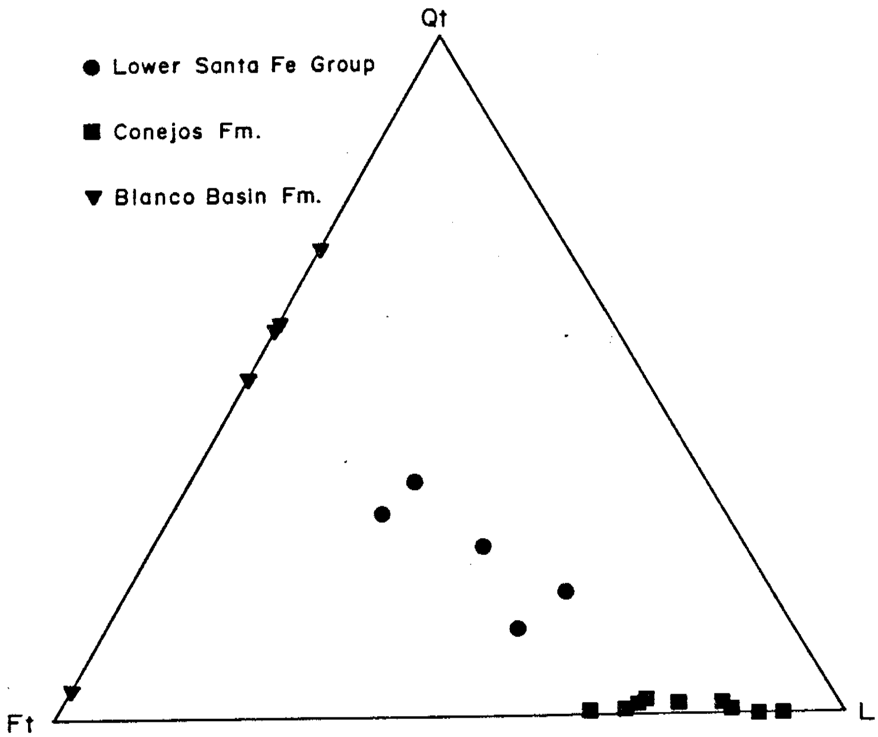


Figure 4: Ternary diagram of sandstone compositions from subsurface units in the Alamosa Basin. Qt = total quartz, including polycrystalline grains + quartzite + chert; Ft = total feldspar; L = sedimentary + volcanic + metamorphic lithic grains. Each symbol represents at least 500 points counted in a single sample. See Appendix 3 for data tables and sample locations.

consolidation and cementation, and depositional facies characteristics. Tweto (1979) correlated it with the "Eocene Echo Park Alluvium" (Echo Park Formation of Epis and Chapin, 1974). Covarrubias (1988) termed the formation "Eocene red beds". Baltz (1965) believed the formation to be similar to the Blanco Basin Formation of Cross and Larsen (1935; Larsen and Cross, 1956) although he did not specifically assign that name. Huntley (1979) and Burroughs (1981) applied the name Vallejo Formation due to the apparent similarity of these beds to the "Eocene... fluvial red-beds occurring along the west flank of the Culebra Range" described by Upson (1941). The Culebra Range is part of the Sangre de Cristo Range southeast of the study area. Petrologic characteristics of the Vallejo Formation at its type locality are more typical of upper Tertiary rocks, which casts doubt that it is older than Miocene (Brister, unpublished data, 1989). Regardless of the name chosen, both Huntley and Burroughs believed their "Vallejo" beds in the subsurface to be pre-Oligocene.

The best evidence for the identity of the redbeds in the Monte Vista graben comes from recent drilling in the San Juan sag (Gries, 1985b) west of the San Luis Basin (Fig. 5). The San Juan sag is separated from the Monte Vista graben by a basement high called "Del Norte high" by Gries (1989). As seen in Figure 5, the redbeds of the Monte Vista graben can be correlated across the Del Norte high, into the San Juan sag, and eventually to outcrops

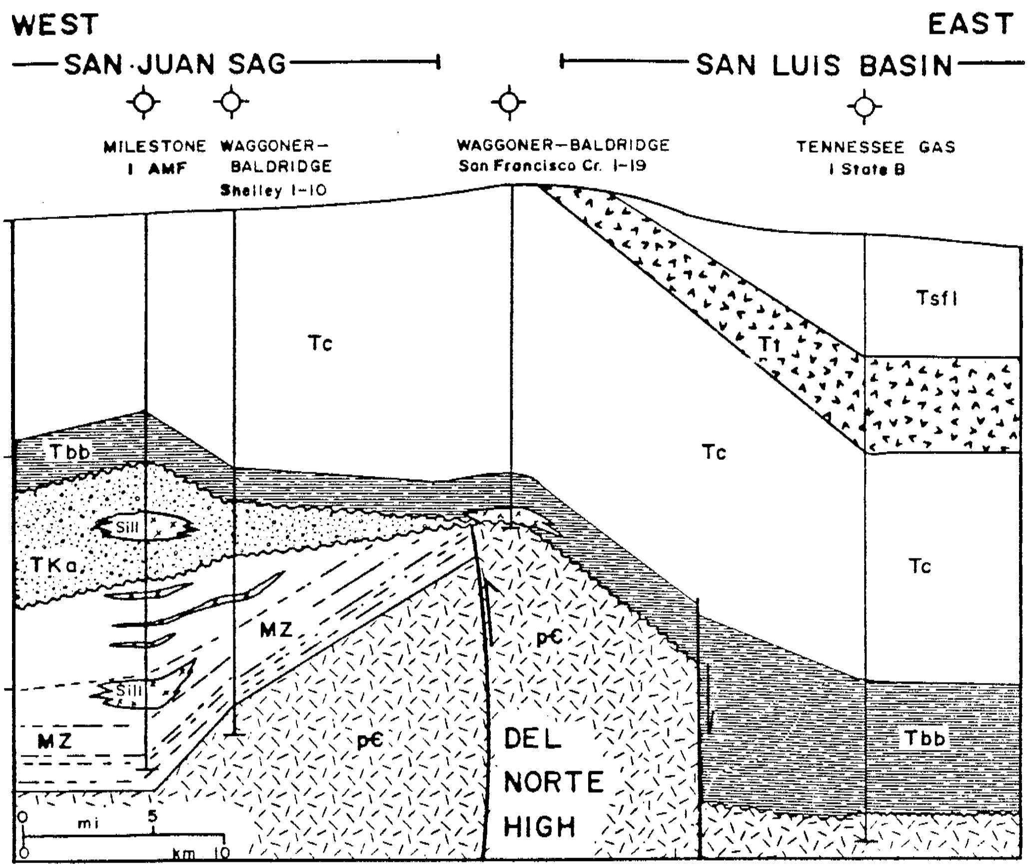


Figure 5: Generalized west-east cross-section between the San Juan sag and San Luis Basin in the general vicinity of Del Norte, Colorado. Figure modified from Gries (1989). MZ = Mesozoic sedimentary formations; TKa = Animas Formation; Tbb = Blanco Basin Formation; Tc = Conejos Formation; Tt = ash-flow tuffs; Tsfl = lower Santa Fe Group.

some 45km to the west, along the western flank of the San Juan Mountains. Their age in the San Juan sag is generally believed to be Eocene because, like the Blanco Basin Formation to the west, they are bracketed by unconformable contact with the Paleocene Animas Formation below and the Oligocene Conejos Formation above, and are considered lateral equivalents of part of the lower Eocene San Jose Formation (Dunn, 1964; Lucas, 1984; Smith and others, 1985; Brister, 1989a). The petrologic characteristics of the redbeds encountered in the Monte Vista graben are similar to those of the Blanco Basin Formation in general and are easily accomodated by the petrologic variability between, and within, Blanco Basin outcrops (see Part 1).

It may be argued that the term "Blanco Basin Formation" may not be the most appropriate name for this formation because the name should be restricted to deposits in the San Juan sag which by definition lies west of, and adjacent to, the San Luis Basin (Kelley, 1955; Gries, 1985b, 1989). The history of the Monte Vista graben was somewhat different from that of the San Juan sag, although both basins received Eocene sediments. However, as seen in Figure 5, the two basins obviously were connected over parts of the Del Norte high. Creating a new name for the formation in the Monte Vista graben would be unsuitable because there are no surface exposures from which to measure a type section, and the well data that exists is too poor in quality and quantity to be considered for the same purpose. Therefore, there is no better alternative at present than to use the name "Blanco Basin Formation" for these redbeds.

Occurrence: The Blanco Basin Formation has been drilled in six of the wells shown in Figure 3. This formation is thicker in the subsurface beneath the eastern edge of the San Juan volcanic field than anywhere yet described. The thickest sections penetrated by drilling were 696m in the Triton/Weco/UPRC 21-B Hellgate well, and 643m in the Tennessee Gas Transmission 1-State B well. These sections are far thicker than the typical thickness of the Blanco Basin, which is about 175m. A possible explanation for the great thickness in these wells is that they occur adjacent to a major Laramide basin-bounding fault zone separating the Laramide Monte Vista basin from the Del Norte high (Fig. 5).

Wells drilled west of this fault zone on the Del Norte high contain condensed sections of the Blanco Basin Formation. They are the Waggoner-Baldridge San Francisco Creek 1-19 well with 159m, and the Heartland #1 La Escondido Uno well with only 49m. The Amerada F-1 State well in the vicinity of the Alamosa horst drilled 115m and is the easternmost known occurrence of Blanco Basin equivalent rocks. The Tucker #1 Thomas well bottomed within the Blanco Basin Formation, drilling only 34 meters as estimated from a description by Powell (1958).

Conejos Formation (Tc)

The Conejos Formation is a series of intermediate-composition volcaniclastic rocks and lava flows which were derived from volcanoes active in the San Juan volcanic field from 35-30 Ma. (Lipman and others, 1970). The Conejos volcanic rocks are high-K, subalkalic, and commonly range from andesite to quartz latite (silicic dacite) in composition (Lipman, 1989). Lithologic units in the formation vary depending upon distance from vents and/or periodic extrusive activity. These include volcanic breccias of both "hot" and "cold" origin and emplacement (these range from mono- to heterolithologic and include, but are not limited to, avalanche and debris-flow deposits), lava flows, autobrecciated flows, stream-laid conglomerate and sandstone, and organic-rich lacustrine claystone. Ash-flow tuffs are rare (Lipman, 1975), but some of the volcaniclastic deposits are tuffaceous, containing glass shards and rare reworked welded tuff fragments. The above description applies well to the package of rocks marked Conejos Formation on Figure 2. As seen in Figure 4, Conejos sandstones from wells in the Alamosa Basin are lithic-rich; this lithic component is generally 100% intermediate-composition volcanic rock fragments.

Only one Conejos vent has been demonstrated to occur in the study area: that of the Summer Coon volcano (Lipman, 1968; Noblett and Loeffler, 1987) located on the western edge of the basin north of the town of Del Norte. Other sources for Conejos deposits in the Alamosa Basin are located to the southwest, where vents have been documented in the Platoro, Colorado, area (Lipman, 1975), and possibly the south, from vents in the San Luis Hills (Burroughs, 1971, 1972, 1981; Thompson and Machette, 1989). The vents responsible for the Bonanza Tuff and related andesitic breccias (Steven and Lipman, 1976) comprise a possible northern source for Conejos-equivalent volcaniclastic detritus.

The Conejos units present in the Alamosa Basin were probably deposited on the distal fringes of vent-complexes. In general, those wells along the western side of the Alamosa Basin have a high percentage of flows and coarse volcaniclastic rocks, but this percentage decreases eastward in favor of finer grained deposits. The Conejos Formation also decreases in thickness eastward to a zero edge over the central part of the basin. The thickest section drilled in the study area was 2300m in the Triton/WECO/UPRC 21-B Hellgate well, which is situated on the northern flank of the Summer Coon volcano. Most other wells drilled in the western half of the Alamosa Basin have penetrated 1.3-1.5 km of the Conejos Formation. The easternmost occurrence of the Conejos Formation is in the Amerada F-1 State well which penetrated only 400m.

Ash-Flow Tuffs (Tt)

Perhaps the most significant new information reported in this paper concerns the distribution of a package of interbedded ash-flow tuffs and tuffaceous clastic rocks marked Tt on figures 2 and 5. This package is important because it: 1) occurs throughout the basin; 2) separates Rio Grande rift-related deposits above it from pre-rift formations below it; 3) has been radiometrically dated (in the San Juan Mountains) and has been demonstrated to represent a short interval of time; 4) shows distinctive (although non-unique), identifiable characteristics on borehole geophysical logs and reflection seismic lines. These characteristics used in conjunction with petrologic examination allow the utilization of the package as a time marker in the stratigraphic sequence.

The ash-flow tuffs in this sequence are part of a series of volcanic rocks, 26-30 Ma (Steven and Lipman, 1976), originating in the eastern San Juan volcanic field. Only the most voluminous flows made their way to the Alamosa Basin area, perhaps finding few obstacles in their way as they traveled down the slopes of the volcanic field to lower ground. The key to their identity are outcrops in the eastern foothills of the San Juan Mountains where the tuffs dip at angles of less than 10° into the basin. The 29.5-28.4 Ma Treasure Mountain Tuff (Lipman and Steven, 1970; Lipman, 1989), erupted from the southeastern San Juan caldera complex and the 28.4 Ma Masonic Park Tuff (Lipman and others, 1970; Steven and others, 1974; Lipman, 1989) erupted from the Mount Hope caldera contributed the majority of the material to the tuff package in the southern part of the Alamosa Basin. Likewise, the 27.75 Ma Fish Canyon and 27.35 Ma Carpenter Ridge tuffs (Olson and others, 1968; Lipman, 1989) from the central caldera cluster dominate the tuff sequence to the north.

Identification: The greatest problem in extrapolating the ash-flow tuffs of the San Juan volcanic field into the subsurface of the Alamosa Basin, and probably why it has not been attempted in any detail before, is that they are not easily identified in the available well cuttings. More than simple binocular microscopic examination of cuttings is required for the tuffs to be distinguished from lava flows of similar composition. The cuttings, usually on the order of a few millimeters across, are often too small for megascopic examination for such features as pumice and welding textures that are available for identifying ash-flow tuffs in outcrop. A lithic- and crystal-rich welded tuff, ground up to sand size by a drill bit, may be mistaken for any number of volcaniclastic deposits.

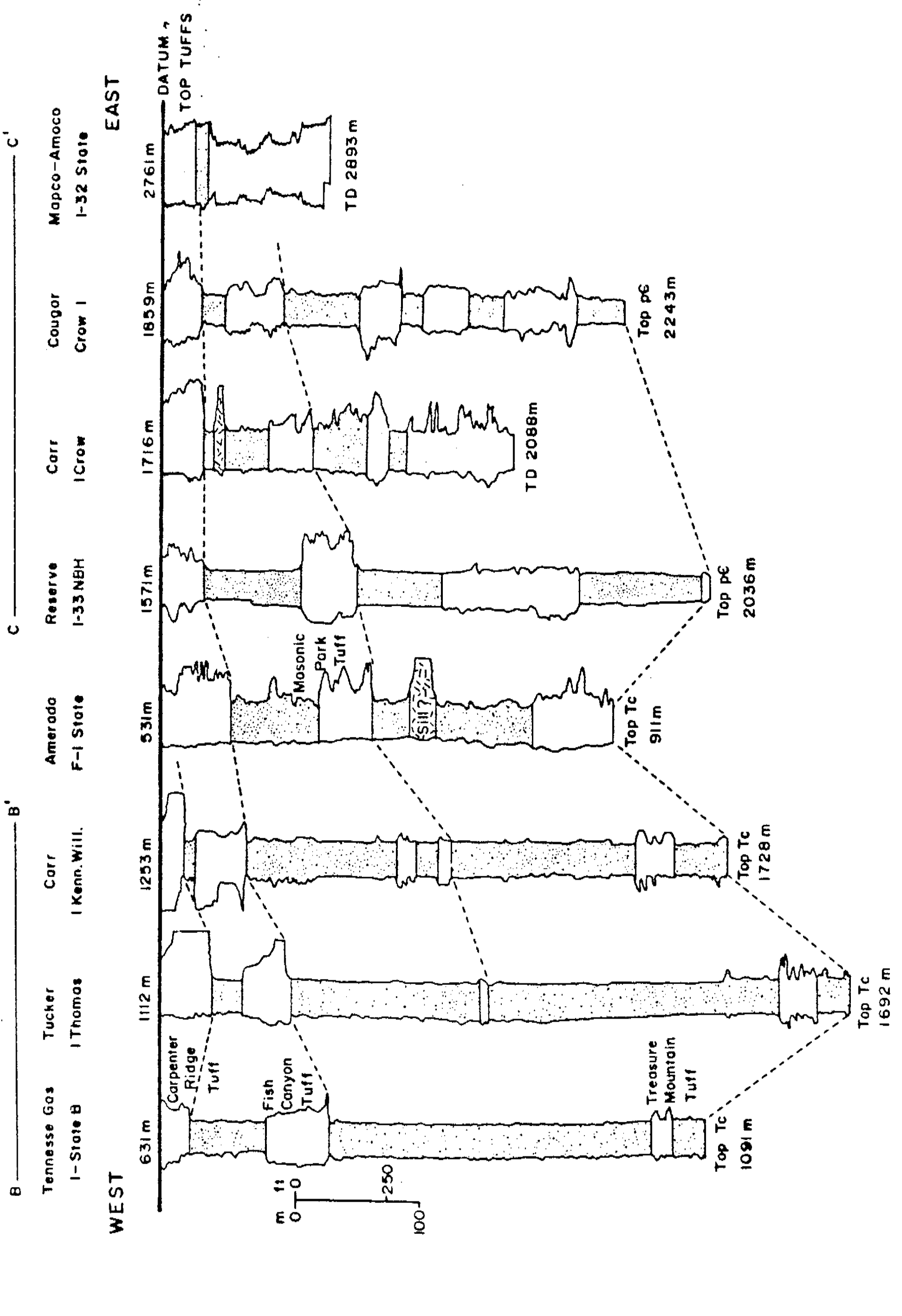
Contamination of samples by caving of the borehole during drilling is a problem when studying cuttings of ash-flow tuffs. The units directly above the tuff package in the basin often contain detritus from a variety of sources, both volcanic and nonvolcanic. When cavings make up a majority of a sample, and the contaminating material is reworked tuffaceous material, then it may be impossible to obtain a representative sample of the ash-flow tuff unit desired.

Similarly, when radiometrically dating a sample, if all contaminating material is not picked out of a sample prior to mineral separation and age dating, results will yield false ages. An example is an Eocene age obtained from a "flow" in the Reserve 1-33 NBH well reported in Gries (1985a). In this case, Precambrian detritus in sandstones above the dated unit probably contaminated the dated cuttings, causing an older age to be determined. No Eocene volcanism has been documented for the surrounding region, the Eocene being a period of volcanic quiescence. The dated interval (5515-57') is reinterpreted as an ash-flow tuff within the late Oligocene tuff package.

The following criteria were found to be useful in identifying welded ash-flow tuffs. 1) They have high resistivity log response, usually ranging from 20-100 ohmms. 2) The cuttings may resemble chert but contain phenocrysts. 3) Thin sections of the sample show distinctive welded shard shapes and possibly pumice. Commonly the uppermost samples of a unit, generally less densely welded, contain pumice fragments and perlite. Unfortunately, densely welded and devitrified and/or altered tuffs may completely lack evidence of shards or pumice. When these conditions are encountered exclusively, tuff units may not be distinguishable from lava flows.

Figure 6: Photomicrograph of welded ash-flow tuff (Carpenter Ridge Tuff) from cutting chip. Sample from 651m depth (1688m above sea level) in Tennessee Gas 1 State B well. Frame width approximately 1 mm.

Figure 7: Well log comparison of Oligocene ash-flow tuff package in Alamosa Basin illustrating tentative correlations; drillholes indicated are on Figure 3. Log curves are spontaneous potential (left) and resistivity (right); exception is Mapco-Amoco 1-32 State well (gamma ray on left; density on right). Datum is top of the ash-flow tuffs/base of Santa Fe Group (depth of datum listed above heavy line). Unit underlying tuffs and depth of contact indicated at bottom. A similar package of tuffs to that in the Amerada F-1 State well is present in the Energy Service #1 Alamosa Geothermal well but electric logs are not available. Stippled areas are unwelded tuffs and tuffaceous sediments; unstippled areas are welded units.


B
C
B'
C'
WEST
EAST
Tennesse Gas
I-State B
Tucker
I Thomas
Carr
I Kenn. Will.
Amerada
F-I State
Reserve
I-33 NBH
Carr
I Crow
Cougar
Crow I
Mapco-Amoco
I-32 State
631 m
1112 m
1253 m
531m
1571m
1716 m
1859 m
2761m
DATUM - TOP TUFFS
Carpenter Ridge Tuff
Fish Canyon Tuff
Treasure Mountain Tuff
Mosonic Park Tuff
Sill?
Top Tc
1091 m
Top Tc
1692 m
Top Tc
1728 m
Top Tc
911 m
Top p€
2036 m
TD 2088m
Top p€
2243 m
TD 2893 m
m ft
0 0
250
100

Correlation: Figure 7 is a cross-section constructed from borehole geophysical logs drawn such that the datum is the top of the tuff package. In each well shown, there are no lava flows or welded tuffs above this horizon. The figure illustrates which units have been positively identified as ash-flow tuffs using criteria outlined above. Tentative correlations have been drawn between the logs based primarily on log response rather than petrographic criteria. It is assumed that any given ash-flow tuff will have a similar log response between two wells over a relatively short distance, thus pattern recognition of log curves was helpful in correlation. Resistivity curve profiles for the tuff units may mimic welding profiles.

Petrographic criteria was considered less significant in correlation than shape of log curves because of the variability of samples, high degree of welding and devitrification of some samples, and the scarcity of high quality samples. Petrographically, samples within a single tuff unit may vary greatly in color, degree of welding, composition and crystal:lithic:vitric ratios. Such variation is common within single ash-flow tuff sheets, and these criteria may not be diagnostic of a given tuff over a long distance.

Provided the tentative correlations in Figure 7 are correct, the cross-section displays some interesting characteristics of the tuff package. First, it can be observed that the westernmost (which are also the northernmost) wells generally lack significant Masonic Park Tuff and have a condensed section of Treasure Mountain Tuff compared to those wells further south and east. This may be due to the fact that these northern wells are near the distal edge of the Masonic Park and Treasure Mountain tuffs which were erupted from the Mt. Hope and southeastern caldera complex (see Fig. 1). It may also be attributed to the nearby Summer Coon volcano (Fig.3) of Conejos age which might still have been topographically high enough to stand in the way of the ash flows, creating a shadow. For the same reasons, wells to the southeast generally lack a recognizable section of Carpenter Ridge Tuff.

Prior to this study, it was believed that the late Oligocene San Juan tuffs pinched out in the Monte Vista graben (Tweto, 1979) or over the Alamosa horst (Burroughs, 1981). The explanation for such pinching-out was that the Alamosa horst prevented tuffs from reaching the eastern half of the basin. Figure 7 shows that if a topographically high area existed, it provided no impediment to ash flows moving across it. In fact, it is likely that the ash flows may have reached eastward beyond the present-day Sangre de Cristo Range, which in all likelihood did not exist at the time (Burroughs, 1981; Scott, 1975). Also, there is no apparent thinning of ash-flow tuffs in wells (Amerada F-1 State, and Energy Service Geothermal) over the horst area. There is, however, overall thinning of the inter-tuff clastic deposits eastward in the wells, suggesting increasing distance from the major source of these sediments and/or a positive paleotopographic gradient to the east. The sum effect of this sedimentation may have been to blanket and subdue existing topography. The intertuff sedimentary units are unique because they are not common near the source calderas. These sediments probably represent reworking of unwelded tuffs deposited in the time periods between emplacement of the welded tuff units and\or the unwelded tops of the tuff units. The geophysical log character of the sedimentary units is that of fine-grained clastic rocks. The top of the tuffs in the subsurface is an east-dipping surface today, due to post-emplacement tilting.

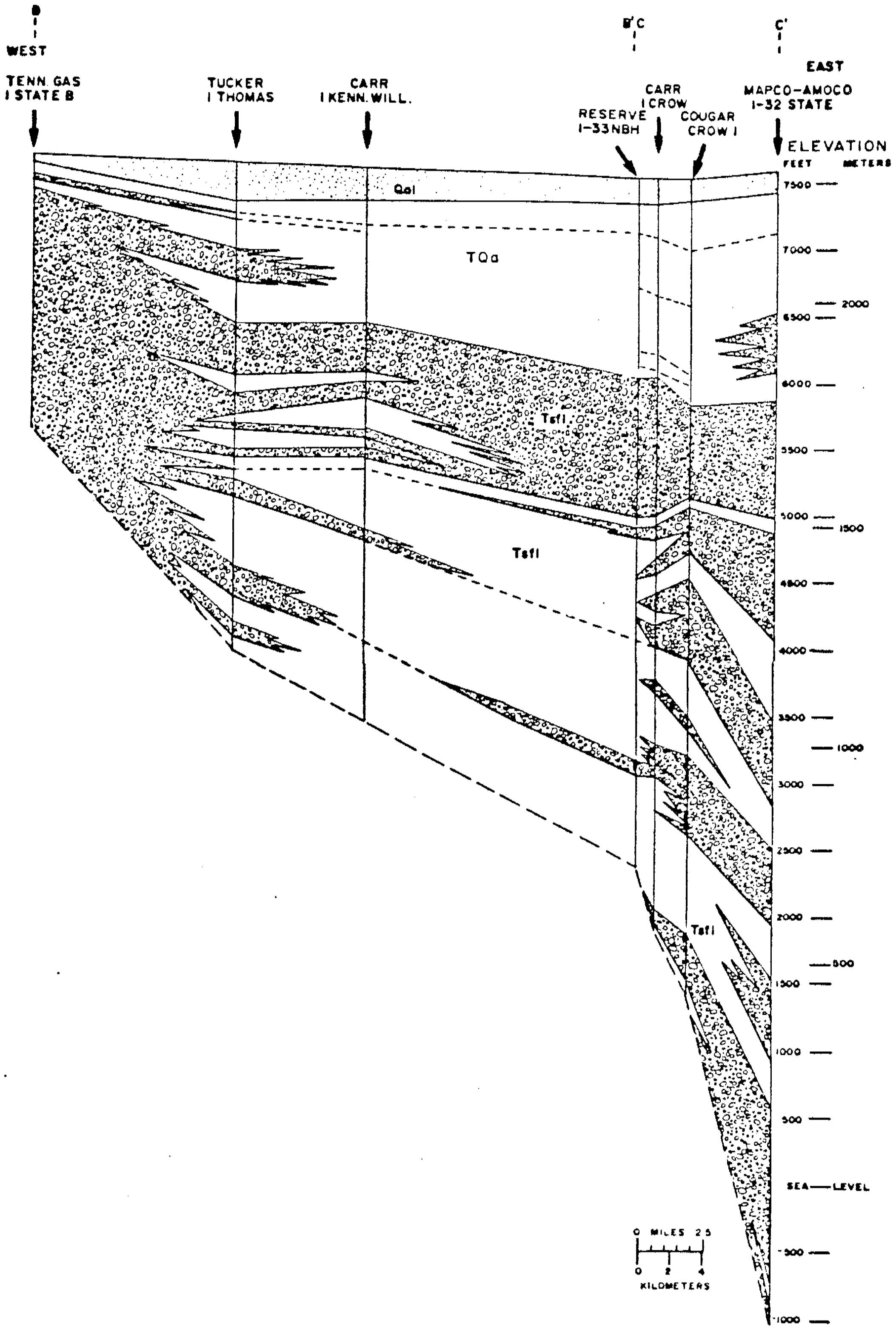
Clearly, further petrographic work and age dating should be pursued to confirm the tentative correlations shown in Figure 7. Considering the condition of existing borehole samples, any future drilling efforts which penetrate the ash-flow tuff horizons should make special preparations to either collect as large a volume of drill cuttings as possible, or ideally, to core the intervals.

Santa Fe Group (Tsfl and Ta)

The Santa Fe Group includes all Cenozoic sediments above the late Oligocene tuffs (except Holocene alluvium) and can be roughly divided into two units, the lower Santa Fe Group and the upper Santa Fe Group, based upon lithologic criteria. The lower Santa Fe Group is ubiquitous in the subsurface of the basin and represents large-scale sedimentary response to half-graben development from late Oligocene to Pliocene. The upper Santa Fe Group, named the Alamosa Formation, represents lacustrine and fluvial sedimentation ranging in age from Pliocene to Quaternary. Cross-section B-B' (Fig. 8), summarized from well data, illustrates the stratigraphy of the Santa Fe Group in the Alamosa Basin.

Lower Santa Fe Group: The lower Santa Fe Group in the Alamosa Basin has historically been called the Santa Fe Formation (Siebenthal, 1910b; Powell, 1958). However, beginning with Spiegel and Baldwin (1963) modern usage of "Santa Fe" is as a group term "that includes all the synrift basin fill, both volcanic and sedimentary, ranging in age from late Oligocene to Quaternary, but excluding deposits that postdate entrenchment of the Rio Grande in middle Pleistocene time" (Chapin, 1988, p.169). Burroughs (1981) has suggested that the lower Santa Fe Group may be divided into formations based on composition and provenance. No attempt has been made in this study to subdivide the lower Santa Fe Group because of lack of sufficient subsurface data. The age of lower Santa Fe Group sediments in the Alamosa Basin is poorly constrained, but ranges from about 26 Ma to about 4.5 Ma. The older age is approximately the end of ash-flow volcanism in the eastern San Juan Mountains (Steven and others, 1967; Lipman, 1989). The younger age marks the beginning of

Figure 8: Combined cross-sections B-B' and C-C' illustrating facies characteristics of Santa Fe Group and Quaternary deposits (simplified). Light stippled pattern is late Pleistocene and Holocene alluvium; coarse pattern indicates units with abundant coarse deposits, probably representing proximal to medial alluvial fan facies. Unpatterned areas in lower Santa Fe Group are dominated by fine-grained deposits of distal alluvial fan to mudflat facies. Fine-grained deposits in Alamosa Formation (upper Santa Fe Group) are demonstrated lacustrine facies. Base of section is top of ash-flow tuff package. Depositional thinning of the cross-section interval over the Alamosa horst is less pronounced northward from the Amerada F-1 State well; therefore, the cross-sections are arranged to show probable correlation between units in wells from west to east. Dashed lines are thin, persistent sandstone beds. Tsfl = lower Santa Fe Group; TQa = Alamosa Formation (upper Santa Fe Group). Note the vertical scale is elevation relative to sea level.


B
WEST
TENN. GAS
1 STATE B
TUCKER
1 THOMAS
CARR
1 KENN. WILL.
B'C
C'
EAST
CARR
1 CROW
RESERVE
1-33NBH
COUGAR
CROW 1
MAPCO-AMOCO
1-32 STATE
ELEVATION
FEET
METERS
Qal
TQa
Tsfl
Tsfl
Tsfl
7500
7000
6500
2000
6000
5500
5000
1500
4500
4000
3500
1000
3000
2500
2000
500
1500
1000
500
SEA — LEVEL
-500
-1000
0 MILES 2.5
0 2 4
KILOMETERS

tholeiitic basalt volcanism and construction of the Taos Plateau volcanic field which blocked surface drainage in the southern San Luis Basin (Lipman and Mehnert, 1979) and was responsible for the widespread lacustrine system of the Alamosa Formation.

The grain size and composition of the lower Santa Fe Group varies depending primarily upon proximity to sources and character of dispersal systems. Well samples from the study area are of claystone, sandstone and conglomerate. The claystone and sandy mudstone in the lower Santa Fe Group are compact but soft, nonfissile, and may be micaceous. They deepen in color with increasing depth in the basin, but are always variegated. Typical colors include tan, pink, buff, orange, brick red, light olive, and light gray to black. Most of these colors are indicative of an oxidizing environment of deposition. A coal seam was penetrated in fine-grained units in the Mapco-Amoco #1-32 State well at 1774m depth (see Appendix 3). There are no known bedded evaporites in the sequence, but scattered selenite crystals occur in the cuttings.

