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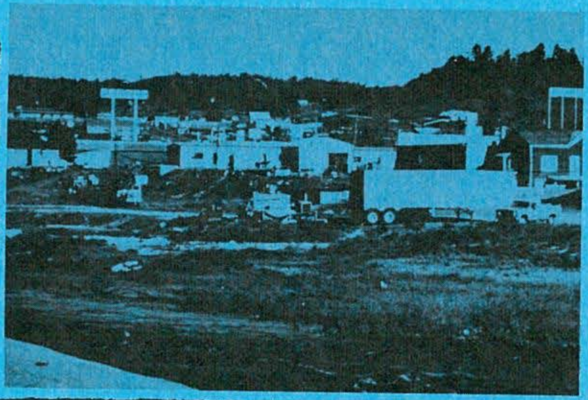
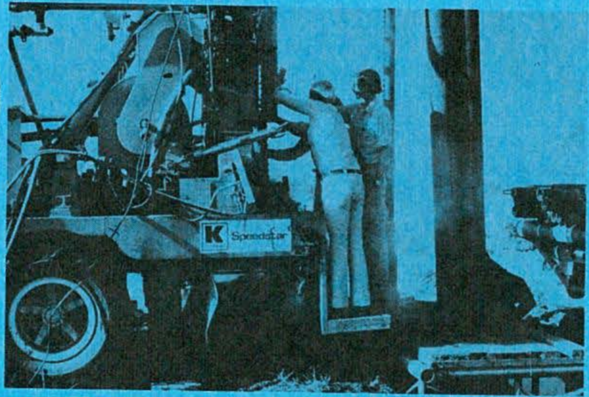
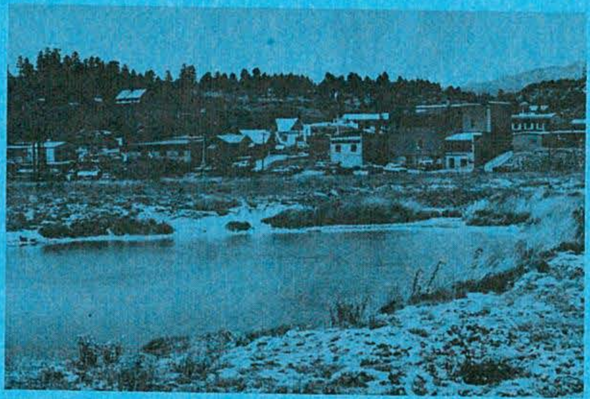
Hydrogeologic and Geothermal Investigation of Pagosa Springs, Colorado



by Michael J. Galloway





COLORADO GEOLOGICAL SURVEY
DEPARTMENT OF NATURAL RESOURCES
DENVER, COLORADO
1980

Cover photos: Drilling site and rig at Pagosa Springs.

HYDROGEOLOGIC AND GEOTHERMAL INVESTIGATION OF PAGOSA SPRINGS, COLORADO

by

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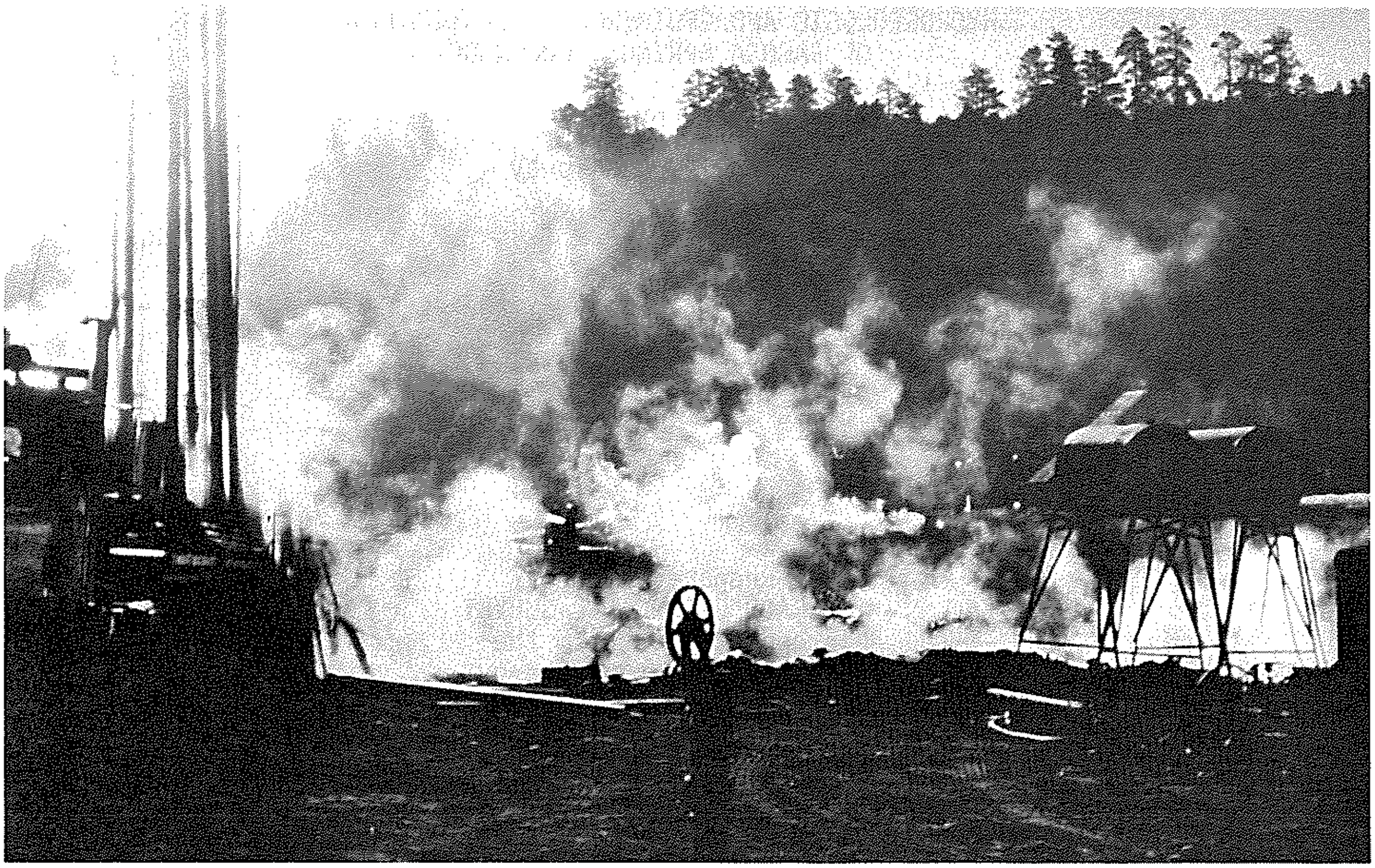

Drilling at Pagosa Springs. Photo by Michael Galloway

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INTRODUCTION

The Colorado Geological Survey is involved in an ongoing investigation of various geothermal reservoirs within the State of Colorado in order to assess the geothermal potential of the State. Funding for this investigation is supplied by the U.S. Department of Energy, Division of Geothermal Energy through the State Coupled Program, Contract Number AS07-77ET28365. This is the final report of one such study in Pagosa Springs, Colorado.

Pagosa Springs, Archuleta County, Colorado, is located 280 mi (448 km) southwest of Denver and 65 mi (106 km) east of Durango (Fig. 1) and has a population of about 1325 (Koulet and Armstrong, 1978). The area of investigation includes 211 mi^2 (550 km^2), centered on the city of Pagosa Springs (Fig. 1). Pagosa Springs is located on the northeastern edge of the San Juan Basin approximately 15 mi (24 km) west of the continental divide, at an elevation of 7000 ft (2121 m). Precipitation, 65% of which falls as snow, ranges from 49 in. (125 cm) at higher elevations to 24 in. (60 cm) at the lower elevations. Vegetation is very dense in much of the higher elevations of the area, but thins significantly at lower elevations, particularly on soil developed from the various shales.

Pagosa Springs was selected for this study because of probable geothermal resource potential and community interest. Adequate subsurface temperature (Barrett and Pearl, 1978) and measured surface flows justified further reservoir investigation. Initially, a reservoir assessment and confirmation study was to be used by the local school district for a planned new high school. During the early phases of this program, a school bond issue was defeated. However, community interest remained high for the use of the geothermal water and it was decided to continue the investigation.

A Program Opportunity Notice (PON) was submitted by Pagosa Springs in July, 1978 with the aid of two Denver consulting firms and has since been accepted by DOE. The PON proposes to establish a district heating system utilizing the test wells drilled by the Colorado Geological Survey (CGS) and existing hot water wells.

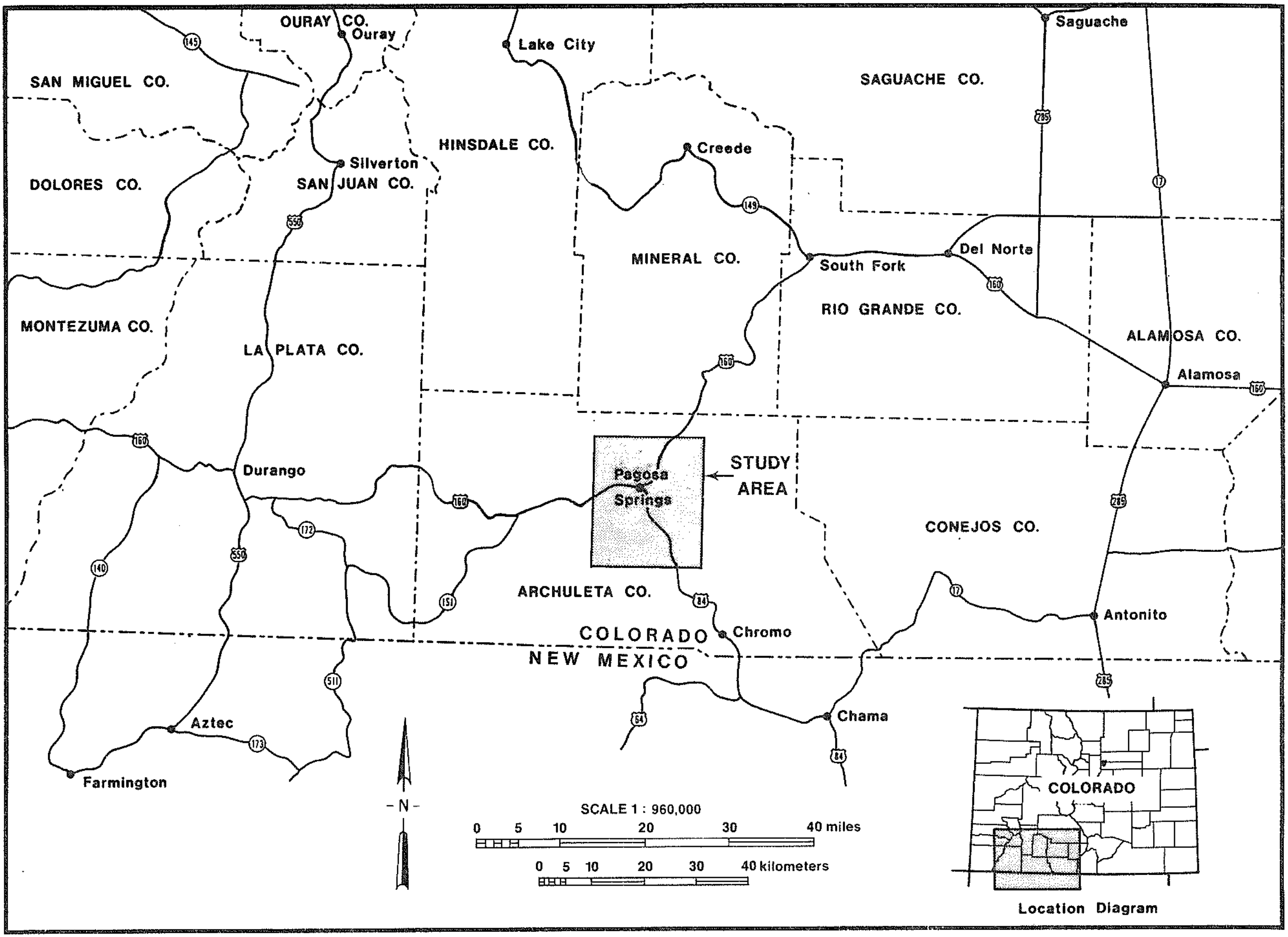


Figure 1 - Index Map of the Pagosa Springs Study Area

ACKNOWLEDGMENTS

Maps and illustrations were drafted by Mark V. Persichetti. The manuscript was typed by Becky Andrews.

GEOLOGY

Introduction

Pagosa Springs is located on the Archuleta anticlinorium (Ryder, 1977a) which divides the San Juan basin to the southwest from the Chama basin to the east and the San Juan sag to the northeast (Fig. 2). A 12,000 ft (3700 m) section of Upper Triassic through Tertiary sedimentary and volanic rocks unconformably rests on Precambrian basement rocks. Several normal fault trends and Tertiary dikes occur in the mapped area.

Previous Work

The Pagosa Springs 7 1/2' Quadrangle was mapped by Hail (1965) in considerable detail. The 15' quadrangles to the southwest, southeast, and northeast were mapped in various degrees of detail by Dunn (1964) and Wood and others (1948). Studies of regional interest include Ryder (1977a and b), Read and others (1949), and Steven (1974). Except for the Pagosa Springs Quadrangle, these maps have been modified by air-photo interpretation and field mapping during this study.

Stratigraphy

Precambrian

Rocks of Precambrian age have been encountered in several wells in southern Archuleta County (Wood and others, 1948; Ryder, 1977a & b; and Barrett and Pearl, 1976) (Table 1). Restored stratigraphic sections by Ryder (1977a) show the occurrence of Precambrian igneous and metamorphic rocks at shallow depths beneath all of southeastern Archuleta County.

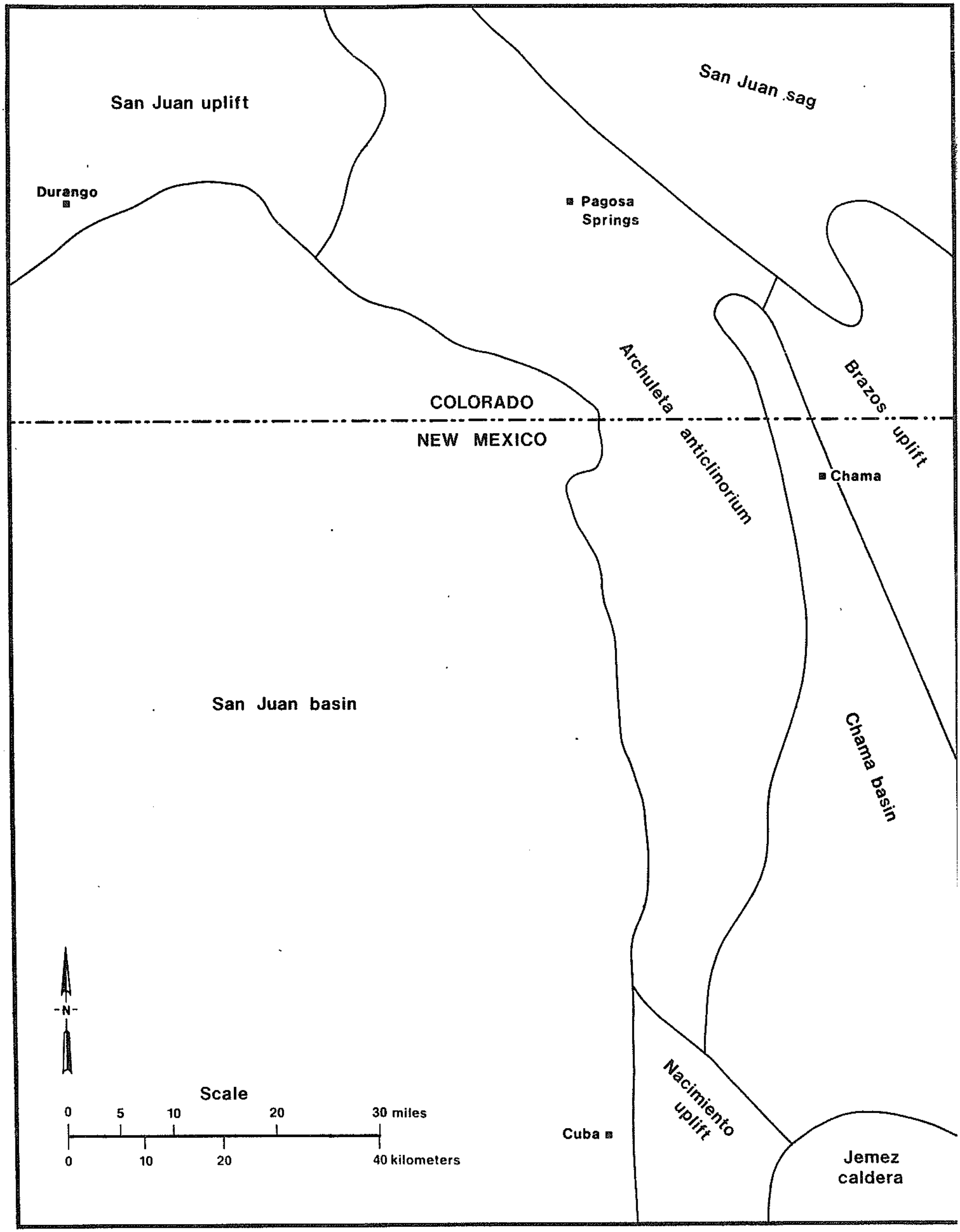


Figure 2 – Regional Structure of the Pagosa Springs Area, Colorado

Upper Triassic and Jurassic (?)

In the Piedra Canyon, 20 mi (32 km) west of Pagosa Springs, the Dolores Formation is 335 ft (10.2 m) thick and is comprised of red, brownish-red, gray, and purple shale, sandstone, and conglomerate (Wood and others, (1948) and unconformably overlies the Precambrian basement. On the Sunetha anticline, 3 mi (5 km) southwest of Pagosa Springs, 37 ft (11 m) of the Dolores Formation were encountered in a Wildcat oil well. The Dolores Formation was not seen in the CGS test holes or in outcrops in the map area.

