GEOTHERMAL RESOURCES OF SOUTH CENTRAL COLORADO AND THEIR RELATIONSHIP TO GROUND AND SURFACE WATERS

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GEOTHERMAL RESOURCES OF SOUTH CENTRAL COLORADO AND THEIR RELATIONSHIP TO GROUND AND SURFACE WATERS

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GEOTHERMAL RESOURCES OF SOUTH CENTRAL COLORADO AND THEIR RELATIONSHIP TO GROUND AND SURFACE WATERS

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ABSTRACT

The northern San Luis and Upper Arkansas Valleys of south central Colorado contain numerous surface and subsurface characteristics which indicate environments favorable for the occurrence of a geothermal energy source. The area extends from Buena Vista in the Upper Arkansas Valley southward to Mineral and Valley View Hot Springs in the northern San Luis Valley and covers about 1,380 square miles (3,590 km^2). The entire area of interest is referred to in this report as a single Known Geothermal Resource Area (KGRA).

The tectonic evolution of the KGRA occurred in several distinct phases, ranging in time from Precambrian to Holocene, culminating in a post-Laramie period of widespread volcanic activity in the Middle Cenozoic, and periods of block-faulting associated with the development of the Rio Grande rift zone from middle Miocene to Holocene time. An early period of rifting produced the Upper Arkansas graben and the San Luis graben; while later periods fragmented the area into northwest-trending uplifts and basins. The latest activity along the Sangre de Cristo fault occurred less than 10,000 years ago as evidenced by displacements of up to 25 feet (7.6 m) on Late Wisconsinian alluvial fans. The Rio Grande rift zone cuts across all earlier structural trends and is unrelated to prior tectonic and volcanic features.

Rock types in the KGRA range from Precambrian igneous and metamorphic rocks, Paleozoic marine carbonate sequences and terriginous sequences, Early Cenozoic volcanic and minor intrusive rocks to Middle and Late Cenozoic fluviatile, mudflow, glaciofluvial and alluvial deposits.

The San Luis and Upper Arkansas Valleys are north-trending structural basins flanked on the east and west by mountains consisting of Precambrian, Paleozoic, and Tertiary rocks. Possibly as much as 30,000 feet (9,140 m) of unconsolidated to semiconsolidated alluvial deposits locally underlies the San Luis Valley and up to about 10,000 feet (3,050 m) underlies the Upper Arkansas Valley.

The northern San Luis Valley and Upper Arkansas Valley, in association with the Rio Grande rift, are favorable for the occurrence of commercial geothermal energy sources. Characteristics indicating the occurrence of a commercial geothermal energy source include: 1) relatively youthful volcanic activity, 2) favorable tectonic history, 3) the presence of thermal springs and wells, and 4) above normal heat flow. Volcanic rocks along or peripheral to the Rio Grande rift in Colorado were emplaced generally 40 to 20 million years ago with younger extrusions occurring only 4,000 years ago. Relatively youthful tectonic activity is represented by pronounced fault scarps in Quaternary deposits in both the northern San Luis Valley and Upper Arkansas Valley. The KGRA contains numerous hot or warm springs; geothermometry analyses of spring waters and water from observation wells indicate potential geothermal reservoir temperatures ranging from 60°C to 360°C. Heat flow calculations reveal a rate which is about twice the world average.

Investigations conducted in the KGRA included office research, studies of imagery, water quality monitoring, and field investigations. Field investigations included a short test well drilling program and a series of surface-geophysical investigations. The latter included bipole-dipole and quadripole resistivity surveys, reflection seismic traverses, and magnetotelluric and Schlumberger soundings. Several resistivity lows have been identified within the KGRA and are treated as manifestations of geothermal reservoirs.

In this report it is concluded that the potential geothermal reservoirs are intermediate to high temperature hydrothermal convection systems with hot water being the predominant fluid. The source of heat is believed to be due to the combined effects of rifting, residual heat from volcanic activity, and heat released from deep seated igneous rock. The KGRA's geothermal system is believed to be linked to the surface and ground-water regimes by faulting and by direct or close contact with hot rock.

Any development of geothermal energy resources in the KGRA will possibly be accompanied by changes in local inflow-outflow relations, changes in hydraulic characteristics of aquifers, create varying degrees of water pollution problems, and might result in environmental hazards. If the degree of any of these potential effects is substantial, developers of geothermal resources can expect legal action by holders of prior-vested water rights, and agencies responsible for enforcing the Colorado Water Quality Control Act and the State's numerous river compacts.

It is believed that most of the adverse effects of developing geothermal resources in Colorado can be alleviated, if not eliminated, by reinjection practices.

INTRODUCTION

In an attempt to dampen the effects of future energy crises the Federal government is examining every possibility in the search for new energy resources. Sources of energy being examined by various agencies of the government are solar energy, nuclear fusion, windmills, ocean currents, and geothermal energy.

Developments in the field of geothermal research have resulted both in a gradual improvement of research methodology and a gradually expanding knowledge of the whereabouts of regional and local centers of geothermal activity. Equipped with this knowledge both public and private entities can conduct more efficient research. It is due to such knowledge that part of the San Luis Valley and part of the Upper Arkansas Valley are two of the many areas in Colorado which have been designated as Known Geothermal Resource Areas (KGRAs).

SCIENTIFIC OBJECTIVES

Because the geothermal features in the subject KGRA are associated with and probably directly related to the hydrologic features in those areas it is anticipated that any future geothermal resource development will have some impact on the areas' water resources. Although it is safe to assume that some impact on the areas' water resources is inevitable, little is known as to whether the impact will be beneficial, adverse or a combination of the two. The purpose of this investigation therefore, is twofold: (1) to identify and evaluate the potential geothermal resources of the KGRA; and (2) to define the relationship between those geothermal resources and the ground and surface water resources of the KGRA, and to predict the potential impact of geothermal resource development upon those water resources.

An effective evaluation of the relationship between the areas' geothermal resources and ground water resources necessarily requires reasonable assessment of the characteristics of the local geothermal system. To meet this requirement a combination of geological, geophysical, and geochemical methods were applied. The results of these are presented in this report.

Knowledge attained during the course of this study should yield to future investigators and developers of geothermal resources in Colorado some insight regarding technology requirements, and will hopefully allow them to make reasonably accurate predictions concerning potential impact created by the development of geothermal resources. Such knowledge should lead to development procedures designed to keep adverse effects to a minimum. The study should aid water administrators by yielding information which might influence legal and regulatory considerations. The research was supported by U.S. Geological Survey Grant Nos. 14-08-0001-G-226 and 14-08-0001-G-330.

ACKNOWLEDGEMENTS

Sincere appreciation is extended to residents of the northern San Luis and Upper Arkansas Valleys who allowed investigations to be conducted on their properties. Chaffee and Saguache County Governments cooperated by furnishing valuable advice on public relations and rights of way, and local gas and power companies furnished valuable information on buried gas and power lines.

Appreciation is also extended to the Colorado School of Mines Geophysics Department which, under the direction of Dr. George Keller, was contracted to conduct numerous geophysical surveys, evaluate geophysical data, and submit interim reports. The Colorado Geological Survey furnished geothermometry data for the KGRA's hot and warm springs and assisted in acquiring water samples from streams in the Upper Arkansas Valley. Various staff members of the Colorado Division of Water Resources assisted in the preparation of the final report.

GEOLOGY

GEOGRAPHIC AND GEOLOGIC SETTING

The study area is located in the southern Rocky Mountains of Colorado about 110 miles (176 km) southwest of Denver. Access is by U.S. Highways 285 and 50 which traverse the area in north-south and an east-west directions respectively. Encompassing an area of approximately 1,380 square miles (3,590 km^2), the KGRA is loosely bounded on the north by the Mt. Princeton and Cottonwood Hot Springs and the town of Buena Vista. It extends southward approximately 60 miles (96 km) to Mineral Hot Springs and Moffat (fig. 1). The width varies from 12 to 35 miles (20-58 km). Nine contiguous U.S. Geologic Survey quadrangle maps provide topographic coverage of the KGRA (fig. 2) at scales of 1:62500 or 1:24000.

Elongate north-to-south, the area consists of two intermontane basins separated by an east-west drainage divide which separates it into two subareas: 1) the Upper Arkansas Valley to the north and 2) the northern San Luis Valley to the south. The two valleys are internal downfaulted, structural and depositional basins within the larger Rio Grande rift zone (fig. 3).

The Upper Arkansas Valley is bounded on the west by the Sawatch Range, the eastern flank of which is cut longitudinally by the major Late Cenozoic graben that constitutes the valley of the Upper Arkansas River. The Sawatch Range consists of predominantly Precambrian metamorphic and igneous rocks and Tertiary intrusives (fig. 4). Relief between the valley floor and the crest of the Sawatch Range is about 7,000 feet (2,100 m). Bedrock relief may be as much as 17,000 feet (5,200 m).

On the east, the Upper Arkansas Valley is bounded by the Arkansas Hills, a line of low mountains marking the southernmost extension of the Mosquito Range. This range constitutes the upthrown block on the east side of the Upper Arkansas Valley graben. The Mosquito Range consists of Precambrian metamorphic and igneous rocks capped by complexly folded and faulted Paleozoic sedimentary rocks and relatively flat-lying Tertiary volcanics (fig. 4).

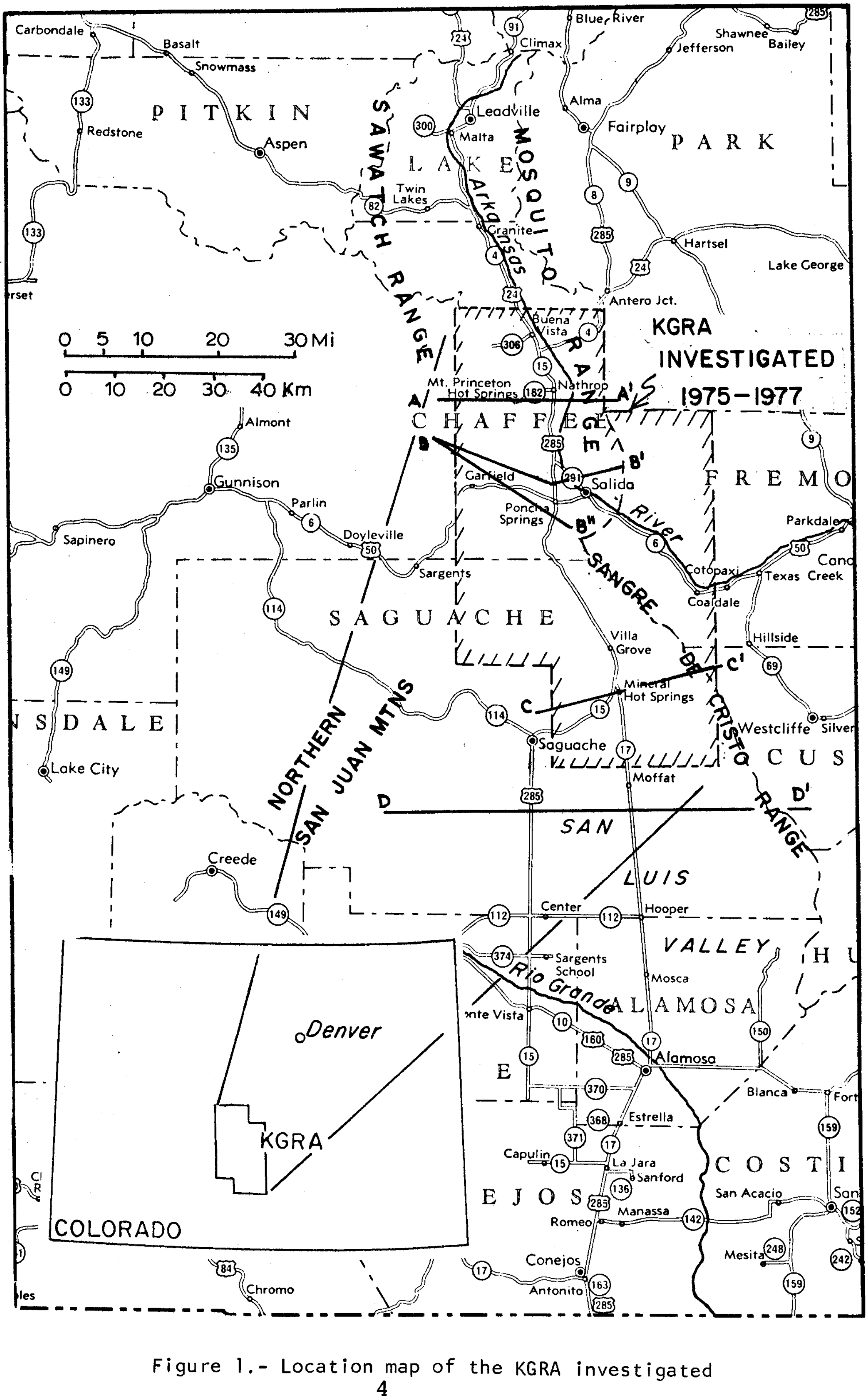


Figure 1.- Location map of the KGRA investigated

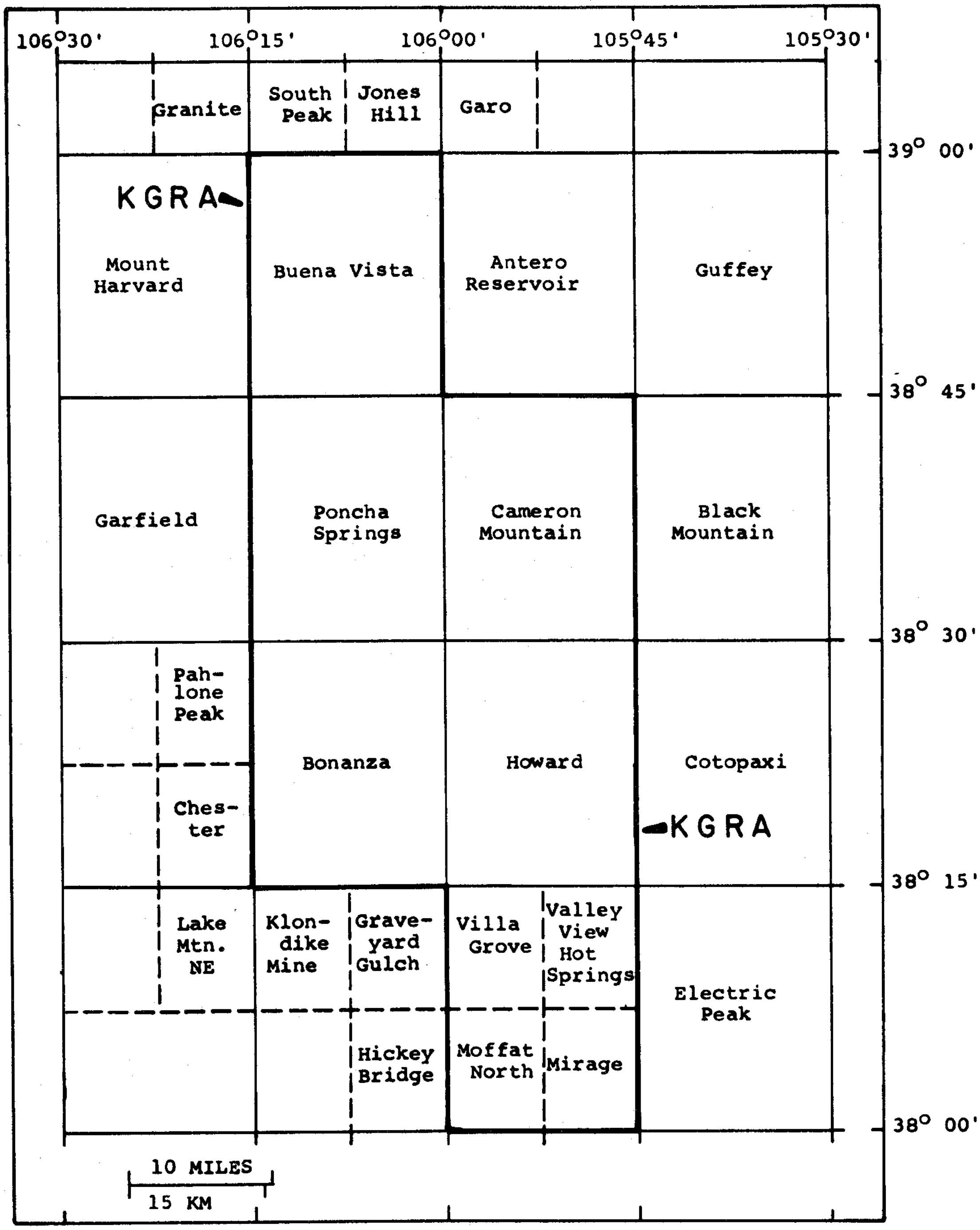


Figure 2. Index of topographic quadrangles covering the KGRA and surrounding area.

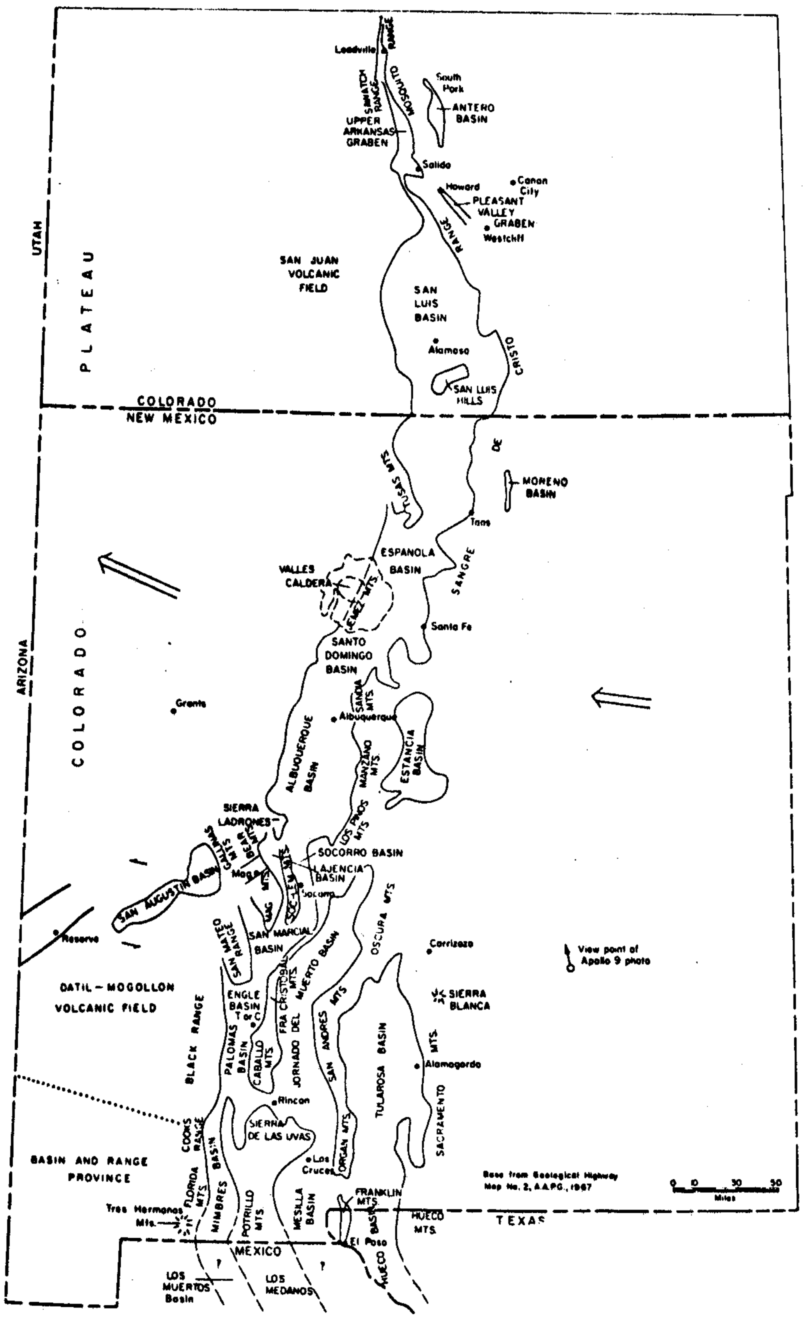


Figure 3. Generalized map of the Rio Grande rift. Arrows represent apparent vectors of movement. After Chapin, 1971, p. 193.

The northern San Luis Valley, the relatively narrow northern extension of the San Luis Valley, lies between Poncha Pass on the north and the Mineral Hot Springs-Moffat area to the south (fig. 1). Like the Upper Arkansas Valley, the northern San Luis Valley is one of the areal topographic features reflecting Late Cenozoic tectonic activity in south-central Colorado. The approximate present structural boundaries of the northern San Luis Valley were defined in middle to late Miocene times by initial graben development as the San Luis block subsided along high-angle normal faults coincident with the down-faulting of the Upper Arkansas graben. The northern San Luis Valley is bounded on the west by crystalline Precambrian metamorphic and igneous rocks of the Sawatch Range and the Tertiary, volcanic Cochetopa Hills which include the Bonanza volcanic center.

On the east, the northern San Luis Valley is bounded by the northern Sangre de Cristo Range which is the uplifted block developed during the initial stages of formation of the San Luis graben. The western flank of the northern Sangre de Cristo Range is abruptly terminated by a major north-south normal fault along which the northern Sangre de Cristo horst was uplifted (fig. 5). The core of the northern Sangre de Cristo Range consists of Precambrian metamorphic and igneous rocks and is capped by complexly folded and faulted Paleozoic sedimentary rocks and minor amounts of Tertiary sedimentary and volcanic rocks (fig. 5). Relief between the valley floor and the crest of the northern Sangre de Cristo Range is about 7,800 feet (2,400 m) but bedrock relief may range up to 37,000 feet (11,300 m) (Gaca and Karig, 1966; Kleinkopf and others, 1970).

The Upper Arkansas Valley basin and the northern San Luis Valley basin are part of the northern extension of the Rio Grande rift zone which extends from southern New Mexico to central Colorado, a distance of over 600 miles (970 km). Faulting associated with the Rio Grande rift zone has resulted in localized occurrences of thermal springs such as Cottonwood, Poncha and Mt. Princeton Hot Springs in the Upper Arkansas Valley, and Valley View and Mineral Hot Springs, and the Fullenwider warm springs in the northern San Luis Valley.

The initial development of the Rio Grande rift zone began in middle to late Miocene time. This was accompanied by volcanic activity, mainly along the central and western portions of the rift zone. Rifting, as a result of crustal

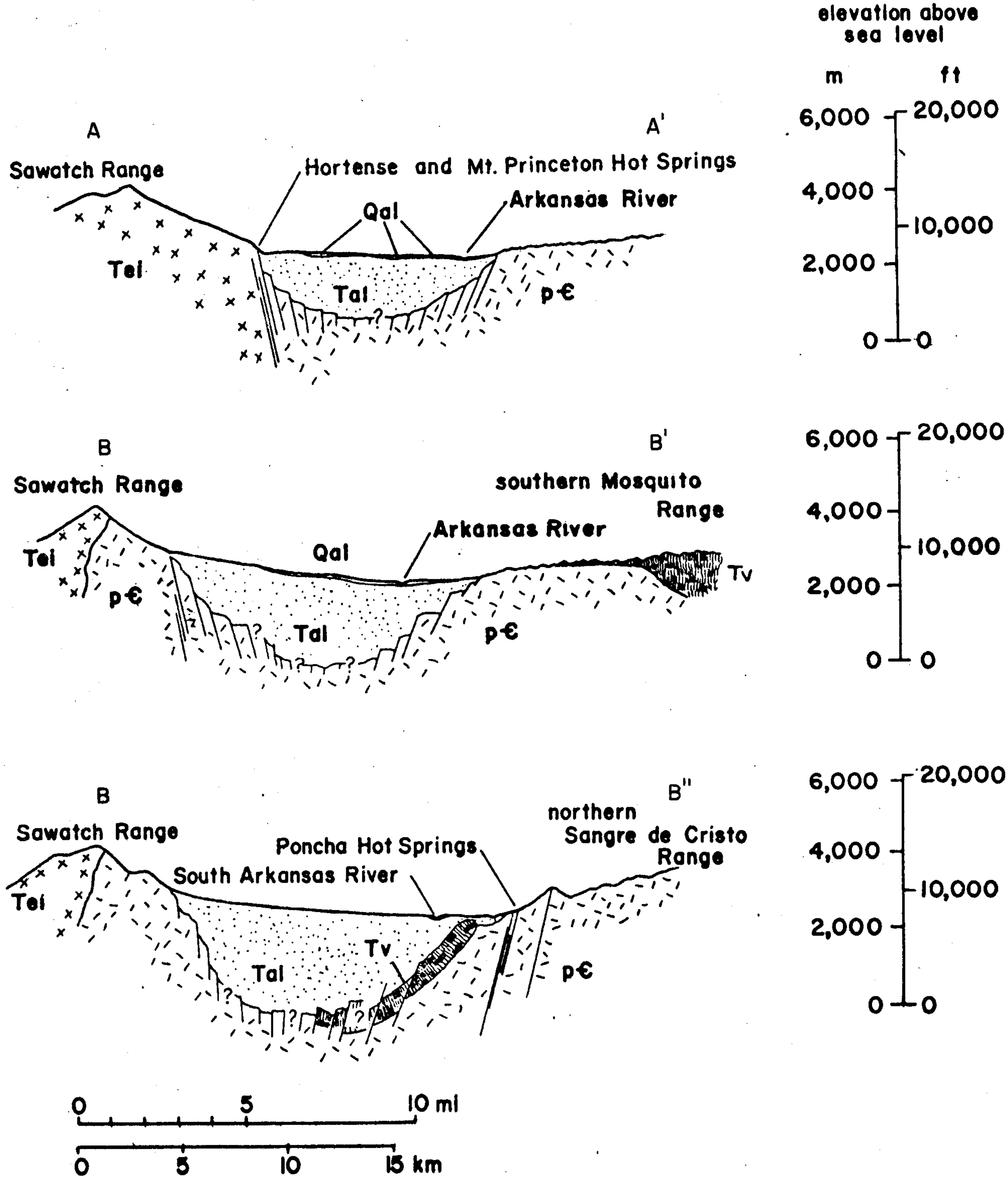


Figure 4. Generalized cross sections of the Upper Arkansas Valley, Colorado. Qual, Tal, undifferentiated alluvial deposits of Quaternary and Tertiary age; Tv, extrusive igneous rocks, Tei, intrusive igneous rocks; pC, undifferentiated Precambrian rocks. Elevation datum is mean sea level. For location of cross sections see figure 1.

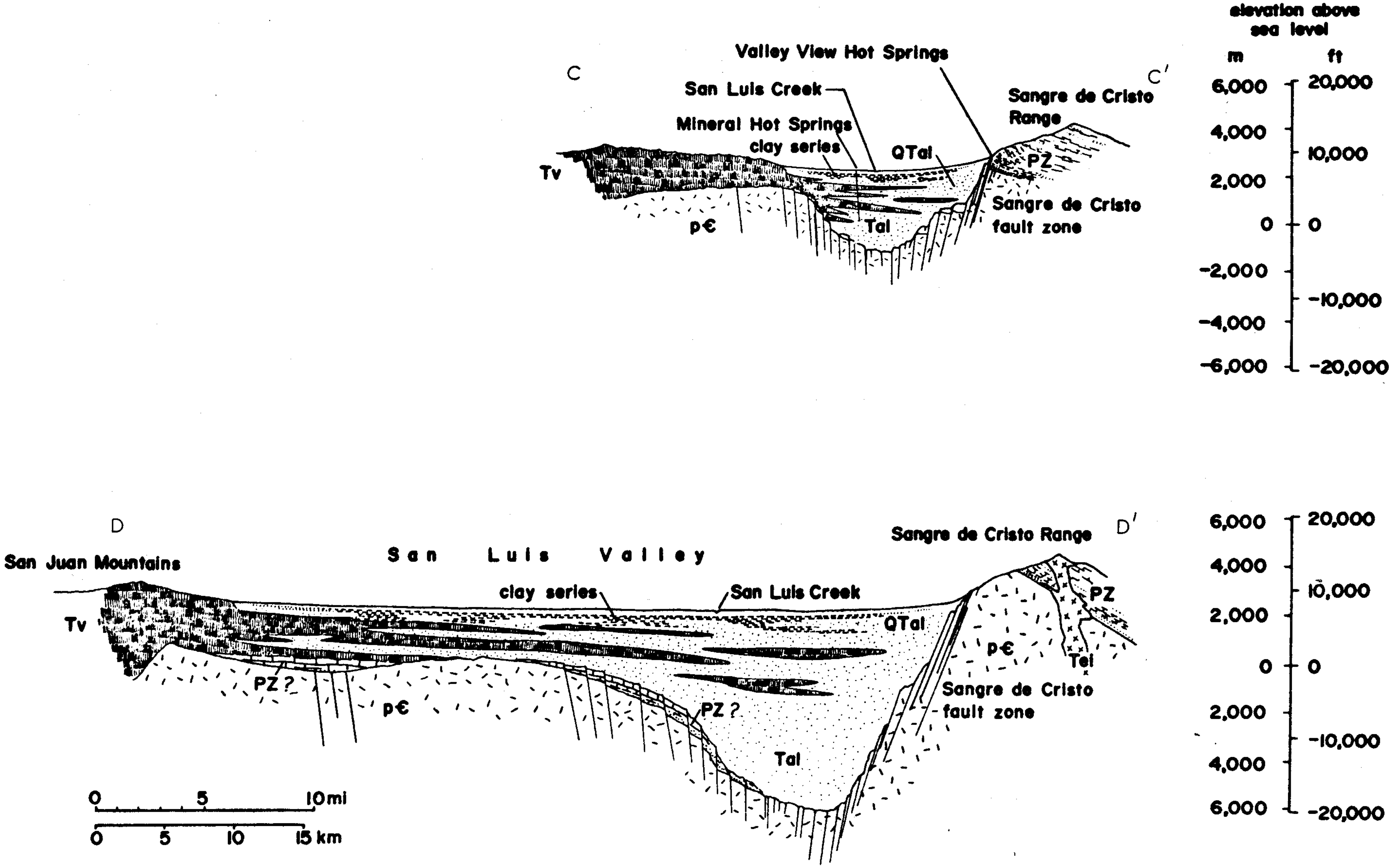


Figure 5. Generalized cross sections of the northern part of San Luis Valley Colorado. Qal, Tal, undifferentiated alluvial deposits of Quaternary and Tertiary age; Tv, extrusive igneous rocks; Tei, intrusive igneous rocks; PZ, undifferentiated Paleozoic rocks; pC undifferentiated Precambrian rocks. Elevation datum is mean sea level. For location of cross sections see figure 1.

stretching accompanied by abundant normal faulting, provided avenues for the ascent of magmas and hydrothermal fluids. This is particularly evident along the west side of the rift zone, but to a much lesser extent along the east side. The differential movement of fault blocks and attendant upward movement or protrusions of magmas are conducive to the occurrence of geothermal cells. The occurrence of hot springs is one of the indicators of the existence of a geothermal cell. Block faulting and concurrent volcanism, high heat flows, and hot springs are all present in the KGRA.

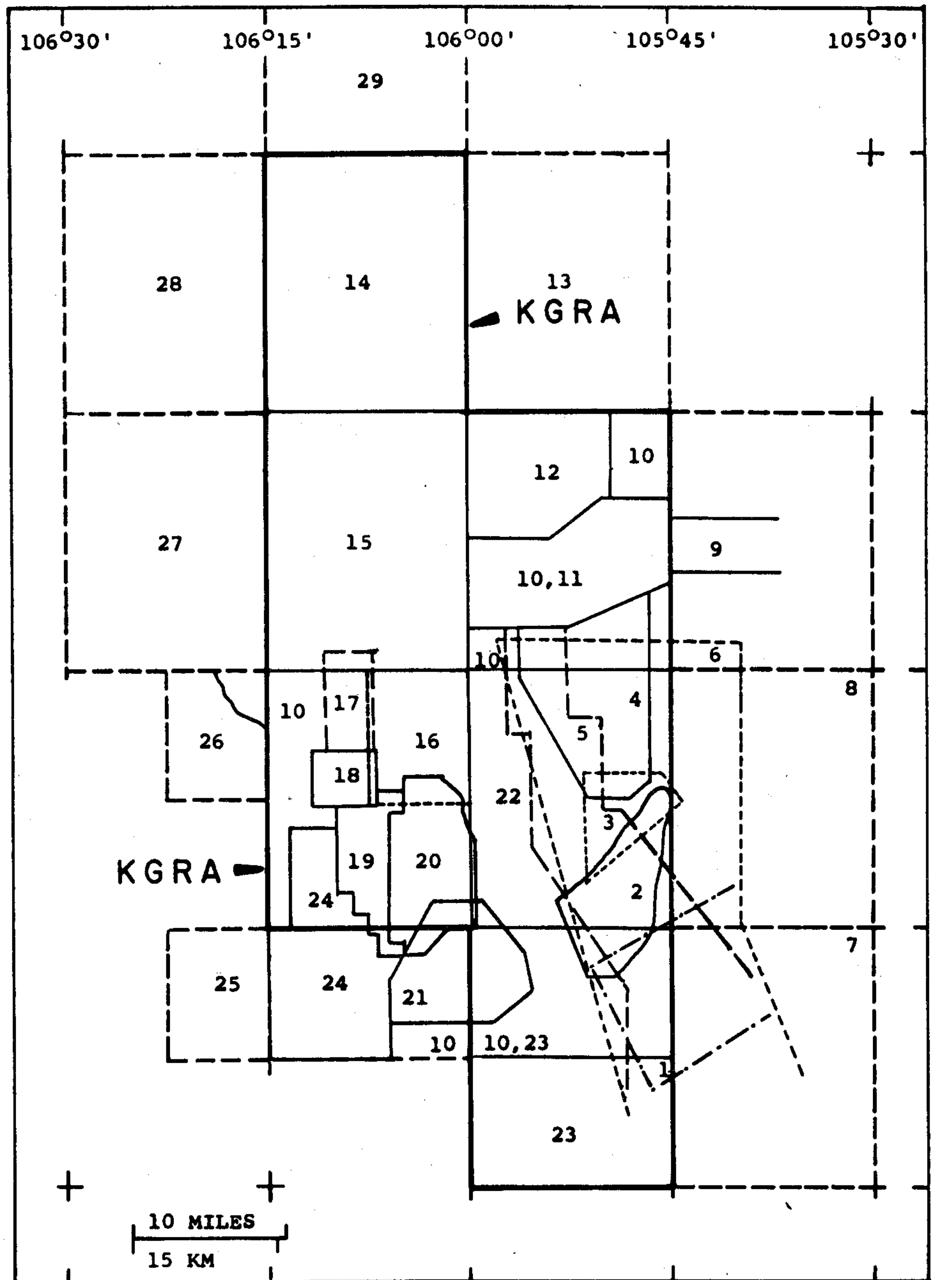
Extensive and detailed geologic studies have been made in the area by numerous investigators (fig. 6). These sources have been used exclusively to prepare the geologic map of the KGRA. Figure 7 is the index to the separate geologic map sheets prepared for this investigation. Other than to include a structural interpretation, based on a seismic survey of the northern San Luis Valley, no attempt has been made to expand the geologic mapping done by previous investigators.

Because surficial alluvial deposits cover and obscure all of the details of the valley floors, little is known about the obviously complex geology of the valley floors of the Upper Arkansas and northern San Luis Valleys. Therefore, it was necessary to use geophysical methods to investigate the subsurface geology, particularly in the northern San Luis Valley.

Prior to the geophysical investigation, three shallow observation wells, 500 to 1,000 feet (152-305 m) in depth, were drilled in the late fall of 1975 in the area south of Valley View Hot Springs and east of Mineral Hot Springs (fig. 8). These wells were drilled for the purpose of obtaining aquifer data and to determine if there were any indications of geothermal activity. The area of this initial study (fig. 1) was selected on the basis of the occurrence of two known hot springs, favorable structural conditions, reconnaissance geophysical information, accessibility and geologic map coverage. The results of this initial study are contained in a report completed in 1976 (Romero and Fawcett, 1976).

STRATIGRAPHIC SUMMARY

The rock types found within the KGRA include Precambrian igneous and metamorphic rocks, Paleozoic sedimentary



1. Nolting (1970)
2. Wychgram (1972)
3. Nicholayson (1972)
4. Pierce (1969)
5. Litsey (1958)
6. Peel (1971)
7. Scott and Taylor (1974)
8. Taylor, Scott, Wobus and Epis (1975)
9. DuHamel (1968)
10. Knepper (1974)
11. Lowell (1969)
12. Normand (1968)
13. De Voto (1972)
14. Scott (1975)
15. Scott, Van Alstine and Sharp (1975)
16. Van Alstine (1975)
17. Kouther (1968)
18. Perry (1971)
19. Burbank (1932)
20. Mayhew (1969)
21. Bridwell (1968)
22. Taylor, Scott, Wobus (1975)
23. Scott (1976)
24. Marrs (1973)
25. Bruns (1971)
26. Olsen (1977)
27. Dings and Robinson (1957)
28. Brock and Barker (1972)
29. Tweto (1972)

Figure 6. Index of geologic mapping done in the KGRA.

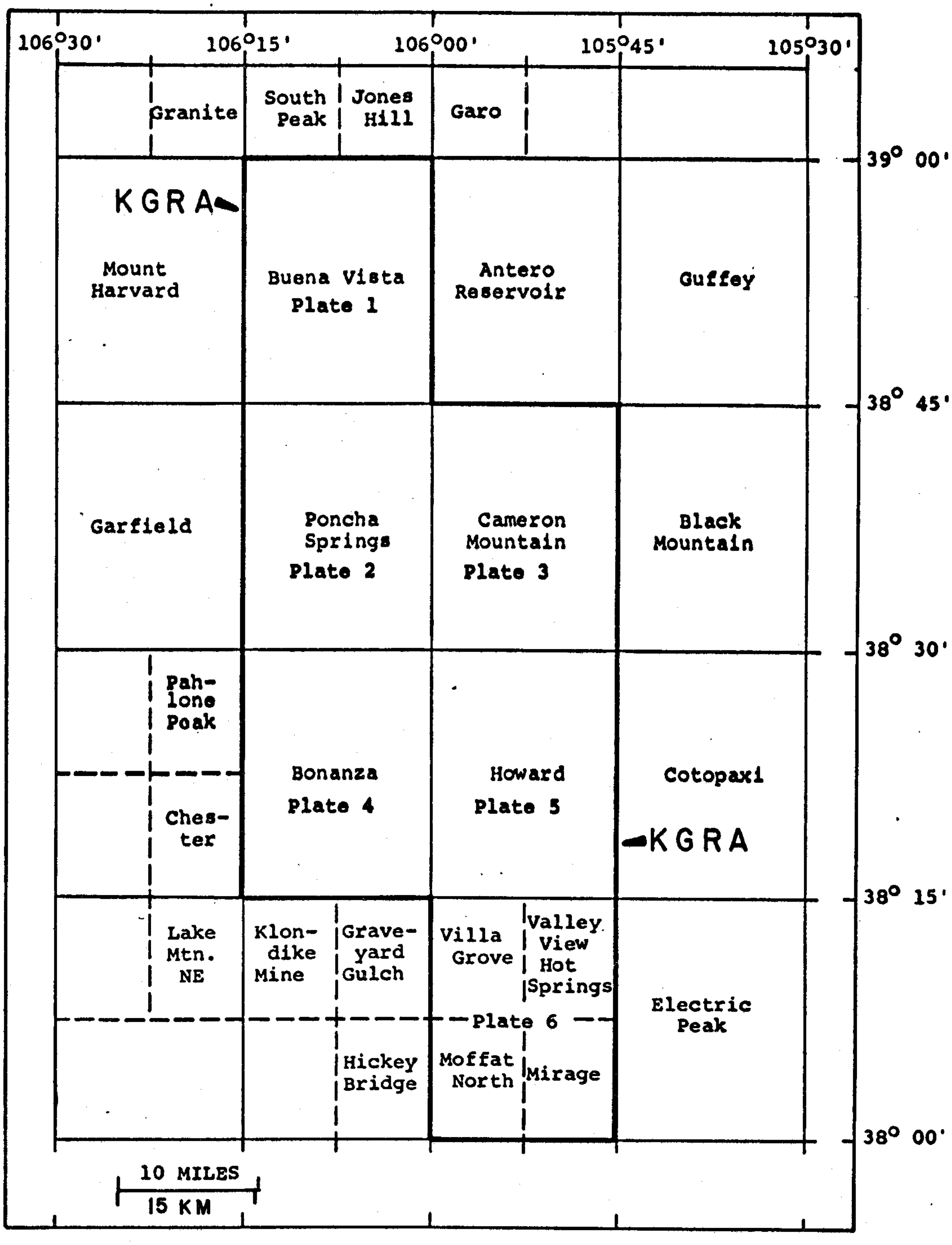


Figure 7. Index of individual geologic maps covering the geology of the KGRA for this report.

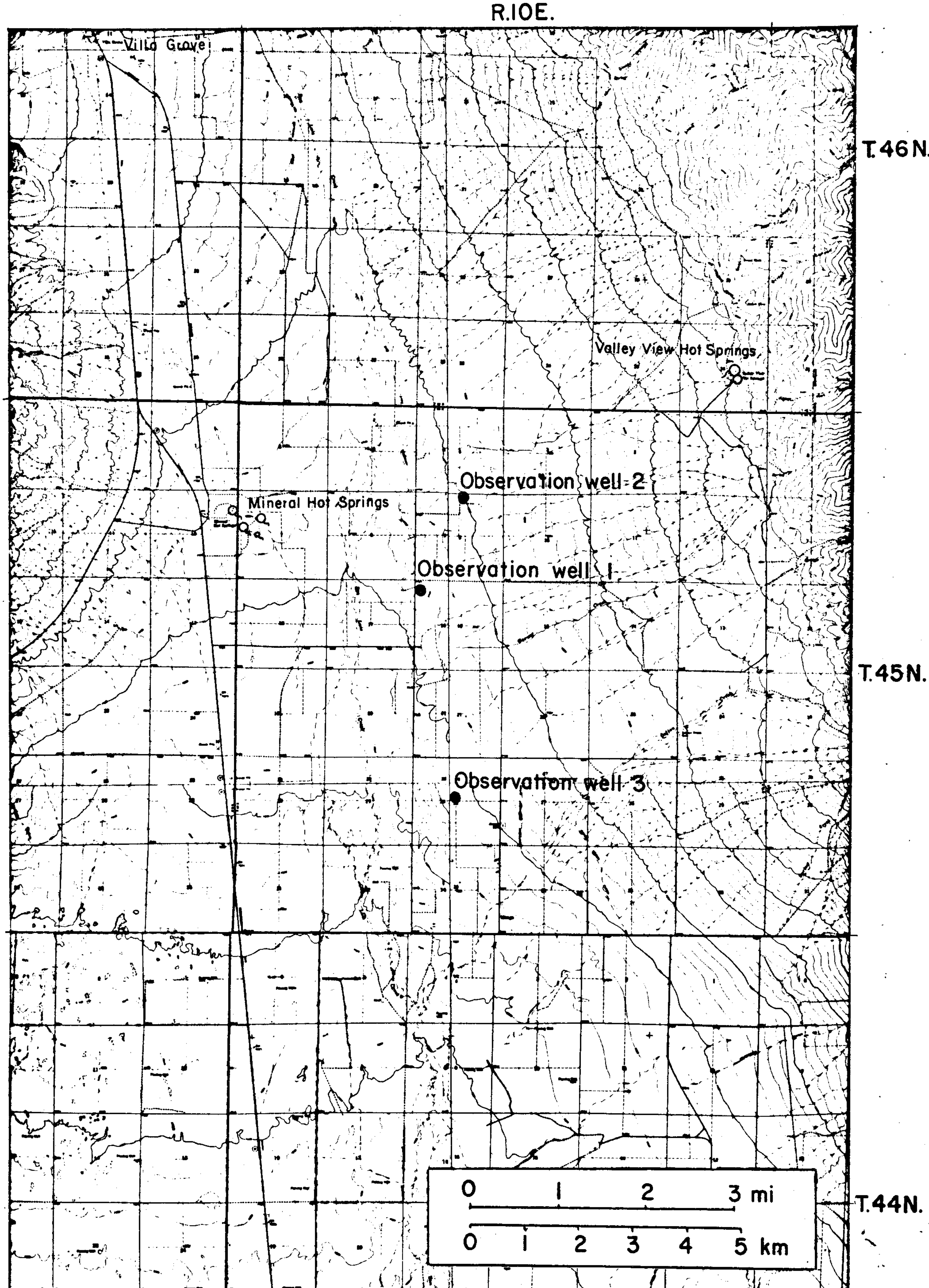


Figure 8. Location map showing the observation wells drilled in the study area of the KGRA.

rocks, Tertiary intrusive bodies, sedimentary and volcanic rocks and Quaternary deposits. With the exception of the Cretaceous intrusive Whitehorn stock, Mesozoic rocks are not present. In general, Quaternary deposits occupy the floors of the Upper Arkansas and northern San Luis Valleys, Tertiary intrusives and volcanics and Tertiary and Paleozoic sediments are found along the sides of the valleys and at higher elevations. Precambrian rocks form the cores of the mountain ranges bounding the KGRA on the east and west.

Precambrian

Precambrian metamorphic and igneous rocks are exposed over approximately 25% of the KGRA. They are found in the Sawatch Range, in the Kerber Creek area and in the northern Sangre de Cristo and southern Mosquito Ranges.

Metamorphic rocks are the oldest and also the dominant Precambrian rock type. They are generally light-to-dark colored gneisses and schists of varying mineralogic composition and textural types. The metamorphic rocks can generally be classed as banded and layered gneisses, amphibolites, quartz-mica gneisses and schists or mica-feldspar gneisses and schists. In the Buena Vista area, Limbach (1975) dated the banded and layered gneiss and the amphibolite as being older than 1700 m.y. (million years).

The Precambrian igneous rocks are generally light colored and occur as batholiths or smaller bodies intruding the older metamorphic rocks. Rock types include gneissic quartz monzonite, granodiorite, granite and dikes and sills. The dikes and sills are of varying composition and are generally too small to be shown at the scale of the maps. Radiometric age determinations range from Boulder Creek age to Silver Plume age (± 1700 m.y. to ± 1400 m.y.). An erosional unconformity with less than 10 feet(3 m) of relief separates the Precambrian rocks from the overlying sedimentary rocks (Litsey, 1958).

Lower and Middle Paleozoic

Numerous outcrops of Lower and Middle Paleozoic sedimentary rocks (Cambrian to Mississippian) are found in the northern Sangre de Cristo and southern Mosquito Ranges along the eastern boundary of the KGRA. Along the western boundary, these rocks have a more restricted occurrence, being found only south of the South Arkansas River in the area of Kerber Creek and in the southern Sawatch Range. These Lower and Middle Paleozoic sediments are predominantly carbonate rocks with minor quartzose sandstones.

Within the KGRA, six Lower and Middle Paleozoic formations have been mapped by previous investigators (fig. 9). These formations, mapped collectively on the geologic plates, have an average aggregate thickness of about 1,000 feet (300 m). Locally, thicknesses very from 630 to 1,200 feet (192-365 m).

The Sawatch Quartzite (Late Cambrian) is the oldest formation and, where present, unconformably overlies the Precambrian rocks. Pre-Ordovician erosion apparently removed much of the Sawatch Quartzite within the KGRA (Gableman, 1952). It is found at three localities: (1) Kerber Creek area, (2) the Turret area north of Salida, and (3) the Buffalo Peaks area. In the absence of the Sawatch Quartzite, the Lower Ordovician Manitou Dolomite is found at the base of the Paleozoic sedimentary sequence, unconformably overlying Precambrian rocks.

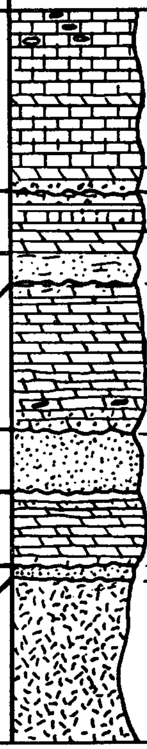
In ascending order, the remaining Lower and Middle Paleozoic sedimentary sequence consists of the Harding Sandstone and Fremont Dolomite of Ordovician age, the Chaffee Formation of Devonian age and the Leadville Limestone of Mississippian age. The Leadville Limestone is the top of the Lower and Middle Paleozoic sedimentary section and characteristically has a karst topography developed on its upper surface. No Silurian rocks are present in the KGRA, probably having been removed by pre-Devonian and subsequent erosion.

Upper Paleozoic

Upper Paleozoic (Pennsylvanian and Permian) sediments are terrigenous rocks and have a widespread occurrence in the northern Sangre de Cristo and southern Mosquito Ranges. Their thickest aggregate section, at least 18,000 feet (5,500 m), is in the Howard area. To the west, these rocks are found only in the Kerber Creek area.

The Upper Paleozoic sedimentary rock sequence and nomenclature developed by De Voto and Peel (1972) south of Whitehorn stock and by De Voto (1971) north of Whitehorn stock is used in this report (fig. 10).

SYSTEM	FORMATION		LITHOLOGIC DESCRIPTION
MISS.	LEADVILLE LIMESTONE 210′-350′		Limestone, blue to gray, fine-grained, massive bedded; interlayered with gray to black, medium-grained dolomite. Intraformational breccias locally at base; black to gray chert in upper portion
DEV.	CHAFFEE FM	DYER DOLOMITE 0′-123′	Dolomite, microcrystalline, weathers yellow to tan, interlayered thin-bedded cherty limestone.
		PARTING QUARTZITE 0′-62′	Sandstone, quartz, red to pink, locally variegated siltstone and shale, limestone and conglomerate.
ORD	FREMONT FM. 229′-300′		Dolomite and interlayered sandy and cherty dolomite, gray, thick- to massive-bedded, pit and cusp weathering surfaces.
	HARDING SS. 60′-116′		Sandstone, quartzitic, white, fine- to medium-grained; weathers red to brown, silica cement
	MANITOU FM. 90′-225′		Dolomite and dolomitic limestone, brown to gray, thin-bedded, lenses and nodules of chert along bedding planes.
CAMB.	SAWATCH QUARTZITE 0′-25′		Sandstone, quartzitic, white, fine- to medium-grained, thin-bedded; silica cement.
PRECAMBRIAN			Igneous and metamorphic rocks.



Feet 0 100 200 300

Figure 9. Composite stratigraphic column of the Lower and Middle Paleozoic rocks of the KGRA. After Knepper, 1974. Multiply feet by 0.3048 to find meters.

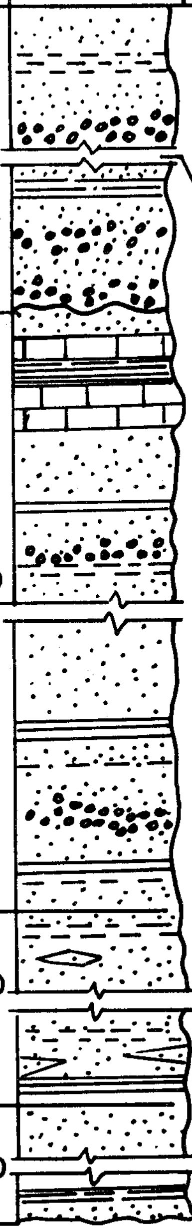
System	Formation	Thickness (feet)	Graphic Column	Lithologic description
Permian	Sangre de Cristo Formation	9000		Upper member: Thin, cyclic, drab red, brown, coarse, arkosic sandstones, conglomerates, micaceous siltstones and shale; includes the Crestone Conglomerate which grades into the upper member.
Pennsylvanian		6000		Lower member: Thick, cyclic, red, maroon, gray-green, arkosic sandstones, siltstone, minor limestones.
	Minturn Formation	6000		Sandstone, medium- to coarse-grained, conglomerates, siltstones, dominantly gray, green, tan; dark colored shales, interbedded limestones and gypsum beds in upper part.
	Sharpsdale Formation	1000		Sandstones, arkosic, locally conglomeratic, red shales, siltstones, micaceous; lenticular limestones.
	Kerber Formation	600		Sandstone, quartzitic, gray, tan, conglomeratic, white kaolinite matrix; interbedded dark, carbonaceous shales.
LOWER AND MIDDLE PALEOZOIC ROCKS.				

Figure 10. Composite stratigraphic column of the Upper Paleozoic rocks (Pennsylvanian and Permian) in the KGRA south of Whitehorn stock. After Wychgram, 1972. Multiply feet by 0.3048 to obtain meters.