Although organic material occurs in the fine-grained rocks, they did not yield significant pollen, perhaps due to oxidation or to overwashing while processing the cuttings at the drill site. The lowermost Santa Fe beds have been reported to be early Tertiary in age on the basis of pollen analyses (Huntley, 1976; Gries, 1985a). However, the pollen assemblages were sparse, not particularly indicative of any specific Tertiary age, and contained a few specimens of probable Eocene age which may have been reworked. Lithologic and stratigraphic criteria discussed above provide strong evidence that these sediments post-date late Oligocene ash-flow tuff volcanism. A rhyolite sill(?) in the Mapco-Amoco 1-32 State well at the base of the Santa Fe Group but above the Oligocene ash-flow tuff package, yielded a whole-rock K-Ar age of 22.2 Ma (R. Gries, 1984, unpub. data).

Some generalized observations of Santa Fe Group sandstones from the basin indicate that Precambrian detritus tends to increase in abundance eastward in the basin towards the Sangre de Cristo Range. All sandstones examined are lithic-rich with a majority of these fragments being of volcanic origin. Sandstone samples from the deepest part of the Baca graben are tuffaceous, but contain significant amounts of Precambrian material. On a ternary diagram (Fig. 4), these sandstones span the range in composition between samples of the Blanco Basin Formation and the Conejos Formation.

The lower Santa Fe Group sediments indicate provenance from two primary sources. The San Juan volcanic field to the west and northwest provided an influx of intermediate-composition volcanic debris. Such deposits of late Oligocene-Pliocene age derived from the San Juan Mountains are usually referred to as the Los Pinos Formation (Butler, 1946, 1971; Manley, 1981) which Chapin (1988) has included in the Santa Fe Group. Interbedded volcanic flows are rare in the Santa Fe Group of the Alamosa Basin; however, Hinsdale basalts ranging in age from 25.7 to 26.4 Ma are interbedded with these sediments in the San Luis Hills along the southern border of the basin (Thompson and Machette, 1989). In the San Juan volcanic field the Hinsdale basalts range in age from 26 to 5 Ma (Lipman, 1975; 1969; Steven and others, 1974).

The second source was the rising Sangre de Cristo Range to the east which was a source of detritus from Precambrian granitic and metamorphic rocks and Paleozoic limestones and clastic rocks. The Sangre de Cristo Range was at least partially volcanic-covered in the late Oligocene and thus was also a source for some volcanic material.

Another possible source of sediment that has been suggested is stream-flow from the Upper Arkansas graben into the Alamosa Basin (Hanna and Harmon, 1989). A possible connection between the San Luis Basin and Upper Arkansas graben has been postulated due to the presence of the Mio-Pliocene Dry Union Formation (Tweto, 1961) in a narrow graben north of Poncha Pass, Colorado (Van Alstine, 1968, 1970; Knepper and Marrs, 1971, Taylor, 1975). However, neither surface mapping nor gravity surveys indicate significant Dry Union/Santa Fe deposits at Poncha Pass, but instead, demonstrate that a topographic and/or structural barrier existed in the area during the Miocene and Pliocene (Knepper, 1976).

Although outcrops of the lower Santa Fe Group are rare, they do occur in places along the basin margins. In one location along the Sangre de Cristo fault zone, a fault slice of lower Santa Fe Group is exposed at the surface (marked "Urraca outcrop" on Fig.3; for exact location refer to Gries and Vandersluis, 1989, p.35). The outcrop was mistakenly mapped as Vallejo Formation by Johnson (1969). This deposit contains interbedded fluvial conglomerates and pebbly sandstones with beds less than a meter thick. Pebble imbrications suggest a south-southwest stream flow direction which paralleled the Sangre de Cristo fault zone at this location. Current indicators show that the braided stream was draining parallel to the axis of the paleobasin. The rocks are well indurated and reddish brown, probably due to post-depositional cementation and oxidation. Such reddening of Santa Fe Group sediments has been reported elsewhere in the Rio Grande rift by Chapin and Lindley (1986) and has already been noted as common for nearby deep-basin well samples. Composition of the pebbles in the outcrop reflect two provenances. Pebbles from the Sangre de Cristo Range include Precambrian granitic and metamorphic rocks and minor amounts of Paleozoic arkoses, graywackes, siltstones, shales, limestones and cherts. Pebbles derived from the San Juan volcanic field include volcanic rocks of intermediate composition and minor flow-banded rhyolite and ash-flow tuff.

Alamosa Formation: The Alamosa Formation (Siebenthal, 1910a) is a fluvio-lacustrine formation deposited conformably upon the uppermost beds of the lower Santa Fe Group in the Alamosa Basin. The depositional environment of the Alamosa Formation was dominated by reducing lacustrine conditions (Huntley, 1979) as demonstrated by the predominance of gray, black, and green claystones. Well samples often contain fossil debris including ostracods, bones, peat and wood fragments, and mollusc shell fragments. Organic material taints water from some wells and is a source of methane, the discovery of which has helped stimulate intermittent oil and gas wildcat drilling in the basin (Gries, 1985a). Toward the top of the section are persistant, poorly cemented sandstone horizons which can be correlated over broad areas of the basin. These mark the beginning of a return to drier and/or higher energy conditions in the basin. These beds have been extensively drilled in the basin because they are fresh-water bearing and artesian. They are the primary source of ground-water for agriculture in the San Luis Valley.

A recent research effort sampled some 20 meters of surface outcrop of the Alamosa Formation at Hansen's Bluff near the town of Alamosa (Fig.3) and found the beds to be Pleistocene (0.6-0.9Ma) in age (Rogers, 1984). The outcrop contains volcanic ash, a variety of fish, bird, and mammalian bones, and fresh-water molluscs. The great thickness of underlying Alamosa deposits (the formation ranges up to 550 m thick) suggest that the formation probably ranges in age as far back as the Pliocene. The Hansen's Bluff deposits are overlain by Quaternary alluvium and probably predate the capture of drainage in the Alamosa Basin by the Rio Grande in middle to late Pleistocene.

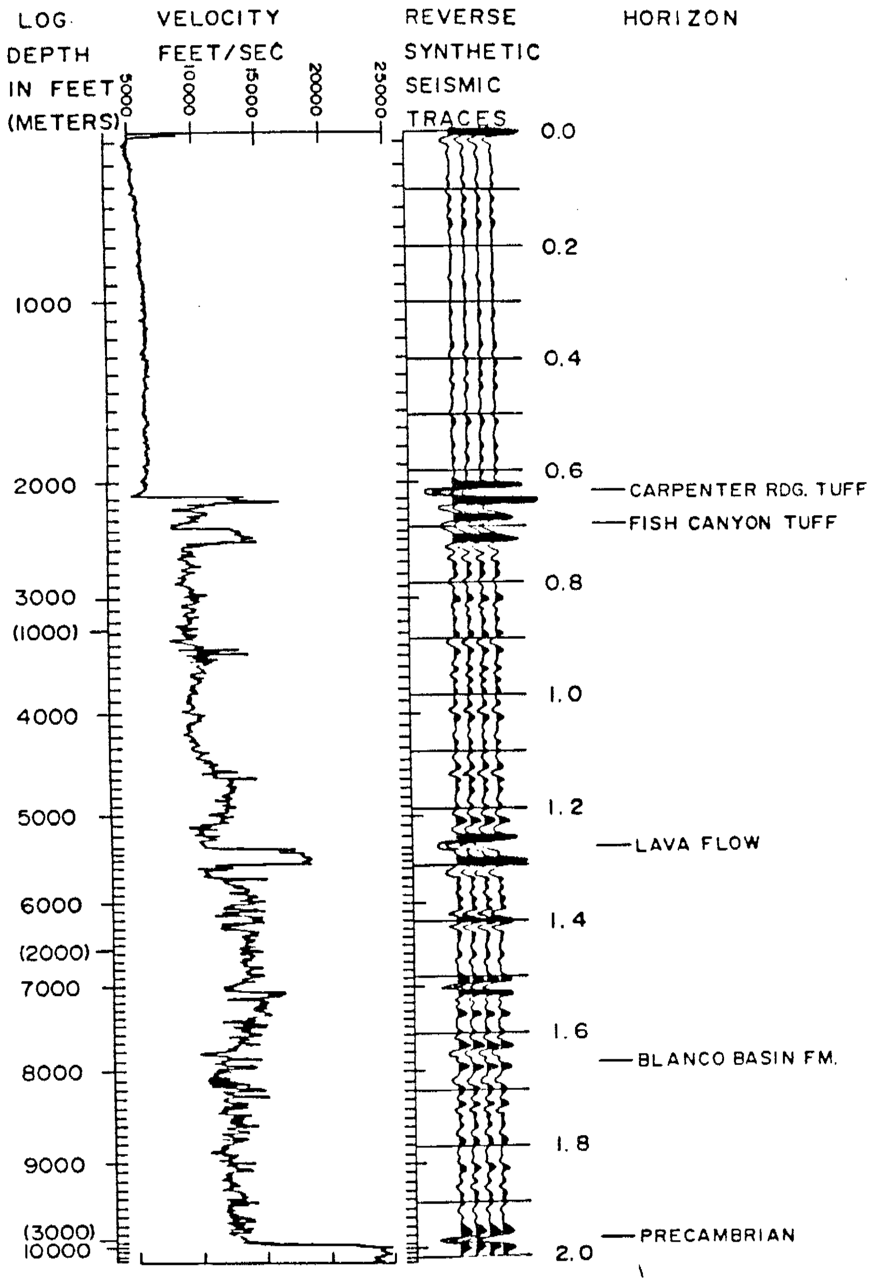
INTERPRETATION OF SEISMIC DATA

Seismic characteristics

Figure 9 is a synthetic seismogram from a well which contains all the stratigraphic units in the basin. The strongest reflectors on the seismogram occur at about 0.6 seconds (two-way travel time). This set of reflectors marks the late Oligocene welded ash-flow tuffs and the base of the Santa Fe Group. This strong reflection package occurs in every seismic line examined in the Alamosa Basin. Because the top of the tuffs is the transition between Rio Grande rift and pre-rift deposits, any faults which offset these reflectors are a result of the rifting events. Faults which offset units below these reflectors, but not the reflectors themselves, are pre-rift in origin. Thus, this reflection package is of major importance in deciphering the tectonic history of the basin.

Another strong reflector on Figure 9 occurs at about 1.25 seconds. This is a local reflector associated with a 75m-thick lava flow within the Conejos Formation. Such reflectors in the Conejos are generally not far-ranging.

Figure 9: Synthetic seismogram from the Tennessee Gas Transmission 1 State B well in the Monte Vista graben. For other synthetic seismograms in the area, see Gries (1985a). Provided to author by R. Randy Ray. Tsfl = lower Santa Fe Group; Tt = ash-flow tuffs; Tc = Conejos Formation; Tbb = Blanco Basin Formation.


LOG DEPTH IN FEET (METERS)
VELOCITY FEET/SEC
REVERSE SYNTHETIC SEISMIC TRACES
HORIZON
5000
10000
15000
20000
25000
1000
2000
3000
(1000)
4000
5000
6000
(2000)
7000
8000
9000
(3000)
10000
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
CARPENTER RDG. TUFF
FISH CANYON TUFF
LAVA FLOW
BLANCO BASIN FM.
PRECAMBRIAN

A weak double reflection occurs at about 1.95 seconds and marks the top of the Precambrian basement. This double reflection is typical of this contact basinwide.

An interpreted seismic line across the Alamosa Basin (Fig. 10) illustrates the seismic characteristics of the lithostratigraphic units present. The top of the late Oligocene tuffs is the strong reflector that is not visibly faulted in the western half of the basin, but is faulted and tilted down to considerable depth in the Baca graben to the east. Well control helps to distinguish this reflector from internal reflectors of the Santa Fe Group in the deeper parts of the Baca graben.

Below the strong tuff reflections, the Conejos and Blanco Basin formations contain reflectors which vary from strong and continuous, to weak and discontinuous. In some cases a weak reflection occurs at the contact between the two formations; however, well control is generally necessary to correctly identify the contact. The Conejos-Blanco Basin package of reflectors thins eastward to zero over the central high of the Alamosa Basin.

Above the strong tuff reflectors is a complex series of reflectors corresponding to the Santa Fe Group. The Alamosa Formation is distinguished by low-amplitude, weak reflectors typical of unconsolidated fine-grained lithologies. The transition to the lower Santa Fe Group is marked by a change to higher amplitude, more continuous reflectors characteristic of interbedded coarse and fine

Figure 10: Seismic line 1, Crosses the Alamosa Basin from west to east (modified from Gries, 1985a; Gries and Brister, 1989). See Figure 3 for location. Vertical scale in two-way travel time; see Figure 2 for approximate depth conversion.

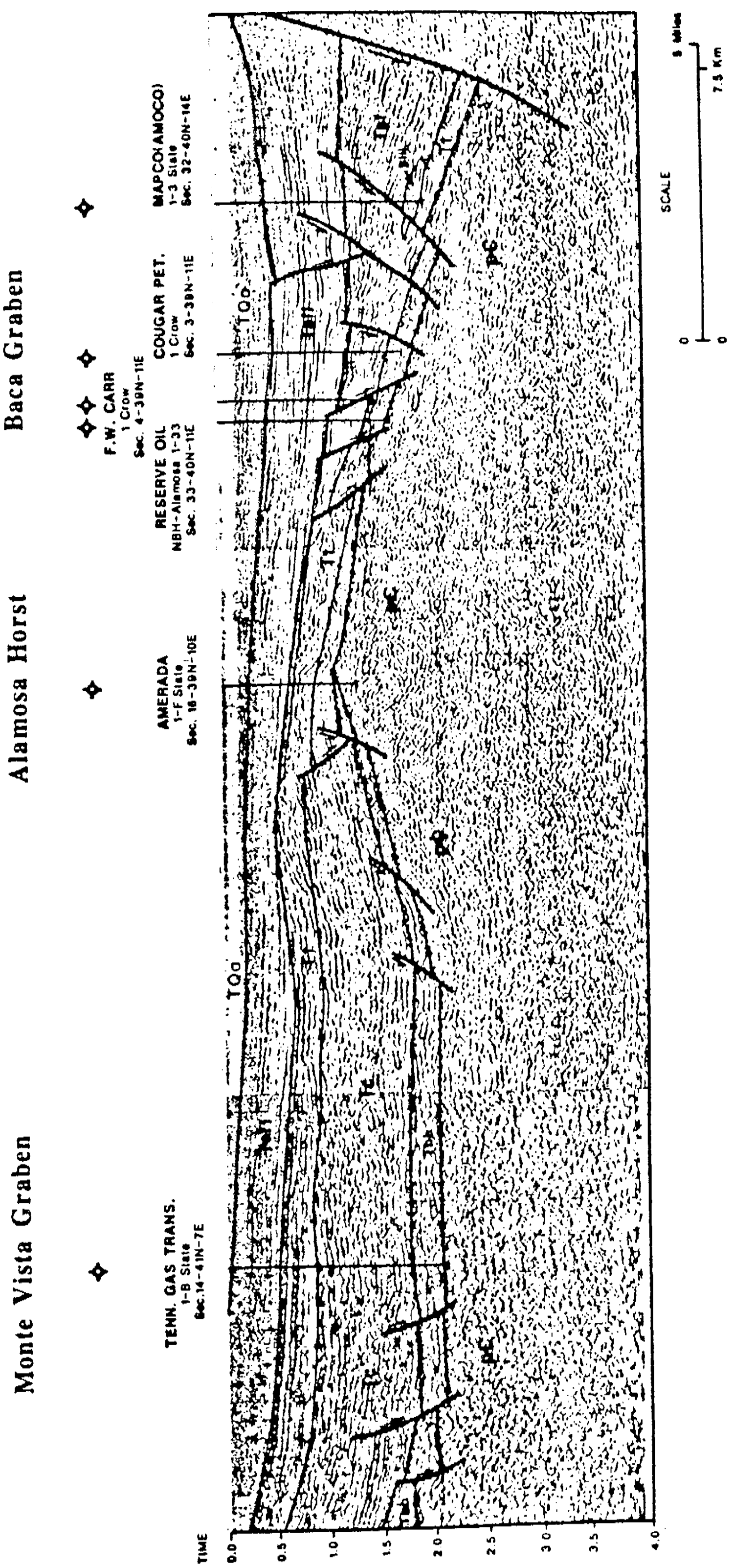
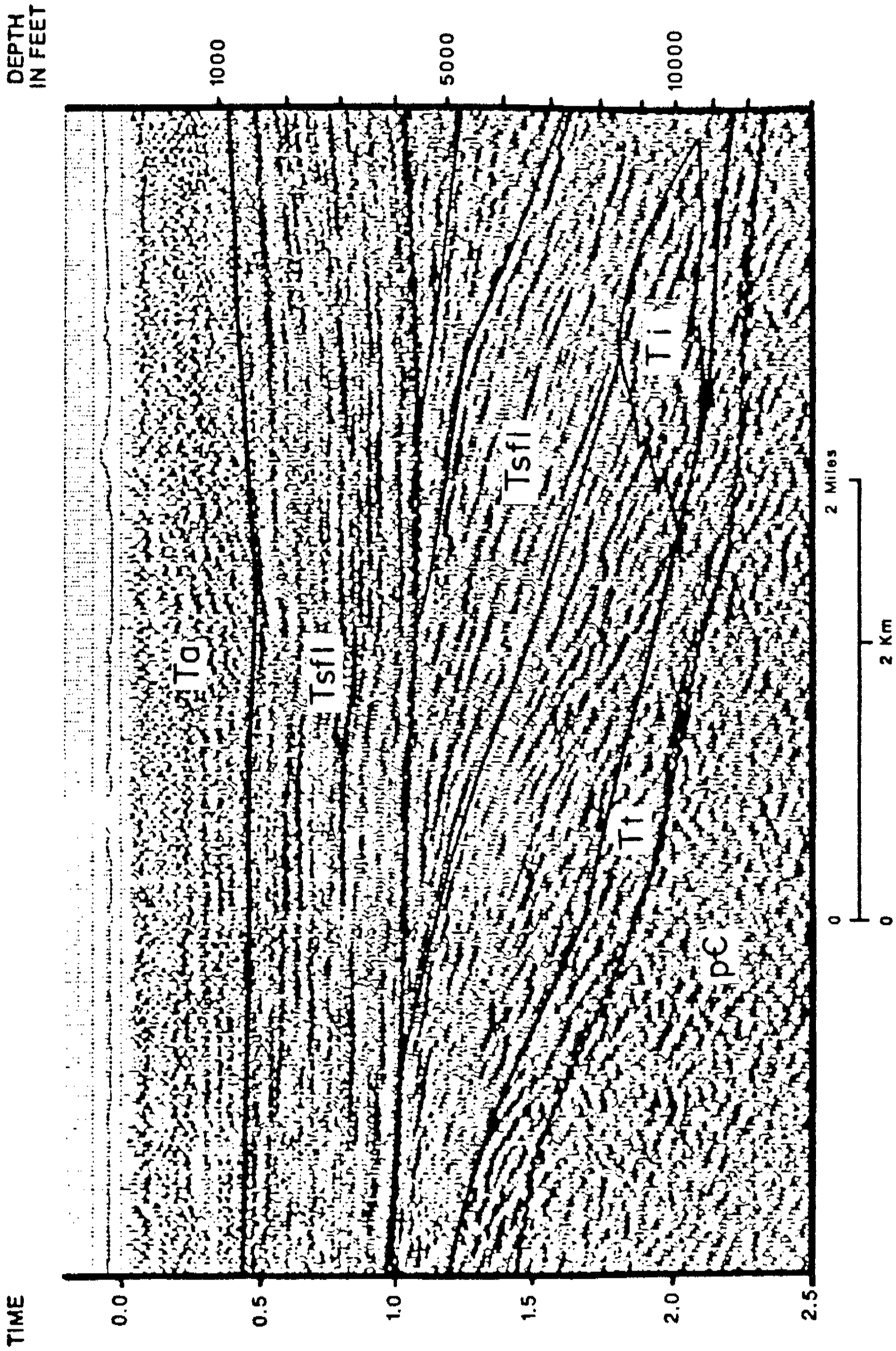

Monte Vista Graben
Alamosa Horst
Baca Graben
TENN. GAS TRANS.
1-B State
Sec.14-41N-7E
AMERADA
1-F State
Sec. 16-39N-10E
RESERVE OIL
NBH-Alamosa 1-33
Sec. 33-40N-11E
F.W. CARR
1 Crow
Sec. 4-39N-11E
COUGAR PET.
1 Crow
Sec. 3-39N-11E
MAPCO(AMOCO)
1-3 State
Sec. 32-40N-14E
TQa
TIME
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
SCALE
0
5 Miles
0
7.5 Km

Figure 11: Seismic line 2, showing angular unconformity within the lower Santa Fe Group (after Gries, 1985a; Gries and Brister, 1989). See Figure 3 for location.

Baca Graben


TIME
0.0
0.5
1.0
1.5
2.0
2.5
DEPTH IN FEET
1000
5000
10000
Ta
Tsfl
Tsfl
Ti
Tt
p€
0
2 Miles
0
2 Km

clastic lithologies. The lower Santa Fe Group is characterized by two seismic packages, best illustrated on Figure 11. The upper package is relatively flat lying and unfaulted, and traceable to some extent across the basin. The lowermost package dips moderately to the east, is highly faulted, and appears limited in extent to the Baca graben. The intervening angular unconformity within the lower Santa Fe Group can be seen on a number of seismic lines from the southern part of the Baca graben, and has some obvious implications for its early tectonic development. Although an increase in bed dip in the Baca graben is suggested in Figure 8 starting at about 1400m elevation, there is not an abrupt change in sample composition to mark this boundary. The mudstones and claystones common to the lower Santa Fe Group do not seem to radically change color across this boundary, although they do become reddened towards the base of the lower package.

Isochron maps

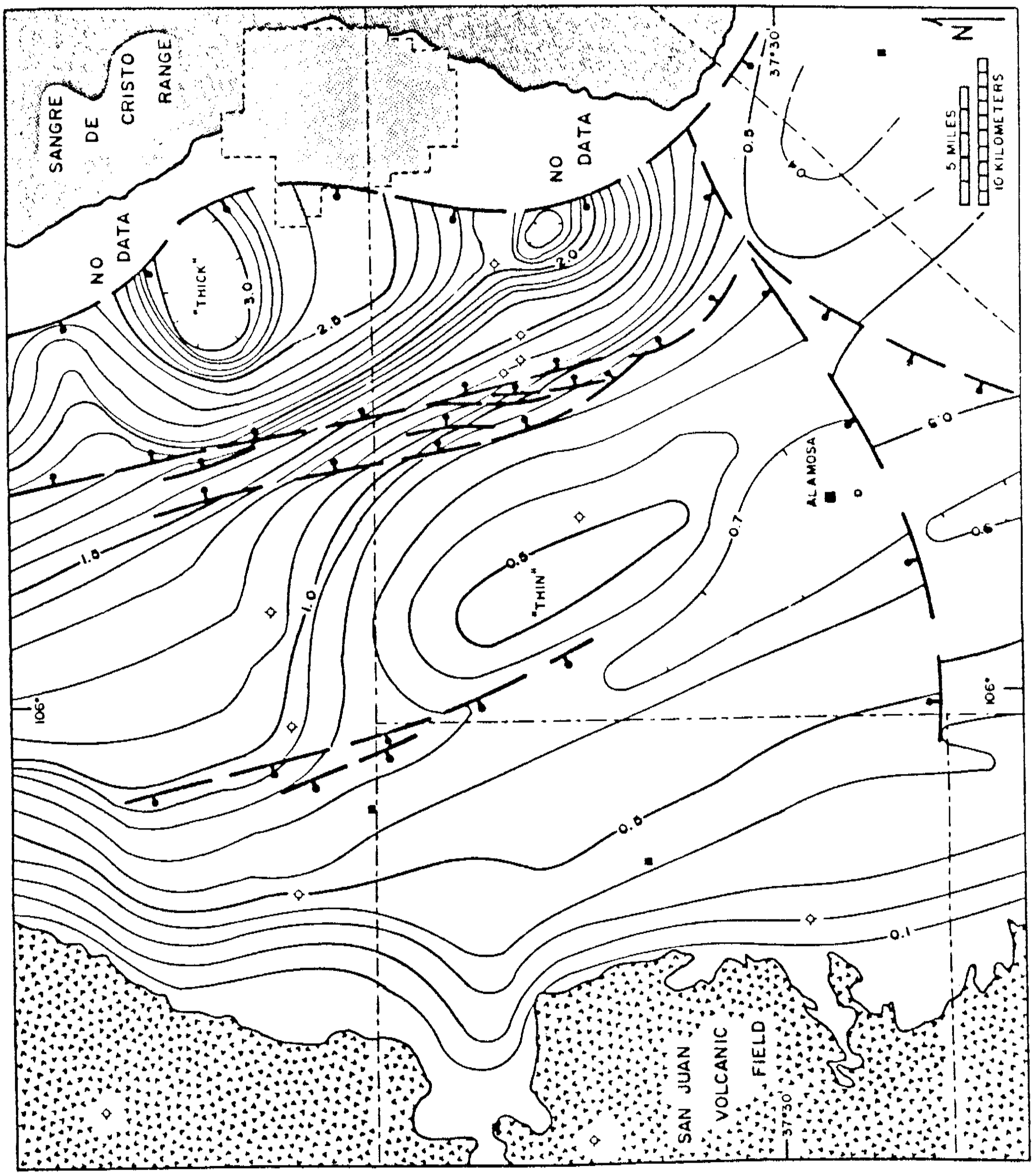
The presence of a recognizable, ubiquitous horizon which essentially separates prerift and synrift rock units in the Alamosa Basin has great implications for reconstructing its tectonic history. Borehole data is too scarce for constructing isopach maps of prerift and synrift Tertiary intervals. However, the top and base of these intervals are readily identified on the 350+ km of seismic lines in the basin. The top of the rift-related interval is simply a horizontal datum at 0 seconds. The base of the rift interval and the top of the pre-rift interval is the uppermost strong reflector of the tuff package. The base of the pre-rift Tertiary interval is the Precambrian double reflection.

Isochron maps made for these intervals from published and unpublished seismic lines are Figures 12 and 13. Published seismic lines used in constructing the isochron maps are indicated on Figure 3. The maps are not intended to show detailed depth and structure of the basin; rather, they illustrate general trends of "thickening" or increasing of the two-way time intervals in the grabens and "thinning" or decreasing of the intervals across the central basement high. No depth conversion is offered because of the scarcity of well control. Faults or fault zones which offset reflectors within the intervals are indicated by dashed lines. These maps compare favorably with gravity studies conducted in the area (Gaca and Karig, 1965; Davis, 1979; Keller and others, 1984).

Rift-basin geometry

From figures 10 through 12, it can be seen that the rift-related architecture of the Alamosa Basin is essentially that of a first-order, east-tilted half graben. Basinwide, prerift lithostratigraphic units have been tilted eastward from their prerift positions; however,

Figure 12: Isochron map: contoured two-way travel time interval between surface datum and top of Oligocene ash-flow tuff reflectors. Fault zones depicted have demonstrated synrift displacement. Contour interval 0.1 seconds.


SANGRE DE CRISTO RANGE
NO DATA
NO DATA
"THICK"
3.0
2.5
2.0
1.5
1.0
"THIN"
0.5
0.7
0.9
0.6
0.5
0.1
ALAMOSA
SAN JUAN VOLCANIC FIELD
37°30'
106°
N
5 MILES
10 KILOMETERS

tilting within the Baca graben is more pronounced than in the Monte Vista graben. The western hinge of the first-order rift graben occurs within the San Juan volcanic field, west of the depositional basin (Lipman, 1975; Phillips, 1985). The western edge of the depositional basin occurs where volcanic units of the San Juan volcanic field dip into the basin beneath the Santa Fe Group. Faulting along this margin is minor but has a distinctive style (Lipman, 1969). Faults generally have only a few meters or tens of meters of normal displacement and fault planes dip steeply to the west. However, due to the eastward dip of the beds, the net displacement of the volcanic rocks over the region is downward to the east.

The eastern boundary of the basin is the Sangre de Cristo fault zone. In plan view, it is concave towards the basin along part of its length. Here it forms a reentrant into the Sangre de Cristo Range; the site of the present Great Sand Dunes National Monument. Further south, it is convex toward the basin, forming the distinct promontory of the Blanca Peak massif. Fault displacement is difficult to assess with any confidence. Based strictly on well control, the thickness of graben fill adjacent to the fault zone is at least 3 km. A seismic line by Stoughton (1977) indicates that the greatest thickness of fill occurs in the Baca graben adjacent to the Sangre de Cristo fault zone near the Great Sand Dunes National Monument. A reasonable estimation of the depth of the basin at this locality is about 5.6 km. When the difference in elevation between the valley floor and the top of the Sangre de Cristo Range immediately adjacent to the dunes area (about 2 km) is added, the total vertical displacement of basement at the Sangre de Cristo fault zone is about 7.6 km. Basement relief has been estimated from gravity studies to be 7 km (Davis and Keller, 1978), approximating the estimate from seismic data in this paper. The fault plane dips steeply (>45^{o}) to the west and remains steeply dipping to the depths of resolution on seismic lines.

The southern boundary of the Alamosa Basin is a fault or fault zone which is entirely in the subsurface south of the town of Alamosa. It separates the Alamosa Basin from the San Luis Hills, an intrabasin horst block which brings Oligocene volcanic rocks to the surface. The Baca graben appears to end abruptly at this zone, accounting for the great increase in isochron gradient at that location in Figure 12. South of this zone, the eastern graben is deflected some 20 km eastward to form the Culebra reentrant (Fig. 1) south of the Blanca massif. The San Luis Hills horst block (considering its subsurface extent rather than its surface expression) occurs along trend of the Alamosa horst. The Conejos-like volcanic rocks that occur in the northeastern San Luis Hills must thin northward because they appear to be lacking in the eastern part of the Alamosa Basin.

The Alamosa Basin is divided into the two second-order half grabens by the central basement high, the Alamosa horst, which is not a true horst in the common sense. This north-trending feature is marked by high gravity and conspicuous thinning of synrift sediments. The eastern side of the "horst" is formed by a combination of strong eastward tilt of the basement and stepping down of the basement by numerous normal faults. In a sense, the Alamosa horst is simply the western edge of an east-tilted basement-cored crustal block. The western margin of the "horst" is a hinge zone marked by monoclinal folding and less pronounced normal faulting of the ash-flow tuff package (Figs. 2 and 10).

The high gravity gradient on the western side of the Alamosa horst seen in gravity maps (e.g. Keller and others, 1984) is not the result of major rift-related block faulting as suggested by Tweto (1979) because faults along its western edge (Figure 12) show relatively minor displacement of syn-rift units. Instead, the gravity gradient is attributable to pre-rift structural relief which developed along the eastern margin of the Paleogene Monte Vista basin.