Upper Jurassic

The Entrada Formation unconformably overlies the Dolores Formation and Precambrian igneous and metamorphic rocks in the Pagosa Area. Two hundred and thirty ft (70 m) of buff-, gray-, or white-mottled, massively crossbedded and cliff-forming sandstone is exposed in Piedra Canyon (Wood and others, 1948). The Entrada Sandstone is 117 ft (36 m) thick on the Sunetha anticline and 90 ft (27 m) in the CGS test well. "Sand grains are commonly round or subround, frosted, fine to coarse, and cemented by calcium carbonate, iron carbonate, and clay." (Wood and others, 1948) (See Table 13).

The Wanakah Formation conformably overlies the Entrada Formation. Along the Piedra River, the Pony Express Limestone member consists of 26 ft (8 m) of thin or papery-laminated, crinkled, fetid limestone and thin sandstone beds (Wood and others, 1948). One hundred and seven ft (33 m) of limestone and gypsum were logged on the Sunetha anticline and 96 ft (29 m) in the CGS test well. Along the Piedra River, the light-red sandstone and shale member consists of 70 ft (21 m) of red and pink sandstone, siltstone, and shale (Wood and others, 1948). This compares to 80 ft (21 m) in the Sunetha anticline and 50 ft (15 m) in the CGS test well.

The Morrison Formation, which is divided into two members, conformably overlies the Wanakah Formation. The white sandstone member, or "Upper La Plata" member, a massive white or light-gray sandstone, varies in thickness from 110 ft (33 m) along the Piedra River, to 218 ft (66 m) on the Sunetha anticline, and 56 ft (17

m) in the CGS test well. The overlying variegated sandstone and shale member is 334 ft (101 m) thick along the Piedra River, 420 ft (127 m) thick on the Sunetha anticline, and 519 ft (157 m) thick in the CGS test well. This member consists of gray, olive, brown, red-brown, and variegated shale interbedded with sandstone.

Upper Cretaceous

The Morrison Formation is disconformably overlain by the 117-270 ft (55-83 m) thick Dakota Sandstone (Wood and others, 1948). The lower member is buff, cross-bedded, massive, medium- to coarse-grained, and conglomeratic and is overlain by a dark-gray to buff, carbonaceous, silty middle shale member. The upper member is a buff, cross-bedded, massive, medium- to fine-grained sandstone (Wood and others, 1948) (see Table 13).

Although the Mancos Shale, which overlies the Dakota Sandstone, can be subdivided into numerous members, for mapping purposes the Mancos is undivided in this report. Hail (1965) (Plate 1), divides the Mancos into upper and lower parts, based on the amount of calcareous material versus shale. The Mancos Shale varies in thickness from 2100 ft (636 m) to 2370 ft (718 m) and is predominantly dark-gray to black, carbonaceous, moderately massive to fissile shales, interbedded with thin discontinuous sandstones and blocky, fossiliferous limestones.

Overlying and intertonguing with the Mancos Shale is the Mesa Verde Formation, which is composed of buff to gray, cliff-forming sandstones and interbedded gray shales. On the Piedra River, the Mesa Verde Formation is 365 ft (111 m) thick. Northeast of Pagosa Springs, the Mesa Verde Formation changes laterally into shales and thin sandstone beds and it is difficult to differentiate from overlying and underlying shales (Wood and others, 1948).

The Lewis Shale, consisting of 2400 ft (727 m) of dark- to light-gray shale, overlies and intertongues with the Mesa Verde Formation.

Cretaceous and Tertiary Rocks

The Animas Formation consists of gray, buff, brown, olive, and purple, fine- to coarse-grained sandstone, conglomerate, shale and siltstone 400-500 ft (120-150 m) thick. Pebbles and cobbles of Paleozoic and Precambrian rocks and angular to sub-rounded fragments of volcanic glass, andesite, and latite are common (Wood and others, 1948).

Blanco Basin rocks, up to 400 ft (121 m) thick, are similar to those of the Animas Formation; consisting of feldspathic sandstone and pebble conglomerate and silty shale. However, unlike the Animas Formation, metamorphic and plutonic rock fragments are abundant, and volcanic detritus is lacking (Dunn, 1964).

The Conejos Quartz Latite is the basal formation of the Potosi volcanic field (Dunn, 1964). This unit represents up to 5050 ft (1515 m) of erruptive volcanic and volcano-clastic rocks which comprise the majority of large rock exposures on the west side of the San Juan Mountains. Volumetrically, the Conejos Quartz Latite is the largest of the San Juan Mountains volcanic units (Dunn, 1964).

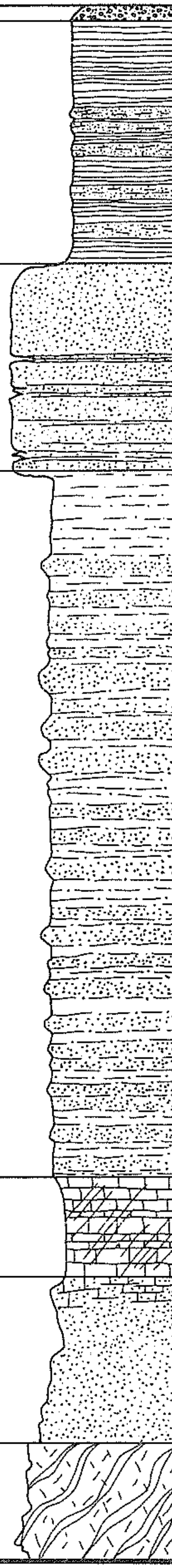
Numerous concordant plutons, including granodiorite, diorite, and syenites, found in the area are tentatively dated as Conejos (Dunn, 1964). North of Pagosa Springs, Cretaceous intrusives have been encountered in drill holes; for example, the oil exploration hole BMG 1 Quartz Creek (T.36N., R.2E., Sec. 5) (Ryder, 1977). These intrusives may be part of a subvolcanic batholith postulated by Lipman and others (1978) that lies beneath the San Juan volcanic field.

Lamprophyre and diabasic intrusives of Latest Miocene age occur throughout the area. Dikes up to 12 ft (3 m) wide and 8.5 mi (14 km) long, trend north-northeast and constitute the Archuleta dike swarm (Dunn, 1964). Bake zones up to 5 ft (1.5 m) wide are particularly prominent in the Mancos and Lewis shales. Evidence of hydrothermal alteration associated with the dikes is not seen (Dunn, 1964).

Quaternary Deposits

Terraces

Quaternary gravels occur on several surfaces in the area but are not subdivided in this report. These surfaces were described by Wood and others (1948) as pediments



AGE	FORMATION	THICKNESS (ft)	LITHOLOGY	DESCRIPTION
QUATERNARY	ALLUVIUM	10		Soil, sand, gravel, rounded boulders
UPPER CRETACEOUS	MANCOS SHALE	227		Shale, soft, very dark brownish gray, fissile. Locally contains some detrital sand, flakes of biotite. Pyrite in tiny (0.2 mm or less) clusters of cubes at 105 to 120 ft. Shale calcareous at 120 ft, and white calcite veinlets 120 to 160 ft. **237**
UPPER CRETACEOUS	DAKOTA SANDSTONE	198		Fine- to medium-grained, well-sorted arkosic sandstone with clots and streaks of carbonaceous matter. Some shales show slickensides, hydrothermal euhedral quartz, and pyrite crusts up to 1 mm thick on fragments of sandstone and shale. Barite clots occur with pyrite and euhedral quartz, up to 1 mm long. Sandstone, quartzite, light gray, medium- to coarse-grained, slightly arkosic. Sparse carbonaceous and shaly laminations. Pyrite on fractures at 399-402 ft. **435** Shale, black, with abundant quartz, silt and sand
JURASSIC	MORRISON	681		Sandstone, light greenish gray, very poorly sorted, poorly rounded, frosted grains. Some white and light greenish clays. Sparse disseminated pyrite cubes. Shale, medium gray and medium greenish gray, soapy, swells and disintegrates in water Sandstone, white, well rounded, frosted grains, medium- to coarse-grained, cemented by soft white clay. 20% chert pebbles. Pyrite in clots and single euhedral crystals on fragments. 30% sandstone, medium-grained, well sorted, calcareous cement. 20% sandstone, white, hard, chalcedonic(?) cement and altered white chalky lithic grains. 50% siltstone, medium dark brownish red. Lithic arenaceous sandstone, fine- to medium-grained, light to medium bluish grayish green, some gray and reddish brown. Well sorted, slightly to very calcareous. Sandstone, arkosic, light gray, medium-grained, well sorted. Sericitized feldspar and lithic fragments. Euhedral pyrite on fractured surfaces. Siltstone, dark purplish gray with pale green streaks, poorly sorted. Abundant fine-grained mica in some fragments. Alternating shales, sandstones and siltstones as above. Shale, medium to reddish brown, slightly to very **1116** calcareous
JURASSIC	WANAKAH	96		Limestone-anhydrite. White crystalline anhydrite in nodules 2-5 mm with fetid medium to dark gray finely crystalline limestone. Ave. 40% anhydrite. 1128-1139 ft, 60-70% anhydrite. **1212**
JURASSIC	ENTRADA	159		Limestone platy, laminated, 1-2 mm, black, 5% gypsum nodules. Few coarse (1 cm) selenite cleavage fragments. Sandstone, light gray, fine- to coarse-grained, very poorly sorted, well rounded, high sphericity, frosted grains, calcareous. At 1288 ft, rock is pale pink, arkosic, very hard, non-calcareous. Rock is carbonaceous at 1218 ft. Pyrite is found as tiny disseminated crystals, interstitial grains and 1-2 mm thick pyrite veinlets from 1228 to 1258 ft. 1258-1369 ft, rare disseminated crystals. **1371**
PRE-CAMBRIAN	BASEMENT			Gneiss, 40% fine-grained foliated biotite, 40% feldspar porphyroblasts. 0.5-1 mm, including 10% pink to orange to red microcline and 30% plagioclase, locally sericitized. 20% clear, glassy quartz in small grains in biotite. Red aplite at 1390. Granite, fine-grained, weak foliation. Migmatite lenses of pegmatitic orange microcline and quartz in biotite schist and gray granite schist. **1483-TD** Biotite gneiss

Figure 3 – Stratigraphic Section from Test Well P-1, Pagosa Springs, Colorado

but have been subsequently referred to as terraces by Dunn (1964). This author agrees with the latter interpretation because these features do not have the geomorphic characteristics of a pediment.

Alluvium

All alluvial deposits along the major river valleys and many tributaries and deep surficial material on broad upland areas are mapped as recent alluvium (Plate 1).

See Dunn (1964) for detailed lithologic and stratigraphic descriptions of preceeding formations.

Structure

Regional

The name Archuleta anticlinorium was first applied to the structural divide between the San Juan and Chama basins, the major structures of this region, by Wood and others (1948)(Fig. 2). The term has since been used by Dunn (1964) and Ryder (1977 a and b). "The Archuleta anticlinorium is characterized by 1) west- to northwest-trending, upright and inclined, plunging, cylindrical folds, 2) northwest-trending, longitudinal faults, and 3) northeast-trending transverse faults." (Ryder, 1977b). The anticlinorium is 75 mi (121 m) long and 6 to 16 mi (10 to 26 km) wide (Kelly and Clinton, 1960). This complex zone of faults and folding is the northward continuation of the basement cored Nacimiento and San Pedro Mountains of New Mexico (Wood and others, 1948 and Ryder, 1977b) (Fig. 2).

Except for minor structural growth during Paleozoic time, Ryder (1977b) attributes most of these structures to Laramide activity, which was strongly influenced by differential movement of faulted Precambrian basement. Many of these structures were probably rejuvenated during Middle to Late Tertiary uplifting and tilting (Ryder, 1977b).

Local

Faulting

The dominant fault trend in the Pagosa area is N40°W and vertical. Minor faulting occurs in east-west and north-south directions. Dip-separations range from a high of 300 ft (100 m) to less than 10 ft (3 m), which are relatively small compared to the lengths of these faults (Plate 1). The major fault in the Pagosa Springs area is a northwest-trending normal fault with 300 ft (100 m) of vertical displacement (Plate 1 and Fig. 4). The fault trace is relatively unaffected by topography, suggesting the fault is nearly vertical. This fault is here named the Eight Mile Mesa fault, after the prominent mesa which is transected by this fault (Plate 1).

Dunn (1964) attributes the faulting to flexing of brittle beds over the crest of the Archuleta anticlinorium which is thought to have grown after the deposition of the Eocene(?) Blanco Basin Formation. This implies that faulting occurred during Late Eocene time. Many of the faults displace dikes of Late Miocene age and other faults cross-cut, but do not displace dikes, making some of the faulting of Late Miocene age.

Folds

The Sunetha and Stinking Springs anticlines, trending N40°W, are the only named folds in the mapped areas. Two other anticlines, trending N60°W, occur near Pordonia Point and Oak Brush Hill in the southwest corner of the map area (Plate 1). A third anticline, trending N45°W, occurs on the eastern edge of the map. Relief on the bottom of the Dakota Sandstone is 525 ft (160 m) for the Sunetha anticline and 225 ft (70 m) for the Stinking Springs anticline (Fig. 4).

GEOPHYSICS

Introduction

Several geophysical surveys were run in the Pagosa Springs area during the

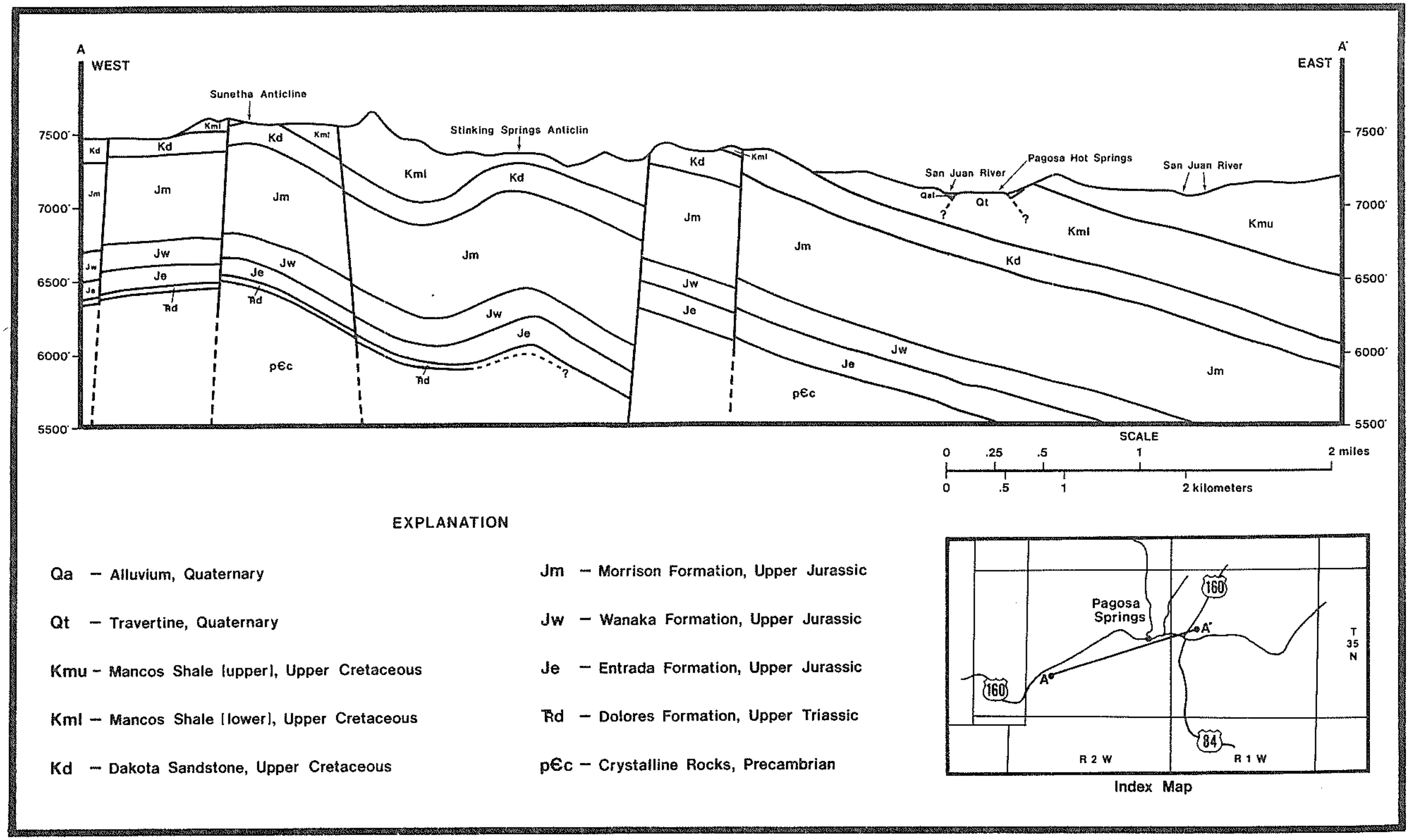


Figure 4 — Cross Section through the Pagosa Springs Area, Colorado

summer of 1977 by Geophysics Fund, Inc. (GFI) of the Colorado School of Mines for the CGS. These included two resistivity surveys, a seismic reflection survey, and a soil mercury survey. Unfortunately, none of these methods successfully defined subsurface conditions. However, the dipole and bipole surveys did delineate the same near-surface anomaly as the hot water well data.

Seismic Reflection Survey

Using a vibrator source, GFI ran three lines through the Pagosa area (Fig. 5). Utilizing a stratigraphic section from the Gramps Oil Field, located 20 mi (32 km) southeast of Pagosa Springs, three marker horizons were picked: Precambrian top 4000 ft (1212 m), Dakota Sandstone top 1600 ft (485 m), and the Mancos - Mesa Verde marker 400-500 ft (121-152 m). Later field work, additional data from oil and water wells, and confirmation by the geothermal test hole indicate the Dakota marker to be at approximately 400-500 ft and the Precambrian at 1400-1500 ft.