South of Whitehorn stock, in the southern Mosquito Range, detailed mapping by various investigators (fig. 6), has shown the presence of four persistent, mappable formations. They are, in ascending order: the Pennsylvanian Kerber, Sharpsdale and Minturn Formations and the Permo-Pennsylvanian Sangre de Cristo Formation (De Voto and Peel, 1972)(fig. 10). North of Whitehorn stock, the Kerber and Sharpsdale formations have disappeared due to facies changes and become the Belden Formation (De Voto, 1971). The Minturn Formation is found both north and south of Whitehorn stock. The Permo-Pennsylvanian Sangre de Cristo Formation is confined to the area south of Whitehorn stock; however, lithologically equivalent rocks are mapped as the Maroon Formation north of Whitehorn stock (De Voto, 1972). The various formation relationships and thickness variations are summarized in Figure 11.

Mesozoic

Although no Mesozoic sedimentary rocks have been found in the KGRA, indirect evidence (Peel, 1971) indicates widespread Mesozoic deposition. However, subsequent erosion during the period of the Laramide orogeny removed any Mesozoic rocks that were deposited within the KGRA.

The only rocks of Late Mesozoic-Early Cenozoic age in the KGRA are in the Whitehorn stock. The stock, a complex intrusive body composed of granite, granodiorite, tonalite, quartz gabbro and gabbro, is entirely contained within Paleozoic strata except at its southwestern margin where it is in fault contact with Precambrian rocks. Radiometric dating has given a Late Cretaceous age of 69 m.y. (G. R. Scott, 1971, reported by Wychgram, 1972). It was emplaced during the early stages of the Laramide orogeny.

The Laramide orogeny began in the Late Cretaceous and continued into the Early Cenozoic. By late Eocene time the Laramide highlands had been reduced to a surface of relatively low relief extending from central Colorado into New Mexico. This erosion surface truncated all of the major Laramide structures in the KGRA. It is upon this erosion surface that the Middle Cenozoic volcanic rocks lie. The Late Cenozoic was characterized by rifting and complex block faulting which resulted in the development of down-faulted structural basins in which the upper Tertiary detrital sediments were deposited.

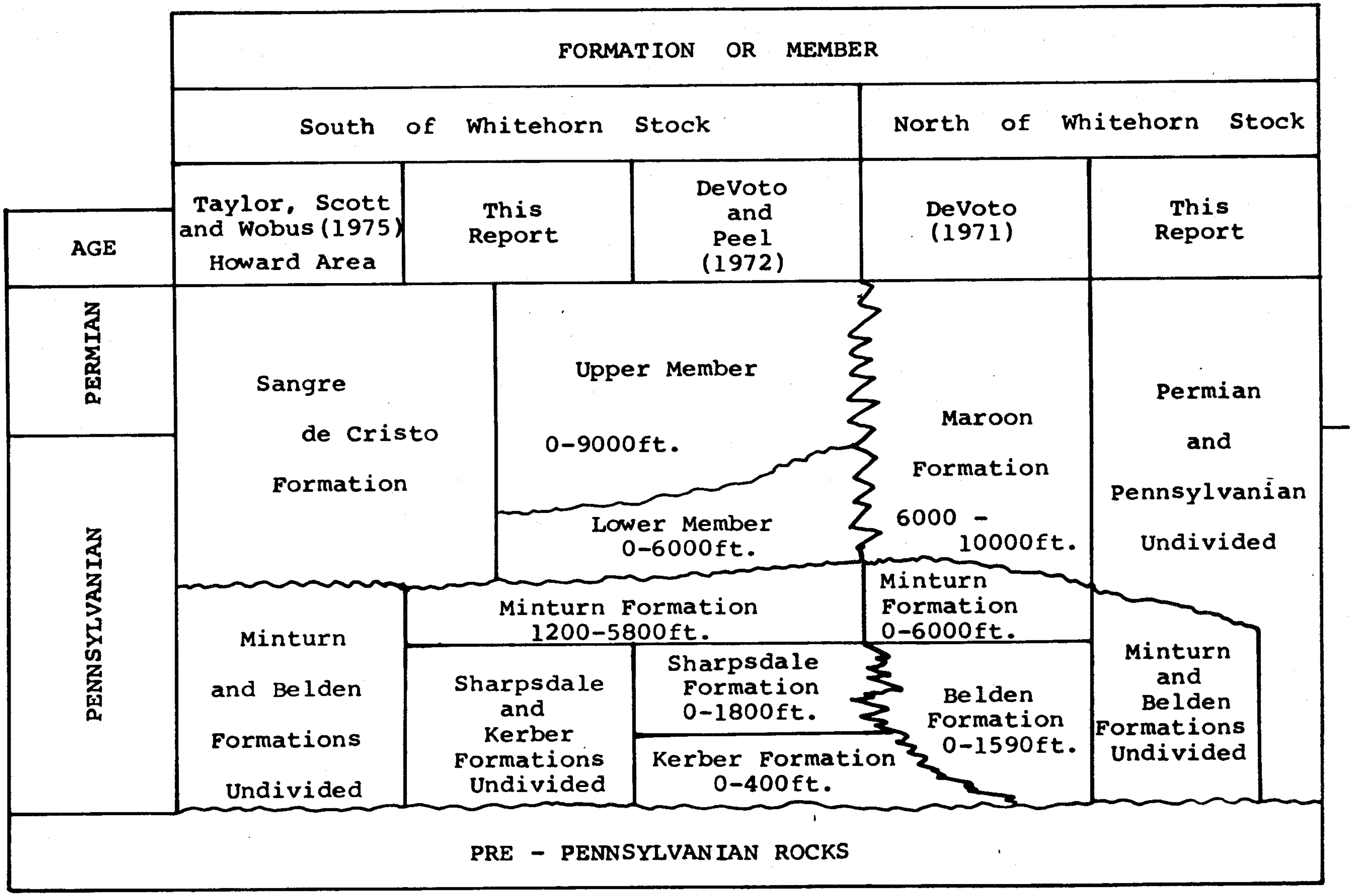


Figure 11. Stratigraphic summary of the Upper Paleozoic rocks (Pennsylvanian and Permian), north and south of Whitehorn stock, in the KGRA. Multiply feet by 0.3048 to obtain meters.

Cenozoic

Early and Middle Tertiary--In late Eocene(?) or early Oligocene time, a period of regional volcanism began in central and western Colorado. This continued into the Miocene, with the most vigorous activity in the Oligocene (Steven and Epis, 1968). During this time there was both plutonic and volcanic activity.

Intrusive Rocks: The Tertiary intrusive rocks in the KGRA range in age from Eocene(?)(Limbach, 1975; Scott, 1975), to Miocene and occur in two main areas: 1) the Mt. Princeton intrusive complex in the Sawatch Range, and (2) the Rito Alto and Slide Rock Mountain stocks in the northern Sangre de Cristo Range. Dikes and sills of varying composition are associated with the intrusive bodies.

The Mt. Princeton intrusive complex consists of several intrusive bodies occupying an area of approximately 170 square miles (440 km^2). The northeastern portion of this complex extends into the KGRA in the Sawatch Range. At least 11 distinctive rock types are found in the complex (Dings and Robinson, 1957), with at least four, ranging in age from Eocene(?) to Oligocene, being found in the KGRA. These are quartz diorite, Mt. Princeton quartz monzonite, Mt. Antero granite and Mt. Aetna quartz monzonite porphyry. Exact age relationships have not yet been established but radiometric dating of the Mt. Princeton quartz monzonite indicates an age of 36 $\pm$ 2 m.y. (Limbach, 1975; Scott, 1975). The youngest associated rock type in the area appears to be a small intrusive body or plug of rhyolite located about 3 miles (5 km) south of Mt. Princeton Hot Springs and just north of Raspberry Gulch. Radiometric dating places the age of this rhyolite at 22 $\pm$ 1 m.y. (Limbach, 1975). A small batholith of the Mt. Princeton quartz monzonite is the dominant rock type of the complex in the KGRA.

The Rito Alto stock (middle Miocene, Steven, U.S. Geological Survey, reported by Knepper, 1974), is the most southerly of the three intrusive bodies along the northern Sangre de Cristo-Mosquito Range trend. It is located about 4 miles (7 km) northeast of Valley View Hot Springs on the east flank of the northern Sangre de Cristo Range. It is a complex intrusive body which outcrops over an area of about 3 square miles (8 km^2). It consists principally of tonolite with some rhyolite and granite.

The Slide Rock Mountain stock, the central of the three intrusive bodies along the Sangre de Cristo-Mosquito Range trend, is located southeast of Coaldale on the eastern flank of the northern Sangre de Cristo Range. This stock is an elliptical-shaped body of relatively homogeneous light-colored, biotite quartz monzonite with an outcrop area of about 2 square miles (5 km^2). It is cut by two small, northwest-trending faults (Wychgram, 1972).

Volcanic Rocks: Extrusive volcanic rocks and attendant small intrusive bodies occur in two major areas of the KGRA (fig. 12): 1) the Bonanza area (Bonanza volcanic sequence), and 2) the Cameron Mountain area (Northern volcanic sequence). There are two other minor areas of occurrence, but their relationships with the two major areas are not yet fully understood. The volcanics of the Buffalo Peaks area are presently age dated as being almost contemporaneous and probably associated with the Oligocene volcanics of the Northern volcanic sequence as used in this report (Sanders, Scott, and Naeser, 1976). The volcanic rocks in the Poncha Pass area extend northward to the Arkansas River and may possibly be related to both the Bonanza volcanic sequence and the Northern volcanic sequence (Van Alstine, 1975; Scott, 1975). The extrusive rocks are primarily flows, breccias, tuffs and ashflow tuffs. The attendant small intrusives occur as dikes, sills, plugs and irregularly shaped bodies of rhyolite, latite, andesite, monzonite and gabbro (Mayhew, 1964).

Bonanza Volcanic Sequence--The Bonanza volcanic sequence, of Oligocene age, occupies an area of about 180 square miles (465 km^2) in the southwest part of the KGRA (fig. 12). This sequence of volcanic rocks is a northeastward extension of the larger San Juan volcanic field in south-western Colorado. At least nine distinguishable rock units are present within the KGRA. The oldest is the Rawley Formation or Andesite (Steven and Epis, 1968), consisting predominantly of latite and andesite flows. Radiometric dating (Lipman and others, 1970) places its age at 34.2 $\pm$ 0.2 and 33.4 m.y. The stratigraphic rock units and their interrelationships are shown in figure 13.

Northern Volcanic Sequence--A variety of volcanic rocks of late Eocene(?) to Miocene age are found in the northern and eastern parts of the KGRA. These are generally

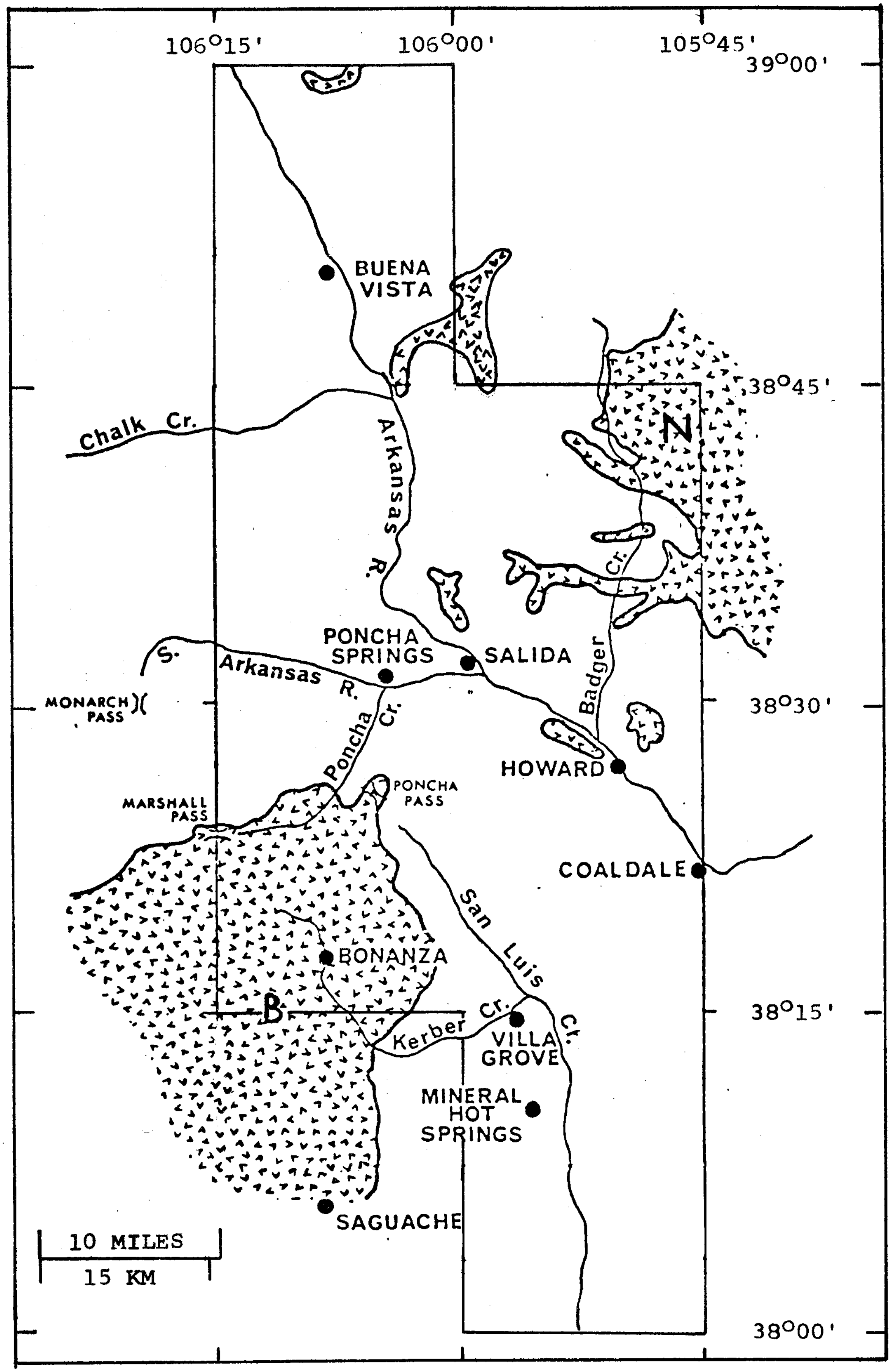


Figure 12. Map showing the areal distribution of volcanic rocks in the KGRA. B, Bonanza volcanic sequence; N, Northern volcanic sequence. After Knepper, 1974 and Scott, 1975.

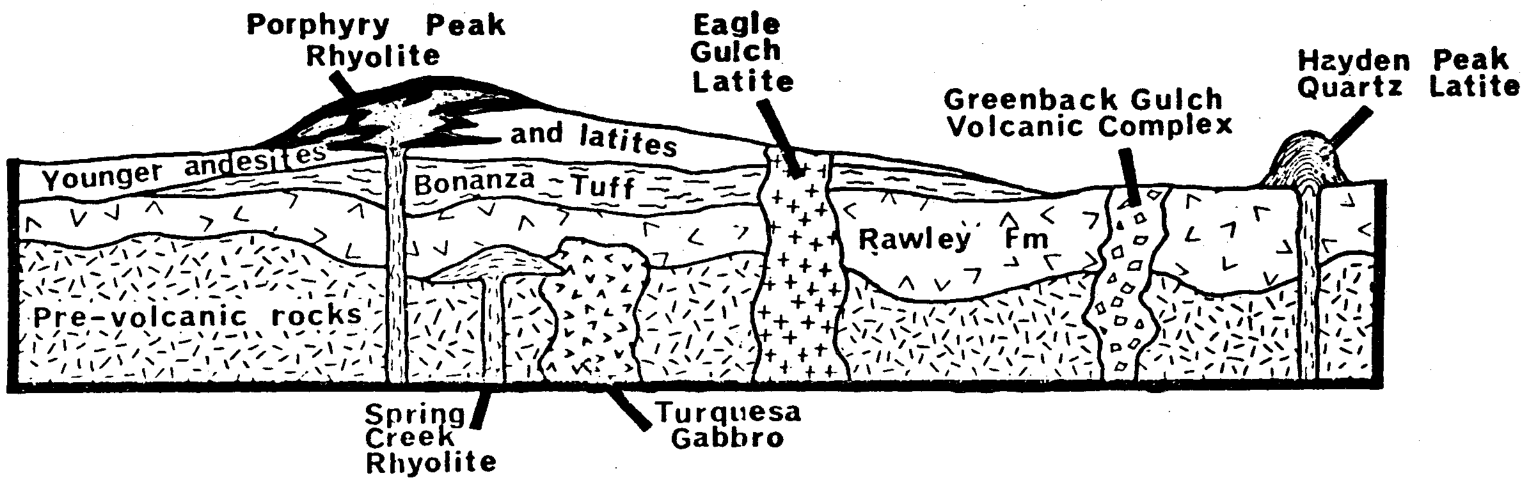


Figure 13. Diagrammatic cross-section of the volcanic rocks of the Bonanza volcanic sequence showing generalized structural and stratigraphic relationships. After Knepper, 1974.

related to the Thirtynine Mile volcanic field to the north and northeast. Erosion has removed much of the original volcanics but considerable thicknesses have been preserved in the generally east-west trending paleovalleys of Oligocene-Miocene age in the northern Sangre de Cristo and southern Mosquito Ranges. Detailed mapping in the area of the KGRA and the Antero Reservoir quadrangle (fig. 6) has helped to partially identify the complexity of volcanic units extending into the KGRA from the north and establish their relationship to the Thirtynine Mile volcanic field. Figure 14 summarizes the stratigraphic terminology of the Northern volcanic sequence as used in this report. Figure 15 summarizes the nomenclature of the Thirtynine Mile volcanic field (Epis and Chapin, 1977).

Although the volcanic rocks in the Poncha Pass area have been included in the Northern volcanic sequence (fig. 14), the relationship has not been fully established. The Gribbles Park and Wall Mountain Tuffs of the Northern volcanic sequence have been identified in this area. Van Alstine (1975) mapped a series of trachyandesite flows in the same area, and it is not known if these latter are related to the Northern volcanic sequence or the Bonanza volcanic sequence.

Upper Tertiary--The Upper Tertiary, post volcanism, sedimentary rocks are widespread in the northern half of the KGRA. Primarily coarse-to-fine grained detrital sediments, they were deposited in depressions caused by block-faulting along the Rio Grande rift zone in Miocene to late(?) Pliocene times and are preserved in structural and topographic lows. These sediments consist of poorly to moderately consolidated, interbedded, generally light-colored, tuffaceous claystones, siltstones, sandstones and conglomerates. Four formations have been recognized and mapped in the KGRA: (1) the Browns Canyon Formation, (2) the Santa Fe(?) Formation, (3) the Dry Union Formation, and (4) the Trump-Wagontongue Formation.

The Browns Canyon Formation (Van Alstine, 1969), has a very restricted occurrence north of Poncha Springs and west of Browns Canyon. Considered to be Miocene by Van Alstine (1969), Scott and others (1975), suggest it may be of Oligocene and Miocene age and is possibly correlative with the upper part of the Antero Formation of Johnson (1937).

(1) De Voto (1971)	(2) Knepper (1974)	(3) Epis and Chapin (1974)	(4) Van Alstine (1975)	5a) Scott (1975) 5b) Taylor, Scott, Wobus (1975) 5c) Scott, Van Alstine, Sharp (1975)	This Report	Radiometric Age (millions of years)	AGE
	Antero Fm.			5b) Andesite Plug	Andesite Plug		PLIOCENE
	Andesite of Big Baldy				Andesite of Big Baldy		AND/OR
	Boulder Gravels				Boulder Gravels		MIOCENE
	Silicic Felsite of Section 36				Silicic Felsite of Section 36		?
	Upper Andesite, Waugh Mtn. Latite	Andesite of Waugh Mountain		5b) Andesite at Waugh Mountain	Waugh Mountain Andesite	3) 18.9±1.2	
				5b) Tuff	Tuff		MIOCENE
	Nathrop Volcanics			5a) Nathrop Volcanics	Nathrop Volcanics	28.0±0.8-29.1±0.9 (Van Alstine, 1969)	?
Trachytic Tuff (Ash-flow 7)	Trachytic Tuff *Agate Creek Tuff	Gribbles Park Tuff	Upper Rhyolitic Ash-flow Tuff	5c) Gribbles Park Tuff	Gribbles Park Tuff	3) 28.6±0.6-29.5± 0.7	LATE OLIGOCENE
	Rawley Fm.		#Trachyandesite Flows		Trachyandesite Flows		
	Antero Fm. (?)	East Gulch Tuff		5b) East Gulch Tuff	East Gulch Tuff		
	Rhyodacite Ash and Flow			5c) Rhyodacite Ash and Flow	Rhyodacite Ash, Flow and Mudflow		
	*Agate Creek Tuff *Rawley Fm.		#Squirrel Gulch Flow	5c) Rhyodacite (Flow)	Rhyodacite (Flow)	33.2±1.3-33.7±2.1 (Van Alstine, 1974)	
				5a) Ashflow, breccia 5b) Ashflow	Volcanic Breccia		OLIGOCENE
Buffalo Peaks Andesite				5a) Buffalo Peaks Andesite	Buffalo Peaks Andesite	37.1±3.4-34.0±3.5 (Sanders et al, 1976)	
Antero Fm.	Antero Fm. *Badger Cr. Tuff	Antero Fm.		5b) Antero Fm.	Antero Fm.	3) 33.0±	
Castlerock Gulch Andesitic Tuff	*Badger Creek Tuff	Badger Creek Tuff		5b) Badger Creek Tuff	Badger Creek Tuff	3) 31.6±3.1-34.0±3.5	
				5a) Hypersthene Hrnblnd Andesite	Hypersthene Hornblende Andesite		
				5c) Quartz pyroxene Latite	Quartz Pyroxene Latite		
Lower Andesite 39Mile Volc. Field	Antero Fm.	Thirtynine Mile Andesite			Thirtynine Mile Andesite	3) 34.1±1.1	
Lower Volcanic Conglomerate	*Antero Fm.	Tallahassee Creek Conglomerate		5a) Tallahassee Cr. Conglomerate	Tallahassee Creek Conglomerate		EARLY OLIGOCENE
Agate Creek Tuff	Agate Creek Tuff	Wall Mountain Tuff		5c) Wall Mountain Tuff	Wall Mountain Tuff	3) 34.8±1.1-36.2±0.8 and 35.4±1.1	

Figure 14. Generalized composite stratigraphic summary and nomenclature usage of the Northern volcanic sequence. (*) indicates partial inclusion of formation. (#) indicates that it has not been determined whether unit should be assigned to the Northern or the Bonanza volcanic sequence.

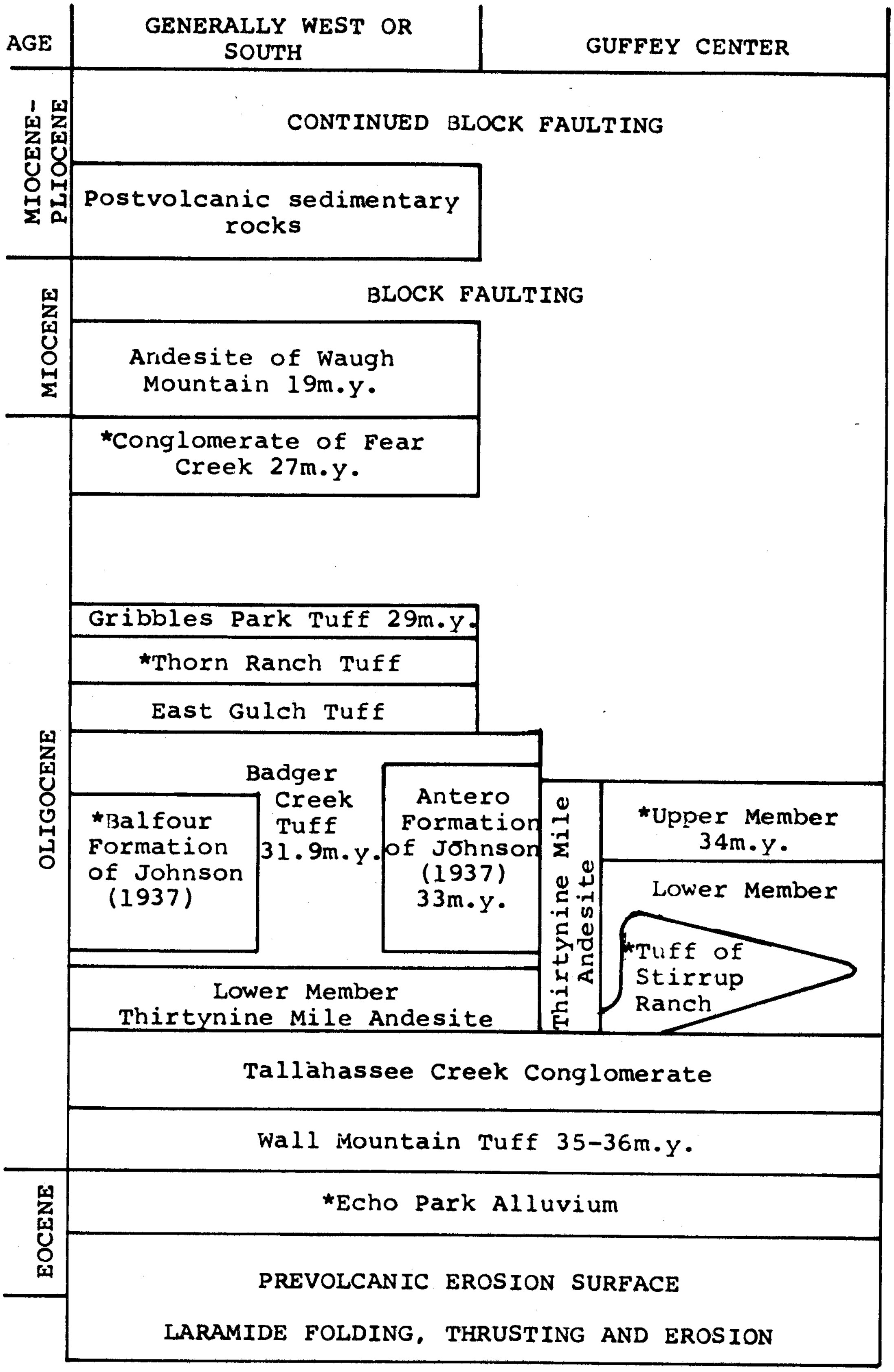


Figure 15. Generalized composite stratigraphy of the Thirtynine Mile volcanic field (after Epis and Chapin, 1974). (*) indicates unit not identified or not present in the KGRA.

Taylor and others (1975) have mapped some small, poorly defined outcrops northwest of Villa Grove as Santa Fe(?) Formation. South of the area of the KGRA, the Santa Fe Formation has a thickness in excess of 10,000 feet (3,000 m) and may represent an uninterrupted period of deposition from early Eocene through early Pliocene time (Huntley, 1976).

The Dry Union Formation, Miocene and Pliocene, has the greatest areal distribution of the Upper Tertiary sediments in the KGRA. It occurs in both the Upper Arkansas and northern San Luis Valleys and attains its greatest thickness along the western edge of the Upper Arkansas Valley graben. Van Alstine (1975) and Taylor and others (1975) have differentiated an upper and lower part, of Upper Pliocene and Upper Pliocene to Miocene age respectively, in the Poncha Springs-Howard area. Taylor and others (1975) have remapped the Howard area and included the Pleasant Valley conglomerate of Pierce (1969) in the lower party of the Dry Union Formation. Lowell (1971) describes a series of lava flows interbedded with Dry Union boulder gravels in the vicinity of Tenderfoot Hill, just east of Salida. This indicates Dry Union sedimentation was contemporaneous with volcanism in this area. This was first recognized by Bhutta (1954). Van Alstine (1970) described several detached blocks of Lower and Middle Paleozoic material at various stratigraphic levels in the Dry Union Formation southwest of Poncha Springs and perched on Precambrian rocks in the Sawatch Range to the west. Van Alstine (1970) ascribes these blocks to recurrent gravitational sliding off the flank of the Sawatch anticline and the fault at the western margin of the late Tertiary trough (Plate 2).

The Trump-Wagontongue Formation (De Voto, 1971) extends southward from the Antero Reservoir quadrangle into the northeastern part of the KGRA.

Quaternary

Pleistocene: Deposits of Pleistocene age consist of stream terrace and pediment gravels, various alluvial fan and morainal deposits of glacial and glacio-fluvial origin during pre-Wisconsinian and Wisconsinian glaciation. While separate sequences have been developed for the Upper Arkansas Valley and the northern San Luis Valley, the two sequences are in part contemporaneous but have not been directly correlated. The Upper Arkansas Valley Pleistocene deposits are predominantly stream terrace and pediment gravels with lesser amounts of morainal deposits. In the northern San Luis Valley, large Pleistocene alluvial fans dominate the floor of the valley. They are composed of locally derived debris from the mountains to the east and the west, and are part of the Alamosa Formation as used by Powell (1958). Morainal deposits are found in a few of the larger stream valleys in the northern Sangre de Cristo Range. Small occurrences of travertine are found in the vicinity of Wellsville and Coaldale.

Holocene: Several types of Holocene deposits are common to both the northern and southern parts of the KGRA. Alluvial fans are generally small, steeply-sloped and locally coalesce along some of the present-day streams. Colluvium, talus and landslide deposits are locally present. Other alluvial deposits include present-day stream alluvium and associated flood plain deposits and eolian sands. Travertine or tufa deposits are found in the vicinity of Mineral Hot Springs.

STRUCTURE

Prior to Middle Cenozoic time, the area of the KGRA had undergone two major periods of tectonic activity. The earliest, in the Upper Paleozoic, was characterized by block-faulting. The later Laramide orogeny, in the Late Cretaceous-Early Cenozoic, was characterized by folding, faulting and igneous intrusion. By the end of the Eocene the uplifted Laramide highlands had been reduced to relatively low relief. This erosion surface truncated all major Laramide structures. In the Middle Cenozoic a period of regional plutonism and widespread volcanic activity was initiated and extended from the late Eocene into the middle Miocene. Following the Middle Cenozoic volcanism, a period of tectonism began in the middle or late Miocene and continued into Quaternary time.

Late Cenozoic block-faulting was superimposed on a tectonic framework that had already undergone two separate periods of structural activity during Late Paleozoic and Laramide times. Structures initiated during the Late Paleozoic were reactivated and influenced the evolution of Laramide structures in the KGRA. The resultant Laramide structures locally influenced Late Cenozoic block-faulting.

Generally, the Rio Grande rift zone cuts across earlier structural trends and regionally is unrelated to previous tectonic or volcanic features. The evolution of the Rio Grande rift zone appears, therefore, to be more related to conditions in the lower crust and upper mantle rather than to the local tectonic framework.

The Upper Arkansas Valley is separated from the northern San Luis Valley by a drainage divide. These two valleys are structural as well as depositional basins. The topography of the KGRA reflects the complex block-faulting associated with the regional evolution of the Late Cenozoic zone of block-faulting extending from southern New Mexico into south-central Colorado.

During the late Miocene and Pliocene, initial graben development had produced the north-trending Upper Arkansas and northwest-trending San Luis grabens, separated by a topographic or structural divide. The approximate structural boundaries of the present northern San Luis Valley were outlined as the San Luis block subsided along high-angle, normal faults coincident with the block down-faulting of the Upper Arkansas graben (fig. 16). These structural basins were enhanced by continued tectonic activity and accompanying periods of sedimentation. The mountain ranges (Sawatch, Mosquito and northern Sangre de Cristo Ranges) bordering these valleys are major block uplifts. The volcanic mountains bordering the northern San Luis Valley on the west were primarily built prior to the rifting in the late Cenozoic.

Knepper (1974) believes that the San Luis and Upper Arkansas grabens were never a single structurally-continuous unit. The southernmost limit of the Upper Arkansas graben was in the vicinity of Alder (fig. 16) 11 miles (18 km) south of Salida and the two basins are structurally separated by the South Arkansas tilted fault block. Van Alstine (1970) postulates a Tertiary trough that structurally linked the Upper Arkansas and northern San Luis Valleys and refers to it as the San Luis-Upper Arkansas graben. The initial development of the Upper Arkansas and San Luis grabens was followed, during the late Pliocene-early Pleistocene, by the formation of a series of major, northwest-trending, block-faulted uplifts and basins (fig. 17).

In the northern San Luis Valley, the western flank of the Sangre de Cristo Range is marked by a prominent

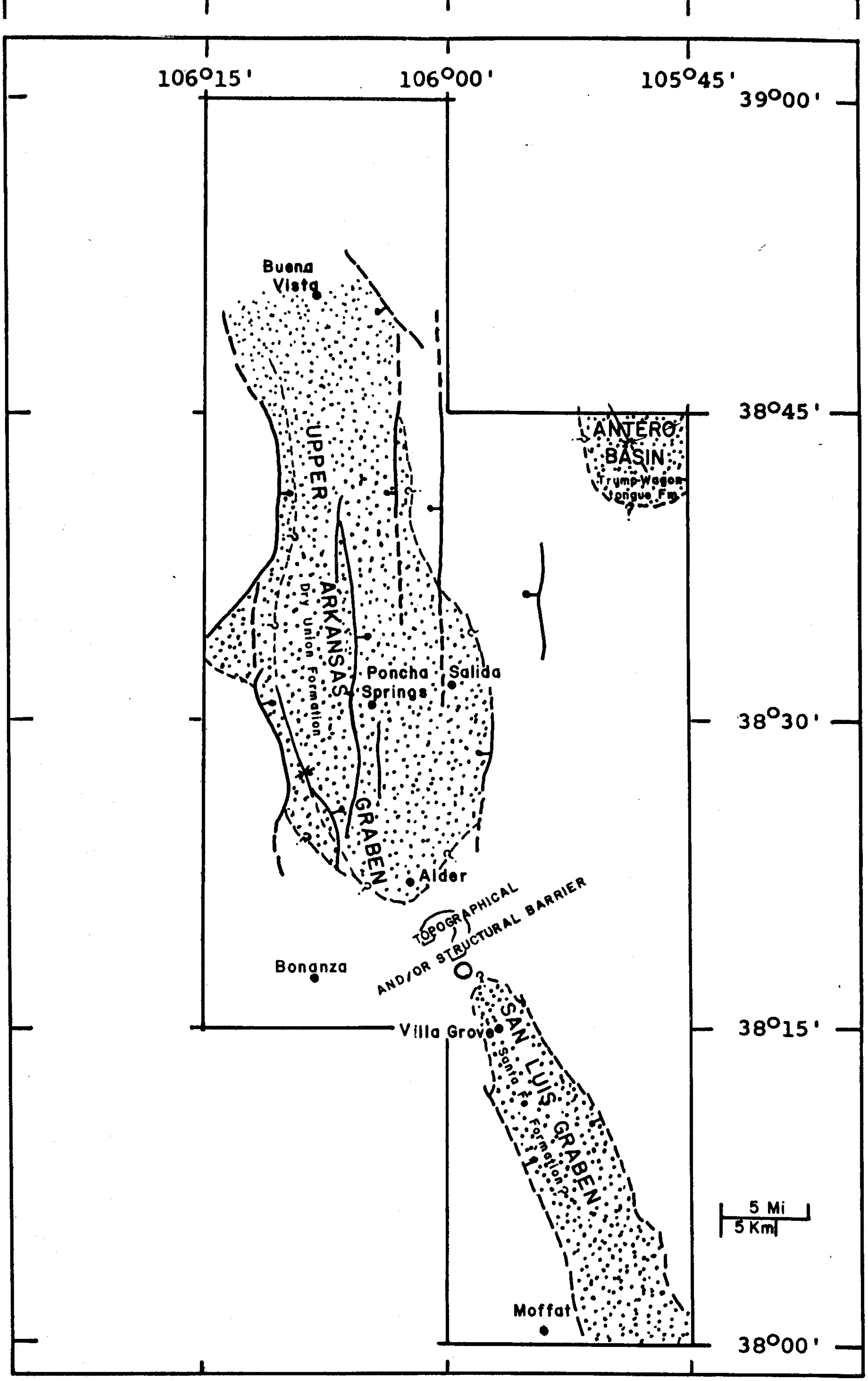


Figure 16. Tectonic map of the Miocene-early Pliocene structural configuration in the area of the KGRA. Stippled areas identify the location and distribution of Miocene and lower Pliocene graben-fill sediments. Adapted from Knepper, 1974 and Limbach, 1975.

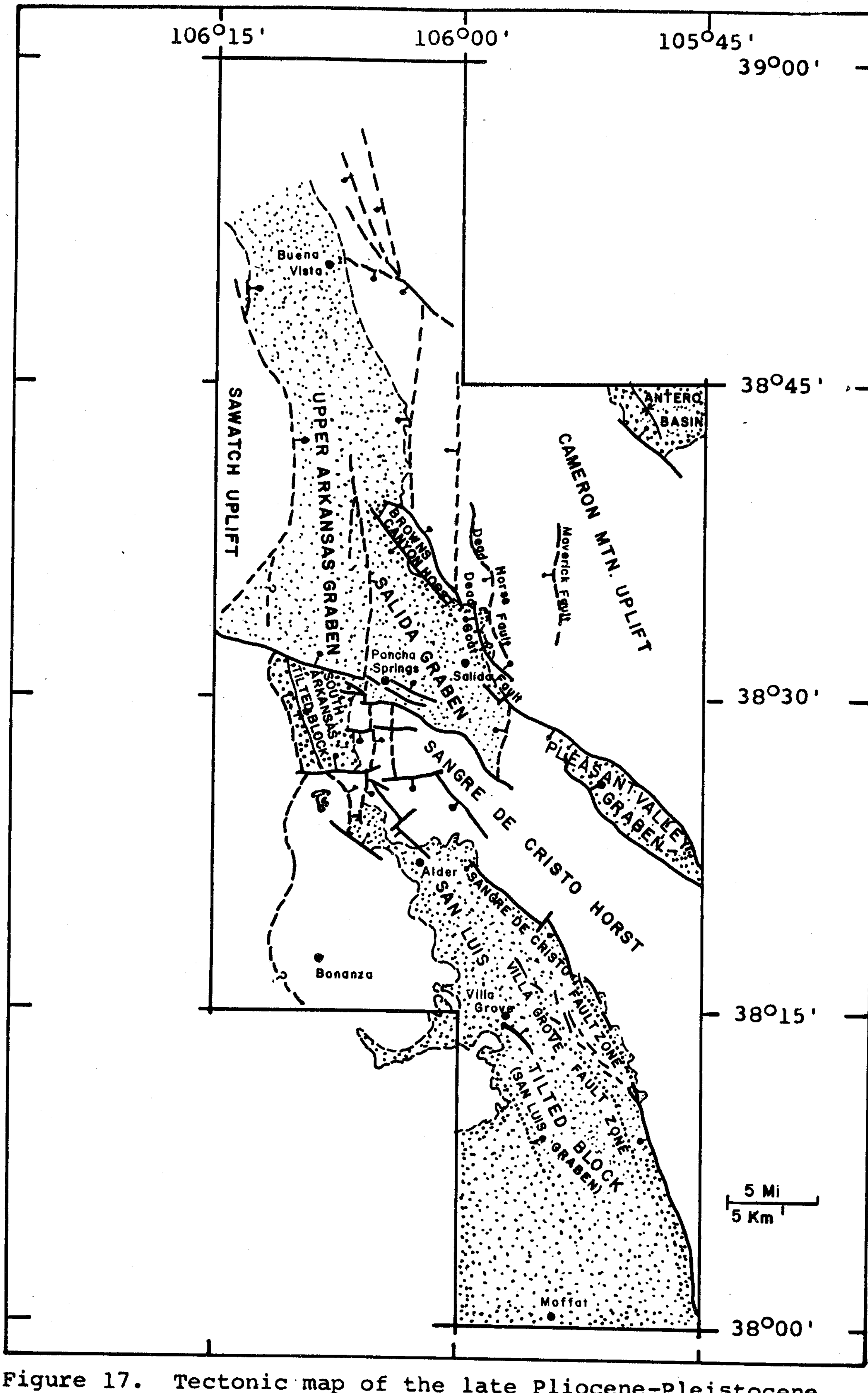


Figure 17. Tectonic map of the late Pliocene-Pleistocene structural configuration within the KGRA. Stippled areas identify the location and distribution of late Pliocene and Pleistocene deposits. Adapted from Knepper, 1974 and Limbach, 1975.

topographic linear feature that cuts across various geologic structures. It is marked by hot and cold springs and recent fault scarps, and extends from Poncha Pass southward out of the KGRA. This linear feature, interpreted as the trace of a major normal fault or fault zone of Late Tertiary age, has been named the Sangre de Cristo fault (Litsey, 1958). This is the master fault separating the Sangre de Cristo Range from the San Luis Valley and clearly marks the eastern boundary of the structural basin. The valley has been interpreted as an eastward-tilted block basin (Knepper, 1974) on the basis of the gentle valleyward, easterly dip of the easternmost volcanic rocks in the Bonanza area and the absence of any well-defined faults or fault systems marking the western edge of the valley. Geophysical investigations carried out in connection with the geothermal study, support this interpretation (Keller, 1977; Stoughton, 1977).

Recent structural adjustments along the Sangre de Cristo fault have produced displacements of up to 25 feet (7.6 m) on the surfaces of alluvial fans along most of the western edge of the Sangre de Cristo Range in the KGRA. The faulted gravels are Wisconsinian outwash fan deposits of Pinedale age, indicating that fault movement has occurred less than 10,000 years ago. The fault trace is frequently marked by springs and linear-aligned vegetation, particularly groves of aspen and willows along fault-controlled spring occurrences.

A second zone of recent faults trends northwestward from the vicinity of Valley View Hot Springs towards Villa Grove. The fault zone,referred to as the Villa Grove fault zone (Knepper, 1974, p. 179),is marked by a number of southwest-facing fault scarps developed in the Pleistocene alluvial fans of the northern San Luis Valley. The fault zone widens in a westward direction but the heights of the fault scarps diminish markedly in this direction. Displacement varies from 25 feet (7.6 m) near Valley View Hot Springs to less than five feet (1.5 m) at the northwest end. The Villa Grove fault zone may be the diffused surface expression of buried, high-angle, normal fault scarps associated with the Late Cenozoic rifting (Knepper, 1974; Stoughton, 1977). Northeast-facing recent fault scarps along the southwestern edge of the Villa Grove fault zone may possibly reflect the western margin of a sub-graben north and east of Mineral Hot Springs (Keller, 1977; Stoughton, 1977). The existence of at least one fault-bounded graben, or sub-graben, is supported by a number of geophysical surveys made in the northern

San Luis Valley (Gaca, 1965; Behrendt and Bajwa, 1974, Jordan, 1974; Keller, 1977; Stoughton, 1977; Arestad, 1977). Gaca (1965) postulated a thickness of 16,000 feet (5,000 m) for the sediments in the graben. Later studies (Jordan, 1974; Arestad, 1977; Stoughton, 1977) indicate thicknesses of 4,000-5,800 feet (1,200-1,800 m) of post-Eocene basin fill sediments in the sub-grabens north and east of Mineral Hot Springs. Greater thicknesses may exist southeast of this area (Stoughton, 1977). Mineral Hot Springs occurs along the buried trace of the western boundary fault of the San Luis graben (Knepper, 1974; Stoughton, 1977).

During the summer of 1977, geophysical studies were made in the KGRA for the Colorado Division of Water Resources by the Geophysical Department of the Colorado School of Mines. Interpretations of the results of these studies (Keller, 1977; Arestad, 1977; Stoughton, 1977) have delineated a number of potential, geothermal areas--the Buena Vista and Salida basins and the northern San Luis Valley. These studies also outlined a number of heretofore inferred, buried structural features associated with the Laramide orogeny and the Cenozoic tectonism in the northern San Luis Valley. The buried structures, based on interpretation of geophysical studies, are shown on Plates 5A and 6A.

Laramide structures, which have been delineated as a result of the geophysical studies, are the buried south-eastern or eastern extensions of the Eastern anticline, the Villa Grove fault, the Clayton syncline and fault, the Nolan and Kerber faults, and the Kerber Creek-Major Creek fault zone which transects the valley from west to east. Other buried structures have also been delineated (Plates 5A and 6A).

Late Cenozoic structural features consist of asymmetrical graben development in which the structural blocks are progressively down-faulted to the east within the basin and a west-bounding fault coinciding approximately with the west topographic margin of the valley. The deepest grabens are located in the central part of the valley and are bounded on the east by the Villa Grove fault zone. Other Late Cenozoic structures are normal or vertical faults transversing the basin or transecting the north-south graben features (Stoughton, 1977).

GROUND WATER

The hydrogeology of the San Luis Valley has been described by Siebenthal (1910), Powell (1958), and Emery and others (1971, 1972, 1973), and Huntley (1976). The hydrogeology of the extreme southern portion of the valley near the Colorado-New Mexico state line has been investigated in part by Phillips (1974). Much of the description that follows is taken directly from these reports. To date there have been no comprehensive hydrogeologic studies of the Upper Arkansas Valley.

San Luis Valley

The San Luis Valley is a large north-trending structural depression that is downfaulted on the eastern border and hinged and (or) possibly faulted on the western side (fig. 4). The valley is locally underlain with possibly as much as 30,000 feet (9140 m) of semi-consolidated to unconsolidated clay, silt, sand, gravel, and interbedded volcanic rocks of Oligocene and Holocene age (Gaca and Karig, 1966; Kleinkopf and others, 1970). Recent investigations by Jordan (1974) and Stoughton (1977) suggest that reinterpretation of existing gravity data might reduce the figure by two thirds.

Total annual water supply to the San Luis Valley averages about 2,500,000 acre feet (3080 cubic hectometers, hm^3). Of this about 1,500,000 acre feet (1850 hm^3) is inflow from surrounding mountains and 1,000,000 acre feet (1230 hm^3) is from precipitation on the valley floor. Discharge from the valley averages about 2,000,000 acre feet (2460 hm^3) by evapotranspiration and about 500,000 acre feet (616 hm^3) as flow across the state line (Emery and others, 1971).

Ground water in the San Luis Valley occurs in two types of aquifers--unconfined and confined. These aquifers possibly contain between 1 and 2 billion acre feet (2.47×10^6 hm^3) of water in storage in the upper 6,000 feet (1,800 m). Confining conditions are created over most of the valley by a series of discontinuous and lenticular clay layers generally referred to as the "blue clay" (bluish gray clay has locally been observed) or, more correctly, the "clay series." Discontinuity of the clay series undoubtedly causes varying degrees of hydraulic connection between aquifers. Confined conditions were present in the three wells constructed during November, 1975. It is currently suspected that confined conditions extend into the northernmost portions of the valley--possibly to within six or seven miles (about 10 km) of Poncha Pass. In observation wells 1 and 3, the principal confining layer is the predominantly clay and shale series lying between depths from about 450 feet (137 m) and 800 feet (244 m).

Unconfined ground water underlies the entire San Luis Valley, at depths ranging from less than six feet (1.8 m) throughout much of the valley floor to over 20 feet (6.1 m) along the flanks of the surrounding mountains. Thickness of the unconfined aquifer ranges from 50 to 200 feet (15-61 m).

Water is recharged to the unconfined aquifer by infiltration of precipitation, ground water inflow from peripheral areas, infiltration of applied irrigation water, leakage from canals and ditches, discharges from springs, uncontrolled discharges from flowing wells, and probably from local upward leakance of water from the underlying confined aquifer system. In the northern half of the San Luis Valley, a closed hydrologic basin, all discharge of water from the unconfined aquifer, with minor exception of local discharge into the confined aquifer, is by evapotranspiration (Huntley, 1976).

South of the Rio Grande, discharge of ground water is by evapotranspiration, seepage to streams, and other water conveyance systems, and probably by discharge into underlying volcanic rocks (Phillips, 1974; Winograd, 1959, p. 32, 33).

Maps of the shape and slope of the water table, depth to water, and various other miscellaneous hydrogeologic features have been prepared by Emery and others (1971, 1973), Huntley (1976), and Powell (1958).

Confined ground water also occurs almost everywhere in the valley. It is encountered from about the top of the clay series to depths possibly exceeding 15,000 feet (4600 m). Emery (1973, p. 6) showed that flowing wells can be obtained in an area of about 1,400 square miles (3626 km^2).

It is believed that the principal source of recharge to the confined aquifer is from the highly fractured and permeable volcanic sequence of rocks which outcrop in the

San Juan Mountains and dip eastwards under the valley floor. Huntley (1976, p. 154) states that the principal component of ground water motion in ash flow tuffs in the region, is parallel to bedding. Ground water recharge to the confined aquifer along the east side of San Luis Valley is believed to be confined to a narrow 1.1 mile (1.8 km) wide strip extending westward from the base of the Sangre de Cristo Mountains. Huntley (1976, p. 161) suggests that presence of confining clays along the eastern margin of the valley only slightly affects ground water recharge to the confined aquifer. The principal sources of discharge from the confined aquifer is by wells, springs, upward leakance of water through the clay series into the unconfined aquifer, and possibly by losses through volcanic rocks in the extreme southern end of the valley (Phillips, 1974; Winograd, 1959).

The quality of water in the confined aquifer is generally better than that in the unconfined aquifer. It is generally of excellent quality near the valley perimeter, a reflection of the quality of recharge water, but worsens in quality as it moves down-gradient. The concentration of dissolved solids in 68 samples from wells tapping the confined aquifer in the northern San Luis Valley ranged from 70 to 890 mg/l (Emery and others, 1971; Huntley, 1976). Results of analyses of water from the three observation wells constructed during November 1975 are shown in table 1 and analyses of water from Mineral Hot Springs and Valley View Hot Springs are shown in table 2. The quality of the water from the hot springs is possibly a reflection of the quality of water from deeper parts of the confined aquifer and could be an indication of the quality of water which would be discharged should the geothermal reservoirs be developed. It is quite possible that water within the geothermal reservoirs contains a significantly higher concentration of dissolved solids. Additional observation well construction and water quality analyses will be required to support either premise.

The concentration of dissolved solids in 324 water samples from the unconfined aquifer in the northern San Luis Valley ranged from 52 to 13,800 mg/l (Huntley, 1976; Emery and others, 1971). The quality of water in the unconfined aquifer worsens toward the closed basin. This can be attributed to: 1) leaching of chemicals from fertilization practices; 2) solution of minerals from rocks and aquifer material; and 3) the concentrating effect of evapotranspiration.

Table 1a. Results of analysis of water from observation well 1
Northern San Luis Valley, Colorado. Location, NW 1/4
NW 1/4 sec. 16, T. 45 N., R. 10 E., N.M.

ALK TOT (AS CACO3)	MG/L	52	PH FIELD		6.8
ARSENIC DISSOLVED	UG/L	1	PHOS ORTHO DIS AS P	MG/L	0.01
BICARBONATE	MG/L	63	PHOSPHATE DIS ORTHO	MG/L	0.03
BORON DISSOLVED	UG/L	50	POTASSIUM DISS	MG/L	1.7
CADMIUM DISSOLVED	UG/L	0	RESIDUE DIS CALC SUM	MG/L	430
CALCIUM DISS	MG/L	17	RESIDUE DIS TON/AFT		0.53
CARBONATE	MG/L	0	SAR		7.4
CHLORIDE DISS	MG/L	5.0	SELENIUM DISSOLVED	UG/L	0
FLUORIDE DISS	MG/L	1.6	SILICA DISSOLVED	MG/L	12
HARDNESS NONCARB	MG/L	0	SILVER DISSOLVED	UG/L	0
HARDNESS TOTAL	MG/L	50	SODIUM DISS	MG/L	120
IRON DISSOLVED	UG/L	50	SODIUM PERCENT		33
LITHIUM DISSOLVED	UG/L	0	SP. CONDUCTANCE FLD		660
MAGNESIUM DISS	MG/L	1.8	SULFATE DISS	MG/L	240
MANGANESE DISSOLVED	UG/L	5	WATER TEMP (DEG C)		17.0
MERCURY DISSOLVED	UG/L	0.0	YIELD-WELL-GAL./MIN.		50
NO2+NO3 AS N DISS	MG/L	0.00	ZINC DISSOLVED	UG/L	0

CATIONS	(MG/L)	(MEQ/L)	ANIONS	(MG/L)	(MEQ/L)
CALCIUM DISS	17	0.849	BICARBONATE	63	1.033
MAGNESIUM DISS	1.8	0.149	CARBONATE	0	0.000
POTASSIUM DISS	1.7	0.044	CHLORIDE DISS	5.0	0.142
SODIUM DISS	120	5.220	FLUORIDE DISS	1.6	0.035
			SULFATE DISS	240	4.997
			NO2 + NO3 AS N D	0.000	0.000
	TOTAL	6.260		TOTAL	6.255

PERCENT DIFFERENCE = 0.04

Table 1b. Results of analysis of water from observation well 2 Northern San Luis Valley, Colorado. Location, NW 1/4 NE 1/4 sec. 9 T. 45 N., R. 10 E., N.M.