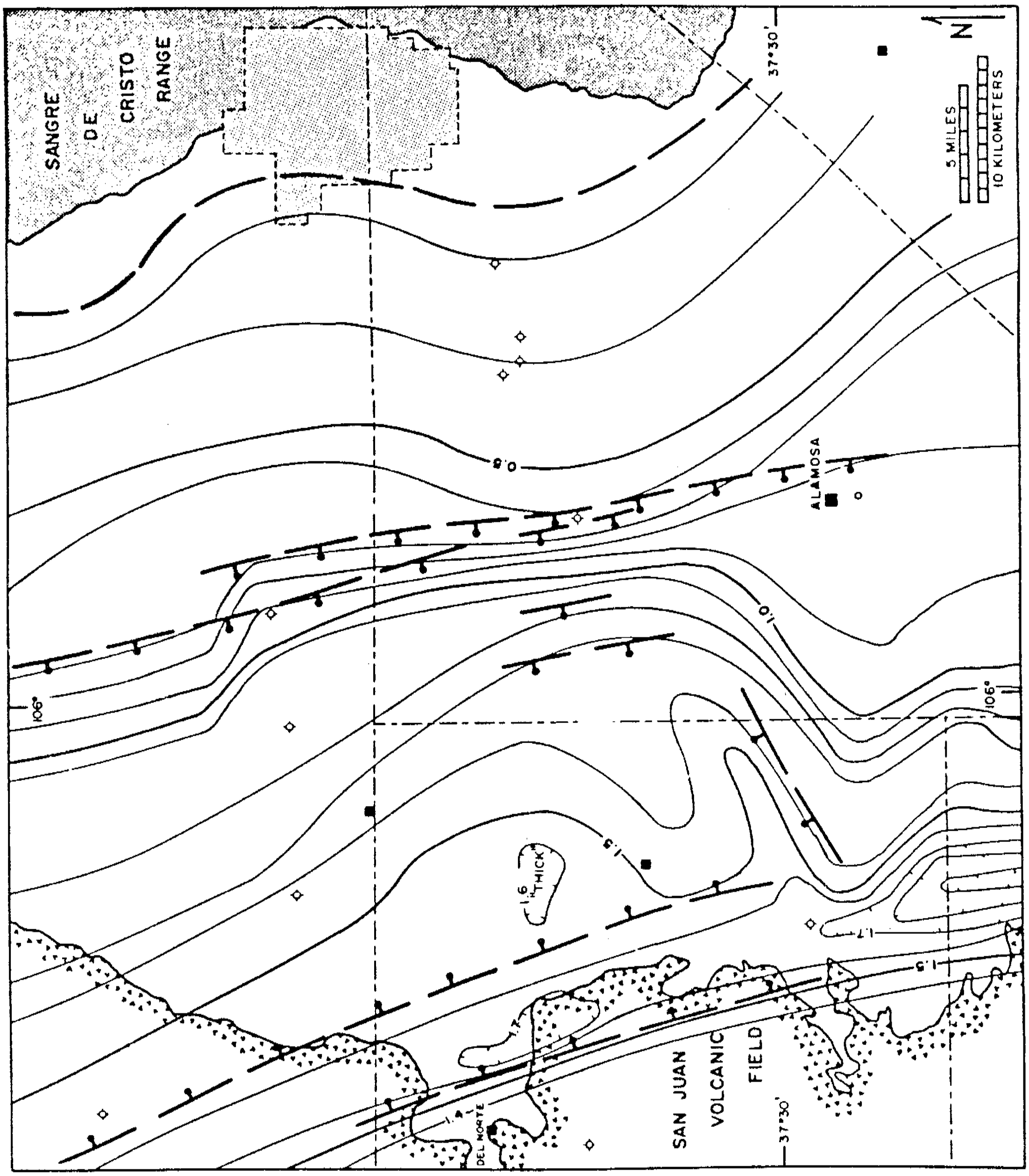
The synrift seismic interval over the horst area is "thinnest" west of the Amerada F-1 State well, but "thickens" northward along the trend of the horst. The basement high is not a present on seismic lines in the northern part of the basin in the vicinity of the Carr #1 Kennedy Williams well (Stoughton, 1977). The positive gravity anomaly on Bouguer and residual gravity anomaly maps of Keller and others (1984), thought to be a northern extension of the Alamosa horst, must instead represent dense basement rock in this area. The only manifestation of the Alamosa horst in this location as seen in Figure 12 is a flattening of the east-sloping surface on top of the ash-flow tuff package. Along the northern border of the study area, the Monte Vista graben and Alamosa horst essentially merge into an east-sloping bench, whereas the Baca graben continues to be a deep, narrow trough extending into the northernmost reaches of the San Luis Basin.

Pre-rift basin

Figure 13, the contoured two-way time interval between the top of the late-Oligocene tuffs and the top of the Precambrian, illustrates that the area of the present-day Monte Vista graben was a depositional basin during the Paleogene. This basin was bounded on the east by a north-trending fault zone, along a basement shoulder. This fault zone does not coincide exactly with the present-day western margin of the Alamosa horst, but as mentioned previously, is probably in part responsible for the steep gravity gradient between the present Monte Vista graben and Alamosa horst.

The faults bounding the basin on the west, at about the longitude of Del Norte, are north-northwest trending. These faults created the structural relief which

Figure 13: Isochron map: contoured two-way travel time interval between top of Oligocene ash-flow tuff reflectors and top Precambrian reflectors. Fault zones depicted have demonstrated prerift displacement. Contour interval 0.1 seconds.


SANGRE DE CRISTO RANGE
ALAMOSA
SAN JUAN VOLCANIC FIELD
DEL NORTE
5 MILES
10 KILOMETERS
N
37°30'
106°
0.5
1.0
1.5
1.6 THICK
1.7

distinguishes the Del Norte high today (Fig. 5). Both the Blanco Basin and Conejos formations appear to thicken eastward across this fault zone, indicating that it was active during their deposition. This fault zone was also active during rifting, but with an opposite sense of displacement. The Paleogene Monte Vista basin appears to end southward at about the latitude of Alamosa. Its northwestern extent is beyond the northwestern corner of Figure 13.

TECTONIC DEVELOPMENT

The stratigraphy and geometry of the Alamosa Basin are the cumulative results of three Tertiary tectonic events: Laramide uplift and wrench-faulting, Oligocene volcanism, and late Oligocene to Quaternary development of the Rio Grande rift. The region was also active tectonically during the Pennsylvanian-Permian Ancestral Rocky Mountain orogeny. Indirect evidence suggests that faults with demonstrated Tertiary movement may be reactivated older structures.

Pre-Tertiary tectonic setting

No post-Precambrian, pre-Eocene, strata occur in the boreholes studied. During the early and middle Paleozoic, the San Luis Basin region was part of a broad highland which lay to the south of the east-west-trending central Colorado sag of Eardley (1951, Pls. 3 & 4). Unfortunately, little evidence of the uplift or of deposition along its flanks has survived later tectonic events (Ross and Tweto, 1980). Parts of this highland were reactivated in Pennsylvanian to Permian time as the Uncompahgre-San Luis highland (Tweto, 1980), apparently bounded on the east by reactivated Precambrian structures (Sutherland, 1972; De Voto, 1980). It was this uplift that was responsible for the coarse synorogenic deposits of the Sangre de Cristo Formation exposed in the Sangre de Cristo Range east of the Alamosa Basin. Denudation of this uplift continued until the Jurassic, when Middle to Late Jurassic non-marine deposits lapped onto the old highland, eventually inundating it (Berman and others, 1980). Cretaceous non-marine and marine strata were deposited over the area (Haun and Weimer, 1960) until onset of Laramide tectonism in latest Cretaceous time.

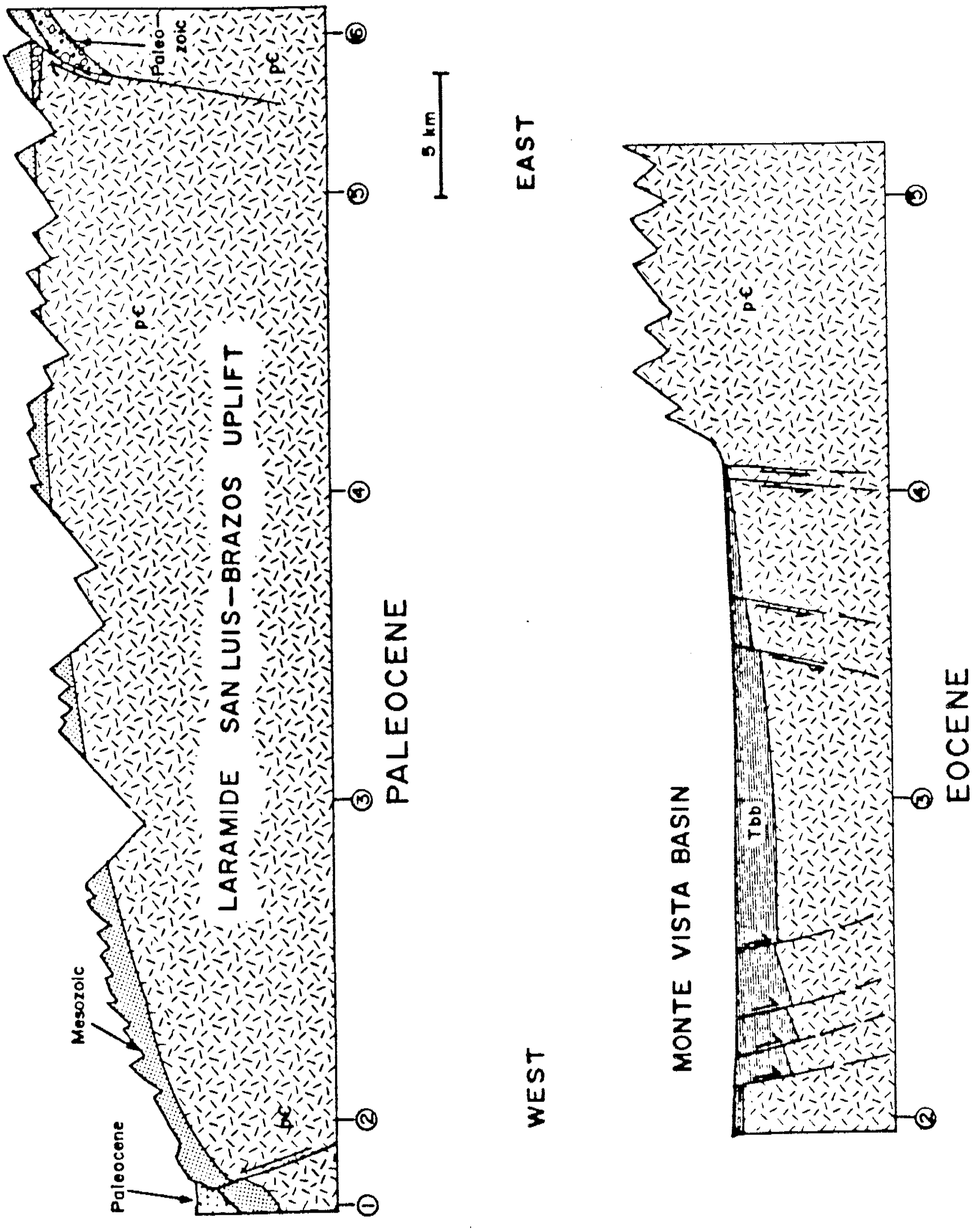
Laramide history

The Laramide orogenic event, extending from late Campanian into Eocene time was a period of uplift and erosion in a broad region including the San Luis Basin-Sangre de Cristo Range area and the Brazos uplift (Tweto, 1975), collectively referred to here as the San Luis-Brazos uplift. Two pulses of uplift are recorded in the synorogenic sedimentary deposits of the San Juan sag and San Juan Basin. The first pulse, marked by the Animas Formation (Late Cretaceous-Paleocene), initiated uplift of the region and stripping of post-Precambrian strata from the San Luis-Brazos uplift (Fig. 14A). The Animas Formation contains volcanic detritus recording nearby Laramide volcanic activity, but it becomes increasingly arkosic upwards in its section, indicating that the uplift was being unroofed to expose its Precambrian core. The known fault style of the eastern part of the uplift was that of west-dipping reverse faults which flatten at depth (Lindsey and others, 1983) and low-angle thrust faults (Schavran, 1984). The western boundary of the uplift was probably monoclinal (Brister 1989a) because extensive thrusting has not been demonstrated to have occurred.

An angular unconformity between the Animas and the Blanco Basin/San Jose formations indicates that a second pulse of tectonic activity began in late Paleocene, extending into the Eocene (Cather and Chapin, 1990). North-northeast translation of the Colorado Plateau during late Laramide time resulted in wrenching in a north-south zone along the axis of the Southern Rocky Mountains in New Mexico and Colorado (Chapin and Cather, 1981; Chapin, 1983) and north-south compression within uplifts in Wyoming (Gries, 1983; 1990). This episode involved reactivation of the western margin of the San Luis-Brazos uplift due to development of a wrench-fault system (Fig. 14B), formation of the Monte Vista basin, and rejuvenation of sedimentation westward into the San Juan sag-San Juan Basin areas.

The Blanco Basin Formation in the Paleogene Monte Vista basin beneath the Alamosa Basin was deposited in a

Figure 14: Cross-section reconstructions of Alamosa Basin area for early and late stages of Laramide orogeny. Sections follow line A-A' (Fig.3). Circled numbers: 1) San Juan sag; 2) Del Norte high; 3) Monte Vista graben; 4) Alamosa horst; 5) Baca graben 6) Sangre de Cristo Mountains.


WEST
EAST
5 km
Paleocene
Mesozoic
Paleozoic
pC
LARAMIDE SAN LUIS–BRAZOS UPLIFT
PALEOCENE
MONTE VISTA BASIN
Tbb
EOCENE
1
2
3
4
5
6

depocenter developed within the western part of San Luis-Brazos uplift which was apparently segmented by wrench faulting. This basin can be classified as an Echo Park-type basin using the terminology of Chapin and Cather (1981) or as an axial basin using the terminology of Dickinson and others (1988). Figure 14B depicts Eocene paleogeography for the Alamosa Basin area as deduced from drilling data and the isochron map in Figure 13. The wrench fault-bounded Eocene basin was approximately 20-25km wide and at least 60km long in a north-northwest trend with its thickest preserved deposits occurring along the fault system on the west side. As suggested in Figure 5, it had an open drainage connection to the San Juan sag to the west during at least the latter part of its history. The surrounding, deeply weathered remnants of the San Luis-Brazos uplift supplied mixed fine-grained and coarse basement-derived detritus to the basin.

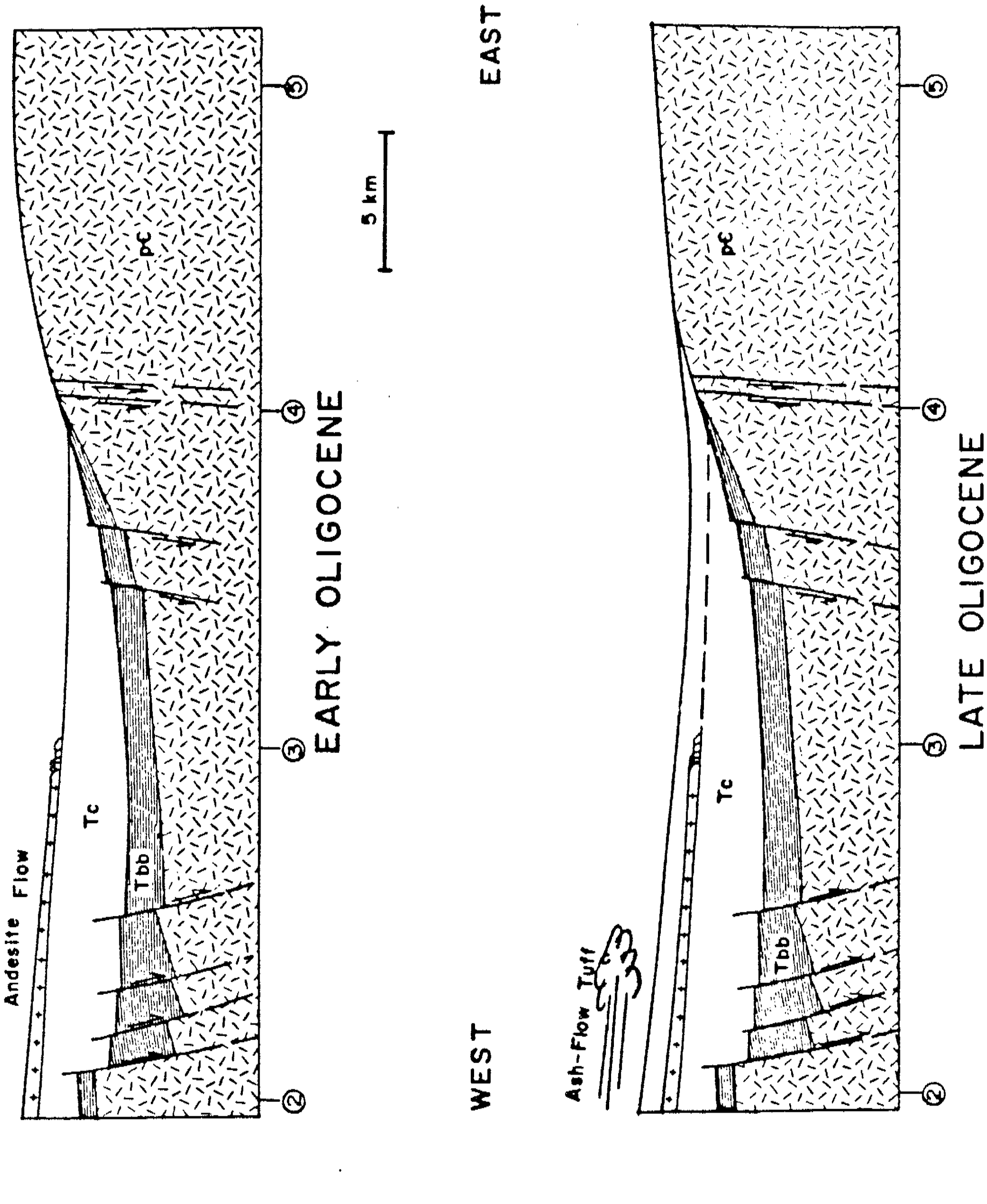
The effect of 30+ million years of Laramide uplift and erosion of the San Luis-Brazos uplift was to subdue the mountain chain and fill the adjacent basins. This resulted in the development of a wide-ranging, low-relief, geomorphic surface in the region (Steven, 1975), commonly referred to as the late Eocene erosion surface (Epis and Chapin, 1975). This surface is now buried deeply beneath Oligocene volcanic strata; it was developed on the Blanco Basin Formation in the western half of the basin and the eroded Precambrian basement in the eastern half. An unconformity marks the late Eocene erosion surface between the top of the Blanco Basin Formation and volcaniclastic rocks of the basal Conejos Formation. Generally, there is not much angularity visible between the two formations on seismic lines. Most drill cuttings from the lowermost Conejos Formation contain minor amounts of basement detritus, either removed from remnant high areas or reworked from Blanco Basin sediments. Oligocene stream channels eroded into the Eocene surface in Colorado have been described by Epis and others (1980).

Oligocene volcanism

The Oligocene was a time of widespread andesitic volcanism in a north-trending band along the axis of the Southern Rocky Mountains. This period of volcanism has been attributed to rising magmas in a continental-arc tectonic setting during a change from a flat-dipping to a steep-dipping subduction zone along the western North American margin (Lipman, 1983a). During this event, volcanic rocks were deposited several kilometers thick in the San Juan volcanic field. As illustrated in Figure 15, the faults bounding the Paleogene Monte Vista basin were active during Conejos deposition. Assuming this basin was formed in the Eocene due to wrench faulting, then wrenching at the basin-bounding faults probably continued into the early Oligocene.

This relationship of early Oligocene subsidence within

Figure 15: Cross-section reconstructions of Alamosa Basin area for Oligocene volcanic episodes. Sections follow line A-A'(Fig.3). Circled numbers described in Figure 14.


EARLY OLIGOCENE
LATE OLIGOCENE
WEST
EAST
5 km
Andesite Flow
Ash-Flow Tuff
Tc
Tbb
pC
2
3
4
5

late Laramide wrench basins occurs elsewhere in the Southern Rocky Mountains. Northeast of the Alamosa Basin in Colorado, the lower Thirtynine Mile Andesite (about 36.6-34.5 Ma) is anomalously thick in the Echo Park basin (C.E. Chapin, 1989, oral commun.) indicating that the basin was continuing to receive sediments into the Oligocene. As with the Paleogene Monte Vista basin, 29 Ma ash-flow tuffs were able to flow across the Echo Park basin after it was filled.

Lozinsky (1988, 1989) has documented a similar subsidence history for Laramide Echo Park-type basins in the subsurface of the Albuquerque Basin, a Rio Grande rift basin in New Mexico. The southern Galisteo-El Rito (Gorham and Ingersoll, 1979) and northern Carthage-La Joya basins (Chapin and Cather, 1981), now buried beneath Santa Fe Group deposits, contain thick accumulations (over 2500 m maximum) of both Eocene and Oligocene rocks.

By 29 Ma, a period of extension had begun in southern Colorado as evidenced by north-northeast-trending dikes in the San Luis Hills mapped by Bartlett (1984) and dated by Burroughs (1972). This information fits well with data in a regional study of dated dikes by Aldrich and others (1984). Volcanism accompanying this early period of extension was primarily associated with caldera formation in the San Juan volcanic field and emplacement of regional ash-flow sheets, such as those deposited across the Alamosa Basin (Fig. 15). This early extension preceded development of rift-related half grabens in the San Luis Basin.

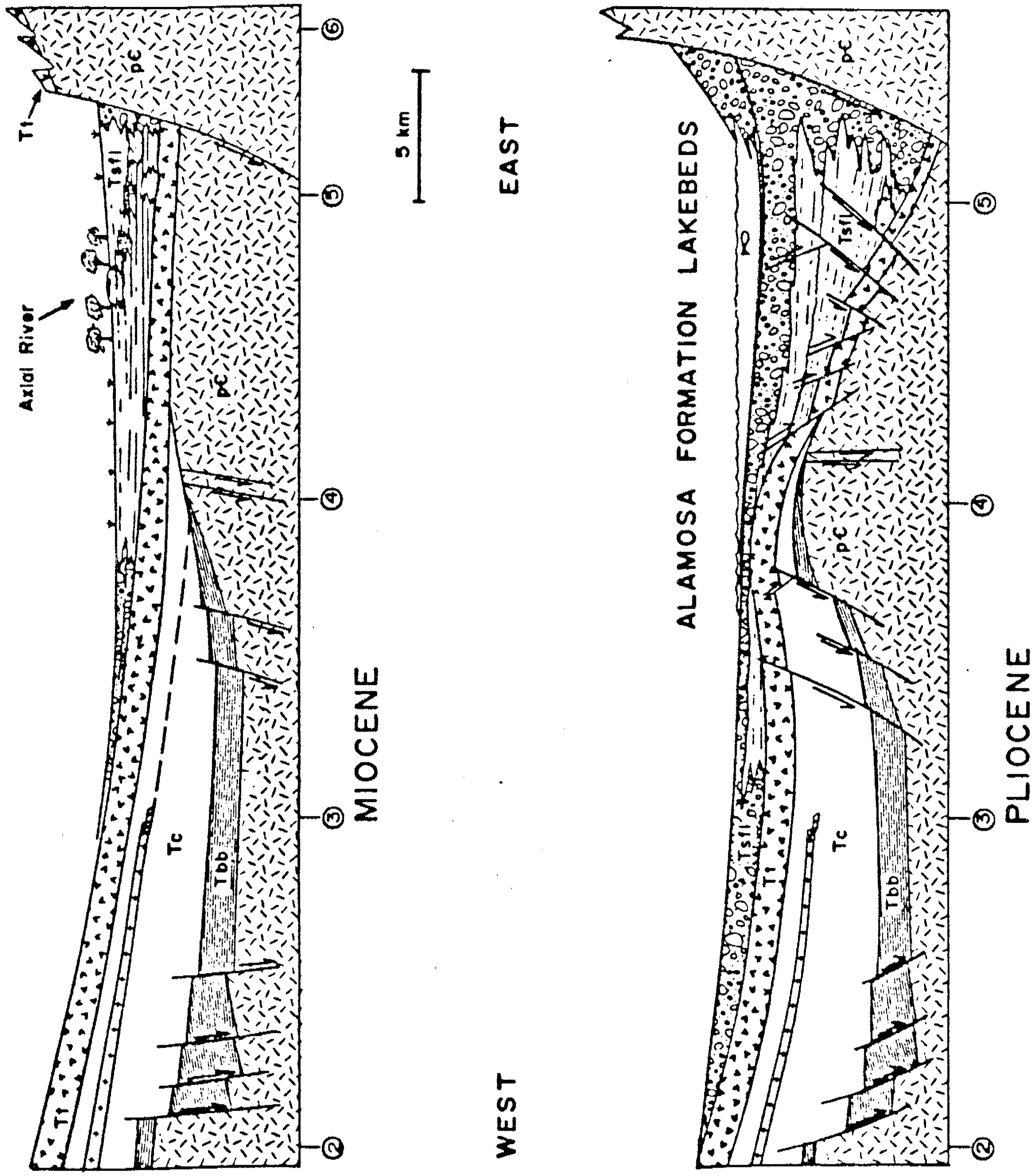
Neogene rifting

Criteria that indicate the beginning of the Rio Grande rift event have been discussed in some detail by Chapin (1971, 1979, 1988). The initiation of rifting in the Alamosa Basin is fairly well constrained by the stratigraphy of its western margin. Structures directly associated with rifting were not active until after emplacement of the uppermost late Oligocene ash-flow tuff (Carpenter Ridge Tuff, 27.35 Ma, Lipman, 1989). Several lines of evidence support this conclusion. First, there is no evidence that the pre-27Ma ash-flow sheets ponded in areas soon to become grabens. Secondly, sediments deposited between the ash-flow sheets (described in a previous section) thin eastward, indicating that the Baca graben had not yet begun to form. Where these sediments are thickest is in an area of structural sagging along the western edge of the Paleogene Monte Vista basin. There is no evidence that sagging in that vicinity continued after initiation of rifting. A third line of evidence is that where faults cut the late Oligocene tuffs, they cut across the entire package. As seen on reflection seismic lines, the lower tuffs in the package are not more highly faulted than upper tuffs. This indicates that the entire tuff package was emplaced prior to significant rift faulting.

The rift event began at about 27Ma. This conclusion is supported by several observations. At about this time, the composition of regional volcanism changed from dacitic to basaltic. The Hinsdale basalts (as old as 26.8 Ma) lie atop the ash-flow tuffs of the San Juan volcanic field in angular unconformity (Lipman and Mehnert, 1975; Lipman, 1975, 1976). Rift-related sediments of the Los Pinos Formation are interbedded with the Hinsdale basalts and in some places underlie the basalts. However, the overwhelming bulk of the Los Pinos Formation overlies the basalts. Following emplacement of the basalts, the eastern edge of the San Juan volcanic field was uplifted, tilted eastward, and deeply eroded. Other dated evidence for initiation of rifting is the 26.5 Ma Amalia Tuff (Lipman and others, 1986; Lipman, 1988) interbedded with the Los Pinos Formation in the Tusas Mountains along the west side of the southern San Luis Basin (Lipman, 1983b; Manley, 1981).

Early in the rift event, the eastern half of the Alamosa Basin was strongly tilted due to downfaulting against the Sangre de Cristo Range (Fig. 16). Seismic lines and cross-sections demonstrate episodic faulting on the basin-bounding faults during the rift event. This is demonstrated in angular relationships within the lower Santa Fe Group and the cyclic pattern of alternating coarse and fine deposition. Streams flowing from the San Juan volcanic field carrying a coarse volcanic load emptied into the Alamosa Basin, developing alluvial fans at their

Figure 16: Cross-section reconstructions of Alamosa Basin area for late Tertiary Rio Grande rift episodes. Sections follow line A-A'(Fig.3). Circled numbers described in Figure 14.


MIOCENE
PLIOCENE
WEST
EAST
5 km
ALAMOSA FORMATION LAKEBEDS
Axial River
Tt
Tsll
Tc
Tbb
pC
②
③
④
⑤
⑥

mouths, perhaps much like the present-day wet alluvial fan constructed where the Rio Grande enters the San Luis Basin at the town of Del Norte. A broad piedmont extended as a veneer eastwards across the western half of the basin towards the eastern (Baca) narrow graben.

Undoubtedly, the Sangre de Cristo Range was also supplying material to the basin. Shorter, steeper alluvial fans were constructed along the eastern margin of the Baca graben. Rift half-grabens such as the Baca tend to develop axial drainage systems that closely parallel the faulted margin of the graben due to increased subsidence along the margin (Leeder and Gawthorpe, 1987; Mack and Seager, 1990). The sediment load from alluvial fans is redistributed within such the axial stream systems. This probably accounts for the mix of Precambrian and volcanic detritus in the lower Santa Fe Group of the Baca graben. The fault-slice of lower Santa Fe Group cropping out on the western edge of Blanca Peak (Urraca outcrop, Fig. 3) contains current indicators suggesting axial stream deposition parallel to the mountain front. This outcrop is probably a remnant of the early period of sedimentation. Recent fission-track dating of apatite in Precambrian rocks making up Blanca Peak indicate rapid uplift of the Blanca massif between 28 and 18 Ma (Kelley, 1990). This probably coincided with rapid subsidence and down-to-the-east tilting of the Baca half graben.

The angular unconformity visible in Figure 11 is evidence for a change in fault activity and degree of tilting of the Baca graben. Sediments above this unconformity are only gently tilted, and not as intensely faulted as the lowermost package of Santa Fe rocks. The basin-wide coarsening trend above the angular unconformity at the top of the lower Santa Fe Group represents response of drainage systems to this episode of tectonic activity.

Taylor (1975) has estimated a post-7 Ma period of intense uplift on the order of 1-2 km of the northern Sangre de Cristo range. Chapin (1979) has described strong regional uplift elsewhere in the Southern Rocky Mountains between 7 and 4 Ma. By the end of this period of uplift, the newly elevated alpine areas provided conditions of increased precipitation under which the remainder of the Santa Fe Group was deposited. By about 4.5 Ma, the northern half of the San Luis Basin was prevented from draining to the south by the San Luis Hills horst, and could not drain around the horst due to the presence of the Servilleta flood basalts of the Taos Plateau. Internal drainage created conditions for lake formation and lacustrine sedimentation common to the Alamosa Formation (Fig.16).

Elsewhere in the rift at this time, basins were being integrated into the ancestral Rio Grande. By middle Pleistocene time, integration of the upper Rio Grande drainage system with the lower Rio Grande system (Gulf of Mexico terminus) in the the Trans-Pecos Texas region below

El Paso, caused lowering of base levels, dissection of basins, and stranding of geomorphic surfaces (Gile and others, 1981). The Rio Grande integrated basins as far north as the southern San Luis Basin during this down-cutting episode, but did not exist north of its present confluence with the Red River of New Mexico (Wells and others, 1987). The Servilleta basalts north of the Red River and the San Luis Hills horst served as a hydrologic divide until middle to late Pleistocene when the Rio Grande was able to erode a gorge through these barriers. This event occurred after 0.69 Ma, the youngest documented age of the Alamosa Formation (Rogers and others, 1985), but before 0.3Ma (Wells and others, 1987).

Reactivation of structures

It has been demonstrated numerous times that recurrent motion on basement faults is common in the Southern Rocky Mountains (e.g. Weimer, 1980). In the San Luis Basin region of Colorado and New Mexico, several fault zones have probably undergone reactivation. The western margin of the Laramide San Luis-Brazos uplift was active during both the early and late Laramide phases. The fault zone separating the Del Norte high from the Laramide Monte Vista basin underwent minor reactivation (in opposite sense of motion) during Neogene rifting. The fault zones in the Alamosa horst area were probably active in the Precambrian and late Paleozoic as well as during the Cenozoic tectonic events

(Sutherland, 1972; DeVoto, 1980; Figs. 12, 13). Sales (1983) has illustrated that the Sangre de Cristo fault zone may have been a Laramide thrust along which the San Luis Basin side of the fault collapsed during the Rio Grande rift event. Collapse of Laramide uplifts to become rift-graben floors has been documented elsewhere in the rift (Cather and Johnson, 1984; Chapin and Seager, 1975).

SUMMARY

1) The Alamosa Basin is a subbasin of the San Luis Basin of the Rio Grande rift, which ranges in age from late Oligocene to Recent. The Alamosa Basin is a composite basin consisting of two half grabens separated by a central subsurface structural high called the Alamosa horst.

2) The western half graben, the Monte Vista graben, is superimposed upon a narrow north-northwest-trending late Laramide (Eocene) basin (the Monte Vista basin) containing up to 835m of nonvolcanic redbeds of the Blanco Basin Formation. The Blanco Basin Formation was deposited on Precambrian basement and is overlain by up to 2300m of volcanic rocks of the Conejos Formation.