A major east-west-trending fault postulated by GFI to be just north of the hot spring cannot be substantiated. The only north-south vibroseis line was shifted about one-quarter mile (.4 km) (Fig. 5) along nearly the same east-west line as the postulated fault. Also, subsurface data from water wells do not indicate any displacements over 25 ft (8 m) of the sedimentary units across the Pagosa area.

Resistivity

Dipole-Bipole Survey (depth of penetration up to 1000 m)

This survey covered approximately 12 mi^2 (32 km^2) centered on Pagosa Springs. The bipole source was located 1.5 mi (2.4 km) south-southeast of the town along U.S. Highway 84 and was 2500 ft (750 m) long (Fig. 5).

Background resistivities range from 150-400 ohm-meters in the Pagosa Springs area (Fig. 5). Any area within the 100 ohm-meter contours should be considered anomalous and probably represent thermal reservoirs at depth (Keller, 1977). The significance of some of these anomalous areas, however, can be discounted because of the following observations. The anomaly northeast of Pagosa Springs along the

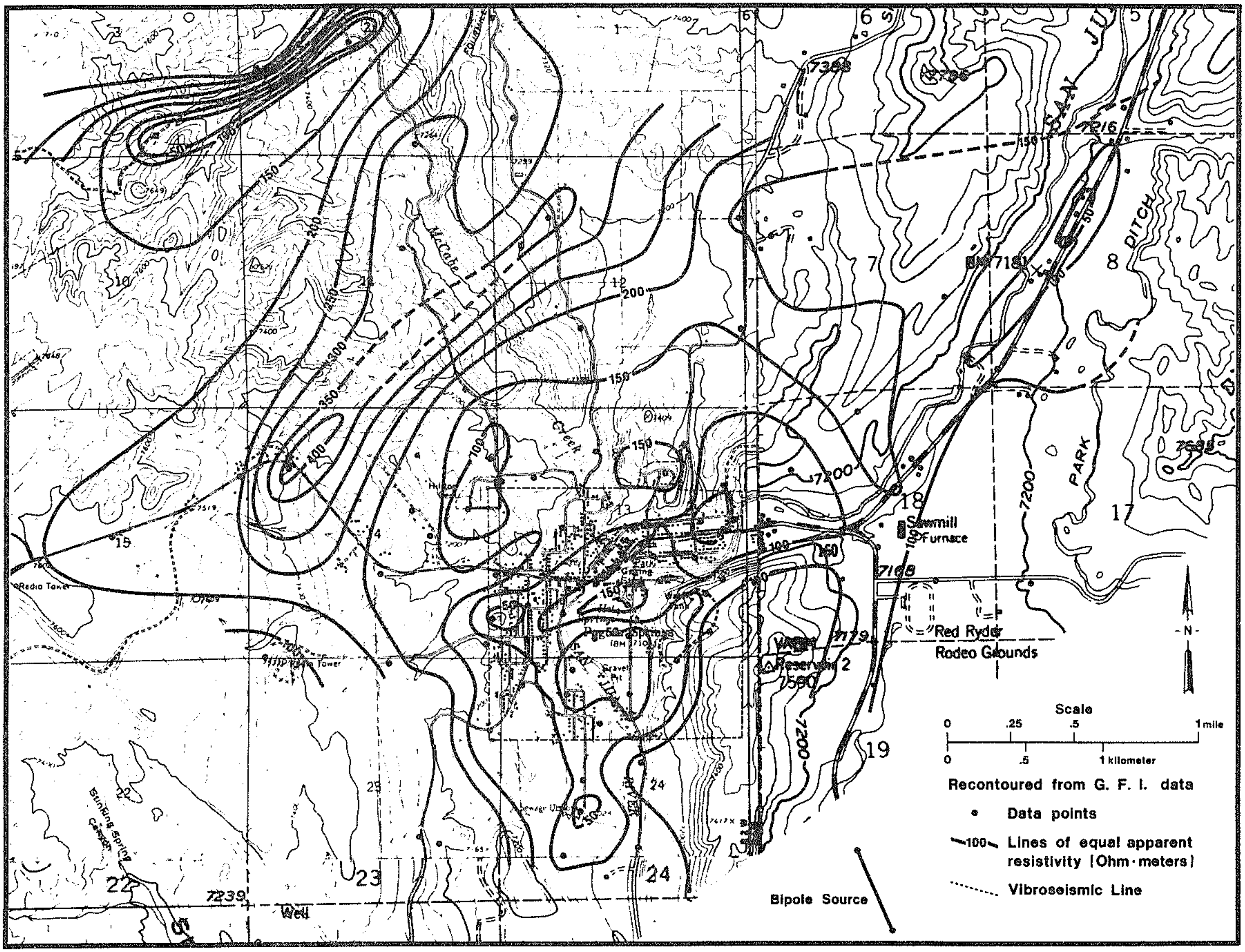


Figure 5 – Dipole – Bipole Resistivity, Pagosa Springs, Colorado

San Juan River is defined by a single low reading. Also, heat flow from two CGS wells within 1 mi (1.6 km) were the lowest in the area, 2.15 and 3.05 H.F.U. (Plate 2). The large anomaly 2.5 mi (4 km) northwest of Pagosa Springs is located along a buried gas pipeline and, therefore, suspect. The anomalies just northeast and northwest of the major spring anomaly cannot be explained as easily (Fig. 5). It is not known whether they represent hot water at depth or are due to some lithologic or cultural effects, but shallow wells drilled in these areas did not encounter hot water. The main anomaly is centered over the spring area (Fig. 5). The lowest resistivity values here are just south of the spring vent, suggesting either down-gradient discharge to the south or the main reservoir is south of the spring vent.

The shape of the southward extension of this anomaly does suggest down-gradient discharge. The resistivity high which partially divides the major anomaly into two sections has not been explained. These readings could be in error because of the difficulty in making good ground contact on the travertine mound, or it could represent an influx of cold water into and mixing with the thermal water. More points around the spring may have been useful.

Dipole-Dipole Survey - (depth of penetration up to 60 m)

The low resistivity values from this survey appear to center around the known hot springs (Fig. 6). This implies (1) the conduit is restricted to a well defined area beneath the spring, or (2) the deep survey failed to penetrate beneath the highly conductive hot water zone and therefore the dipole-bipole contour pattern is actually describing the near-surface conditions.

Soil Mercury Survey

The soil mercury survey failed to delineate any anomalous areas and will not be discussed here.

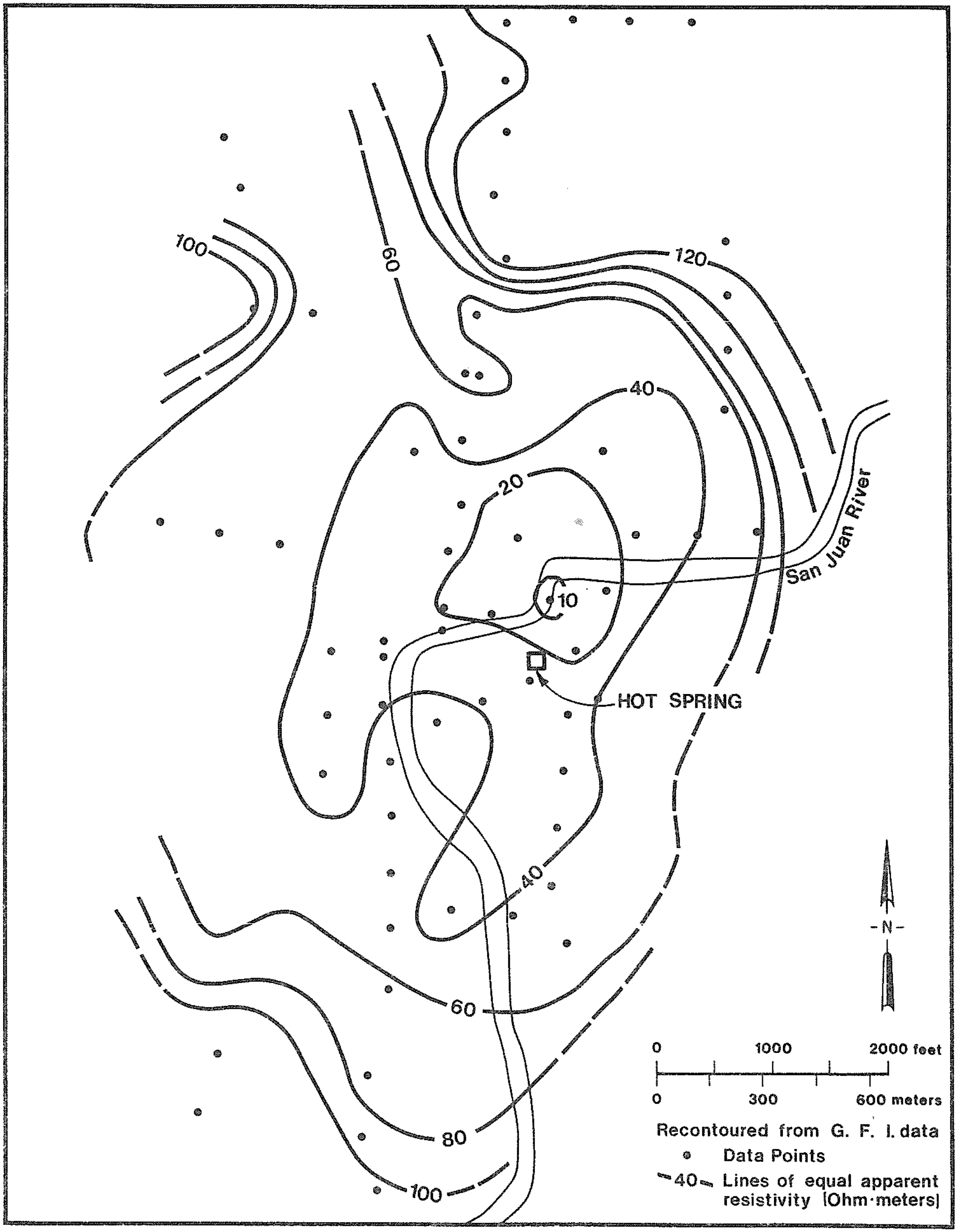


Figure 6 – Dipole – Dipole Resistivity, Pagosa Springs, Colorado

GEOTHERMAL

Introduction

The citizens of Pagosa Springs have used thermal water since the late 1800's. As many as 30 wells have been drilled to provide thermal water in heating systems and recreation. However, due to corrision problems and plentiful and inexpensive natural gas, many of the wells were abandoned. Now, increases in energy costs have made geothermal energy more appealing. As an indirect outcome of the CGS study, Pagosa Springs has been awarded a grant to use the thermal water in a district heating system.

In addition to the geothermal test well, a heat flow study and a survey of existing springs and hot wells were carried out. These studies will be discussed in this section.

Previous work

Except for brief geochemical and geothermometry studies, such as Barrett and Pearl (1977) and White and others (1976), very little published work has been done on the thermal system at Pagosa Springs.

Hot Springs

The main thermal spring, "A", is located near the top of a fairly large travertine mound on the east side of the San Juan River (Plate 1). The mound covers an area of approximately 0.03 mi^2 (0.07 km^2) mostly on one side of the river. A few large travertine blocks can be found on the other side of the river, but it is not known if they are in place. Elevation of the mound ranges from 7055 ft (2151 m) at the river to 7077 ft (2158 m) near the actual pool. The main spring or pool is about 25-35 ft (8-10 m) in diameter and of unknown depth. It has been reported that the spring has been probed to 100 ft (38 m) (Crouse, 1977, oral comm.) and 850 ft (260 m) (Vail, 1896) without finding the bottom. The validity of the last probe is uncertain. At one time the spring may have discharged a large quantity of water over the surface of the mound (Vail, 1896), but since wells have been drilled in the area, the water level appears to have dropped. Presently, the spring discharges through fractures and caverns below the surface and apparently feeds springs located at the periphery of the mound (Plate 2). Numerous outlets leading into the mound can be seen around the edge of the natural pool. Temperatures, discharge data, and chemical analyses are listed in Tables 2 and 3.

Thermal Wells

There are 27 known hot wells that have been drilled since the early 1900's in Pagosa Springs (Table 4), and only about half of these are in operation today. All of the wells presently in use, and presumably those which have been abandoned, are artesian. Piezometric pressures have been measured on only two of these wells (Table 4) because of poor well head conditions. The corrosiveness of the water made work on most well heads risky.

The areal extent of hot wells is limited to 0.04 mi^2 (0.1 km^2) (Plate 2). On the fringes of this area, warm water was encountered in wells 13DBAC (18), 13CBDC (17), and 13DCCC (25) (Plate 2). Outside this fringe area, only cold water was encountered (Plate 2).

Complete chemical analyses are available for only two wells, 13 CADC1 and 13 DBCD1 (Table 5). There seems to be no significant difference between the water of these wells and the spring water.

Heat Flow Study

Six 300 ft (100 m) deep holes were drilled by G.F.I. around the Pagosa Springs area to aid in interpretation of the geophysical data and in selection of a test drilling site. These holes were located at about the same elevation and purposely kept from flowing hot and cold water areas to increase the reliability of the readings.

All holes were cased with 2-inch PVC and sealed at the bottom. The casing was filled with water and the hole backfilled. After stabilization, the gradients were measured at 10 ft (3 m) intervals, using a Gearhart-Owen temperature probe. Thermal conductivities were estimated by Arthur L. Lange of Amax Inc. Gradients measured by Amax correlated extremely well with CGS data (Table 6).

TABLE 1. Wells Which Have Encountered Precambrian Rock, Archuleta County, Colorado

WELL NAME	LOCATION	ELEVATION (ft above MSL)	DEPTH TO PC (ft)	PRE-CAMBRIAN LITHOLOGY	DEPTH (ft) THERMAL WATER ENCOUNTERED	WATER TEMP. (°C)
Wirt-Franklin No. 1 - Sullenberger	35N02W 28	7580	1323	Granite		
Phillips No. 1 Crowley	32N01E 12	7672	1515	Quartzite		
Cameron No. 1 Bramwell	33N01E	8000	2300			
Hughes No. 51 Gramp's	33N02E 24	8100	2217			
Dutch Crowley Artesian Well	32N02E 19ADD	7752	1732	Quartzite	1732-1741	70
Hughs No. 1 Johnny Miller	32N03E 2	9010	4148			
Eoff Artesian Well	34N01W 18AB	7160	1303	Quartzite	1313-1327	39
P-1 (CGS Test Well)	35N02W 13CADC5	7060	1371	Granite/ Quartzite	1371-1483	44

TABLE 2. Inventory of Thermal Spring Vents, Pagosa Springs, Colorado

Vent Number	Temp. (°C)	Discharge (gpm)	Elevation (ft)	Conductance (mmhos/cm)	pH
A	55	0	7077	4200	6.5
B	44	50-75	7065	4050	
C	41	25-35	7060	4150	
D	43-49	less than 1 gpm for each vent	7063		
E	55		7073		

TABLE 3. Chemical Analysis of Hot Spring Vent A, Pagosa Springs, Colorado

Constituents	Concentration (Mg/l)
Arsenic (As)	.1
Boron (B)	2.3
Cadium (Cd)	0
Calcium (Ca)	230
Chloride (Cl)	180
Fluoride (F)	4.8
Iron (Fe)	.02
Lithium (Li)	2.9
Magnesium (Mg)	24
Manganese (Mn)	200
Mercury (Hg)	0
Nitrogen (N)	0.01
Phosphate (PO_4)	
Ortho diss. as P.	0.07
Ortho	0.21
Potassium (K)	85
Selenium (Se)	0
Silica (SiO_2)	59
Sodium (Na)	730
Sulfate (SO_4)	1,300
Zinc (Zn)	.01
Alkalinity	
As Calcium Carbonate	702
As Bicarbonate	856
Hardness	
Noncarbonate	0
Total	670
Specific conductance (Micromohs):	4,340
Total dissolved solids (TDS)	3,040
pH, Field	6.5
Discharge (gpm):	260
Temperature (°C):	54

From Barrett and Pearl (1976)

TABLE 4. Thermal Well Inventory, Pagosa Springs, Colorado

WELL LOCATION	TEMP. (°C)	ELEVATION (ft above MSL)	WELL DEPTH (ft)	CASING DIA. (in)	PRESSURE (PSI)*	WATER LEVEL DATE MEAS.	WATER LEVEL ELEVATION (ft above MSL)		USE	YIELD (GPM)	AQUIFER	DATE DRILLED OR ABANDONED OWNER
35N02W												
1. 13CAAC	56	7100	340	8	Flowing			1.	H	30	M/D	1968; Methodist Church
2. 13CAAD1	58	7090	384	6	Flowing			2.	H	4490(?)	D	1920's; Superior Auto
3. 13CAAD2		7090						3.	A			1975; Universal Telephone
4. 13CAAD3		7085						4.	A			1964; Rexall Drug
5. 13CACD		7075			Flowing			5.	H			Vic Poma
6. 13CADA1	54	7078						6.	T/M			1954; Pagosa Springs
7. 13CADA2		7078						7.	A			Pagosa Springs
8. 13CADB1	59	7079	301		36.5	9/18/78	7163	8.	H	400	M?/D	1955; Buhler
9. 13CADB2		7080			Flowing			9.	U			Citizen's Bank
10. 13CADB3	54	7080			Flowing			10.	H			1900's; Adobe Inn
11. 13CADB4		7080			Flowing			11.	H			Mark Wilsey
12. 13CADB5	54-67(?)	7080	282	4.5	Flowing			12.	H	140(?)	M?/D	1921; Glen Edmonds
13. 13CADC1	56	7063	85		36.5	9/18/78	7147	13.	H	3-500	M	1930; Archuleta County
14. 13CADC2	56	7063	85		Flowing			14.	A	100	M	1920; Archuleta County
15. 13CADC3	44+	7063	85		Flowing			15.	U		M	1935; Archuleta County
16. 13CADC4	57	7065	85		Flowing			16.	H			Vic Poma
17. 13CBDC	31	7100			Flowing			17.	U			Archuleta County
18. 13DBAC	34	7065	468	4	Flowing			18.	M	50-100	D/Mr	1960; O.L. Sanders
19. 13DBBB1	51	7100			Flowing			19.	M			School District No. 50
20. 13DBBB2		7100						20.	A			School District No. 50
21. 13DBCC1		7065	385		Flowing			21.	U		D	Spring Inn
22. 13DBCD1	46	7065	400+		Flowing			22.	R		D?/Mr	Mike Giordano
23. 13DBCD3	43	7065			Flowing			23.	R			1954; Mike Giordano
24. 13DBCD2	52	7065	400+		Flowing			24.	R		D?/Mr.	Mike Giordano
25. 13DCCC	22	7080	213		Flowing	12/14/73	7120	25.	S	45	M?/D?	Morgan
26. 24BCDD	2	7030	500		Flowing			26.	A		D?/Mr.	School District No. 50
P-1 13ACDC5	44	7060	1483	6	84	11/28/78	7254		U	200	pC	1978; CGS (Temporary)
O-2 13ACDC6	44	7060	780	6.5	60	8/15/78	7199		U	500	D/Mr.	1978; CGS (Temporary)
32N01E 19ADD	70	7742	1741	8	Flowing				I	225	pC	Crowley
34N01W 7CDD	39	7120	1331	8	Flowing				I	300	pC	Griffith

Explanation:

USE
- H - Heating
- A - Abandoned
- U - Unused
- T - Tourist Attraction
- M - Melting Snow
- R - Recreation
- I - Irrigation
- S - Stock

AQUIFERS
- M - Mancos Shale
- D - Dakota Sandstone
- Mr - Morrison Formation
- pC - Precambrian Basement

*Pressures were not measured on most wells. Refer to text.
Sequential numbers refer to well locations on Plate 2.