ALK. TOT (AS CACO3)	MG/L	112	PH FIELD		7.9
ARSENIC DISSOLVED	UG/L	0	PHOS ORTHO DIS AS P	MG/L	0.01
BICARBONATE	MG/L	136	PHOSPHATE DIS ORTHO	MG/L	0.03
BORON DISSOLVED	UG/L	8	POTASSIUM DISS	MG/L	2.7
CADMIUM DISSOLVED	UG/L	0	RESIDUE DIS CALC SUM	MG/L	305
CALCIUM DISS	MG/L	57	RESIDUE DIS TON/AFT		0.41
CARBONATE	MG/L	0	SAR		0.5
CHLORIDE DISS	MG/L	1.6	SELENIUM DISSOLVED	UG/L	0
CLUORIDE DISS	MG/L	0.2	SILICA DISSOLVED	MG/L	16
HARDNESS NONCARB	MG/L	88	SILVER DISSOLVED	UG/L	0
HARDNESS TOTAL	MG/L	200	SODIUM DISS	MG/L	16
IRON DISSOLVED	UG/L	60	SODIUM PERCENT		15
LITHIUM DISSOLVED	UG/L	0	SP. CONDUCTANCE FLD		498
MAGNESIUM DISS	MG/L	14	SULFATE DISS	MG/L	130
MANGANESE DISSOLVED	UG/L	10	WATER TEMP (DEG C)		12.0
MERCURY DISSOLVED	UG/L	0.0	YIELD-WELL-GAL./MIN.		30
NO2+NO3 AS N DISS	MG/L	0.15	ZINC DISSOLVED	UG/L	130

CATIONS	(MG/L)	(MEQ/L)	ANIONS	(MG/L)	(MEQ/L)
CALCIUM DISS	57	2.845	BICARBONATE	136	2.230
MAGNESIUM DISS	14	1.152	CARBONATE	0	0.000
POTASSIUM DISS	2.7	0.070	CHLORIDE DISS	1.6	0.046
SODIUM DISS	16	0.696	FLUORIDE DISS	0.2	0.011
			SULFATE DISS	130	2.707
			NO2+NO3 AS N D	0.15	0.011
	TOTAL	4.761		TOTAL	5.002

PERCENT DIFFERENCE = -2.47

Table 1c. Results of analysis of water from observation well 3 Northern San Luis Valley, Colorado. Location, SW 1/4 NE 1/4 sec. 28, T. 45 N., R. 10E., N.M.

ALK TOT (AS CACO3)	MG/L	98	PH FIELD		9.5
ARSENIC DISSOLVED	UG/L	0	PHOS ORTHO DIS AS P	MG/L	0.00
BICARBONATE	MG/L	120	PHOSPHATE DIS ORTHO	MG/L	0.00
BORON DISSOLVED	UG/L	10	POTASSIUM DISS	MG/L	1.1
CADMIUM DISSOLVED	UG/L	0	RESIDUE DIS CALC SUM	MG/L	193
CALCIUM DISS	MG/L	36	RESIDUE DIS TON/AFT		0.26
CARBONATE	MG/L	0	SAR		0.5
CHLORIDE DISS	MG/L	1.5	SELENIUM DISSOLVED	UG/L	0
FLUORIDE DISS	MG/L	0.2	SILICA DISSOLVED	MG/L	14
HARDNESS NONCARB	MG/L	31	SILVER DISSOLVED	UG/L	0
HARDNESS TOTAL	MG/L	130	SODIUM DISS	MG/L	12
IRON DISSOLVED	UG/L	130	SODIUM PERCENT		17
LITHIUM DISSOLVED	UG/L	2	SP. CONDUCTANCE FLD		990
MAGNESIUM DISS	MG/L	9.6	SULFATE DISS	MG/L	59
MANGANESE DISSOLVED	UG/L	5	WATER TEMP (DEG C)		14.0
MERCURY DISSOLVED	UG/L	0.0	YIELD-WELL-GAL./MIN.		50
NO2+NO3 AS N DISS	MG/L	0.15	ZINC DISSOLVED	UG/L	40

CATIONS	(MG/L)	(MEQ/L)	ANIONS	(MG/L)	(MEQ/L)
CALCIUM DISS	36	1.797	BICARBONATE	120	1.967
MAGNESIUM DISS	9.6	0.790	CARBONATE	0	0.000
POTASSIUM DISS	1.1	0.029	CHLORIDE DISS	1.5	0.043
SODIUM DISS	12	0.522	FLUORIDE DISS	0.2	0.011
			SULFATE DISS	59	1.229
			NO2+NO3 AS N D	0.15	0.011
	TOTAL	3.136		TOTAL	3.259

PERCENT DIFFERENCE = -1.92

Table 2. Results of analyses of water from hot springs in northern San Luis Valley and Upper Arkansas Valley. After Pearl and Barrett, 1975.

Name	Alkalinity (As Ca CO3)	Arsenic	Bicarbonate	Boron	Cadium	Calcium	Chloride	Flouride	Hardness NonCarb.	Hardness Total	Iron	Lithium	Magnesium
	mg/l	ug/l	mg/l	ug/l	ug/l	mg/l	mg/l	mg/l	mg/l	mg/l	ug/l	ug/l	mg/l
Cottonwood Hot Spring A	60	2	73	90	0	6.2	30	14	0 0	18	20	160	0.5
Mt. Princeton Hot Spg. A	58	1	71	20	0	11	4.4	9.1	0	20	40	90	0.5
Mt. Princeton Hot Spg. G	60	1	73	10	0	12	3.8	8.3	0	22	10	80	0.5
Hortense Hot Spring	68	3	83	40	1	4.5	9.8	18	0	13	40	140	0.5
Hortense Hot Wtr. Well	62	2	75	30	0	6.4	8.3	14	0	20	40	120	1.0
Mineral Hot Spring A	275	32	335	350	1	60	41	3.6	0	200	220	320	13
Mineral Hot Spring C	280	28	341	370	0	60	43	4.2	0	210	20	330	14
Mineral Hot Spring D	286	26	349	370	0	55	39	3.9	0	190	30	330	13
Poncha Hot Spring A	177	2	216	80	0	20	49	11	0	53	20	190	0.7
Poncha Hot Spring B	176	2	214	70	0	18	48	12	0	47	50	180	0.5
Poncha Hot Spring C	176	6	214	80	0	24	49	11	0	63	40	200	0.8
Valley View Hot Spg. A	98	1	120	8	0	51	0.8	0.4	91	190	10	0	15
Valley View Hot Spg. B	105	2	128	8	0	46	2.6	0.3	68	170	20	10	14
Fullenwider Warm Spg.	95	1	116	50	0	21	15	4.4	0	70	20	100	4.2

Name	Manganese	Mercury	Nitrate	Phosphate	Potassium	Selenium	Silica	Sodium	Sulfate	Zinc	Total Dissolved Solids
	ug/l	ug/l	mg/l	mg/l	mg/l	ug/l	mg/l	mg/l	mg/l	ug/l	mg/l
Cottonwood Hot Spring A	0	0	0.08	0.04	2.8	0	60	110	110	10	370
Mt. Princeton Hot Spg. A	10	0	0.14	0.05	2.1	0	60	57	55	10	245
Mt. Princeton Hot Spg. G	10	0	0.24	0.04	1.9	0	57	50	58	0	229
Hortense Hot Spring	0	0	0.06	0.05	3.2	0	72	93	97	10	340
Hortense Hot Wtr. Well	10	0	0.02	0.01	2.8	0	72	84	92	0	318
Mineral Hot Spring A	20	0	0.14	0.04	14.	0	48	130	170	0	643
Mineral Hot Spring C	30	0	6.5	0.04	14	0	50	150	190	0	723
Mineral Hot Spring D	20	0	2.0	0.03	14	0	48	140	170	8	665
Poncha Hot Spring A	40	0.1	0.05	0.05	8	0	81	190	200	10	667
Poncha Hot Spring B	40	0.1	0.02	0.04	7.8	0	83	190	190	0	655
Poncha Hot Spring C	50	0	0.02	0.05	8.3	0	81	190	200	4	670
Valley View Hot Spring A	20	0	0.57	0.01	2.5	1	21	3.5	96	0	252
Valley View Hot Spring B	0	0	0.22	0.01	2.2	0	19	3.7	82	0	234
Fullenwider Warm Spring	5	0		0.02	1.6	0	27	80	120	8	

The hydraulic properties of the unconfined and confined aquifers are given in table 3 (from Emery and others, 1971). Table 4 shows the results of recovery tests on observation wells 1, 2, and 3. Locations are shown in figure 8. Low transmissivity values are to a large degree representative of the interval perforated. Caving sand and gravel layers in the upper 200 feet (60 m) of material penetrated, and intermittent swelling clays below depths of about 100 feet (30 m) prevented the insertion of packers. It is believed that the swelling nature of the clays formed, at least, some degree of isolation of the tested intervals.

Analysis of a core obtained from the interval 934-935 feet (284.7 - 284.9 m) in observation Well 3 gives an indication of the character of a semiconsolidated, conglomeratic sandstone. Vertical permeability (hydraulic conductivity) ranged between 0.24 and 3.0 gpd/ft^2 (0.0098 - 0.123 m/d) and horizontal permeability (hydraulic conductivity) ranged between 0.07 and 0.037 gpd/ft^2 (0.0029 - 0.0015 m/d). Specific storage is 1.0 x 10^{-5}/ft (3.05 x 10^{-5}/m) and porosity is 3.6%. The relatively high vertical permeability (hydraulic conductivity) illustrates the cored horizon's capability to transmit water more readily in a vertical direction than in a horizontal direction.

Upper Arkansas Valley

The Upper Arkansas Valley is a narrow structural trough extending northward from near Salida to the Continental Divide at Tennessee Pass north of Leadville; a distance of about 65 miles (104 km). The valley has been classified as a graben with a tectonic history similar to that of the San Luis Valley. It is underlain by extensive deposits of predominantly unconsolidated clay, silt, sand, and gravel (fig. 3). In the northern end of the graben, the deposits possibly extend to a depth of one or two thousand feet (about 300-600 m). Near Buena Vista, the estimated thickness of the deposits is about 4,600 feet (1,400 m) (Zohdy and others, 1971). Near Salida it has been estimated that possibly 4,000 to 10,000 feet (1220-3050 m) of deposits are locally present (Knepper, 1974; Van Alstine, 1968).

Total annual water supply to the Upper Arkansas Valley is about 1,586,000 acre feet (1,956 hm^3) of which about 1,486,000 acre feet (1,833 hm^3) is from

Table 3. Hydraulic properties of the unconfined and confined aquifers of San Luis Valley, Colorado. Multiply feet by 0.3048 to find meters: gpd/ft by 0.0124 to find m^2/d; gpm by 0.06309 to find lps.

System or series	Geologic unit	Hydrologic unit	Thickness (feet)	Physical character	Hydrologic character	Water supply
Holocene to Oligocene	Valley fill	Unconfined aquifer	0-200	Unconsolidated clay, silt, sand, and gravel.	Transmissivity ranges from 1,000 to 250,000 gallons per day per foot. Specific yield is estimated to be 0.20.	Yields as much as 3,000 gallons per minute.
		Confined aquifer	50-30,000	Unconsolidated clay, silt, sand, and gravel inter-bedded with volcanic flows and tuffs.	Transmissivity ranges from 4,000 to 300,000 gallons per day per foot in zone tapped by existing wells. Storage coefficient is estimated to be 0.0001. Water is under artesian pressure.	Yields as much as 4,000 gallons per minute.
Precambrian	Crystalline rocks			Granite, gneiss, and schist.	Not water bearing.	None.

Table 4. Results of recovery tests of observation Wells 1, 2, and 3.

Well	Location	Depth ft	Depth m	Discharge gpm	Discharge lps
1	NW/4 NW/4 sec. 16, T. 45N., R. 10E., N.M.	1030	314	50	3.1
2	NW/4 NE/4 sec. 9, T. 45N., R. 10E., N.M.	540	164	23	1.4
3	SW/4 NE/4 sec. 28, T. 45N., R. 10E., N.M.	935	285	60	3.8

Well	Perforated Interval ft	Perforated Interval m	Transmissivity gpd/ft	Transmissivity m^2/d	Specific Capacity gpm/ft	Specific Capacity lps/m
1	455-495	138-151	1150	14.3	0.8	0.16
2	885-915	270-278	60	0.7	1.5	0.31
3	820-865	250-264	233	2.9	0.4	0.08

precipitation and about 100,000 acre feet (123 hm^3) is from transmountain diversions (Colo. State Engineer's records, five year average). Transmountain diversions will increase substantially by 1980. Discharge of water from the valley averages about 1,016,000 acre feet (1,253 hm^3) per year by evapotranspiration, and about 514,000 acre feet (634 hm^3) per year as stream flow and ground water underflow at Wellsville south of Salida.

The principal source of ground water in the Upper Arkansas Valley is from the unconsolidated deposits along the valley floor. The quantity of ground water in storage in these deposits is unknown. It is possible that if the southern end of the Upper Arkansas graben is downfaulted in excess of 5,000 feet (about 1,500 m), as much as 4 to 6 million acre feet (4,900-7,400 hm^3) of water is in storage. Depth to water in the alluvial aquifer ranges from less than 10 feet (about 3 m) in valley bottoms to over 150 feet (about 46 m) in some high terrace deposits.

Water is recharged to the alluvial aquifer principally by infiltration of precipitation, ground water inflow from peripheral areas, and infiltration of water from streams issuing from the mountains. Secondary sources of recharge are from infiltration of applied irrigation water, leakage from small irrigation ditches, and from springs. Discharge from the aquifer is by evapotranspiration, seepage to streams, and ground water outflow in the Arkansas River alluvium.

Concentration of dissolved solids in ground water near Buena Vista is generally less than 100 mg/l. Concentration in alluvial deposits near Salida is generally less than 250 mg/l (Colorado Department of Health, 1971; Gregg and others, 1961). This indicates that water quality deteriorates from north to south. Although the quality of the valley's ground water is probably locally affected by the infiltration of water from thermal springs, it is believed that the effects are neither significantly adverse nor of wide areal extent. Results of analyses of water from Cottonwood, Mount Princeton, Hortense, and Poncha Hot Springs are given in table 2.

Preliminary evaluation of existing drillers' logs indicate that aquifer properties of the Arkansas Valley alluvium are probably similar to those of typical mountainous valley fill deposits for which data has been established (Wilson, 1965). Reported well yields in the Upper Arkansas Valley range from about one gallon per minute to about 1,500 gpm (0.06 l/s-95 l/s). Transmissivity probably ranges between about 10,000 and 200,000 gpd/ft. (124 - 2,480 m^2/d), permeability between about 40 and 200 gpd/ft^2 (1.64 - 8.2 m/d), and specific yield between about 15 and 25%.

Little is known of the hydraulic properties of the sedimentary, igneous, and metamorphic rocks of the mountainous parts of the study area. Mining activities have shown that the rocks do yield water, particularly in highly fractured areas, and that except in highly mineralized zones, the water is of fair to excellent quality.

GEOTHERMAL RESOURCES

GEOLOGY OF THE KGRA RELATED TO GEOTHERMAL RESOURCES POTENTIAL

The KGRA under investigation lies within the sphere of influence of the mechanisms responsible for the formation of the Rio Grande rift. The rift has been recognized as a major continental split which extends from El Paso, Texas northward about 600 miles (965 km) to Tennessee Pass north of Leadville, Colorado (fig. 3). The rift, which began about 18 million years ago, is not a single trough but a series of north-trending basins arranged en echelon and separated by narrow constrictions or channels (Chapin, 1971; Hoffman, 1975; Reiter, 1975). The possibility that the rift extends northward is supported by tectonic and seismic evidence (Grose, 1972, 1974; Hadsell, 1968; Stevens and others, 1972). Eardly (1962) suggests that the rift is closely associated with the Rocky Mountain Trench, and Chapin (1971) proposed a model incorporating differential movement of the continental plate east and west of the rift (fig. 18). Knepper (1974) argues that the San Luis Valley and Upper Arkansas Valley never formed a continuous depression.

Numerous surface and subsurface manifestation of heat flow support the possibility that the rift system is closely associated with potentially commercial geothermal energy sources. Characteristics of the Rio Grande rift which may indicate environments favorable for the occurrence of a commercial geothermal energy source include: 1) relatively youthful volcanic activity; 2) favorable tectonic history; 3) thermal springs and wells; and 4) above normal heat flow.

Volcanic Activity

Most of the volcanic rocks now exposed along or peripheral to the Rio Grande rift were emplaced from about 40 to 20 million years ago (Oligocene through early Miocene). During this time, much of southwestern Colorado was covered by a large composite volcanic field. The field has since been fragmented by tectonism and erosion into the San Juan, Thirtynine Mile, West Elk, Rosita-Silver Cliff, Rabbit Ears, and other smaller volcanic fields (Steven and others, 1972). Most of the extrusive rocks are predominantly light-colored quartz latites, latite, and rhyolite, and dark-colored olivene latite. Andesitic

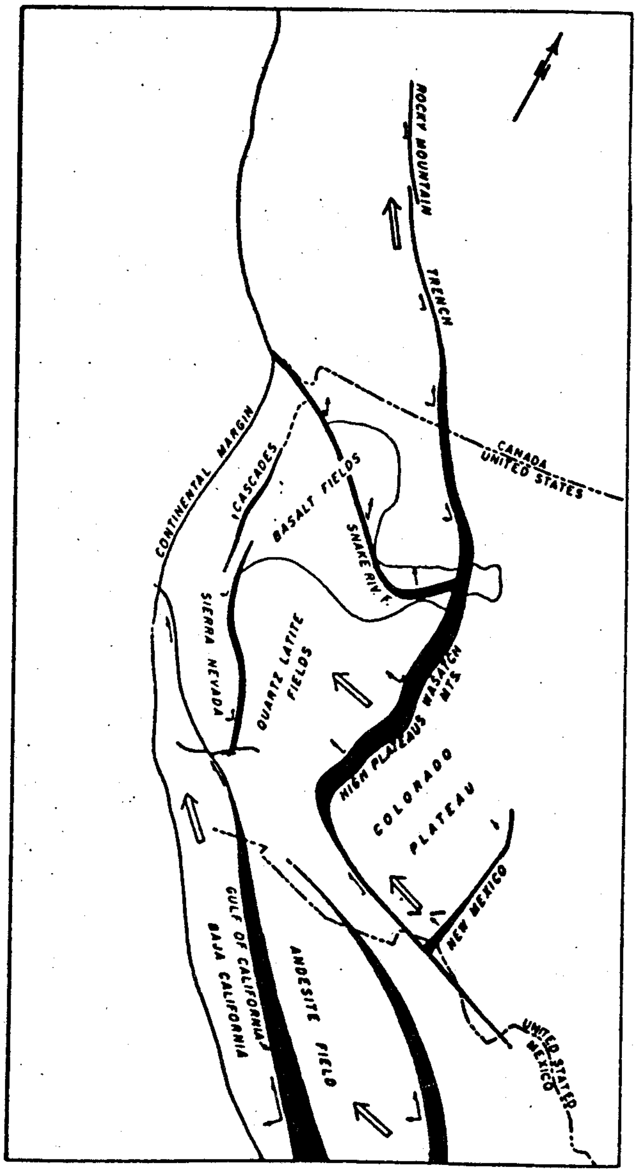


Figure 18. Diagrammatic map exploring the concept of extension and drift affecting North America. Solid black lines represent recognized rifts. Small arrows represent apparent vectors of movement; large arrows the apparent resultant direction of movement. After Chapin, 1971, p. 194.

flows, ash flows, breccias, and tuffs occur locally. Intrusive rocks are largely granodiorite, quartz monzonite, quartz latite, andesite, and rhyolite. In the San Luis Hills (southern San Luis Valley) quartz latites are intruded by stocks of monzonite and syenite (Larsen and Cross, 1956). In the Bonanza volcanic sequence laharic breccias, ash-flow tuffs, basalts, and latite have been identified. Total thickness of the volcanic rocks formed during this period is at least 6,000 feet (1,800 m). Volcanic activity in close association with crustal rifting began about 20 million years ago (Early Miocene) and has continued sporadically into the Quaternary. The youngest of these rocks has been dated at about 4,000 years.

Relatively youthful volcanic rocks in the immediate vicinity of the Rio Grande rift include the Hinsdale Formation (Middle Miocene to Middle Pliocene) and the Servilleta Formation (Upper Pliocene to Lower Pleistocene). Outliers of the Hinsdale Formation are present in the extreme southwestern part of the KGRA.

The Hinsdale Formation is a group of lavas ranging in composition from rhyolite to basalt, and are among the most widespread of any of the volcanic series in the San Juan Mountains. Along the west flank of the Rio Grande rift, the basalts of the Hinsdale Formation are faulted on the east and tilted upward on the west. In the southern San Luis Valley, Hinsdale lavas project beneath the valley floor and are inter-layered with clays, sands and gravels (Larsen and Cross, 1956). The youngest Hinsdale rocks in Colorado are found in the Los Mogotes shield volcano about 10 miles (16 km) west of Antonito in the southern part of the San Luis Valley.

The youngest volcanic rocks within the rift system have also accumulated in the southern part of the San Luis Valley. Assigned to the Servilleta Formation, the rocks are about 4.5 to 3.6 million years old and occur as olivene tholeitic basalt flows over 800 feet (240 m) thick. Lipman (1969) suggests that Servilleta basalts were derived from depths of about 9 to 12 miles (15-20 km) while the basalts peripheral to the Rio Grande rift were generated from depths of about 22 to 43 miles (35-70 km). This suggests that rifting resulted in an upward protrusion of hot mantle rocks and forms a locus for abnormally high heat flow.

Tectonic History

The single most important tectonic feature, relative to geothermal resources of Colorado is the Rio Grande rift. In Colorado, significant tectonic expressions of the rift are believed to extend from the San Luis Valley northward to the Upper Arkansas Valley ending north of Leadville. The San Luis Valley is the deepest graben along the entire rift with bedrock relief up to possibly as great as 37,800 feet (11,520 m).

Structures in the northern Sangre de Cristo and San Juan Mountains are indicative of both horizontal and vertical forces (Gableman, 1952, and Litsey, 1958). The eastern edge of the Rio Grande rift along the base of the Sangre de Cristo Mountains is bounded by normal faulting. In the northern part of the Upper Arkansas Valley, the western base of the Mosquito Range is also bounded by normal faulting. Toward the east, the dip of the faults progressively increase and locally culminate as reverse faults. Uplift of the Mosquito Range probably occurred as a series of step-like movements along numerous longitudinal faults (Emmons, Irving, and Longhlin, 1927, p. 97). It is not presently known if this mechanism is repeated along the Sangre de Cristo fault.

The western side of the San Luis Valley is bounded mainly by east-dipping San Juan volcanic rocks of mid-Tertiary age. The rocks project eastward and at a depth are believed to be interlayered with the valley's thick sequence of alluvial deposits. Locally, folds have been identified where the volcanic rocks have been eroded off underlying Paleozoic rocks (Jordan, 1974).

The geometry of the faults within the rift is probably quite complex. Identification of numerous fault scarps along the valley floor strongly supports the conjecture that the rift is still undergoing development. The normal block faulting, so common within and peripheral to the Rio Grande rift, has been termed a local invasion of Basin and Range type faulting, that is, deformation responsive to local tension rather than deformation responsive to compression (Grose, 1972). It is possible that faulting locally extends to hot rock produced by upwelling of the mantle and provides avenues of ascent for thermal fluids. This partially accounts for the KGRA's thermal springs and high heat flow.

Although the Rio Grande rift is still tectonically active it is not particularly seismically active in Colorado. In Colorado, the band of "high" seismic activity occurs in a weak lineation roughly paralleling the Colorado Mineral Belt (suggesting that some events might be associated with mining activities). Grose (1974) reports that only a few of the earthquake epicenters are known to correlate with faults related to the Rio Grande rift. Future microseismic surveys might reveal above normal seismic activity.

The Rio Grande rift has been shown to be seismically more active in New Mexico (Hoffman, 1975). The first documented account of an earthquake along the rift is a newspaper report of an event on April 28, 1868, near Socorro. Since that time, a large number of earthquakes have occurred along the rift, six of which were of an intensity of VII or greater (modified Mercalli scale). The most active seismic area occurs between Socorro and Albuquerque.

Crompton (1976) conducted a seismic survey of the Mount Princeton area near Buena Vista where he monitored seismic signals originating from large mining blasts. He concludes that the existence of identifiable boundaries on both the east and west side of the Upper Arkansas graben supports the interpretation that the Upper Arkansas Valley is a continuation of the Rio Grande rift of New Mexico and Southern Colorado.

Thermal Springs and Wells

Studies have shown that about one third of the thermal springs in Colorado lie along the Rio Grande rift. Other occurrences include the western margin of the San Juan volcanic field, along the Front Range, and in the Hahn's Peak area in northern Colorado. Figure 19 shows the location and temperature contours of hot springs for which physical and chemical data are available. The hottest springs in the state are located in the south end of the Upper Arkansas Valley. The springs are located along large normal faults directly related to the Rio Grande rift.

Hortense Hot Springs in Chaffee County discharges water with a temperature range of 74°C-84°C. Mount Princeton Hot Springs, one mile (about 1.5 km) east, discharges water in the temperature range of 48°C-57°C, and Cottonwood Hot Springs, about six miles (9.5 km) north, near Buena Vista, discharges water with a temperature range of 49°C and 62°C (Pearl, 1972). All of these springs occur near the contact of Precambrian granite and monzonite intrusive rocks of Tertiary age.

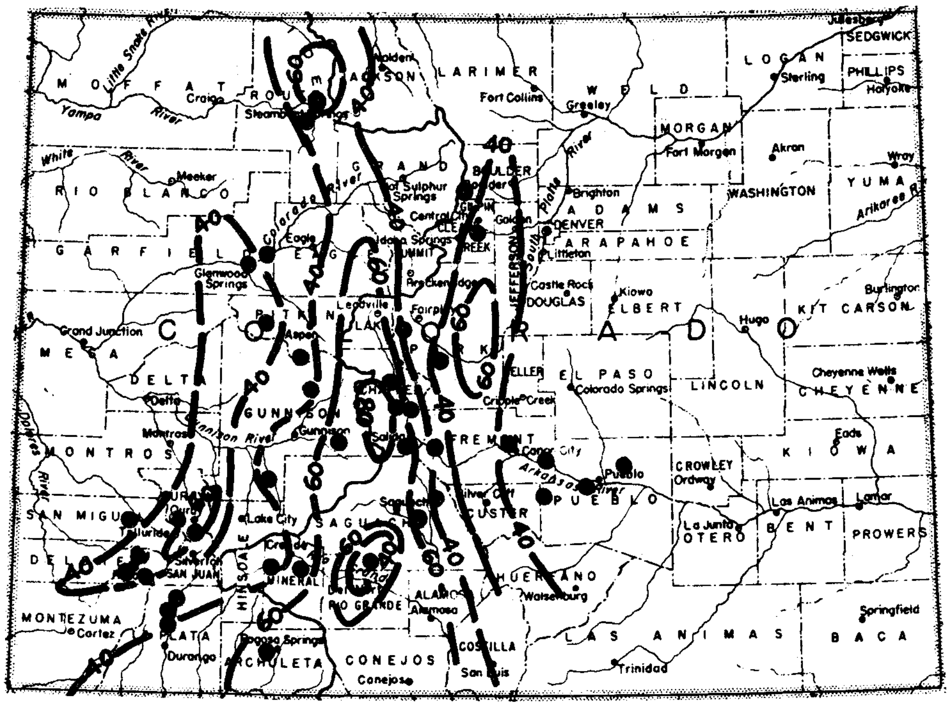


Figure 19. Generalized contour map of thermal spring temperatures in Colorado. Large dots represent thermal springs and wells. Contour interval 20°C. Modified after Grose (1975).

Poncha Springs is located about 15 miles (24 km) south of Mount Princeton Hot Springs. There are approximately 40 springs in this group, including several warm mud springs discovered during late 1975. Temperature of the discharged water ranges between 55°C-69°C. These springs also occur near Precambrian and Tertiary contacts.

Farther south, two well-known hot springs and numerous warm springs occur. Valley View Hot Springs is located along the Sangre de Cristo fault. Mean temperature of the springs is 36°C. Mineral Hot Springs is located about seven miles (11 km) southwest of Valley View Hot Springs. At one time, hot water issued from over 30 openings. Now less than ten are active, and this number varies by season and (according to local inhabitants) "wet or dry" years. The springs are reported to be more active during prolonged wet periods. Mean temperature of Mineral Hot Springs is 60°C.

Although Mineral Hot Springs issue from Quaternary deposits of the valley floor, it is believed that their location is fault controlled. Field investigations, and reports by Knepper (1974) and Marrs (1971), suggest the springs might be related to north-south and/or northwest-southeast trending faults (pl. 8).

In their preliminary appraisal of geothermal reservoir temperatures, Pearl and Barrett (1975) present data which support the geothermal potential of the KGRA (table 5). The estimated reservoir temperatures in the Arkansas Valley portion of the KGRA range between 110°C and 200°C. Estimated reservoir temperatures in the northern part of the San Luis Valley range between about 60°C and 360°C. In both areas, the low range of values was derived from the SiO_2 geothermometer and the high values from Na-K and Na-K-Ca geothermometers. Geothermometer studies by other investigators also indicate that the SiO_2 geothermometer generally yields lower temperature estimates than the Na-K and Na-K-Ca geothermometers (Barrett, 1976 personal communication).

Several springs which are not hot but are considered to be of thermal origin have recently been found in the KGRA. One of these occurs about four miles (6.4 km) southeast of Valley View Hot Springs in Cotton Creek Canyon. A small warm spring was recently located on a ranch about five miles (8 km) northwest of Villa Grove. The latter spring, referred to as Fullenwider Warm Spring, was observed by the authors in 1975 and samples of water were taken from the spring for geothermometer analysis in 1976. The Colorado Geological Survey reports that calculated reservoir temperatures range from 40°C to 122°C.

Table 5. Reservoir temperatures estimated by the use of SiO_2 and Na-K-Ca geothermometers. Data regarding hot springs is after Pearl and Barrett (1975)

Spring Name	Surface Temperature (°C)	Na-K Geothermom. Temp. (°C)	Na-K-Ca Geothermom. Temp. (°C)	SiO_2 Geothermom. Temp. (°C)	Mixing Model
Mt. Princeton Hot Springs "A"	54	149	175	110	201
Mt. Princeton Hot Springs "G"	49	150	173	107	
Hortense Hot Spring	81	146	188	118	168
Hortense Hot Water Well	82	144	181	118	164
Cottonwood Hot Springs	58	132	172	110	174
Mineral Hot Springs "A"	60	206	240	98	83
Mineral Hot Springs "C"	60	197	232	100	93
Mineral Hot Springs "D"	59	202	237	98	83
Valley View Hot Springs "A"	37	356	294	62	35
Valley View Hot Springs "B"	32	338	281	58	31
Poncha Hot Springs "A"	71	155	199	122	96
Poncha Hot Springs "B"	66	154	198	124	95
Poncha Hot Springs "C"	63	157	199	125	103
Fullenwider Warm Spring	18	122	40	70	-
Observation well 1		108	137	40	
Observation well 2		235	223	55	
Observation well 3		196	-	67	

Water at temperatures in the range of 20°C-60°C has been found in numerous water wells in the San Luis Valley (Emery and others, 1972; Klein, 1971; Powell, 1958). Most of these wells are located several kilometers south of the study area, tap the confined aquifer, and are generally less than 4,000 feet (1,200 m) in depth. Silica content of one of the wells in Saguache County in sec. 27, T.41N., R.10E., N.M. P.M. indicates a reservoir temperature of about 104°C.

No hot water was encountered in the observation wells constructed during the drilling phase of this program. Temperature surveys were made by a commercial company about 30 days after each well was completed and test pumped. Temperature profiles of each well are shown on figures 20 and 21. The temperature profile of observation well 2 illustrates a gradient of 8.5°C per 1,000 feet (304.8 m), near the normal thermal gradient. The overall gradients of wells 1 and 3 are also near normal; however, they show certain characteristics which are most interesting from a geothermal standpoint. The temperature-gradient curve of well 1 is concave up. From this it is logical to assume that if this trend is continuous, temperatures approaching 110°C might exist at a depth of about 4,000 feet (1,200 m). The temperature gradient of well 3 is normal to a depth of about 800 feet (244 m). Between 800 and 860 feet (244 - 262 m) the gradient increases to about 40°C per 1,000 feet (304.8 m), then decreases to the normal rate. This characteristic is probably related to the degree of lithification and texture of the materials penetrated in the interval 700 to 920 feet (213-280 m). Most of the materials penetrated to a depth of about 800 feet (244 m) consisted of relatively poorly consolidated beds of clay, sand and gravel. Between 800 and 900 feet (244 to 274 m) a moderately consolidated, calcareous, fine to coarse sandstone was penetrated. The last few meters of hole penetrated a moderately consolidated but poorly textured cobble gravel. The fact that a sharp increase in temperature gradient occurred in material that is well consolidated is of particular significance. The curve not only shows the capacity for the consolidated material to conduct heat, but also shows the capacity of a consolidated layer to mask or absorb heat. This could possibly lead an investigator to false conclusions regarding identification of geothermal cells if the only data available from an alluvium-filled basin are from shallow wells (penetrating unconsolidated material only) and other geothermometers are unknowingly yielding false indications

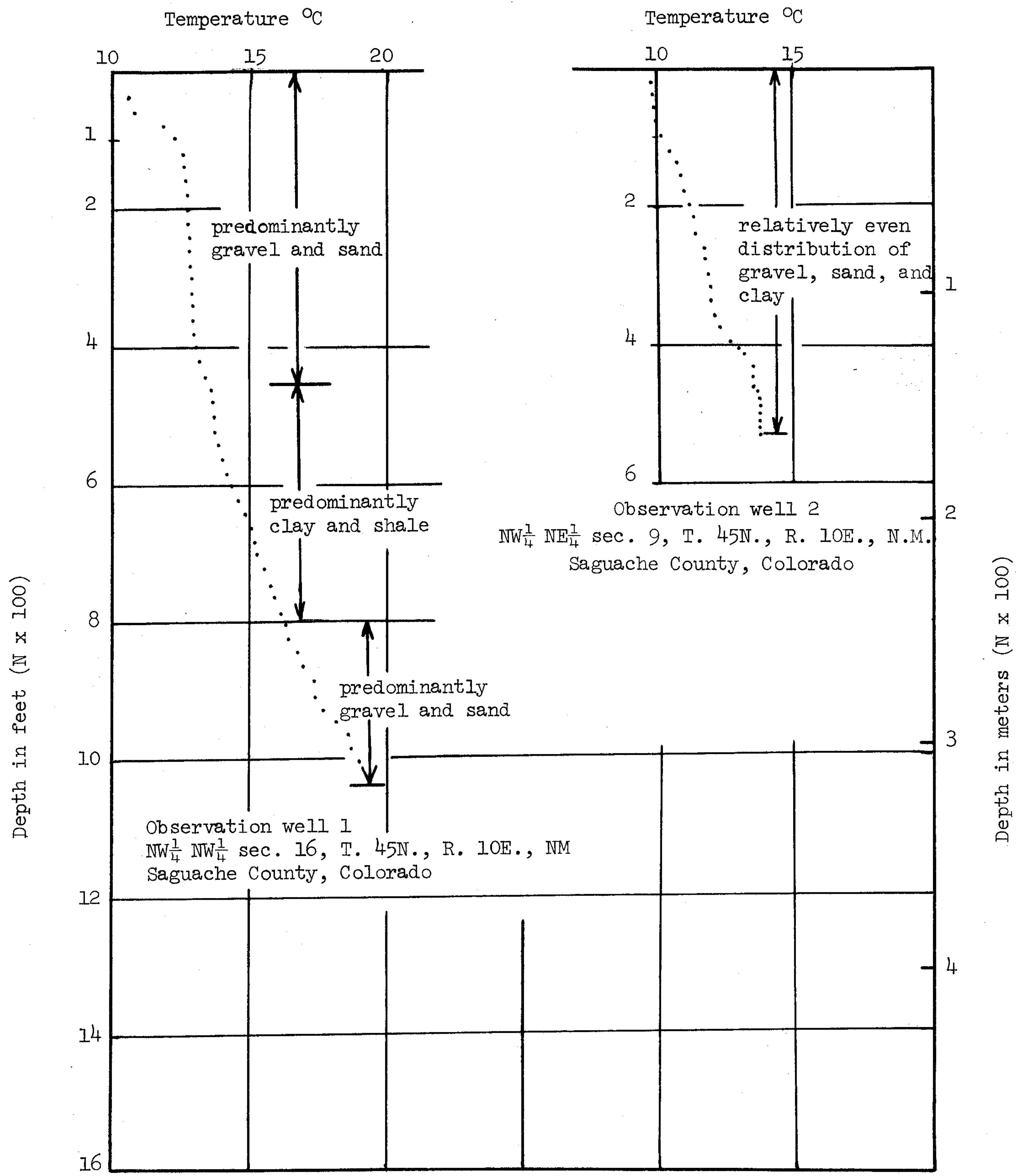


Figure 20. Temperature profiles of observation wells 1 and 2 in the northern San Luis Valley, Colorado.

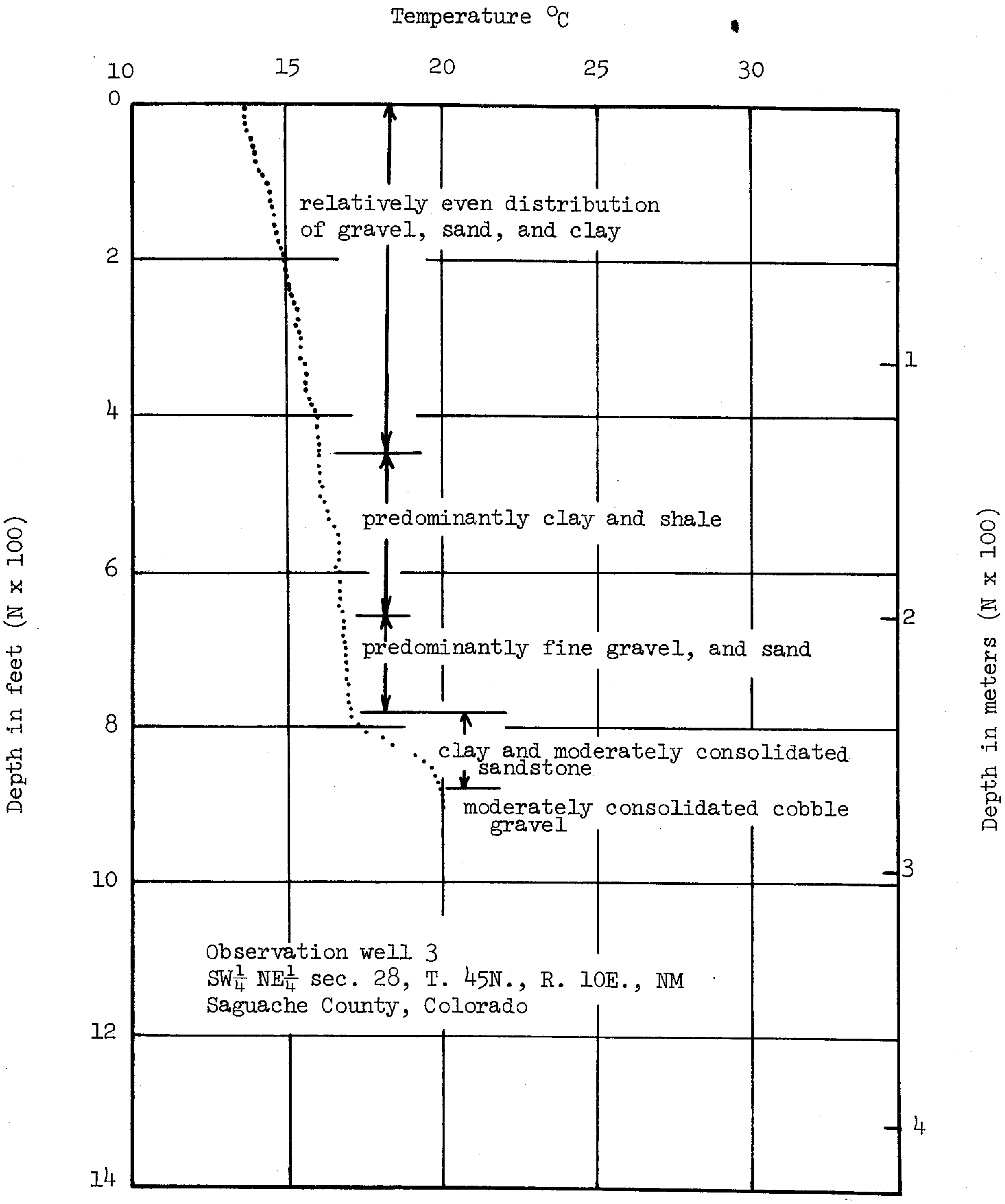


Figure 21. Temperature profile of observation well 3 in northern San Luis Valley, Colorado.

because of physiochemical changes which might have taken place during circulation of ground water. Ground water movement is indicated by nonlinear behavior of the temperature gradient curve.

The existence of numerous hot springs, warm springs, and evidence from geothermometer analyses supports the premise that a significant geothermal cell or system of cells occur at relatively shallow depths. This might be particularly true in the northern part of the San Luis Valley, where geothermal waters possibly have been subjected to masking by ground water circulation in the extensive hydraulic system known to exist in the area. This premise is also supported by extensive reconnaissance grade heat flow studies in the region.

Calculations to determine reservoir temperatures involve numerous important assumptions. These are (Fournier and others, 1974): 1) temperature-dependent reactions occur at depth; 2) all constituents involved in a temperature-dependent reaction are sufficiently abundant so that supply is not a limiting factor; 3) water-rock equilibration occurs at the reservoir temperature; 4) little or no reequilibration or change in composition occurs at lower temperature as the water flows from the reservoir to the surface; 5) hot water coming from deep in the system does not mix with cooler shallow ground water. Renner and others (1975) state that assumptions 1, 2, and 3 are generally valid for the SiO_2 and Na-K-Ca geothermometers. Reliability of results decrease in waters high in free CO_2 and in low temperature systems which have equilibrated with chalcedony or amorphous forms of silica. The predicted temperatures of such systems will be too high. Although assumption 5 is generally invalid, Fournier and Truesdell (1974) have developed analytical methods for examining mixed waters. Results of mixing model calculations by Pearl and Barrett (1976) are given in table 5.

Heat Flow

The locations, values, and preliminary heat flow contours from stations in Colorado and part of New Mexico are shown in figure 22 (from Reiter and others, 1975). The most obvious feature of the contour map is the zone of high heat flow paralleling the western part of the Rio Grande rift and extending into north-central Colorado. This anomalous zone locally exhibits heat flows which are twice the world average rate of 1.5×10^{-6} calories/ cm^2 - sec (1.5 heat flow units, HFU) and is probably a

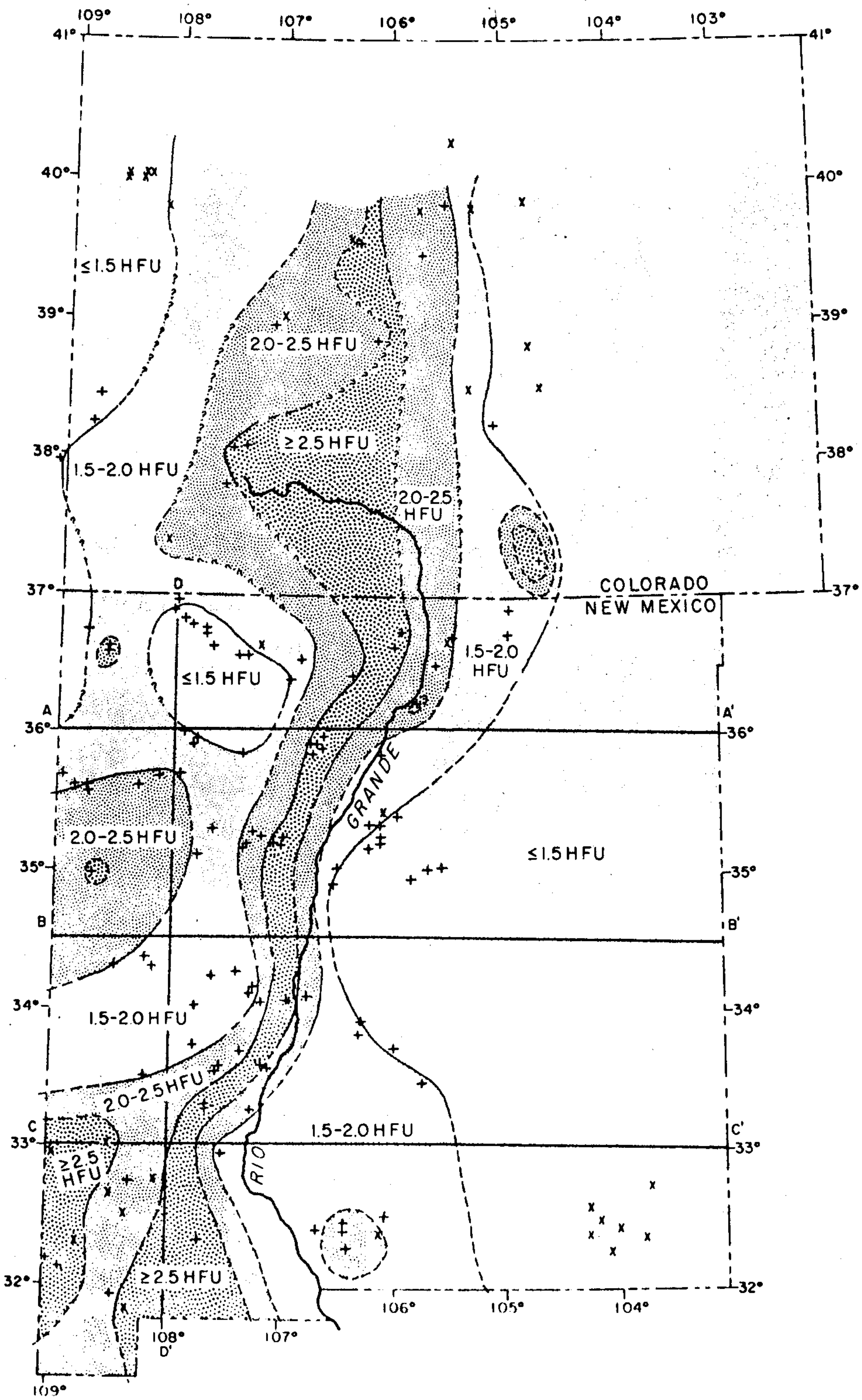


Figure 22. Heat-flow contour map of New Mexico and southern Colorado. Contour interval, 0.5 HFU. Plus signs and Xs indicate control sites measured by New Mexico Institute of Mining and Technology and other investigators. After Reiter and others, 1975, p. 816.

direct consequence of a geothermal resource associated with the rift. Chapin (1971) suggests that crustal stretching along the west side of the rift resulted in tension faulting which extends to great depths and is providing avenues for ascent of magmas and hydrothermal solutions. Olmsted and others (1975) describe many hot springs in central Nevada where hot water emerges from steeply dipping faults that might extend to depths of several kilometers. Renner and others (1975) state that the water might be of surface origin, has circulated downward, is heated by thermal conduction, and has then risen to discharge along the fault traces. Diment and others (1975) report the heat of some hot spring systems is related to the regional geothermal gradient, which is higher in some regions than in others. Chapin's crustal stretching theory supports this statement. Diment and others also describe the cooling effect of a "thermal blanket." They state that if a region (San Luis Valley for example, author's addition) is blanketed by low-conductivity sediments, the temperatures at depth will be higher than those used in their models. The effect of the blanket is evidently small for low heat flow and thin blankets, but is substantial for a thick blanket and a high heat floor. Facca (1973) states that grabens are preferred sites of magmatic intrusions, the chief of which is the fact that in a graben the overburden is less than in the adjoining positive structures, so that magma can intrude to a level where its energy is balanced by the weight of the overlying stratigraphic series. Often there is a minimum of rock overburden in a graben, so that the presence of cryptovolcanism is a definite possibility, even in the absence of hot springs. Reiter and others (1975) note that local high heat flow values might be biased toward mining regions and areas of hydrothermal activity. Alternatively, low values might be a consequence of the cooling effect of ground water movement in fractured hardrock or in deep alluvial basins. Koenig (1970, p. 9) reports that infiltration of cool ground water in steam-producing wells in New Zealand has rendered them non-commercial.

The volcanic and tectonic history of the KGRA, the presence of numerous hot springs, and a zone of high heat flow along the Rio Grande rift indicate the presence of an exploitable geothermal energy resource. Late Tertiary volcanic rocks are present and structural control of warm and hot springs is suggested by their alignment along known faults or fault zones.

The eastern portion of the San Luis Valley and western portion of the Upper Arkansas Valley to a certain degree resemble the Basin and Range structural province. In such areas, geothermal resources are related to graben-type troughs and possibly a series of step-like faults. The KGRA is made more complex by the presence of intrusive and/or extrusive rocks on both sides of the valley floors. Koenig (1970, p. 2) states that even in the absence of youthful volcanism, wells drilled along the margins of deep fault-bounded alluviated basins can hardly fail to tap hot aquifers. McNitt (1973) summarizes environments favorable for the production of geothermal resources. Environments which are applicable to the KGRA are: 1) fault block terrains in Cenozoic hinterland regions without Quaternary volcanism; 2) Cenozoic rift zones without Quaternary volcanism; and 3) sedimentary basins in Cenozoic hinterlands without Quaternary volcanism. Expected reservoir temperatures ranged from 190°C for environment (1) to 85°C for environment (3). This range is within that predicted from geothermometry calculations and described in the thermal springs and wells section of this report.

RESULTS OF THE GEOPHYSICAL PROGRAM

As a means of supporting the hydrogeological investigation in the KGRA, a series of geophysical surveys were conducted. Geophysical investigations began in May, 1976 and extended into early 1977. These included the bipole-dipole, quadripole, Schlumberger, magnetotelluric and telluric types of electrical surveys, reflection seismic traverses, and a short gravity survey. The latter was conducted for the sole purpose of comparison with earlier gravity surveys of part of the northern San Luis Valley.

The geophysical surveys were closely coordinated with previous hydrogeologic and basic physical investigations. Principal categories of information required for the selection of survey "sites" are geographical, physical and geochemical. Geographical investigations involved identification of the areas to be investigated, an evaluation of topography and access roads, coordination with landowners and local governments, and consideration of local drainage patterns, streams, and man-made water distribution facilities. In addition, liaison had to be maintained with local electric and gas supply companies who maintain a series of buried electric cables and gas lines in certain parts of the KGRA. Physical considerations included locations of hot and warm springs, known and postulated faults and fault systems, and determination of the suitability of an area for a particular type of survey. Most of the geochemical investigations were conducted by the Colorado Geological Survey during spring and summer 1976, and had no influence on selection of geophysical survey sites. Plate 9 shows the locations of principal sources of the geophysical survey data.

Electrical Resistivity Methods

The applicability of electrical resistivity to the exploration of geothermal resources is well known. Among numerous published case histories describing the technique are: Cheng (197); Hermance, Thayer and Bjornsson (1975); Keller (1970); Meidav (1970); Palmason (1975); U.S. Bureau of Reclamation (1971, 1974); and Zohdy, Anderson, and Muffler (1973). As a general rule, rocks or rock materials such as sand and gravel have an extremely high resistivity when they contain no moisture. The existence of water, which usually contains various ions, results in a marked decrease in resistivity. Resistivity continues to decrease with increasing porosity, hydraulic conductivity, water saturation, ion concentration, temperature, and the presence of clay, shale, or other porous but nonpermeable rocks. All of these factors, except for ion concentration and presence of clayey materials, are favorable to the geothermal reservoir.

Three factors which prevent electrical resistivity methods from being a relatively perfect geothermal exploration tool are: 1) the effect of dry steam; 2) the presence of brine; and 3) the presence of clayey materials (Meidav and Tonani, 1975). In a steam field, there would probably be a central resistivity high because the reservoir rocks are filled with dry steam which, like any gas, is characterized by a very high resistivity. Brine or water containing excessive concentrations of conductive ions have the capacity to possess an electrical resistivity of less than 1 ohm-m (Meidav and Tonani, 1975). The natural accumulation of brine in basins, or some form of geologic trap, and associated low resistivity, therefore, have no relationship to the potential geothermal reservoir which might or might not occur in the area. Low resistivities also occur in strata rich in clayey materials. Therefore, low resistivity zones in sedimentary basins cannot be adjudged to represent geothermal conditions without some independent evidence (Meidav and Tonani, 1975).