3) The eastern half graben, the Baca graben, was tilted strongly down to the east during the early phase of rifting (late Oligocene-early Miocene) and contains in excess of 2.5 km of synrift sediments in its deepest parts. A pronounced angular unconformity within the Baca graben separates strongly tilted sediments from younger, only

slightly tilted sediments. The Baca graben is superimposed over the eastern part of the eroded San Luis-Brazos highland.

4) Several regional ash-flow sheets of late Oligocene age (29-27 Ma) were deposited across the Alamosa Basin area and form an important marker horizon with distinctive geophysical and petrologic characteristics. These tuffs separate prerift sediments and structures from those of rift age. In the eastern half of the basin, the ash-flow tuffs rest directly on Precambrian basement, while in the western half of the basin, they overlie the Conejos Formation.

5) The Alamosa "horst" is a composite structural high coincident with the west, monoclinal margin of the Baca half graben. Minor arching of the late Oligocene ash-flow sheets and overlying Santa Fe Group sediments occurred during strong down-to-the-east tilting of the Baca half graben. The high gravity gradient of the western side of the horst is attributed to structural relief at the eastern margin of the Paleogene Monte Vista basin rather than to rift-related faults. To the north, the Alamosa "horst" becomes a bench on the east-sloping upper surface of the ash-flow tuff package. A pronounced gravity high in this area must be caused by density differences within the Precambrian basement.

6) The Alamosa Basin is separated from the Laramide San Juan sag to the west by the Del Norte high, a narrow

(about 10km wide) north-trending horst of Precambrian rock. The Eocene Blanco Basin Formation is thickest (up to 835m) along the east side of the Del Norte high. The Monte Vista basin and the San Juan sag were connected across the Del Norte high during at least part of Blanco Basin sedimentation.

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APPENDICES

APPENDIX 1

Palynology of Blanco Basin Formation

Palynological analysis was done upon five samples from the Blanco Basin Formation by palynologist Dr. E.B. Robertson. What follows is a description of sample location (by Brister) followed by a description of contents and interpretation (by Robertson).

Sample 40: this sample was from mudstone at the principle reference section, Rio Chama site.
Contents:
-gray vitrinite (evidence of extensive oxidization)
-Undifferentiates sporomorphs
-Angiosperms: Artemesia spp. (sagebrush contaminant)
Interpretation:
-contaminated sample

Sample 198: this sample was also taken from mudstone at the principle reference section, Rio Chama site.
Contents:
-gray vitrinite (evidence of extensive oxidization)
Interpretation:
-none

Sample 75: this sample was from mudstone at reference section, east fork San Juan River.
Contents:
-woody fragments
-sieve plates ???
-Fungal: Septohyphaeites spp. (Maas-Rec)
Interpretation:
-probably related to sample I-91; it has same fungal component

Sample 91: this sample taken also from a mudstone at reference section, east fork Rio Chama
Contents:
-Fungal: Ctenosporties wolfei (Maas-E.Oli)
Septohyphaeites spp. (Maas-Rec)
-Ferns: Laevigatosporites spp.
Deltoidospora spp.
-Gymnosperms: Ephedripites spp.
Pinuspollenites spp.
-Angiosperms: Brevitricolpites spp.
Tricolpites spp.

-Phytoplankton: Mystridium spp.
Interpretation:
-This is an early Tertiary sample. It has the beginning of a fungal association that I have found in Colorado and Utah in the Early Eocene...the Mystridium indicates some souring from a marine or estuarine source.

Sample 106: This sample was collected from coally siltstone at lower contact of formation at Oil Creek reference section.

Contents:
-Undifferentiated spores
-Fungal: Lacrisporonites spp.
Pluricellaesporites spp.
Septohyphaeites spp. (Maas-Rec_
Microthyrites spp.
-Ferns: Stereisporites antiquasporites
Deltoidosporites.
-Gymnosperms: Pinuspollenites spp.
Vitreisporites spp.
-Angiosperms: Nyssapollenites spp.
Reticolpites spp.
-Phytoplankton: Mystridium spp.
Interpretation:
-This association, especially the fungal component, looks like a Late Paleocene-Early Eocene association that characterizes the Eocene in the Piceance Creek Basin.

PALEOCURRENT DATA FROM REFERENCE SECTIONS, BLANCO BASIN FORMATION

Types: i = pebble imbrication
ps = parting step lineation
t = trough or channel orientation
x = cross-bedding

Table A1-1: Paleocurrent data, from principal reference section A (37°03'14" N Lat., 106°32'27" W Long.).

Type	Azimuth	Type	Azimuth	Type	Azimuth
ps	215	ps	225	ps	225
ps	215	ps	235	ps	235
ps	235	ps	245	ps	245
ps	245	ps	245	ps	245
ps	255	ps	255	ps	255
ps	255	i	232	i	107
i	104	i	165	i	99
i	187	i	165	i	287
i	105	i	254	i	285
i	266	i	120	i	348
i	322	i	245	i	225
i	295	i	245	i	236
i	265	i	213	i	258
i	147	i	265	i	150
i	172	i	245	i	150
i	255	i	135	i	315
i	205	i	107	i	99
i	287	i	285	i	348
i	225	i	236	i	282
i	150	i	76	i	165
i	187	i	165	i	105
i	254	i	266	i	120
i	322	i	245	i	295
i	245	i	255	i	213
i	147	i	255	i	305
i	185	i	175	i	185
i	300	i	285	i	285
i	135	i	335	i	280
i	335	i	175	i	220
i	210	i	325	i	295
i	15	i	335	i	20
i	335	i	240	i	335
i	290	i	250	i	270
i	270	i	330	i	340
i	195	i	140		

$n = 104$
$\bar{x} = 227^{\circ}$

Table A1-2: Paleocurrent data, reference section B at Castle Creek (37°11'30" N Lat., 106°45'50" W Long.).

Type: all azimuths are for imbrications

75	295	285	65	135	35	35	325
235	145	35	235	85	295	325	285
315	75	105	305	245	245	175	325
200	115	285	285	5	115	265	175
295	265	255	75	265	150	265	275
305	155	55	65	85	235	65	135
245	305	95	40	55	25	150	145
135	255	75	245	225	75	105	25
295	235	245					

$n = 67$
$\bar{x} = 180°$

Table A1-3: Paleocurrent data, reference section C at Oil Creek (37°16'52" N Lat., 106°47'05" W Long.).

All azimuths are for imbrications

245	245	255	125	235	255	129	135
115	108	85	258	125	115	255	145
245	195	125	105	135	145	270	225

$\underline{n}$ = 24
$\bar{x}$ = 178°

Table A1-4: Paleocurrent data, reference section D at East Fork San Juan River (37°23'15" N Lat., 106°51'06" W Long.).

Type	Azimuth	Type	Azimuth	Type	Azimuth
i	234	i	120	i	268
i	287	i	242	i	225
i	235	i	315	i	245
i	325	i	315	i	245
i	305	i	245	t	315
t	275	t	290	t	265
t	295	t	235	t	282
t	265	t	250	t	255
t	255	t	255	t	255
t	255	ps	235	ps	215
ps	195	x	245	x	245
x	275	x	245		

$n = 35$

$\overline{X} = 247^{\circ}$

Table A1-5: Paleocurrent data, reference section E at Poison Park (37°32'10" N Lat., 107°14'42" W Long.).

Basal Conglomerate

Type	Azimuth	Type	Azimuth	Type	Azimuth
i	190	i	175	i	205
i	155	i	155	i	155
i	195	i	195	i	165
i	195	i	185	i	185
i	195	i	205	i	135
i	195	i	215	i	205
i	195	i	315	i	215
i	55	i	215	i	5
i	185	i	165	i	165
i	185	i	185	i	165
i	205	i	195	i	165
i	205	i	215	ps	180
ps	185	ps	175	t	155

n = 39
$\bar{x}$ = 182°

Upper conglomerate (16.5m above base)

Type	Azimuth	Type	Azimuth	Type	Azimuth
i	175	i	275	i	225
i	215	i	225	i	195
i	145	i	195	i	5
i	355	i	285	i	255
i	265	i	325	i	155
i	245	i	185	i	155
i	185	i	155	i	85
i	55	i	75	i	325
i	165	i	295	i	135
i	105	i	245	i	285
i	175	i	185	i	205
i	185	i	195	i	205
i	175	i	195	i	155
i	155	i	335	i	165
i	115	i	85	i	245
i	235	i	135		

n = 47
x = 194

Cumulative for entire section: n = 86
$\bar{x}$ = 189°

APPENDIX 2

SUMMARY OF DRILL HOLE DATA, SAN JUAN SAG

This information was obtained through analysis of geophysical logs and microscopic examination of drill cuttings (intervals noted) and represents a summary of the author's own interpretation. The wells are listed in the order as in Table 2-1. Wells 9-15 on Table 2-1 are included in Appendix 3. Specific observations about the lower Tertiary rocks in each well are included. All depth and thickness information is listed in feet.

Operator: Champlin Petroleum Company
Well: #1 Federal 34A-13
Location: sec 13 T35N R4E, SW SE
County: Conejos
State: Colorado
TD: 6751 ft KB: 9463 ft GL: 9436 ft
Date logged: November 1985
Logs used in study: dual induction-SFL; borehole compensated sonic; litho density compensated neutron
Sample interval examined: 60-3000 ft

Formation Tops (depths in feet from kelly bushing):
Spudded in: Conejos Formation
2815 Blanco Basin Formation
2970 Mancos Shale
4230 Greenhorn Limestone Member
4400 Dakota Sandstone (+ Todilto Member, Wanaka Fm.)
6200-TD Precambrian basement

Notes: The Blanco Basin Formation in this well is only 155 ft thick at most and is a coarse arkosic conglomerate in its lower 50 ft. The upper 105 ft is questionably Blanco Basin in that the resistivity log response indicates interbedded mudstone/sandstone whereas the samples show mostly volcanic debris. Experience from other wells suggests that recovery for the mudstone interval was poor due to overwashing. The Blanco Basin Formation overlies the Carlile Member of the Mancos Shale. Igneous intrusions occur in the Niobrara Member of the Mancos Shale from 4005-4160 ft (155 ft thick) and in the Dakota Sandstone from 4520-5550 ft.

Operator: Waggoner-Baldridge Operating
Well: #1-10 Federal Horseshoe Mountain
Location: sec 10 T39N R5E, NE SE
County: Rio Grande
State: Colorado
TD: 7361 ft KB: 8334 ft GL: 8320 ft
Date logged: January 1990
Logs used in study: geologist's strip log, drilling rate
Sample interval examined: selected samples 3000-6800 ft

Formation Tops (depths in feet from kelly bushing):
Spudded in: Conejos Formation
5770 Blanco Basin Formation
5810 Mancos Shale
6210 Greenhorn Limestone Member
6615 Dakota Sandstone (+ Junction Creek Sandstone)
7275-TD Precambrian basement

Notes: The lower Conejos Formation in this well was made up of numerous thin flows, hydrothermally altered breccia and tuffaceous sandstone which contained substantial Precambrian basement-derived detritus, either from eroded Blanco Basin Formation or from basement. The Blanco Basin in this well is only 40 ft thick and is predominantly micaceous, sandy mudstone with variable light green and red colors. This thickness of the Blanco Basin suggests that a fault may cut the drilled interval, or the formation was erosionally thinned prior to Conejos deposition. The Blanco Basin Formation overlies the Niobrara Member of the Mancos Shale which is intruded by a 40 ft thick sill from 6100-6140 ft.

Operator: Meridian Oil Company
Well: South Fork Federal #23-17
Location: sec 7 T39N R4E County: Rio Grande
State: Colorado
TD: 13586 ft KB: 10086 ft GL: 10066 ft
Date logged: September 1988
Logs used in study: dual induction-SFL; borehole compensated sonic; compensated neutron-litho-density
Sample interval examined: 5300-9500 ft

Formation Tops (depths in feet from kelly bushing):
Spudded in: Conejos Formation
5865 Blanco Basin Formation
6590 Animas Formation
9010 Kirtland/Fruitland/Pictured Cliffs
9500 Lewis Shale
10680 Mancos Shale
12988 Greenhorn Limestone Member
13330-TD Dakota Sandstone to Morrison Formation

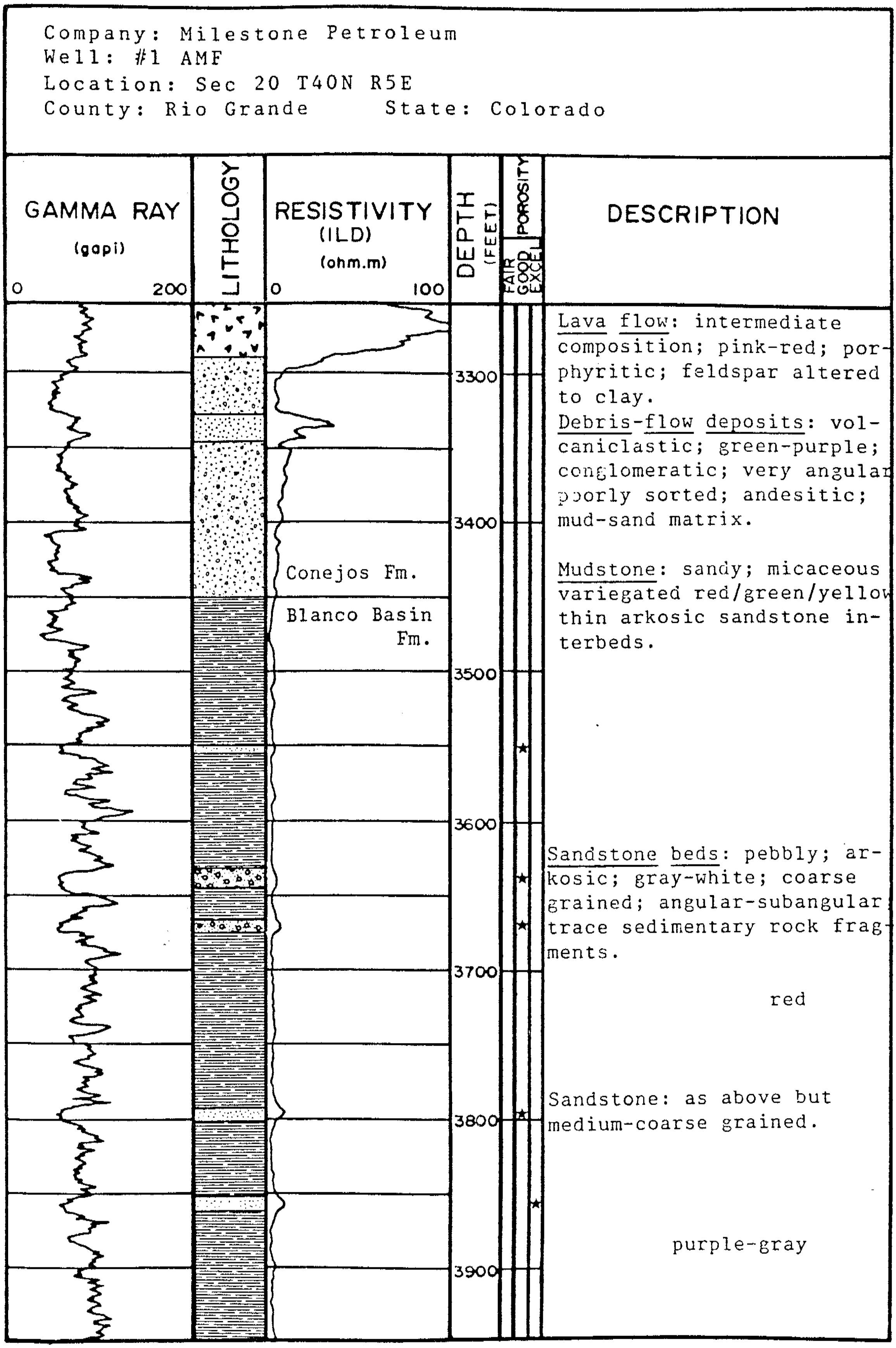
Notes: The base of the Conejos Formation was picked on the basis of both geophysical logs and cuttings examined. The Conejos Formation is shaley within its lower parts. Shale within the interval 5210-5860 ft ranges from tan to black. Volcaniclastic units in the intervals 5600-5670 and 5820-5860 ft contain minor Precambrian basement detritus. The Blanco Basin Formation is made up of variegated mudstone (mostly red and light green hues) and coarse arkosic sandstone. Broken pebbles of iron-stained granite are common. The contact with the Animas Formation is not distict on logs but is seen in cuttings by a loss of reddish colors in mudstone and presence of andesitic detritus in addition to arkosic detritus. Rhyolitic intrusions occur in the Animas at the following intervals: 7950-7995 and 8100-8120 ft. Coal and brown mudstone are common below 7850 ft. The contact with the Kirtland/ Fruitland/Pictured Cliffs is uncertain, but samples below 9010 ft are light gray, contain significant coal (although log response does not indicate coal beds) and log response is similar to logs from the northeastern San Juan Basin (e.g. Pan American Pagosa-Jicarilla #1, sec.23 T32N R3W). Numerous 5-20 feet thick intrusions occur in the Lewis and upper Mancos formations. The Mancos is also intruded in the interval 11620-12490 ft.

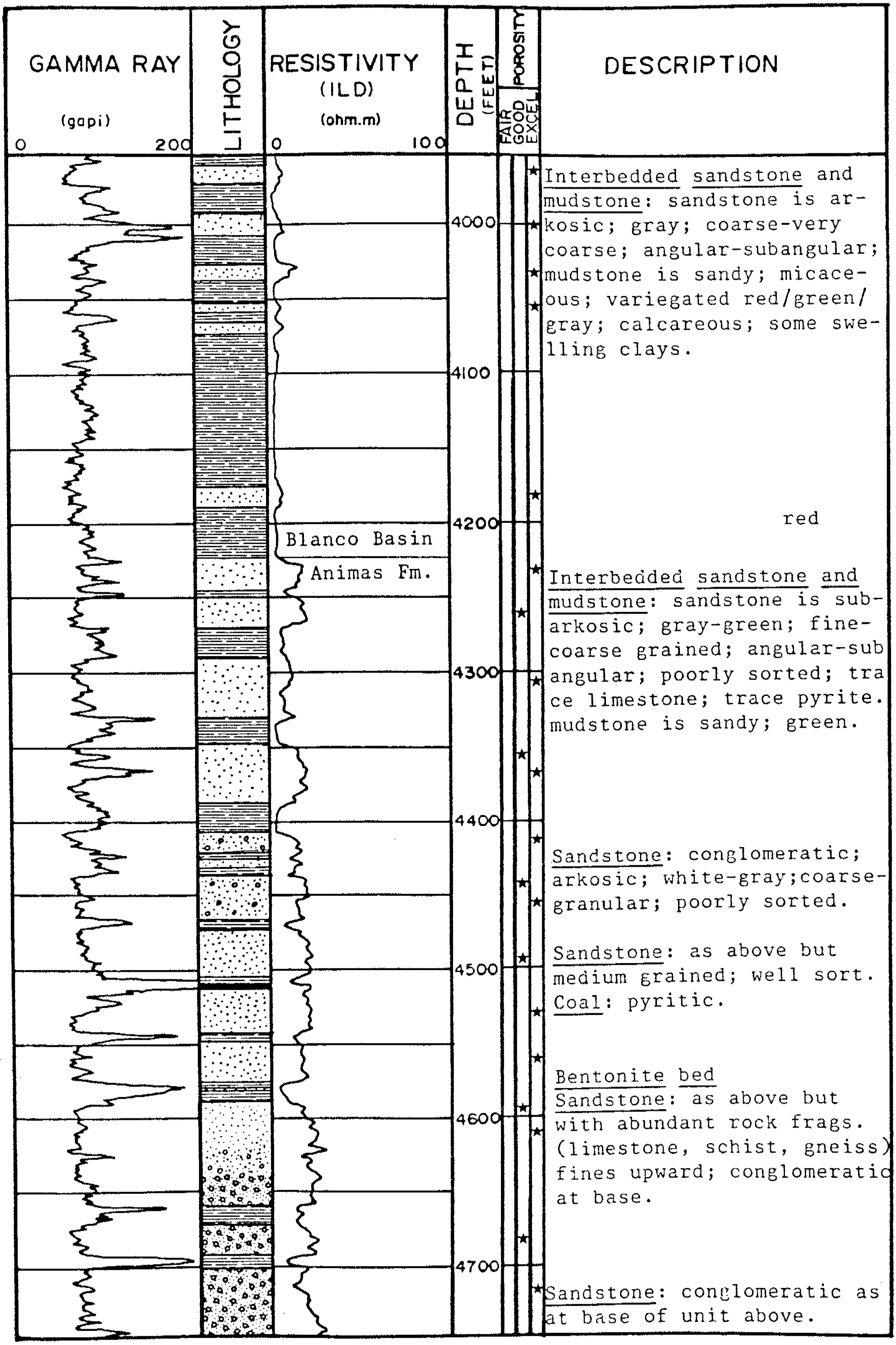
Operator: Milestone Petroleum
Well: AMF #1
Location: sec 20 T40N R5E, NW SE
County: Rio Grande
State: Colorado
TD: 9447 ft   KB: 7999 ft   GL: 7987 ft
Date logged: October 1984
Logs used in study: dual induction-SFL; litho-density compensated neutron; long-spaced sonic
Sample interval examined: 3250-6350 ft

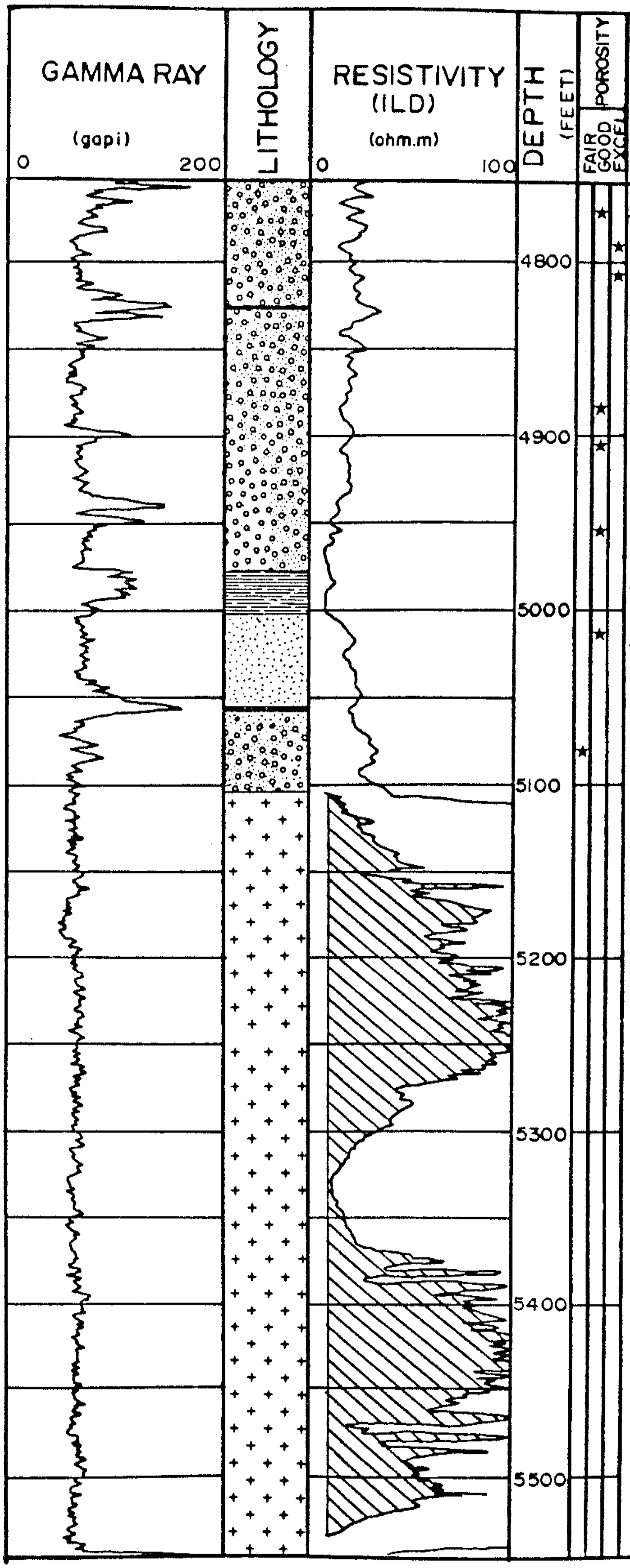
Formation Tops (depths in feet from kelly bushing):
Spudded in: Quaternary alluvium (covering Conejos Fm)
3450 Blanco Basin Formation
4230 Animas Formation
6240 Lewis Shale
7050 Mancos Shale
8880 Greenhorn Limestone Member
9200-TD Dakota Sandstone to Morrison Formation

Notes: The cuttings examined from this well were of good quality in the lower Tertiary interval. A composite interpretive log follows which is typical of the Blanco Basin and Animas Formations.

Porosity indicated in log is estimate based upon density-neutron and gamma ray logs. Good = 10-15%


Company: Milestone Petroleum
Well: #1 AMF
Location: Sec 20 T40N R5E
County: Rio Grande State: Colorado
GAMMA RAY
(gapi)
0
200
LITHOLOGY
RESISTIVITY
(ILD)
(ohm.m)
0
100
DEPTH
(FEET)
POROSITY
FAIR
GOOD
EXCEL
DESCRIPTION
3300
3400
3500
3600
3700
3800
3900
Conejos Fm.
Blanco Basin Fm.
Lava flow: intermediate composition; pink-red; porphyritic; feldspar altered to clay.
Debris-flow deposits: volcaniclastic; green-purple; conglomeratic; very angular poorly sorted; andesitic; mud-sand matrix.
Mudstone: sandy; micaceous variegated red/green/yellow thin arkosic sandstone interbeds.
Sandstone beds: pebbly; arkosic; gray-white; coarse grained; angular-subangular trace sedimentary rock fragments.
red
Sandstone: as above but medium-coarse grained.
purple-gray


GAMMA RAY
(gapi)
0
200
LITHOLOGY
RESISTIVITY
(ILD)
(ohm.m)
0
100
DEPTH
(FEET)
POROSITY
FAIR
GOOD
EXCEL
DESCRIPTION
4000
4100
4200
4300
4400
4500
4600
4700
Blanco Basin
Animas Fm.
Interbedded sandstone and mudstone: sandstone is arkosic; gray; coarse-very coarse; angular-subangular; mudstone is sandy; micaceous; variegated red/green/gray; calcareous; some swelling clays.
red
Interbedded sandstone and mudstone: sandstone is subarkosic; gray-green; fine-coarse grained; angular-subangular; poorly sorted; trace limestone; trace pyrite. mudstone is sandy; green.
Sandstone: conglomeratic; arkosic; white-gray;coarse-granular; poorly sorted.
Sandstone: as above but medium grained; well sort.
Coal: pyritic.
Bentonite bed
Sandstone: as above but with abundant rock frags. (limestone, schist, gneiss) fines upward; conglomeratic at base.
Sandstone: conglomeratic as at base of unit above.



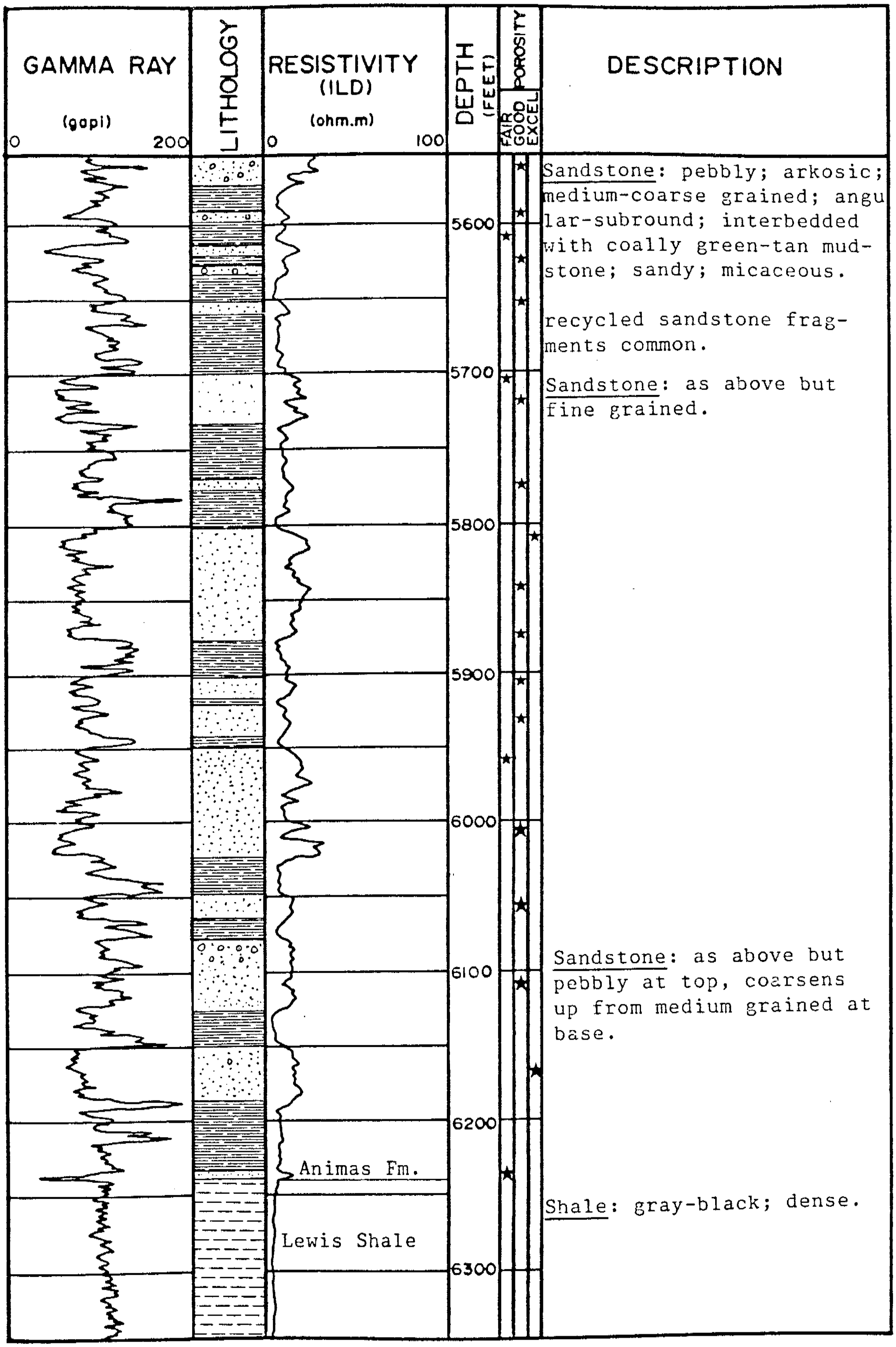
DESCRIPTION

Sandstone: arkosic; pebbly; gray-green; medium-granular angular-subround; poor sort traces of pyrite, metamorphic and sedimentary rock fragments; coal seams.

Mudstone: sandy; green.

Sandstone: arkosic; fine-coarse grained, becomes pebbly at base; coal seam.

Latite sill: gray; porphyritic.


GAMMA RAY
(gapi)
0
200
LITHOLOGY
RESISTIVITY
(ILD)
(ohm.m)
0
100
DEPTH
(FEET)
POROSITY
FAIR
GOOD
EXCEL
DESCRIPTION
5600
5700
5800
5900
6000
6100
6200
6300
Animas Fm.
Lewis Shale
Sandstone: pebbly; arkosic; medium-coarse grained; angular-subround; interbedded with coally green-tan mudstone; sandy; micaceous.
recycled sandstone fragments common.
Sandstone: as above but fine grained.
Sandstone: as above but pebbly at top, coarsens up from medium grained at base.
Shale: gray-black; dense.