TABLE 5. Chemical analyses of water from thermal wells, Pagosa Springs, Colorado

Constituents	CONCENTRATIONS (Mg/l) 35N02W13CADC1	35N02W13DBCD1	34N01W18AB
Arenic (As)	.09	.08	.02
Boron (B)	1.8	1.9	.45
Cadium (Cd)	0	0	0
Calcium (Ca)	250	230	640
Chloride (Cl)	170	160	20
Fluoride (F)	4.5	4.4	2.6
Iron (Fe)	.02	.21	3.0
Lithium (Li)	2.8	2.9	.4
Magnesium (Mg)	25	24	29
Manganese (Mn)	.27	.25	.22
Mercury (Hg)	0	0	0
Nitrogen (N)	0.01	0	
Phoshate (PH_4)			
Ortho diss. as P	0.05	0.04	
Ortho	0.15	0.12	
Potassium (K)	89	91	22
Selenium (Se)	0	0	0
Silica (SiO_2)	52	51	45
Sodium (Na)	780	780	160
Sulfate (SO_4)	1,500	1,600	1,800
Zinc (Zn)	.01	.01	.03
Alkalinity			
As Calcium Carbonate	704	618	175
As Bicarbonate	858	753	213
Hardness			
Noncarbonate	23	56	1,500
Total	730	670	
Specific conductance (Micromohs):	6,300	6,000	2,500
Total dissolved solids (TDS)	3,320	3,320	2,830
ph, Field	6.5	6.5	7.0
Discharge (gpm):	30		50
Temperature (°C):	56	53	39

From Barrett and Pearl (1976)

Table 6. Geothermal Gradients and Heat Flow

Hole Number	Total Depth(M)	Formation at T.D.	Gradient 1,°C/km(1)	Gradient 2,°C/km	Gradient 3,°C/km	Gradient 4,°C/km	Heat Flow (H.F.U.)(2)
G-1	48	Dakota Sandstone	158.9 / 158.8	127.5 / 130.8	58.3 / 78.0		4.76
G-2	87	Mancos Shale	114.1 / 78.0	52.0 / 56.1	200.3 / 146.4	132.7 / 113.4	4.17
G-3	86	Dakota Sandstone (?)	55.6 / 37.8	230.7 / 159.0	101.7 / 96.6		3.59
G-4	84	Dakota Sandstone (?)	110.7 / 99.8	66.0 / 59.0	153.8 / 128.0		2.97
G-5	88	Mancos Shale	83.2 / 83.2				3.05
G-6	87	Mancos Shale	78.9 / 71.0	59.9 / 58.7			2.15

(1) Numerator is CGS data, denominator is Amax Inc. data
Gradients 1-4 refer to straight-line segments of temperature versus depth curves. Depth increases from 1-4.

(2) Heat flow calculations are from Arthur L. Lange of Amax Inc.
Refer to Plate 2 for hole locations.

Calculated heat flows show a progression of low to high from east to west across the Pagosa Springs area (Plate 2). However, the validity of hole G-1 is questionable because it is only 154 ft (47 m) deep, compared to approximately 300 ft (100 m) for the other 5 holes. The GFI drill rig could not penetrate the Dakota Sandstone, which was encountered at a depth of 154 ft (47 m).

HYDROLOGY

Introduction

The near surface groundwater regime is dominated by the San Juan River and its tributaries and by local structures. As a consequence, the relatively abundant surface water and poor quality water in the shallow aquifers, has limited groundwater development. The varying geology and scarcity of data make any attempt at system definition a generalization at best.

The two main aquifers exploited in the Pagosa area, are the Mancos Shale and Dakota Sandstone, however, a few wells have been drilled in the Morrison Formation. Hot water wells were discussed above and will not be included here. The hot water - cold water relationship will be discussed in the conclusions.

Previous Work

No known published work discusses the hydrogeology of the Pagosa area. Pearl (1972) briefly comments on the groundwater availability in southern Archuleta and Hinsdale counties. An unpublished U.S. Soil Conservation Service (SCS) map (1969) gives a few well locations and water levels around Archuleta County. Iorns and others (1965) discuss the surface hydrology, including water quality, of the San Juan River drainage basin.

Aquifers

Alluvium

The extent and thickness of alluvium in the Pagosa area is both limited and variable. As in the lithologic description, alluvium includes all surficial deposits of Holocene age. Many wells in the Pagosa area are completed in the alluvium because of its water bearing charactertistics and shallowness. Groundwater occurs generally under water-table conditions, but may be locally semi-confined. Yields range from 5 gpm (.3 l/s) to 60 gpm (4 l/s) with specific capacities of .1 to 600 gpm/ft (Table 7). This gives estimated coefficients of transmissivity ranging from 1000 gpd/ft to 60,000 gpd/ft.

Groundwater in the alluvium is generally good quality due to recharge by the various streams and rivers during high flows. Alluvial groundwaters in the Pagosa area tend to be a calcium bicarbonate type (Iorns and others, 1965). However, in irrigated areas, water returned to the streams via the alluvium tends to be of poorer quality; higher in dissolved solids, particularly sulfate.

Mancos Shale

The Mancos Shalé is exposed over much of the mapped area, particularly around Pagosa Springs (Plate 1). Most of the wells in this area, are completed in either the Mancos or the Mancos and overlying alluvium and are as much as 200 ft (60 m) deep (Table 7).

Groundwater flow in the Mancos Shalé is the result of both fracture and intergranular porosity. Many of the discontinuous sands yield moderate amounts of water under semi-confined conditions. Without being able to identify and correlate specific aquifers, the construction of water level or piezometric surface maps from well data is very difficult. Also, because the water level data are distributed over a 20 year period, the water surface map should be inconsisent and somewhat random. However, in plotting the data, it became apparent that the data are more regular than expected and the resultant contour pattern fits reasonably well with known surface hydrologic conditions (Plate 3, Fig. 1). This may be due to a pervasive fracture network superimposed over the porous units. The fractures may interconnect isolated porous units sufficiently to "smooth out" water pressures within the numerous Mancos aquifers, allowing the formation to become, in a sense, homogeneous. Also, seasonal and annual fluctuations may not be significant with respect to the contour interval chosen (Plate 3, Fig. 1).

The water surface map (Plate 3, Fig. 1) suggests areas of local recharge to the west, north, and east of Pagosa Springs. This may or may not include the area of Mancos exposure adjacent to the Eight Mile Mesa fault southwest of Pagosa Springs. A local discharge area occurs about 2 km south of Pagosa Springs along the San Juan River. Recharge to the San Juan River may occur along much of its course through the Mancos Shale, but because of limited data, this is not apparent in Plate 3, Fig. 1. These areas of recharge and discharge correlate very well with geologic and topographic conditions.

Yields and specific capacities of wells in the Mancos Shale are highly variable. Yields range from 1-2 gpm (.06-.12 l/s) to 20-30 gpm (1.3-2 l/s). Specific capacities range from .01 to 200 gpm/ft and average .4 gpm/ft. Many of the higher values are due to reported drawdowns of zero, which may be in error. Estimated coefficients of transmissivity, assuming a storage coefficient of 0.2, range from less than 100 gpd/ft to 30,000 gpd/ft. Some of the wells with high specific capacities may also be partially completed in alluvium.

Groundwater quality of the Mancos Shale is generally poor. Total dissolved solids range from 1000 to 2500 mg/l, with particularly high concentrations of sodium, calcium, iron, and sulfate. Dissolved hydrogen sulfide is also common. However, there are undocumented claims of relatively good quality groundwater from the Mancos, and these may be from wells completed in relatively clean discontinuous sands which may be in connection with alluvium.

Dakota Sandstone

The Dakota Sandstone is exposed along the crest of the Sunetha and Stinking Springs anticlines and on the northeast side of the Eight Mile Mesa fault (Plate 1). Generally, because of economics, wells that are completed in the Dakota Sandstone are limited to areas of Dakota exposure or very thin Mancos Shale (Plate 3, Fig. 2).

Groundwater flow in the Dakota Sandstone is the result of fracture porosity and is confined. Individual aquifers cannot be identified using available data, but it is probable that at least two semi-independent aquifer (fracture) systems exist, separated by black shale sequences.

TABLE 7
Well Inventory, Pagosa Springs Area, Colorado

WELL LOCATION	ELEVATION (ft above MSL)	WELL DEPTH (ft)	CASING DIA. (in)	WATER LEVEL DEPTH (ft)	WATER LEVEL DATE MEAS.	ELEVATION (ft above MSL)	USE	Pumping Data Yield (GPM)	Pumping Data Drawdown (ft)	Pumping Data Specific Capacity (gpm/ft)	Aquifer	Owner
32N								32N				
01E04DB		35	5 1/2	2	6/2/75			8	32	.25	A	Phillip Sayles
02E03DB		45	7	14	9/10/72			20	0	200	M?	Frances Bramwell
01W13BDB		130	4	60	7/2/74			2	110	.02	A/M	John Albert Martinez
01W24DB		57	7	30	9/10/70		D	4	45	.09	A	Ben F. Trujillo
03W11CD		76	6 5/8	28	2/27/67		D	15	30	.5	A/M	Modesta Ortiz
04W17AD		65	6 5/8	40	5/4/67		D	5	20	.08	A?	Chris Chavez
04W18BB		85	6 5/8	60	11/11/69		D	10			A/M?	Ernest Herrera
05W04CC		160	6	50	9/29/73			3			M	Clifford Sappington
05W16BCB		206					Id	3	42		M	Denver & Rio Grande W. RR
05W17BA		123	6 5/8	70			I	12		.07	M?	Vernon Clark
05W17ACD		116	6 5/8	24			C	10			M?	Willard Seibel
33N								33N				
01E10CA		140	6	60	7/18/66			12	130	.09	M?	B.C. Gibson
02E13CD		35	4	10	8/16/74			20	0	200	A	Wm. Hughes
02E24CC		30	4	4	8/6/74			20	0	200	A	Wm. Hughes
02W01BD		25	8	12	5/25/66		D	10	15	.67	A	James Berry
02W01BA		225	4	180	9/25/75		D	4	200	.02	M	Joseph Doyle
02W028CC		50	8	25	5/6/66		D	20	30	.67	A	T.J. Bond
02W32AA		35	6 5/8	6	7/29/72		D	15			A?	Alwin Bever
02W32AC		26	6 5/8	10	7/30/71		D	5			A/M	San Juan River Land Dev.
03W16AB		72	6	50	5/13/70		D	6	54	.11	M	Juan Garcia
03W16AA		90	4	60	9/11/75		D	5	0	50	M	Margarita Garcia
07W11CD		120	6	70	9/11/73			1.5	115	.01	D ?	Ira & Janice Peacock
34N								34N				
01E01CB		41	7	12	9/10/70			10	20	.5	A	Willard March
01E03CD		150		62	7/24/65			30			A/M?	Charles Olgestep
01E12AD		39	8	8	7/28/67			5	35	.14	A	Robert Hand
01E31AD		40	6 5/8	8	7/26/71			10			M?	U.S. Forest Service
02E06BBC		12	6				D				A?	Ruby Sisson
02E06AC1		20	36	8	9/1/38						A?	M.V. Beighley
02E6AC2		80	8	30	5/18/64							M.V. Beighley
01W05CD	7400	76		48	6/13/63	7352	D				M?	V.N. Chameers
01W05AC	7440	121	8	36	6/10/67	7404	D	2	100	.02	M	Dorothy Anderson
01W06BC	7240	115	6 5/8	55	4/19/71	7185	D	4			M	Division of Fish & Game
01W08BD	7240	160	7	65	5/6/71	7175	D	3	150	.02	M	Ken Hamblin
01W16BB	7300	170	6	80	7/20/71	7220	D	2	160	.01	M	Dolores Geffert
01W27DCC		35	8	28	6/14/65		D	40	0	400	A	D.C. Slade
01W28DB		85	4	60	10/28/75		D	4	0	40	A?	Brice C. Finley
01W31AD		11	8	5	6/27/71		D	10	6	1.67	A	Robert Brooks
01W31AA		82	5 1/2	12	9/27/72		D	10			M?	Edward J. Hart
01W32BD1		10	8				D				A	William Moyers
01W32BD2		70	6	50	10/10/67		D	2	60	.03	A	B.T. Collver
01W32AA		108	6	68	8/2/68		D	10	96	.10	A	Irvin Mathes

WELL LOCATION	ELEVATION (ft above MSL)	WELL DEPTH (ft)	CASING DIA. (in)	WATER LEVEL DEPTH (ft)	WATER LEVEL DATE MEAS.	ELEVATION (ft above MSL)	USE	Pumping Data Yield (GPM)	Pumping Data Drawdown (ft)	Pumping Data Specific Capacity (gpm/ft)	Aquifer	Owner
01W32BC1	6840	232	6	150	9/11/68	6690	D	1	228		M	Dean N. Owens
01W32BC2	6840	150	6 5/8	70	8/15/69	6770	D				M	Bunleson T. Collver
01W32BA	7000	117	7	67	9/25/71	6933	D	3	105	.03	M	George Buldain
01W34AA1		100	6	40	8/29/68		D	10	80	.13	M	Delbert Hart
01W34AA2		20	4	8	6/16/76		D	10	10	1.0	A	Beverly M. Still
01W35AC1		50	6	18	9/1/69		D	2	40	.05	M?	Frank Farrar
01W35AC2		102	6	15	6/24/71		D	6	80	.08	M	Frank Farrar
01W35BC		16	60	4	10/26/74		D	2	6	.33	A	Robert Jewett
02W15BC	7150	45	6	20	8/27/68	7130	D	20	20	1.0	M	Robert Blair
02W29DD	6780	345	5	140	5/28/72	6640	D	2	306	.01	M	Fred Martinez
03W01A	7360	100	4	50	11/24/73	7310	D	10	60	.17	D	Sam & Peggy Ellis
03W01CA		165	5 1/2	48	6/21/73		D	5	140	.04	M	A.B. Granby
03W01DD		28	5	8	11/16/73		D	7	20	.35	A/M?	David McNeily
03W01DB		110	6	20	12/2/75		D	2	95	.02	M	David Bell
03W03BB		49	8	38	6/65		D	11			M	J. R. Welch
03W03BD		100	6 5/8	81	6/25/68		D	10			M	John Welch
03W11CC		140	5	60	10/21/72		D	10	108	.09	M	Robert D. Whittington
03W11BD		65	5	30	8/10/74		D	6			M	Tom Fite
03W12BA		135	5	16	10/5/72		D	9	67	.13	M	Art Hamilton
03W12BB		70	6	43	9/24/75		D	4	64	.06	M	Hubert Renick
03W14BB		77	6	30	6/12/75		D	10	58	.17	M	William Morgan
03W14BD		154	6	85	6/10/75		D	5	110	.05	M	Ralph Oldham
03W15ABB		40	8	15	6/13/64		D	60	0	600	A	R. L. Tiday
03W26CC		60	7	50	4/21/67		D	10	60	.17	M	M. W. McGilvray
04W14ABB		125	6 5/8	50	11/24/73		D	2.5	115	.02	M	Colo. Div. of Wildlife
04W07UDB		135	7	38	6/58		D	2				Southern Ute Tribe
04W08CDC		187	7	42			C				M	Charles Blunden
07W15BA		200	7	115	3/31/73			14			D	Floyd & Arlene Beaver
07W19CC		95	5 1/2	14	9/12/73			15	52	.29		Donald Anderson
35N								35N				
01W05AA1	7190	50		8		7182	D	12			Mv	James Watkins
01W05AA2	7190	40		12		7178	D	10			Mv	James Watkins; Ray T.
01W7CC1	7150	41		12		7138	D	6			M	V. A. Poma
01W7CC2	7150	70		20		7130	D	15			M	L. M. Adams
01W7CC3	7150	70(?)		4		7146	D	15			M	J. B. Hersch, C. McCoy
01W07DD1	7160	41	6	12	5/21/71	7148		6	27	.22	M	V. A. Poma
01W07DD2	·7160	10	14	4	1965	7156		15			A?	Joseph Hersch
01W08AB		220		0	4/18/72						D	Ward Carpenter
01W8CC	7180	72		8		7172	D	30			M	Troy Barber
01W8AB	7235	220		0(?)		7235?	D	4			M	W. F. Carpenter
01W14BBB		25	8	10	11/20/65			10	20	.5	A	P. W. Birdsall
01W15BC		74	7	36	11/24/73			34	0	340	A	Edward Neiman
01W15BD	7540	74		36		7504	D	15			MV/A	Edward Neiman
01W17BB	7195	105		54	4/15/59	7141		12			M?	Paul A. Decker
01W17DB	7280	540		0		7280 ?	D					H. Cole