Bipole-Dipole Resistivity--Much of the text which follows is quoted from the Colorado School of Mines Geophysics Department report to the Colorado Division of Water Resources (Keller, 1977).

The bipole-dipole resistivity method was used for horizontal reconnaissance of the area surveyed. In this method, a large current is caused to flow in the ground around a grounded cable usually several kilometers in length. The behavior of the current, which is controlled by the electrical structure of the earth around the bipole source, is monitored by measuring the electric field intensity at many points around the source. Plate 9 shows the locations of the bipole-dipole sources. The same locations were utilized for the quadripole resistivity survey.

At each source, two source bipoles placed at right angles to each other were used. Each source consisted of a length of cable varying from two to three kilometers and grounded at each end. A 25 KVA motor generator set was used as a primary power supply. Power output was transformed to 800 volts AC, rectified, and switched to form periodically reversing direct current to the source cable. The amount of current provided to the source cable varied from 25 amperes to 65 amperes. The electric field intensity was measured at usually 60 to 120 receiver locations around each of the source locations and components were recorded in two approximately orthogonal directions to completely define the electric field vector. In some cases, more than two values were measured at a single location using several sources. Results of the bipole-dipole survey are presented in the form of apparent resistivity. For details concerning layout of bipole arrays, variation of apparent resistivity with distance, and derivation of pertinent equations, the reader is referred to Keller (1977), and Keller and others (1975). Plate 10 is one interpretation of the results from the bipole survey. Apparent resistivity is contoured in ohm-meters.

In the Upper Arkansas Valley, three areas of low apparent resistivity are identified. The northernmost area lies in the vicinity of Buena Vista and Cottonwood Hot Springs. The 15 ohm-meter contour which is open toward the northwest and the 70 ohm-meter "high" are probably closely associated with Cottonwood Hot Springs. Plate 10 shows these resistivity anomalies lie near the western margin of the Upper Arkansas graben.

The southernmost area of low resistivity in the Upper Arkansas Valley lies in Poncha Creek valley about 2 miles (3.2 km) west of Poncha Pass. There are no known surface manifestations of geothermal energy in this area and it is suggested that the resistivity low might be due to the presence of a pocket of high salinity water in the complex of highly fractured Tertiary rocks west of Poncha Pass, or is an expression of deeper parts of the synclinal trough of Tertiary sediments over the Poncha Pass area (Knepper, 1974; Van Alstine, 1968).

The most prominent resistivity low extends from southeast of Salida northwestward to an area about one mile (1.6 km) northwest of Poncha Springs. Values of apparent resistivity as low as 6 to 7 ohm-meters were measured south of Salida, and resistivity is less than 20 ohm-meters over an area of 23 to 31 square miles (60-80 sq. km). The low resistivity coincides with the southern boundary of the Upper Arkansas graben and might be associated with the presence of shaley materials and/or the presence of high salinity ground water occurring in the ground water dam along the south edge of the graben. It is also possible that the resistivity low is due to hot water. The trend of this low parallels the trend of numerous hot and warm springs in the Wellsville (6.3 miles--10 km--southeast of Salida) and Poncha Springs areas. In addition, studies of ERTS imagery have revealed the presence of a structural lineation about 125 miles (200 km) in length in the immediate proximity of, and parallel to, the general trend of the resistivity low (fig. 23). Paralleling this structure is a 15 mile (24 km) wide zone about 100 miles (160 km) in length containing the hot and warm springs of the Poncha Springs and Wellsville areas, and hot and warm springs beyond the boundaries of the designated KGRA. If they are indeed related to the structure, the springs within the KGRA are also possibly related to and represent surface manifestations of a significantly extensive geothermal system (Barbier and Fanelli, 1975).

The absence of a significant resistivity low in the Mount Princeton Hot Springs area is unexpected. Crompton (1976) identified a seismic velocity anomaly in the area and Arestad (1977) shows a faint low resistivity pattern along Chalk Creek with the most conductive portion at Mount Princeton Hot Springs. The anomalous 200 ohm-meter contour which is open to the west is suggestive of the presence of a substantial quantity of vapor. Geothermometry is in partial agreement as calculated reservoir temperatures range as high as 188°C (table 5).

Figure 23.- Reproduction of ERTS image of south-central Colorado showing area represented on maps in this report and structural lineation (arrows) bisecting the KGRA.

In the northern San Luis Valley, one area of low apparent resistivity has been identified about five miles (8 km) northwest of Villa Grove. The low is in the immediate vicinity of Fullenwider Warm Spring. The spring is probably associated with the resistivity low. Since the spring lies near the end of the northwest-trending Villa Grove fault zone, it is believed to be closely related to it.

Both Mineral and Valley View Hot Springs cannot be associated with a significant resistivity anomaly. A somewhat diffuse resistivity "low" of 100 ohm-meters covers the area and is open against the Sangre de Cristo fault zone. Quadripole resistivity, Schlumberger, and seismic surveys of the area (this report) indicate that low resistivity water occurs in the vicinity of highly-faulted igneous and sedimentary rocks in the deeper portions of the basin.

Quadripole Resistivity--The quadripole resistivity method differs from the bipole-dipole method in that two separate bipole sources at the same location are used. Layout of the sources is normally in the form of an "X"; variations are not uncommon so long as the sources are orthogonally located. Instrumentation and data reduction are also somewhat different and are designed to eliminate false anomalies produced by channeling of current by various earth-structural configurations. Details concerning instrumentation, data reduction, etc., can be found in Arestad (1977) and Morris (1975).

Plate 11 is a quadripole average resistivity map of the KGRA with contours in ohm-meters. Note that after elimination of possible false anomalies recorded by the bipole-dipole survey, several bipole-dipole resistivity lows are reidentified.

In the Upper Arkansas Valley, the resistivity lows in the Buena Vista-Cottonwood Hot Springs area are either markedly reduced or totally eliminated. Arestad (1977) interprets the 50 ohm-meter contour as representing resistive valley boundaries and the anomaly about three miles (4.8 km) south of Buena Vista as being of quadripole source origin. A poorly defined anomaly along Chalk Creek is probably an expression of subsurface structures and/or geothermal features associated with Mount Princeton Hot Springs. Arestad (1977) identifies resistivity lows paralleling Chalk Creek with both north-south and east-west bipole sources.

Again, the most striking resistivity low is in the Salida area, along the southern boundary of the Upper Arkansas graben. The area covered by the 20 ohm-meter contour is about 56 square miles (145 km^2); about twice the area identified in the bipole-dipole survey. The 10 ohm-meter anomalies in the east half of the 20 ohm-meter low are probably source oriented. The 10 ohm-meter anomaly on the west follows the trend described in the bipole-dipole section of this report and is probably an expression of shaley materials, high salinity ground water, or thermal activity.

The resistivity anomaly about 3.2 kilometers west of Poncha Pass is similar to the bipole-dipole results and indicates a minimal number of false anomalies. Arestad (1977) believes the anomaly is primarily structurally oriented.

In the northern San Luis Valley, a significant resistivity low (50 ohm-meter) occurs north of Villa Grove in about the same general vicinity as the low identified with bipole-dipole methods. A 100 ohm-meter "low" trends in a general northwest-southeast direction and roughly parallels the Villa Grove fault zone. Resistivity increases along the flanks of the valley and toward the north. Arestad (1977) attributes this increase to thinning of valley-fill sediments, to increasing distance from the source, and to the influence of igneous and volcanic rocks.

Neither Mineral nor Valley View Hot Springs exhibit low apparent resistivities by the quadripole method. In fact, resistivities are higher than resistivities for other valley source areas. High resistivities east and west of the valley floor are due to the influence of predominantly igneous and volcanic rocks. The 200 ohm-meter contour along the southeast part of the KGRA is possibly representative of the southern end of a horst block which has tentatively been identified by recent Colorado School of Mines investigations (G. V. Keller, personal communication). Decreasing resistivity toward the Villa Grove fault zone might be due to increasing depth of the basin to the north (Arestad, 1977).

Schlumberger Soundings--Although bipole-dipole and quadripole surveys yielded much information on the horizontal distribution of resistivity anomalies, they provided only general information on variation of resistivity with respect to depth. To obtain more detailed information on the resistivity profile at a few selected sites, the Schlumberger sounding method was used.

In the Schlumberger method, a sounding is made with four electrodes placed along a straight line. The outer pair of electrodes is used to drive a current into the ground, while the inner pair is used to measure the voltage drop caused by this current. In making a Schlumberger sounding, the distance between the two outer electrodes is increased stepwise with the voltage between the two inner electrodes measured at each increment. Short spacing between the outer electrodes assumes shallow penetration of current flow, and computed resistivity will reflect properties of shallow earth materials. As electrode spacing is increased, more current penetrates to greater depths, and computed resistivity will reflect properties of earth materials at greater depths (Colorado School of Mines, 1977). Plate 9 shows the locations of the Schlumberger sounding locations within the KGRA.

At each sounding location, the electrode array was expanded from a minimum separation between current electrodes of 230 feet (70 m) to about 11,500 feet (3.5 km). Twenty-seven separate electrode separations were used over this range. Both the amount of current driven into the ground and the voltage between the receiver electrodes were recorded on strip charts. For details concerning the method of interpretation, the reader is referred to Keller (1977). Results of the Schlumberger soundings are shown in part in figures 24, 25 and 26. These profiles were chosen because they coincide with vibroseis (seismic reflection) profiles which will be described in a later section of this report.

Figures 24, 25, and 26 are resistivity cross sections along seismic profiles AB, CC', and DE (plate 9 and figs. 31, 32, 33). Resistivities exceeding 100 ohm-meters appear to be generally confined to surficial and immediately underlying deposits which have been tentatively identified by Stoughton (1977) as belonging to the Santa Fe Formation. The high resistivities probably reflect good quality water in the upper sediments of this part of the San Luis Basin. Exceptions can be seen in sections AB and CC' where local high resistivities occur at depths of about 1,500 feet (457 m) and 500 feet (152 m) respectively. These highs might be indicative of local extensions of fresh-water bearing sediments originating from the San Juan mountains, or heretofore unrecognized high density

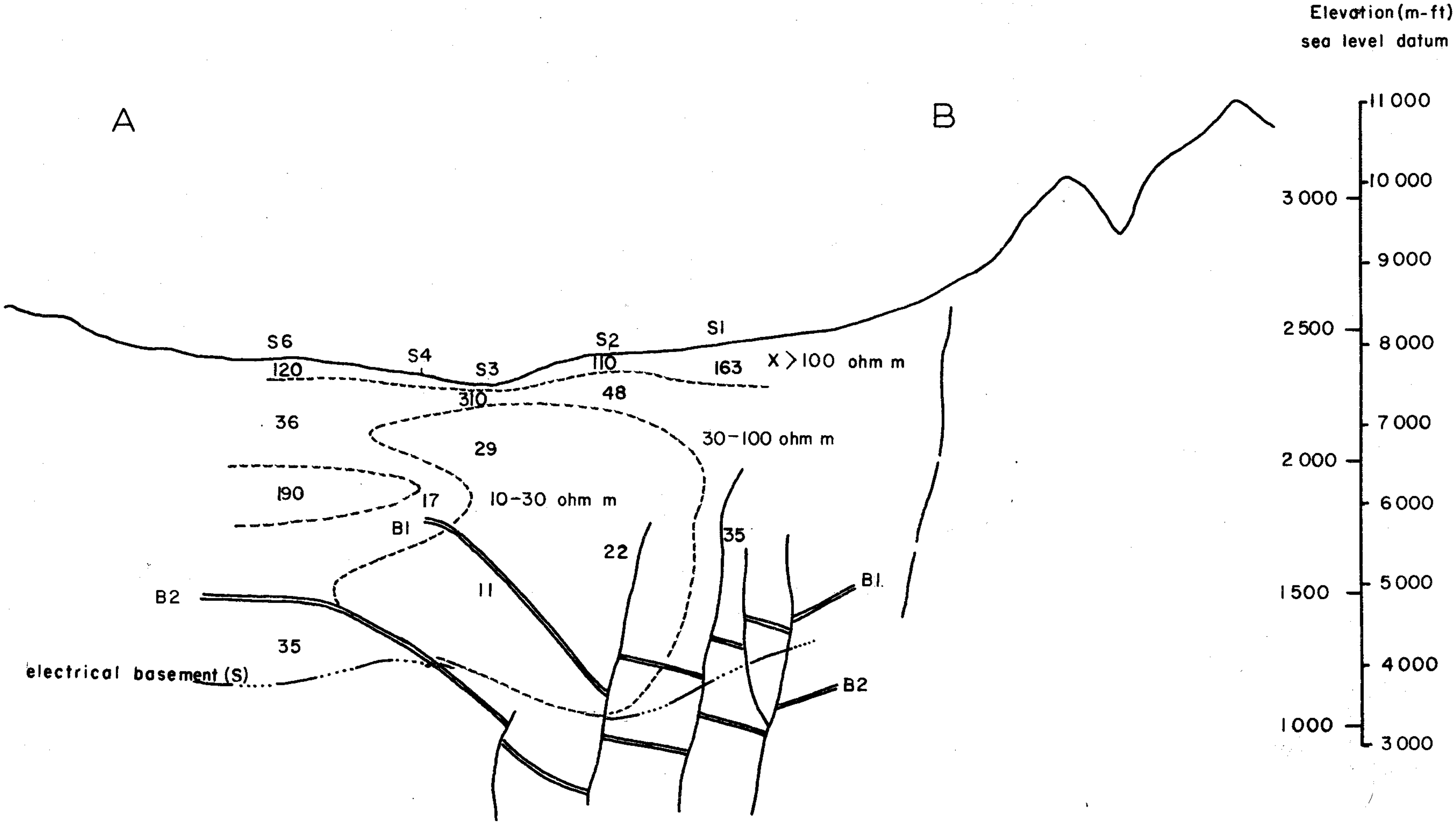


Figure 24.- Electrical and seismic cross section along line AB. S2, S3, etc., represent locations of centers of schlumberger sounding arrays. Numbers below S2, S3, etc., represent computed apparent resistivity in ohm-meters.

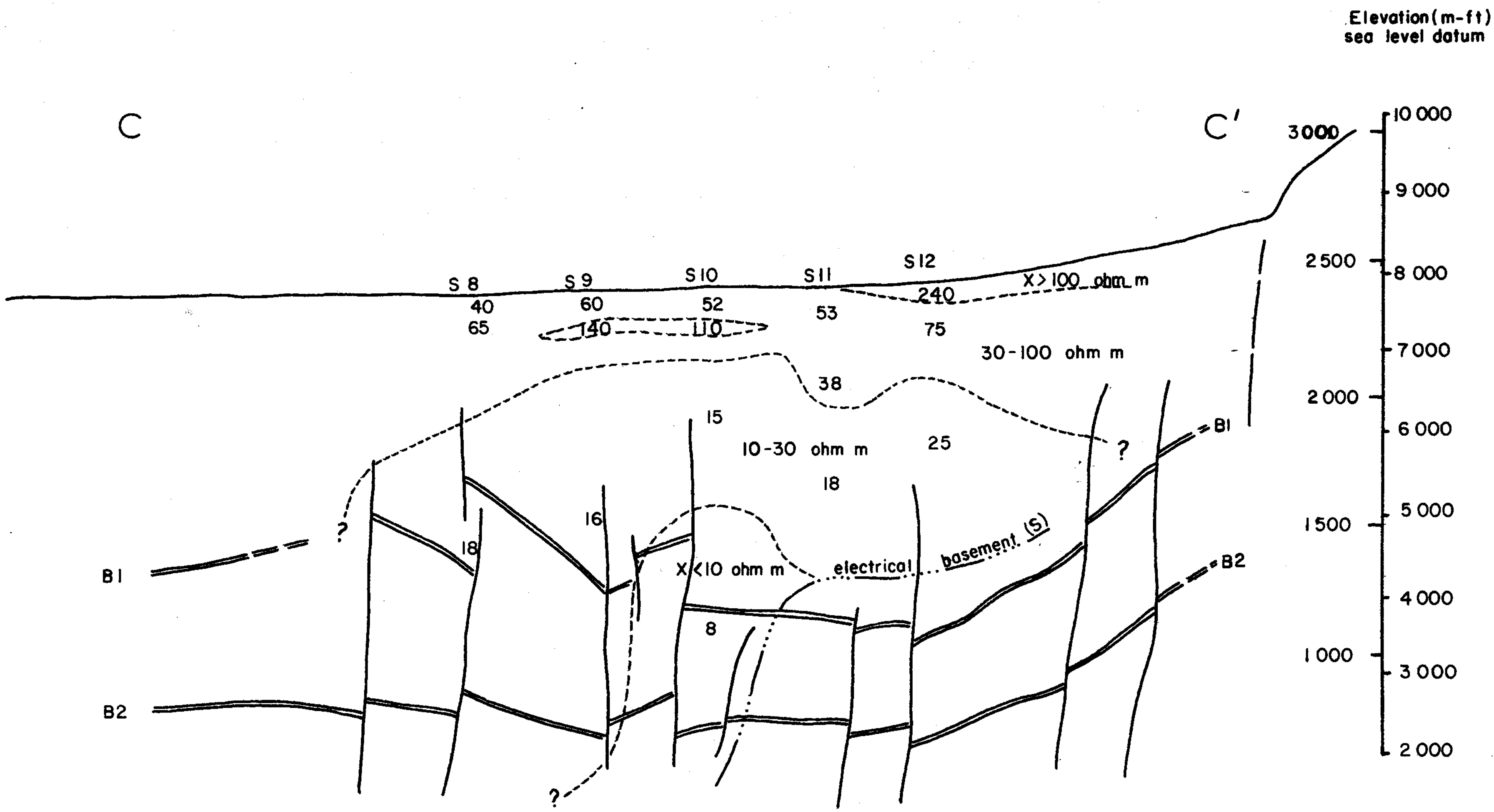


Figure 25.- Electrical and seismic cross section along line CC'. S8, S9, etc., represent locations of centers of schlumberger sounding arrays. Numbers below S8, S9, etc., represent computed apparent resistivity in ohm-meters.

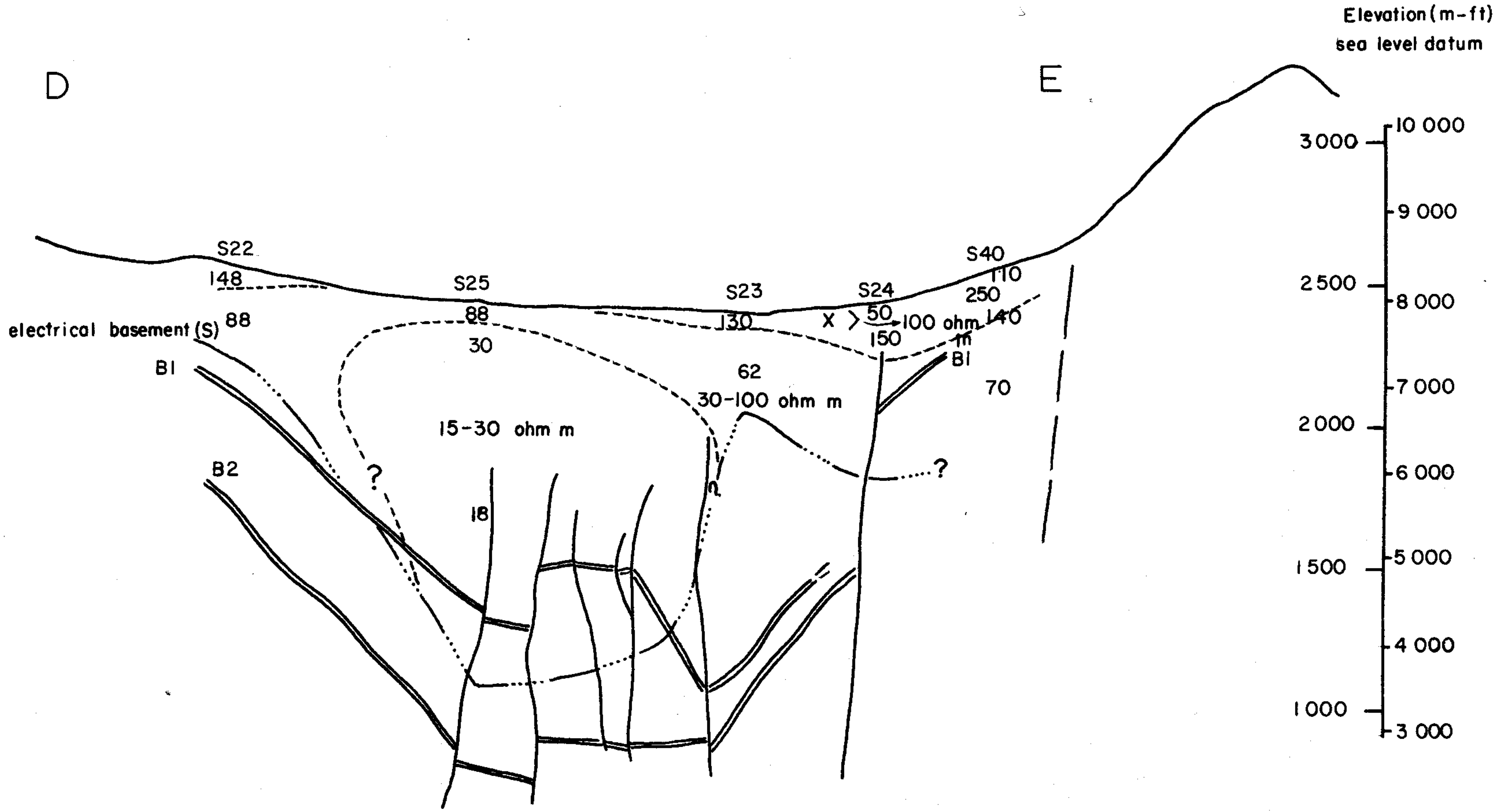


Figure 26.- Electrical and seismic cross section along line DE. S22, S23, etc., represent locations of centers of schlumberger sounding arrays. Numbers below S22, S23, etc., represent computed apparent resistivity in ohm-meters.

volcanic rocks possessing low water saturation. The figures also indicate that low resistivities (10-30 ohm-meters and 10 ohm-meters or less) are probably closely associated with fault systems which extend into lower parts of the northern San Luis Basin. Resistivity cross section CC' shows a significant resistivity low extending into the northern San Luis Basin from the south. The trend of the electrical basement in this section might be representative of the horst-graben structure tentatively identified during late summer 1977 (G. V. Keller, personal communication).

Soundings 34, 35, and 36 were made southwest of Buena Vista. No particularly conductive layer was found in the section and Keller (1977) suggests that a more extensive sounding program might locate the beds giving rise to areas of low resistivity mapped by bipole-dipole and quadripole resistivity methods.

Soundings 31, 32, and 33 were made near the south boundary of the Upper Arkansas graben. Table 6 shows the results of the soundings. The last figure after each resistivity reading (in ohm-m) indicates the lower extent (in m) of that reading.

Table 6. Results of Schlumberger soundings at locations 31, 32, and 33

Sounding 31	Sounding 32	Sounding 33
150 ohm-m to 29 m	130 ohm-m to 34 m	300 ohm-m to 23 m
67 ohm-m to 70 m	43 ohm-m to 214 m	18.5 ohm-m to 710 m
140 ohm-m to 105 m	21 ohm-m to 214 m	Basement
45 ohm-m to 410 m	Basement	
then 20 ohm-m		
Basement deeper than 1,000 m		

A moderately conductive layer extends from a depth of about 76 feet (23 m) in the vicinity of Sounding 33, and 1,345 feet (410 m) in the vicinity of Sounding 31, to basement which varies greatly in depth for the three soundings. Basement is here defined as that depth below which resistivity no longer continues to decrease. Presence of the conductive layer in this area is in support of resistivity lows mapped by bipole and quadripole methods. Soundings 27 through 30 did not reveal a significantly conductive horizon.

Magnetotelluric and Telluric Measurements--The magnetotelluric method is capable of detecting conductive zones in the earth's crust and upper mantle at depths ranging from a few kilometers to a few tens of kilometers. Resistivity can be measured at these great depths because it makes use of natural electromagnetic fields which contain extremely low frequencies and which are very intense compared to those that can be generated with man-made equipment (Keller, 1977). The natural electromagnetic field of the earth contains a wide range of frequencies. High frequencies are representative of shallow depths, while low frequencies are representative of far greater depths. By isolating the various frequencies, an investigator can determine how resistivity varies with depth in the earth. Magnetotelluric methods have been applied in numerous geothermal investigations and appear to be most useful in regional reconnaissance studies of geothermal energy (Palmason, 1975, and Whiteford, 1975).

Computation of values of apparent resistivity from field recordings involved conversion of field data to digital form, transfer of data to punched cards, Fourier analysis to separate frequency components, and final computation of apparent resistivity for each frequency. Sounding curves consisting of apparent resistivity values are then plotted as a function of frequencies (Keller, 1977).

All of the curves, of which figure 27 is representative, showed the uniform characteristics of apparent resistivity increasing linearly with decreasing frequency (recall that low frequencies are representative of great depths). If more conductive layers were present at great depth, the apparent resistivity values would tend to decrease at the lowest frequencies. The conclusion of the Colorado School of Mines investigators is that for the area surveyed by this method, heat flow is not high enough to render rocks in the lower crust anomalously conductive.

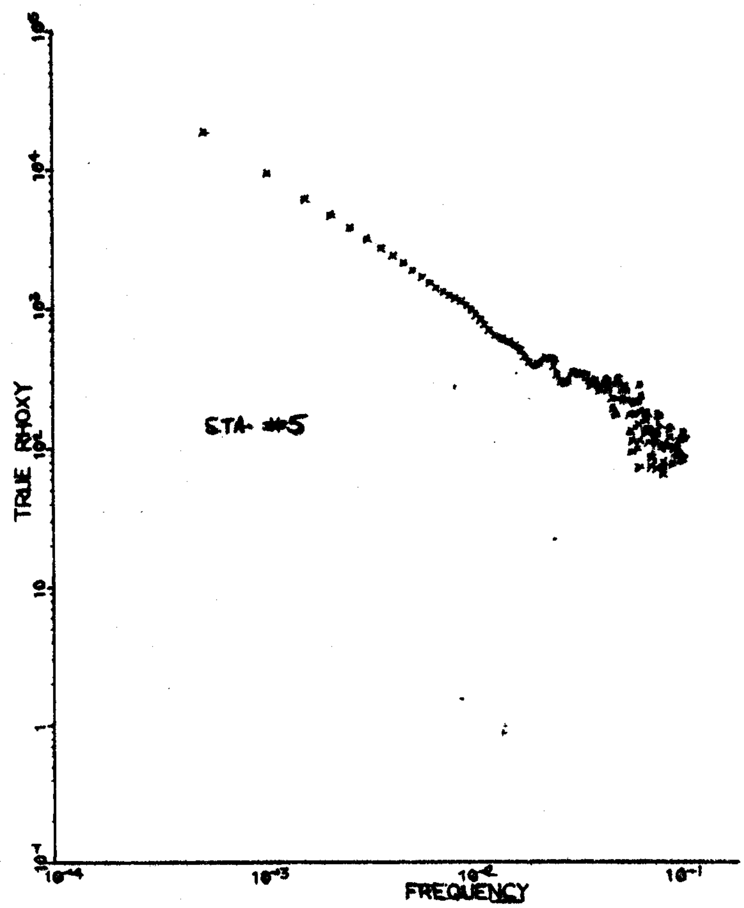


Figure 27. Magnetotelluric plot for station 5. This curve is representative of all magnetotelluric soundings conducted within the KGRA.

The above conclusion does not support suggestions that the Rio Grande rift extends into and beyond the northern San Luis Valley, and that geothermal manifestations at the land surface is related to upswelling of the mantle. If it does exist, it either has not been detected by the limited number of magnetotelluric soundings conducted, or some, as yet unknown, deeply buried structures are masking it.

Apparent resistivity was also plotted for a higher frequency (thus representing shallower depths), in this case, 3 cycles per second. Results are shown plotted next to the station locations on figure 28. The area immediately east and southeast of Villa Grove expresses only moderately low apparent resistivity. This corresponds to results obtained from the other electrical surveys in this area. South of Mineral Hot Springs, apparent resistivity values decrease abruptly by one order of magnitude. This might reflect a major structural boundary in the northern San Luis Valley, with thick sequences of conductive rocks being present in the deeper parts of the valley (refer to figure 25).

Two telluric profiling traverses were used to provide better definition of the location of the east-west boundary in the vicinity of Mineral Hot Springs. In telluric profiling, only the electric field is recorded (Palmason, 1975; Zohdy and others, 1974). Two pairs of electrodes are laid out, with the electric field components detected by the electrodes being recorded simultaneously. The electrode pairs are laid out in line so that the same component of telluric current is detected by each. The electric field will then be proportional to the average resistivity beneath the pairs of electrodes. The array is moved along a traverse by advancing the rear electrode pair to the front end of the array as successive measurements are made. In this way, the ratio of apparent resistivities between successive midpoints of the array can be determined.

Telluric ratio measurements were made along two traverses running from north to south across the Mineral Hot Springs boundary with the locations of the traverses being shown as AA' and BB' on figure 28. The telluric ratio is dimensionless but it is equal to the ratio of apparent resistivities measured at three cycles per minute and so can be converted to resistivity by comparison with

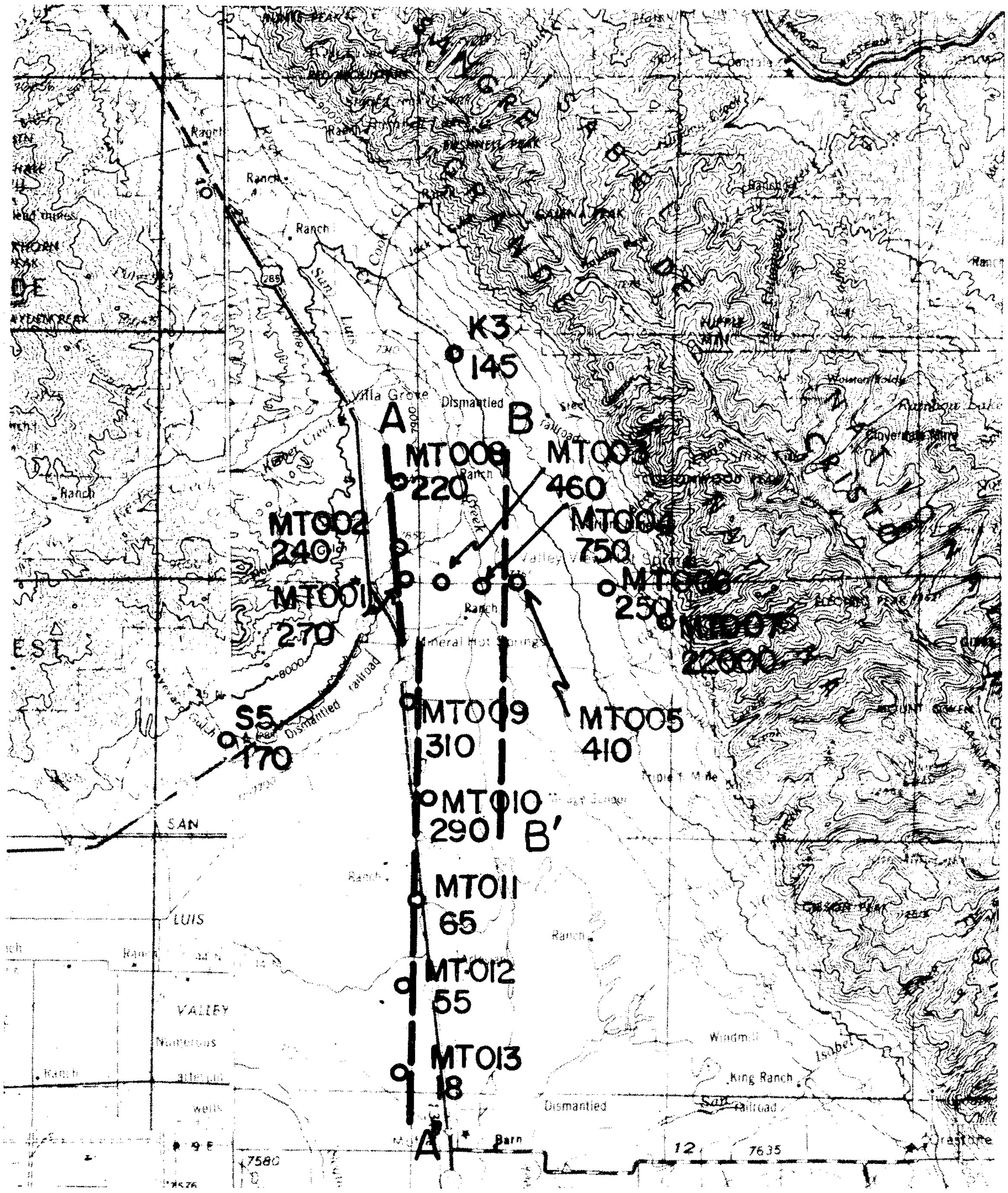


Figure 28. Station locations for magnetotelluric and telluric survey and locations of telluric-profile lines. Station K3 is equivalent to T3 on plate 8 overlay 1. Last digits of other stations are equivalent to last digits on overlay 1. Figures below station designator represents apparent resistivity in ohm-meters.

magnetotelluric resistivities at points along the traverses. The locations where magnetotelluric soundings were made are shown for comparison on the figure.

Profile AA' on figure 29 is approximately 24 kilometers in length. It shows a maximum ratio of approximately 25 to 1 indicating that the apparent resistivity at a frequency of three cycles per minute also varies by a ratio of 25 to 1 along the traverse. The highest resistivities are measured over an interval extending approximately 5 miles (8 km) south of Mineral Hot Springs and 2.5 miles (4 km) north. At the north end of the line, the telluric ratio decreases, reflecting the relatively lower resistivities in the Villa Grove basin. To the south, the telluric ratio values drop abruptly at two locations, suggesting that the basin south of the Mineral Hot Springs area is fault-controlled with the conductive section becoming thicker at two faults. Immediately over Mineral Hot Springs, the telluric ratio is relatively low for a short interval, reflecting the low resistivities at the Springs.

The telluric ratio profile along traverse BB' is shown in figure 30. The northernmost point on this profile is high on the pediment on the east side of the valley. The very high telluric ratio at this location indicates that this end of the traverse has crossed a major fault separating an uplifted block of basement on the north from a section with some alluvial cover on the south. Traverse BB' shows an abrupt drop in telluric ratio at a location which is almost due east from the location of the most northerly drop in telluric ratio on traverse AA'. Because of time limitations the ratio measurements could not be carried far enough south on the traverse BB' to see if the second step in telluric ratio would be present there also.

Seismic Methods

Active seismic methods were applied to parts of the KGRA, not to examine or identify geothermal fluids, but to investigate the structural attitude of rocks at depth. Identification of geologic structures should serve as means of estimating ground water circulation, potential hydraulic conductivity, porosity, and perhaps even water quality. There is some evidence, however, that some structures mapped by seismic methods in geothermal areas

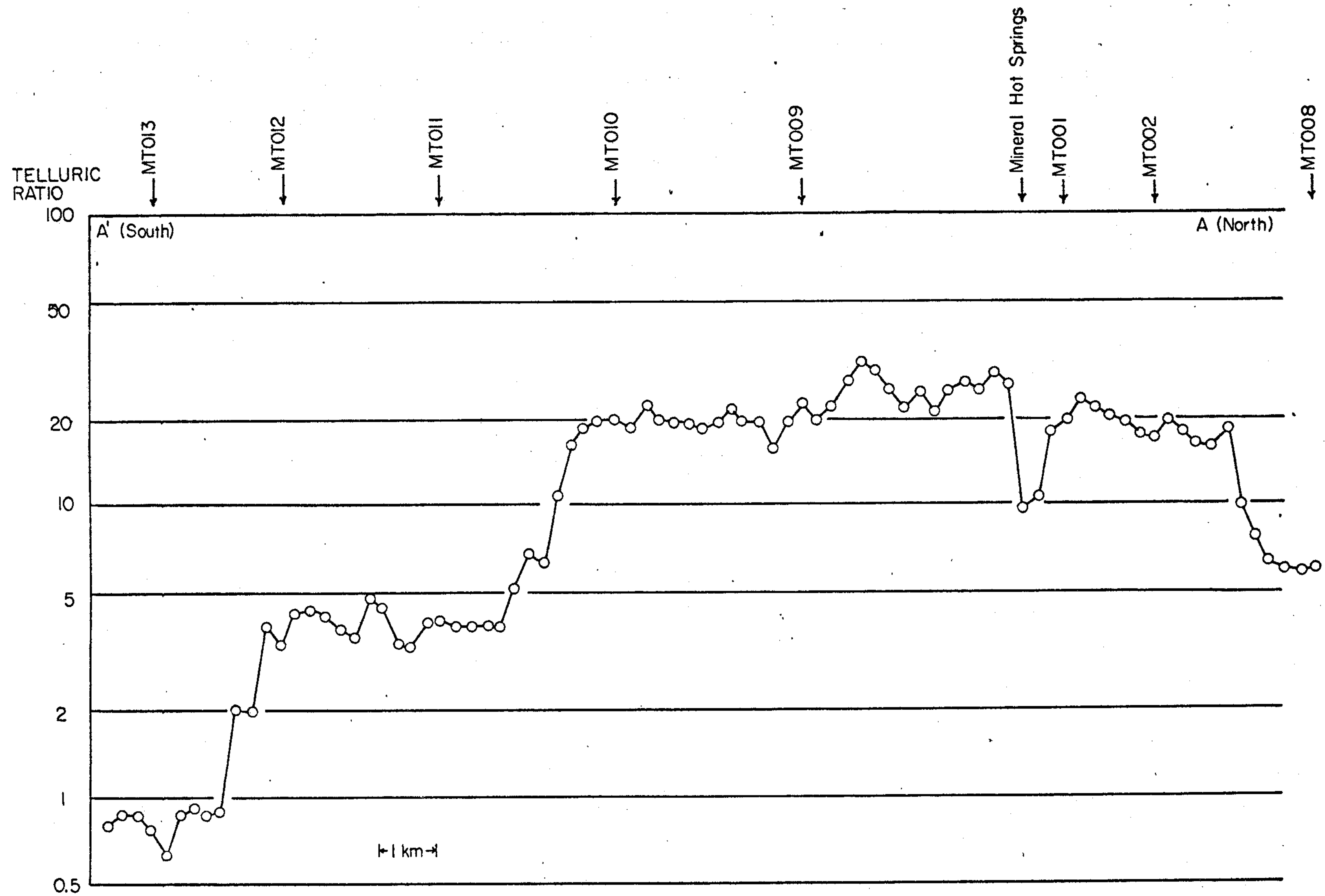


Figure 29.- Telluric profile AA'. After Keller, 1977

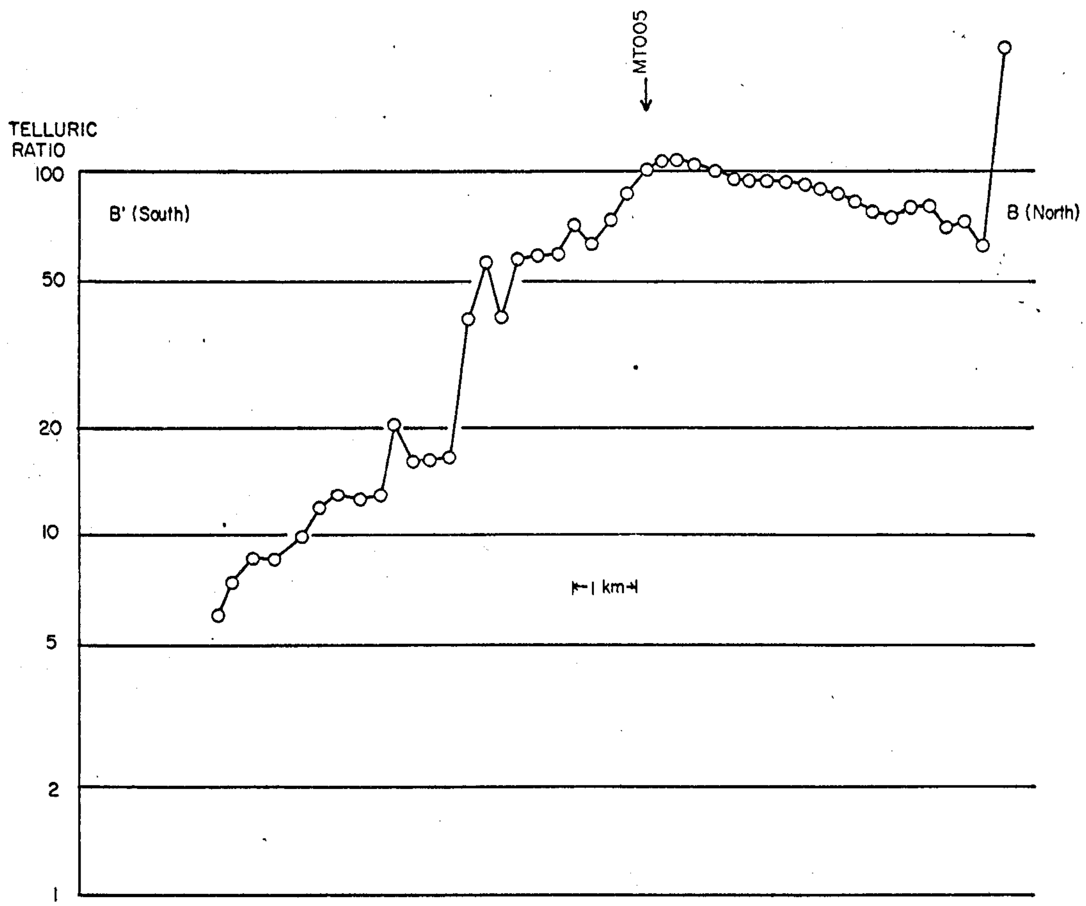


Figure 30. Telluric profile BB' . After Keller, 1977.

might be a direct result of a hot-water system in contact with the host rock. Hayakawa (1970) has had some success with seismic techniques in the Matsukawa field in Japan, but strongly emphasizes concurrent geological geochemical, and other geophysical studies.

Seismic Reflection Survey--A seismic reflection survey was carried out in the vicinity of Villa Grove and Mineral and Valley View Hot Springs (plate 9). Interpretation of the results are presented in figures 31, 32, and 33. The three traverses were located along dirt roads, and elevations were obtained from U.S. Geological Survey topographic maps.

The Vibroseis technique was used as a source of seismic waves. Reflected signals are recorded on magnetic tape and are reprocessed to form an interpretable seismic record (Geyer, 1970).

For the Vibroseis traverses in the KGRA, a single fourteen and a half ton truck-mounted vibrator was used. During operation, the frequency at which the vibrator oscillated varied at each transmission. Frequency sweeps used were 58 to 12 Hertz and 48 to 8 Hertz with a duration per sweep being eight seconds. After each transmission, the pad was lifted, the truck was moved ahead for a short distance, and the procedure was repeated. The vibrations transmitted into the ground were detected with a 24-geophone group (each group consisting of 14 geophones distributed evenly in a series pattern over a distance of 200 feet) connected to a master cable from the recording truck. Signals from each of the geophone groups, and the sweep signal were recorded on a DES 10,000 Digital Recording System and recorded on magnetic tape. The magnetic tapes were sent back to the Colorado School of Mines, Golden Campus, for processing using the Raytheon 703/Phoenix System at the Department of Geophysics. The 24 data channels and the sweep channel were individually processed with time domain and frequency domain oriented programs. The resulting data was then reprocessed to acquire information on frequencies and noise and improved by appropriate filtering. The improved data was then "treated" with a time-wave speed function, appropriately stacked and re-processed. For details concerning geophone layout, spread arrangements, and Phoenix processing, the reader is referred to Keller (1977), and more recently, Stoughton (1977).

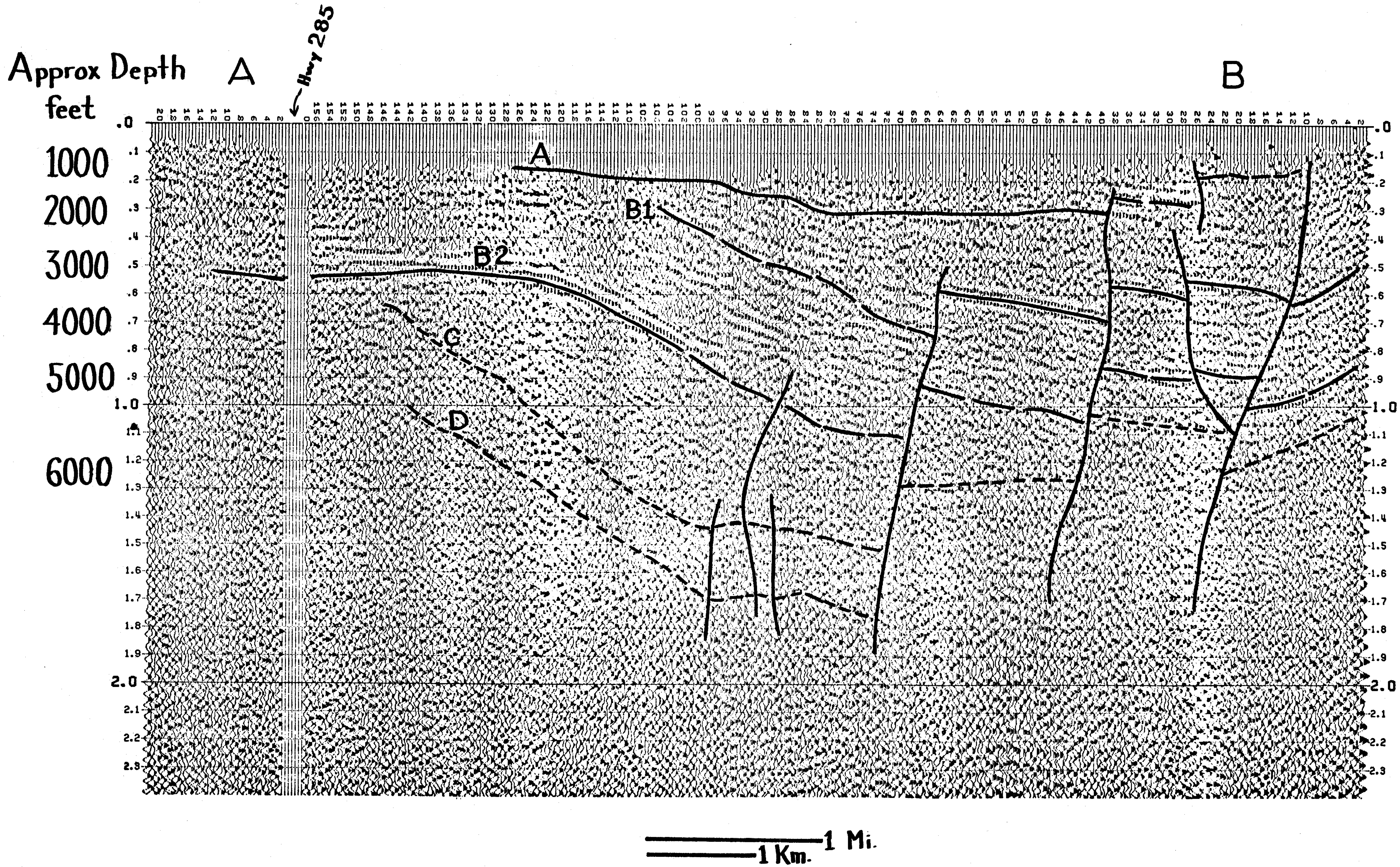


Figure 31.— Seismic cross section A-B

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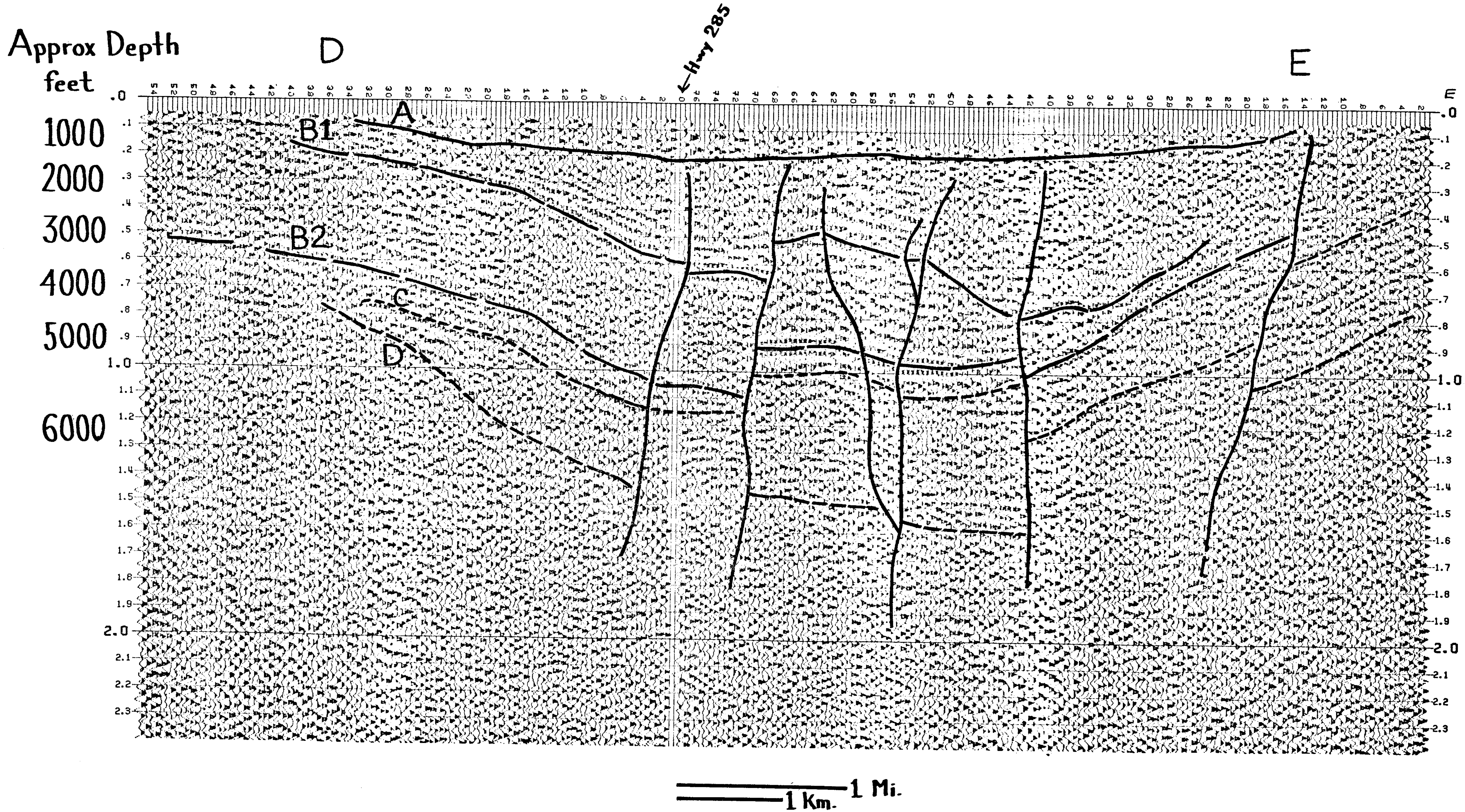

Figure 33.— Seismic cross section D-E

COLORADO DIVISION OF WATER RESOURCES 1977

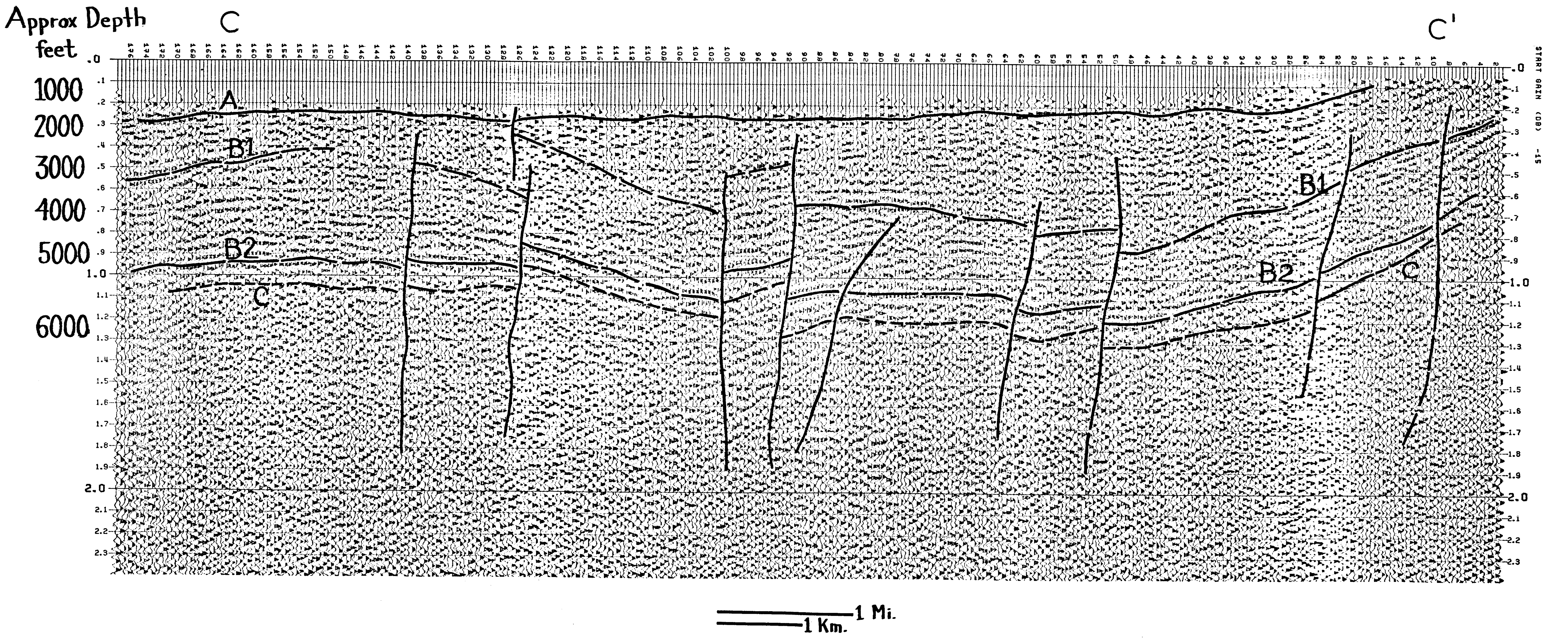

Figure 32.—Seismic cross section C–C'

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Seismic cross sections A-B, C-C', and D-E (figs. 31, 32, 33) illustrate possible geologic structure in northern San Luis Valley near Mineral and Valley View Hot Springs, and Villa Grove. Seismic horizons were picked primarily on the basis of event character, such as wave shape, frequency and amplitude. The disorderly appearance of parts of the figures might be partially due to static problems caused by lateral variations in near surface velocities and the presence of unconsolidated surface alluvium. Considerable shallow reflection data were lost because of the late arrivals of waves travelling through low velocity surface alluvium (Stoughton, 1977).