Operator: Kirby Petroleum
Well: Jynnifer 1-9
Location: sec 9 T 40N R5E, SW NE SE
County: Rio Grande
State: Colorado
TD: 9264 ft KB: 8193 ft GL: 8165 ft
Date logged: February 1985
Logs used in study: dual laterolog; litho-density compensated neutron; borehole compensated sonic
Sample interval examined: 3800-5950 ft

Formation Tops (depths in feet from kelly bushing):
Spudded in: Quaternary alluvium (covering Conejos Fm)
4580 Blanco Basin Formation
5180 Animas Formation
5900 Lewis Shale
6140 Mancos Shale
7700 Greenhorn Limestone Member
8150 Dakota Sandstone
8600-TD Morrison to Junction Creek to Precambrian

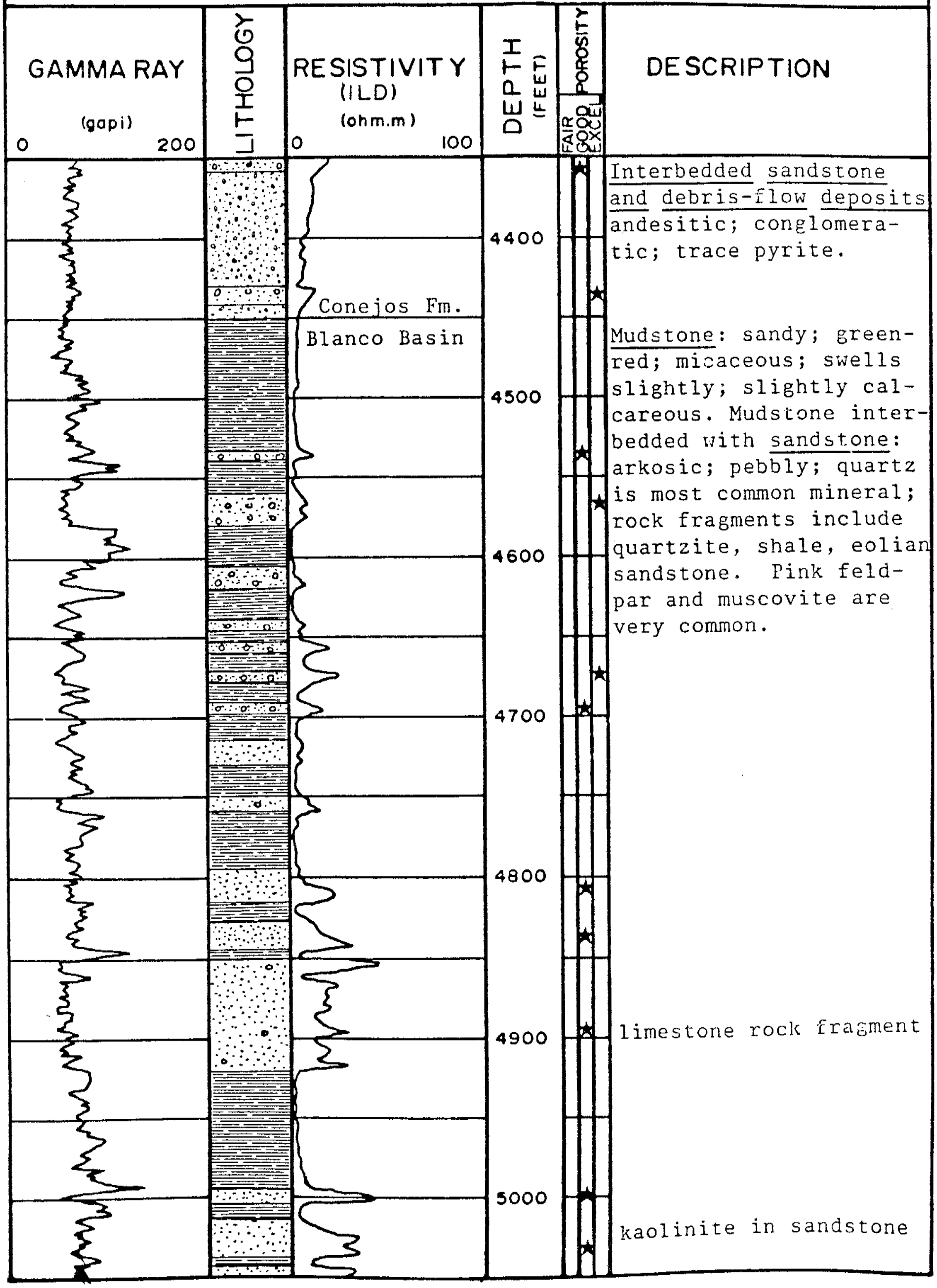
Notes: Samples for lower Tertiary units were probably overwashed because most traces of mudstone has been removed from the samples) ; A sill intrudes the Mancos Shale from 6620-6780 ft.

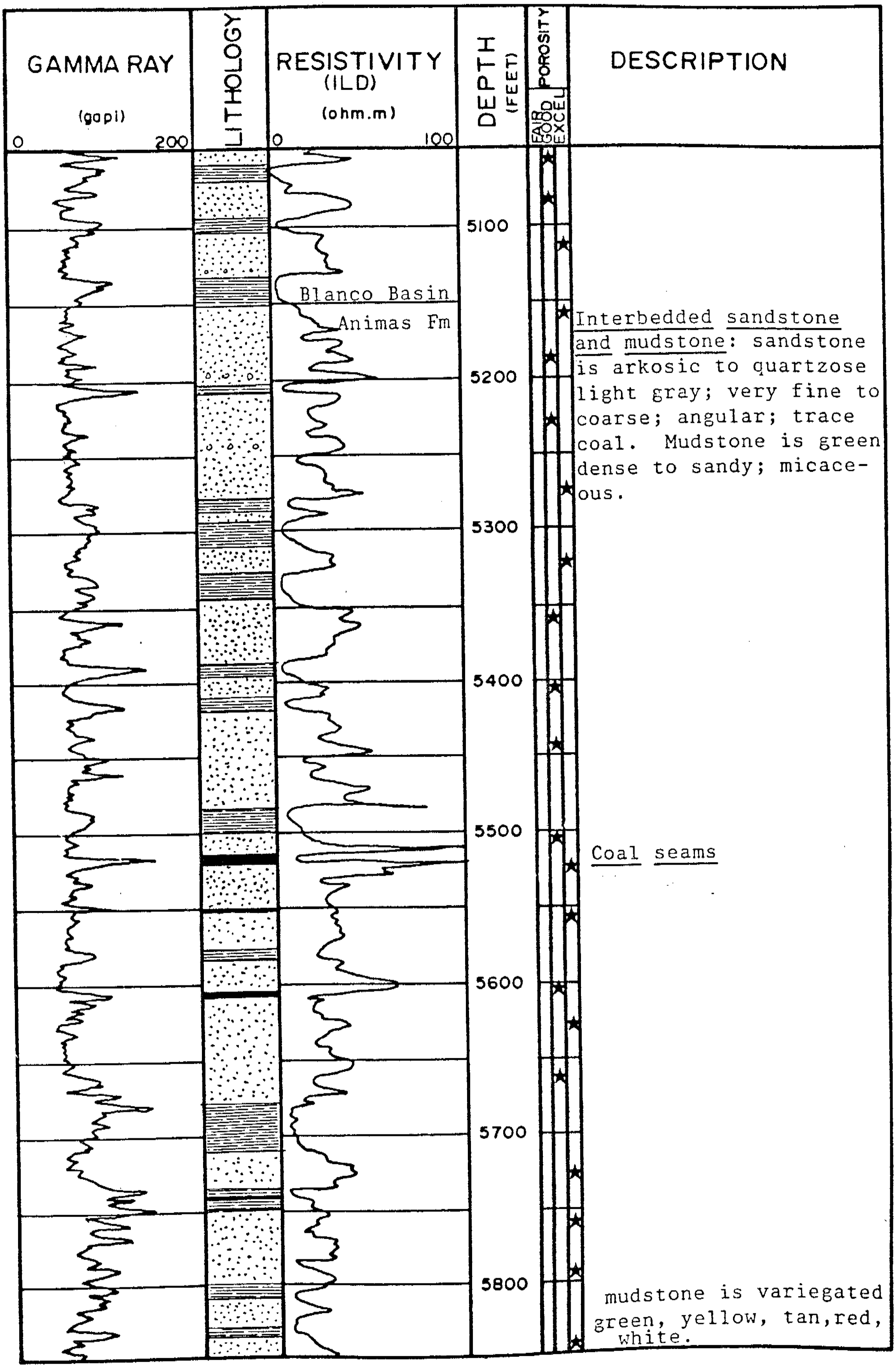
Operator: Waggoner-Baldridge Energy
Well: Shelley #1-10
Location: sec 10 T40N R5E, NW SW
County: Rio Grande
State: Colorado
TD: 9011 ft KB: 8178 ft GL: 8161 ft
Date logged: December 1985
Logs used in study: dual induction-SFL; litho-density, compensated neutron
Sample interval examined: 4350-6100 ft

Formation Tops (depths in feet from kelly bushing):
Spudded in: Quaternary alluvium (covering Conejos Fm)
4450 Blanco Basin Formation
5150 Animas Formation
5970 Lewis Shale
6550 Mancos Shale
7570 Greenhorn Limestone Member
8000 Dakota Sandstone
8160 Morrison Formation
8450 Junction Creek Sandstone
8540-TD Precambrian basement

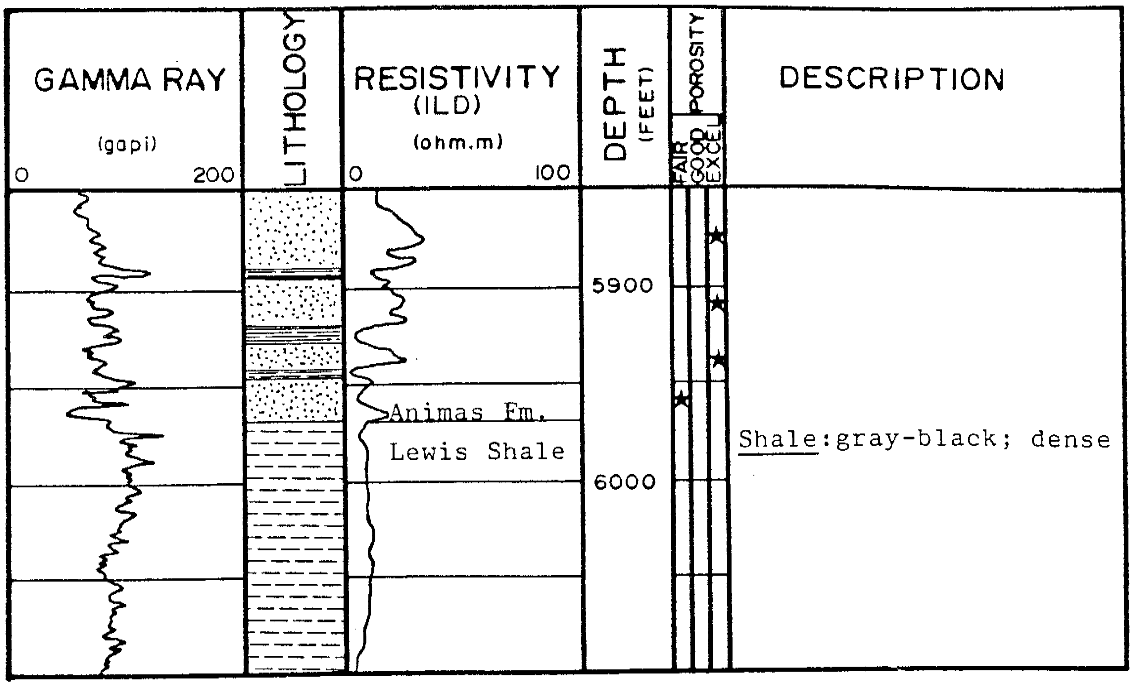
Notes: Samples from this well from the lower Tertiary are representative of these units; therefore a composite interpretive log follows. More notes follow the log.

Company: Waggoner-Baldridge Energy
Well: Shelley #1-10
Location: sec 10 T40N R5E, NW SW
County: Rio Grande
State: Colorado





GAMMA RAY
(gapi)
0
200
LITHOLOGY
RESISTIVITY
(ILD)
(ohm.m)
0
100
DEPTH
(FEET)
POROSITY
FAIR
GOOD
EXCEL
DESCRIPTION
5100
5200
5300
5400
5500
5600
5700
5800
Blanco Basin
Animas Fm
Interbedded sandstone and mudstone: sandstone is arkosic to quartzose light gray; very fine to coarse; angular; trace coal. Mudstone is green dense to sandy; micaceous.
Coal seams
mudstone is variegated green, yellow, tan, red, white.



More notes: Conejos Formation sandstones are gray-green, con-taining subrounded to angular andesitic and more felsic lithic fragments. Swelling clay is present in the matrix; and pyrite is present in trace amounts. Andesite rock fragments are more common towards the top of the section.

The volcanic breccias are composed of pebble or larger (?) size andesite, rhyolite, and quartz latite lithic fragments in a sandy/muddy matrix similar to that in the sandstones above. The well cuttings for this lithology are angular; overall rock color is green. Calcite (vein or fracture filling?), pyrite, and kaolinite are common.

Two rhyolitic(?) lava flows are present in the examined interval. The rock is leucocratic and porphyritic, con-taining phenocrysts of quartz, hornblende, and biotite. These flows occur at the intervals 3730-3745 and 4130-4215 ft.

The Blanco Basin Formation consists primarily of two interbedded lithologies. The most common rock type in the interval 4500-5010 ft is green and red, silty/sandy, micaceous, bentonic, and slightly calcareous mudstone. Color mottling on some samples of red mudstone suggests that the green coloration is secondary. Within the mudstones, occur thin (generally less than 20 ft thick) pebbly sandstone units.

Blanco Basin sandstones are quartzose, silty, light gray in color, moderately to poorly sorted (grain size range is fine to pebble size) and slightly calcareous.

Quartz is the dominant mineralogy, although small amounts of feldspar, and mica are present. Matrix clays are kaolinite and bentonite. Rounded, frosted grains of probable Jurassic origin occur throughout this formation in the sandstones and mudstones.

The Animas Formation contains the same lithologies as the Blanco Basin, but sandstone predominates. Traces of coal were identified from this unit. The resistivity log character for this unit indicates coarsening upwards sequences.

Operator: Needham-Medford
Well: Needham-Medford 1-33
Location: sec 33 T41N R5E, SW NE
County: Saguache
State: Colorado
TD: 8821 ft   KB: 8197 ft   GL: 8180 ft
Date logged: March 1985
Logs used in study: dual induction laterolog
Sample interval examined: none

Formation Tops (depths in feet from kelly bushing):
Spudded in: Conejos Formation
3950 Blanco Basin Formation
4370 Animas Formation
5155 Lewis Shale
5920 Mancos Shale
7310 Greenhorn Limestone Member
7720 Dakota Sandstone
7890 Morrison Formation (+ Junction Creek Sandstone)
8460-TD Precambrian basement

Notes: all formation tops were picked based upon log response.

Operator: Champlin Petroleum
Well: #1 Federal 24-A1
Location: sec 1 T44N R5E
County: Saguache
State: Colorado
TD: 3266 ft   KB: 8950 ft   GL: 8923 ft
Date logged: December 1985
Logs used in study: dual induction/SFL, litho-density/compensated neutron, borehole compensated sonic
Sample interval examined: 380-TD

Formation Tops (depths in feet from kelly bushing)
Spudded in: ash-flow tuff
580 Conejos Formation
2230 Blanco Basin Formation
2630 lower Mancos Shale

2730 Dakota Sandstone
2965 Morrison Formation
3065 Junction Creek Sandstone
3130-TD Precambrian basement

Notes: Blanco Basin Formation is very coarse, cuttings are pebble-sized chips of granite, schist, quartzite

Table A2-1: Paleocurrent data for lower member, Animas Formation at Oil Creek

Location: Oil Creek (37°16'11" to 26" N lat., 106°46'13" to 39" W long.)
Types: i = pebble imbrication; ps = parting step lineation; t = trough

Type	Azimuth (in degrees)	Type	Azimuth (in degrees)
ps	150	ps	135
t	210	i	70
i	125	i	165
i	165	i	155
i	165	i	165
i	195	i	195
i	165	i	145
i	185	i	175
i	115	i	155
i	185	i	115
i	125	i	125
i	125	i	195

Total = 1500
n = 24
$\bar{X}$ = 154

Table A2-2: Paleocurrent data for upper member, Animas Formation, all locations.

Locations:
k = Klutter Mountain (37°04'50" N lat. 106°58'35" W long.)
o = Oil Creek (37°16'35" N lat. 106°46'49" W long.)
c = Castle Creek (37°12'10" N lat. 106°46'34" W long)
h = Highway 160 (37°22'23" N lat. 106°54'22" W long.)
f = Fish Creek (37°14'05" N lat. 106°44'03" W long.)
co = Coal Creek (37°19' N lat. 106°53'18" W long)

Types: i = pebble imbrication; ps = parting step lineation;
t = trough or channel orientation; x = cross-bedding;
l = limbs or logs (parallel to length)

Type	Location	Azimuth	Type	Location	Azimuth
i	k	260	i	k	120
i	k	130	i	o	255
i	o	245	i	o	255
i	o	245	ps	o	175
i	o	175	i	o	165
i	c	360	i	c	345
i	c	335	i	c	365
i	c	372	i	c	355
i	c	365	i	c	205
i	c	195	l	c	130
i	c	225	i	c	300
i	c	390	ps	h	224
i	h	290	i	h	115
i	h	255	i	h	335
i	h	165	i	h	238
i	h	238	i	h	225
ps	f	262	t	co	255
i	co	195	i	co	195
t	co	225	t	co	200
t	co	200	t	co	245
l	co	125	t	co	145
t	co	195	t	co	150
t	co	135	ps	co	145
ps	co	125	ps	co	165

Total = 11,014
n = 48
$\overline{x}$ = 229

APPENDIX 3

Table A3-1: Point-count results from drill cuttings, Blanco Basin Formation in San Luis Basin. SFC = Waggoner-Baldridge San Francisco Creek #1-19 well (sec.19 T39N R6E). TGT = Tennessee Gas Transmission 1 State B well (sec.14 T41N R7E). WECO = Triton/WECO/UPRC 21-B Hellgate well (sec.8 T42N R6E). Sample number indicates depth from kelly bushing. Listed grain parameters explained in Table 1, Part 1.

Sample	SFC	TGT	TGT	TGT	TGT	WECO
number	5210	8100	8720	9600	8470	10320
Qt	459	1374	71	720	1002	251
Qm	386	1300	71	720	897	225
Qp	73	74	0	0	105	26
Qpc	15	60	0	0	54	0
Qite	58	14	0	0	51	26
Ft	331	626	1606	527	747	251
Fp	21	31	181	147	86	39
Fk+Fi	310	595	1425	380	661	212
L	0	0	0	0	0	0
total	790	2000	1677	1247	1749	502
Qm:Ft:Lt where Lt=L+Qp						
%Qm	49	65	4	58	51	45
%Ft	42	31	96	42	43	50
%Lt	9	4	0	0	6	5
total%	100	100	100	100	100	100
Qt:Ft:L where Q=Qm+Qp						
%Qt	58	69	4	58	57	50
%Ft	42	31	96	42	43	50
%L	0	0	0	0	0	0
total%	100	100	100	100	100	100

Table A3-2: Point-count results from drill cuttings, Conejos formation in San Luis Basin. HRT = Heartland #1 La Escondido Uno well (sec.3 T37N R7E). ESG = Energy Service Geothermal well (sec.15 T37N R10E). Sample number indicates depth from kelly bushing. Listed grain parameters explained in Table 1, Part 1.

Sample number	HRT 6200	HRT 6920	ESG 6010	TGT 4510	TGT 4900	TGT 5690	TGT 5920	TGT 5970	TGT 6870	TGT 7060
Qt	8	10	9	8	7	13	3	6	0	0
Qm	8	10	9	8	6	5	3	6	0	0
Qp	0	0	0	0	1	8	0	0	0	0
Ft	130	100	72	101	130	119	157	66	40	53
L	373	402	419	391	363	368	340	428	460	447
Lv	373	402	419	391	362	354	337	428	460	447
Lm	0	0	0	0	0	0	0	0	0	0
Ls	0	0	0	0	1	14	3	0	0	0
total	511	512	500	500	500	500	500	500	500	500
Qm:Ft:Lt where Lt=L+Qp										
%Qm	2	2	2	2	1	1	1	1	0	0
%Ft	25	20	14	20	26	24	31	13	8	11
%Lt	73	78	84	78	73	75	68	86	92	89
total%	100	100	100	100	100	100	100	100	100	100
Qt:Ft:L where Q=Qm+Qp										
%Q	2	2	2	2	1	3	1	1	0	0
%F	25	20	14	20	26	24	31	13	8	11
%L	73	78	84	78	73	73	68	86	92	89
total%	100	100	100	100	100	100	100	100	100	100

Table A3-3: Point-count results from drill cuttings, lower Santa Fe Group, San Luis Basin. RES = Reserve 1-33 NBH well (sec.33 T40N R11E). MAP = Mapco-Amoco 1-32 State well (sec.32 T40N R12E). Sample number indicates depth from kelly bushing. Listed grain parameters explained in Table 1, Part 1.

Sample number	RES 4700	MAP 5430	MAP 5820	MAP 6290	MAP 8170
Qt	66	129	149	87	174
Qm	38	91	145	76	160
Qp	28	38	4	11	14
Ft	176	158	213	126	179
L	258	213	138	287	147
Lv	258	182	125	287	147
Ls	0	31	13	0	22
Lm	0	0	0	0	0
total	500	500	500	500	500
Qm:F:Lt where Lt=L+Qp					
%Qm	8	18	29	15	32
%Ft	35	32	43	25	36
%Lt	57	50	28	60	32
total%	100	100	100	100	100
Q:F:L where Q=Qm+Qp					
%Qt	13	26	30	18	35
%Ft	35	32	42	25	36
%L	52	42	28	57	29
total%	100	100	100	100	100

SUMMARY OF DRILL HOLE DATA, SAN LUIS BASIN

This summary is the author's own interpretation of stratigraphic units in the San Luis Basin based upon analysis of geophysical logs and commercial lithologic logs and microscopic examination of drill cuttings (intervals noted). The wells are listed in the order as in the TABLE OF CONTENTS. Some new composite interpretive logs are included to supplement other publically-available data. All depths and thicknesses are listed in feet.

Operator: Orrin Tucker
Well: #1 Thomas
Location: NE1/4 NE1/4 NE1/4 sec.13 T41N R8E
County: Saguache
State: Colorado
TD: 3023 ft   KB: ?   GL: 7600 ft
Date logged: September 1951
Logs used in study: electrical microlog, published strip log
Sample interval examined: none

Formation Tops (depths in feet from kelly bushing (?))
Spudded in Quaternary alluvium
300 Alamosa Formation
1210 Lower Santa Fe Group
3650 Oligocene tuffs (Carpenter Ridge Tuff)
3885 Fish Canyon Tuff
4520 Masonic Park Tuff (?)
5360 Treasure Mountain Tuff
5550 Conejos Formation
7910-TD Blanco Basin Formation

Notes: strip log published by Powell (1958, p.275-280).

Operator:Heartland Oil and Gas Inc.
Well: No.1 La Escondido Uno
Location: sec.3 T37N R7E
County: Rio Grande
State: Colorado
TD: 8120 ft   KB: 7941 ft   GL: 7929 ft
Date logged: November 1989
Logs used in study: dual induction guard log; spectral density dual spaced neutron; mudlog

Sample interval examined: 2062'-TD

Formation Tops (depths in feet from kelly bushing)
Spudded in Los Pinos Formation
2550 Conejos Formation
6949 Blanco Basin Formation
7110-TD Precambrian granite-gneiss basement

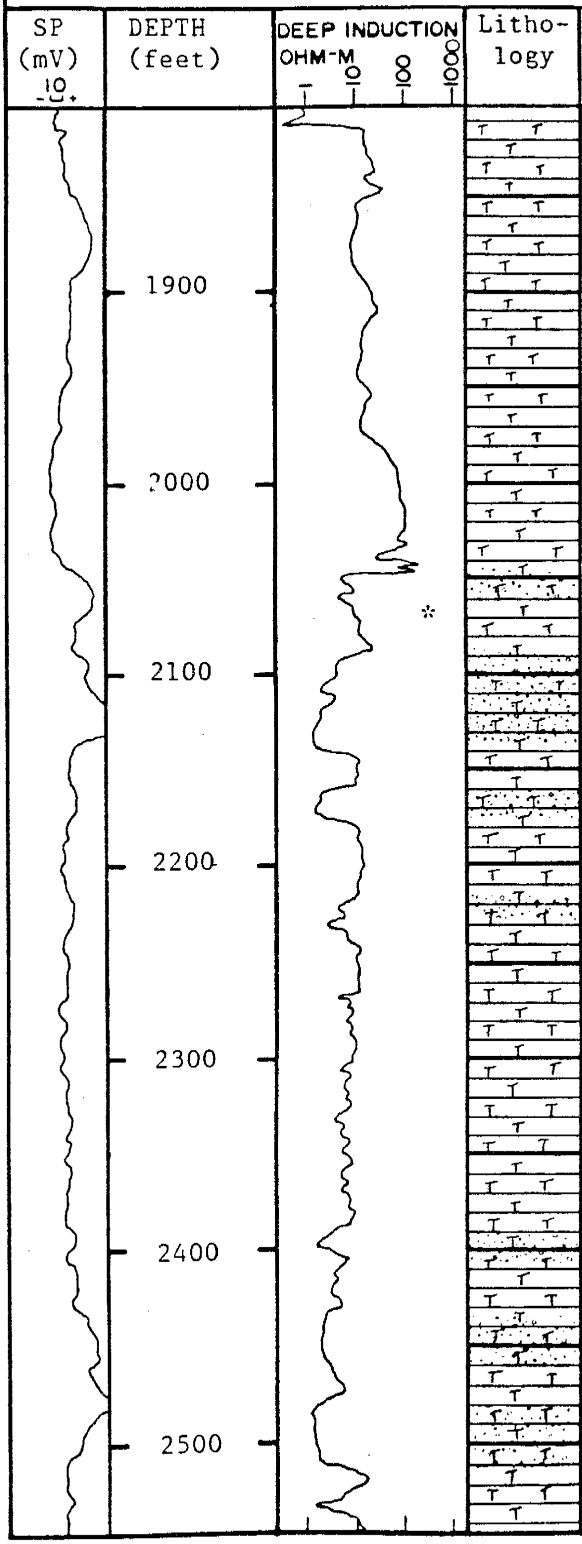
Notes: This well was spudded on a Quaternary-Tertiary pediment gravel surface developed over the Los Pinos Formation (Miocene-Pliocene). The water table was struck at about 400'(?); probably in Los Pinos gravels at-or-near the top of the Hinsdale Basalt (if it occurs). Prior to the first preserved sample at 2062', the well drilled (from top to bottom) Los Pinos gravels with interbedded Hinsdale Basalt, Masonic Park Tuff, and Treasure Mountain Tuff. This stratigraphic section is inferred from outcrops between the well site and Rock creek, 1.5 miles west of the well site.

The unit from 2062' to 2550' is a series of ash-flow tuffs and nonwelded, reworked tuffs (tuffaceous sandstones) with high resistivity, slightly high gamma, and high density compared to the Conejos Formation volcaniclastic rocks further down the hole. This unit is probably Treasure Mountain Tuff.

The Conejos Formation was evidenced by a slight increase in drilling rate, decrease in tuff content, and an increase in andesitic lava flow rock fragments when compared to overlying tuffs. The Conejos Formation in this well can be roughly divided into 3 units; an upper unit with andesite lava flows, a middle unit containing ash-flow tuff (generally lacking significant mafic minerals), and a lower unit with andesite lava flows. Each of these units contain thick sections of volcanic breccia, conglomerate, and sandstone. Flows and tuffs are best distinguished from other lithologies by monolithologic cuttings and high resistivity (deep induction resistivity greater than 10 ohmm in this well).

The base of the Conejos/top of the Blanco Basin Formation was drilled at 6949' as evidenced by lower density and resistivity and relatively higher gamma ray than the Conejos and a change in sample lithology to soft claystone/mudstone. A number of cuttings of mudstone showed evidence that color had been altered (half of grain red grading to green in other half). Sand grains <u>within</u> individual mudstone grains indicate a Precambrian, non-volcanic source.

Heartland Oil and Gas Inc.
No.1 La Escondido Uno
Sec. 3 T37N R7E Rio Grande County, Colorado



REMARKS

TOP OF LOG IN TREASURE MOUNTAIN TUFF

Note: * indicates see attached detailed description.