TABLE 7
Well Inventory, Pagosa Springs Area, Colorado (continued)

WELL LOCATION	ELEVATION (ft above MSL)	WELL DEPTH (ft)	CASING DIA. (in)	WATER LEVEL DEPTH (ft)	WATER LEVEL DATE MEAS.	ELEVATION (ft above MSL)	USE	Pumping Data: Yield (GPM)	Pumping Data: Drawdown (ft)	Pumping Data: Specific Capacity (gpm/ft)	Aquifer	Owner
01W18DAC	7180	85	6	27	5/8/65	7153		35	30	1.17	M	San Juan Lumber
01W18AA	7170	100	6 5/8	28	10/4/61	7142		3	50	.06	M	Delbert Thayer
01W18DD	7180	185	7	174?	6/4/65	7006 ?	D	20	150	.13	M	Leon Montroy
01W18DC	7170	130	8	97	6/20/60	7073	D	5	105	.05	M	Victor Cole
01W19BA	7190	125	8	85	12/15/58		D	25	110	.23	M	Leon Montroy
01W19BDC	7160	125	8	85	12/1/60	7075	C	25	110	.23	M	Leon Montroy
01W19AB	7170	35	7	5	11/20/71	7165	D	10	20	.5	M	Leon Montroy
01W23DD	8000	47		20	8/3/68	7980	D	5			A	Felipe Maez
01W23DB	7960	105	5	40	5/2/72	7920	D	10			Mv?	Tom Read
01W30AB	7120	134	8	65	12/6/65	7055	D	4	125	.03	M	John Lord
01W30DD1	7220	86	8	30	7/6/70	7190	D	4	801	.05	M	Stanley Wrobel
01W30DD2	7220	203	6	65	8/7/71	7155	D	2	190	.01	M	Stanley Andrews
01W30AC	7120	70	4	30	4/17/74	7190	D	3	60	.05	M	M. B. Lord
01W31ADA	7240	247	6	89	1973	7151	D	6				Mark Smith
01W31AD1	7235	130	8	50	12/22/66	7185	D	5	120	.04	M	O. L. Sanders
01W31AA	7230	60	8	36	10/14/67	7194	D	30	62	.48	M	Jimmie Cooper
01W31DD	7260	107	8	38	5/24/68	7222	D	6	90	.07	M	George Masco
01W31DC	7240	278	6	68	7/6/67	7172	D	4	260	.02	M ?	Lionel Adams
01W31AD3	7235	140	8	97	11/22/69	7138	D	4	120	.03	M	O. L. Sanders
01W31DA	7235	54	8	10(?)	12/11/69	7225	D	4	40	.1	M	First Baptist Church
01W31AA2	7230	87	8	20	6/24/70	7210	D	2	80	.03	M	V. Day
01W32AA	7440	42	6	18	11/30/66	7422	D	10	30	.33	A ?	Archule
01W32BB	7240	65	8	31	6/23/69	7209	D	2	52	.04	M	Earle Wise
01W32CC1	7325	125	7	80	10/12/71	7245	D	6	110	.05	M	Albert Schnell
01W32CC2	7325	121	6	80	11/6/71	7245	D	10	90	.11	M	Jim Boatright
01W32BA	7360	115	6	76	12/17/71	7284	D	10	80	.13	M	Robert Houser
01W32BB2	7240	750	8	23	11/7/71	7217	D	15	70	.21	D	Ilene Moore
01W32CC3	7325	97	6	30	11/25/71	7295	D	8	90	.09	M	Troy Barber
01W32CC4	7325	145	6	80	5/15/72	7245	D	6			M	Hal F. Eier
01W34AC	7720	100	8	28	9/9/67	7692	D	10	80	.13	M	Mitchell Swanson
01W36AD		113	8	60?	10/27/67		D	5	100	.05	Mv	R. O. Nelson
02W01CCC	7300	150	4	1	10/15/73	7299	D	15	10	1.5	M	Norbert Buchholz
02W07BB	7615	148	10	Flowing	8/1/66	7615 +	D	45	112	.40	D	U.S.D.A. F.S.
02W08DB	7520	170	6	140	6/21/71	7380	D	10	0	100	D/M?	Fred Ebeling
02W10CC	7630	138	6 5/8	32	9/24/62	7598	D	3	56	.05	D	T. L. Carrigan
02W12CB	7400	125	4	30	8/25/64	7370	D				M	Edna Turney
02W12BD	7280	80	4	4	8/29/73	7276	D	5	10	.5	M	P. A. Wedemeyer
02W14AAB	7240	47	8	35	5/65	7205	D	1	45	.02	D	E. R. Crouse
02W14BB	7400	124	8	30	1/25/66	7370	D	5	92	.05	D	Harry Smith
02W15BD	7600	50	7	6	9/27/62	7594	D	10	31	322	M	T. L. Corrigan
02W15BC	7595	85	6 5/8	54	8/12/64	7541	D	8	74	.11	D	USDA FS
02W15AAA1	7485	46	8	28	8/13/65	7457	D	10	38	.26	M	Lee V. Ogden
02W15ACA	7600	67	8	38	8/27/65	7562	D	20	38	.53	M	Santana Lujan
02W15AAA2	7485	65	8	45	10/21/65	7440	D	5	55	.09	M	William F. Wilber
02W15CB	7602	122	8	54	11/11/65	7548	D	5	115	.04	D	USDA FS

WELL LOCATION	ELEVATION (ft above MSL)	WELL DEPTH (ft)	CASING DIA. (in)	WATER LEVEL DEPTH (ft)	WATER LEVEL DATE MEAS.	ELEVATION (ft above MSL)	USE	Pumping Data Yield (GPM)	Pumping Data Drawdown (ft)	Pumping Data Specific Capacity (gpm/ft)	Aquifer	Owner
02W15DAA	7580	66	8	58	2/1/66	7522	D	3	56	.05	D	Robert Snow
02W15DD	7480	67	8	56	2/12/66	7424	D	30	101	.3	D	Milton D. Remey
02W15CB2	7602	107	8	54	3/1/66	7548	D	1	100	1.01	D	Gerard Cripe
02W15AC1	7620	81	8	40	7/31/66		D	4	76	.05	M	Henry Trujillo
02W15ACA2	7620	170	8	90	9/28/66	7530	D	2	160	.01	D	Santana Lujon
02W15CA	7580	78	8	48	10/24/66	7532	D	4	75	.05	D	Forrest E. Bozani
02W15AC3	7600	75	8	20	10/10/66	7580	D	5	65	.08	M	C. E. Gay
02W15CC	7510	94	8	40	11/12/70	7470	D	1	80	.01	D	Fred Harmon
02W15DA	7500	80	4 1/2	10	12/6/72	7490	D	15	11	1.36	D	Robert Snow
02W15BD2	7600	90	4	20	9/20/75	7510	D	5	70	.07	D	1st Assembly of God Ch.
02W16BAAA	7560	70	7	22	6/14/72	7538	D	3			D	Stanley Belmear
02W16ADC	7610	300	6 5/8	270	6/19/71	7340	C	1	0	10	D	Over Niter Inc.
02W16DA1	7595	320	8	250	9/28/65	7345	I	30	220	.14	D	R. J. Sullivan
02W16DA2	7595	104	6	15	9/9/71	7580	D	6	90	.07	D	Fred Ebeling
02W20DB1	7540	200	6 5/8	32	3/28/66	7508	C	5	150	.03	D	Navajo Trail Truck-O-Tel
02W20DB2	7540	110	6 5/8	30	3/25/66	7510	D	4	60	.07	D	Jim Garven
02W20DB3	7540	78	6 5/8	30	3/25/66	7510	D	4	36	.11	D	Bernie Harris
02W20DB4	7540	72	8	26	4/19/66	7514	D	10	50	.2	D	Marol Harris
02W20DC	7540	93	6 5/8	60	3/16/67	7447	D	3	20	.2	D	M. W. Mendal
02W20DBA	7529	70	10				C					Wt. Williams
02W20DBB	7524	200	6	72	1974	7452					D	Eaton Industries
02W20CD	7515	82	6	30	5/13/67	7485	D	5	70	.07	D	F. A. Thompson
02W32ODB5	7540	66	8	16	8/15/67	7524	D	6	55	.11	D	Milo Smith
02W20DB6	7540	70	10	35	11/27/67	7505	D	6	64	.09	D	M. T. Williams
02W20DB7	7540	125	8	60	11/15/69	7480	D	10	75	.13	D	M. T. Williams
02W20BD	7520	73	8	13	10/2/69	7507	D	2	65	.03	D	Vern L. Smith
02W20AB	7495	135	5	60	9/21/72	7435	D	12	85	.14	D	M. W. Mendell
02W21BCD		35	8	5	5/23/62		D	4			A?	J. F. Whitefield
02W21BDB		35	8	8	5/23/62		D	4			A	J. F. Whitefield
02W21AB	7517	200	8	175	10/12/65	7342	D	2	190	.01	M	Herbert Tishner
02W21BB	7500	42	8	20	6/15/70	7480	D	10	30	.33	M	Navajo Trail Corp.
02W22CC	7360	46	6	Flowing	9/25/71	7360 +	D	15	15	1.0	D	W. W. Scoggins
02W23AD	7140	130	7	50	6/8/58	7090	D	10	70	.14	D	W. F. Wall
02W23AD2	7140	50	6	23	11/3/68	7117	D	6	43	.14	D	Donald Martinez
02W23AC	7260	52	6	32	11/16/78	7228	D	5	45	.11	D	Roger Sanchez
02W23AB1	7260	25	6 5/8	10	3/5/70	7250	D				D	Reymundo Maez
02W23DD	7200	53	8 5/8	5	5/13/70	7195	D				D	David Maez
02W23DA	7180	21	6	10	8/17/71	7170	D	6	16	.38	D	Reymundo Maez
02W23DB	7210	30	6	6	6/29/74	7204	D	6	24	.25	D	Felipe Maez
02W23AB2	7260	100	6	47	9/6/73	7213	D	8	65	.12	D	Reymundo Maez
02W24DB		20	6	12	5/11/66		D	5	12	.42	A	A. M. Gomez
02W24BC	7100	50	8	22	5/1/70	7078	D	5	40	.13	M	Harland Pierce
02W26BD	7200	45	8	39	4/26/66	7161	D	10	35	.29	D	John Snow
02W26DC	7085	140	4	85	5/56	7000	D				M?	Jeanette Smith
02W27ADA	7160	130	6 1/4	20	7/21/74	7140	D	4	97	.04	M	Wm. V. Flowers
02W29CB	7435	65	6	45	8/30/71	7390	D	10	60	.17	D	Harley Merrick

TABLE 7
Well Inventory, Pagosa Springs Area, Colorado (continued)

WELL LOCATION	ELEVATION (ft above MSL)	WELL DEPTH (ft)	CASING DIA. (in)	WATER LEVEL DEPTH (ft)	WATER LEVEL DATE MEAS.	ELEVATION (ft above MSL)	USE	Pumping Data Yield (GPM)	Pumping Data Drawdown (ft)	Pumping Data Specific Capacity (gpm/ft)	Aquifer	Owner
02W29DD	7620	182	6	92	2/10/72	7528	D	12	110	.11	M	Fred Smith
02W29DC	7560	150		90	10/20/73	7470	D	6	110	.06	D?	Stunt Dodge
02W29CC	7460	126	5	44	10/12/72	7416	D	12	103	.12	D	S. E. La Rose Jr.
02W29DD2	7620	200	4	160	12/5/74	7460	D	2	170	.01	M	L. A. Wunsch
02W32AA	7640	200	5	65	10/25/71	7575	D	7	170	.04	D/M	C.R.C. Rye
02W32AC	7545	135		23	7/5/73	7522	D	10	87	.12	M?	Jack Shoemaker
02W32AD	7670	150	4	100	10/2/75	7520	D	5	120	.04	M	Allen W. Gilpin
02W33DBD	7560	420	6	236	1974	7324	D					Eaton Industries
02W36AA1	7320	85	6 5/8	70	6/16/65	7250	D	20	90	.22		Co. St. Dept. of Highways
02W36AA2		194	6	144	8/31/67	7176	D	20	0	.20	D	Co. St. Dept. of Highways
02.5W25AA		242	6	80	11/12/71		D	10	202	.05	D	Eaton International
02.5W27AD		35	6	12	9/17/75		D	6	25	.24	A/M	Robert Chance
02.5W35AC		60	6	44	12/12/68		D	3	50	.06	M	Raymond Baugham
02.5W35AB		170	6	101	9/5/75		D	6	135	.04	M	Verrita Faye Stevens
03W01CD		42	5	30	10/21/71		D	8	30	.27	M	Harold Arnoldson
01E34DB		185	8	150	6/3/69			2	160	.011	M	Melvin Lattin
02E20DDA		42	5 1/2	24	2/26/63		D	4	26	.15	A?	Steve Vidal
02E20DDB		29	7	16	2/23/63		D	30	0	300	A	F. E. Farkley
02E20DBB		80	8	68	7/6/65		D	30	0	300	A?	H. S. Wallis
02E20DDD		51	8	10	6/25/65		D	30	20	1.5	A	Richard G. Leech
02E20DB1		45	8	22	6/8/66		-	20	34	.59	A	James C. Hayes
02E20DB2		81	8	60	6/15/66		-	15	70	.21	A	Leon R. Lance
02E20DB3		75	8	50	6/25/66			20	55	.36	A	Morris Justice
02E20DD1		22	8	12	7/6-7/67			20	0	200	A	Francis LeBaron
02E20DB4		92	8	72	9/14/68			12	81	.15	A	Leon R. Lance
02E20DD2		32	8	15	9/21/68			10	23	.44	A	Francis LeBaron
02E20DB5		118	7	71	8/14/70			10	80	.13	A	K. W. Timmerman
02E20DB6		110	6 5/8	80	11/9/72			10			A	Orin J. Merrell
02E25AA		36	7	20	9/25/70			8	20	.4	A	R. L. Read
02E28BB		75	7	35	5/2/67			10			A	4M Enterprises, Inc.
02E29AA1		33		16	2/21/63			30			A	K. Seaver
02E29AA2		31		16	2/20/63			30			A	E. E. Richards
02E31AC		14	24	8	5/10/46			9			A	X. V. Beighley
02E31CD		78	4	6	9/18/72			4	10	.4	A ?	T. S. McConnell
36N								36N				
01W22CC		300	6 5/8	50	8/19/66		D	75			M	Hanna Construction
01W28AA1		51	8	20	9/8/66		D	35	0	350	L	H. C. Carmody Inc.
01W28AA2		80	6 5/8	20	8/15/66		D	5	45	.11	L	Charles Godfrey
01W30CD1		42	8	30	11/7/67		D	5	35	.14	L	Louis Poma
01W30CD2		67	8	28	6/7/71		D	4	50	.08	L	Louis Poma
01W36BB		95	5	16	9/29/72		D	4			L	Louis Poma
02W11ACB		120					D	15			M	David Goodman
02W22AC		57	6	18			D	6	50	112	A?	Pentab Properties
02W31DC	7820	143	6 5/8	130	8/7/64	7690	D	30	142	.21	D?	U.S.D.A. F.S.
02.5W14AB		300	4	165	10/6/75		D	5	210	.02	M	Marion Smith

WELL LOCATION	ELEVATION (ft above MSL)	WELL DEPTH (ft)	CASING DIA. (in)	WATER LEVEL DEPTH (ft)	WATER LEVEL DATE MEAS.	ELEVATION (ft above MSL)	USE	Pumping Data Yield (GPM)	Pumping Data Drawdown (ft)	Pumping Data Specific Capacity (gpm/ft)	Aquifer	Owner
03W35BBB		125	8	105	10/20/64		D	1	125	.01	D?	S. Gilbert
37N								37N				
01E16CC	7000	80	6 5/8	25	8/12/66			10	45	.07	A	Charles Ferris
01E20AD		18	17	6	10/4/74			10	6	1.7	A	Glen H. Arthur
01E29AA		38	8	25	11/21/67			5	35	.14	A	Frank Teal
03E9DC		100	8 5/8	90	6/10/61			30			M	John Taylor
38N								38N				
01W13BDB		131	7	72	8/10/64		D	3	83	.04	M	W. R. Duke
03W17CC		62	8	42	6/2/60		D	5			M	U.S.D.A. F.S.
03W19CD		70	7	15	9/1/60		D	15	0?	150	M?	U.S.D.A. F.S.
03W19CAD		55	7	12	9/5/60		D	15	0?	150	M?	U.S.D.A. F.S.
03W30ACC		28	8	23	6/10/64		D	20	0?	200	A	Emmit. Evans
03W30AC		28	8	15	8/25-27/69		D	10	23	.44	A	C. B. Norton
03W31AA		51	8 5/8	41	6/11/67		D	4	45	.09	A?	U.S.D.A. F.S.

Explanation:

USE

D - Domestic
C - Commercial
Id - Industrial
I - Irrigation

AQUIFER

A - Alluvium
L - Lewis Shale
Mv - Mesaverde Formation
M - Mancos Shale
D - Dakota Sandstone

Problems with the Dakota Sandstone data are similar to those discussed for the Mancos Shale. As with the Mancos Shale, the contours drawn from this data seem to fit reasonably well with known geologic and hydrologic conditions.