East-west profiles A-B and D-E show a structural block that is hinged and/or faulted on the western margin of the northern San Luis Basin and dips gently eastward. The east side of the basin in this area is bounded by several blocks which have been significantly displaced and lie nearly horizontal to steeply dipping to the west. Increasingly greater amounts of lateral displacement of the earth's crustral extension is reflected by the degree of vertical block down-faulting necessary to compensate for the void produced by tension and resultant rifting (Keller, 1977, pp. 24, 25; and Stoughton, 1977, p. 70). North-south profile C-C' shows the boundary of the down-thrown block in the valley and expresses normal faults as nearly vertical lines. The structure between locations 90 and 102 on profile C-C' has been interpreted as a thrust fault by Keller (1977) and as a reverse fault by Stoughton (1977).

Event "A" on the seismic profiles is interpreted by this writer to represent the predominantly undisplaced boundary between the Alamosa Formation (Quaternary) and Santa Fe Formation (Tertiary). The relatively high-speed event might be representative of the higher degree of lithification of the Santa Fe Formation. Events B1 and B2 are tentatively interpreted by the Keller (1977) as Oligocene-aged volcanic rocks which originated in the San Juan Mountains, particularly in and around the Bonanza volcanic field. Rocks possibly present are ash flow tuffs, rhyolite, latite, and andesite units. Because much of the faulting was contemporaneous with volcanic eruptions, displacements along the fault is greater in the older strata than in the younger. Stoughton (1977, p. 53) interprets these high-speed events as being associated with density contrasts between late Paleozoic shales and sandstone with an underlying carbonate section. This interpretation is in part supported by Jordan (1974). Events

C and D are interpreted by Keller (1977) as poorly reflecting Paleozoic rocks underlying the Santa Fe Formation. Precambrian rocks are believed to underlie event D. Stoughton's stratigraphic interpretation of events C and/or D is in general agreement although his overall structural interpretation is different.

Gravity Investigation

A few gravity measurements in the immediate vicinity of Mineral Hot Springs were obtained during late summer 1976. The purpose of these measurements was to acquire data which could be compared with results and interpretations of investigations by other investigators.

Results of gravity investigations in the northern San Luis Valley have been presented in reasonable detail by Gaca (1965), Jordan (1974), and Stoughton (1977). All that will be mentioned here is that the presence of a regional gravity low in the area north of Mineral Hot Springs has been verified and probably represents the graben structure mentioned previously. Behrendt and Bajwa's gravity map (1972) shows a series of gravity lows along the axis of the San Luis Valley. These indicate that the San Luis Basin is strongly dominated by a series of north-trending horsts and grabens (Huntley, 1976, p. 85).

ASSESSMENT OF THE REGIONAL GEOTHERMAL SYSTEM

Assessment of the geothermal system, or systems, responsible for surface manifestations of geothermal energy, reservoir temperatures estimated from geochemistry and resistivity anomalies obtained from geophysical surveying includes a tentative classification of the geothermal field, or fields, encountered during this investigation. Once the system has been categorized, it can be modeled and advanced exploration and/or development techniques can be applied. Facca (1973, p. 61) describes a relatively simple classification which emphasizes the physical properties of the fluids withdrawn. A more useful classification is presented by White and Williams (1975, p. 3). Their classification is based not only upon physical properties of geothermal fluids but also, and emphatically, upon the physical--geologic system responsible for a geothermal field's existence. White and Williams' categories are related to the fact that although temperature generally increases with depth below land surface, the rates of increase vary from place to place, depending upon local hydrogeology. Table 7 is a reproduction of the White and Williams table which will be utilized in this report.

Table 7. Categories of geothermal resource base (heat in the ground at temperatures above 15°C to specified depths and without regard for recoverability).

	Temperature Characteristics	Natural fluid supply
1. Hydrothermal convection systems (relatively high temperatures at shallow depths; heat content estimated only to 3 km depth; see Renner and others, this volume).		
a. Vapor-dominated systems	~240°C	Available; not always adequate.
b. Hot water systems		
(1) High-temperature systems	>150°C	Available; not always adequate.
(2) Intermediate-temperature systems	150°C to ~90°C	Available; not always adequate.
(3) Low-temperature systems (not tabulated; many in Waring, 1965)	<90°C	Available; not always adequate.
2. Hot igneous systems (excluding hydrothermal convection systems in (1) above; heat content estimated from 0 to 10 km depth; see Smith and Shaw, this volume).		
a. Assumed part still molten	>650°C	Inadequate.
b. Assumed not molten but very hot ("hot dry rocks")	<650°C	Generally inadequate.
3. Conduction-dominated areas (by heat-flow provinces, utilizing available data on heat flows, radiogenic heat production, and thermal conductivity of rocks; heat contents estimated for 0 and 3 and 3 to 10 km depth; see Diment and others, this volume. This category includes the Gulf Coast geopressured environment with its fluid fraction specially considered by Papadopulos and others, this volume).	15° to ~300°C	Adequate in parts of sedimentary basins, generally inadequate elsewhere.

Classification of the Geothermal System

Renner and others (1975) and Nathenson and Muffler (1975) have made a preliminary classification of the geothermal systems in the KGRA and no attempt to seriously refute their classification will be made in this report. However, an attempt will be made to examine possible reasons for their classification and present conclusions formulated as a result of recent investigations.

Renner and others (1975, pp. 32, 33) have associated the major hot springs of the KGRA with hydrothermal convection systems dominated by hot water with temperatures ranging from 150°C to about 90°C. Such systems are assumed to occur at relatively shallow depths hence heat content, or stored heat, is estimated only to about 9,800 feet (3000 m). This classification is supported by geothermometry, temperature profiles of observation wells 2 and 3 (this report), and by evidence briefly discussed in the following section. Nathenson and Muffler (1975, p. 120) suggest geothermal manifestations along the Rio Grande rift is due to high thermal conductivity of rocks in proximity to the rift, thereby classifying the KGRA as occurring in a conduction-dominated area. Available data on heat flows in this classification are estimated for depths up to about 33,000 ft. (10,000 m).

<u>Source of the Heat</u>--Results of magnetotelluric studies (this report, and Keller, 1977) indicate that rifting of the earth's crust and upwelling of the mantle is possibly not significant in the northern San Luis Valley and Upper Arkansas Valley. This is partially substantiated by lack of active seismic activity in the area. However, passive seismic investigations, heat-flow characteristics which extend northward from Texas and New Mexico, render such a conclusion open to question.

If the Rio Grande rift and upwelled mantle does exist in the KGRA, the source of heat responsible for the numerous geothermal manifestations discussed previously is obvious. Concluding that the rift is the sole source of heat, however, is probably not totally correct as numerous other possible sources must be considered. These are: (1) residual heat related to San Juan and Thirtynine Mile volcanic activity; (2) heat released from large volumes of deep seated hot igneous rock and related to geothermal gradient; (3) heat generated by the decay of radioactive elements such as uranium, thorium, and potassium (Diment and others, 1975, p. 87); and (4) heat generated by hydrothermal reactions occurring in mineralized zones of the crust.

In their description of igneous-related geothermal systems, Smith and Shaw (1975, pp. 58-83) indicate that basalts and andesites that form most volcanoes have probably risen from the mantle to the surface. As a result their heat is dispersed rather than stored and does not provide useful geothermal concentrations. High-silica volcanic rocks commonly are associated with magma chambers in the shallow crust and can sustain high temperature convection systems for thousands of years. In addition some hot spring systems might derive their heat not from young silicic volcanic systems but from older volcanic systems or from very young igneous systems with no surface expression. The volcanic rocks exposed within the KGRA range in composition from basaltic to silicic with the silicic types slightly predominating. It is therefore possible that if the geothermal manifestations within the KGRA are of volcanic origin both shallow and deep sources of magma are implied.

Diment and others (1975, pp. 84-103) indicate the heat of some geothermal systems is due to the regional geothermal gradient. Renner and others (1975, p. 52) quote examples in the Great Basin where hot springs emerge from faults believed to extend to depths of a few kilometers. Water from the hot springs is possibly entirely of surface origin, circulating downward, heated by thermal conduction and then rising and discharging at the surface. The occurrence of the KGRA's hot springs along known faults and fault zones believed to extend to the lower crust is similar to Great Basin examples. Nathenson and Muffler (1975, p. 120) include the Rio Grande rift as an area of higher than normal heat flow due to either radiogenic heat production and/or thermal conductivity of rocks.

For heat related to both volcanic sources and to geothermal gradient, most of the heat is believed to originate deep within the earth with heat from natural radioactivity contributing a significant quantity (Renner and others 1975, p. 51). Diment and others (1975, pp. 84-103) however, state that regions of radioactive heat generation are limited in occurrence and areal extent.

Because of limited knowledge of the occurrence of radioactive elements within the KGRA and the general absence of substantial quantities of anomalously hot water in Colorado mining districts, the authors of this report conclude that the source of heat is a combination of the results of rifting and (1) and (2) as briefly described above. It is unknown at this time which source is predominant, although it is likely that the effects of rifting increase toward the south.

Mechanism of Recharge and Discharge--Figures 34, 35, and 36 indicate that the heat flux to the surface is by conduction in deep parts of the KGRA and by convection in the shallow parts. In the northern San Luis Valley (figs. 34, 35) heat originates in deep seated igneous rocks, hot remnants of San Juan volcanic rocks, and, to an unknown extent by effects (upwelling of the mantle) of the Rio Grande rift. In the Tertiary, Paleozoic, and upper part of the Precambrian section, convection cells are formed locally but do not extend a substantial distance above the top of what is tentatively classified as highly permeable Oligocene age ash flow tuff, rhyolite, latite, and andesite units. Surface manifestations of the convection cells are warm and hot springs in the proximity of faults or fault zones believed to extend into the convection cells. Descending cool water comes in contact with the convection cells or conduits leading to the land surface from peripheral areas, intermixes with hot water in transit, and discharges as warm or hot springs.

In the Upper Arkansas Valley heat is believed to originate primarily from deep parts of the Mt. Princeton batholith (fig. 36). Parts of the convection cells believed to underlie the Mt. Princeton and Cottonwood Hot Springs areas possibly extend into a significant (as yet unidentified) fault zone which extends into the lower parts of the batholith and which might be in association with the northern extension of the Rio Grande rift. The limited areal extent of convection cells in the Tertiary and Quaternary valley fill in the Mt. Princeton-Cottonwood area might be due to depression by relatively unrestricted movement of cool ground water. The relatively large areal extent of the convection cell in the Salida-Poncha Springs area might be attributed both to restricted ground water movement at the south end of the Upper Arkansas graben and to as yet unknown geothermal properties of the large east-west structure identified in ERTS images.

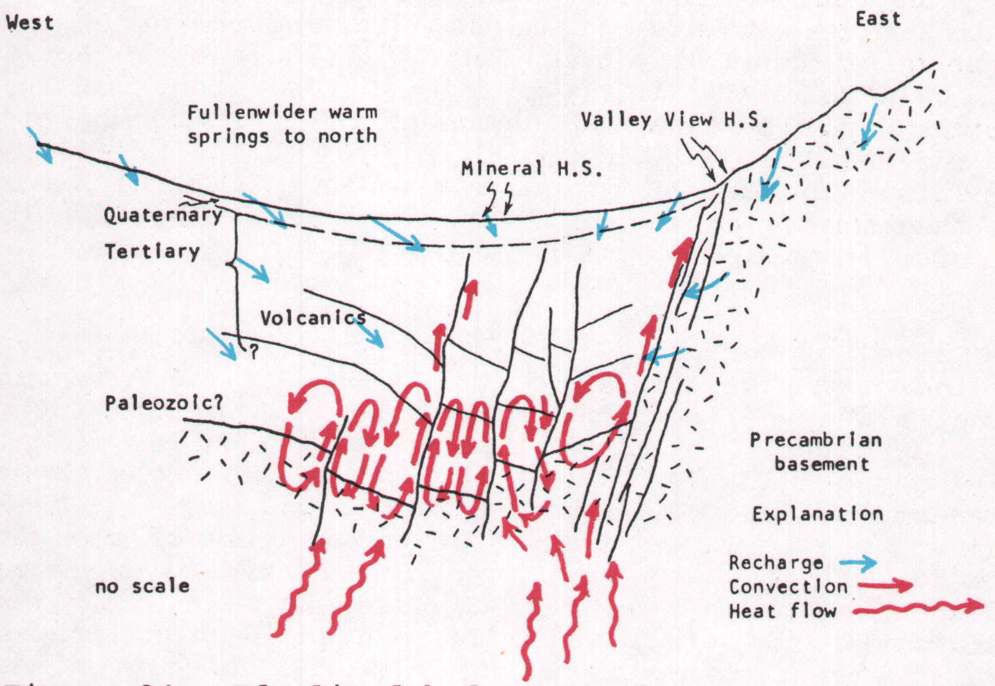


Figure 34. Idealized hydrogeologic cross section of the Mineral and Valley View Hot Springs area showing proposed mode of recharge, convection of hot water, and direction of heat flow in deep-seated rocks.

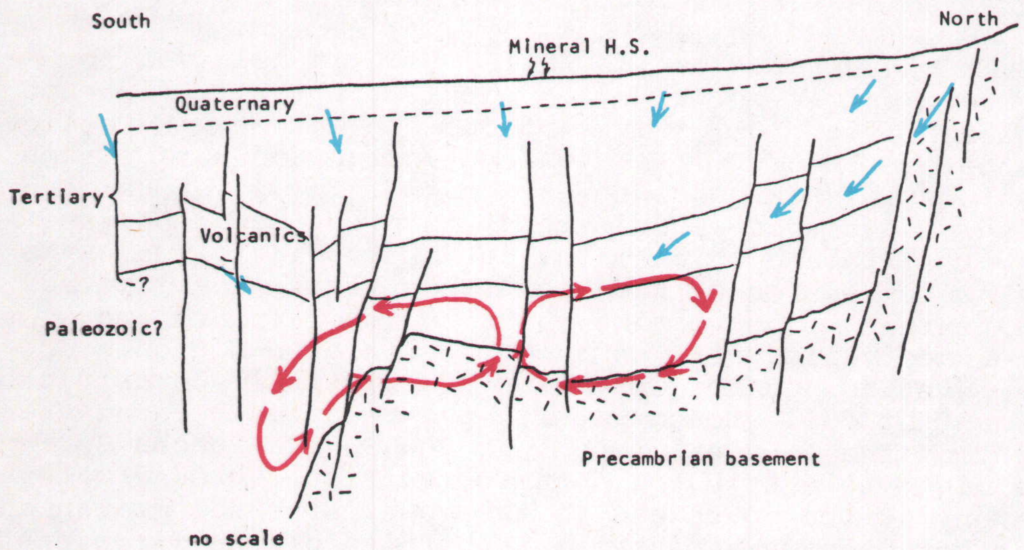


Figure 35. Idealized hydrogeologic cross section of Mineral-Valley View Hot Springs area. Explanation as above.

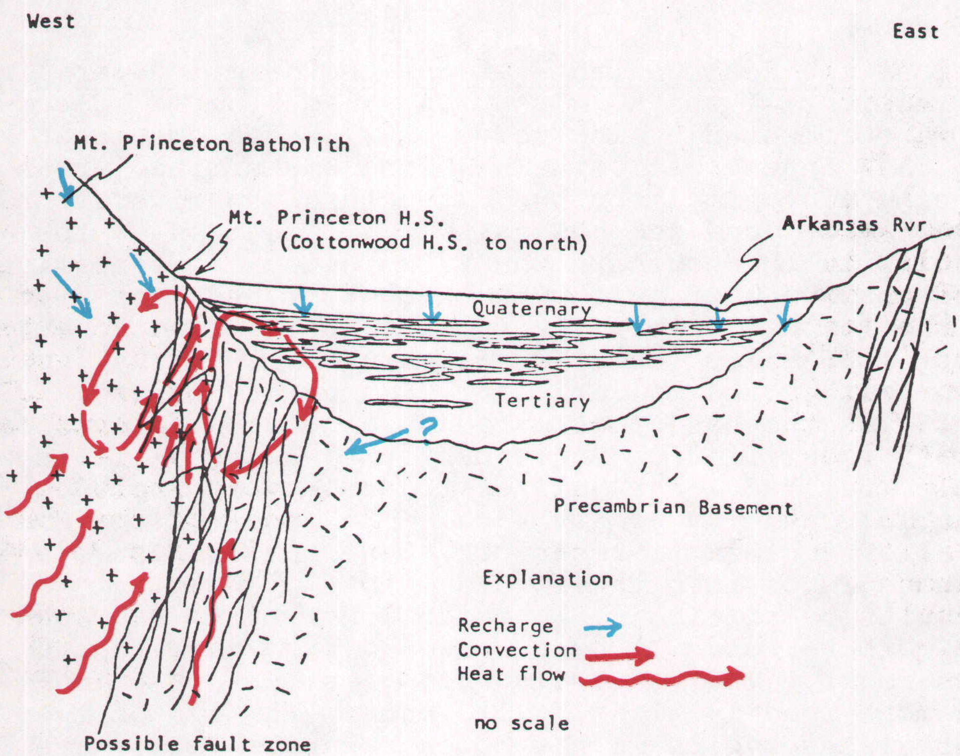


Figure 36. Idealized hydrogeologic cross section of the Mount Princeton Hot Springs area showing proposed mode of recharge, convection of hot water, and direction of heat flow in deep-seated rocks.

The above models are admittedly oversimplifications of the KGRA's geothermal systems. Additional geophysical surveys (electrical and seismic), geochemical studies, and strategically located observation well construction are required to more accurately describe the true dynamic systems.

Dimensions and Heat Contents of the Geothermal Reservoirs--The dimensions of the KGRA's potential geothermal reservoirs were computed by inclusion of all data obtained during this investigation. These include surface areas containing geothermal springs, structural considerations and geochemical and geophysical data. The tops of the reservoirs in the northern San Luis Valley are tentatively assumed to have average depths of about 3,000 feet (900 m) below the land surface. Their bases are assumed to extend to about 1.86 miles (about 3 km) which is near the limit for economic geothermal drilling (Renner and others, 1975, p. 53). Ten thousand feet extends well below "electrical basement" identified by Schlumberger soundings. It is possible that the lower half of the reservoir includes a substantial quantity of dry rock. The model of the San Luis Valley geothermal reservoir,shown in figures 34 and 35,assumes a possible three-fold origin of heat: (1) results of rifting; (2) residual heat from San Juan volcanic rocks; and (3) heat released from deep seated igneous rocks. The model also suggests heat is transferred more readily along fault zones. The top of the geothermal reservoirs in the Upper Arkansas Valley are assumed to have average depths of 2,500 feet (750 m) in the Cottonwood-Mt. Princeton Hot Springs area, and a depth of about 0.62 miles (1.0 km) in the Salida-Poncha Springs area. Three kilometers is again the lower limit of the bases. Figure 36 is an idealized geologic section of the Upper Arkansas Valley. This model indicates a substantial quantity of heat might originate from the roots of the Mt. Princeton stock with fault controlled propagation of hot fluids. In both models the areas of both the top and the base of each reservoir are assumed to be identical.

Table 8 lists pertinent geothermal characteristics of the potential geothermal cells associated with the KGRA's hot springs. Geochemical temperatures are averages of reservoir temperatures calculated by Barrett and Pearl (1975). Subsurface area is obtained from surface manifestations, structural considerations, and geochemical and geophysical data. Thickness is 1.86 miles (about 3 km)

Table 8. Average reservoir temperatures in °C, subsurface area, volume, and heat content of potential hot-water convection systems in the northern San Luis and Upper Arkansas Valleys.

	Surface	Na-K	Na-K-Ca	SiO_2	Mixing Model	Area km^2	Vol km^3	Heat Content 10^{18} cal
Cottonwood H.S.	58	132	172	110	174	22.0	49.5	3.9
Mt. Princeton H.S. (include Hortense)	67	148	190	111	178	69.9	157.3	13.4
Poncha H.S.	67	156	199	124	98	62.2	124.4	9.6
Fullenwider Warm Spring	18	122	40	122		28.0	58.8	2.8
Mineral H.S.	60	202	236	99	86	31.9	66.9	5.6
Valley View	34	347	288	60	33	31.9	66.9	6.7

minus depth to the top of the reservoir. Volume is calculated from area and thickness. Heat content in calories is calculated as a product of assumed volume, volumetric specific heat of 0.6 cal/cm^3°C, and reservoir temperature less 15°C, ambient surface temperature; for simplicity assumed constant for the United States (White and Williams, 1975, p. 53).

Table 8 shows that in terms of energy the geothermal system in the Upper Arkansas Valley contains approximately 26.9 x 10^{18} calories of stored heat. The northern San Luis Valley system contains approximately 15.1 x 10^{18} calories. The quantity of recoverable heat in the systems is a function of natural heat flow, stored heat, geometry, and effective depth of the systems, hydraulic properties of the reservoirs, availability of recharge waters, and rate of depletion of heat (Bodvarsson, G., 1970; Bolton, 1973; and Dutcher and others, 1972). For this investigation it is assumed that the average initial recovery for both the Upper Arkansas and northern San Luis systems is 25% (White and Williams, 1976, p. 150). At a recovery factor of 25% the 26.9 x 10^{18} calories of stored heat in the report Arkansas Valley geothermal system(s) is equivalent to the heat of combustion of 4.64 x 10^9 barrels of oil or 1.04 x 10^9 short tons of coal. Similarly the heat in the northern San Luis Valley system is equivalent to the combustion of 2.60 x 10^9 barrels of oil or 5.81 x 10^9 short tons of coal.

Estimated Usable and Recoverable Storage--In this report the estimated usable and recoverable storage are those recoverable geothermal waters underlying the potential target areas described under the Classification and Dimensions sections. Criteria utilized in calculations included (after Dutcher and others, 1972, p. 38):

1. Thickness of water-bearing deposits within the target area.

2. Division of the deposits into units on the basis of hydraulic conductivity, porosity, and specific yield.

3. Assign a thickness value to each identified unit.

4. Assume areal extent of each unit is uniform in each target area.

5. Apply a safety or recovery factor of 75%.

6. Compute recoverable geothermal water in storage in each unit using the following equation:

$$Rg_w = AHS_y\ (0.75) \text{ or } Rg_w = AHP\ (0.75)$$

in which Rg_w is the estimated usable recoverable geothermal water in storage, A and H are the area and saturated thickness respectively of each storage unit, S_y and P are the specific yield or estimated effective porosity of the saturated deposits, whichever is applicable. Effective porosity is defined as the ratio of the drainable volume of water to the volume from which it is drained (Todd, 1959, p. 23). Effective porosity, therefore, is the same as specific yield. In this report effective porosity is 80% of total, or measured porosity. The fraction 0.75 is a safety or recovery factor.

The chemical quality of water from the KGRA's hot and warm springs is relatively good (this report, and Barrett and Pearl, 1976). Because of this, the authors are tentatively assuming that all of the water within the volumes measured for heat content is usable. Total water saturation is also assumed.

Upper Arkansas Valley: In the Cottonwood and Mt. Princeton Hot Springs area the top and base of the geothermal reservoirs lie at depths of 750 m and 3 km respectively. The upper 820 feet (250 m) of the reservoirs are possibly composed of Tertiary deposits (Dry Union Formation) with hydraulic properties somewhat similar to those of the Santa Fe Formation in the San Luis Valley. Huntley (1976, p. 65) reports samples of the Vallejo and Santa Fe Formations express porosities ranging from 20 to 27%. This upper division is classified as zone Za1. The lower 1.24 miles (2 km) (one Za2) is believed to consist of fractured Tertiary intrusive and Precambrian rocks. The effective porosity of these rocks possibly ranges between 8×10^{-6} to 1.6×10^{-5} (after Snow, in Hollister and Weimer, 1968).

The top of the geothermal reservoir in the Poncha Springs-Salida area lies at a depth of about 0.62 miles (1 km). The upper 820 feet (250 m) of the reservoir lies in the Dry Union Formation, as described above (Za1).

The next lower unit is possibly a 1,000 ft. thick (300 m) section of Rawley Andesite with an assumed specific yield of 5% (Huntley, 1976, pp. 54, 55). This unit is designated Zalv. Underlying the Rawley Andesite are 4,760 feet (1450 m) of Precambrian and possibly, early Tertiary intrusive rocks with effective porosity ranging from 8×10^{-5} to 1.6×10^{-5}.

The estimated total usable and recoverable water from the three areas in the Upper Arkansas Valley is shown in table 9.

Northern San Luis Valley: In the northern San Luis Valley the top and base of the geothermal reservoirs lie at depths of 2,950 feet (900 m) and 1.86 miles (3 km) respectively. The rocks of the reservoirs have been subdivided into four units as follows: (1) zone Zs1--Santa Fe Formation with an average effective porosity of 0.19; (2) zone Zs2--a complex of Tertiary volcanic rocks with an assumed effective porosity of 5%; (3) zone Zs3--Paleozoic rocks with an effective porosity of about 2%; (4) zone Zs4--Precambrian and possibly early Tertiary intrusive rocks with an effective porosity ranging from 8×10^{-6} to 1.6×10^{-5} (table 9).

Total usable and recoverable geothermal water in storage in the Upper Arkansas Valley is estimated to be 5.00 million acre feet (6.17×10^3 hm^3) and in the northern San Luis Valley 4.44 million acre feet (about 5.48×10^3 hm^3) for a grand total within the KGRA of 9.44 million acre feet (1.16×10^4 hm^3).

THE RELATION BETWEEN GEOTHERMAL RESOURCES AND WATER RESOURCES

The surface and ground water regimes of the KGRA are linked to the area's geothermal system by faulting and by direct or close contact with the geothermal reservoir(s). Extensive faulting of the region has locally resulted in the formation of conduits through which water heated by geothermal activity is allowed to ascend and locally discharge on the land surface as thermal springs. All of the springs investigated in the KGRA are related to faulting which is believed to be associated with the Rio Grande rift. Part of the water discharged by the springs repercolates to the ground water system and part

Table 9. Summary of usable and recoverable water in storage from various zones within the KGRA's geothermal reservoirs. Expressed in acre feet and cubic hectometres.

Upper Arkansas Valley

	Cottonwood H.S.		Mt. Princeton H.S.		Poncha-Salida	
Zone	AF	hm^3	AF	hm^3	AF	hm^3
Za1	$6.32 x 10^5$	$7.80 x 10^2$	$2.02 x 10^6$	$2.49 x 10^3$	$1.79 x 10^6$	$2.21 x 10^3$
Za1v					$5.59 x 10^5$	$6.90 x 10^2$
Za2	320	0.39	346	0.43	136	0.17
Subtotal	$6.32 x 10^5$	$7.80 x 10^2$	$2.02 x 10^6$	$2.49 x 10^3$	$2.35 x 10^6$	$2.90 x 10^3$

Total for upper Arkansas Valley - 5.00×10^6 AF = 6.17×10^3 hm^3

Northern San Luis Valley

	Fullenwider W.S.		Mineral and Valley View H.S.	
Zone	AF	hm^3	AF	hm^3
Zs1	$4.78 x 10^5$	$5.89 x 10^2$	$2.21 x 10^6$	$2.73 x 10^3$
Zs2	$3.81 x 10^5$	$4.69 x 10^2$	$8.75 x 10^5$	$1.08 x 10^3$
Zs3	$1.54 x 10^5$	$1.89 x 10^2$	$3.48 x 10^5$	$4.30 x 10^3$
Zs4	213	0.26	4.19x10	0.52
Subtotal	$1.01 x 10^6$	$1.25 x 10^3$	$3.43 x 10^6$	$8.11 x 10^3$

Total for northern San Luis Valley = $4.44 x 10^6$ AF = 5.48×10^3 hm^3

discharges into local stream systems. A small quantity is immediately lost as direct evaporation.

It is possible that discharges of thermal waters occur underground. Such discharges could occur where fractures or conduits associated with a geothermal source are deeply buried by or are adjacent to permeable Quaternary or Tertiary deposits. The fractures or conduits through which thermal waters are ascending might encounter beds of highly permeable sands, gravels, or volcanic rock, for example, overlain by substantial beds of swelling clay. There is great potential for such phenomena to occur in the deep alluvial basin of the San Luis Valley and along the base of the heavily glaciated Sawatch Range.

Water discharged at the land surface from known thermal springs in the northern part of San Luis Valley flows over Quaternary valley fill. Part of the water repercolates into the shallow alluvial deposits and part flows into San Luis Creek. In addition to seepage losses, water in San Luis Creek is either diverted for irrigation purposes or, during periods of high runoff, flows into the lower parts of the closed basin where it will be lost by non-beneficial evapotranspiration.

Most of the thermal water which percolates to the ground, either near the springs or along its course to lower elevations, recharges the area's shallow or confined aquifer systems. Water-table contours of the basin indicate that ground water movement in the unconfined aquifer is toward the south (Emery and others, 1971). It is possible that a small quantity of water recharges the confined aquifer system along the peripheral parts of the valley floor and in the extreme northern end of the valley where confining layers are possibly poorly developed.

Most of the known thermal springs in the Upper Arkansas Valley are less than one quarter mile (about 400 m) from a perennial stream and most of the spring waters are rapidly incorporated in streams tributary to the Arkansas River. A small but as yet unknown quantity recharges local alluvial aquifers when the latter occur between points of spring discharge and points of discharge into the stream.

Geophysical surveys of the San Luis Valley graben indicate that perhaps 20,000-30,000 feet (about 6,000-9,000 m) of Quaternary and Tertiary sedimentary and volcanic rocks may be present locally (Gaca and Karig, 1965; Kleinkopf and others, 1970; Stoughton, 1977). It is therefore quite possible that the deepest parts of the alluvial basin are quite close to, if not in contact with, the system responsible for the surface manifestations of geothermal energy. A somewhat similar situation might locally occur in the Upper Arkansas Valley where the Dry Union Formation is possibly over 10,000 feet (about 3,000 m) thick (Van Alstine, 1968). Additional geologic and geophysical data will have to be evaluated before more definite statements can be made regarding such associations.

Potential Effects of Geothermal Resources Development on Ground Water Resources

Any development of geothermal energy resources in Colorado will probably be accompanied by changes in local inflow-outflow relations, by changes in hydraulic characteristics of aquifers, and could result in controversial environmental hazards. This portion of the report describes in general terms an analysis of the possible effects and will identify possible means by which potentially adverse effects might be monitored, alleviated, or perhaps eliminated.

Initial development of geothermal energy resources within the KGRA described in this report will probably be confined to the withdrawal of hot water. It is well known that hot water can be utilized for space heating, agricultural purposes, health spas, and small industry.

Possible Changes in the Flow Regime--Large scale withdrawals of water from the KGRA's geothermal reservoirs might result in substantial changes in local or regional ground water inflow-outflow relations. The nature and intensity of the changes will depend upon the location(s) of the geothermal production wells, their yields, drawdowns, pumping duration, and steps taken to control or alleviate the potential changes.

Upper Arkansas Valley: Geothermal resource development in the Upper Arkansas Valley will probably occur within the narrow valley floor. Initial development of the reservoir(s) will probably be slow and widely separated. Priority will undoubtedly be placed upon space heating with agriculture, health spas, and small industry. Withdrawal rates will probably be low in the Buena Vista-Mt. Princeton area and slow to moderate in the more densely populated Poncha Springs-Salida area. Hot water removed from the reservoir will be replaced by cool water migrating from peripheral areas. These areas include the Tertiary intrusive-Precambrian rocks along the Sawatch Range and the alluvial deposits of the Arkansas Valley.

Colorado Division of Water Resources records indicate about 600 water wells have been constructed in the alluvial deposits of the Upper Arkansas Valley. About 95% of these are less than 100 feet (30 m) deep and the remainder (except one 100 m deep) are less than 200 feet (60 m) deep. Because of this, nothing is known of the lithologic properties of the deeply buried sediments of the Upper Arkansas graben. It is believed that significant thicknesses of as yet unidentified interstratified clay might impart a semi-confined condition to lower parts of the graben. Under such conditions, recharge could occur along strata predominantly confined to deep parts of the graben. Since movement of water recharging a developed geothermal reservoir should have a greater horizontal component than a vertical component (hydraulic conductivity extrapolation after Huntley, 1976, p. 65), recharge is expected to occur over a relatively wide area.

It is probable that the effects of recharge from deep-lying strata will extend to the conduits associated with hot springs. If the conduits are in direct hydraulic contact with the developed geothermal reservoir a reduction of spring discharges should be expected. The economic effect on existing facilities utilizing hot water can be lessened by utilization of a portion of the developed geothermal waters.

Although the geothermal reservoir in the Upper Arkansas Valley might be semi-confined (test drilling is obviously necessary to confirm or refute this), some effect upon the valley's shallow water wells should be expected. Possible spherical flow patterns developed during withdrawals of geothermal water might lower the water level in shallow wells to a significant degree. This is undesirable because it implies that shallow ground water which would otherwise be utilized by well owners, and which is tributary to the surface water system is being diverted toward the developed geothermal reservoir. Some legal implications will be briefly discussed in a later section of this report.

Recharge of cool, potentially high quality water to the geothermal reservoir(s) might have the effect of cooling the reservoir (and thus reducing its life) and/or improving the quality of water withdrawn. The latter would be particularly beneficial with respect to the legal complications involved with discharges of water into a system containing water of better chemical and physical quality.

Northern San Luis Valley: Depending upon the degree of well development and utilization, the potential effects of extracting water from the geothermal reservoirs in the San Luis Valley are far reaching, both in magnitude and extent. The possible effects are numerous, hydrogeologically complex, and might result in legal action by holders of prior vested water rights. Since it is likely that geothermal development might extend into the central and southern parts of the San Luis Valley, the entire valley is considered in the following discussion that follows.

Withdrawals of hot water will occur from depths exceeding 3,000 feet (900 m) or well into the confined aquifer system of the valley. Withdrawals of water from the confined aquifer system will tend to establish a new equilibrium in which a reduction in natural discharge, an increase in recharge, or a combination of these effects occurs. Water withdrawn from depths of 4,000 to 5,000 feet (1200-1500 m) for example, would be replaced by water from other parts of the aquifer. Potentiometric surface declines created by a producing geothermal well or well field would expand outward and encompass significant portions of the basin. It is safe to assume that given enough time, the potentiometric surface decline will develop to such a magnitude that many once-flowing irrigation, domestic, and stock wells will have to be pumped and perhaps deepened. Plate 12 is a map showing the configuration of the potentiometric surface of the confined aquifer and the area of flowing wells as of 1970.

The first areas affected will probably be those in the immediate vicinity of the developed reservoirs. Huntley (1976, pp. 155-160) described vertical ground water flow components which indicate that locally, water withdrawn from a deep geothermal reservoir will be replaced by a substantial quantity of ground water percolating vertically from above or below the area of withdrawal. In those areas where the horizontal flow component is predominant, the effects of withdrawal will extend laterally and possibly significantly lower the potentiometric surface in peripheral areas of the valley. Of particular concern is a 360 to 400 square mile (about 950 km^2) area in the general vicinity of Alamosa where not only a large number of wells tapping the confined aquifer are in existence, but where it is believed by state and federal investigators that water from the confined aquifer recharges the unconfined aquifer and, particularly, streams tributary to the Rio Grande.

As mentioned above, extensive withdrawals of water from the geothermal reservoir(s) might also affect the quantity of recharge to the unconfined aquifer. The possible reduction of recharge from the confined aquifer will not be redescribed. A second possibility of reduced recharge lies in the strong probability that a substantial portion of recharge to the confined aquifer originates as percolation of precipitation along the margins of the San Luis Valley near the limits of the blue clay or clay series (this report). In these areas or zones, downward migrating precipitation and seepage from streams entering the valley is believed to recharge both aquifers. If the influence of withdrawals of water from the geothermal reservoir(s) is substantial it is conceivable that recharge otherwise destined for the unconfined aquifer will be diverted to lower levels (the confined aquifer). Such a phenomenon might have both detrimental and beneficial affects.

Detrimental affects will primarily involve a possible lowering of the water level in the unconfined aquifer and an associated reduction of local discharge into the Rio Grande. Beneficial effects might result in reduction of runoff or seepage into the closed basin increasing the agricultural potential in currently waterlogged areas.

Ground Water Pollution--Of particular concern regarding geothermal resource development in Colorado is the possible effect of harmful chemical effluents. Since geothermal fluids commonly contain excessive amounts of dissolved mineral matter, associated environmental problems must be considered. Releases of hydrogen sulfide, ammonia, arsenic, boron, copper, fluorides, nitrate, sodium, and radon are most important. Such releases are detrimental to man's health, corrode materials, directly and indirectly damage crops, and are hazards to livestock (Andersen, 1975, p. 1317). In some cases thermal waters are of sufficient purity to be used for agricultural and industrial purposes (Bowen, 1973, p. 212).

The possible impact of thermal loading on the KGRA's aquifer system will not be treated in detail in this report. It is suggested, however, that possible future attempts to utilize the region's geothermal resources include thermal monitoring of streams.

Upper Arkansas Valley: Results of chemical analyses of water from hot springs in the Upper Arkansas Valley (Barrett and Pearl, 1976) show that water developed from geothermal reservoirs might not cause serious ground water pollution problems. The only elements which are present in concentrations in excess of U.S. Public Health Service requirements for drinking and culinary purposes (1962) are fluoride and sodium. Fluoride concentration ranges from 0.1 to 19 parts per million, ppm, with an average of about 11 ppm at each spring area. The recommended maximum concentration of fluoride is 1.5 ppm. Sodium concentration ranges from 50 to 200 ppm, averaging 100 ppm at Cottonwood Hot Springs, 70 ppm at Mt. Princeton, and 190 at Poncha Hot Springs. The recommended range is from 10 to 200 ppm. Average conductivities of water from Cottonwood, Mt. Princeton, and Poncha Hot Springs are 490, 348, and 956 micromhos respectively.

From an agricultural viewpoint, developed geothermal waters percolating into the shallow ground water system should have no particularly detrimental affects. Analyses of water by Barrett and Pearl (1976) indicate that all of the spring waters tested are of a relatively good to fair agricultural quality. Most of the harmful constituents are present in concentrations expressed in micrograms per liter (0.000001 gm/l). Conductivity, TDS, sodium absorption ratio (SAR), and salinity hazards are generally higher than in ground water in the Upper Arkansas Valley and might cause some concern. Table 10 lists representative conductivities, TDS, SAR, and salinity hazards for the KGRA's hot and warm springs, ground water from Quaternary deposits in the Upper Arkansas Valley, and water from unconfined and confined aquifers in the northern and central San Luis Valley.

Table 10. Representative conductivities (micromhos per cm at 25°C), TDS, SAR, and salinity and sodium hazards of water from springs and ground water sources in the KGRA

	Conduct.	TDS	SAR	Hazard: Salinity	Hazard: Sodium (alkali)
Spring(s)					
Cottonwood	490	340	6.87	Medium	Low
Mt. Princeton	338	260	2.18	Medium	Low
Poncha	956	666	1.00	High	Low
Fullenwider	530	332	3.7	Medium	Low
Mineral	1014	680	4.4	High	Low
Valley View	334	237	0.11	Medium	Low
Area					
Buena Vista (Ark. Rvr. alluvium)	96	57	0.2	Low	Low
Northern S.L.V. (unconf.)	532	375	1.4	Medium	Low
(unconf.)	490	333	8.7	Medium	Low
(conf.)	163	149	0.4	Low	Low
(conf.)	1880	1210	25.0	High	High
Central S.L.V. (unconf.)	834	531	2.5	High	Low
(unconf.)	4070	2660	91	Very High	Very High
(conf.)	316	266	6.7	Medium	Low
(conf.)	1540	1010	46.0	High	Very High

Northern San Luis Valley: The possibility of contamination of aquifers from waters discharged from geothermal reservoirs in the San Luis Valley is somewhat problematical, particularly if the chemical quality of water from hot springs is fairly typical of water which might be withdrawn from the associated geothermal reservoir(s). Close examination of table 10, and data presented by Barrett and Pearl (1976), Emery and others (1972, 1973), and Huntley (1976) reveals that the chemical quality of hot water from the KGRA's thermal springs is about equal to, and in some cases better than, the quality of typical water from both the unconfined and confined aquifers. Plates 13, 14, 15 and 16 (reproduced directly from Emery and others, 1973) show the areal distribution of the salinity and sodium (alkali) hazard of water in the unconfined and confined aquifers of the San Luis Valley.

Clearly much of the ground water in the aquifers of the San Luis Valley is of marginal quality and further chemical deterioration must be prevented. If in the future the geothermal reservoirs are developed and the chemical quality of discharged waters is poorer than that of water from affected aquifers,steps must be taken to prevent further deterioration. If, however, geothermal waters are of the quality indicated in table 10, beneficial effects should result--dilution of poor quality water, for example.

Land Subsidence and Seismic Activity--One of the potential hazards of extracting substantial quantities of hot water from the geothermal reservoirs of the KGRA is the threat of land subsidence. Most investigators agree that the common cause of land subsidence is the withdrawal of water, gas, or petroleum from confined zones in partially consolidated sedimentary deposits. This removal of fluids results in a reduction of the artesian pressure and an increase in overburden load on the formation(s). When the overburden load is increased, more of the stress is transferred to the matrix in the deposits. This change in stress results in changes in particle, pore, and bulk volume of the rock, and ultimately, compaction of compressible beds. Although a small part of the subsidence may be elastic in nature and tend to rebound when the stresses are removed, most of the change is non-elastic and nonrecoverable (Dutcher and others, 1972, p. 51).

Land subsidence caused by the extraction of geothermal waters is generally well documented. Dutcher and others (1972, p. 51) quote a report of subsidence seven miles

(11 km) outside the Cerro Prieto field in Mexico even though extensive development had not yet begun. Hatton (1970) reports the area of maximum subsidence in the Wairakei field lies outside the production field. Stilwell, Hall, and Tawhai (1975) report substantial subsidence in the Wairakei, Broadlands, and Kawerau fields in New Zealand, and the U.S. Bureau of Reclamation (1971, 1972) documents subsidence in the Mesa field in southern California. The reports by Dutcher, as well as by Hatton (1970), are particularly significant because they indicate land subsidence is not necessarily confined to the immediate vicinity of a producing geothermal field.

The major hydrogeological effect caused by aquifer compaction is the reduction of the aquifer's capacity to store and yield water. In summarizing his investigation of part of the San Joaquin Valley in California, Poland (1961, pp. B-54, B-54) reported that water obtained during compaction of clayey interbeds and confining beds may be equal to or greater than that derived from compaction of the coarse fraction of the aquifer. He also states that the water yield from the clayey beds is large only during the first decline of artesian pressure. If pressures are allowed to recover, and then were drawn down again through the same interval, the additional compression of the clayey beds would be only a small fraction of that in the first phase. It is reasonable to conclude that compression of beds from the extraction of geothermal fluids materially reduces the beds capacity not only to store and yield fluids but also reduces their capacity to accept reinjected fluids.

Accompanying land subsidence is the possibility of seismic activity. It has already been shown that parts of the Rio Grande rift are tectonically and seismically active. Experience at the Rocky Mountain Arsenal near Denver has shown that earthquakes have resulted from temperature and pressure changes caused by both fluid injection (Hollister and Weimer, 1968) and fluid withdrawal (Hoover and Dietrich, 1969). Contrarily, Cameli and Carabelli (1975) report a reinjection experiment in Italy produced no increase in background seismic activity.

Possibilities of land subsidence and seismic activity in the Upper Arkansas Valley might be relatively high in the southern part of the upper Arkansas graben and along the west flank of the valley floor between Buena Vista and Salida. Changes in the hydraulic character of the deep-lying sediments might occur, but should not result in serious threats to the area's agricultural and industrial economies, whose water needs are satisfied from predominantly surface supplies. Seismic activity might be significant along the west flank of the valley floor where relatively recent tectonic activity has been identified (this report).

Land subsidence and possible seismic activity caused by extractions of large quantities of geothermal water in the San Luis Valley might have most serious affects upon the aquifer system. If subsidence is widespread, it might significantly lower southward-trending gradients of the potentiometric surface and the overlying water table of the unconfined aquifer. Such a phenomenon would not only reduce ground water flow to southern parts of the basin but also has the potential to increase local salinity hazards by reducing the rate of vertical and horizontal leaching.

Potential Effects of Geothermal Resources Development on Surface Water Resources

Another possible risk associated with the development and utilization of geothermal resources is the contamination of surface waters by geothermal fluids. Pearl (1975) notes that many geothermal resource developments in the western United States will be located in the headwater regions of rivers whose water quality, in many instances, is less than 500 mg/l. Because state and federal water laws prohibit degradation, any thermal waters containing dissolved solids in excess of dissolved solids content of rivers will probably have to be treated before release, or perhaps be reinjected.

It was previously shown that the potential chemical quality of water from the KGRA's geothermal reservoirs is equal to or better than the chemical quality of some ground water obtained from some water wells. This condition does not exist with the KGRA's surface water resources which generally exhibit excellent quality water. Table 11 shows representative conductivity, TDS, SAR, salinity, and sodium (alkali) hazards for major streams within or related to the KGRA. Additional data will be found in Emery and others (1973), Powell (1958), U.S. Bureau of Reclamation (1969), U.S. Geological Survey (1965, 1966), and Appendix 1.

Table 11 shows that the general chemical quality of surface water in the Upper Arkansas Valley is typical of

Table 11. Representative conductivities (micromhos per cm at 25°C), TDS, SAR, and salinity and sodium hazards of water from major streams within or related to the KGRA

Stream	Conduct.	TDS	SAR	Hazard	
				Salinity	Sodium (alkali)
Cottonwood Creek	90	58	0.2	Low	Low
Chalk Creek	122	87	0.3	Low	Low
Ark. River (S)	160	95	0.2	Low	Low
Ark. River (C)	370	250	0.7	Medium	Low
Ark. River (JM)	2580	2300	3.7	Very High	Low
Kerber Creek	300	189	0.5	Medium	Low
Open drain	538	325	1.1	Medium	Low
Rio Grande	377	276	1.3	Medium	Low
Head Lake (cb)	19030	17134	112.0	Very High	Very High

(S) Near Salida

(C) Near Canon City

(JM) Below John Martin Reservoir

(cb) In closed basin

that of high mountain streams in non-industrialized areas. Near Salida,conductivity is generally below 200 micromhos and salinity and sodium hazards are low. About 50 miles (80 km) downstream, near Canon City, chemical quality begins to deteriorate rapidly. At the Colorado-Kansas line conductivity has increased to about 2,500 micromhos and the salinity hazard is very high. This increase is due to factors such as agricultural and industrial activities, and reuse of water.

Clearly the possible discharge of developed geothermal waters into the surface water system in the Upper Arkansas Valley might have a measurable affect upon those waters. Holders of adjudicated water rights, supported by provisions of the Colorado Water Quality Control Act of 1965 might have legitimate grounds upon which to demand cleanup or cease and desist orders if it can be shown that the developed geothermal water is noticeably deteriorating the surface waters.

It is equally clear that the chemical quality or water in the lower Arkansas River is so poor that discharges of developed geothermal water in the Upper Arkansas Valley should have no perceptible affect other than perhaps upgrading the quality. This assumes that the chemical quality of water from the Upper Arkansas Valley's hot springs is truly representative of the water which might be developed for geothermal energy purposes.

Table 11 shows that the general chemical quality of surface water in the San Luis Valley is good to excellent. Exceptions are found in many lakes within the closed basin where chemical quality is very poor. Should developed geothermal water in the northern and central San Luis Valley enter the surface water system its ultimate destination should be the closed basin. The reaction of holders of vested water rights in areas peripheral to the closed basin is highly problematical. Since the potential chemical quality of some developed geothermal waters might equal or exceed the quality of some surface waters, geothermal discharge might be welcomed. Excessive discharges of such water, however, might create an increase in the areal extent of water-logged soils.

Should discharges of geothermal water be allowed to enter the Rio Grande or its major tributaries,caution must be exercised with respect to strict adherence to provisions of the Rio Grande Compact of 1938 which is quoted here in part:

> "In the event that works are constructed after 1937 for the purpose of delivering water into the Rio Grande from the Closed Basin, Colorado shall not be credited with the amount of such water delivered, unless the proportion of sodium ions shall be less than 45 percent of the total positive ions in that water when the total dissolved solids in such waters exceeds 350 parts per million . . ."

In addition to possible deterioration of chemical quality of both ground and surface waters, there is the impact of possible thermal loading on the temperature regime of the KGRA's streams. This type of pollution is not discussed in detail in this report but is mentioned because of the additional constraints such pollution might have on future geothermal development. Of particular interest at this time is a seven mile (11 km) reach of the upper Arkansas River between Salida and Buena Vista which is being considered for designation as a Wild-Scenic River.

Potential Effects of Geothermal Resources Development Upon Other Areas in Colorado

If geothermal resources are developed in other areas of Colorado the potential detrimental affects upon those areas' water resources will be similar to those described in this report. This study is unique because of the relatively large range of physio-chemical conditions within the region which could be affected by potential geothermal development. As excellent quality water of the Upper Arkansas Valley nears Canon City it begins to degrade. Between Canon City and the Colorado-Kansas state line the water is of poor quality. A relatively full range of water quality conditions exist in the San Luis Valley depending upon location with respect to the central portion of the closed basin.

Conditions in other potential KGRAs within Colorado (such as Glenwood and Pagosa Springs) are different because the associated geothermal reservoirs are probably more closely associated with surface streams with long (80 miles (130 km) or more) reaches containing excellent quality water. The conductance and TDS of water from the Colorado River about 18 miles (30 km) upstream from Grand Junction, for example, is generally less than 1,100 micromhos and 800 ppm respectively. Hot water issuing from Glenwood Hot Springs has conductances as high as 36,800 micromhos and TDS as high as 20,200 ppm (Barrett and Pearl, 1976). The San Juan River about,20 miles (32 km) downstream from Pagosa Springs,typically has a conductance of less than 400 micromhos and TDS less than 300 ppm. Hot water issuing from Pagosa Springs has conductance as high as 6,000 micromhos and TDS to 3,320 ppm (Barrett and Pearl, 1976).

Clearly the development of geothermal resources in other potential KGRAs in Colorado must proceed with caution. Unfortunately, constraints imposed by water quality controls will possibly affect decisions to develop geothermal energy in some areas as the cost of treatment or reinjection could render marginal geothermal enterprises uneconomic.