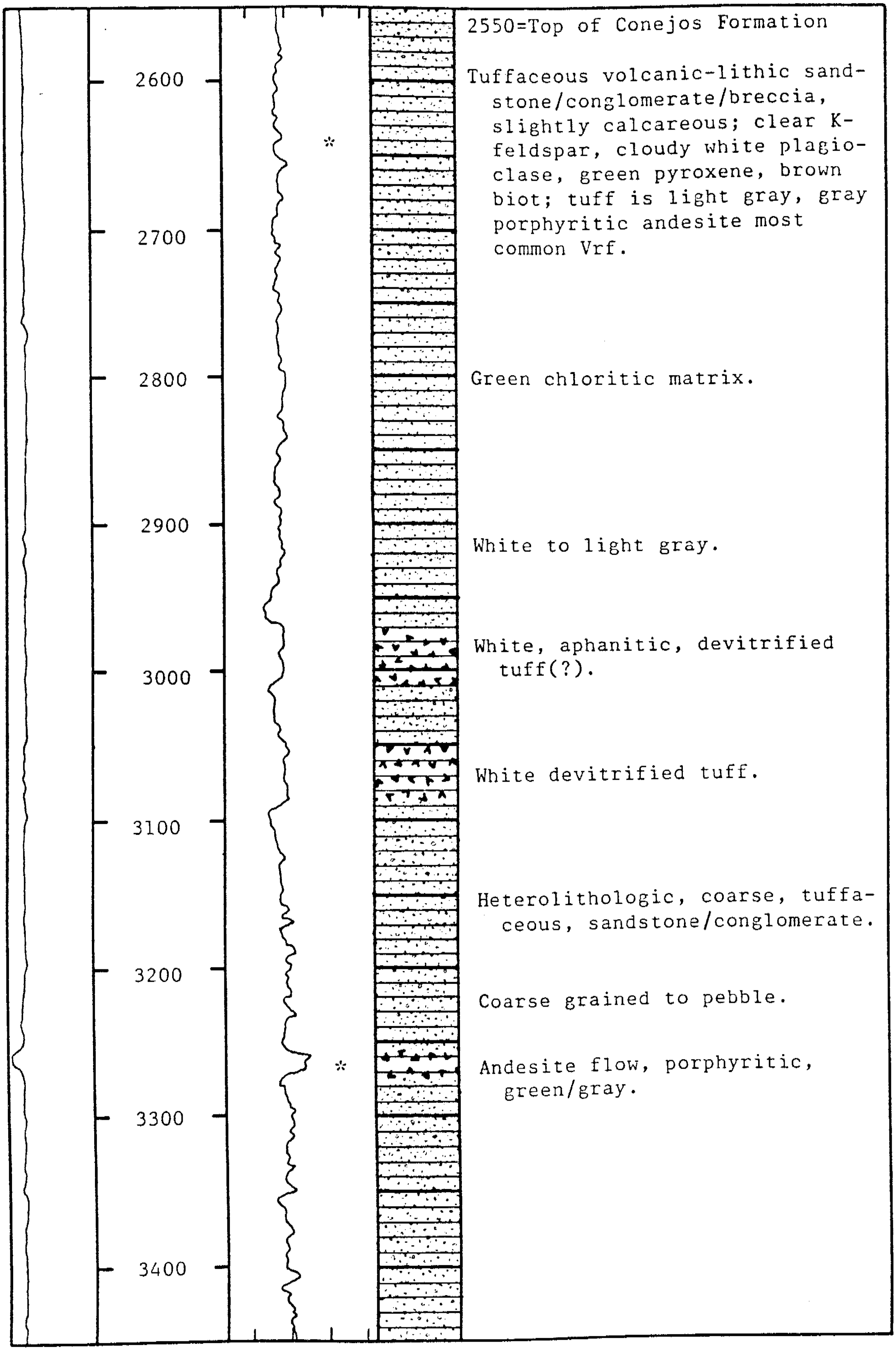
Gray

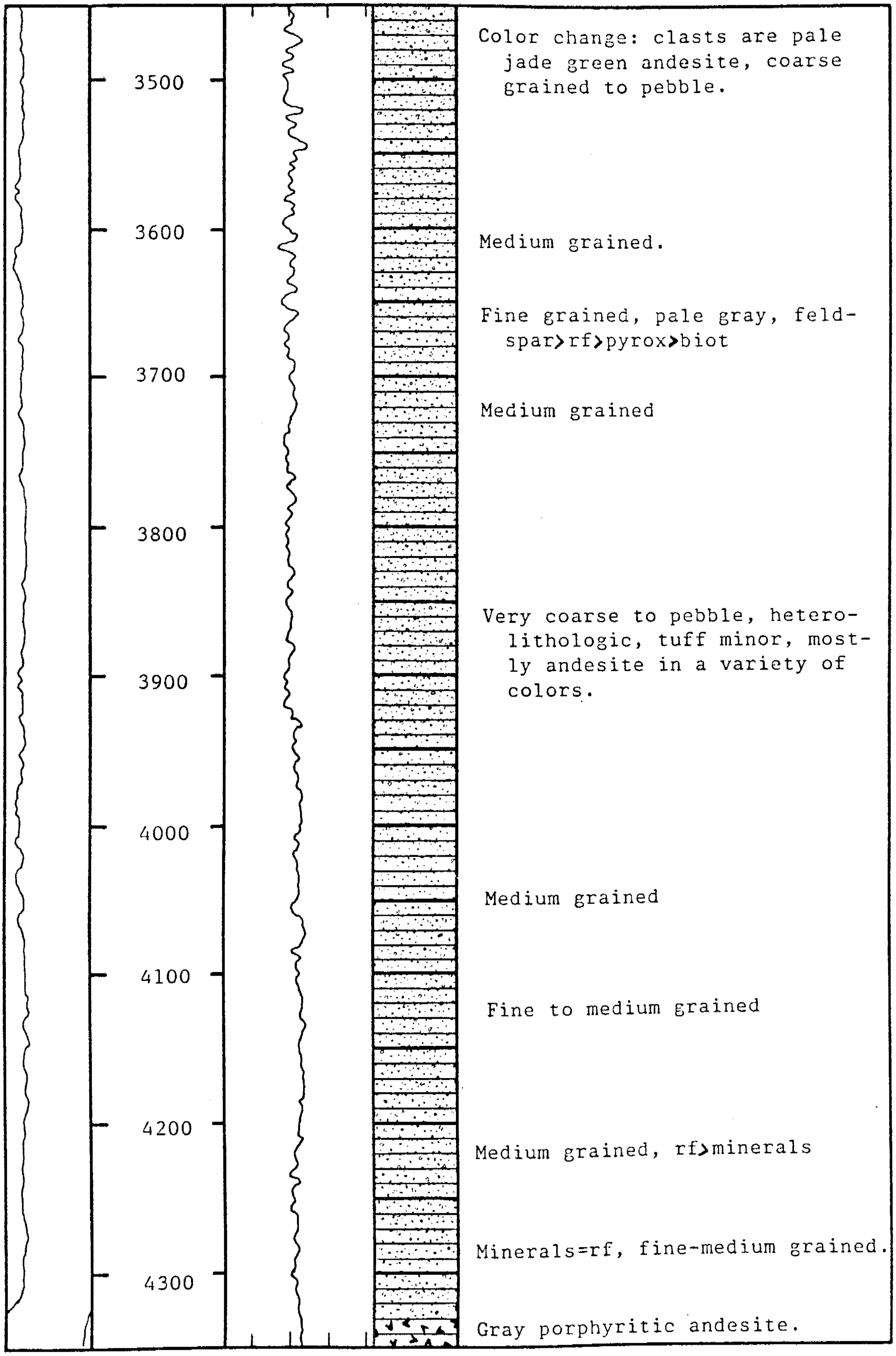
Interbedded tuffs: glassy, aphanitic (rare feldspar phenocrysts) ash-flow tuff and reworked tuff. Minerals include white to clear feldspars, large black biotite, green pyroxene; obsidian and perlite common.

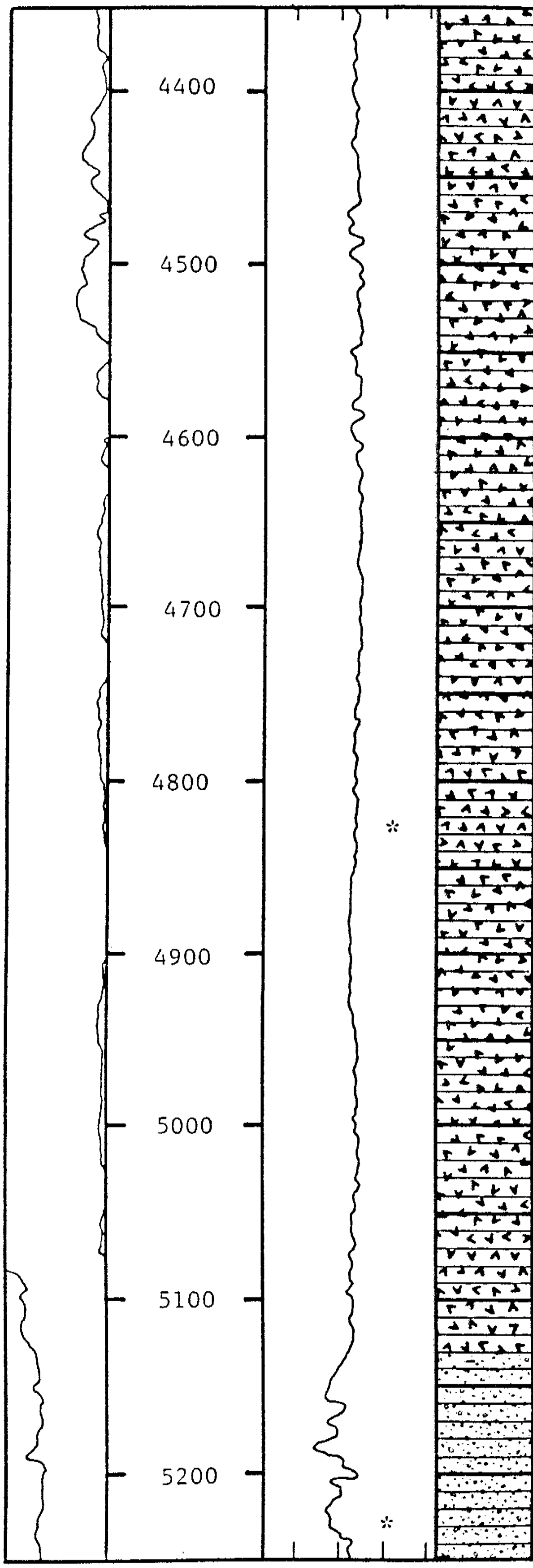
Gray

Gray

2550=Base Treasure Mtn. Tuff


2550=Top of Conejos Formation
Tuffaceous volcanic-lithic sandstone/conglomerate/breccia, slightly calcareous; clear K-feldspar, cloudy white plagioclase, green pyroxene, brown biot; tuff is light gray, gray porphyritic andesite most common Vrf.
2600
2700
2800
Green chloritic matrix.
2900
White to light gray.
White, aphanitic, devitrified tuff(?).
3000
White devitrified tuff.
3100
Heterolithologic, coarse, tuffaceous, sandstone/conglomerate.
3200
Coarse grained to pebble.
Andesite flow, porphyritic, green/gray.
3300
3400


3500
3600
3700
3800
3900
4000
4100
4200
4300
Color change: clasts are pale jade green andesite, coarse grained to pebble.
Medium grained.
Fine grained, pale gray, feldspar>rf>pyrox>biot
Medium grained
Very coarse to pebble, heterolithologic, tuff minor, mostly andesite in a variety of colors.
Medium grained
Fine to medium grained
Medium grained, rf>minerals
Minerals=rf, fine-medium grained.
Gray porphyritic andesite.



Gray, fine grained cuttings; andesite lava flow.

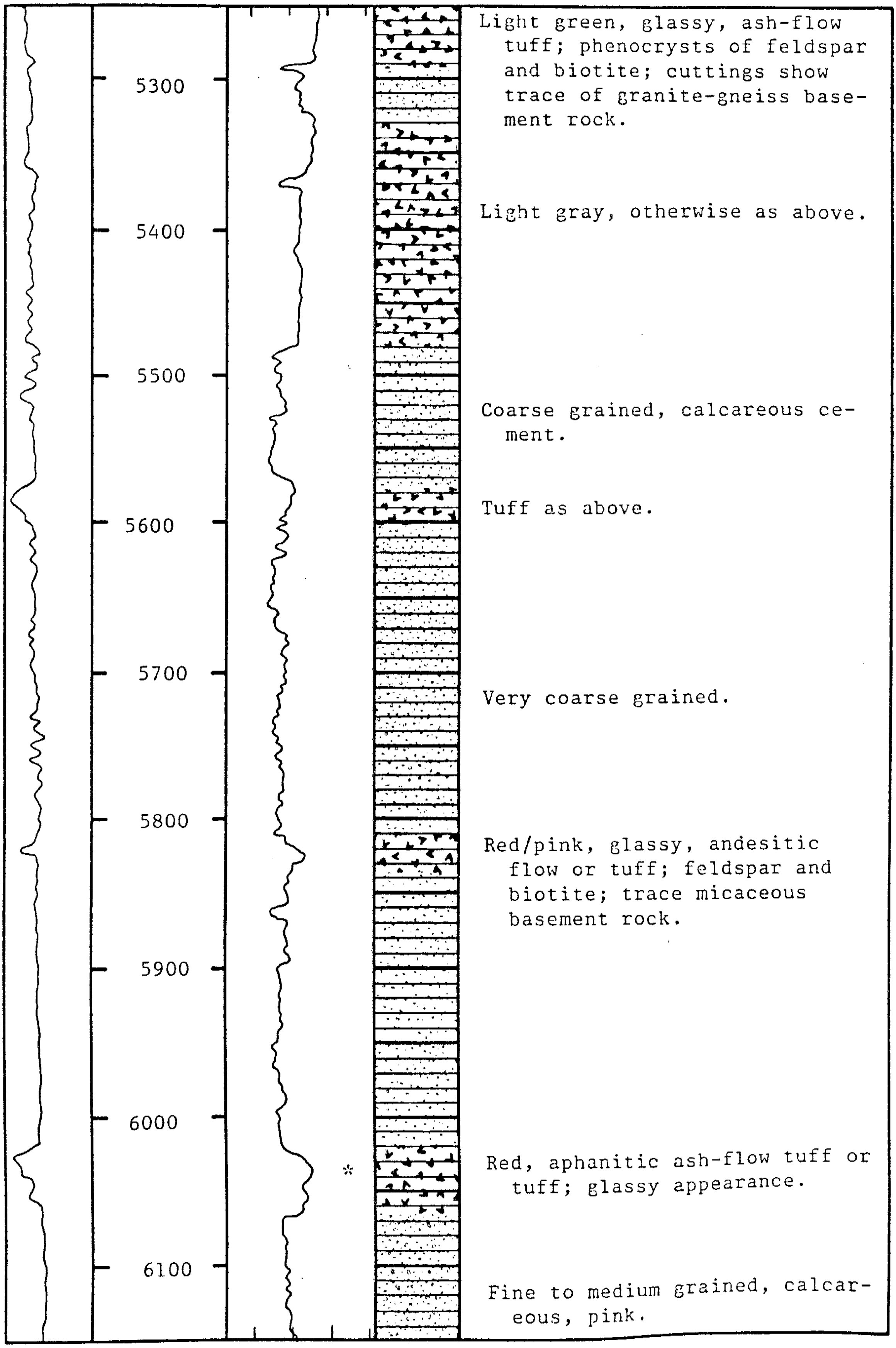
Sample is monolithologic with few cavings.

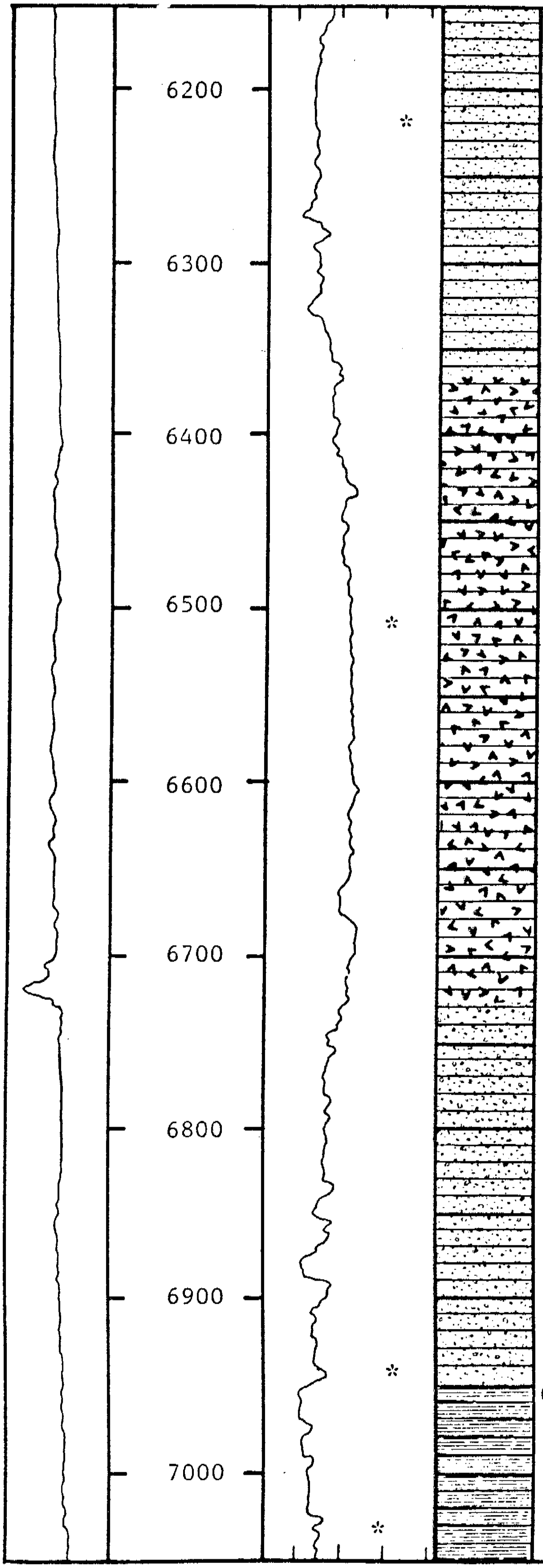
Light gray.

Medium gray.

Medium grained cuttings.

Fine grained, well sorted, volcaniclastic sandstone.
fs>vrf>biot+pyrox.


5300
5400
5500
5600
5700
5800
5900
6000
6100
Light green, glassy, ash-flow tuff; phenocrysts of feldspar and biotite; cuttings show trace of granite-gneiss basement rock.
Light gray, otherwise as above.
Coarse grained, calcareous cement.
Tuff as above.
Very coarse grained.
Red/pink, glassy, andesitic flow or tuff; feldspar and biotite; trace micaceous basement rock.
Red, aphanitic ash-flow tuff or tuff; glassy appearance.
Fine to medium grained, calcareous, pink.



Calcite crystals common.

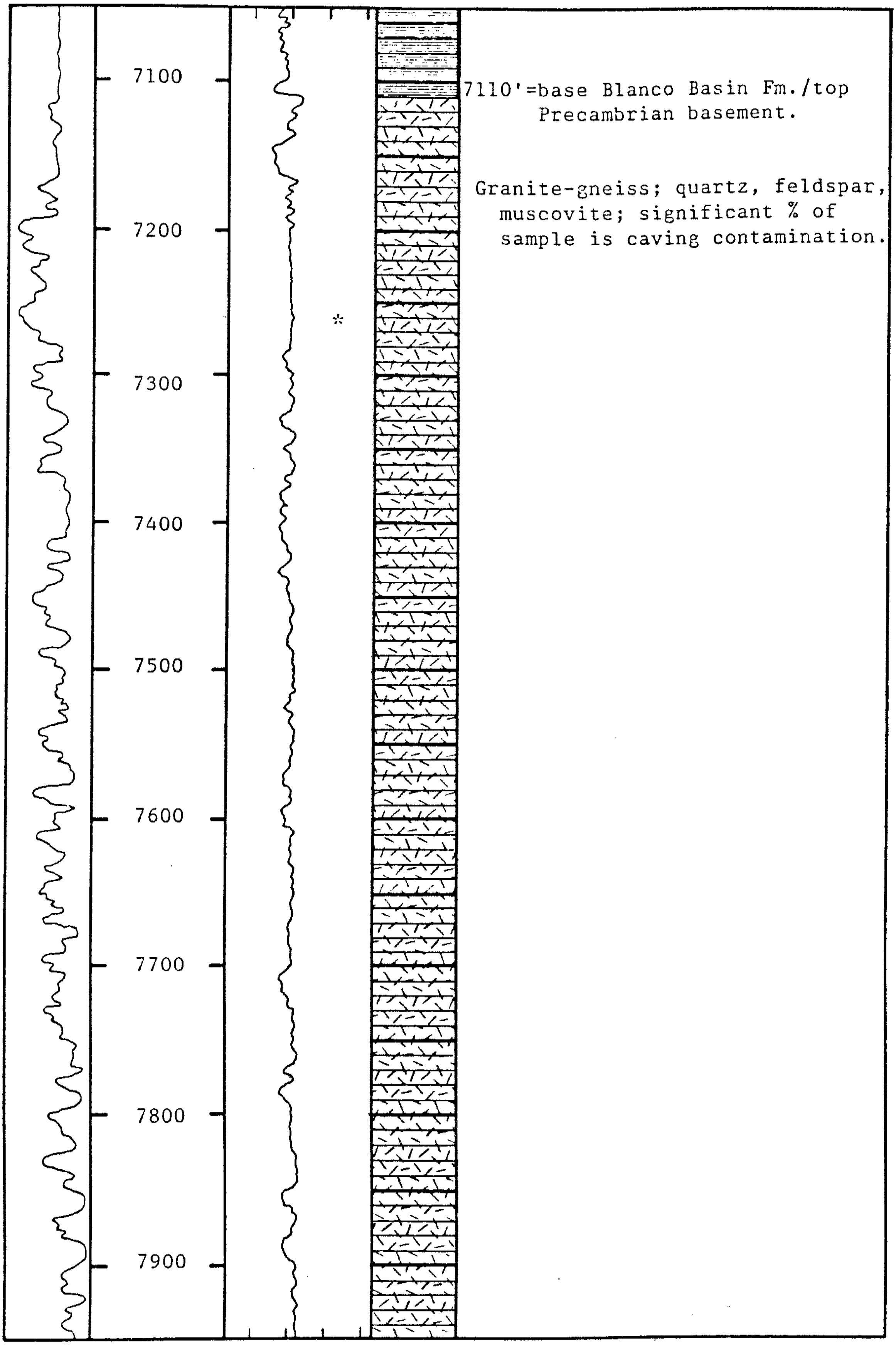
Glassy gray welded tuff is common constituent.

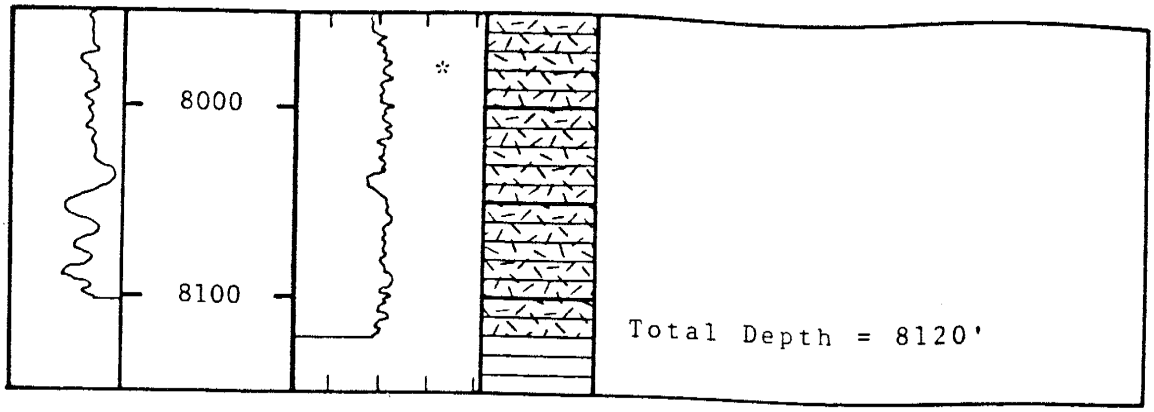
Dark gray/green, fine grained cuttings, porphyritic andesite with coarse feldspar phenocrysts.

Coarse grained, calcareous, light gray mudstone is occasional grain.

6949'=base Conejos Fm./top Blanco Basin F.

Gray, green, and red-brown claystone with sandy, micaceous mudstone.


7100
7110'=base Blanco Basin Fm./top Precambrian basement.
Granite-gneiss; quartz, feldspar, muscovite; significant % of sample is caving contamination.
7200
*
7300
7400
7500
7600
7700
7800
7900



Thin Section Descriptions

2062'-70' Ash-flow tuff. Cuttings are light green and have a glassy appearance; color ranges to dark gray or white; minerals include large biotites up to 2mm in size, clear to white feldspar, black glass (obsidian), clear perlite, green pyroxene. Thin section: In ppl, color is light to medium brown to light green, samples go extinct in x-nic (typical for glass); moderately welded (flattening of shards & pumice), devitrified and altered (glass converting to zeolite and clay). Phenocrysts include: plagioclase, sanidine, biotite, pyroxene. Other constituents: pumice and volcanic rock fragments. Cavings: basalt

2620'-30' Volcanic-lithic conglomerate. Cuttings are medium gray, slightly calcareous, containing dark gray andesite and minor glassy light-medium gray tuff. Cuttings are coarse-pebble in size. Thin section: No interstitial sedimentary-origin material was found adhering to any grains; however, the variety of volcanic rock fragments suggests a heterogenous mix of brownish (ppl) tuffaceous fragments, and mafic to intermediate flow rock fragments. Minor occurence of calcite spar (after plagioclase?). Phenocrysts in the flow rock: Plagioclase, opaque (magnetite(?) with some altered to hematite), pyroxene, sanidine, hornblende, biotite. Phenocrysts in tuff: sanidine, plagioclase, biotite.

3250'-70' Andesitic lava flow. Cuttings are medium to coarse volcanic rock fragments, generally green/gray. Thin section: Sample is phenocryst-rich with plagioclase the most abundant. Other minerals include sanidine, pyroxene, biotite, and hornblende. Some plagioclase is concentrically zoned. Minor occurrence of calcite spar. Cavings represented are tuff and fine grain size minerals from volcanic sandstone (?).

4790'-4830' Andesitic lava flow. Cuttings are monolithologic, medium gray, and medium grained. Thin section: This sample is essentially the same as sample interval 3250'-70' but finer grained. Tuffaceous grains are absent from this sample.

5210'-30' Volcanic-lithic sandstone. Cuttings are fine grained, well sorted. Minerals in thin section: pyroxene, plagioclase, sanidine, gold to red biotite, hornblende. Sample is tuffaceous and volcanic-lithic fragment-rich. Calcite spar is present.

6020'-40' Rhyolitic ash-flow tuff or lava flow. Cuttings are reddish and aphanitic. Thin section: finely crystalline glassy flow or ash-flow tuff; distinctive appearance due to presence of opaque needles which are 30% of sample and show alignment in the same direction. Calcite spar adheres to some grains. Faint shard-like texture is aligned with opaques. Micro-laths of feldspar make up parts of groundmass. Contains darker rfs with similar characteristics as groundmass, needles do not cross boundary between the two.

6200'-20': Tuffaceous sandstone. Cuttings contain white devitrified tuff and are calcareous. Thin section: calcite is abundant in the sample and takes several forms: 1) cement in fine-grained sandstone, 2) replacement of volcanic lithic grains (near total replacement of all minerals and groun- mass, 3) microspar grains showing ghosts of glass shards, 4) spar and microspar of unknown origin. These forms suggest that the deposit is one where calcite is being deposited as a secondary mineral rather than as a sedimentary limestone. Presence of a variety of volcanic rock fragments as well as fine mineral grains suggest that the deposit is lithic sandstone.

6500'-20' Andesitic flow. Cuttings are of a dark gray, porphyritic lava flow with phenocrysts of white feldspar. Thin section: black groundmass (opaque in x-nic) with phenocrysts of plagioclase and sanidine, minor small pyroxenes.

6920'-40' Volcanic breccia/conglomerate. Cuttings have a sandy matrix, and are calcareous. Light gray mudstone is present (slightly calcareous), but majority of cuttings are rock fragments from lava flows. Thin section: a variety of fragments were found including feldspathic, micaceous siltstone and sandstone, volcanic rock fragment, claystone fragments, granite/gneiss rock fragments, minor tuffaceous material. Calcite is common as a replacement mineral in some feldspars and is also present as spar cement and as microspar cement in siltstone/sandstone.

7040'-60' Sandy mudstone and claystone. Cuttings are gray and minor gray/green and red/brown dense claystone plus a minor occurrence of sandy red/brown mudstone. Black obsidian is present (caving?) and is distinguished from coal by its hardness, inability to burn and presence of feldspar phenocrysts. In thin section, some grains are laminated, and display alignment of opaques (organics?). Some grains are calcareous. Silty (quartz and feldspar silt) grains tend to be micaceous. Granitic rock fragments are present. No volcanic rock fragments were found within the mudclast grains, thus nonvolcanic.

7255'-70' and 8070-8090' Granite-gneiss. Cuttings are mostly quartz and feldspar. Thin section: minerals include strained and vacuoled quartz, orthoclase and microcline, plagioclase, muscovite, biotite. Some quartz has a composite texture resembling metamorphic quartzite; some of these are schistose. A notable few of the samples between 7255' and TD contained abundant gray claystone similar to that above 7110', however, this is probably caving contamination of the samples (note wash-cut in the well at 7000'...cavings from this washout can only contaminate samples below this horizon). There is no correlation between the shale-rich samples and high gamma/low resistivity/low density on the geophysical logs.

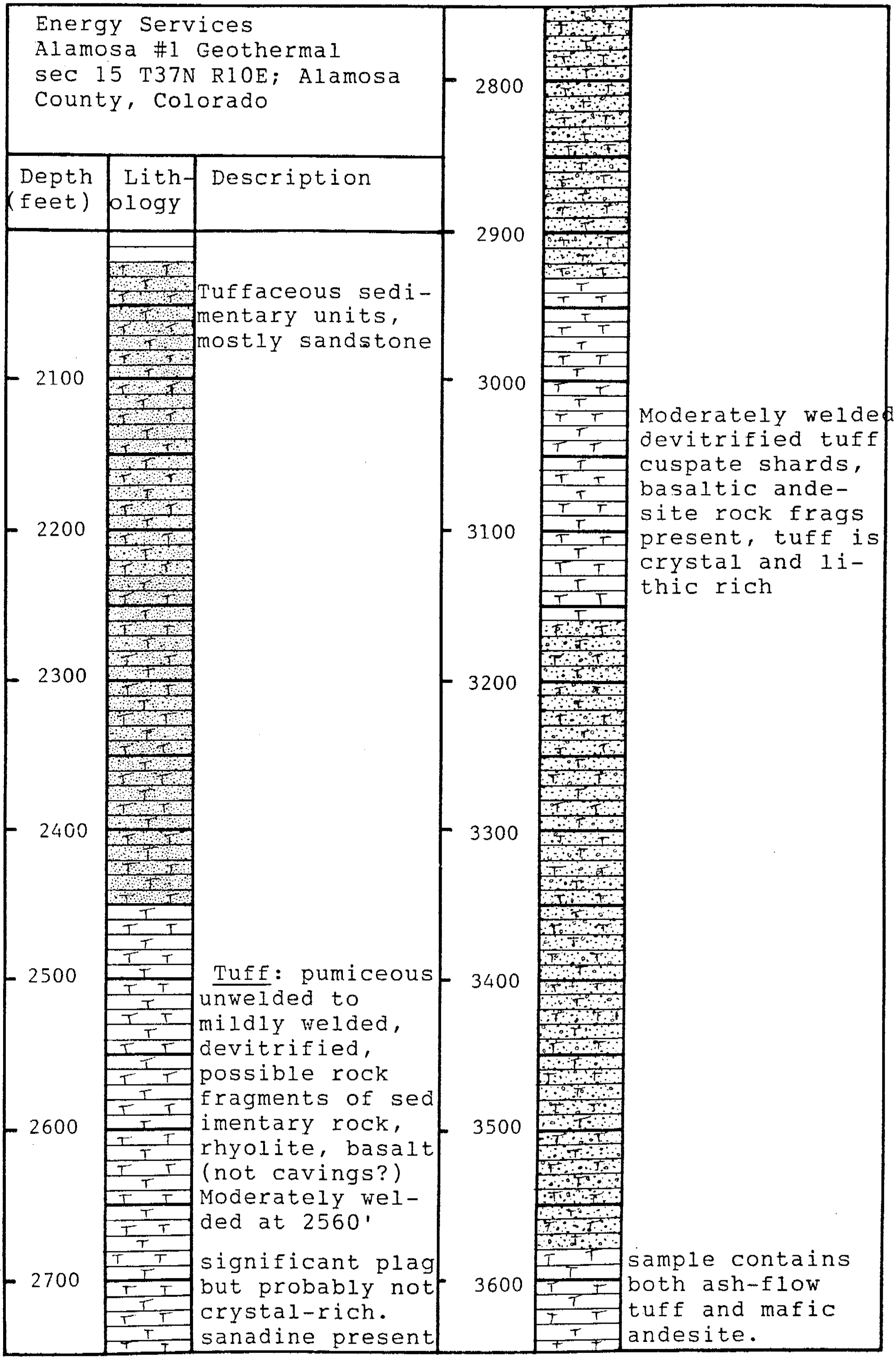
Operator: Energy Services
Well: Alamosa #1 Geothermal
Location: sec 15 T37N R10E
County: Alamosa
State: Colorado
TD: 7125 ft KB: ? GL: 7535 ft (approximate)
Date logged: 1982(?)
Logs used in study: drilling rate (geolograph), gamma and neutron from 1780-2500'
Sample interval examined: 2020-TD