Areas of recharge, as defined by the piezometric surface map (Plate 3, Fig. 2), correspond extremely well with exposures of Dakota Sandstone (Plate 1). Plate 3, Figure 2 indicates that Pagosa Springs may be an area of regional discharge from the Dakota Sandstone. The Dakota is not exposed in this area, suggesting discharge occurs through fractures and/or faults into Mancos Shale and possibly the surface. The delineation of the discharge area, however, does not reflect accurate measurement of hydraulic head on flowing wells within this area.

Adequate well data does not exist to determine the effect of the Eight Mile Mesa fault on the piezometric surface.

Water Quality

The quality of groundwater from the Dakota Sandstone is highly variable. Much of the water is very similar to that of the Mancos Shale while some of the water is much lower in total dissolved solids and meets national drinking water standards. Sufficient analyses are not available to make any generalization as to water quality distribution.

Other Aquifers

Sufficient data are not available to discuss aquifers below the Dakota Sandstone.

DRILLING PROGRAM

Introduction

The intention of the CGS test drilling program at Pagosa Springs was to confirm the existence of a thermal reservoir at depth and to evaluate the reservoir with respect to various hydrologic characteristics. Since the intended use of the thermal waters was direct application purposes, a depth limit of 2000 ft (610 m) was considered to be the economic limits of this type of development.

Locating the test well sites proved to be a difficult problem. Geophysical, geological, hydrological and heat flow surveys were not definitive, but indicated that an anomally did exist and was restricted to an area of one square kilometer, centered under the downtown area (Plate 2). However, the main obstacles in locating a drilling site were land ownership and physical space to drill; county, city, and school district land parcels were either too small or located on the fringes of the anomally. Most other land was privately owned.

Fortunately, Mr. Bill Lynn, District Water Commissioner, Colorado Division Water Resources, owner of the land between the San Juan River and the county courthouse allowed the use of his land for test drilling. A legal agreement was reached between Mr. Lynn and the county, city and school district regarding the ownership of the well and the sale and distribution of any produced water. Although equipment movement would be somewhat difficult due to several saturated areas, this land would provide easy access to the river for both the disposal and the pumping of water needed in the drilling program. This site also was sufficiently close to existing wells to permit pressure monitoring during drilling and testing phases.

All preliminary work, including well design, location, permits, and contractor selection, started in January, 1978. Since project preliminaries consumed more time than planned and the contractor was delayed by poor weather, the actual drilling was postponed until June 10, 1978. Drilling difficulties, due mostly to large quantities of flowing hot water, required the eventual cutback of the intended program and extension of the entire drilling project schedule. Drilling was finally suspended on September 20, 1978 because of a lack of funds and little indication of higher temperatures within the targeted depths, 2000 ft (610 m).

Predrilling Phase

Using U.S. Department of Energy (DOE) guidelines, an environmental report was prepared by the Denver Research Intitute (Koulet and Armstrong, 1978). This report describes the proposed drilling activity and various environmental aspects of the site.

Specifications for the drilling program were started in early January, 1978. Existing well data and surface geology were used to determine expected depths to the various formations. The suspected subsurface geology and meager hydrologic data were incorporated in the well designs and locations. Two slim observation holes were planned, one 2000 ft (610 m) deep, the second 400 ft (123 m) deep. The main test hole was to be 2000 ft (610 m) deep. The three holes were to be located with respect to each other so as to provide the most reliable data during the reservoir testing phase.

Because high volumes of thermal water were expected, discharge to the San Juan River was required during both the drilling and testing phases. This required a discharge permit from the Colorado Department of Health. The request for a permit was submitted January 16, 1978 and permission granted March 27, 1978. The Air Pollution Control Division of the Department of Health determined on March 20, 1978 that a permit was not required.

In compliance with the Colorado Geothermal Act of 1974, a drilling permit was required from the Colorado Oil and Gas Commission. A permit application was submitted February 8, 1978 and approved by the commission March 20, 1978. Pearl and others (1978) discuss problems associated with the permitting process.

The drilling specifications were submitted to 15 capable drilling contractors in the Rocky Mountain region. Of these, three bids were returned within the specified time. The bids for one test well and two observations holes, as stated above, were as follows:

1) James Drilling Company Wheatridge, Colorado	$167,773.50
2) Layne-Western Company, Inc. Denver, Colorado	$310,840.00
3) XL Drilling Montrose, Colorado	$508,752.50

The capabilities of these bidding contractors were evaluated, but because of the bid spread, the ultimate decision had to be based on the lowest bid. Inflation and the high demand for rigs in the Rocky Mountain region resulted in higher bids than expected.

Drilling Phase

Site Preparation

The intended site (Fig. 7) did not require much preparation. Vegetation, trash, and large concrete slabs were removed and flow-lines and mud pits were dug. Originally, the flowline was to extend to the San Juan River, but a change in design plans stopped the flowline about 60 ft (20 m) short, allowing the water to spread, facilitating the cooling (Fig. 7). Water required for drilling was obtained from the San Juan River.

Observation Wells

0-1

This hole was to be a slim 2000 ft (610 m) deep observation well, 0-1. Information gathered from the drilling of this hole would aid in finalizing the design of P-1.

James Drilling Company commenced drilling on June 10, 1978, using a a Speedstar SS-22 drilling rig. Large boulders and unconsolidated soil and sand and gravel required installation of 23.8 ft (7.4 m) of 10.75 in. conductor pipe. Drilling continued rapidly in the Mancos Shale with air-mist until about 300-500 gpm of 56°C water was encountered at a depth of 90 ft (28 m). Drilling continued, using produced water, to the top of the Dakota Sandstone, where 235 ft (73.4 m) of 8.625 in. surface casing was installed and cemented. A 10 in. gate valve and a single stack blowout preventer (BOP) were installed on this casing.

An air-percussion hammer was used to drill through the Dakota Sandstone and into the Morrison Formation. The available compressed air was insufficient to lift the large volumes of thermal water encountered in the Dakota Sandstone and to yield

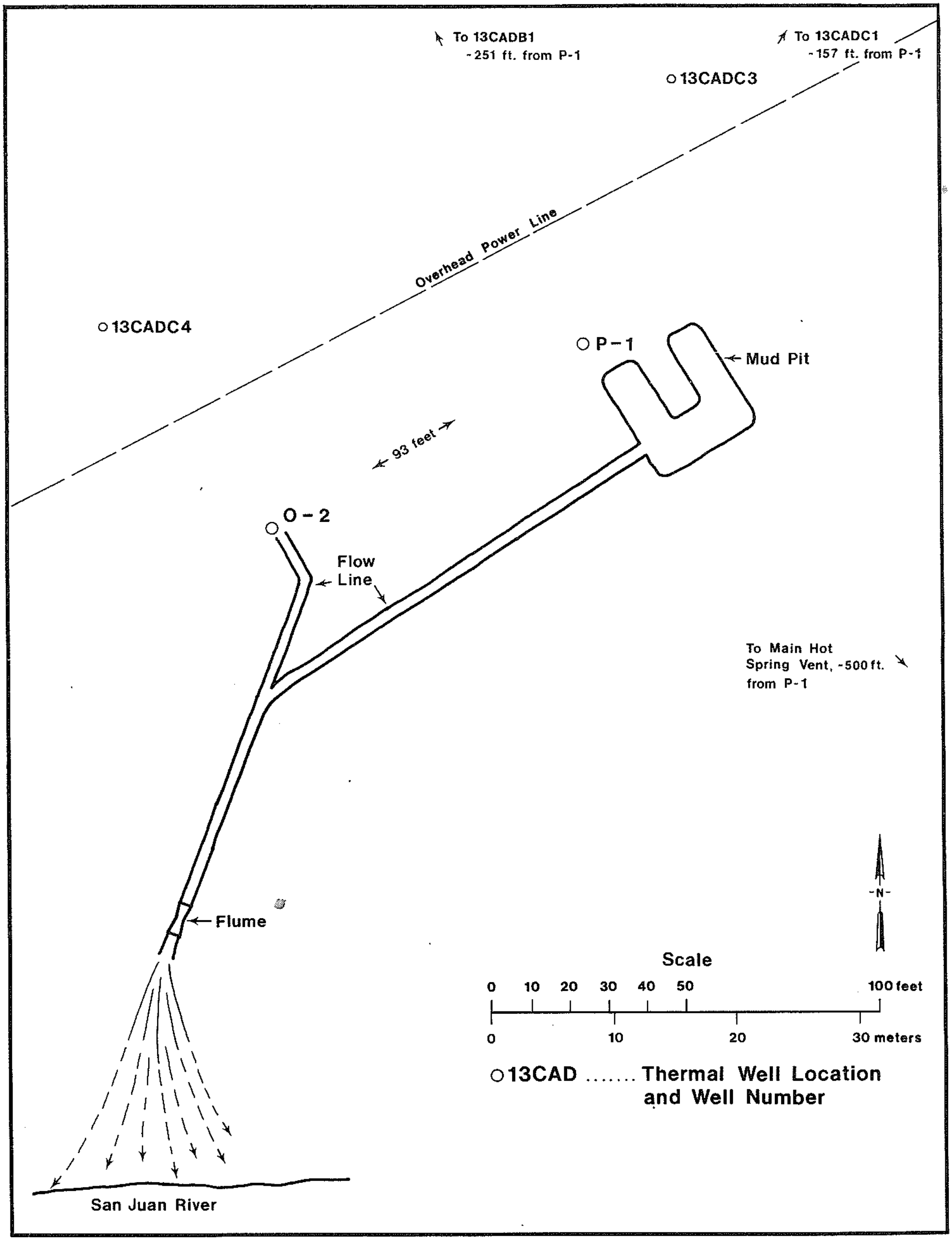


Figure 7 – Site Plan of Test Well Area, Pagosa Springs, Colorado

footage rates. After the repair of the on-board compressor and the addition of a booster, drilling rates again improved to 1-5 ft/min (.03-1.6/min) and only occasionally as low as .2 ft/min (.06 m/min). On June 30, a depth of 780 ft (240 m) was reached, but upon entering the hole on July 5, after a 4-day break, the maximum depth achieved was 640 ft (200 m). Severe caving was occurring between 580 ft (181 m) and about 700 ft (219 m). After nearly 12 hours all attempts to blow caving material from the hole failed, and there was no further recourse but to abandon O-1. Mud could not be used because of the relatively high pressure and high volume thermal water at such shallow depths. Casing could not be installed because the hole diameter would then be too small to proceed to 2000 ft (610 m).

Instead of completely abandoning O-1, it was decided to designate it O-2 (Fig. 7), the shallow observation well, and proceed with the large diameter well (P-1), where hopefully the caving could be handled. The option to drill O-1 later was reserved, dependent on the successful drilling of P-1 and funds remaining.

P-1

On July 26, 1978, 12 ft (3.75 m) of 22 in. culvert was installed to avoid potential problems with unconsolidated gravels and boulders resting on the Mancos Shale. Drilling started July 29 with a 20 in. rotary bit. Thirty-five feet (10.9 m) of 16 in. conductor pipe was installed and cemented. When drilling resumed again on August 15, heavy collars, a reamer, and stabilizer were added to avoid some of the problems encountered in O-2. It was intended to drill through the caving zone in the Morrison Formation, case, and continue down to the Precambrian basement. However, at a depth of 250 ft (78 m), a small-displacement fault was encountered which yielded between 1500-2000 gpm of 60°C water to the surface. This flow had such a drastic effect on existing wells and the spring that the well had to be cased as soon as possible, precluding any testing. Casing (12.625 in.) was run from the surface to a depth of 265 ft (83 m) (the interval between 265 ft [83 m] and 308 ft [96 m] filled with debris from the fault zone) and cemented.

After drilling through the same caving zone as encountered in O-2, the hole was cased with 571 ft (178 m) of 8.875 in. casing and cemented. A 7.875 in. hole was

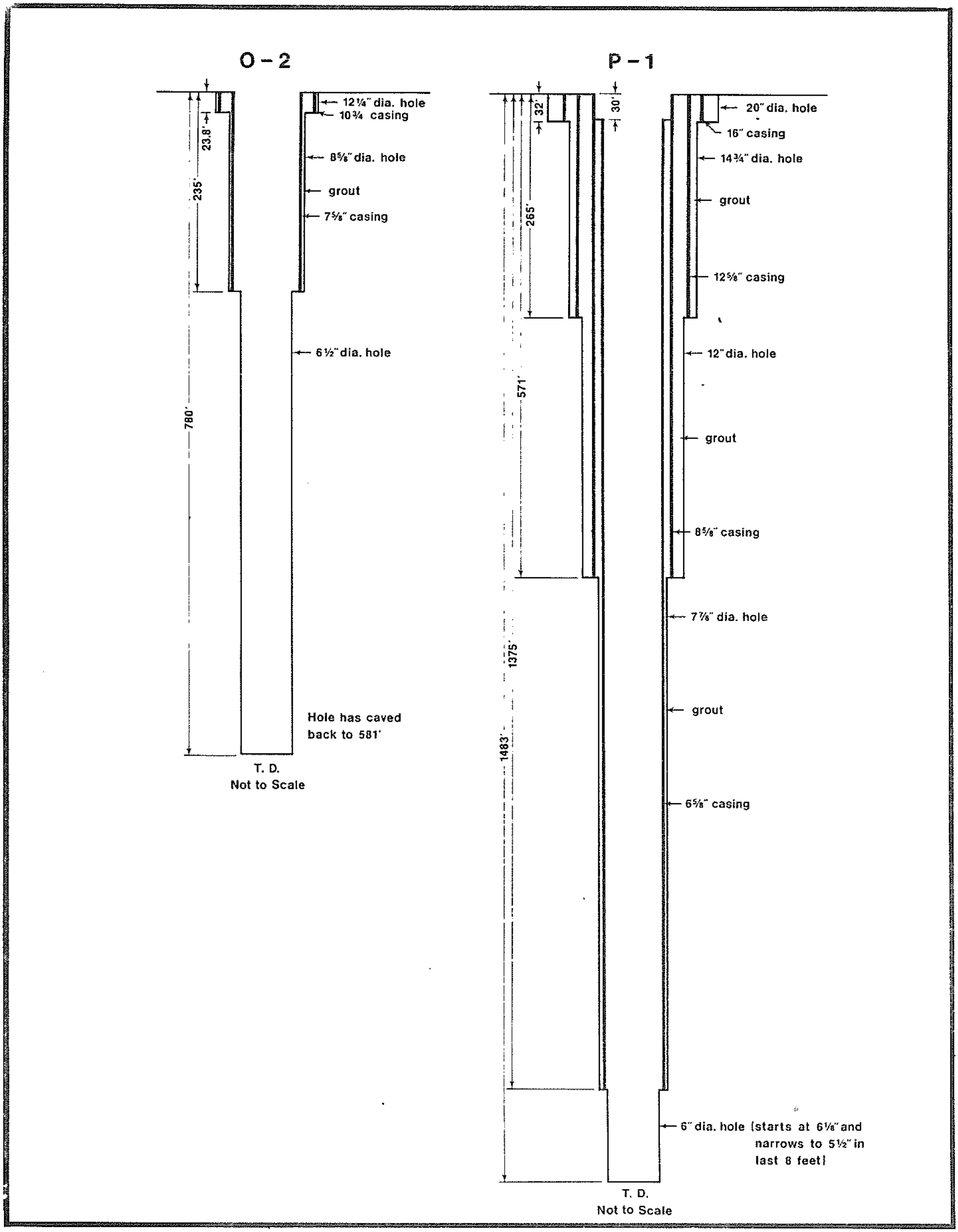


Figure 8 – Well Completion Diagrams of Wells O-2 and P-1

drilled to the top of the Precambrian at 1371 ft (428 m) where another large flow, 1000-1500 gpm at 45°C, was encountered. A back-off tool was used to install 6.625 in. casing from the Precambrian basement to within 30 ft (9 m) of the surface (Fig. 8). After cementing, a 6 in. air-hammer was used to drill to 1475 ft (461 m) in crystalline rock.

A 6 in. diamond core bit was worn out in less than 1 ft in an attempt to core from 1,475 ft (461 m) because of a tight hole and slight dog-legs. A 5.5 in. diamond core bit was used from 1475-1483 ft (461-463 m), where either as a result of poor bit design and/or fractures, all the diamonds around a lip on the circumference of the bit were worn off, causing the air system to pressure-up. Coring was terminated at 1483 ft (463 m). Core recovery of only about 75% was probably due to the intense fracturing.

A series of temperature surveys run under flowing conditions, did not reveal any increases in bottom-hole temperatures. In light of the lower temperatures (45°C), lateness of the season (people were starting to depend on their wells for heat), and the lack of funds, it was decided to terminate the drilling on September 20, 1978.

Subsequent temperature surveys run in November, 1978, under shut-in conditions did not show any elevated temperatures (Fig. 13).

Problems

One of the most difficult and expensive problems was cementing the various casing strings. Haliburton Inc. provided cementing services throughout the project. After the first two attempts at 200 sacks each completely washed out of the hole, a "hot" (CaCl), weighted cement was used after cooling the hole with river water for several hours.

The cement problems were never really solved but were minimized by a procedure developed by Mr. Loyd Franzen (see Recommendations). Both cement overruns, which were typically 100-400%, and extra rig time amounted to a significant cost increase (see Cost Analysis).

Another problem encountered during the latter part of the project was cement which would not set properly. This was attributed to poor quality cement. Haliburton attempted without much success to locate a better source of cement.

Large volumes of flowing thermal water created numerous problems. Before the BOP and rotating head were installed, wash outs around the rig and burns to the driller and helpers were time consuming and annoying, respectively. Steam on cold mornings, hydrogen sulfide gas, corrosion of metal parts, baking of lubrication from various threaded joints all contributed to the job difficulty. On several occasions, high flows increased the air demand sufficiently to require the addition of more compressors and a booster.

The relatively high water pressure at such shallow depths hindered cementing, casing installation, and the ability to shut the well in, prior to the BOP and valve installation.

Equipment failures are common to any drilling program and a fair share of equipment breakdown occurred during the drilling of these two holes. Some of the breakdowns can be attributed to the difficult drilling conditions.