Means of Abating Possible Detrimental Effects of Geothermal Resources Development

Many of the adverse affects upon water resources from developing geothermal resources in Colorado can be alleviated, if not eliminated by reinjection practices. Reinjection of wastes has been shown to be feasible in oil fields and at various geothermal fields throughout the world (Pearl, 1972). Einarsson and others (1975) report that injection of highly mineralized waters into the reservoir from which they have been extracted has the following benefits: (1) recharging the geothermal reservoir is possible in areas of limited natural recharge; and (2)conservation of geothermal energy by limiting the infiltration of cool water which would cool the reservoir at a relatively rapid rate. Disadvantages are: (1) local cooling around the point of injection; (2) the possibility of locating injection wells in formations of lower hydraulic conductivity than that of the production zone; and (3) possible high cost of injection. Kubota and Aosaki (1975) report that hot geothermal water has been reinjected into the reservoir at the Otake field since 1972. They have observed an increase in production with no detrimental affects upon local ground water and surrounding hot springs, and report that seismic activity has not occurred. Gringarten and Sauty (1975) have developed a simple mathematical model for determining the evolution of temperature when water is injected at a temperature different from the initial temperature.

The most serious potential disadvantage of reinjection of geothermal wastes is efficiency and cost of reinjection. This might be significant in areas where hot water is the only product, particularly in areas of low population and limited economic resources. Hopefully a few potential geothermal fields in Colorado will yield water (or steam) hot enough to generate electricity thereby enlarging the area which will benefit from geothermal resources development and allow the developer of such energy to draw upon a larger monetary base to pay for the potential high cost of reinjection.

CONCLUSIONS AND RECOMMENDATIONS FOR ADDITIONAL STUDY

Several potential geothermal target areas in the KGRA investigated have been identified. Additional investigations should be carried out in those areas shown to have the most significant indications of containing a potential geothermal reservoir. In order of significance these areas are: (1) the Salida-Poncha Springs area along the south end of the Upper Arkansas graben; (2) the Cottonwood-Mt. Princeton Hot Springs area; (3) the Mineral-Valley View Hot Springs area (because of its close proximity to deeper parts of the San Luis basin); and (4) Fullenwider warm springs.

Additional investigations should include new or additional seismic reflection surveying (particularly in the Upper Arkansas Valley), more detailed Schlumberger sounding, possibly additional magnetotelluric sounding, and finally deep,strategically located temperature gradient test holes. The latter should exceed 2,000 to 3,000 feet (600-900 m) in depth and should be constructed on the assumption that water exceeding 100°C,or perhaps steam,will be encountered.

The combination of office research, field geologic investigations, geochemical investigations, and application of surface geophysical investigations have resulted in the identification of several potential geothermal target areas.

Although the drilling program resulted in the collection of valuable aquifer data,it did not reveal significant information on possible deep-lying geothermal activity. One conclusion of the drilling program is that temperature-gradient wells in some deep alluvial basins should extend to depths exceeding 2,000 or 3,000 feet (600-900 m).

The existence of numerous hot and warm springs and previous knowledge of many of the KGRA's geologic structures proved to be an asset in selecting geophysical survey sites. Bipole-dipole and quadripole resistivity surveys reveal the presence of numerous resistivity lows which should be examined in more detail by "site-specific" investigations. Results of seismic traverses in the northern San Luis Valley indicate that propagation of some geothermal fluids is probably related to faulting. This premise is partly supported by evidence obtained from telluric soundings. Results of magnetotelluric soundings show that in some parts of the KGRA resistivity does not significantly increase with depth. Some sounding sites were widely spaced, hence it is possible that additional soundings will reveal the opposite.

Evaluation of the potential geothermal system(s) within the KGRA indicates that geothermal resources development will have varied effects upon the region's water resources. If the chemical quality of water from the KGRA's hot and warm springs represents the quality of water which will be withdrawn during geothermal resource development perhaps only minimal, if any, chemical degradation of ground and surface waters will occur. This is particularly true for certain parts of the San Luis Valley and lower Arkansas Valley where some waters are already of marginal to poor quality. Particular concern does exist however, for other parts of Colorado where waters are generally of excellent quality. Other possible effects of geothermal resources development within the KGRA include aquifer compaction and resultant changes in aquifer properties, changes in certain flow regimes, land subsidence, seismic activity, and thermal loading. It is believed that injection of spent geothermal fluids should alleviate most of the potential hazards of geothermal resource development.

LIST OF REFERENCES CITED IN THIS PROPOSAL

Andersen, Stephen Oliver, 1975, Environmental impacts of geothermal resource development on commercial agriculture: A case study of land use conflict: Second U.S. Symposium on the development and utilization of geothermal resources, San Francisco, Proceedings. Lawrence Berkeley Lab., Univ. of Calif., p. 1317.

Arestad, J. F., 1977, Resistivity studies in the Upper Arkansas Valley and northern San Luis Valley, Colorado: Colo. School of Mines unpublished MSc thesis, no. T-1934, 129 p.

Banwell, C. J., 1973, Geophysical methods in geothermal exploration in Geothermal Energy, C. H. Armstead, Ed., Unesco Press.

Barbier, Enrico, and Fanelli, Mario, 1975, Relationships as shown in ERTS satellite images between main fractures and geothermal manifestations in Italy: Second U.N. Symposium on the development and use of geothermal resources, San Francisco, Proceedings, Lawrence Berkeley Lab., Univ. of California, pp. 883-888.

Barrett, J. K., 1976. Colorado Geological Survey, personal communication.

Bhutta, M. A., 1954, Geology of the Salida area, Chaffee and Fremont Counties, Colorado: unpublished Colo. School of Mines D.Sc. Thesis, T-795, 173 p.

Bodvarsson, G., 1970, An estimate of the natural heat resources in a thermal area in Iceland: U.N. Symposium on the development and utilization of geothermal resources, Pisa, Italy. Proceedings (Geothermics Spec. Iss. 2) V. 2, pt. 2., pp. 1289-1293.

Bolton, R. S., 1973, Management of a geothermal field: in Geothermal Energy, UNESCO Press.

Bowen, Richard G., 1973, Environmental impact of geothermal development: in Geothermal Energy, P. Kruger and C. Otte, Eds., Stanford U. Press, Stanford, CA.

Bridwell, R. J., 1968, Geology of the Kerber Creek area, Saguache County, Colorado: Unpublished Colo. School Mines M.Sc. Thesis T-1177, 104 p.

Brill, K. G., Jr., 1952, Stratigraphy in the Permo-Pennsylvanian zeugogeosyncline of Colorado and northern New Mexico: Geol. Soc. America Bull., v. 63, no. 8, pp. 809-880.

Brock, M. R., and Barker, Fred, 1972, Geologic map of the Mount Harvard quadrangle, Chaffee and Gunnison Counties, Colorado: U.S. Geol. Survey Map GQ 952.

Bruns, D. L., 1971, Geology of the Lake Mountain northeast quadrangle, Sagauche County, Colorado: Unpublished Colo. School of Mines M. Sc. Thesis T-1367, 79 p.

Bruns, D. L., Epis, R. C., Weimer, R. J., and Steven, T. A., 1971, Stratigraphic relations between Bonanza center and adjacent parts of the San Juan volcanic field, south-central Colorado, in New Mexico Geol. Soc. Guidebook, 22nd Field Conf., San Luis Basin, Colorado, 1971, pp. 183-190.

Burbank, W. S., 1932, Geology and ore deposits of the Bonanza mining district, Colorado: U.S. Geol. Survey, Prof. Paper 169, 166 p.

Cameli, Gian Mauro, and Carabelli, Edmondo, 1975, Seismic control during a reinjection experiment in the Viterlo region (central Italy): Second U.N. Symposium on the development and utilization on geothermal resources, San Francisco Proceedings. Lawrence Berkeley Lab., Univ. of Calif., pp. 1329-1334.

Chapin, Charles F., 1971, The Rio Grande rift, part 1, modifications and additions: in Guidebook of the San Luis Basin, Colorado, New Mexico Geol. Soc. guidebook, pp. 191-201.

Cheng, W. T., 1970, Geophysical exploration in the Tatun volcanic region, Taiwan: U.N. Symposium on the development and utilization of geothermal resources. Pisa, Italy, Proceedings (Geothermics, Spec. Iss. 2), v. 2, pt. 1, p. 262.

Colorado Department of Health, 1971, Colorado drinking water supplies: Div. of Engineering and Sanitation, 42 p.

Crompton, J. S., 1976, An active seismic reconnaissance survey of the Mt. Princeton area, Chaffee County, Colorado: Colo. School of Mines Thesis T-1942.

DeVoto, Richard H., 1971, Geologic history of South Part and geology of the Antero Reservoir quadrangle, Colorado: Colorado School of Mines Quarterly, v. 66, no. 3, 90 p.

DeVoto, R. H., 1972, Pennsylvanian and Permian stratigraphy and tectonism in central Colorado: Colorado School Mines Quart., v. 67, no. 4, pp. 139-185.

DeVoto, R. H., and Peel, F. A., 1972, Pennsylvanian and Permian stratigraphy and structural history, northern Sangre de Cristo Range, Colorado: Colorado School Mines Quart., v. 67, no. 4, pp. 283-320.

DeVoto, R. H., Peel, F. A., and Pierce, W. H., 1971, Pennsylvanian and Permian stratigraphy, tectonism, and history, northern Sangre de Cristo Range, Colorado, in New Mexico Geol. Soc. 22nd Field Conf., San Luis Basin, Colorado, pp. 141-163.

Diment, W. H., Urban, T. C., Sass, J. H., Marshall, B. V., Munroe, R. J., and Lachenbruch, A. H., 1975, Temperatures and heat contents based on conductive transport of heat: in Assessment of geothermal resources of the United States, 1975: U.S. Geol. Survey Cir. 726, pp. 84-103.

Dings, M. G., and Robinson, C. S., 1957, Geology and ore deposits of the Garfield quadrangle, Colorado: U.S. Geol. Survey Prof. Paper 289, 110 p.

DuHamel, J. E., 1968, Volcanic geology of the upper Cottonwood Creek area, Thirtynine Mile volcanic field: Unpublished Colo. School Mines M.Sc. Thesis T-1167, 120 p.

Dutcher , L. C., and others, 1972, Preliminary appraisal of ground water in storage with reference to Geothermal resources in the Imperial Valley area, California: U.S. Geol. Survey Circ. 649, 57 p.

Eardley, A. J., 1962, Structural geology of North America: Harper and Brothers, New York, p. 510.

Einarsson, Sveinn S., Vides, R., Alberto, and Cuellar, Gustavo, 1975, Disposal of geothermal waste water by reinjection: Second U.N. Symposium on the Development and Use of Geothermal Resources, San Francisco, Proceedings. Lawrence Berkeley Lab., Univ. of Calif., pp. 1349-1351.

Emery, P. A., and others, 1971, Hydrology of the San Luis Valley, south-central Colorado: U.S. Geol. Survey Hydrologic Investigations Atlas HA-381.

Emery, Philip A., and others, 1972, Hydrologic data for the San Luis Valley, Colorado: Colorado Water Conservation Board Basic Data Release 22, 146 p.

Emery, Philip A., and others, 1973, Water in the San Luis Valley, south-central Colorado: Colo. Water Conservation Board, Water Resources Circular 18, 26 p.

Emmons, S. F., and others, 1927, Geology and ore deposits of the Leadville Mining District, Colorado: U.S. Geol. Survey Prof. Paper 148, p. 97.

Epis, Rudy C., and Chopin, Charles E., 1974, Stratigraphic nomenclature of the Thirtynine Mile volcanic field, central Colorado: U.S. Geol. Survey Bull. 1395-C.

Epis, R. C., Scott, G. R., Taylor, R. B., and Chapin, C. E., 1976, Cenozoic volcanic, tectonic, and geomorphic features of central Colorado: Professional Contributions of Colo. School Mines, Studies in Field Geology, no. 8, pp. 323-338.

Facca, Giancarlo, 1973, The structure and behavior of geothermal fields: in Geothermal Energy: C. E. Armstead, Ed., Unesco Press.

Gableman, J. W., 1952, Structure and origin of northern Sangre de Cristo Range, Colorado: Am. Assoc. Petroleum Geologists Bull., v. 36, no. 8, pp. 1547-1612.

Gaca, J. R., 1965, Gravity studies in the San Luis Valley area, Colorado: Unpublished Colo. School Mines M.Sc. Thesis T-1021, 73 p.

Gaca, J. R., and Karig, D. E., 1966, Gravity survey in the San Luis Valley area, Colorado: U.S. Geol. Survey Open-file Report, 43 p.

Geyer, R. L., 1970, The vibroseis system of seismic mapping: Jour., Canadian Soc. Exploration Geophysicists, v. 6, no. 1, pp. 39-57.

Green, J. H., 1964, The effect of artesian-pressure decline on confined aquifer systems and its relation to land subsidence: U.S. Geol. Survey Water Supply Paper 1779-T, 11 p.

Gregg, Dean O., and others, 1961, Public water supplies of Colorado, 1959-60: U.S. Geol. Survey in cooperation with Colorado State University Agricultural Experiment Station, General Series 757.

Gringarten, A. C., and Sauty, J. P., 1975, The effect of reinjection on the temperature of a geothermal reservoir used for urban heating: Second U.N. Symposium on the Development and use of Geothermal Resources, San Francisco, Proceedings. Lawrence Berkeley Lab., Univ. of Calif., pp. 1370-1374.

Grose, L. Trowbridge, 1972, Tectonics: in Geologic atlas of the Rocky Mountain Region; Rocky Mountain Asso. Geologists, Denver, Colorado, pp. 35-44.

Grose, L. Trowbridge, 1974, Summary of Geology of Colorado related to geothermal energy potential; in Proceedings of a symposium on geothermal energy and Colorado, R. H. Pearl (ed.): Colo. Geol. Survey Bull. 35, pp. 11-29.

Hadsell, F. A., 1968, History of earthquakes in Colorado: in Geophysical and geological studies of the relationships between the Denver earthquakes and the Rocky Mountain Arsenal well, Part A: Colo. School Mines Quarterly, v. 63, no. 1, pp. 57-72.

Haun, J. D., and Kent, H. C., 1965, Geologic history of Rocky Mountain region: Am. Assoc. Petroleum Geologist, v. 49, no. 11, pp. 1781-1800.

Hatton, J. W., 1970, Ground water subsidence of a geothermal field during exploitation: U.N. Symposium on the development and utilization of geothermal resources, Pisa, Italy. Proceedings (Geothermics, Spec. Iss., 2), v. 2, pt. 2, pp. 1294-1296.

Hayakawa, M., 1970, The study of underground structure and geophysical state in geothermal areas by seismic exploration: U.N. Symposium on the Development and Utilization of Geothermal Resources, Pisa, Italy, Proceedings (Geothermics, Spec. Iss. 2), v. 2, pt. 1, p. 347.

Hermance, J. F., Thayer, R. E., and Bjornsson, A., 1975, Second U.N. Symposium on the development and utilization of geothermal energy, San Francisco Proceedings. Lawrence Berkeley Lab., Univ. of Calif., p. 1037.

Hoffman, John P., 1975, The seismic history of the Rio Grande rift: U.S. Geol. Survey Earthquake Information Bull., v. 7, no. 3, pp. 8-18.

Hollister, John C., and Weimer, Robert J. (eds.), 1968, Geophysical and geological studies of the relationship between Denver earthquakes and the Rocky Mountain Arsenal well: Colo. Sc. Mines Quarterly, v. 63, no. 1, 251 p.

Hoover, D. B., and Dietrich, J. A., 1969, Seismic activity during the 1968 test pumping at the Rocky Mountain Arsenal disposal well: U.S. Geol. Survey Circ. 613, 35 p.

Jordan, John M., 1974, Geothermal investigations in the San Luis Valley, Colorado: Colo. Sc. Mines, Dept. of Geology, unpub. M.S. thesis, 89 p.

Keller, G. V., 1970, Induction methods in prospecting for hot water: U.N. Symposium on the development and utilization of geothermal resources, Pisa, Italy, Proceedings (Geothermics, Spec. Iss., 2), v. 2, pt. 2, pp. 318-332.

Keller, G. V., 1977, Geophysical Surveys of the Northern San Luis and Arkansas Valleys, Colorado, a report to Colorado Division of Water Resources: Department of Geophysics, Colorado School of Mines, Golden, Colorado.

Keller, G. V., Furgerson, R., Lee, C. Y., Harthill, N., and Jacobson, J. J., 1975, The dipole mapping method: Geophysics, v. 40, no. 3, pp. 451-472.

Klein, John Michael, 1971, Geochemical behavior of silica in the artesian ground water of the closed basin are, San Luis Valley, Colorado: Colo. Sc. Mines, Dept. of Geology, Unpub. M.S. thesis, 121 p.

Kleinkopf, Donald F., and others, 1970, Reconnaissance geophysical studies of the Trinidad Quadrangle, south-central Colorado: U.S. Geol. Survey Prof. Paper 700-B, pp. B78-B85.

Knepper, Daniel H., 1974, Tectonic analysis of the Rio Grande rift zone, central Colorado: Colo. Sc. Mines, Dept. of Geology, unpub Ph.D. dissertation, 237 p.

Knepper, D. H., Jr., 1976, Late Cenozoic structure of the Rio Grande rift zone, central Colorado: Professional Contributions of Colo. School of Mines, Studies in Field Geology, no. 8, pp. 421-430.

Knepper, D. H., and Marrs, R. W., 1971, Geological development of the Bonanza-San Luis Valley-Sangre de Cristo Range area, south-central Colorado: in New Mexico Geol. Soc. 22nd Field Conf., San Luis Basin, Colorado, pp. 249-264.

Kouther, M. J. H., L969, Geology and mineralization of the northwestern part of the Bonanza quadrangle, Chaffee and Saguache Counties, Colorado: Unpublished Colo. School Mines M.Sc. Thesis T-1237, 93p.

Kubota, Katsundo, and Aosaki, Kowashi, 1975, Reinjection of geothermal hot water at the Otake geothermal field: Second U.N. Symposium on the Development and use of geothermal resources, San Francisco, Proceedings. Lawrence Berkeley Lab., Univ. of Calif., pp. 1379-1383.

Larsen, E. S., and Cross, Whitman, 1956, Geology and petrology of the San Juan region southwestern Colorado: U.S. Geol. Survey Prof. Paper 258, 303 p.

Limbach, Fred A., 1975, The geology of the Buena Vista area, Chaffee County, Colorado, unpublished Colo. School of Mines M.Sc. Thesis, 98 p.

Lipman, P. W., Steven, T. A., and Mehnert, H. H., 1970, Volcanic history of the San Juan Mountains, Colorado, as indicated by potassium-argon dating: Geol. Soc. America Bull., v. 81, no. 8, pp. 2329-2352.

Litsey, L. R., 1958, Stratigraphy and structure of the northern Sangre de Cristo Mountains, Colorado: Geol. Soc. America Bull., v. 69, no. 9, pp. 1143-1178.

Lowell, G. R., 1969, Geologic relationships of the Salida area to the Thirtynine Mile volcanic field of central Colorado: unpublished New Mexico Institute of Mining and Technology Ph.D. Thesis, 113 p.

Lowell, G. R., 1971, Cenozoic geology of the Arkansas Hills region of the Southern Mosquito Range, central Colorado: in New Mexico Geol. Soc. 22nd Field Conf., San Luis Basin, Colorado, pp. 209-217.

Mallory, W. W., 1960, Outline of Pennsylvanian stratigraphy of Colorado: in Guide to the geology of Colorado: Geol. Soc. America, R.M.A.G., Colo. Sci. Soc., pp. 23-33.

Marrs, R. W., 1973, Application of remote-sensing techniques to the geology of the Bonanza volcanic center: unpublished Colo. School Mines Ph.D. Thesis T-1531, 279 p.

Mayhew, J. D., 1969, Geology of the eastern part of the Bonanza volcanic field, Saguache County, Colorado: unpublished Colo. School Mines M. Sc. Thesis T-1226, 94 p.

Meidav, T., 1970, Application of electrical resistivity and gravimetry in deep geothermal exploration: U.N. Symposium on the development and utilization of geothermal resources, San Francisco, Proceedings. Lawrence Berkeley Lab., Univ. of Calif., pp. 303-310.

Morris, D., 1975, Quadripole mapping near the Fly Ranch Geothermal Prospect, northwest Nevada: Colorado Sc Mines Thesis T-1699.

Munger, R. D., 1959, Geology of the Spread Eagle Peak Area, Sangre de Cristo Mountains, Colorado: unpublished Univ. of Colorado M.Sc. Thesis, 137 p.

Nathanson, Manuel, and Muffler, L. J. P., 1975, Geothermal resources in hydrothermal convection systems and conduction: Dominated areas; in Assessment of Geothermal Resources of the United States, 1975: U.S. Geol. Survey Circ. 726, pp. 104-121.

Nicolaysen, G. G., 1972, Geology of the Coaldale area, Fremont County, Colorado: unpublished Colo. School Mines M.Sc. Thesis T-1335, 58 p.

Nolting, R. M., III, 1970, Pennsylvanian-Permian stratigraphy and structural geology of the Orient-Cotton Creek area, Sangre de Cristo Mountains, Colorado: unpublished Colo. School Mines M.Sc. Thesis T-1311, 102 p.

Olsen, J. C., 1977, Preliminary geologic map of port of the Pahlone Peak quadrangle, Gunnison, Sagauche and Chaffee Counties, Colorado: U.S. Geol. Survey, open file report 77-325.

Palmason, Gudmundur, 1975, Geophysical methods in geothermal exploration: Second U.N. Symposium on the development and utilization of geothermal resources, San Francisco, Proceedings. Lawrence Berkeley Lab., Univ. of Calif., pp. 1175-1184.

Pearl, Richard Howard, 1972, Geothermal resources of Colorado: Colo. Geol. Survey Special Publication 2, 54 p.

Pearl, Richard Howard, 1975, Hydrological problems associated with developing geothermal energy systems: National Water Well Asso., Ground Water, May-June, 1976 (in press).

Pearl, R. H., and Barrett, J. K., 1975, Collection and collation of geochemical and hydrological parameters of geothermal systems in Colorado, and an evaluation of geothermal reservoir temperatures--a preliminary appraisal: U.S. Geol. Survey, Grant No. 14-08-0001-G221.

Peel, F. A., 1971, New interpretations of Pennsylvanian and Permian stratigraphy and structural history, northern Sangre de Cristo Range, Colorado: unpublished Colo. School Mines M.Sc. Thesis T-1339, 75 p.

Perry, H. A., 1971, Geology of the northern part of the Bonanza volcanic field, Saguache County, Colorado: unpublished Colo. School Mines M.Sc. Thesis T-1362, 72 p.

Pierce, W. H., 1969, Geology and Pennsylvanian-Permian stratigraphy of the Howard area, Fremont County, Colorado: unpublished Colo. School Mines M.Sc. Thesis T-1239, 129 p.

Phillips, E. H., 1974, Hydrogeology of Conejos and Costilla Counties, Colorado: Colorado Division of Water Resources, preliminary reports and maps.

Powell, W. J., 1958, Ground water resources of the San Luis Valley, Colorado: U.S. Geol. Survey Water Supply Paper 1379, 248 p.

Reiter, Marshall, and others, 1975, Terrestrial heat flow along the Rio Grande rift, New Mexico and southern Colorado: Geol. Soc. America Bull., v. 86, pp. 811-818.

Renner, J. L., White, D. E., and Williams, D. L., 1975, hydrothermal convection systems: in Assessment of geothermal resources of the United States, 1975: U.S. Geol. Survey Cir. 726, pp. 5-57.

Romero, John, and Fawcett, D., 1976, Relationship between geothermal resources and ground water in Colorado: Colorado Division of Water Resources, U.S. Geol. Survey grant no. 14-08-0001-G226.

Sanders, Geo. F., 1975, Geology of the Buffalo Peaks, Park and Chaffee Counties, Colorado: Colo. School of Mines M.Sc. Thesis T-1731, 62 p.

Sanders, G. F. Jr., Scott, G. R., and Noeser, 1976, the Buffalo Peaks andesite of central Colorado: U.S. Geol. Survey Bulletin 1405F, pp. 1F-18F.

Scott, G. R., 1970, Quaternary faulting and potential earthquakes in east-central Colorado: U.S. Geol. Survey Prof. Paper 700-C, pp. C11-C18.

Scott, G. R., 1975, Reconnaissance Map of the Buena Vista Quadrangle, Chaffee and Park Counties, Colorado: U.S. Geol. Survey Map MF-657.

Scott, G. R., 1975, Personal communication and unpublished reconnaissance geologic maps of the Villa Grover, Valley View Hot Springs, Moffat North and Mirage Colorado quadrangles.

Scott, G. R., and Taylor, R. B., 1974, Reconnaissance Map of the Electric Peak Quadrangle, Custer and Sagauche Counties, Central Colorado: U.S. Geol. Survey Map MF-628.

Scott, G. R., Van Alstine, R. E., and Sharp, W. N., 1975, Geologic Map of the Poncha Springs Quadrangle, Chaffee County, Colorado: U.S. Geol. Survey Map MG-658.

Siebenthal, C. E., 1910, Geology and water resources of the San Luis Valley, Colorado: U.S. Geol. Survey Water Supply Paper 240, 128 p.

Smith, R. L., and Shaw, H. R., 1975, Igneous-related geothermal systems: in Assessment of geothermal resources of the United States--1975: U.S. Geol. Survey Circ. 726, pp. 58-83.

Stevens, D. N., 1951, Cambrian and Lower Ordovocian stratigraphy of central Colorado: in Lower and Middle Paleozoic rocks of Colorado: Rocky Mtn. Assoc. Geologists Guidebook, 12th Ann. Field Conf., pp. 7-15.

Steven, T. A., 1973, Mid-Tertiary volcanic field in the southern Rocky Mountains (abs): Geol. Soc. America Abstracts with Programs for 1973, v. 5, no. 6, p. 516.

Steven, T. A., and Epis, R. C., 1968, Oligocene volcanism in south-central Colorado: Colorado School Mines Quart., v. 63, no. 3, pp. 241-358.

Steven, T. A., and others, 1972, Upper Cretaceous and Cenozoic igneous rocks: in Geologic atlas of the Rocky Mountain region; Rocky Mountain Asso. Geologists, Denver, Colorado, pp. 229-232.

Stilwell, Wilfred B., and others, 1975, Ground movement in New Zealand geothermal fields: Second U.N. Symposium on the development and utilization of geothermal resources, San Francisco, Proceedings. Lawrence Berkeley Lab., Univ. of Calif., pp. 1427-1434.

Stoughton, D. D. H., 1977, Interpretation of seismic reflection data from the San Luis Valley, south-central Colorado: Colo. School of Mines, unpublished M.Sc. thesis, T1960, 100 p.

Taylor, R. B., Scott, G. R., and Wobus, R. A., 1975, Reconnaissance Geologic Map of the Howard Quadrangle, Central Colorado: U.S. Geol. Survey Map I-892.

Todd, David Keith, 1959, Ground Water Hydrology: John Wiley & Sons, N.Y.

Tweto, Ogden, 1974, Reconnaissance geologic map of the Fairplay west, Mount Sherman, South Peak and Jones H.4 7-1/2 minute quadrangles, Park, Lake and Chaffee Counties, Colorado: U.S. Geol. Survey, Miscellaneous Field Studies, Map MF-555.

Tweto, Ogden, 1977, Nomenclature of the Precambrian rocks in Colorado: U.S. Geol. Survey Bull., 1422-D, 22 p.

U.S. Bureau of Reclamation, 1969, Report on the upper Arkansas River basin: U.S. Bureau Reclamation, Fryingpan-Arkansas Project Office, Pueblo, Colo., pp. 83-85.

U.S. Bureau of Reclamation, 1971, 1972, 1974, several special reports on geothermal investigations at the East Mesa test site, Imperial Valley, Calif. U.S. Bureau Reclamation, Boulder City, Nev.

U.S. Geological Survey, 1965, 1966, Quality of surface water of the United States: U.S. Geol. Survey Water Supply Paper 1964, 1994, pts. 7, 8.

U.S. Public Health Service, 1962, Drinking Water Standards: U.S. Public Health Service Pub. 956.

Van Alstine, R. E., 1968, Tertiary trough between the Arkansas and San Luis Valleys, Colorado: U.S. Geol. Survey Prof. Paper 600-C, pp. C158-C160.

Van Alstine, R. E., 1969, Geology and mineral deposits of the Poncha Springs NE quadrangle, Chaffee County, Colorado: U.S. Geol. Survey Prof. Paper 626, 52 p.

Van Alstine, R. E., 1970, Allochthonous Paleozoic blocks in the Tertiary San Luis-Upper Arkansas graben, Colorado: U.S. Geol. Survey Prof. Paper 700-B, pp. B43-B51.

Van Alstine, R. E., 1974, Geology and Mineral deposits of the Poncha Springs SE Quadrangle, Chaffee County, Colorado: U.S. Geol. Survey Prof. Paper 820, p. 19.

White, D. E., and Williams, D. L., 1975, Assessment of geothermal resources of the United States--1975: U.S. Geol. Survey Cir. 726, pp. 147-155.

Whiteford, Peter C., 1975, Assessment of the audio-magentotelluric method for geothermal resistivity surveying: Second U.N. Symposium on the development and utilization of geothermal energy, San Francisco, Proceedings. Lawrence Berkeley Lab., Univ. of Calif., pp. 1255-1261.

Wilson, Woodrow W., 1965, Pumping tests in Colorado: U.S. Geol. Survey, Colorado Ground Water Circular 11.

Winograd, I. J., 1959, Ground water conditions and geology of Sunshine Valley and western Taos County, New Mexico: New Mexico State Engineer's Office, Tech. Rept. 12, 44 p.

Wychgram, D. C., 1972, Geology of the Hayden Pass-Orient mine area, northern Sangre de Cristo Mountains, Colorado: A geologic remote sensing evaluation: unpublished Colo. School Mines M.Sc. Thesis T-1406, 130 p.

Zohdy, Adel A., and others, 1971, Resistivity sections, upper Arkansas River basin, Colorado: U.S. Geol. Survey open file report 71002, 16 p.

Zohdy, A. A. R., Eaton, G. P., and Mabey, D. R., 1974, Application fo surface geophysics to ground water investigations: Techniques of water resources investigations of the U.S. Geological Survey, Book 2, Chap. Dl.

APPENDIX

Results of water quality analyses of surface water from major streams within the KGRA.

Arkansas River 2.0 miles (3.2 km) north of Nathrop, (Chaffee County) Colorado, August 19, 1976.

ALK•TOT (AS CACO3)	MG/L	48	PHOS ORTHO DIS AS P	MG/L	0.00
BICARBONATE	MG/L	58	PHOSPHATE DIS ORTHO	MG/L	0.00
BORON DISSOLVED	UG/L	20	POTASSIUM DISS	MG/L	0.9
CALCIUM DISS	MG/L	18	RESIDUE DIS CALC SUM	MG/L	80
CHLORIDE DISS	MG/L	1.2	RESIDUE DIS TON/AFT		0.11
FLUORIDE DISS	MG/L	0.3	SAR		0.2
HARDNESS NONCARB	MG/L	13	SILICA DISSOLVED	MG/L	7.0
HARDNESS TOTAL	MG/L	61	SODIUM DISS	MG/L	3.0
IRON DISSOLVED	UG/L	20	SODIUM PERCENT		10
MAGNESIUM DISS	MG/L	3.9	SP. CONDUCTANCE FLD		130
MANGANESE DISSOLVED	UG/L	40	SP. CONDUCTANCE LAB		130
NO2+NO3 AS N DISS	MG/L	0.09	SULFATE DISS	MG/L	17
			WATER TEMP (DEG C)		14.3

CATIONS	(MG/L)	(MEQ/L)	ANIONS	(MG/L)	(MEQ/L)
CALCIUM DISS	18	0.899	BICARBONATE	58	0.951
MAGNESIUM DISS	3.9	0.321	CHLORIDE DISS	1.2	0.034
POTASSIUM DISS	0.9	0.024	FLUORIDE DISS	0.3	0.016
SODIUM DISS	3.0	0.131	SULFATE DISS	17	0.354
			NO2+NO3 AS N D	0.09	0.007
TOTAL		1.373	TOTAL		1.361

PERCENT DIFFERENCE = 0.44

Arkansas River at Brown's Canyon Bridge, Chaffee County, Colorado. August 19, 1976.

ALK•TOT (AS CACO3)	MG/L	58	PHOS ORTHO DIS AS P	MG/L	0.00
BICARBONATE	MG/L	71	PHOSPHATE DIS ORTHO	MG/L	0.00
BORON DISSOLVED	UG/L	20	POTASSIUM DISS	MG/L	1.0
CALCIUM DISS	MG/L	20	RESIDUE DIS CALC SUM	MG/L	94
CHLORIDE DISS	MG/L	1.1	RESIDUE DIS TON/AFT		0.13
FLUORIDE DISS	MG/L	0.4	SAR		0.2
HARDNESS NONCARB	MG/L	9	SILICA DISSOLVED	MG/L	8.2
HARDNESS TOTAL	MG/L	67	SODIUM DISS	MG/L	4.3
IRON DISSOLVED	UG/L	30	SODIUM PERCENT		12
MAGNESIUM DISS	MG/L	4.1	SP. CONDUCTANCE FLD		155
MANGANESE DISSOLVED	UG/L	40	SP. CONDUCTANCE LAB		149
NO2+NO3 AS N DISS	MG/L	0.12	SULFATE DISS	MG/L	19
			WATER TEMP (DEG C)		12.9

CATIONS	(MG/L)	(MEQ/L)	ANIONS	(MG/L)	(MEQ/L)
CALCIUM DISS	20	0.998	BICARBONATE	71	1.164
MAGNESIUM DISS	4.1	0.338	CHLORIDE DISS	1.1	0.032
POTASSIUM DISS	1.0	0.026	FLUORIDE DISS	0.4	0.022
SODIUM DISS	4.3	0.188	SULFATE DISS	19	0.396
			NO2+NO3 AS N D	0.12	0.009
TOTAL		1.548	TOTAL		1.620

PERCENT DIFFERENCE = -2.27

Arkansas River 4.0 miles (6.4 km) north of Poncha Springs (Chaffee County) Colorado. August 19, 1976

ALK,TOT (AS CACO3)	MG/L	61	PHOS ORTHO DIS AS P	MG/L	0.00
BICARBONATE	MG/L	74	PHOSPHATE DIS ORTHO	MG/L	0.00
BORON DISSOLVED	UG/L	20	POTASSIUM DISS	MG/L	1.0
CALCIUM DISS	MG/L	21	RESIDUE DIS CALC SUM	MG/L	95
CHLORIDE DISS	MG/L	1.1	RESIDUE DIS TON/AFT		0.13
FLUORIDE DISS	MG/L	0.4	SAR		0.2
HARDNESS NONCARB	MG/L	8	SILICA DISSOLVED	MG/L	8.3
HARDNESS TOTAL	MG/L	69	SODIUM DISS	MG/L	4.2
IRON DISSOLVED	UG/L	0	SODIUM PERCENT		12
MAGNESIUM DISS	MG/L	4.0	SP. CONDUCTANCE FLD		160
MANGANESE DISSOLVED	UG/L	40	SP. CONDUCTANCE LAB		154
NO2+NO3 AS N DISS	MG/L	0.13	SULFATE DISS	MG/L	18
			WATER TEMP (DEG C)		11.6

CATIONS	(MG/L)	(MEQ/L)	ANIONS	(MG/L)	(MEQ/L)
CALCIUM DISS	21	1.048	BICARBONATE	74	1.213
MAGNESIUM DISS	4.0	0.330	CHLORIDE DISS	1.1	0.032
POTASSIUM DISS	1.0	0.026	FLUORIDE DISS	0.4	0.022
SODIUM DISS	4.2	0.183	SULFATE DISS	18	0.375
			NO2+NO3 AS N D	0.13	0.010
	TOTAL	1.585		TOTAL	1.649

PERCENT DIFFERENCE = -1.97

Chalk Creek 1.0 miles (1.6 km) west of its confluence with the Arkansas River, Chaffee County, Colorado. August 19, 1976.

ALK,TOT (AS CACO3)	MG/L	48	PHOS ORTHO DIS AS P	MG/L	0.00
BICARBONATE	MG/L	58	PHOSPHATE DIS ORTHO	MG/L	0.00
BORON DISSOLVED	UG/L	20	POTASSIUM DISS	MG/L	0.8
CALCIUM DISS	MG/L	19	RESIDUE DIS CALC SUM	MG/L	87
CHLORIDE DISS	MG/L	0.8	RESIDUE DIS TON/AFT		0.12
FLUORIDE DISS	MG/L	0.9	SAR		0.3
HARDNESS NONCARB	MG/L	6	SILICA DISSOLVED	MG/L	11
HARDNESS TOTAL	MG/L	53	SODIUM DISS	MG/L	5.8
IRON DISSOLVED	UG/L	90	SODIUM PERCENT		19
MAGNESIUM DISS	MG/L	1.4	SP. CONDUCTANCE FLD		122
MANGANESE DISSOLVED	UG/L	30	SP. CONDUCTANCE LAB		132
NO2+NO3 AS N DISS	MG/L	0.09	SULFATE DISS	MG/L	18
			WATER TEMP (DEG C)		11.9

CATIONS	(MG/L)	(MEQ/L)	ANIONS	(MG/L)	(MEQ/L)
CALCIUM DISS	19	0.949	BICARBONATE	58	0.951
MAGNESIUM DISS	1.4	0.116	CHLORIDE DISS	0.8	0.023
POTASSIUM DISS	0.8	0.021	FLUORIDE DISS	0.9	0.048
SODIUM DISS	5.8	0.253	SULFATE DISS	18	0.375
			NO2+NO3 AS N D	0.09	0.007
	TOTAL	1.336		TOTAL	1.402

PERCENT DIFFERENCE = -2.40

Cottonwood Creek 3.0 miles (4.8 km) east of Cottonwood Hot Springs, Chaffee County, Colorado. August 19, 1976.

ALK,TOT (AS CACO3)	MG/L	39	PHOS ORTHO DIS AS P	MG/L	0.00
BICARBONATE	MG/L	48	PHOSPHATE DIS ORTHO	MG/L	0.00
BORON DISSOLVED	UG/L	20	POTASSIUM DISS	MG/L	0.9
CALCIUM DISS	MG/L	14	RESIDUE DIS CALC SUM	MG/L	58
CHLORIDE DISS	MG/L	0.6	RESIDUE DIS TON/AFT		0.08
FLUORIDE DISS	MG/L	0.2	SAR		0.2
HARDNESS NONCARB	MG/L	2	SILICA DISSOLVED	MG/L	6.7
HARDNESS TOTAL	MG/L	41	SODIUM DISS	MG/L	2.6
IRON DISSOLVED	UG/L	40	SODIUM PERCENT		12
MAGNESIUM DISS	MG/L	1.5	SP. CONDUCTANCE FLD		90
MANGANESE DISSOLVED	UG/L	0	SP. CONDUCTANCE LAB		92
NO2+NO3 AS N DISS	MG/L	0.07	SULFATE DISS	MG/L	7.3
			WATER TEMP (DEG C)		12.0

CATIONS	(MG/L)	(MEQ/L)	ANIONS	(MG/L)	(MEQ/L)
CALCIUM DISS	14	0.699	BICARBONATE	48	0.787
MAGNESIUM DISS	1.5	0.124	CHLORIDE DISS	0.6	0.017
POTASSIUM DISS	0.9	0.024	FLUORIDE DISS	0.2	0.011
SODIUM DISS	2.6	0.114	SULFATE DISS	7.3	0.152
			NO2+NO3 AS N D	0.07	0.005
TOTAL		0.958	TOTAL		0.971

PERCENT DIFFERENCE = -0.68

Kerber Creek at Villa Grove (Saguache County) Colorado. August 18, 1976.

ALK,TOT (AS CACO3)	MG/L	110	PHOS ORTHO DIS AS P	MG/L	0.01
BICARBONATE	MG/L	134	PHOSPHATE DIS ORTHO	MG/L	0.03
BORON DISSOLVED	UG/L	20	POTASSIUM DISS	MG/L	1.4
CALCIUM DISS	MG/L	38	RESIDUE DIS CALC SUM	MG/L	189
CHLORIDE DISS	MG/L	4.2	RESIDUE DIS TON/AFT		0.26
FLUORIDE DISS	MG/L	0.5	SAR		0.5
HARDNESS NONCARB	MG/L	23	SILICA DISSOLVED	MG/L	17
HARDNESS TOTAL	MG/L	130	SODIUM DISS	MG/L	12
IRON DISSOLVED	UG/L	20	SODIUM PERCENT		16
MAGNESIUM DISS	MG/L	9.2	SP. CONDUCTANCE FLD		300
MANGANESE DISSOLVED	UG/L	360	SP. CONDUCTANCE LAB		301
NO2+NO3 AS N DISS	MG/L	0.08	SULFATE DISS	MG/L	40
			WATER TEMP (DEG C)		8.8

CATIONS	(MG/L)	(MEQ/L)	ANIONS	(MG/L)	(MEQ/L)
CALCIUM DISS	38	1.897	BICARBONATE	134	2.197
MAGNESIUM DISS	9.2	0.757	CHLORIDE DISS	4.2	0.119
POTASSIUM DISS	1.4	0.036	FLUORIDE DISS	0.5	0.027
SODIUM DISS	12	0.522	SULFATE DISS	40	0.833
			NO2+NO3 AS N D.	0.08	0.006
TOTAL		3.211	TOTAL		3.180

PERCENT DIFFERENCE = 0.49

GEOLOGIC MAP OF THE BUENA VISTA QUADRANGLE SOUTH CENTRAL COLORADO

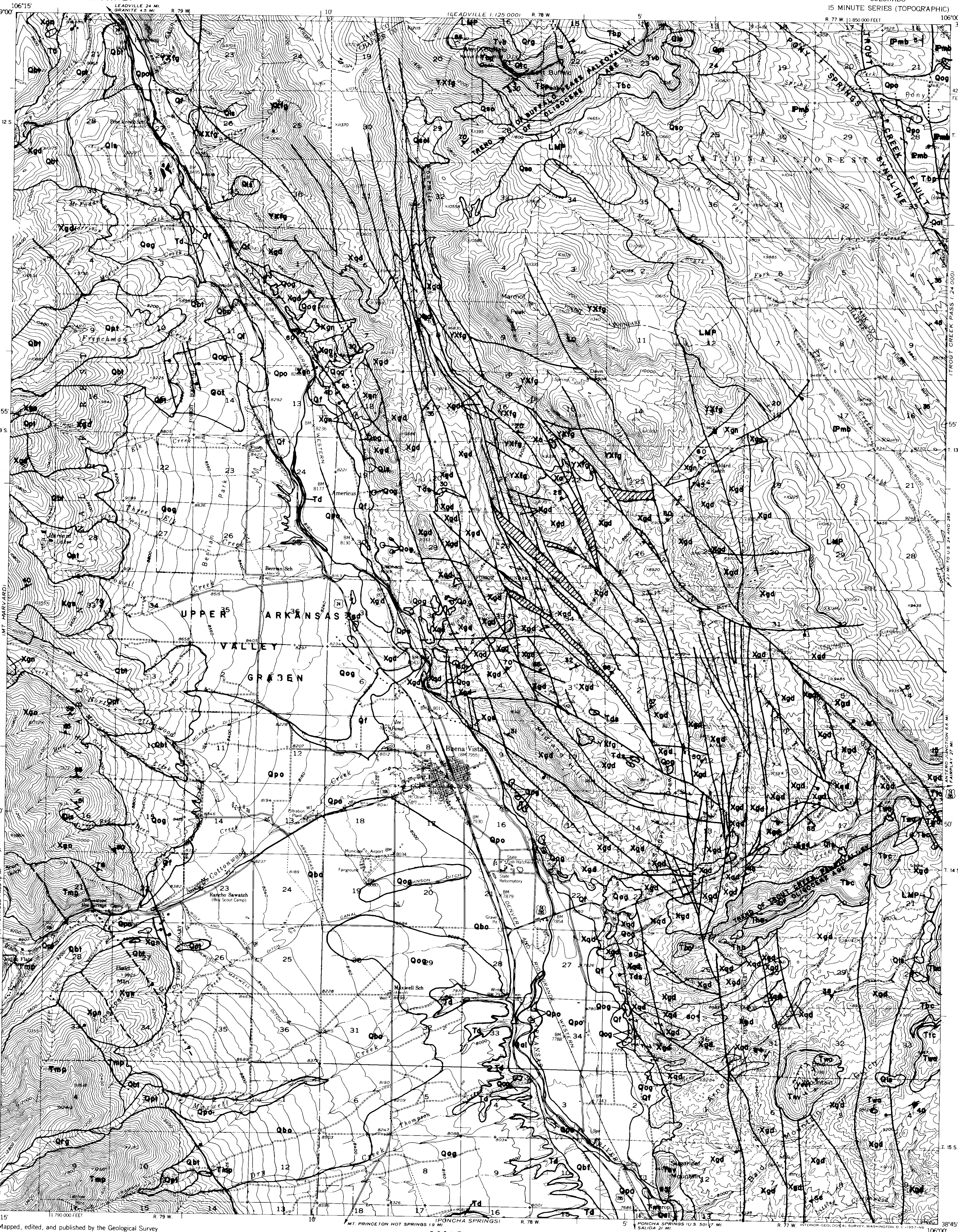
PLATE I

UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

BUENA VISTA QUADRANGLE
COLORADO
15 MINUTE SERIES (TOPOGRAPHIC)

(MT ELBERT)

(GARO)
1:24 000



(GARFIELD)

Mapped, edited, and published by the Geological Survey

Control by USGS and USC&GS

Topography from aerial photographs by multiplex methods
Aerial photographs taken 1953. Field check 1955

Polyconic projection. 1927 North American datum
10,000-foot grid based on Colorado coordinate system, central zone

Dashed land lines indicate approximate locations
Certain land lines are omitted in Ts. 12, 13, 14, and 15 S.-R. 79 W. because of insufficient data

TRUE NORTH
MAGNETIC NORTH
14°
APPROXIMATE MEAN DECLINATION, 1955

SCALE 1:64000

1 0 1 2 3 4 MILES

3000 0 3000 6000 9000 12000 15000 18000 21000 FEET

1 .5 0 1 2 3 4 5 KILOMETERS

CONTOUR INTERVAL 80 FEET
DATUM IS MEAN SEA LEVEL

COLORADO

QUADRANGLE LOCATION

ROAD CLASSIFICATION

Medium-duty — Light-duty —

Unimproved dirt ==========

U.S. Route — State Route

(CAMERON PEAK)

BUENA VISTA, COLO.
N3845—W10600/15
formerly (Buena Vista 1, Colo.)