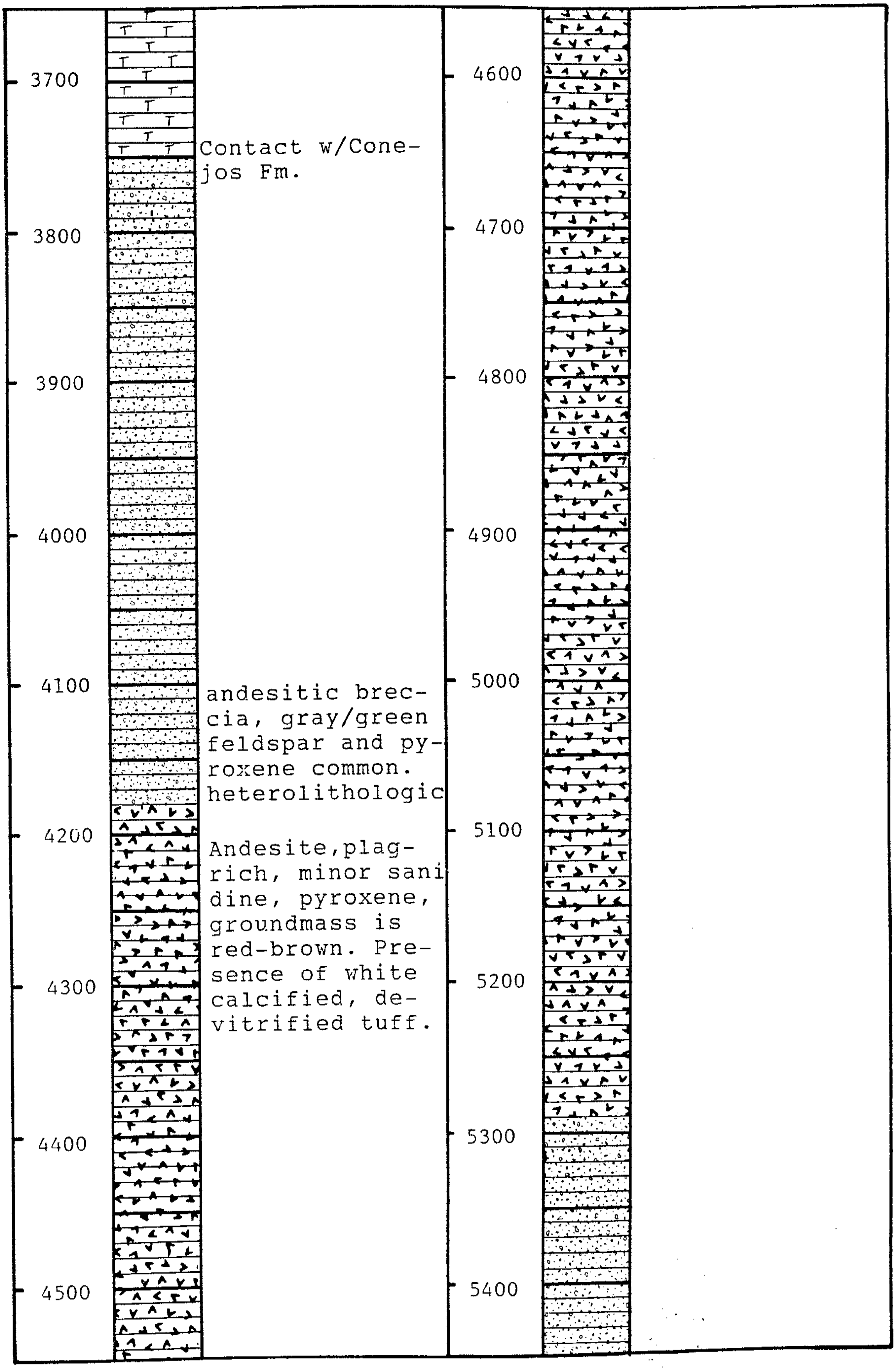
Formation Tops (depths in feet from kelly bushing)
Spudded in: Alamosa Formation (Santa Fe Group)
1980 late Oligocene tuffs
3750 Conejos Formation
6370 Blanco Basin Formation? (see notes)
6780-TD Precambrian basement

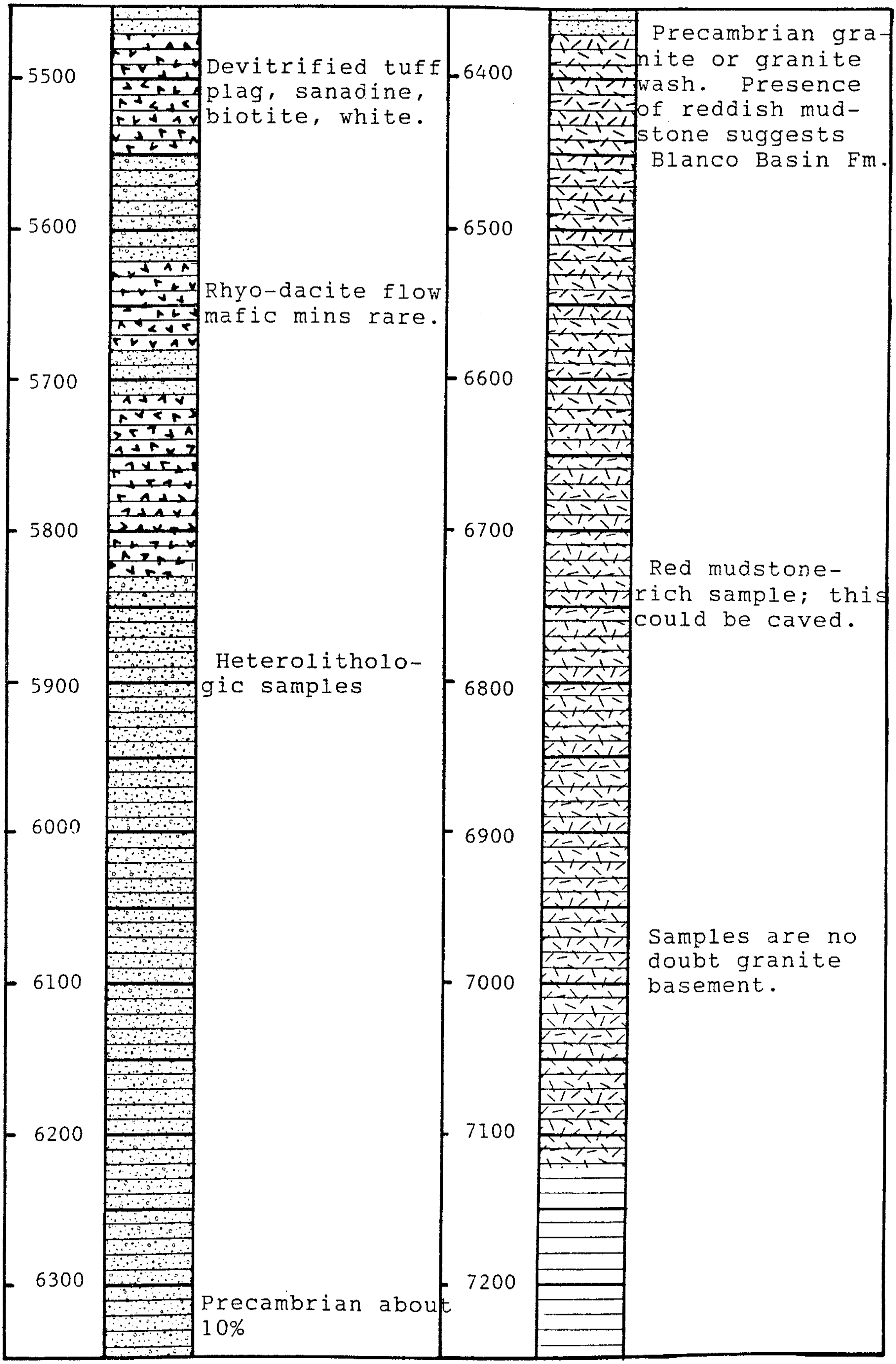
Notes: There is no information to indicate the contact between the Alamosa Formation and the lower Santa Fe Group. The contact between the lower Santa Fe Group and the top of Oligocene tuffs is at about 1980 ft, as marked by increase in gamma and neutron counts. Ash-flow tuffs and interbedded tuffaceous sediments occur in the interval 2450-3750 ft. From cuttings, ash-flow tuffs are tentatively identified as: Fish Canyon Tuff (2450-2750 ft), Masonic Park Tuff (2930-3160 ft), Treasure Mountain Tuff (La Jara Canyon Member? 3580-3750 ft).

From 3750-6370 ft the well drilled Conejos Formation which consists of andesite flows and coarse volcaniclastic facies to 5470 ft. From 5470-6110 ft is a series of tuffaceous pyroclastic deposits. From 6110-6370 ft there is a return to andesitic volcaniclastic rock.

At 6370 ft is a transition to Precambrian-derived material, but volcanic cavings make up a majority of sample to 7125 ft. This is questionably Blanco Basin due to the presence of reddish mudstone (which could also have caved from the Santa Fe Group). The transition could also be the top of Precambrian basement. Available data does not rule out either choice. Abundance of mica and change in drilling characteristics (bit weight and drilling speed) at about 6780 ft might indicate the top of Precambrian.


Energy Services
Alamosa #1 Geothermal
sec 15 T37N R10E; Alamosa County, Colorado
Depth (feet)
Lithology
Description
2100
2200
2300
2400
2500
2600
2700
Tuffaceous sedimentary units, mostly sandstone
Tuff: pumiceous unwelded to mildly welded, devitrified, possible rock fragments of sedimentary rock, rhyolite, basalt (not cavings?) Moderately welded at 2560'
significant plag but probably not crystal-rich. sanadine present
2800
2900
3000
3100
3200
3300
3400
3500
3600
Moderately welded devitrified tuff cuspate shards, basaltic andesite rock frags present, tuff is crystal and lithic rich
sample contains both ash-flow tuff and mafic andesite.


3700
3800
3900
4000
4100
4200
4300
4400
4500
Contact w/Conejos Fm.
andesitic breccia, gray/green feldspar and pyroxene common. heterolithologic
Andesite, plag-rich, minor sanidine, pyroxene, groundmass is red-brown. Presence of white calcified, devitrified tuff.
4600
4700
4800
4900
5000
5100
5200
5300
5400


5500
Devitrified tuff plag, sanadine, biotite, white.
5600
Rhyo-dacite flow mafic mins rare.
5700
5800
Heterolithologic samples
5900
6000
6100
6200
6300
Precambrian about 10%
6400
Precambrian granite or granite wash. Presence of reddish mudstone suggests Blanco Basin Fm.
6500
6600
6700
Red mudstone-rich sample; this could be caved.
6800
6900
Samples are no doubt granite basement.
7000
7100
7200

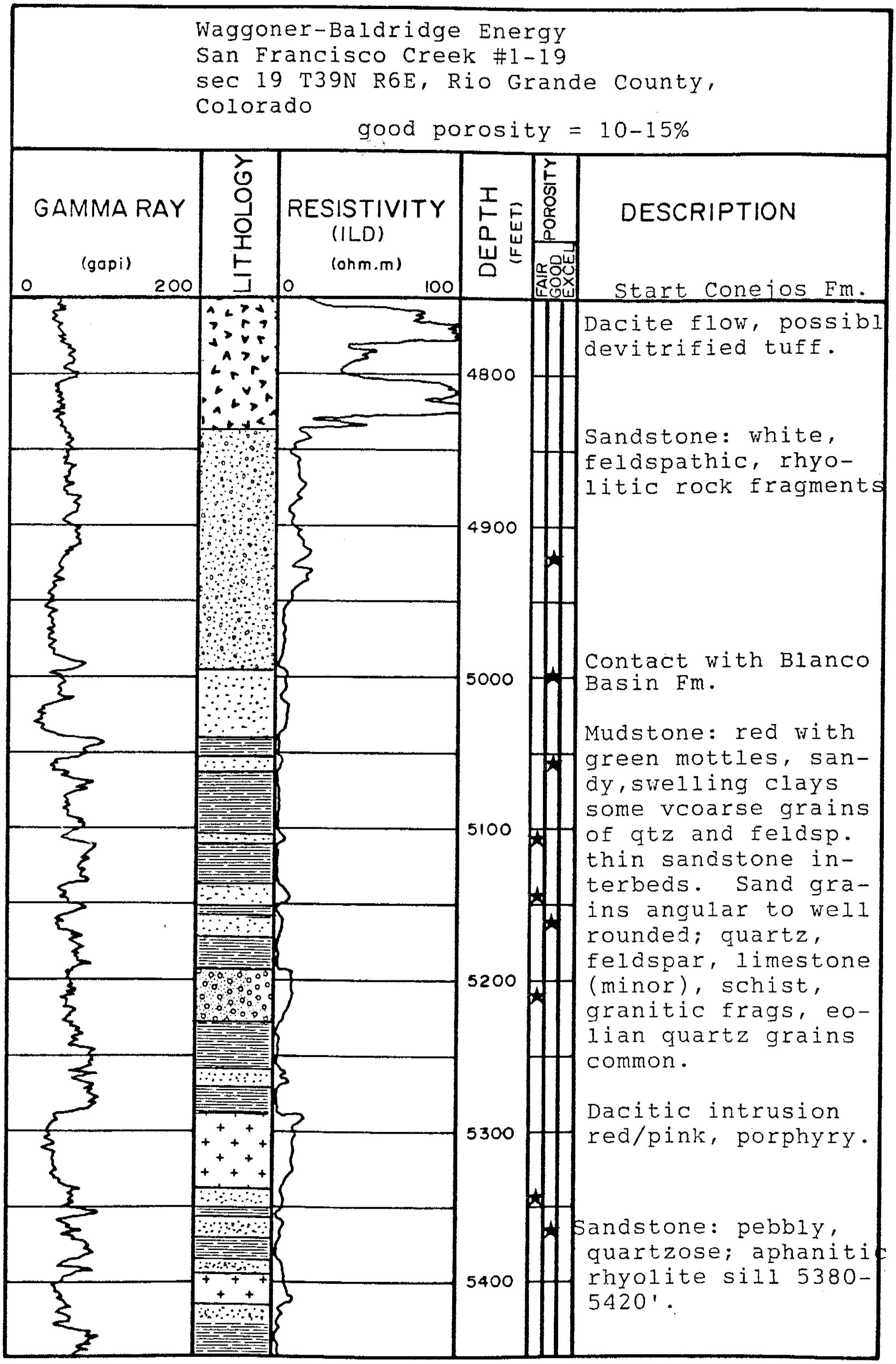
Operator: W.F. Carr
Well: Kennedy and Williams #1
Location: sec 11 T41N R9E, C SW
County: Saguache
State: Colorado
TD: 6831 ft KB:7574 ft GL: 7562
Date logged: August 1952
Logs used in study: electrical
Sample interval examined: none

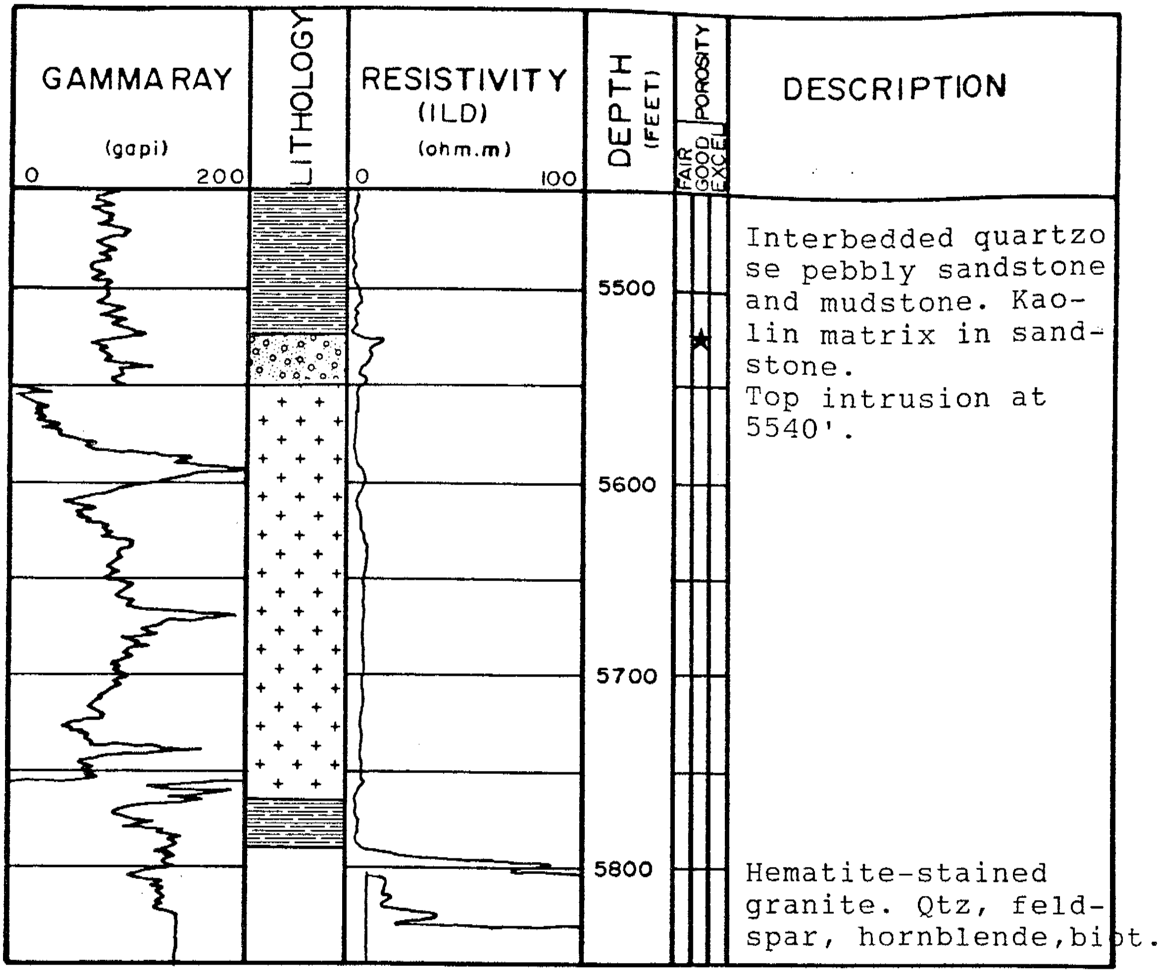
Formation Tops (depths in feet from kelly bushing):
Spudded in Quaternary alluvium
250 Alamosa Formation
1170 Lower Santa Fe Group
4112 Oligocene tuffs (Carpenter Ridge Tuff)
4210 Fish Canyon Tuff
4755 Masonic Park Tuff (?)
5415 Treasure Mountain Tuff
5669-TD Conejos Formation

Operator: Waggoner-Baldridge Energy
Well: San Francisco Creek #1-19
Location: sec 19 T39N R6E, 600 ft FWL, 1930 ft FSL
County: Rio Grande
State: Colorado
TD: 5873 ft KB: 8561.5 ft GL: 8535 ft
Date logged: November 1986
Logs used in study: dual induction/SFL; borehole compensated sonic; litho-density/compensated neutron;
Sample interval examined: 3000'-TD

Formation Tops (depths in feet from kelly bushing):
Spudded in: Conejos Formation (or Treasure Mountain Tuff?)
4990 Blanco Basin Formation
5790-TD Precambrian basement

Notes: 305 ft (total) of silicic (rhyolite?) sills occur in the Blanco Basin Formation at the intervals: 5270-5335 ft, 5380-5420 ft and 5540-5740 ft. A composite interpretive log for the Blanco Basin Formation follows.

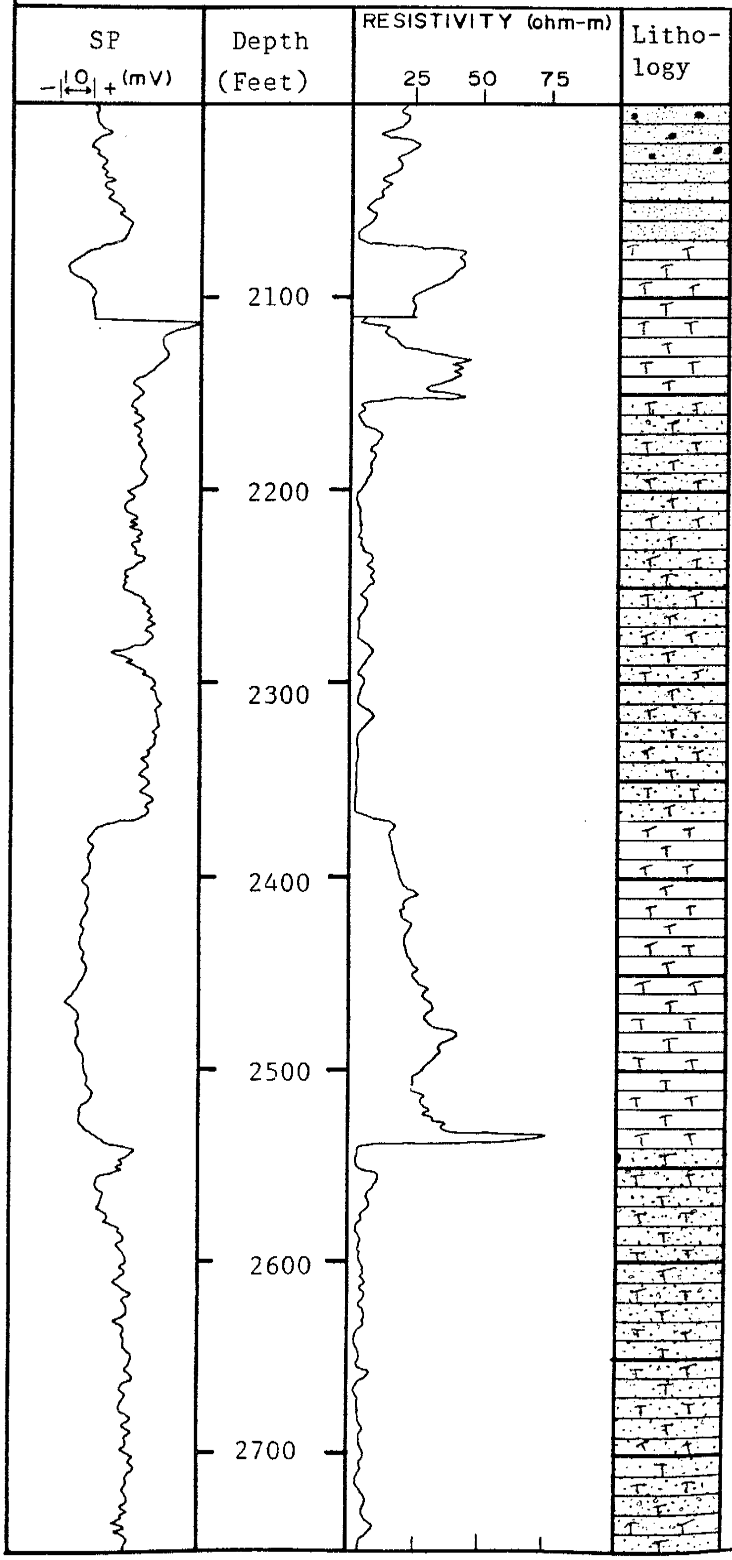

Waggoner-Baldridge Energy
San Francisco Creek #1-19
sec 19 T39N R6E, Rio Grande County,
Colorado
good porosity = 10-15%
GAMMA RAY
(gapi)
0
200
LITHOLOGY
RESISTIVITY
(ILD)
(ohm.m)
0
100
DEPTH
(FEET)
POROSITY
FAIR
GOOD
EXCEL
DESCRIPTION
Start Conejos Fm.
4800
4900
5000
5100
5200
5300
5400
Dacite flow, possibl devitrified tuff.
Sandstone: white, feldspathic, rhyolitic rock fragments
Contact with Blanco Basin Fm.
Mudstone: red with green mottles, sandy, swelling clays some vcoarse grains of qtz and feldsp. thin sandstone interbeds. Sand grains angular to well rounded; quartz, feldspar, limestone (minor), schist, granitic frags, eolian quartz grains common.
Dacitic intrusion red/pink, porphyry.
Sandstone: pebbly, quartzose; aphanitic rhyolite sill 5380-5420'.



Operator: Tennessee Gas Transmission Co.
Well: Colorado State B-#1
Location: sec 14 T41N R7E, SW SE
County: Saguache
State: Colorado
TD: 10350 ft   KB: 7674.5 ft   GL: 7661 ft
Date logged: April 1959
Logs used in study: induction-electrical; microlog
Sample interval examined: thin sections from 2100'-TD; cuttings from 7540'-TD

Formation Tops (depths in feet from kelly bushing)
Spudded in Quaternary alluvium (covering Los Pinos Fm.)
2072 Oligocene tuffs (Carpenter Ridge Tuff)
2370 Fish Canyon Tuff
3435 Treasure Mountain Tuff
3580 Conejos Formation
7810 Blanco Basin Formation
9920 Precambrian basement

Tennessee Gas Transmission Co.
#1-B State
Sec. 14 T41N R7E Saguache County, Colorado



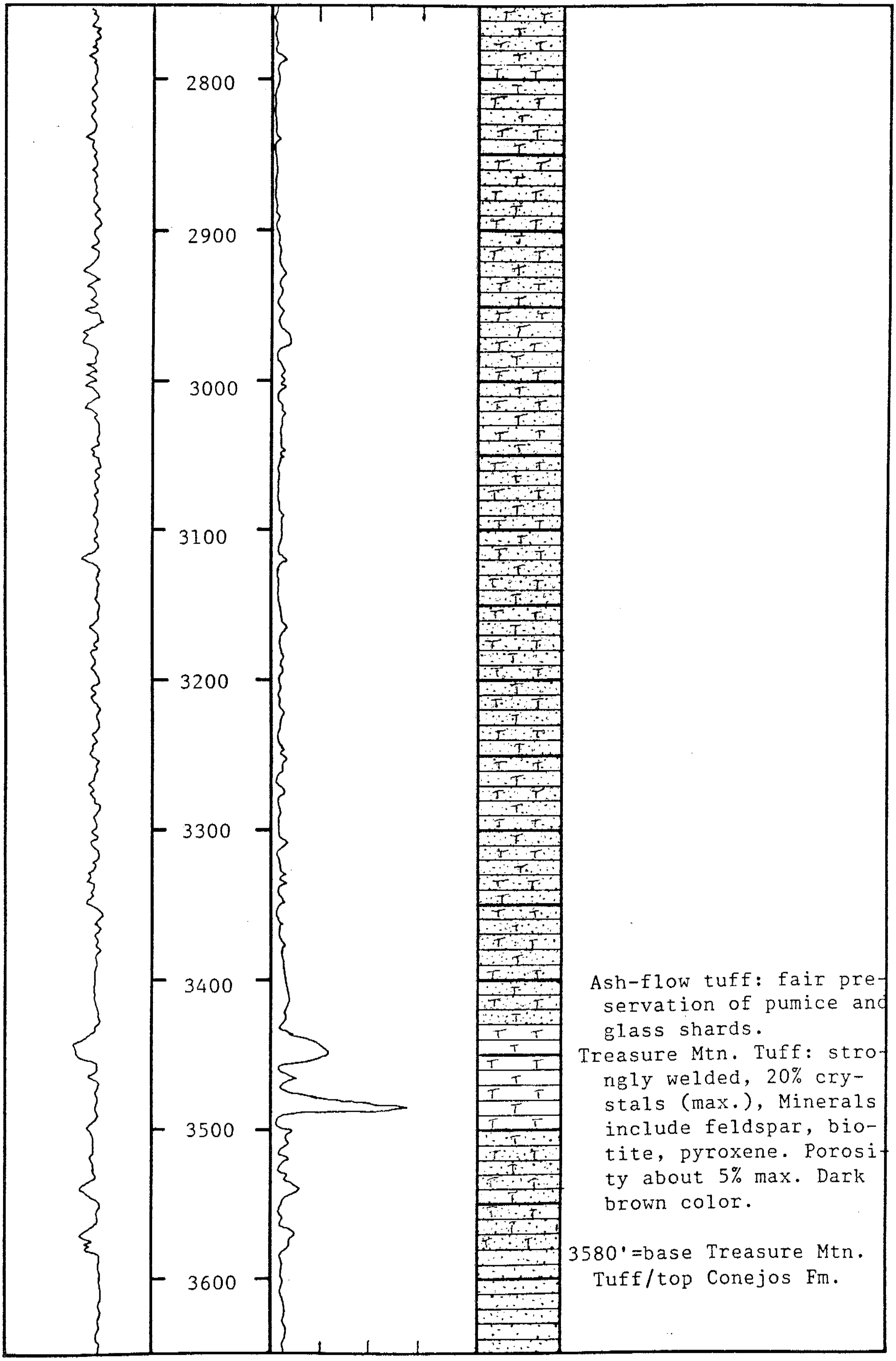
REMARKS

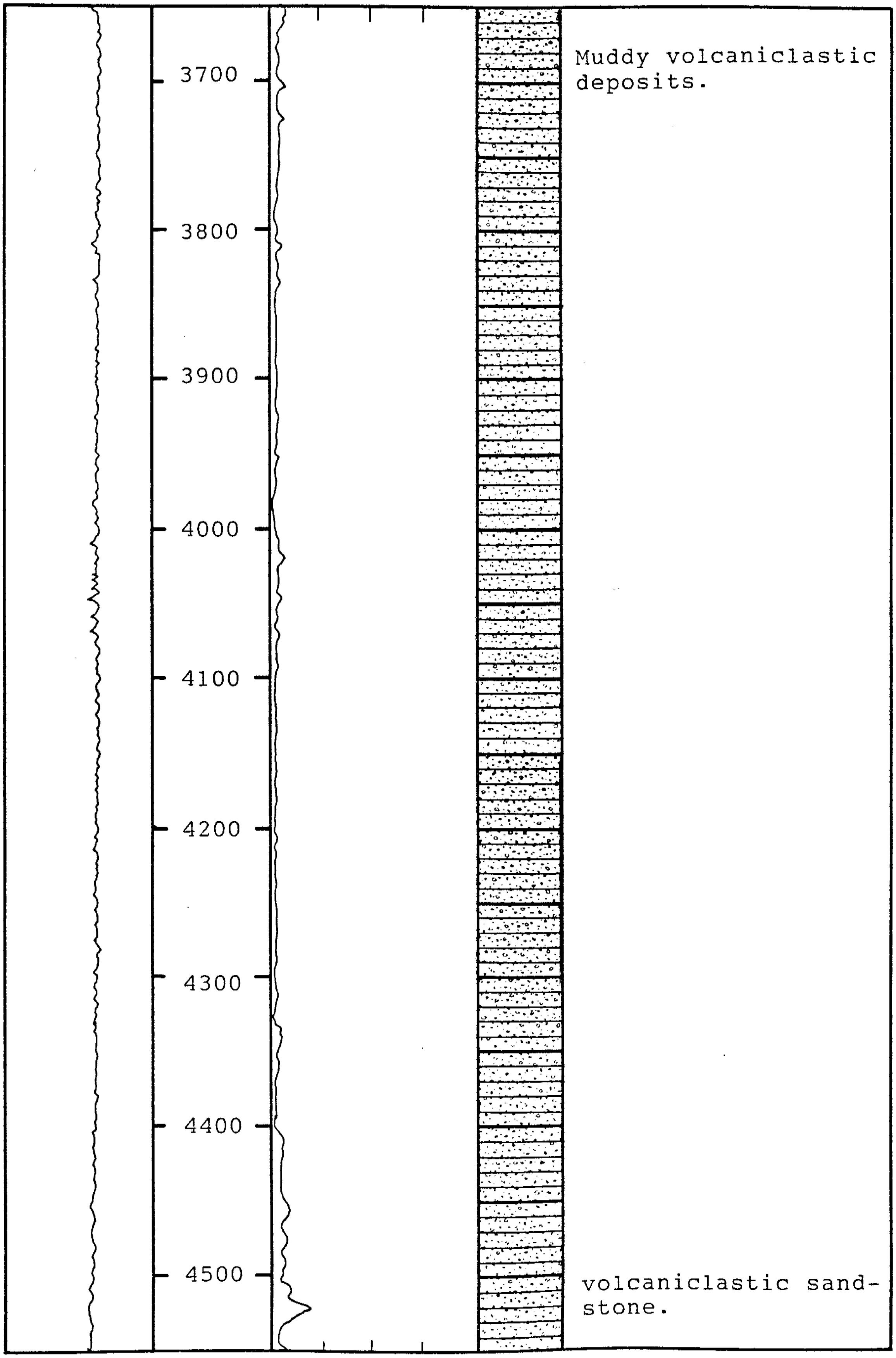
Top of log in Santa Fe Group (Los Pinos Fm).