Difficult hole conditions, such as fractured zones, very hard, silicified sandstones, and caving contributed significantly to increased drilling time and equipment failures.

Recommendations

The procedure developed by Mr. Loyd Franzen, involves staging the cement rather than injecting a calculated amount plus a large overrun. It was found that a smaller amount of cement was required if it were pumped into the well in stages, allowing each stage adequate time to set prior to injecting the next stage. If the "hot" cement was pumped through as slowly as possible, fractures would be filled, with some loss at the surface. It is not known whether each stage reduced the total water flow, but the staging method seemed to allow the final cement injection to stop the flow easier than one or two large injections of cement, while using less total cement.

This procedure may be a significant contribution to work under fractured rock and flowing water conditions. The method, however, should be tested under more quantitatively controlled conditions to more fully evaluate the procedure.

The use of a larger rig may have eliminated much of the time-loss due to wash-out beneath the tires of the Speedstar SS-22 rig. Wash-outs would still occur, but would have little affect on a larger rig. Also, a larger rig would have facilitated the installation, and in several cases, the repair of the BOP and large diameter valve.

Cost Analysis

The maximum contracted amount for the completion of three wells, two at 2000 ft (610 m) and one at 400 ft (122 m) deep, was $167,773.50. This figure was primarily based on various footage rates for drilling and casing installation.

Despite the partial completion of the project (P-1 to 1483 ft., 0-2 to 780 ft.), the total amount expended, excluding direct borehole geophysical logging costs, was $163,588.82.

The major cost categories and percentages of the total are given below. The numerator is the actual amount spent and the denominator is the amount attributed to drilling problems, as discussed above.

	Cost	Percentage of Total Cost
Mobilization and Demobilization	$ 10,000	6.1%
Direct Drilling Costs	71,774 / $15,089	43.9%
Casing, Cement, Wellhead Equipment	$ 72,454.82 / $ 26,511.60	44.3%
Coring	$ 8,190.00 / $ 7,830.00	5.0%
Geophysical Logging (Standby Time)	$ 1,170.00	0.7%
Total Spent	$163,588.82	100%
Total Spent Due to Problems (as discussed above)	$ 49,430.60	30%

TESTING

The testing phase of the project can be divided into two categories: 1) sample collection and analysis and 2) insitu testing. Sample collection and analysis includes the following:

	Sample Collection	Analysis
1.	drill cuttings	Thin section, X-ray, some fluid inclusion
2.	core	Thin section, X-ray, fluid inclusion, and age date
3.	water	Standard analysis, trace elements, tritium, and O^{18}/D

Insitu testing

1. reservoir testing (aquifer tests)
2. drill stem testing
3. pressure monitoring of existing wells
4. semi-continuous monitoring of temperature, pH, conductivity, and discharge
5. borehole geophysics

All of the items under sample collection and analysis have been performed. However, for several reasons, as will be discussed, some items under insitu testing were either deleted or postponed.

Sample Collection and Analysis

Drill Cuttings and Core

Drill cuttings and core were collected and described during drilling. Because detailed descriptions were performed in the laboratory (Tables 13 and 14), the field descriptions will not be reported and are on file with CGS. Drill cuttings were collected every 20 ft (6 m) and more frequently when required by lithologic changes. Approximately 8 ft (2.5 m) of core were recovered from a depth of 1475 to 1483 ft (450 to 452 m).

Standard Analyses

Water samples for the standard analyses were collected in accordance with methods outlined by the U.S. Geological Survey. Various aquifers that were encountered in both P-1 and O-2 were sampled after isolation by casing (Table 8).

The analyses of water from P-1 and O-2 test wells are surprisingly similar to analyses of existing shallow wells and springs, listed in Tables 3 and 5. The total dissolved solids of waters issuing from the basement and the shallow aquifers and hot springs do not vary by more than 200 mg/l. There are, however, slight differences in water chemistry between these zones. When the analyses are plotted on a trilinear diagram, the data points lie along a linear trend in the diamond field (Fig. 9). This indicates that one source of water undergoes base exchange with various clays, exchanging sodium for calcium as the water ascends through various aquifers, while maintaining the same total dissolved solid concentration. Points 1, 4, and 8, are analyses of water from the basement rocks and indicate a calcium sulfate water type.

Points 2, 3, 5, 6 and 7 on Figure 9 are a sodium sulfate water and are from the shallow aquifers and the hot springs. There is a slight decrease in sulfate and increase in bicarbonate as the water ascends, but is yet unexplained (Fig. 9). Points 9, 10, and 11 are analyses of nonthermal water from the Dakota Sandstone, Mancos, and Lewis shales, respectively. The validity of number 10, however, is uncertain. Number 12 is a sample from the San Juan River near Pagosa Springs and has less than 100 mg/l total dissolved solids.

The Precambrian igneous rock, particularly the pegmatitic veining, is probably contributing the relatively high concentrations of boron, flouride, and lithium found in all the thermal water samples (Hem, 1970) (Table 8). The concentrations of these same constituents are much lower or do not occur in analyses of local groundwater. The high concentrations of lead may be associated with the various reduced sulfide species, but the ultimate source within this system is unknown.

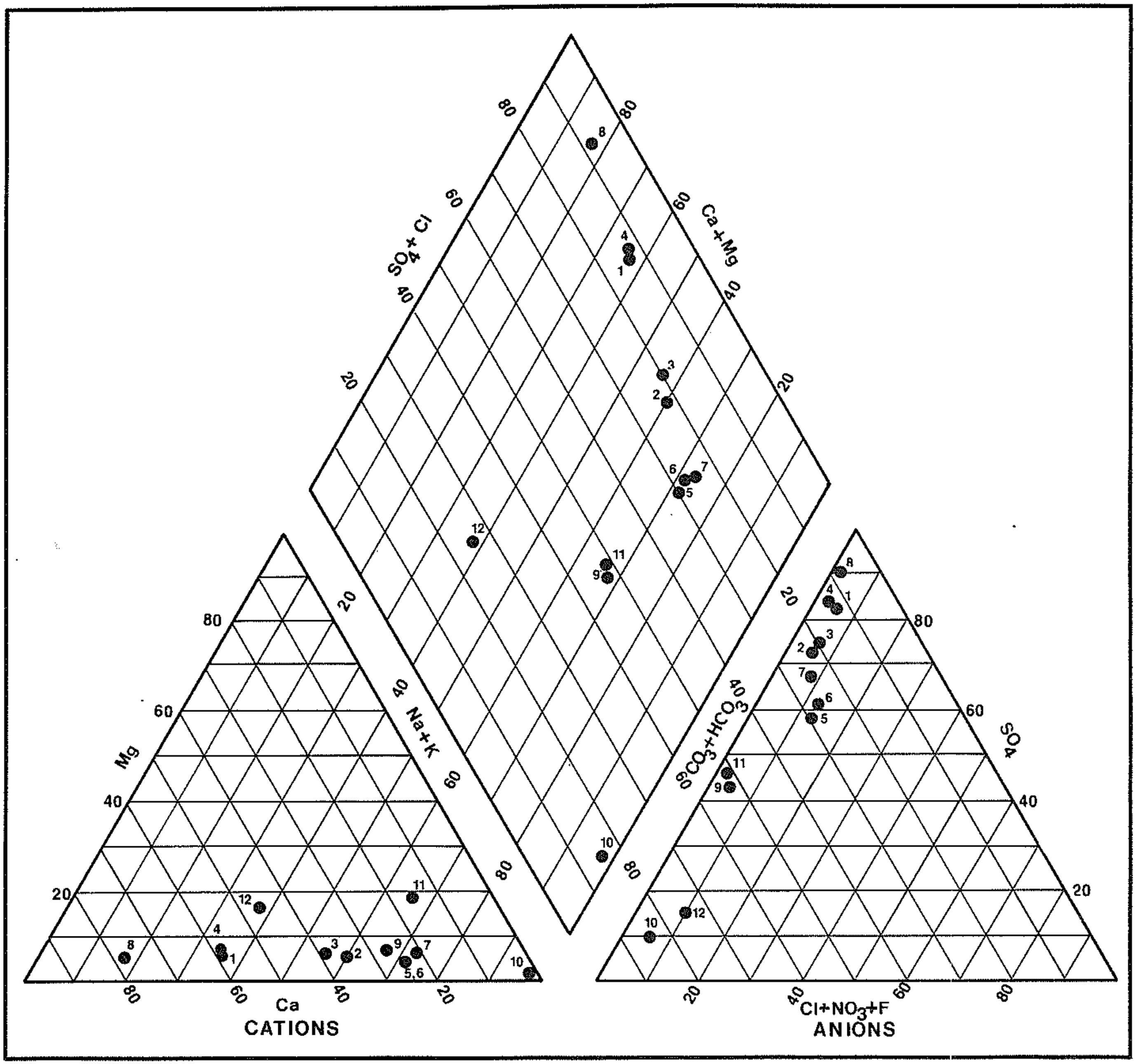


Figure 9 – Trilinear Diagram of Waters from the Pagosa Springs Area

Explanation for Figure 9, Trilinear Diagram of Waters from the Pagosa Springs Area

Sample Numbers	Location
1	P-1, 1375-1475 ft (PC)
2	P-1, 250-585 ft (Kd, Jm)
3	O-2, 230-572 ft (Kd and Jm)
4	P-1, 580-1371 ft (Kd through PC)
5	Spring Vent A (main spring)
6	Courthouse Well (13CADC1) 85-90 ft
7	Spa Motel Well (13CBCD1) (Km?, Kd, Jm)
8	Eoff Well 1313-1327 ft (PC) 399 ft (Kd)
9	Tackett Well (34N01W8DBA) 388 ft (Kd)
10	Tackett Well (34N01W8DBA) 263 ft (Km)
11	Ebeling Well (34N03W22CBC) (Kl)
12	Middle Fork Piedra River near Pagosa Springs (09347200)

TABLE 8. Chemical Analyses of Thermal Waters from the CGS Test Wells

CONSTITUENTS	Well Number / Depth of Sample	CONCENTRATIONS (Mg/L) 0-2 230-572 ft	P-1 250-585 ft	P-1 580-1371 ft	P-1 1375-1475 ft
Alkalinity, Total, as $CaCO_3$		500	540	310	270
Alkalinity, Phenol, as $CaCO_3$		LT 5	LT 5	LT 5	LT 5
As		LT 0.01	0.14	0.01	0.02
Bicarbonate, as $CaCO_3$		500	540	310	270
Bi		0.19	0.17	LT 0.1	LT 0.1
Br		LT 0.1	LT 0.1		
B				0.15	0.15
Ca		390	340	580	565
Carbonate, as $CaCO_3$		LT 5	LT 5	LT 5	LT 5
Cl		100	120	50	91
F		1.7	1.4	2.6	2.3
Hardness as $CaCO_3$		1080	864	1550	1580
Fe		58	0.8	2.5	2.5
Pb		0.08	0.06	0.06	0.08
Li		2.1	2.4	1.2	1.1
Mn		0.78	0.37	0.11	0.13
Mg		39	35	47	42
Hg		LT 0.0002	LT 0.0002	LT 0.0002	LT 0.0002
NO_3		LT 0.01	LT 0.01	0.7	0.7
P, Total		0.9	0.1	LT 0.2	LT 0.2
K		65	71	44	42
Silica, as SiO_2		18.0	20.7	40	46
Na		600	640	360	340
Solids, dissolved		3400	3430	3690	3600
SO_4		1770	1720	1990	1860
Zn		0.08	0.03	0.02	0.02

LT: less than

Oxygen-18 and Deuterium

Two isotopic determinations for oxygen 18 and deuterium were done on the thermal water from the test wells. The determinations for both the shallow water and the water issuing from the Precambrian basement were nearly identical (Table 9).

TABLE 9. Stable Isotope Ratio Analyses

Sampled Zone	D (D/H)	18 (O^{18}/O^{16})
P-1, 571-1068°	-101	-13.7
P-1, 1375-1475°	-99	-13.9
estimated error is	+2 0/00	

If values are plotted on a graph, where O^{18} is the abscissa and D is the ordinate, points fall on the trend of meteoric and slightly heated groundwaters, as defined by Craig (1965) indicating these waters are of meteoric origin.

Tritium Analyses

The results of tritium analysis of all samples from P-1 and 0-2 show the waters to be "dead" with respect to tritium. This implies an age of 25 years or greater (G. W. Gross, written comm., March, 1979). These analyses do not rule out the possibility of mixing young water with large quantities of old water.

Reservoir Characteristics

A six to ten day reservoir test was to be run when drilling was completed. The test was to include the monitoring of several representative hot wells, 0-2, and the pumping well P-1. Unfortunately, because of the disruptive nature of flows from the upper portion of the hole, only one short test during drilling at the 90-100 ft (28-31 m) level was run. The major test of the Precambrian basement was postponed until summer 1979 due to the lateness of the season (September 20). The use of existing hot wells by the owners for space heating precluded their being used as observation wells and would introduce serious errors because of cummulative drawdown.

Aquifer Test

The courthouse well (13CADC1), completed in the Mancos Shale, and O-2, completed in the Dakota Sandstone and Morrison Formation were used as observation wells for "pumping" from P-1 (Fig. 7). The uppermost hot water zone, in the Mancos Shale, was tested by air-drilling into and through the producing zone. This procedure may have resulted in some errors because full penetration of the zone was not instantaneous, but rather during a several minute period. Because discharge varied considerably, due to both drilling operations and a pressure drop within the aquifer adjacent to the hole, discharge was monitored along with the pressure in the observation wells.

In Figure 10, the drawdown in psi divided by discharge in gpm is plotted versus time on semi-log paper for the Courthouse well. The semi-log plot shows some scattering of data which is probably due to errors in reading the pressure guage and fluctuations in discharge because of of drilling operations. Figure 10 shows a general flattening of the curve and therefore increases in T values with respect to time from 5400 to 24,000 gpd/ft (Table 10). However, after 50-60 minutes of "pumping" the curve steepens and the transmissivity decreases to 8000 gpd/ft. The inflexions probably represent various boundary conditions, specifically interconnected fractures, each with its own hydraulic characteristics. The storativity values calculated from the semi-log plot range from $.15 \times 10^{-3}$ to 6×10^{-3}.

The straightline method of analysis (Fig. 10) is invalid for valves of u greater than .01 (Lohman, 1972), where

$$u = \frac{r^2 S}{4Tt}$$

r = radius to pumped well
S = Storativity
T = Transmisivity
t = time (days)

Since t is generally the only variable which can be controlled in an aquifer test, the u value is most dependent on time or length of the test. Assuming reasonable

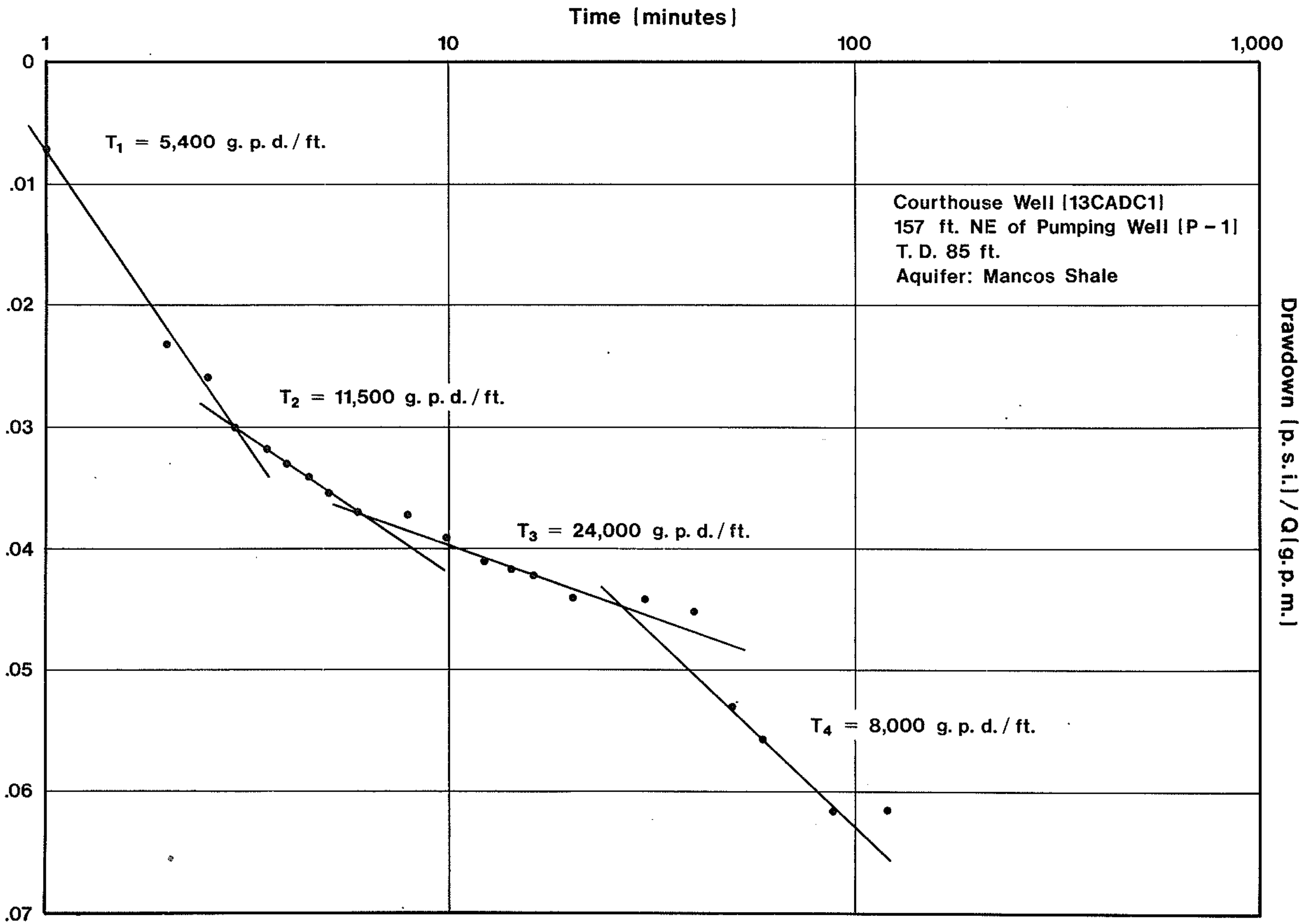


Figure 10 – Time – Drawdown Curve (semi – log) of the Courthouse Well

values of T and S, the u calculated with r and t values from this test is less than .01 and it is therefore valid to use the straightline or Aron-Scott method (Kruseman and de Ridder, 1970).