1955

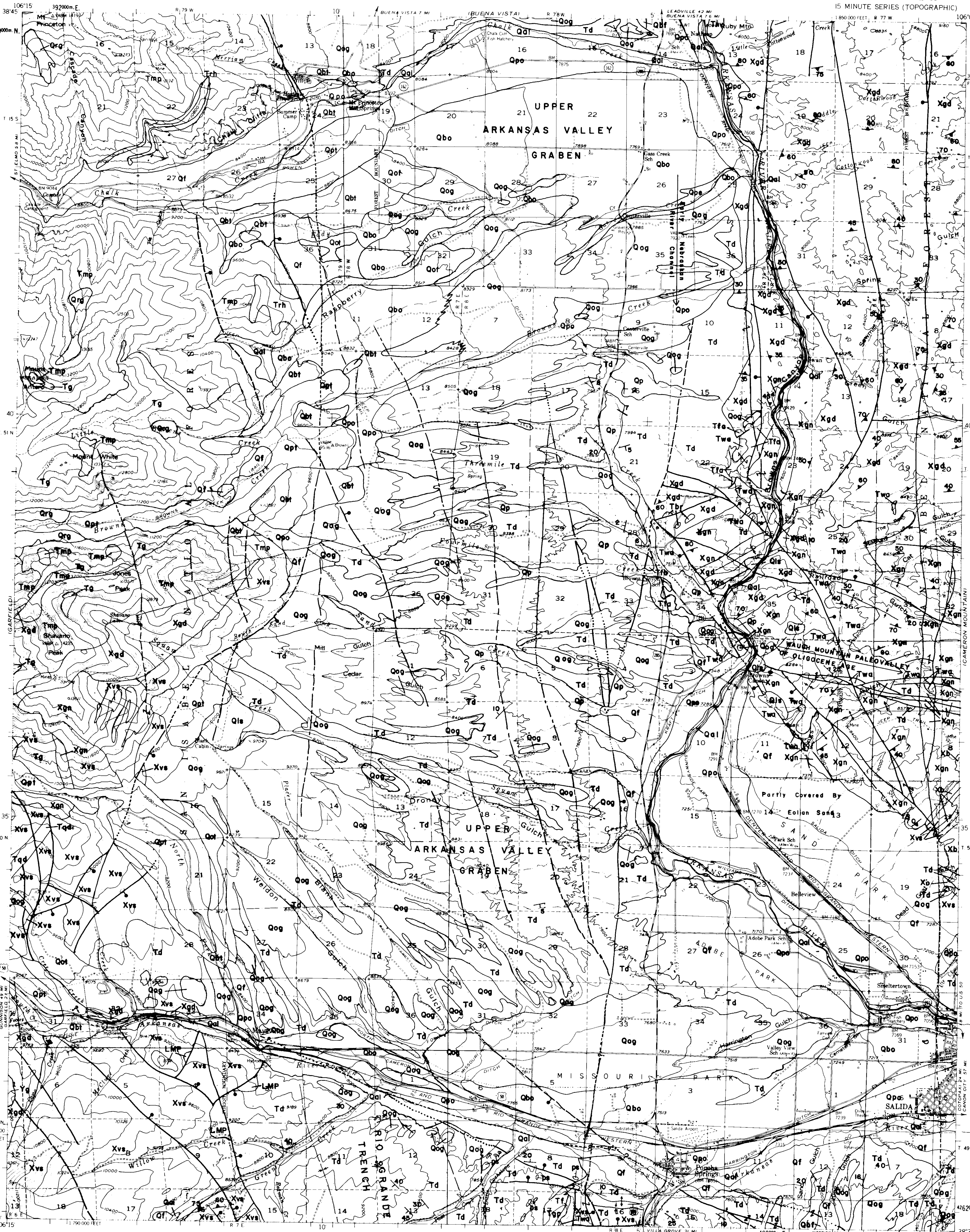
Colorado Division of Water Resources
1977

GEOLOGIC MAP OF THE PONCHA SPRINGS QUADRANGLE SOUTH CENTRAL COLORADO

UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

PLATE 2

PONCHA SPRINGS QUADRANGLE
COLORADO-CHAFFEE CO.
15 MINUTE SERIES (TOPOGRAPHIC)



Mapped, edited, and published by the Geological Survey

Control by USGS and USC&GS

Topography from aerial photographs by photogrammetric methods
Aerial photographs taken 1953. Field check 1956

Polyconic projection. 1927 North American datum
10,000-foot grid based on Colorado coordinate system, central zone
1000-meter Universal Transverse Mercator grid ticks, zone 13, shown in blue

Red tint indicates areas in which only landmark buildings are shown

Dashed land lines indicate approximate locations
Certain land lines are omitted in Ts. 50 and 51 N., R. 7 E. and T. 15 S., R. 79 W. because of insufficient data
Ts. 49, 50, and 51 N., Rs. 6, 7, 8 and 9 E. are based on the New Mexico Principal Meridian
T. 15 S., Rs. 77, 78 and 79 W. are based on the Sixth Principal Meridian

TRUE NORTH — MAGNETIC NORTH — 14°
APPROXIMATE MEAN DECLINATION, 1956

SCALE 1:64000

1 0 1 2 3 4 MILES
3000 0 3000 6000 9000 12000 15000 18000 21000 FEET
1 .5 0 1 2 3 4 5 KILOMETERS

CONTOUR INTERVAL 80 FEET
DATUM IS MEAN SEA LEVEL

COLORADO
QUADRANGLE LOCATION

ROAD CLASSIFICATION
Medium duty — Light duty
Unimproved dirt
U.S. Route — State Route

PONCHA SPRINGS, COLO.
N3830—W10600/15
1956

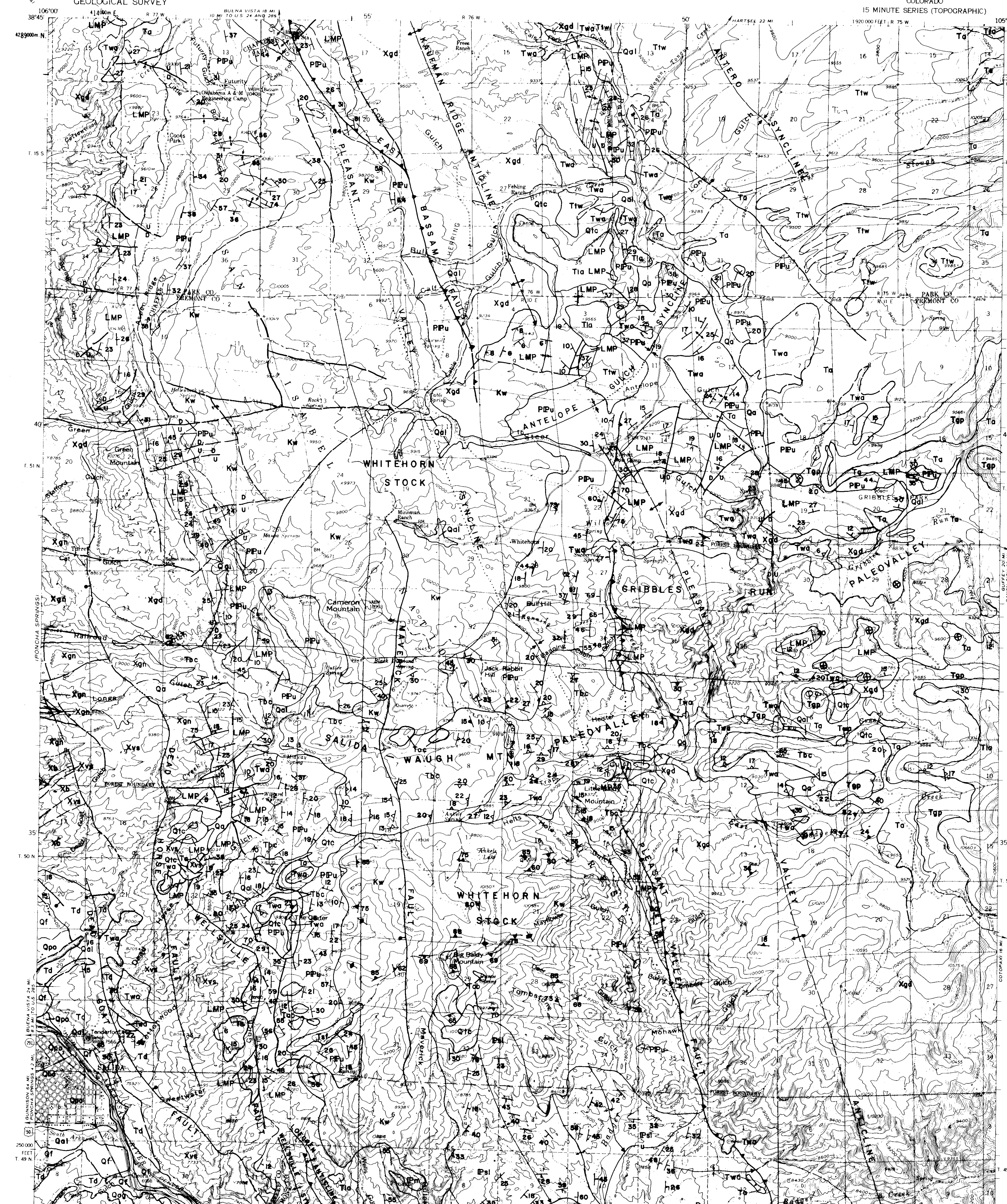
Colorado Division of Water Resources
1977

GEOLOGIC MAP OF THE CAMERON MOUNTAIN QUADRANGLE SOUTH CENTRAL COLORADO

UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

PLATE 3

CAMERON MOUNTAIN QUADRANGLE
COLORADO
15 MINUTE SERIES (TOPOGRAPHIC)



SCALE 1:64000

1 ½ 0 1 2 3 4 MILES

3000 0 3000 6000 9000 12000 15000 18000 21000 FEET

1 .5 0 1 2 3 4 5 KILOMETERS

CONTOUR INTERVAL 40 FEET
DATUM IS MEAN SEA LEVEL

Mapped, edited, and published by the Geological Survey

Control by USGS and USC&GS

Topography from aerial photographs by photogrammetric methods
Aerial photographs taken 1953. Field check 1956

Polyconic projection. 1927 North American datum
10,000-foot grid based on Colorado coordinate system, central zone
1000-meter Universal Transverse Mercator grid ticks, zone 13, shown in blue

Red tint indicates areas in which only landmark buildings are shown

Land lines in Ts. 49, 50 and 51 N.—Rs. 9, 10 and 11 E. based on the New Mexico Principal Meridian
Land lines in T.15 S.—Rs. 75, 76 and 77 W. based on the Sixth Principal Meridian
Dashed land lines indicate approximate locations

Unchecked elevations are shown in brown

14°
TRUE NORTH
MAGNETIC NORTH
APPROXIMATE MEAN DECLINATION, 1956

Colorado Division of Water Resources
1977

COLORADO
QUADRANGLE LOCATION

ROAD CLASSIFICATION

Medium-duty — Light-duty
Unimproved dirt
U.S. Route — State Route

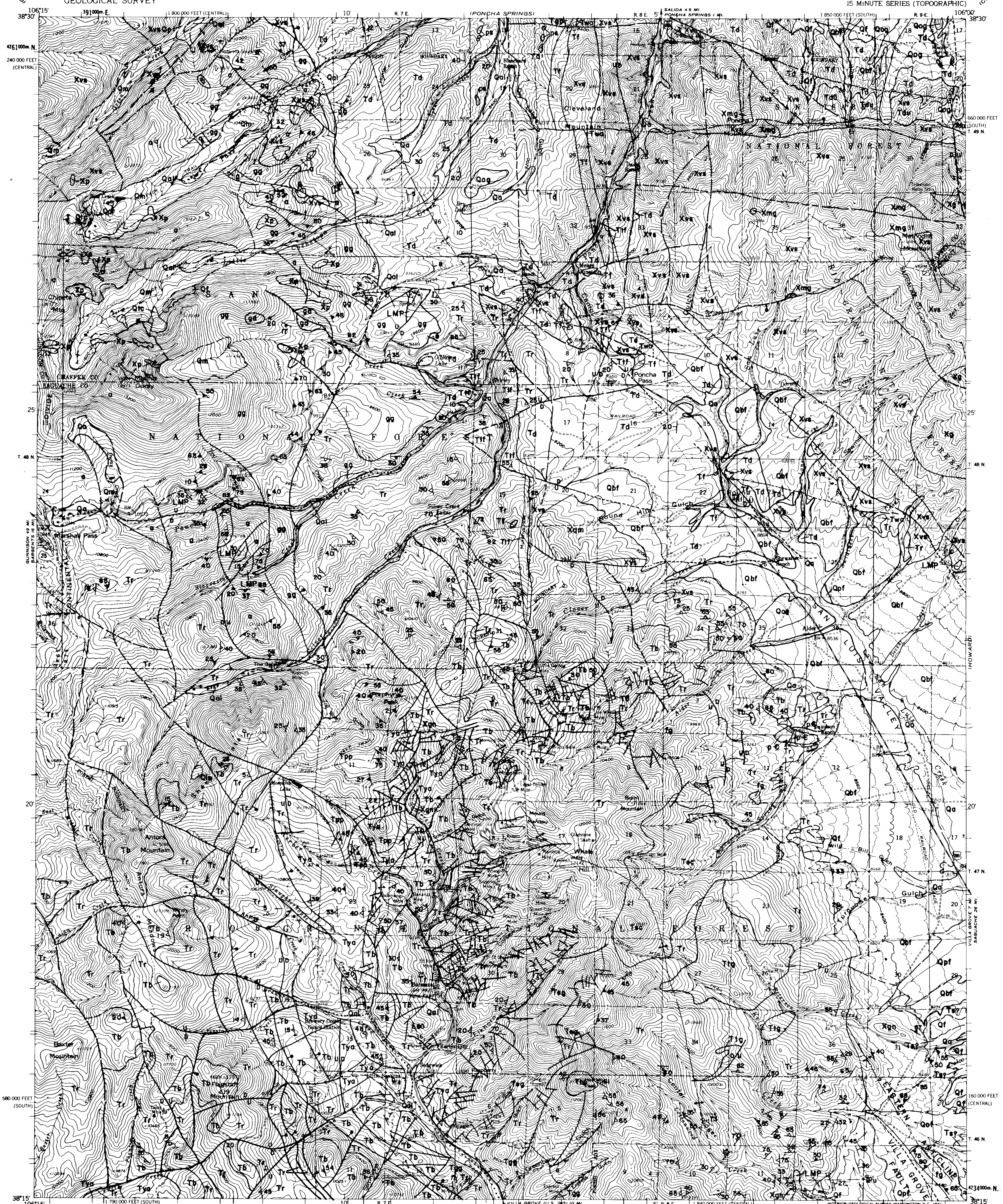
CAMERON MOUNTAIN, COLO.
N3830—W10545/15
1956

GEOLOGIC MAP OF THE BONANZA QUADRANGLE SOUTH CENTRAL COLORADO

UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

PLATE 4

BONANZA QUADRANGLE
COLORADO
15 MINUTE SERIES (TOPOGRAPHIC)



Mapped, edited, and published by the Geological Survey
Control by USGS and USC&GS
Topography from aerial photographs by photogrammetric methods
Aerial photographs taken 1954. Field check 1959
Polyconic projection. 1927 North American datum
10,000 foot grid based on Colorado coordinate system, south and central zones
1000-meter Universal Transverse Mercator grid ticks, zone 13, shown in blue
Dashed land lines indicate approximate locations
Land lines omitted in T. 48 N., R. 7 E. and in parts of Ts. 46 and 49 N., R. 7 E. because of insufficient data.

APPROX MATE MEAN DECLINATION, 1959

SCALE 1:64000

CONTOUR INTERVAL 80 FEET
DATUM IS MEAN SEA LEVEL

ROAD CLASSIFICATION
Medium-duty —— Light-duty ——
Unimproved dirt - - - -
U.S. Route

QUADRANGLE LOCATION

BONANZA, COLO.
N3815—W10600/15
1959

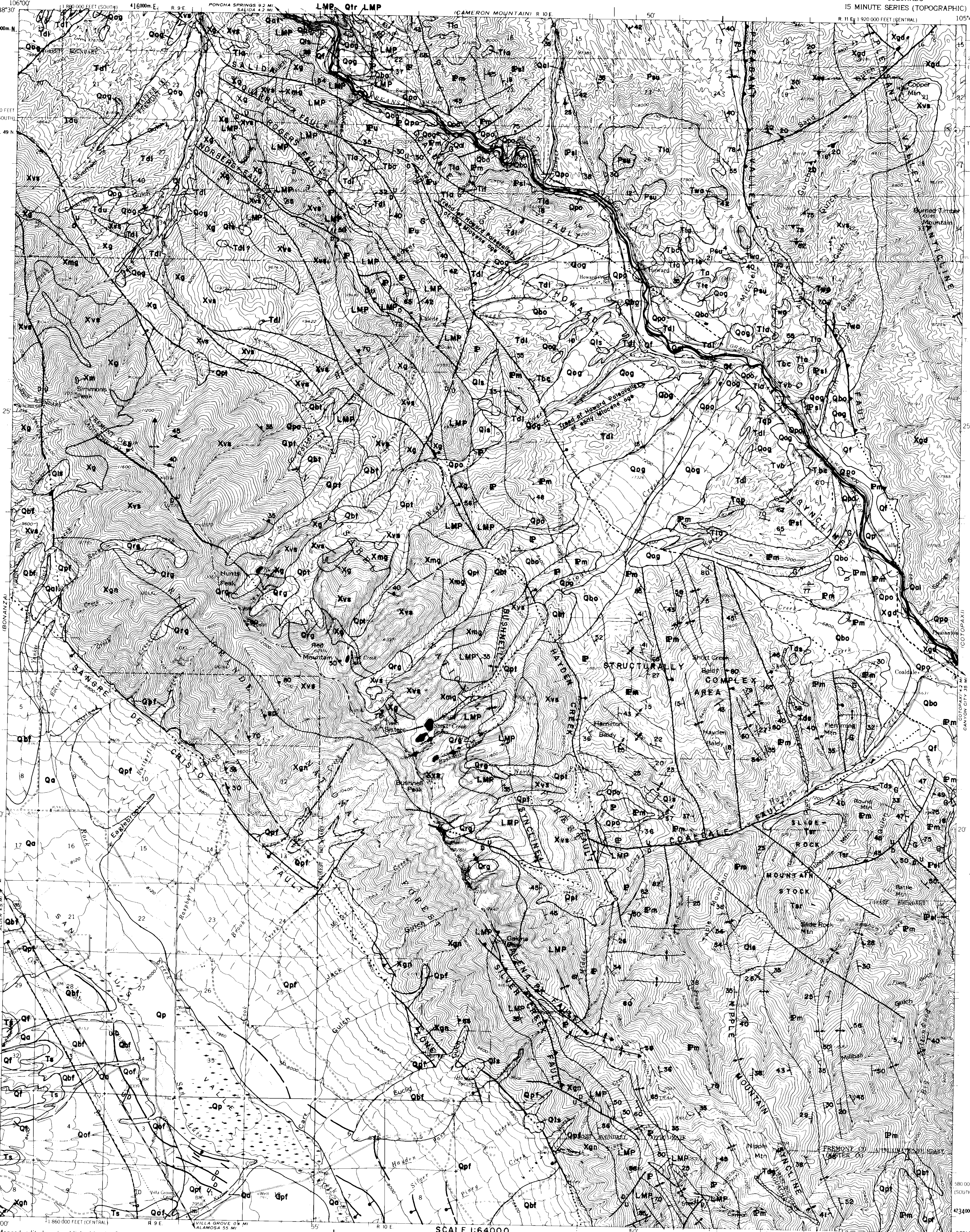
Colorado Division of Water Resources
1977

GEOLOGIC MAP OF THE HOWARD QUADRANGLE SOUTH CENTRAL COLORADO

UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

PLATE 5

HOWARD QUADRANGLE
COLORADO
15 MINUTE SERIES (TOPOGRAPHIC)



Mapped, edited, and published by the Geological Survey
Control by USGS and USC&GS

Topography from aerial photographs by photogrammetric methods
Aerial photographs taken 1954. Field check 1959

Polyconic projection. 1927 North American datum
10,000 foot grid based on Colorado coordinate system, central and south zones
1000-meter Universal Transverse Mercator grid ticks, zone 13, shown in blue

Dashed land lines indicate approximate locations
Land lines omitted in Ts. 46 and 47 N., Rs. 10 and 11 E., T. 48 N., R. 9 E. and in parts of T. 46 N., R. 10 E. and T. 48 N., Rs. 10 and 11 E. because of insufficient data

APPROXIMATE MEAN DECLINATION, 1959

CONTOUR INTERVAL 80 FEET
DOTTED LINES REPRESENT 40-FOOT CONTOURS
DATUM IS MEAN SEA LEVEL

ROAD CLASSIFICATION
Medium-duty — Light-duty
Unimproved dirt
U.S. Route

QUADRANGLE LOCATION

Colorado Division of Water Resources
1977

HOWARD, COLO.
N3815—W10545/15
1959

GEOLOGIC MAP OF THE HOWARD QUADRANGLE SOUTH CENTRAL COLORADO

STRUCTURAL INTERPRETATION
AFTER STOUGHTON, 1977.
BASED ON SEISMIC SURVEY.

PLATE 5A

UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

HOWARD QUADRANGLE
COLORADO
15 MINUTE SERIES (TOPOGRAPHIC)

Mapped, edited, and published by the Geological Survey

Control by USGS and USC&GS

Topography from aerial photographs by photogrammetric methods
Aerial photographs taken 1954. Field check 1959

Polyconic projection. 1927 North American datum
10,000 foot grid based on Colorado coordinate system,
central and south zones
1000 meter Universal Transverse Mercator grid ticks,
zone 13, shown in blue

Dashed land lines indicate approximate locations
Land lines omitted in Ts. 46 and 47 N., Rs. 10 and 11 E.,
T. 48 N., R. 9 E. and in parts of T. 46 N., R. 10 E. and
T. 48 N., Rs. 10 and 11 E. because of insufficient data

APPROXIMATE MEAN
DECLINATION, 1959

ROAD CLASSIFICATION
Medium-duty — Light-duty
Unimproved dirt
U.S. Route

COLORADO
QUADRANGLE LOCATION

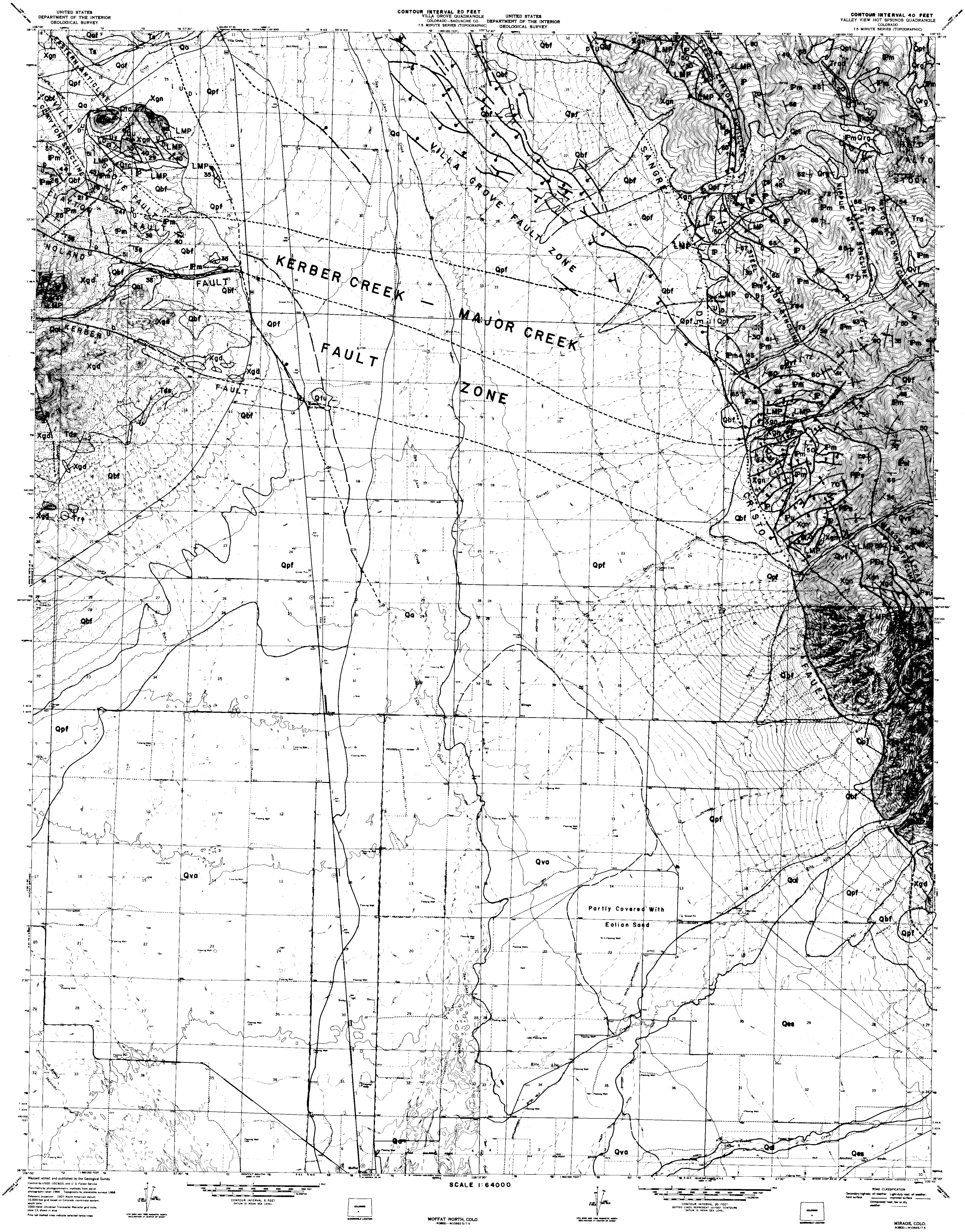
Colorado Division of Water Resources
1977

HOWARD, COLO.
N3815—W10545/15

1959

GEOLOGIC MAP OF THE VILLA GROVE-MOFFAT AREA SOUTH CENTRAL COLORADO

PLATE 6

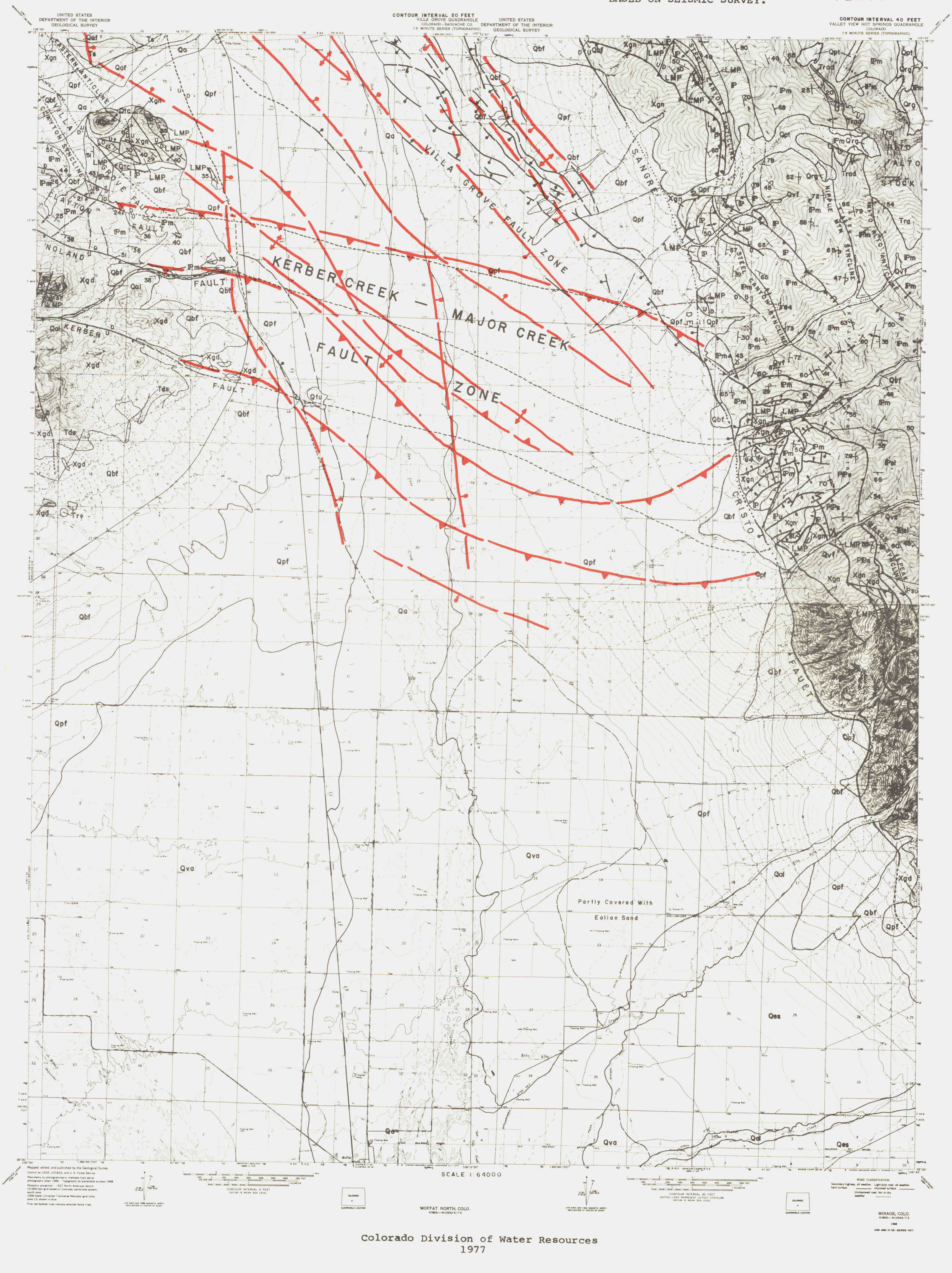


Colorado Division of Water Resources
1977

GEOLOGIC MAP OF THE
VILLA GROVE-MOFFAT AREA
SOUTH CENTRAL COLORADO

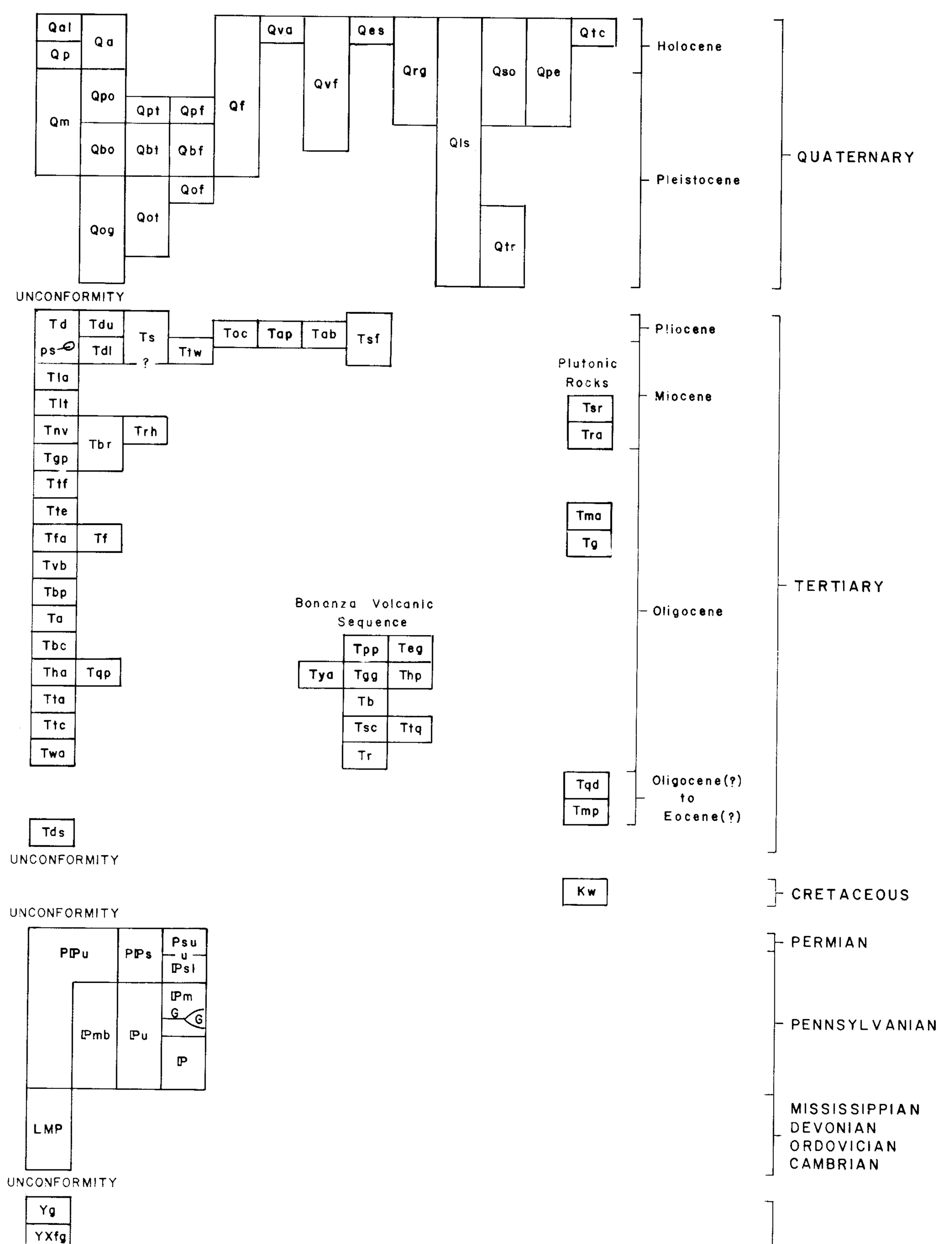
STRUCTURAL INTERPRETATION
AFTER STOUGHTON, 1977.
BASED ON SEISMIC SURVEY.

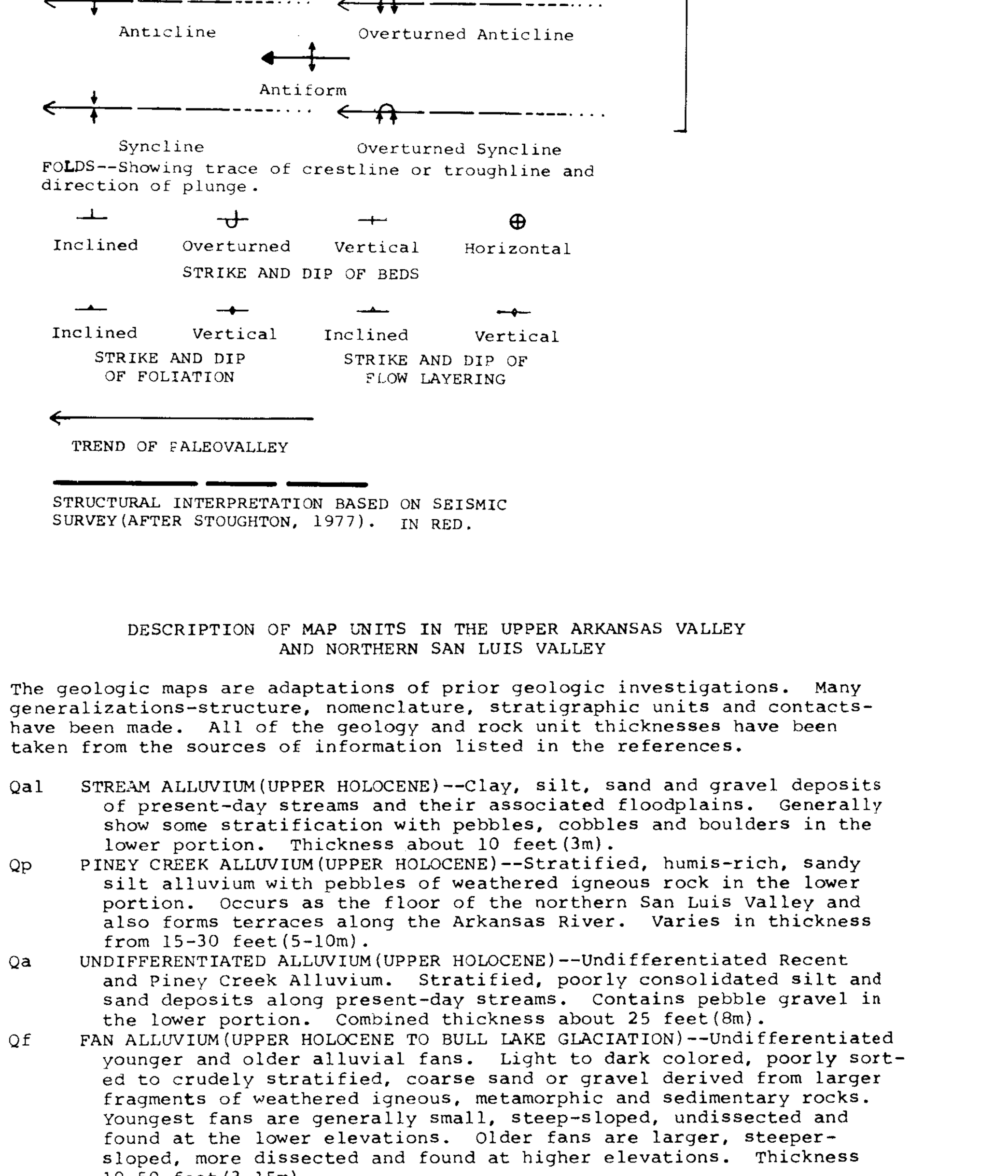
PLATE 6A



Colorado Division of Water Resources
1977

CORRELATION OF MAP UNITS





DESCRIPTION OF MAP UNITS IN THE UPPER ARKANSAS VALLEY AND NORTHERN SAN LUIS VALLEY

The geologic maps are adaptations of prior geologic investigations. Many generalizations-structure, nomenclature, stratigraphic units and contacts-have been made. All of the geology and rock unit thicknesses have been taken from the sources of information listed in the references.

Qal STREAM ALLUVIUM(UPPER HOLOCENE)--Clay, silt, sand and gravel deposits of present-day streams and their associated floodplains. Generally show some stratification with pebbles, cobbles and boulders in the lower portion. Thickness about 10 feet(3m).

Qp PINEY CREEK ALLUVIUM(UPPER HOLOCENE)--Stratified, humis-rich, sandy silt alluvium with pebbles of weathered igneous rock in the lower portion. Occurs as the floor of the northern San Luis Valley and also forms terraces along the Arkansas River. Varies in thickness from 15-30 feet(5-10m).

Qa UNDIFFERENTIATED ALLUVIUM(UPPER HOLOCENE)--Undifferentiated Recent and Piney Creek Alluvium. Stratified, poorly consolidated silt and sand deposits along present-day streams. Contains pebble gravel in the lower portion. Combined thickness about 25 feet(8m).

Qf FAN ALLUVIUM(UPPER HOLOCENE TO BULL LAKE GLACIATION)--Undifferentiated younger and older alluvial fans. Light to dark colored, poorly sorted to crudely stratified, coarse sand or gravel derived from larger fragments of weathered igneous, metamorphic and sedimentary rocks. Youngest fans are generally small, steep-sloped, undissected and found at the lower elevations. Older fans are larger, steeper-sloped, more dissected and found at higher elevations. Thickness 10-50 feet(3-15m).

Qva VALLEY ALLUVIUM(UPPER HOLOCENE AND PLEISTOCENE?)--Alluvium composed of clay, silt, generally fine-grained sands and locally gravel. Generally unconsolidated but shows stratification. Found throughout the San Luis Valley. Thickness in excess of 75 feet(23m).

Qvf VALLEY FILL(HOLOCENE AND PLEISTOCENE)--Undifferentiated deposits of glacial, glacio-fluvial and alluvial origin. May include some talus and colluvium. Depending upon origin, consists of unsorted, coarse debris to roughly stratified silts and sands. All are derived from materials of igneous, metamorphic or sedimentary origin. Found in the larger stream valleys on the west flank of the Sangre de Cristo Range in the northern San Luis Valley.

Qes EOLIAN SAND(UPPER HOLOCENE)--Rounded, moderately well-sorted, fine- to medium-grained sand frosted to varying degrees. Thickness locally greater than 5 feet(1.5m).

Qrg ROCK GLACIER(HOLOCENE TO PINEDALE GLACIATION)--Angular slabs of rock in hummocky flow-sheets found generally on the floors and along the steep walls of glaciated valleys. Some may have a core of ice. Generally found above 9000 feet(2745m).

Qls LANDSLIDE DEPOSITS(HOLOCENE TO PLEISTOCENE)--Light to dark colored, nonsorted hummocky deposits formed by earth flows and debris slides on and below steep slopes. All deposits are bouldery and most are derived from bedrock. May include some talus. About 10-30 feet (3-9m) thick.

Qso SOLIFLUCTION DEBRIS (HOLOCENE TO PINEDALE GLACIATION)--Nonsorted, large angular rock fragments in a fine matrix. Surface is hummocky. Deposited by slow gravity movement and found on the slopes of Buffalo Peaks, north of Buena Vista.

Qpe PEAT DEPOSIT(HOLOCENE AND PLEISTOCENE?)--Extends east-west along Gas Creek in the north central part of Poncha Springs Quadrangle. Up to 10 feet(3m) thick and varies in width from 100-1500 feet(30-475m). Can be used as a fuel.

Qtc TALUS AND COLLUVIUM(UPPER HOLOCENE)--Loose, incoherent, angular rock fragments found at the foot of slopes and cliff bases. Derived from bedrock.

Qm MORAINAL DEPOSITS(PLEISTOCENE)--Undifferentiated glacial deposits consisting of terminal, lateral, recessional and ground moraines. Found at the mouths of the major tributaries of the Arkansas River emptying eastward into the Upper Arkansas Valley. Undifferentiated morainal deposits occur in several of the valleys of the Sangre de Cristo Range in the northern San Luis Valley but are not as extensive as those found to the north. May be included in Valley Fill, Qvf.

PINEDALE GLACIATION(PLEISTOCENE)

Qpo Outwash--Light colored, well-washed, stratified alluvium composed of rounded pebbles, cobbles, boulders and sand. Clasts of Tertiary igneous rocks but predominantly Precambrian igneous and metamorphic rocks. Soils weakly developed. Forms two terrace levels above the Arkansas River. Thickness 10-30 feet(3-9m).

Qpt Till--Nonsorted, nonstratified deposits of bouldery cobbles, pebbles, sand and finer material in the Upper Arkansas Valley and along the east flank of the Sangre de Cristo Range in the Arkansas Valley. Rock fragments are little weathered, rounded to angular, compacted and may be striated. Soils weakly developed. Morainal crestlines sharp, abundant stones project above an irregular, hummocky surface. May be more than 500 feet(150m) thick.

Qpf Fan Alluvium--Dark, poorly sorted, crudely stratified bouldery alluvium on the slopes flanking the northern San Luis Valley and also dominates the floor of the northern San Luis Valley. Composed of angular fragments of gneiss and sedimentary rocks. Thickness not determined but probably quite thick. Shown only in the northern San Luis Valley and included in the Fan Alluvium, Qf, of the Upper Arkansas Valley.

BULL LAKE GLACIATION(PLEISTOCENE)

Qbo Outwash--Light to dark colored, bouldery alluvium composed of cobbles, pebbles and sand, and generally well-washed, well-sorted, stratified, rounded Tertiary igneous and Precambrian igneous and metamorphic rocks. Occurs along the Arkansas River and its tributaries from the west and southwest. Partly overlain by eolian sand in Sand Park north of Salida. Includes a younger and an older outwash occuring as terraces. Thickness 20-30 feet(6-9m).

Qbt Till--Light colored, bouldery sand, moderately compacted. Most clasts are angular and little weathered. Moraine is only slightly hummocky and crestlines are rounded and stones are fewer and more buried than in the Pinedale moraines. Morainal slopes are smooth with few irregularities. Includes an older and younger till. Thickness probably more than 200 feet(65m).

Qbf Fan Alluvium--Light colored, loosely consolidated, poorly sorted, crudely to cross-stratified, silty, bouldery to cobbley sand. Generally found on the slopes flanking the northern San Luis Valley and also along the Arkansas River. Moderately sloped and highly dissected surfaces. May be included in the Fan Alluvium, Qf, of the Upper Arkansas Valley. Several tens of meters thick.

PRE-BULL LAKE GLACIATION(PLEISTOCENE)

Qog Older Gravels and Alluvium--Pediment gravels occur at four different levels capping relatively flat, high-level erosional surfaces developed primarily on the Dry Union Formation. Gravels are light colored, well-sorted and stratified and deeply weathered, forming a sandy and bouldery alluvium. Originated chiefly as outwash gravels and alluvial fan gravels. Clasts are mostly Precambrian igneous and metamorphic rocks with some Tertiary igneous rocks. Variable sorting, locally stratified to cross-bedded. Soils are more strongly developed than on the younger gravels. Thick caliche crust on undersides of boulders. Elevation above the Arkansas and South Arkansas Rivers ranges from 160 feet(50m) to 700 feet(210m). Youngest unit occurs as terraces west of Salida and as a pediment gravel to the southeast of Salida. Thickness of individual unit varies from 20-40 feet(6-12m).

Qot Older Till--Unsorted, nonstratified, bouldery till containing large boulders of igneous rock. Firmly compacted and deeply weathered. Morainal topography lacking.

Qof Older Fan Alluvium--Dark colored, silty, calcareous gravel with rounded cobbles and pebbles of igneous and metamorphic rocks. Found in the southwestern part of the Howard Quadrangle. Thickness more than 40 feet(12m).

Qtr TRAVERTINE(HOLOCENE AND PLEISTOCENE)--A light colored tufa of probable Holocene age occurs at Mineral Hot Springs. North of Wellsville a layered to massive, locally conglomeratic deposit consisting of fragments of Paleozoic limestone and travertine is found.

Td DRY UNION FORMATION(PLIOCENE AND MIOCENE)--Variicolored, interbedded clay, silt, sand and gravel; locally conglomeratic, tuffaceous and bentonitic. Includes floodplain, alluvial fan, lake, mudflow and volcanic ash deposits. Thickness in excess of 5000 feet(1525m) in the Upper Arkansas Valley but less elsewhere. Locally can be separated into upper and lower part.

Tdu Upper part: predominantly a weakly cemented conglomerate composed of angular Precambrian igneous and metamorphic rocks derived from the Sangre de Cristo Range during the last major period of faulting and uplift. Upper Pliocene in age and confined to the area southwest of Salida.

Tdl Lower part: interlayered clay, sand, silt and gravel. Thick-bedded, poorly stratified and becomes coarser-grained towards the base. Upper Pliocene to Miocene in age.

ps Slide blocks of Paleozoic rocks.

Ts SANTA FE(?) FORMATION(PLIOCENE AND MIOCENE)--Poorly sorted, crudely layered gravel composed of boulders, cobbles and pebbles of metamorphic and igneous rocks in a sandy matrix. Exposed only in an area northwest of Villa Grove. Thickness more than 300 feet(90m).

Toc BOULDER GRAVELS(PLIOCENE OR LATE MIOCENE)--Boulder gravels consisting of unstratified, angular to rounded Precambrian, Paleozoic and Tertiary rocks. Occur as erosional remnants resting upon volcanic or pre-volcanic rocks in the Salida-Waugh Mountain paleovalley. Exact stratigraphic position uncertain.

Ttw TRUMP-WAGONTONGUE FORMATIONS(LATE MIOCENE)--The Trump and Wagontongue Formations grade vertically and laterally into each other and are here grouped together. Both are characterized by calcareous conglomerate, conglomeratic fine- to coarse-grained sandstone and siltstone. The Wagontongue Formation is generally finer grained and more arkosic. The combined thickness is more than 1300 feet(395m).

Tap ANDESITE PLUG(PLIOCENE? OR MIOCENE?)--A dark colored, finely crystalline to porphyritic andesite or basaltic andesite plug at the south end of the Pleasant Valley graben. Phenocrysts are set in a very fine-grained to aphanitic groundmass.

Tab ANDESITE OF BIG BALDY(PLIOCENE? OR MIOCENE?)--Dark, basaltic andesite with feldspar phenocrysts in a matrix of dark glass and microlites.

Tsf SILICIC FELSITE OF SECTION 36(UPPER TERTIARY--?PLIOCENE, MIOCENE?)--Highly silicified, purplish, locally fractured and brecciated flow consisting predominantly of crudely banded brownish glass. Found as an elongate, northeast-trending outcrop in Sec. 36, T.50N., R.9E. Overlies pre-volcanic rock and Andesite of Big Baldy. Neither the source nor the stratigraphic position have been determined. Up to 200 feet(60m) thick.

Tla UPPER ANDESITES(WAUGH MOUNTAIN ANDESITE) AND LATITES(MIOCENE AND OLIGOCENE?)--A series of dark colored, andesitic and basaltic flows, flow breccias, minor laharic breccias and tuffs, generally overlying a local, light colored sequence of rhyolitic to latitic flows and flow breccias. Found in the northeastern part of the KGRA. The Waugh Mountain Andesite displays prominent but erratic sheeting. Formerly designated the Upper Andesite of the Thirtynine Mile volcanic field by Epis and Chapin(1968), they are now designated as the Andesite of Waugh Mountain(Epis and Chapin, 1974). Thickness varies from 300-1200 feet(90-365m). Originally radiometric age dated at 18.9 ± 1.2m.y., further investigation indicates they may be as old as 26 to 28 million years. The latites may show flow banding paralleling crudely oriented breccia clasts within the fragmented zone. Thickness varies from 200-700 feet(60-215m).

Tlt TUFF(MIOCENE)--Light colored, water-laid sandstone and conglomerate composed of fragments of hornblende latite. Found along Rough Gulch south of Salida.

Tnv NATHROP VOLCANICS(MIOCENE OR LATE OLIGOCENE)--Rhyolitic, volcanic rocks in the vicinity of Ruby Mountain southwest of Buena Vista. In descending order they include a gray to brownish, flow-banded rhyolite with gas cavities containing spessartine garnet, topaz and other minerals; a perlitic obsidian with obsidian pellets("Apache tears"), and a basal, pinkish, laharic deposit containing up to boulder-sized fragments of pumice. Thickness more than 500 feet (150m). Potassium Argon age determinations have given ages of 28.0 ± 0.8m.y. to 29.3 ± 1.5m.y.

Trh RHYOLITE(MIOCENE)--Gray, porphyritic rhyolite occuring as an intrusive plug and also as dikes in the northwestern part of the Poncha Springs quadrangle. Radiometric age 22 ± 1 to 25.4 ± m.y.(Limbach, 1975).

Tsr SLIDE ROCK MOUNTAIN STOCK(MIOCENE)--A small, hypabyssal, pinkish-gray, finely-crystalline, soda granite stock.

Tra RITO ALTO STOCK(MIDDLE MIOCENE)--A complex intrusive body consisting predominantly of tonalite with rhyolite and granite. Generally equigranular medium- to coarse-grained but the rhyolite is characteristically porphyritic.

Tma MOUNT ANTERO QUARTZ MONZONITE PORPHYRY(OLIGOCENE)--Mottled gray and pink quartz monzonite porphyry characterized by large, pink orthoclase crystals in a medium-crystalline groundmass. Radiometric dating indicates an age of about 24 ± 1m.y.

Tg MOUNT ANTERO GRANITE(OLIGOCENE)--Gray white, medium-crystalline, massive granite. Associated pegmatites are a source of crystalline aquamarine, topaz, smokey quartz and other minerals. Radiometric age dating indicates an age of 30.8 ± 1.1m.y.

Tbr BROWNS CANYON FORMATION(MIOCENE AND OLIGOCENE)--Gray to brown, tuffaceous siltstone, locally ripple-marked and interbedded with sandy or calcareous siltstone, ferruginous claystone and lithic or crystalline tuff. A basal, conglomeratic arkose contains angular to subrounded rock fragments, mainly of the underlying Precambrian quartz monzonite. Floodplain or lacustrine origin and has a thickness of up to 50 feet(15m).

Tgp GRIBBLES PARK TUFF(LATE OLIGOCENE)--A multiple flow, compound cooling unit found along the northeastern edge of the map area and also in the Poncha Pass area. Generally a gray to brown to black, rhyolitic ash flow tuff weathering light gray to brown or red. Moderately to densely welded with well-developed compaction foliation. Characterized by abundant, dark colored, angular, volcanic lithic fragments and pumice lapilli, particularly in the red-weathering member. Correlated with the Trachytic Tuff of DeVoto(1971) to the north and the Upper Rhyolitic Ash-flow Tuff of Van Alstine(1975) west of Poncha Springs. Originally designated Ashflow 7 by Epis and Chapin(1968). Has a composite thickness of about 600 feet(185m). An early Potassium Argon age determination was 34.8 ± 1.8m.y. but later determinations have given Potassium Argon ages of 28.6 ± 0.6m.y. and 29.5 ± 0.7m.y.

Ttf TRACHYANDESITE FLOW(OLIGOCENE)--An undifferentiated upper and lower trachyandesite flow consisting of phenocrysts of plagioclase in a vesicular or amygdaloidal groundmass. Mapped by Van Alstine(1975).

Tte EAST GULCH TUFF(OLIGOCENE)--A light gray, non-welded to slightly welded, rhyolitic ashflow tuff containing black, gray and orange pumice fragments. Weathers light gray to locally light brown. Occurs near the town of Howard where it has a thickness of about 250 feet(75m).

Tfa RHYODACITE ASH AND FLOW AND VOLCANIC MUDFLOW(OLIGOCENE)--Undifferentiated sequence of ash and an overlying flow just west of the Arkansas River in the central part of the Poncha Springs quadrangle. The ash is grayish, altered rhyodacite ash composed of montmorillonite, glass shards, biotite, plagioclase and sparse quartz. Present locally is a 12 foot(4m) white, pumiceous, argillized tuff and a 15-20 foot(4.5-6m) volcanic mudflow unit. Combined thickness is 10-100 feet(3-30m). Flow is grayish, porphyritic rhyodacite showing flow-banding and has a dense groundmass. Up to 50 feet(15m) thick.

Tf RHYODACITE FLOW(OLIGOCENE)--Gray to brown, porphyritic rhyodacite flow with minor, interbedded lithic tuff and a white vitric tuff near the top of the flow. Locally perlitic or columnar to platy. Microcrystalline groundmass is locally vesicular, spherulitic or perlitic glass. Thickness about 150 feet(46m). Potassium Argon dating yields an age of 33.2 ± 1.3 to 33.7 ± 2.1m.y.(Van Alstine, 1974). May be flow unit of the undifferentiated rhyodacite flow and ash sequence, Tfa.

Tvb ASHFLOW AND BRECCIA(OLIGOCENE)--A general classification for two unrelated and widely separated, mappable units. A light colored, welded to partly welded, pumiceous ashflow tuff and an andesitic, red agglomerate are found at the mouth of Kerr Creek southwest of the town of Howard. Sequence thickness about 116 feet(35m). On the middle slopes of Buffalo Peaks is found a sequence consisting of a variably welded, pumiceous, crystal-poor tuff, air-fall tuff, water-laid tuff, breccia and a laharic breccia with a combined thickness of about 835 feet(250m). This latter sequence is older than the Buffalo Peaks andesite.

Tbp BUFFALO PEAKS ANDESITE(OLIGOCENE)--Brown or gray, glassy to trachytic andesite with well-developed columnar jointing. Found north of the town of Buena Vista. Thickness about 565 feet(170m). Radiometrically age dated at 37.1 ± 3.4m.y. to 34.0 ± 3.5m.y.

Ta ANTERO FORMATION OF JOHNSON(1937)(OLIGOCENE)--Two mappable units(Lowell, 1971), a lower ashflow tuff facies underlying and grading laterally into a sedimentary tuff facies which dominates the formation. Lower unit consists of tuff and a brown, unwelded, pumice-rich ashflow tuff with a glass shard matrix. Upper facies is a light colored, coarse- to medium-grained sandstone derived from volcanic rocks and containing sparse Precambrian rock fragments, pumiceous and local, pink, bentonitic beds. Thickness more than 368 feet(115m). About 33.0 ± m.y. old.

Tbc BADGER CREEK TUFF(OLIGOCENE)--A compound cooling unit consisting of a series of light gray to brown, moderately welded, quartz latite ashflow tuffs composed of flattened, devitrified shards and containing light colored pumice lapilli. Included here and found in East Badger Creek, is a local, overlying, gray to purple, holocrystalline latite occuring as distinctive, ledge-forming flows. A lower, greenish, nonwelded flow unit, more that 120 feet(35m) thick, along Trout Creek contains abundant rounded, volcanic and Precambrian rock fragments and some petrified wood and is similar to a unit underlying the Badger Creek Tuff in the Buffalo Peaks paleovalley. The Badger Creek Tuff is both older and younger than the Antero Formation, Ta, (Epis and Chapin, 1974). A thickness of 313 feet(95m) has been measured in the map area but the Badger Creek Tuff may attain a thickness of at least 800 feet(245m) to the north. Though geologically older than the Buffalo Peaks Andesite, Tbp, the two may have been erupted almost concurrently, about 34 million years ago.

Tha HYPERSTHENE-HORNBLENDE ANDESITE(OLIGOCENE)--A dark gray, porphyritic andesite flow characterized by columnar jointing. Resembles the Buffalo Peaks Andesite but is found in the Trout Creek paleovalley.

Tqp QUARTZ-PYROXENE LATITE(OLIGOCENE)--Gray, flow-banded andesite found as small outcrops at the south end of the Howard syncline.

Tta THIRTYNINE MILE ANDESITE(EARLY OLIGOCENE)--Originally termed the Lower Andesite of the Thirtynine Mile volcanic field by Epis and Chapin (1968), it has been renamed the Thirtynine Mile Andesite by Epis and Chapin(1974). As redefined, it consists of a lower and and upper member. The lower member consists mostly of chaotically stratified, unsorted, well-indurated, purple to brown and black breccias of various origins but predominantly of laharic origin. The upper member consists of distinctly stratified andesite flows with lesser amounts of interbedded breccias and ash-fall tuffs. Occurs only in the extreme northeastern corner of the map area as the southermost extension of the more widespread flows to the north. Thickness of the Thirtynine Mile Andesite is in excess of 700 feet(215m). Radiometric age determinations for the upper member give an age of 34.1 ± 1m.y.

Ttc TALLAHASSEE CREEK CONGLOMERATE(EARLY OLIGOCENE)--Originally and informally called the Lower Volcanic Conglomerate by Epis and Chapin(1968), it was renamed and redefined by Epis and Chapin(1974). It consists of poorly sorted, crudely stratified, partially consolidated accumulations of pebbles, cobbles and boulders in a tuffaceous to arkosic, sandy to silty matrix. Clasts are predominantly of volcanic origin but Precambrian clasts are common and generally present. Locally there are clasts of Lower Paleozoic limestone and dolomite. As much as 350 feet(105m) thick.