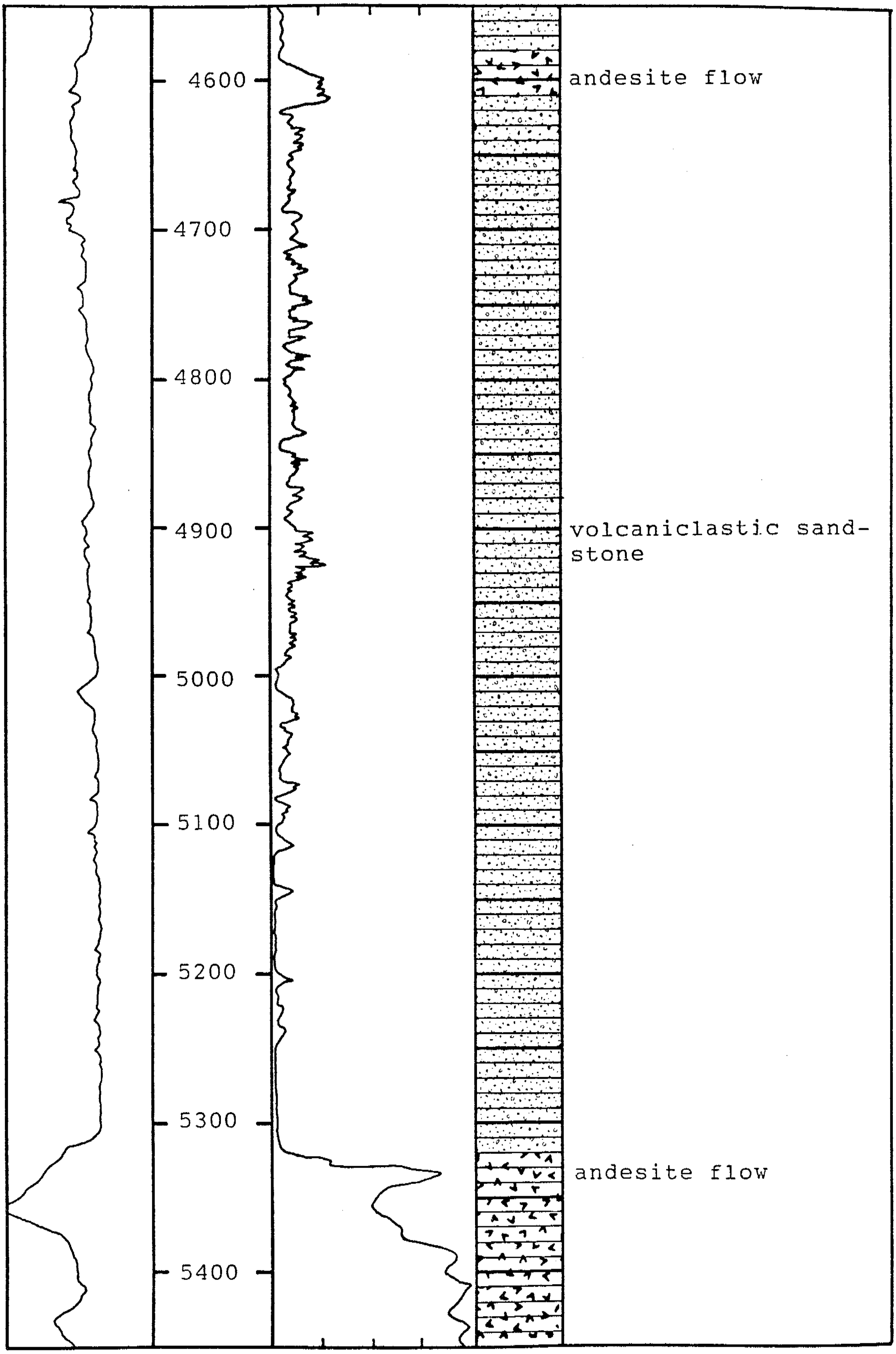
2070=top of Oligocene tuffs.

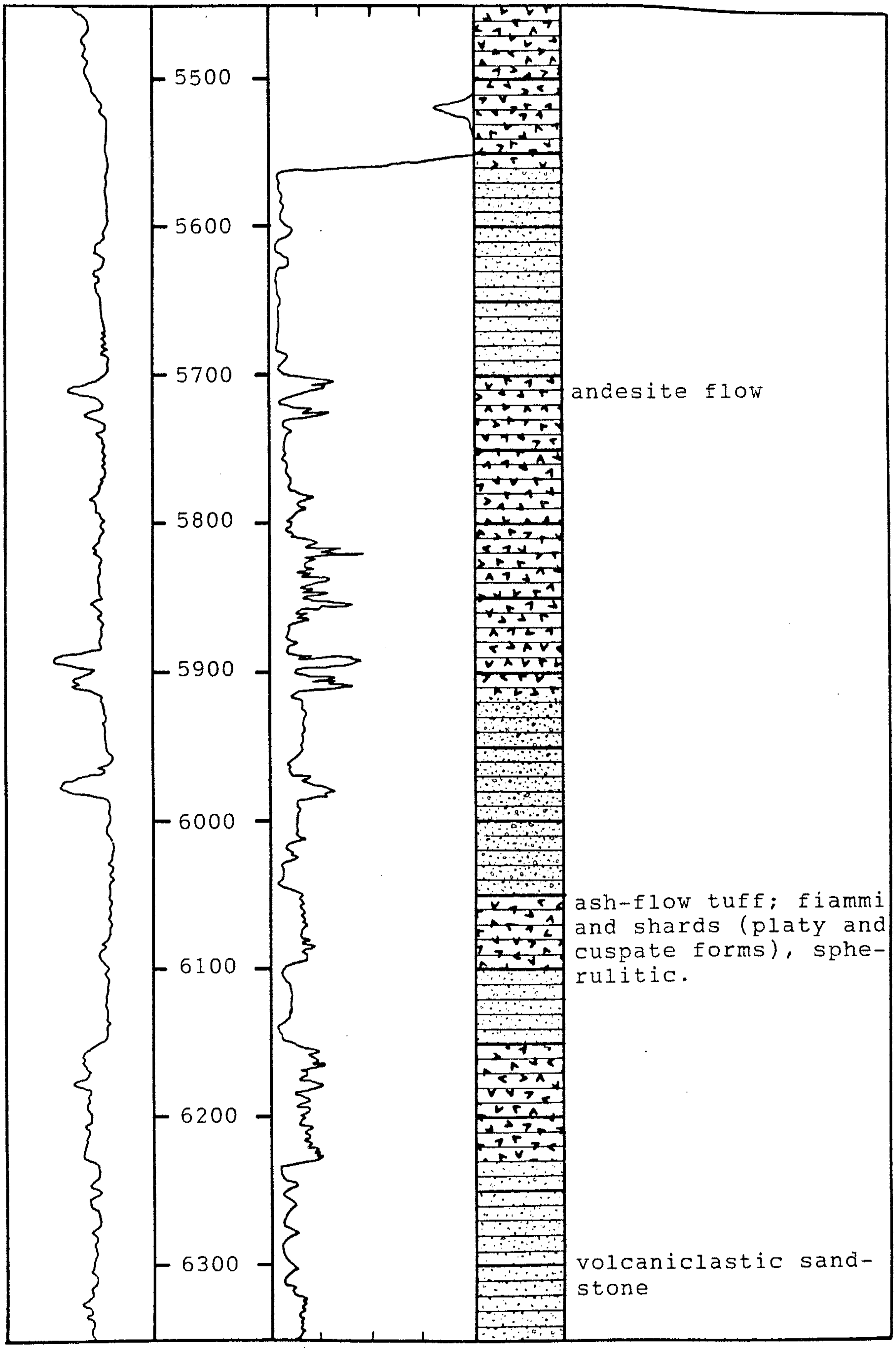
Carpenter Ridge Tuff: Crystal poor (10%), devitrified, moderately welded, axiolitic textures common, crystals include plagioclase, sanadine, biotite, opaque. Porosity up to 11%.

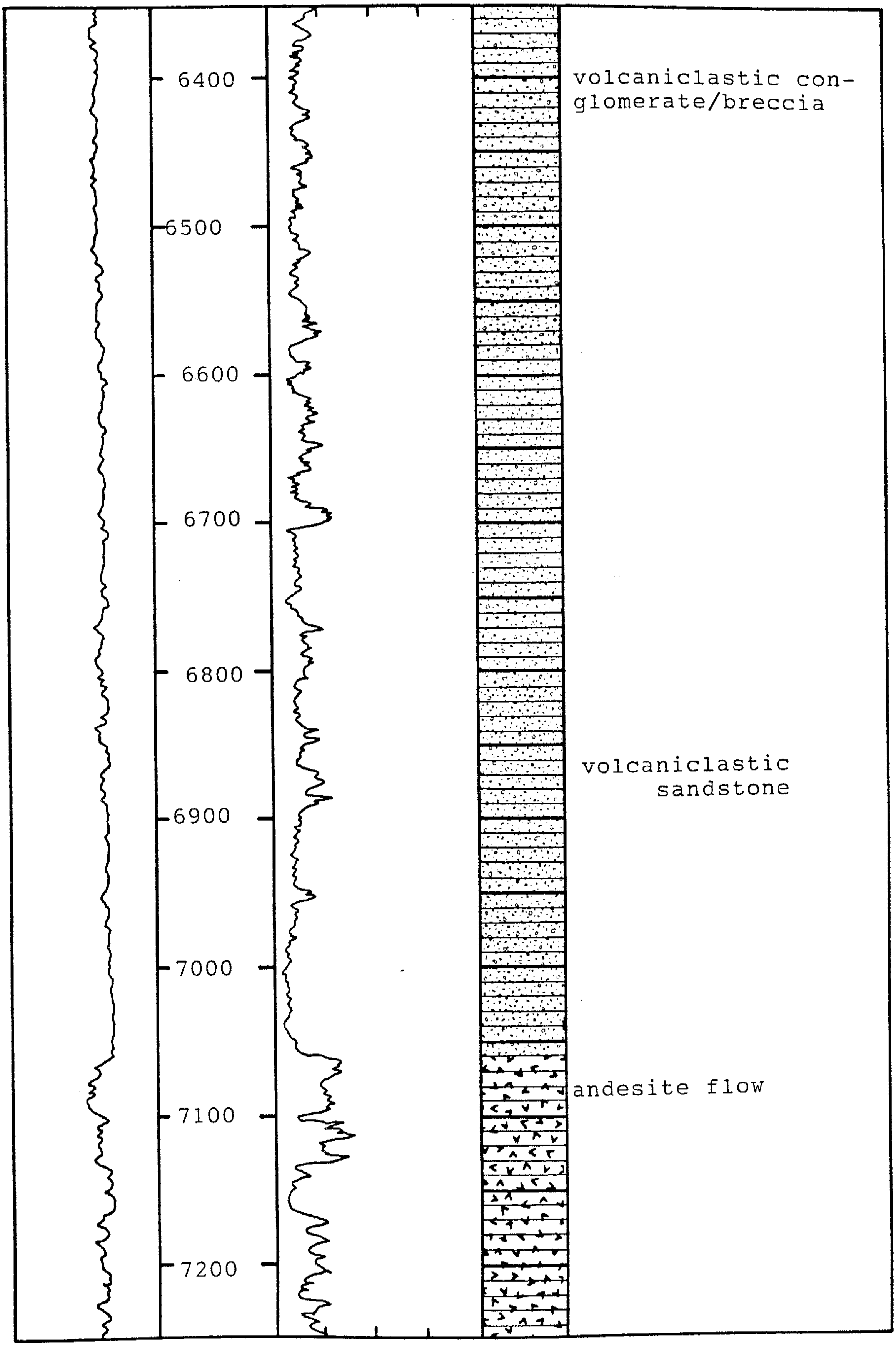
Fish Canyon Tuff: Crystal rich, strongly welded and devitrified ash-flow tuff. Crystals make up 41% of sample. Crystals include: Plagioclase, biotite, sanidine, and traces of resorbed quartz, pyroxene, amphibole, opaques. Porosity up to 6%.


2800
2900
3000
3100
3200
3300
3400
3500
3600
Ash-flow tuff: fair preservation of pumice and glass shards.
Treasure Mtn. Tuff: strongly welded, 20% crystals (max.), Minerals include feldspar, biotite, pyroxene. Porosity about 5% max. Dark brown color.
3580'=base Treasure Mtn. Tuff/top Conejos Fm.

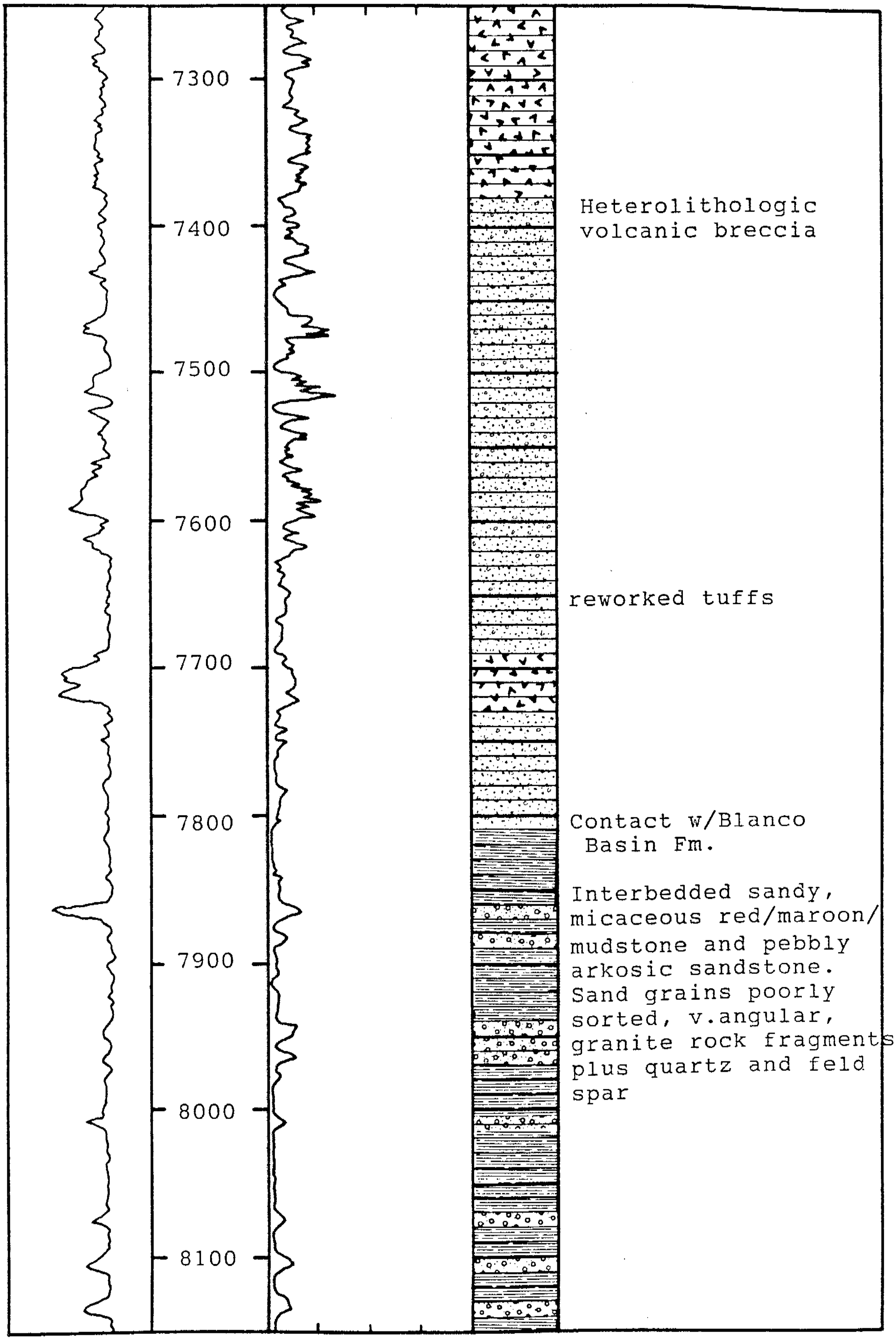

3700
3800
3900
4000
4100
4200
4300
4400
4500
Muddy volcaniclastic deposits.
volcaniclastic sand-stone.

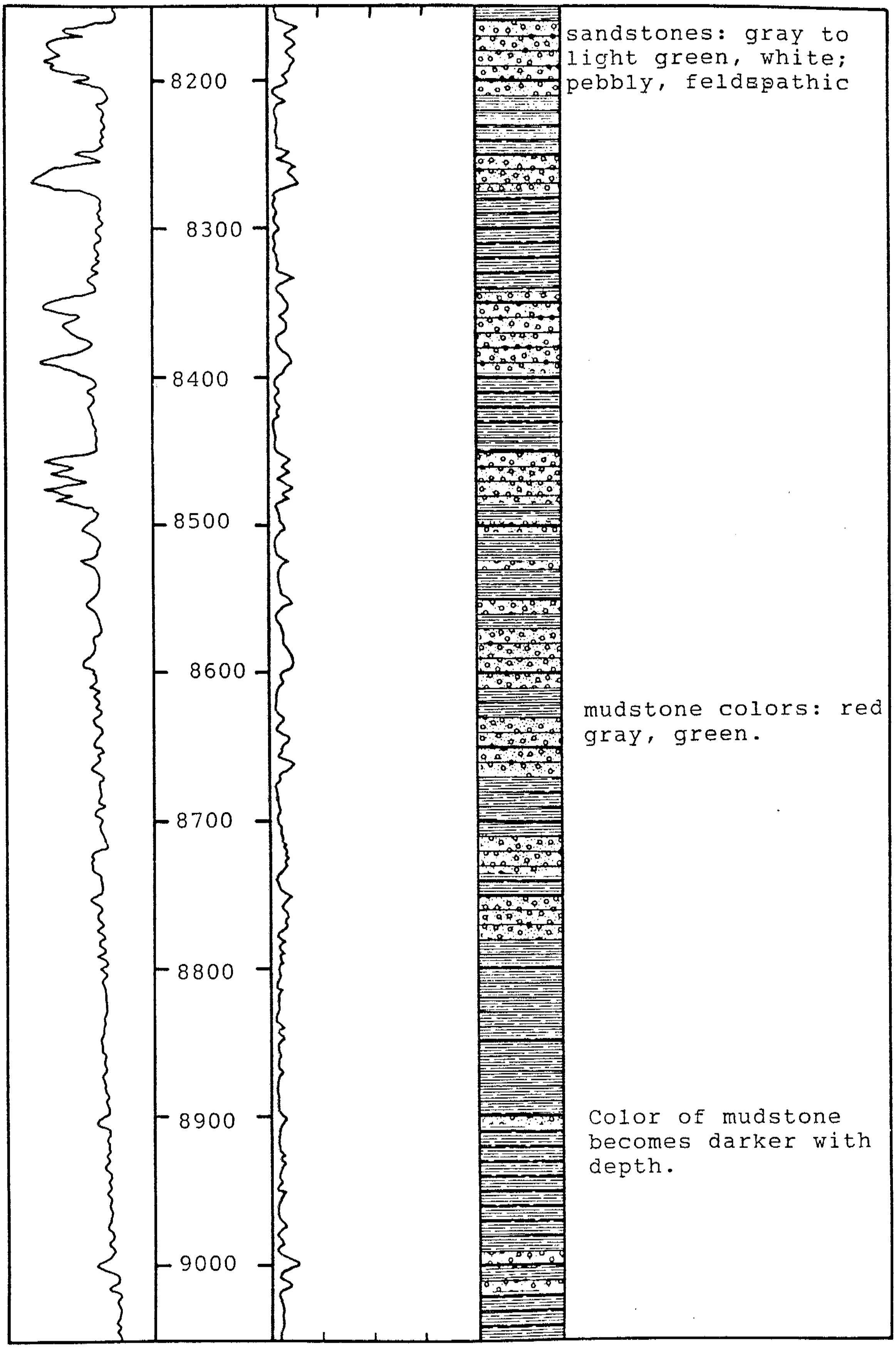

4600
4700
4800
4900
5000
5100
5200
5300
5400
andesite flow
volcaniclastic sand-
stone
andesite flow

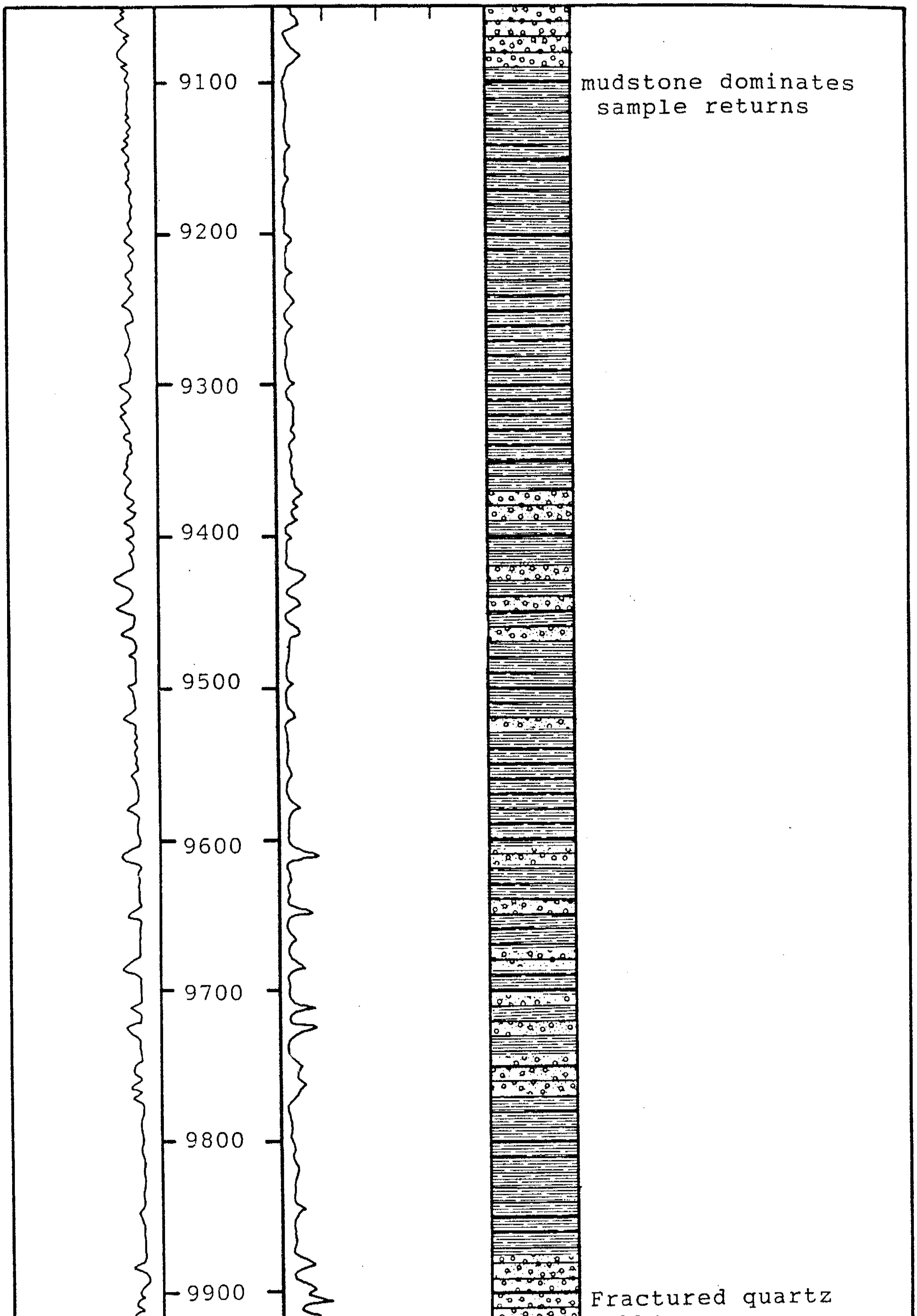

5500
5600
5700
5800
5900
6000
6100
6200
6300
andesite flow
ash-flow tuff; fiammi and shards (platy and cuspate forms), spherulitic.
volcaniclastic sandstone

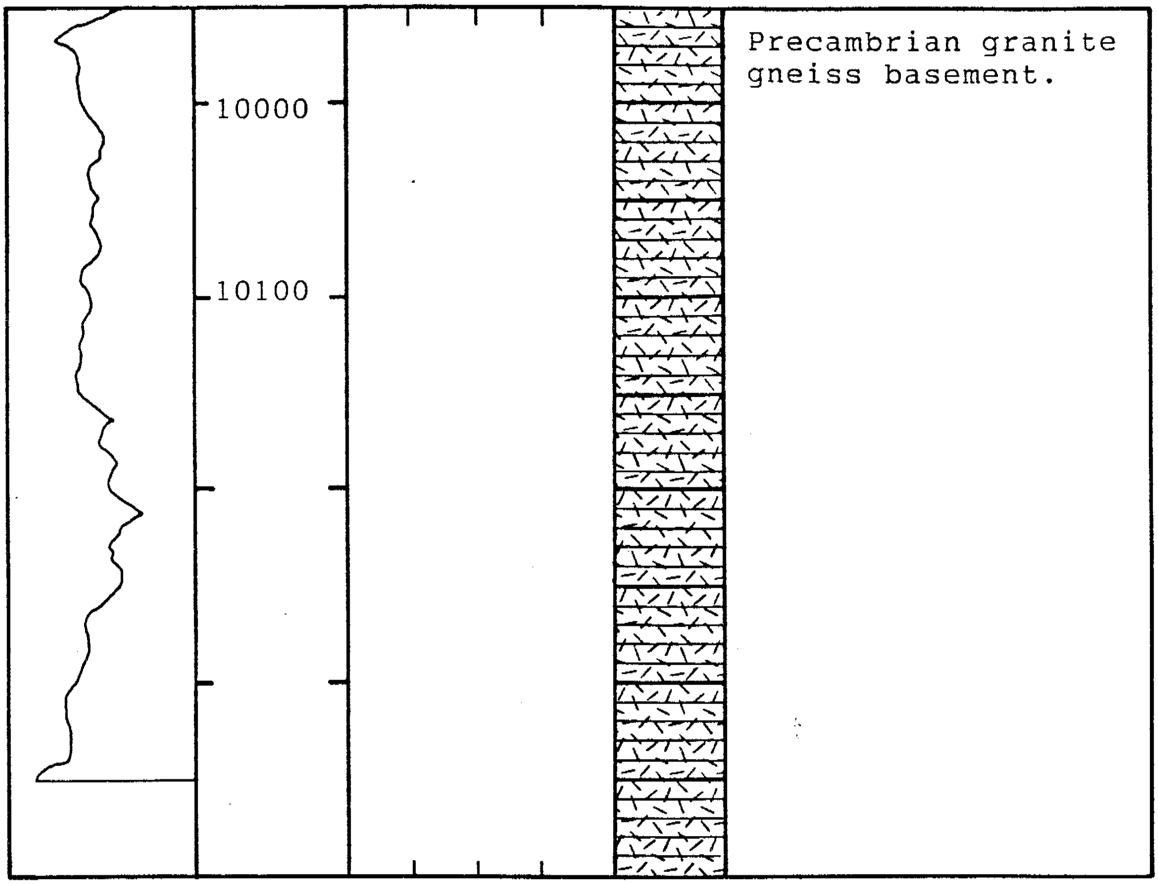


6400
6500
6600
6700
6800
6900
7000
7100
7200
volcaniclastic conglomerate/breccia
volcaniclastic sandstone
andesite flow


7300
7400
7500
7600
7700
7800
7900
8000
8100
Heterolithologic volcanic breccia
reworked tuffs
Contact w/Blanco Basin Fm.
Interbedded sandy, micaceous red/maroon/ mudstone and pebbly arkosic sandstone. Sand grains poorly sorted, v.angular, granite rock fragments plus quartz and feld spar


sandstones: gray to light green, white; pebbly, feldspathic
8200
8300
8400
8500
8600
mudstone colors: red gray, green.
8700
8800
8900
Color of mudstone becomes darker with depth.
9000


9100
9200
9300
9400
9500
9600
9700
9800
9900
mudstone dominates sample returns
Fractured quartz pebbles



Operator: Triton/WECO/UPRC
Well: #1 Hellgate
Location: sec 8 T42N R6E, NE NW
County: Saguache
State: Colorado
TD: 11996 ft KB: 9978 ft GL: 9950 ft
Date logged: December 1988
Logs used in study: dual induction/SFL
Sample interval examined: 3020-TD

Formation Tops (depths in feet from kelly bushing):
Spudded in Conejos Formation
7490 Blanco Basin Formation
11690 Precambrian basement (see notes)

Notes: Drilling problems plaqued this well, probably due to complex geology. The Blanco Basin Formation was intruded by numerous sills (?) ranging in composition from andesite to rhyolite with the latter more common. Most of the sills are only a few meters thick. The sills make geophysical log interpretation impossible without sample control.

Unfortunately, drilling problems resulted in incomplete sample returns. Also, mudstone was removed to some degree from the overwashed samples.

Much of the lower Blanco Basin Formation and Precambrian basement in the well appears to be mylonitized. The faults responsible for mylonitization may also have acted at conduits for the intrusions.

The author's best estimate of maximum thickness of the Blanco Basin Formation in this well (less intrusions) is 2283 ft (696 m). This number does not take into account any fault-related thickening. The samples are similar to those of the nearby Tennessee Gas well with the exception of having a higher sand:shale ratio, and greater presence of granular (or coarser) material in the "sands".

Operator: F. William Carr
Well: J.M. Crow #1
Location: sec 4 T39N R11E, C NE NE
County: Alamosa
State: Colorado
TD: 6581 ft KB: 7536? GL: 7524
Date logged: October 1952
Logs used in study: electrical
Sample interval examined: none

Formation Tops (depth in feet from kelly bushing):
Spudded in Quaternary alluvium
210 Alamosa Formation
1490 Lower Santa Fe Group
5626-TD Oligocene tuffs

Operator: Cougar Petroleum Company
Well: Crow #1
Location: sec 3 T39N R11E, E NE
County: Alamosa
State: Colorado
TD: 7474 ft KB: 7537 ft GL: 7524 ft
Date logged: November 1981
Logs used in study: dual induction/SFL
Sample interval examined: none

Formation Tops (depths in feet from kelly bushing):
Spudded in Quaternary alluvium (covering Alamosa Fm.)
1701 Lower Santa Fe Group
6100 Oligocene tuffs
7360-TD Precambrian basement

Operator: Mapco Production Co.--Amoco Production Co.
Well: State #1-32
Location: sec 32 T40N R12E, 2515 ft FNL, 2164 ft FWL
County: Alamosa
State: Colorado
TD: 9490 ft KB: 7600.2 ft GL: 7583.2 ft
Date logged: July 1974
Logs used in study: dual induction-laterolog; borehole compensated sonic; compensated formation density
Sample interval examined: 4500'-TD

Formation Tops (depths in feet from kelly bushing):
Spudded in Quaternary alluvium
170 Alamosa Formation
1720 Lower Santa Fe Group
8565 Intrusion
9000 more lower Santa Fe Group
9058-TD Oligocene tuffs

Notes: American Stratigraphic Company has an excellent sample log for this well. The formation picks made by Amstrat differ only slightly from those above. The tuffs depicted on the Amstrat log have been confirmed by thin section examination.

Operator: Amerada Petroleum Corp.
Well: Colorado State F #1
Location: sec 16 T39N R10E, C SE SW
County: Alamosa
State: Colorado
TD: 6072 ft KB: 7569 ft GL: 7554 ft
Date logged: October 1959
Logs used in study: induction-electrical; sonic
Sample interval examined: 3210-TD

Formation Tops (depth in feet from kelly bushing):
Spudded in Quaternary alluvium (covering Alamosa Fm.)
850 Lower Santa Fe Group
1742 Oligocene tuffs
2990 Conejos Formation
4310 Blanco Basin Formation
4690 Precambrian basement

Operator: Reserve Oil, Inc.
Well: Reserve NBH Alamosa #1-33
Location: sec 33 T40N R11E, SE SW
County: Alamosa
State: Colorado
TD: 7020 ft KB: 7539 ft GL: 7523ft
Date logged: September 1979
Logs used in study: dual induction-SFL; borehole compensated sonic; compensated neutron-formation density.
Sample interval examined: 4700'-TD

Formation Tops (depths in feet from kelly bushing):
Spudded in Quaternary alluvium (covering Alamosa Fm.)
1500 Lower Santa Fe Group
5155 Oligocene tuffs
6680 Precambrian basement