Twa WALL MOUNTAIN TUFF(EARLY OLIGOCENE)--A gray to brown, crystal-rich, rhyolitic ashflow tuff exhibiting moderate to dense welding. Locally a black, lenticular vitrophyre zone of dense welding overlies a light colored, thin, nonwelded, basal unit. Weathers buff to brown and tends to form prominent cliffs up to 90 feet(27m) high. Unit has a widespread occurrence throughout the KGRA. The Wall Mountain Tuff(Epis and Chapin, 1974) is the Agate Creek Tuff of DeVoto(1964) and the Lower Rhyolitic Ash-flow Tuff of Van Alstine(1969). Thickness in excess of 200 feet(60m). Radiometric age determinations have yielded ages ranging from 34.8 ± 1.1m.y to 37.3 ± 1.9m.y.

Tmp MOUNT PRINCETON QUARTZ MONZONITE(OLIGOCENE? TO EOCENE?)--Gray, equigranular, medium-crystalline granite forming a batholith nearly 20 miles(32m) in diameter. Altered to a pink zeolite in severely sheared, hydrothermal areas. Radio metric age 36 ± 2m.y.(Limbach, 1975).

Tqd QUARTZ DIORITE(OLIGOCENE? TO EOCENE?)--Gray, finely crystalline and equigranular, nonfoliated quartz diorite. Small outcrops are found in the west central part of the Poncha Springs quadrangle.

Tds DIKES AND SILLS(TERTIARY)--Undifferentiated dikes and sills, many of which are too small to be shown on the scale of the maps so that only the larger ones are shown. Average 3-4 feet(1.0-1.25m) in width. Composition variable-rhyodacite and dacite, hornblende dacite, rhyolite and quartz latite and rhyolitic to andesitic.

BONANZA VOLCANIC SEQUENCE(OLIGOCENE)

A sequence of extrusive volcanic rocks and attendant small intrusive bodies found in the southwestern part of the area in the general vicinity of Bonanza. So called to differentiate from the Northern Volcanic sequence, a series of volcanic rocks and intrusives found in the north central and eastern parts of the KGRA.

Tpp PORPHYRY PEAK RHYOLITE--Rhyolites, latites and minor latitic ashflows comprise this unit. Restricted occurrence on and around Porphyry Peak.

Teg EAGLE GULCH LATITE--A small intrusive body of typically gray, porphyritic quartz latite with abundant feldspar phenocrysts but no apparent flow structures. Occurs as an irregular, elongate, northeast-trending intrusive in the vicinity of Eagle Gulch.

Tya YOUNGER ANDESITES AND LATITES--Two separate sequences of latites and andesites. Burbank(1932) mapped a sequence of dark colored latites and andesites in the central Bonanza area. Marrs(1973) mapped a sequence of dark latite and andesite flows in the southwestern Bonanza area. No direct correlation has been established between the two sequences.

Tgg GREENBACK GULCH VOLCANIC COMPLEX--A roughly oval-shaped intrusive complex composed of plutons and dikes of rhyolite, monzonite and latite, large blocks of andesite country rock and bodies of altered breccia. Dikes are primarily rhyolitic and most have prominent flow structures. Between the plutons and dikes are blocks of breccia composed of andesite fragments in a totally altered matrix. Locally there are a few, large blocks of Precambrian hornblende gneiss and a red or green, Paleozoic(?) sandstone. Chaotic rock-type distribution, intense alteration, breccias and the occurrence of presumably deeply buried, pre-volcanic rock types at the surface suggest the complex was a local center of explosive volcanism.

Thp HAYDEN PEAK QUARTZ LATITE--Gray to tan quartz latite with pronounced flow-layering near the base. Outcrops on and around the summit of Hayden Peak and informally named by Mayhew(1969). This is not the Hayden Peak latite of Burbank(1932).

Tb BONANZA TUFF--A series of at least nine ashflow cooling units of a red to buff, biotite-rich, ashflow tuff. Compaction foliation and flattened pumice lapilli are common. Typically contains abundant, purplish andesite fragments. Moderately to highly welded. Originally the Bonanza Latite of Burbank(1932) and renamed Bonanza Tuff by Mayhew(1969).

Tsc SPRING CREEK RHYOLITE--A small intrusive of light brown rhyolite outcropping in the Spring Creek drainage basin just north of the Turquesa Gabbro.

Ttq TURQUESA GABBRO--A dark gray or dark green gabbro. Poorly exposed outcrops in the drainage of Peterson and Kelly Creeks on the east side of the Bonanza pile. Outcrops over an area of about 2 square miles(5 sq. km).

Tr RAWLEY FORMATION--A sequence of andesite and latite flows, commonly with laharic breccias and ash beds. Occasional basalt flows and ashflow tuffs have been identified; local, thin cobble and boulder lenses are interstratified. Thickness of 200-2600 feet(60-790m). Early radiometric dating indicated an age of 33-34m.y., but tentative indentification of Wall Mountain Tuff, Twa, (37.3 ± 1.9m.y.) interlayered with and overlying the Rawley Formation suggests the earlier dating does not represent the earliest eruptions.

Kw WHITEHORN STOCK(LATE CRETACEOUS)--A complex intrusive body composed of granite, granodiorite, tonalite, quartz gabbro and gabbro. The most common rock types are granodiorite and tonalite. The more mafic rock types tend to occur near the eastern margin of the intrusive body. The Whitehorn stock occupies an area of about 40 square miles(103 sq. km) at the southern end of the Mosquito Range in the northeastern part of the KGRA.

PIPu UPPER PALEOZOIC ROCKS(PERMIAN AND PENNSYLVANIAN)--Undifferentiated Permian and Pennsylvanian sedimentary rocks. In descending order, they include:

MAROON FORMATION(PERMIAN AND PENNSYLVANIAN)--Restricted to the Upper Paleozoic sedimentary sequence north of Whitehorn stock. Predominantly red, locally buff, sandstone, conglomerate, siltstone and shale. Fossil evidence indicates a late Pennsylvanian age for the lower Maroon beds and an early Permian age for the upper beds. Thickness varies from 6000-10,000 feet(1830-3050m). Lithologically similar rocks south of Whitehorn stock are mapped as the Sangre de Cristo Formation.

PIPs SANGRE DE CRISTO FORMATION(PERMIAN AND PENNSYLVANIAN)--Brown to green, thin- to thick-bedded, arkosic sandstone, conglomerate and micaceous siltstone. Locally cross-bedded, ripple-marked, mud-cracked. Beds are typically cyclic, grading upward from a basal, coarse-grained material into a finer-grained sandstone, siltstone and shale. Divided into an upper and lower member of Permian and Pennsylvanian age respectively. Both members have similar lithologies but the upper member is generally more coarse-grained, has a more drab color and includes the Crestone Conglomerate member. The Sangre de Cristo Formation is confined to the area south of the Whitehorn stock. A major intraformational unconformity separates the upper and lower members. Thickness 0-15,000 feet(0-4570m).

Psu Upper Member.

IPsl Lower Member.

-u- Major intraformational unconformity mapped by Pierce(1964).

IPu PENNSYLVANIAN ROCKS-- Undifferentiated Pennsylvanian sedimentary rocks. In descending order:

IPm MINTURN FORMATION--Characteristically tan, brown, green, gray or black shale, siltstone, sandstone and conglomerate. Gypsum beds and several interbedded marine limestones occur in the upper part. South of Whitehorn stock, the Minturn overlies the Sharpsdale Formation while north of Whitehorn stock it is stratigraphically above the Belden Formation. Thickness up to 6000 feet(1830m).

G Gypsum bed.

BELDEN FORMATION--Dark gray to black, fissile, carbonaceous shale, shaley siltstone, limey mudstone, thin-bedded, micaceous, coarse- to fine-grained sandstone. Dominant lithology is black shale. South of Whitehorn stock the Belden Formation is replaced, through facies changes, by the Sharpsdale and Kerber Formations. Up to 1600 feet(490m) thick.

IPmb MINTURN AND BELDEN FORMATIONS--Undifferentiated.

IP SHARPSDALE AND KERBER FORMATIONS--Undifferentiated. In descending order:

SHARPSDALE FORMATION--Predominantly red, fine- to coarse-grained, micaceous, feldspathic to arkosic sandstone interbedded with red shale and siltstone. Conglomerate and conglomeratic sandstone are common and thin limestones are present throughout. Found in the southern and central portions of the Sangre de Cristo Range in the KGRA; while northward it is replaced, through facies changes, by the Belden Formation. Up to 1800 feet(550m) thick.

KERBER FORMATION--Occurs at the base of the Upper Paleozoic sedimentary rock sequence south of Whitehorn stock in the KGRA. Typically it is a non-resistant, gray to tan, quartzose sandstone with thinly laminated, carbonaceous shale and locally conglomeratic. Abundant white kaolinite in the matrix material. A few thin, fossiliferous limestones and coal beds are present. North of Whitehorn stock the Kerber Formation is replaced, through facies changes, by the Belden Formation. Up to 400 feet(125m) thick.

LMP LOWER AND MIDDLE PALEOZOIC ROCKS(MISSISSIPPIAN, DEVONIAN, ORDOVICIAN AND CAMBRIAN)--Undifferentiated sedimentary rocks, in descending order:

LEADVILLE LIMESTONE(LOWER MISSISSIPPIAN)--Blue to gray, fine-grained, massive limestone and black to gray dolomite. Intraformational breccias present locally at the base and local, thick-bedded, black and gray chert nodules in the upper part. Upper surface exhibits karst topography and may have large solution cavities partially filled by red, clastic detritus. Thickness 210-350 feet(65-110m).

CHAFFEE FORMATION(MISSISSIPPIAN? AND UPPER DEVONIAN)--Consists of two members, in descending order:

Dyer Dolomite Member--Yellow to gray to tan, microcrystalline dolomite interlayered with thin, cherty limestone. Thickness up to 90 feet(27m).

Parting Quartzite Member--Gray to predominantly red or pink, lithologically variable unit consisting of quartzite, limestone, conglomerate, friable sandstone, siltstone and shale. Up to 62 feet (20m) thick.

FREMONT FORMATION(UPPER AND MIDDLE DEVONIAN)--A dominantly gray, generally massive, coarsely crystalline dolomite locally interlayered with thin, sandy or cherty dolomite. Pit and cusp weathering common. Thickness variable 230-300 feet(70-90m).

HARDING SANDSTONE(MIDDLE ORDOVICIAN)--White to red to brown, well-rounded, well-sorted, fine- to medium-grained, quartzitic sandstone. Thickness varies 60-116 feet(20-35m).

MANITOU FORMATION(LOWER ORDOVICIAN)--Brown to gray, generally thin-bedded dolomite and dolomitic limestone. Locally cherty along stratification planes. Found at the base of the Paleozoic sedimentary sequence except in those areas where the Sawatch Quartzite is present. Thickness 90-225 feet(27-70m).

SAWATCH QUARTZITE(UPPER CAMBRIAN)--Where present, forms the base of the Paleozoic sedimentary section overlying the Precambrian basement rocks. Generally a thin-bedded, white to buff, fine- to medium-grained, quartz sandstone. Generally thins from north to south and west to east in the KGRA. Present in the Kerber Creek area in the southwest and in the Buffalo Peaks-Turret area northeast of Buena Vista. Varies in thickness from 0-100 feet(0-30m).

Yg GRANITE OF SILVER PLUME AGE(PRECAMBRIAN Y)--Pink to gray, medium-crystalline, nonfoliated granite.

YXfg QUARTZ MONZONITE(PRECAMBRIAN Y AND X)--Gray, finely-crystalline, massive to foliated, quartz monzonite. Locally probably includes some quartz monzonite of Silver Plume age.

Xp PEGMATITE(PRECAMBRIAN X)--Light colored, coarsely-crystalline pegmatite composed of quartz and feldspar, muscovite, biotite, magnetite, locally tourmaline, scheelite and fluorite. Varies in width from a few inches to 50 feet(0.05-15m).

Xgd GRANODIORITE OF BOULDER CREEK AGE(PRECAMBRIAN X)--Gray to pink, massive to foliated, medium- to coarse-grained, batholithic granodiorite. Includes porphyroblastic and augen varieties and may have lesser amounts of quartz monzonite. Has an age of about 1700m.y. by Rb/Sr isochron(Taylor et al, 1975).

gd GRANODIORITE(PRECAMBRIAN)--Gray to green, hypidiomorphic, equigranular, fine-grained granodiorite. Mapped by Kouther(1969) and occurs as two small outcrops on the east flank of Mount Ouray, west of O'Haver Lake. Younger than the surrounding Precambrian country rock.

Xmg GRANODIORITE OF METHODIST MOUNTAIN(PRECAMBRIAN X)--Gray, medium-grained, massive, pluton-forming granodiorite found in the south central part of the area.

Xqm QUARTZ MONZONITE(PRECAMBRIAN X)--Mapped by Van Alstine(1975) in the central portion of the Bonanza quadrangle.

fg FINE-GRAINED GRANITE(PRECAMBRIAN)--A classification used by Knepper (1975). Grayish, fine-grained, foliated granite. Outcrops along Alder Creek in the Bonanza quadrangle and is also exposed in the cores of the Eastern and Central anticlines. To the east and southeast, a small extension of the same rock outcrop has been mapped as gneiss, Xgn, by Taylor et al(1975).

Xqd QUARTZ DIORITE OF BOULDER CREEK AGE(PRECAMBRIAN X)--Gray, well-foliated to massive, fine- to coarsely-crystalline quartz diorite. Grades into granodiorite and may be intruded by it. Generally found at outer margins of major granodiorite plutons.

Xa MAFIC AMPHIBOLITE(PRECAMBRIAN X)--Mottled black and green, medium-crystalline, massive amphibolite. outcrops in two small bodies northeast of Buena Vista.

Xg METAGABBRO(PRECAMBRIAN X)--Dark green to black, fine- to medium-grained, generally massive gabbro.

Xgn GNEISS(PRECAMBRIAN X)--Gray to black, layered gneiss. Medium- to finely-crystalline, well foliated and compositionally banded on a scale of a few millimeters to several tens of meters. Variably migmatic with a greater degree of pegmatite veining in the southern part of the area of occurrence than in the north, where it grades into non-migmatic, metavolcanic and metasedimentary rocks. Probably formed from an interlayered sedimentary-volcanic sequence containing intermediate and silicic flows and tuffs with sedimentary interlayers of volcanic detritus mixed with non-volcanic, clastic debris.

a-gg AMPHIBOLITE GNEISS AND SCHIST - QUARTZ-FELDSPAR (GRANITIC) GNEISS AND SCHIST(PRECAMBRIAN)--Designations used by Knepper(1974), and are used here where no other determinations or map correlations were possible. Both overlap and are included in either the gneiss, Xgn, or metavolcanic and metasedimentary rocks, Xvs, classifications used elsewhere.
a: Amphibolite gneiss and schist.
gg: Quartz-feldspar gneiss and schist.

Xvs METAVOLCANIC AND METASEDIMENTARY ROCKS(PRECAMBRIAN X)--Gray to brown, chiefly feldspathic gneisses, biotite-plagioclase metarhyodacite tuffs, metabasalts and metamorphosed sedimentary breccias and tuffs. Characterized by abundant muscovite and little deformation so that original rock textures are well preserved despite metamorphism. In the west and south, grades into gneisses showing more extreme metamorphism and deformation, Xgn. To the north, the degree of metamorphism and deformation is less.

Xb METABASALT(PRECAMBRIAN X)--Gray to green, medium- to finely-crystalline, foliated to non-foliated, locally amygdaloidal rock derived from basalt flows or basalt-bearing mudflows. Found in an area northeast of Salida.

Xm MARBLE(PRECAMBRIAN X)--Gray to white, coarsely-crystalline marble. Occurs as an inclusion in metagabbro on the north side of Simmons Peak, south of Salida.

pC PRECAMBRIAN ROCKS, UNDIFFERENTIATED--Occur as small outcrops in the area just south of Alder in the Bonanza quadrangle.

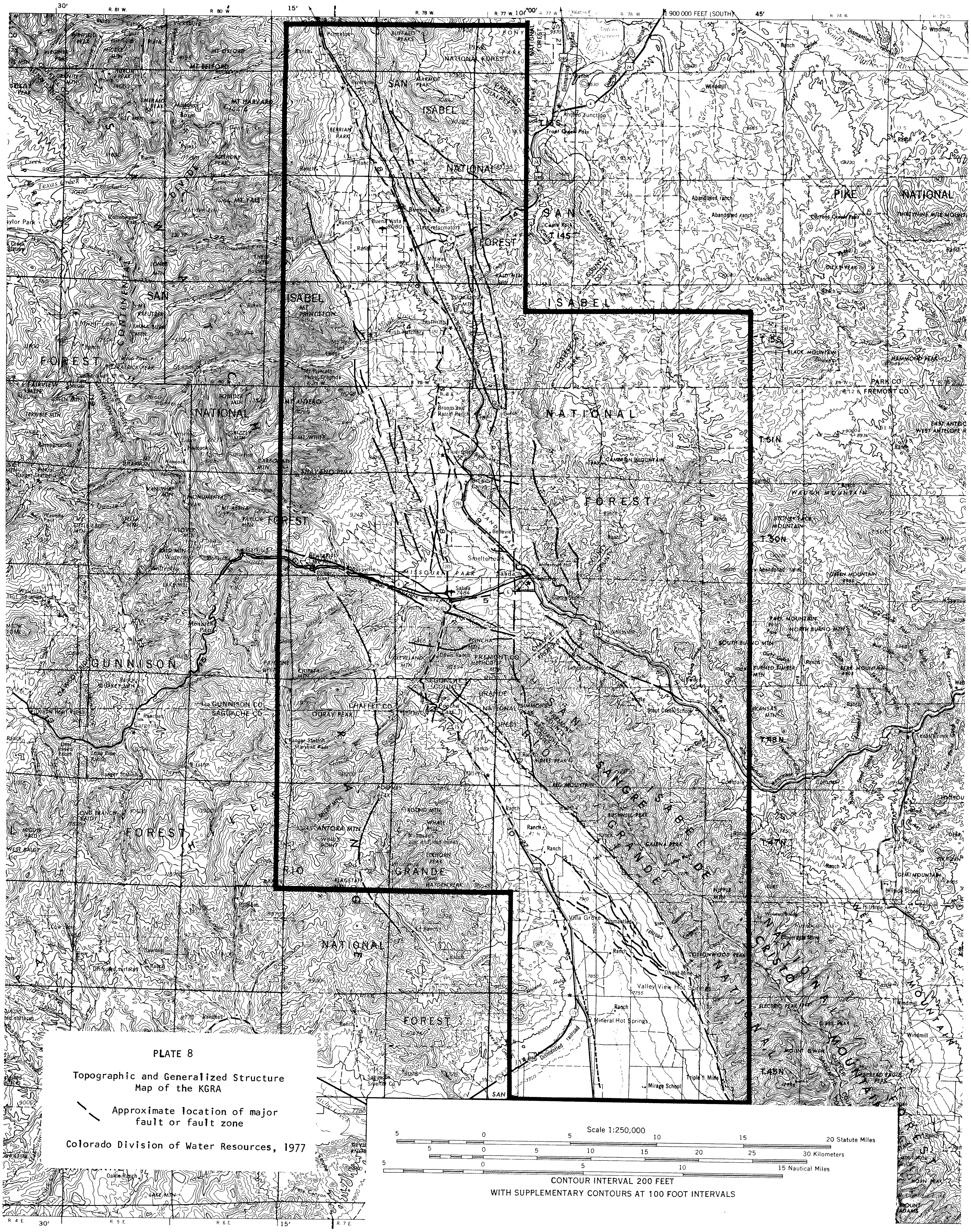


PLATE 8

Topographic and Generalized Structure Map of the KGRA

Approximate location of major fault or fault zone

Colorado Division of Water Resources, 1977

Scale 1:250,000

5 0 5 10 15 20 Statute Miles

5 0 5 10 15 20 25 30 Kilometers

5 0 5 10 15 Nautical Miles

CONTOUR INTERVAL 200 FEET
WITH SUPPLEMENTARY CONTOURS AT 100 FOOT INTERVALS

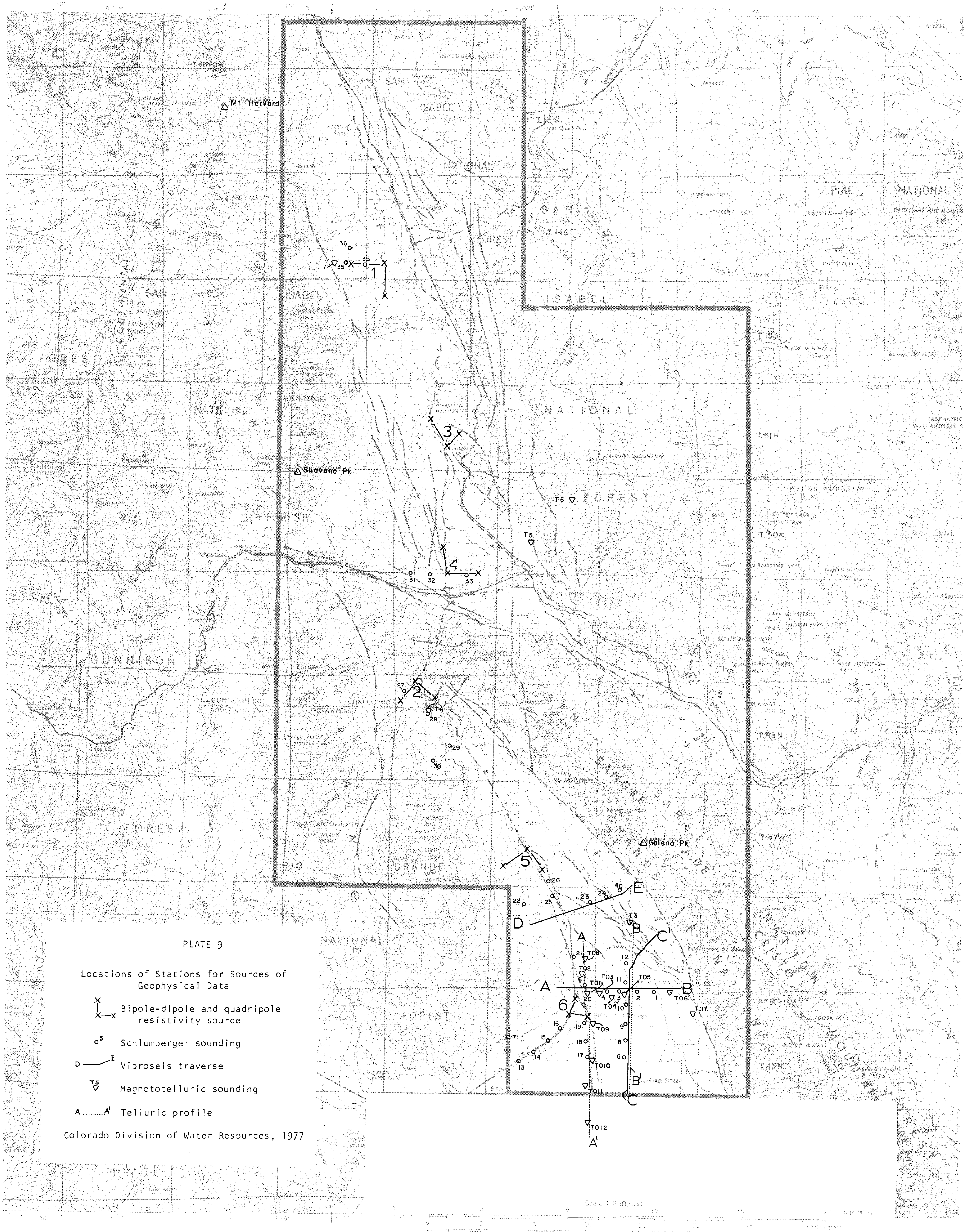


PLATE 9

Locations of Stations for Sources of Geophysical Data

Colorado Division of Water Resources, 1977

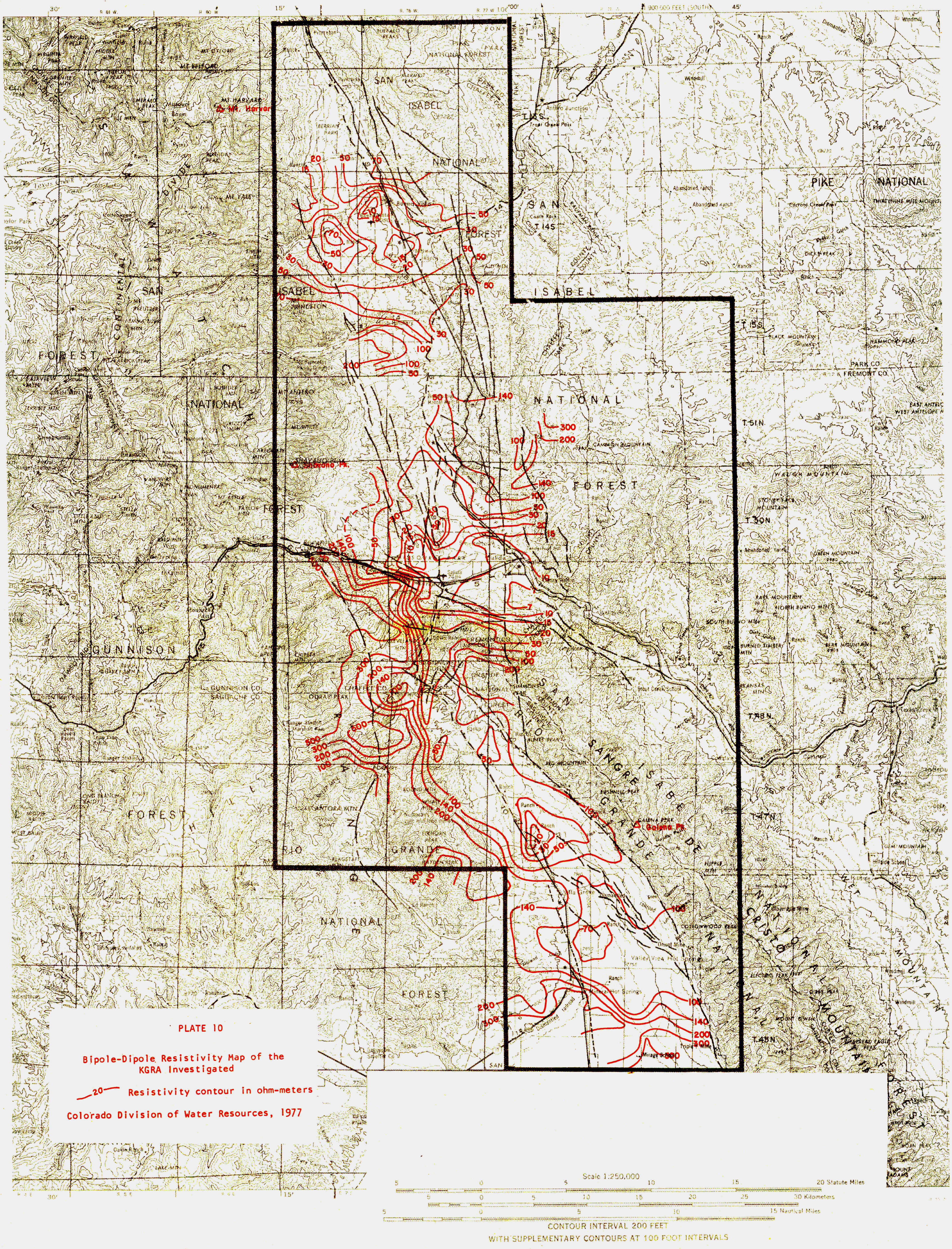


PLATE 10

Bipole-Dipole Resistivity Map of the KGRA Investigated

—20— Resistivity contour in ohm-meters

Colorado Division of Water Resources, 1977

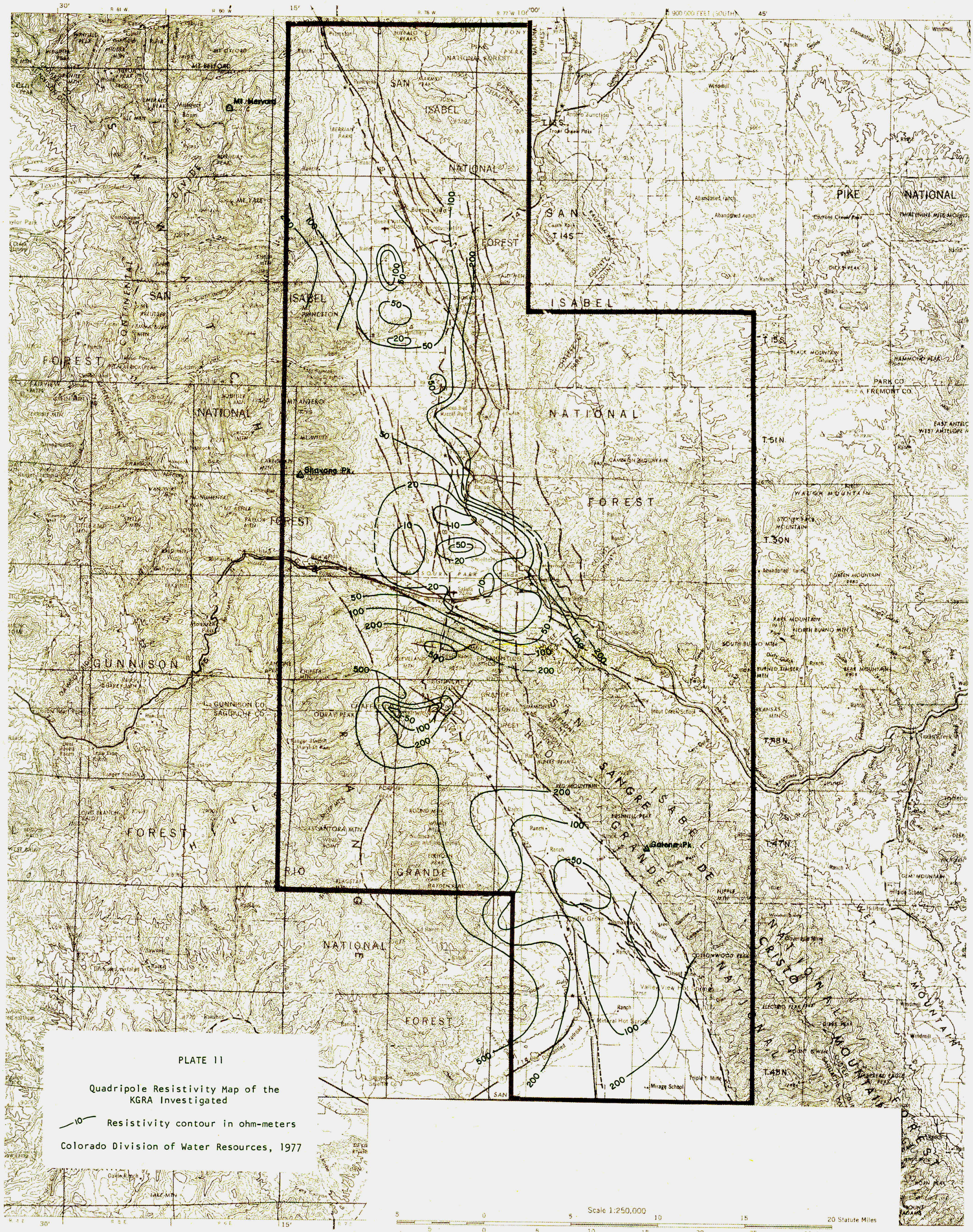


PLATE 11

Quadripole Resistivity Map of the KGRA Investigated

Resistivity contour in ohm-meters

Colorado Division of Water Resources, 1977

Scale 1:250,000

5 0 5 10 15 20 Statute Miles

5 0 5 10 15 20 25 30 Kilometers

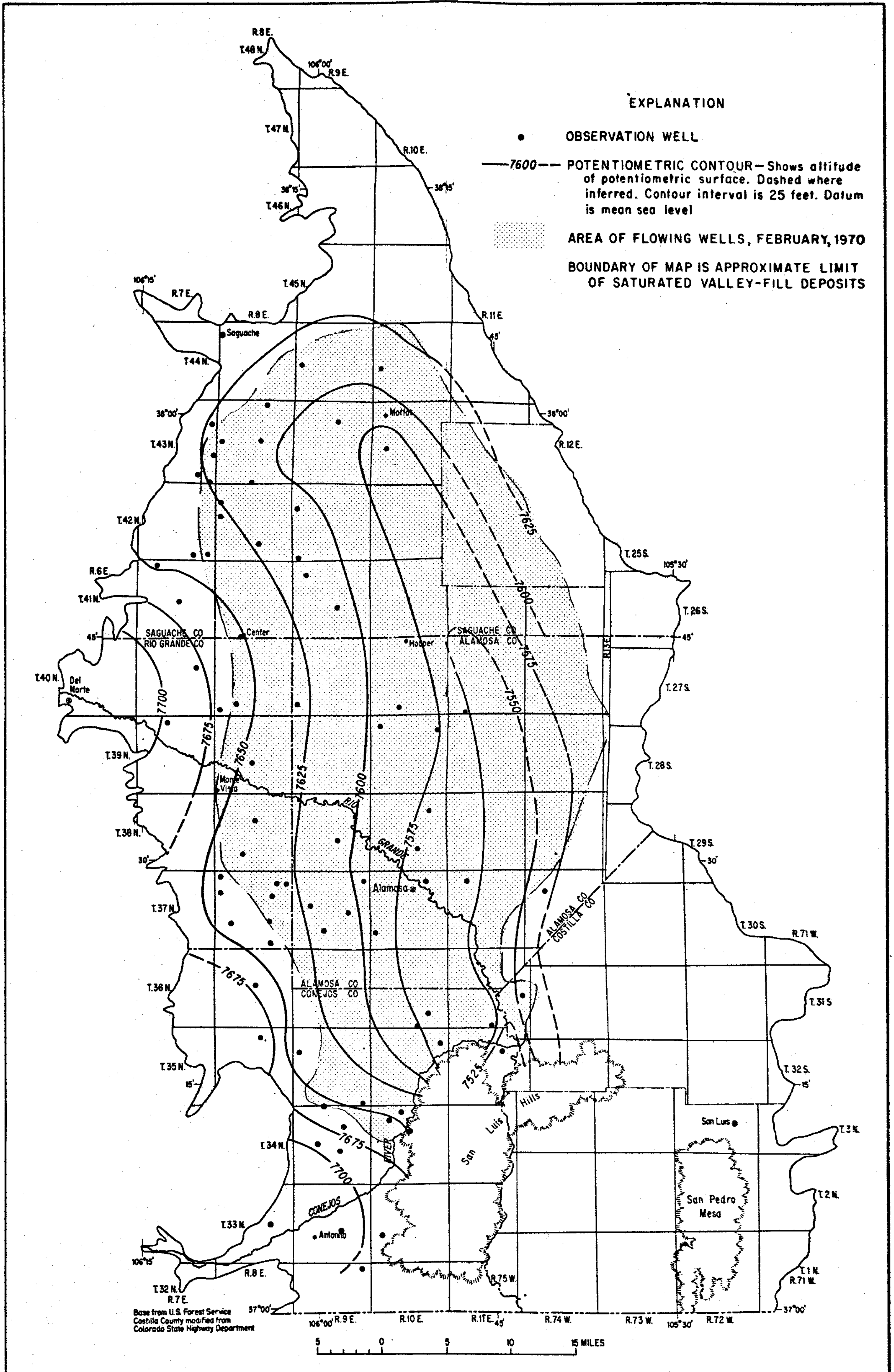
5 0 5 10 15 Nautical Miles

CONTOUR INTERVAL 200 FEET
WITH SUPPLEMENTARY CONTOURS AT 100 FOOT INTERVALS

Prepared in cooperation with the COLORADO WATER CONSERVATION BOARD AND THE COLORADO DIVISION OF WATER RESOURCES, OFFICE OF THE STATE ENGINEER

UNITED STATES DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

COLORADO WATER RESOURCES CIRCULAR 18
PLATE 6



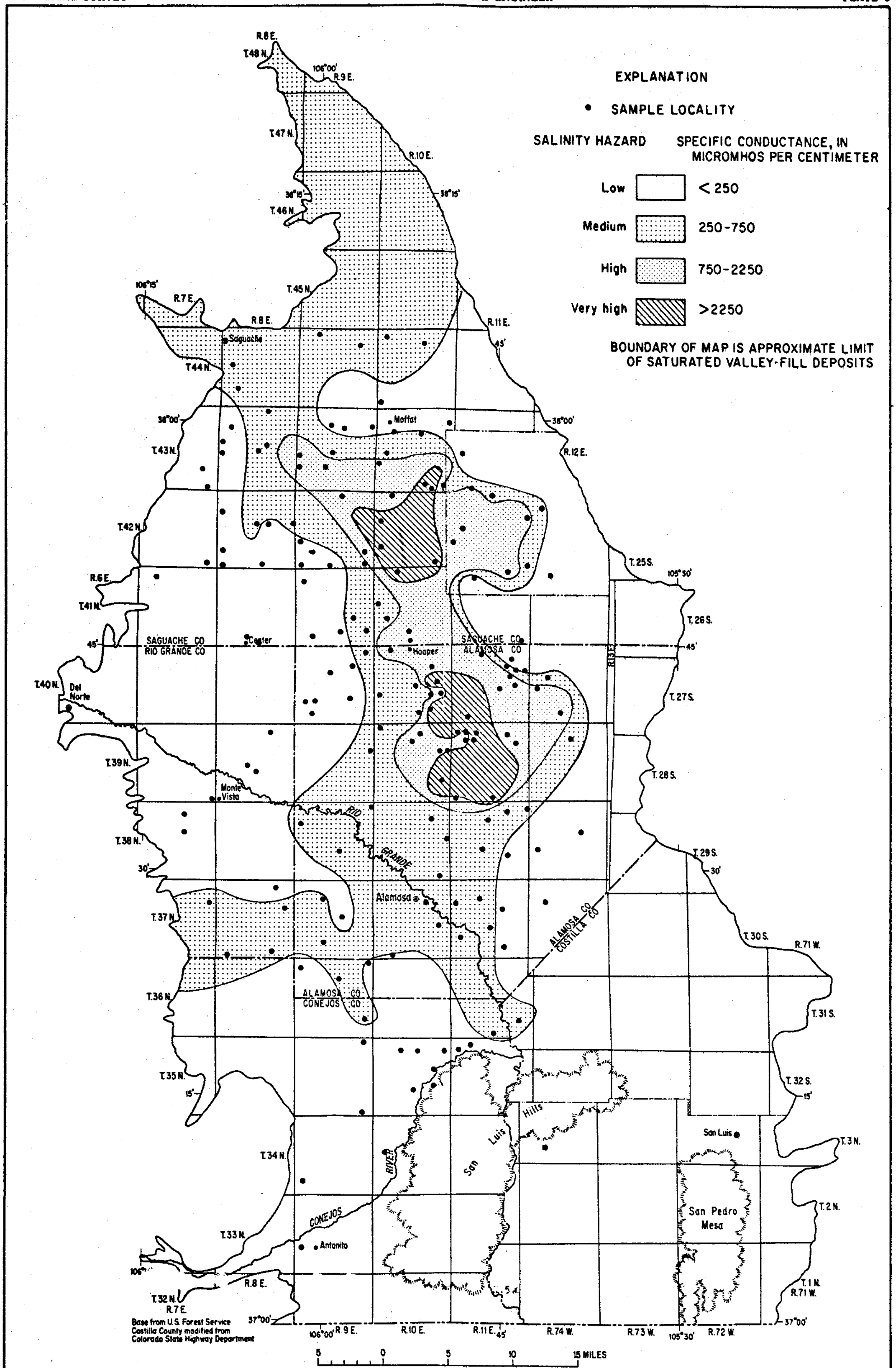
MAP SHOWING CONFIGURATION OF POTENTIOMETRIC SURFACE AND AREA OF FLOWING WELLS, FEBRUARY 1970, SAN LUIS VALLEY, COLORADO

PLATE 13

Prepared in cooperation with the COLORADO WATER CONSERVATION BOARD AND THE COLORADO DIVISION OF WATER RESOURCES, OFFICE OF THE STATE ENGINEER

UNITED STATES DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

COLORADO WATER RESOURCES CIRCULAR 18
PLATE 8



MAP SHOWING AREAL DISTRIBUTION OF SALINITY HAZARD OF WATER IN THE CONFINED AQUIFER, SAN LUIS VALLEY, COLORADO

UNITED STATES DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

Prepared in cooperation with the
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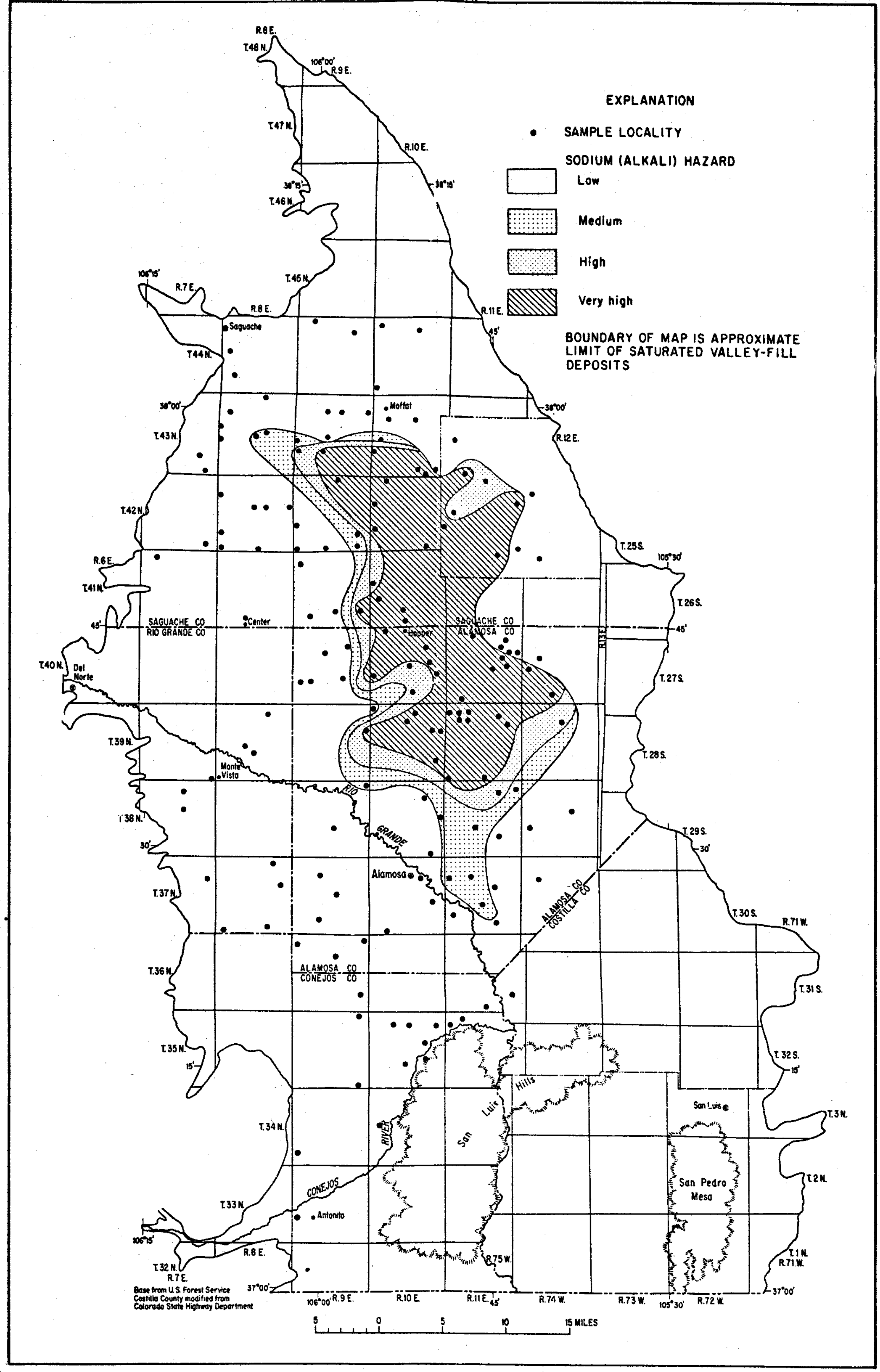
COLORADO WATER RESOURCES CIRCULAR 18
PLATE 9



MAP SHOWING AREAL DISTRIBUTION OF SODIUM (ALKALI) HAZARD OF WATER IN THE CONFINED AQUIFER, SAN LUIS VALLEY, COLORADO

UNITED STATES DEPARTMENT OF THE INTERIOR
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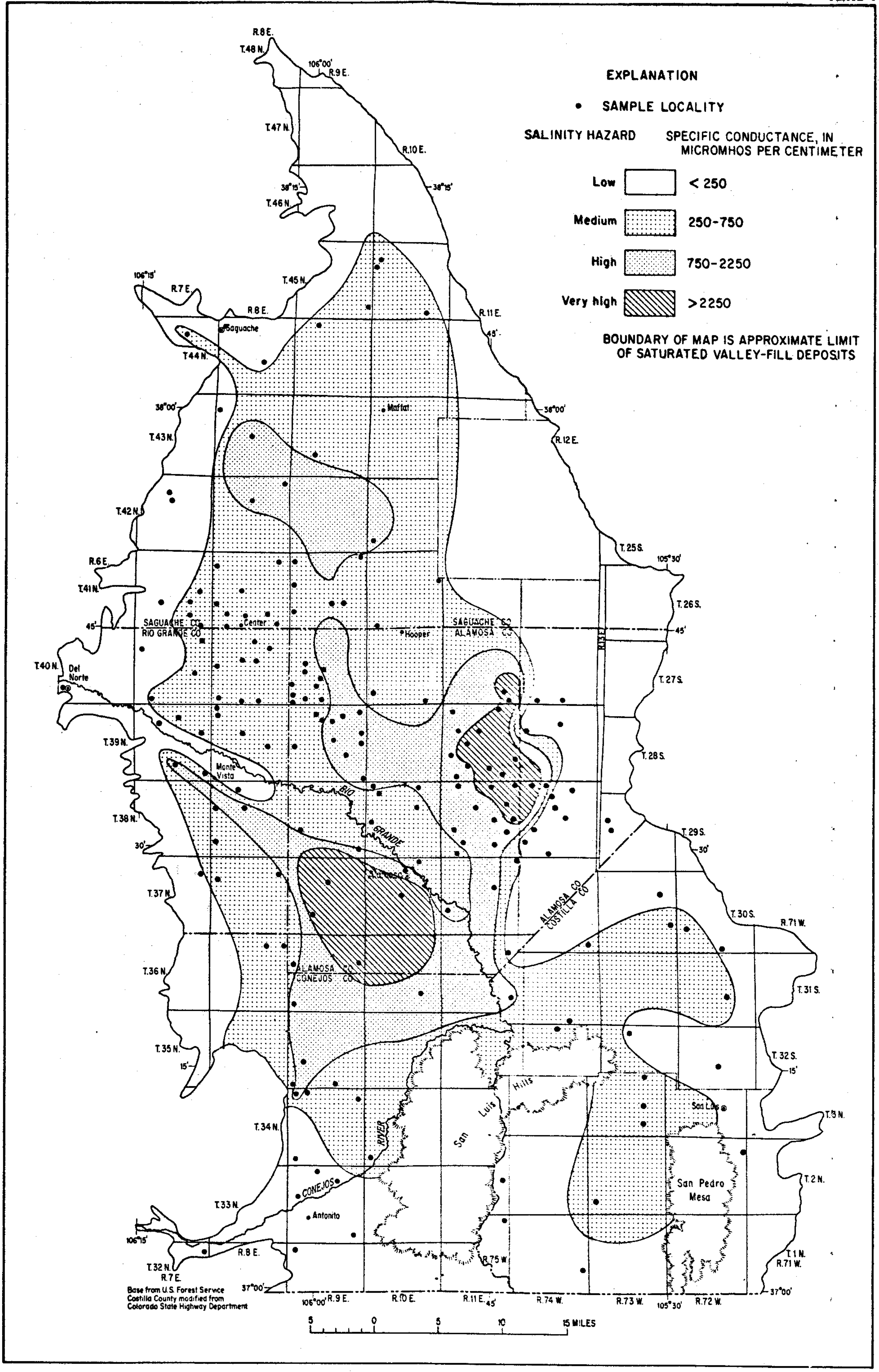
COLORADO WATER RESOURCES CIRCULAR 18
PLATE 4



MAP SHOWING AREAL DISTRIBUTION OF SALINITY HAZARD OF WATER IN THE UNCONFINED AQUIFER, SAN LUIS VALLEY, COLORADO

PLATE 16

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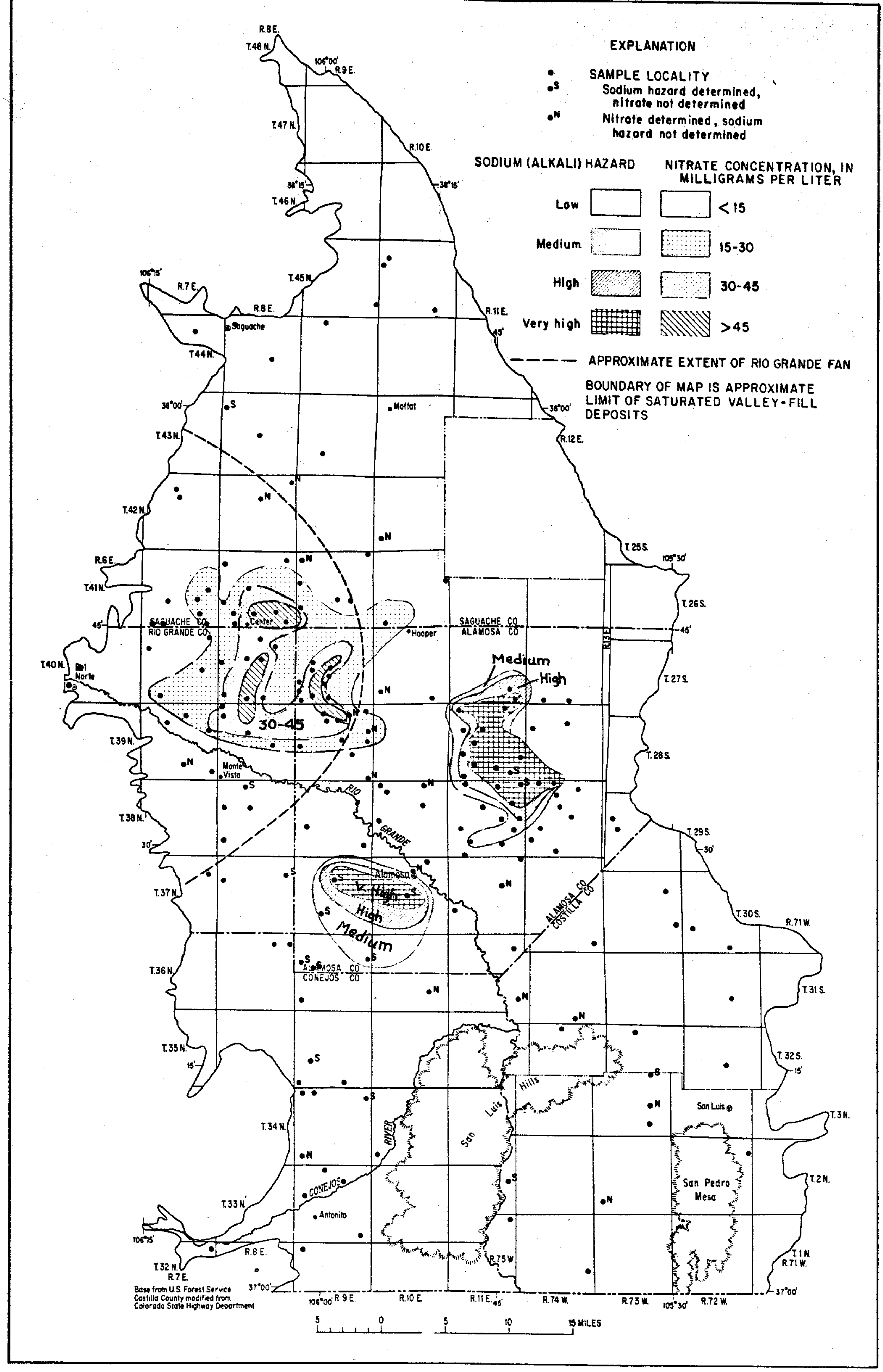
COLORADO WATER RESOURCES CIRCULAR 18
PLATE 5



MAP SHOWING AREAL DISTRIBUTION OF SODIUM (ALKALI) HAZARD AND NITRATE CONCENTRATION OF WATER IN THE UNCONFINED AQUIFER, SAN LUIS VALLEY, COLORADO

COLORADO DIVISION OF WATER RESOURCES, 1977