Figure 11 is a log-log plot of drawdown versus time for both observation wells. Theis and Hantush-Jacob methods were used to calculate T and S values, which are summarized in Table 10. The Theis values for T and S for the courthouse well range from 2400 to 8400 GPD/ft and 1.1×10^{-5} to 1.3×10^{-7}, respectively. Values for O-2 are 54,000 GPD/ft and 8.3×10^{-3}. A single value calculated by the Hantush-Jacob method is 600 GPD/ft.

Several factors reduce the confidence in the accuracy of the calculated T and S values. The test conditions, as discussed above, are a source of considerable error. In addition, the accuracy of calculated values is dependent upon the concepts of the aquifer system.

There is a considerable range in values between the three methods of analysis. The T values calculated by the Theis method are comparable to those of the Aron-Scott method, but the Theis S values are at least 2 orders of magnitude lower. Confined aquifers generally have S values of 10^{-4} to 10^{-5}. The Hantush-Jacob T value of 600 GPD/ft is significantly lower than any of the other values.

Because drawdown was observed in other aquifers during the test (Fig. 11) and a high degree of hydrologic interconnection was noted during drilling, the results of the test are difficult to interpret. If the interconnectivity reponds as a leaky confined aquifer, then the Hantush-Jacob T value is the most valid. However, if the fault system which interconnects the various aquifers is extremely pervasive, the fracture system would respond as a single anisotropic confined aquifer.

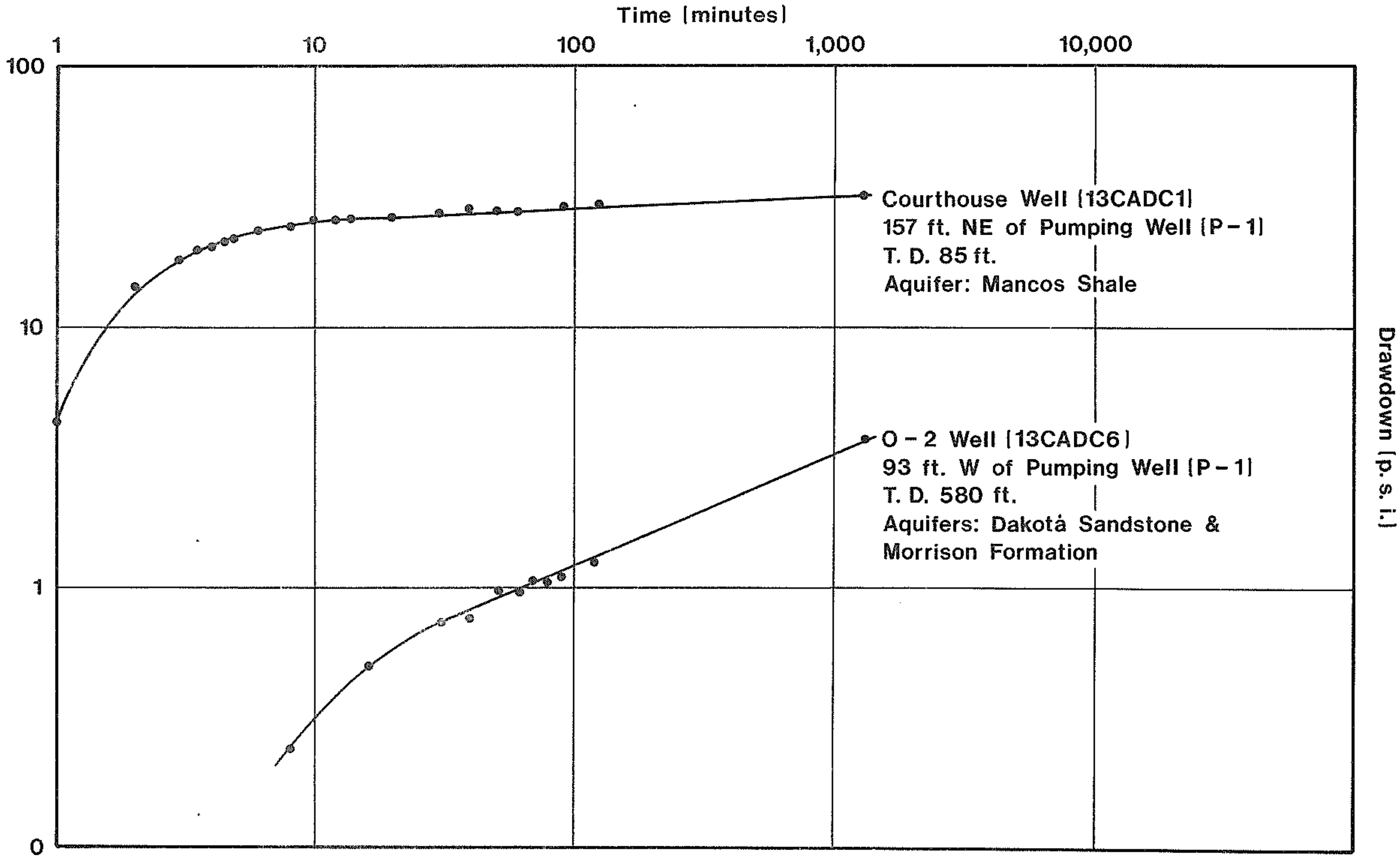


Figure 11 – Time – Drawdown Curves (log – log) of Observation Wells

Unfortunately, the simplicity of this test does not allow for further quantification of this system.

Equations used for Analyses

Aron-Scott

$$T = \frac{264}{(Sw/Q)}$$

$$S = .3T\ (t/r^2_w)_0$$

Theis

$$T = \frac{114.6\ (Q)\ W\ (u)}{s}$$

$$S = \frac{Ttu}{1.87r^2}$$

Hantush-Jacob

$$T = \frac{Q}{4 \quad S}\ L(u,v)$$

$$S = 4T\ \frac{t/r^2}{1/u}$$

Where: T = Transmissivity (GPD/ft)

S = Storativity (Dimensionless)

Q = Flow Rate (GPM)

s = Drawdown (ft)

r_w = radius of well (ft)

r = distance to pumped well (ft)

t = time (days)

w (u) = well function of u

$u = r^2S/4Tt$

L (u,v) = Leakance function of u and v

Temperature, pH, Conductivity, and Discharge

Tables 11 and 12 summarize temperature, pH, conductivity, and flow data collected during drillng from 0-2 and P-1, respectively. Both temperature and conductivity reach a peak in the Dakota Sandstone and show a gradual decrease with depth. pH did not vary by more than a few tenths of a unit. Flow data listed in Tables 11 and 12 are cumulative, except when casing was set. The 40% increase in flow at 1370 ft (418 m) in P-1 was due to possible downhole fracturing. A heavy (barite) mud was used to stop flow for casing and cementing, but was instead taken up by unknown formations as the mud was pumped into the hole under pressure. When pressure was released at the surface and the well was allowed to flow again, mud was washed from the hole and flow had significantly increased.

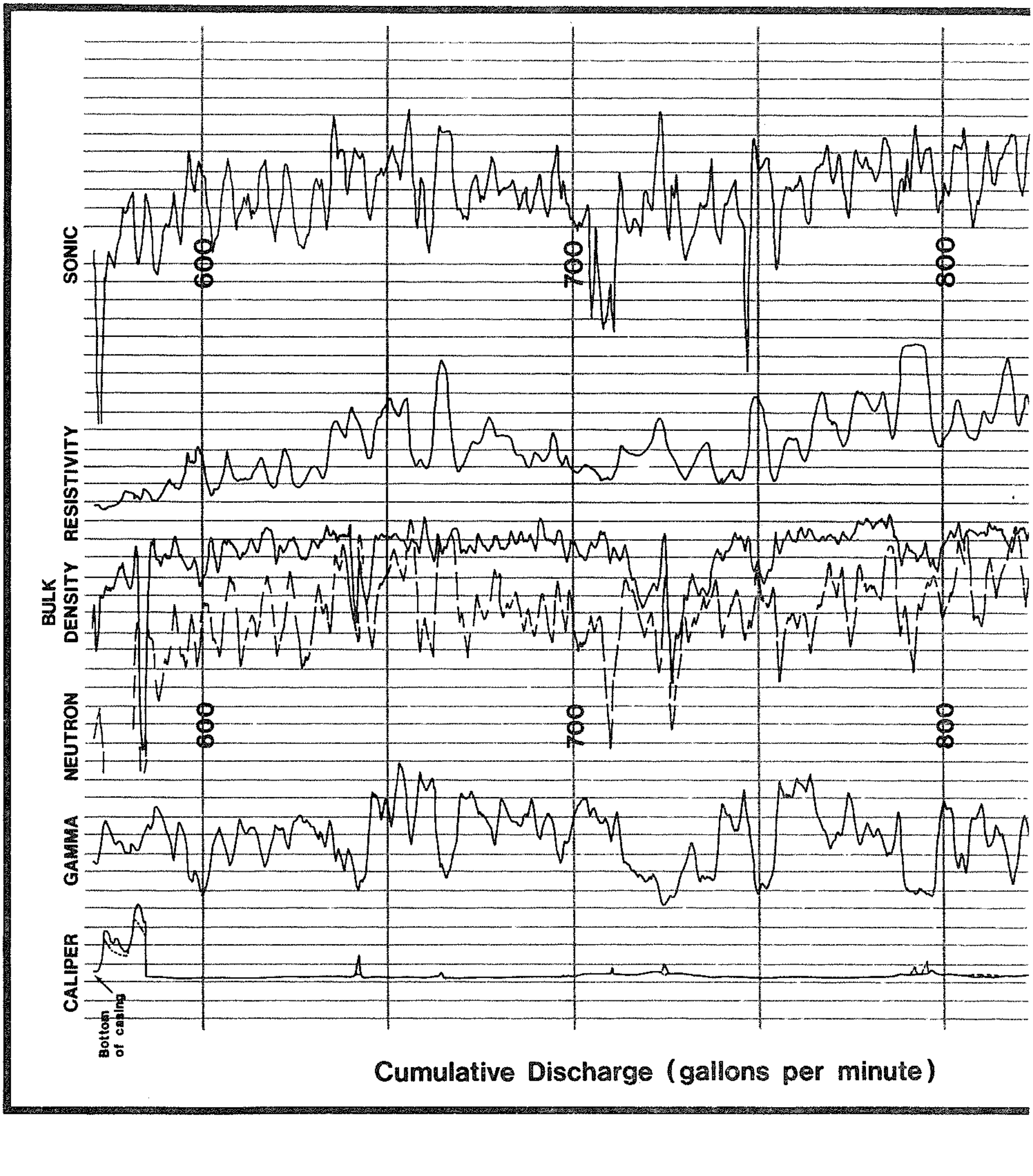
Borehole Geophysics

It was intended that the entire hole be geophysically logged, but because of high flows and associated problems, the upper 571 ft (174 m) were cased prior to logging. Selected commercial logs are presented in Figure 12. The complete original suite of logs are on file with CGS. In addition to the commercial logs, temperature logs were measured on several occassions, using CGS equipment. Selected temperature logs are reported in Figure 13.

Commercial Logs

Caliper Log: The caliper log shows the hole to be relatively smooth walled and free of wash-outs (Fig. 12). This is probably due more to drilling equipment used rather than the lithology. Because of problems encountered in 0-2 and the upper portions of P-1, it was decided to use a reamer and stabilizer for the remainder of P-1.

The major exceptions to the hole uniformity are the large washout beneath the casing at 571 ft (174 m) and a slight ledge at 1250 ft (380 m). The water producing zones correlate moderately well with fractures, as indicated by the caliper log (Fig. 12).


SONIC
RESISTIVITY
BULK DENSITY
NEUTRON
GAMMA
CALIPER
600
700
800
600
700
800
Bottom of casing
Cumulative Discharge (gallons per minute)

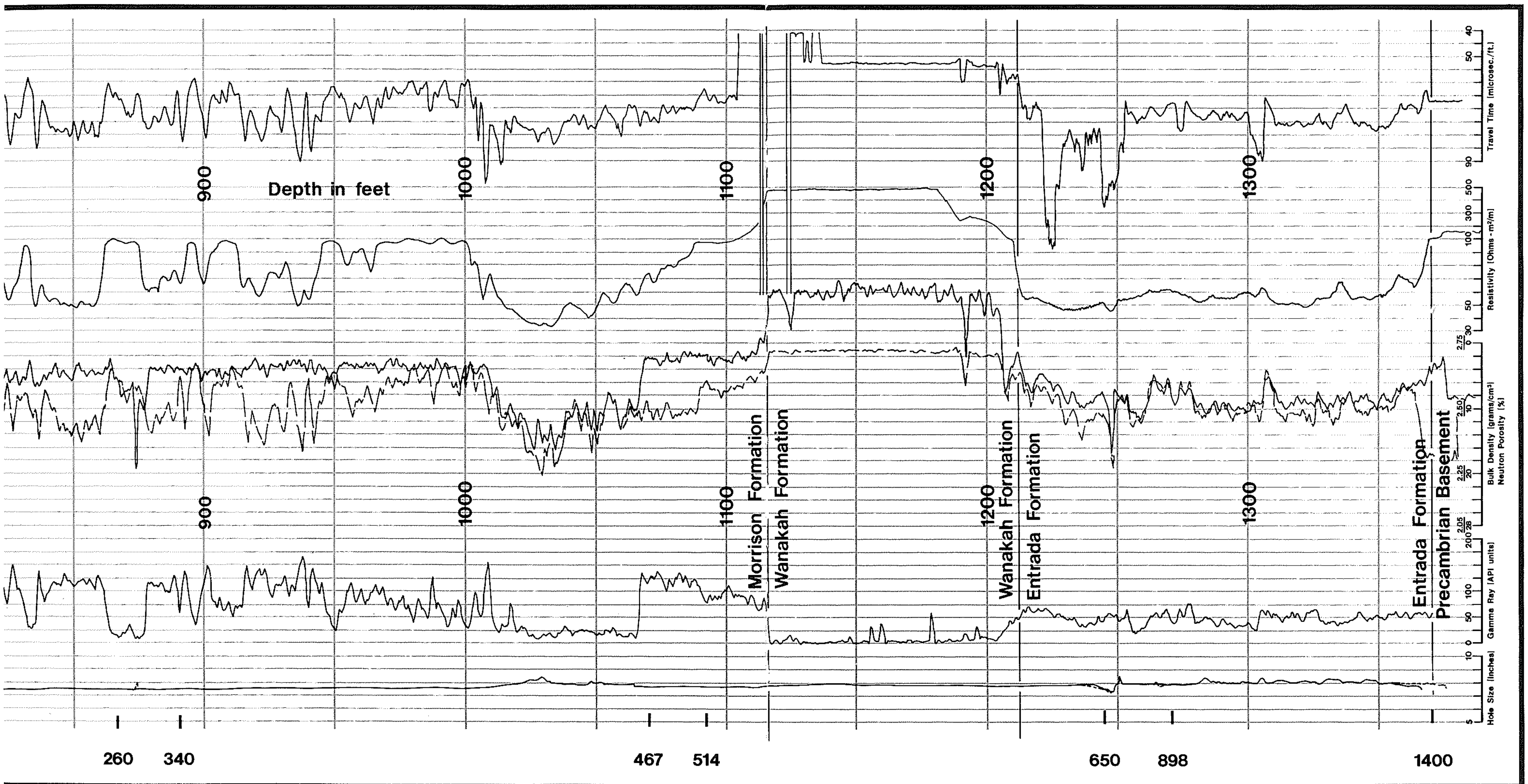


Figure 12 – Geophysical Logs of P-1

TABLE 10. Calculated Values of Transmissivity and Storativity

Method of Analysis	Observation Hole	Courthouse T(gpd/ft)	Courthouse S	0-2 T(gpd/ft)	0-2 S
Aron-Scott		$T_1 = 5400$ $T_2 = 11,500$ $T_3 = 24,000$	$S_1 = .15\times10^{-3}$ $S_2 = 6.3\times10^{-3}$ $S^4 = .3\times10^{-3}$		
Theis		$T_1 = 2,400$ $T_2 = 8,400$	$S_1 = 1.1\times10^{-5}$ $S_2 = 1.3\times10^{-7}$	55,000	8.3×10^{-3}
Hantush-Jacob		600	8×10^{-5}		

TABLE 11. Summary Table of Physical Parameters from 0-2

DEPTH (ft) (ft)	TEMP. (°C)	CONDUCTIVITY (mmhos)	Ph	FLOW (gpm)	COMMENTS
85	25	3150	8.9	20	injected water
90	56	4100	6.5	305	
105	56	3900	6.0		flume washed out
120	56	3900	6.3		
180	56	4100	6.4		
235	56	4100	6.4		casing set
237	50	3900	6.5	30	
244				70	
256				120	during drilling
264	55	4700	6.3	100	
284				85	
304	55	4600	6.4	100	
324	55	4200	6.6	100	
344				100	
364				105	
384	54	4500	6.5	150	200 GPM next morning
424	55			200	
444				200	
464	53			290	temp. at flume
464	53	4400	6.3	290	" " "
504	53	4300	6.4	290	" " "
524	55			470	
544				470	
564	52	3950	6.0	470	
604				470	
624	52	3900	6.3	470	
644				490	
664				490	
704				480	
724	52	3700	6.5	480	after one day
				640	of no drilling
780	50	3550	6.1	470	

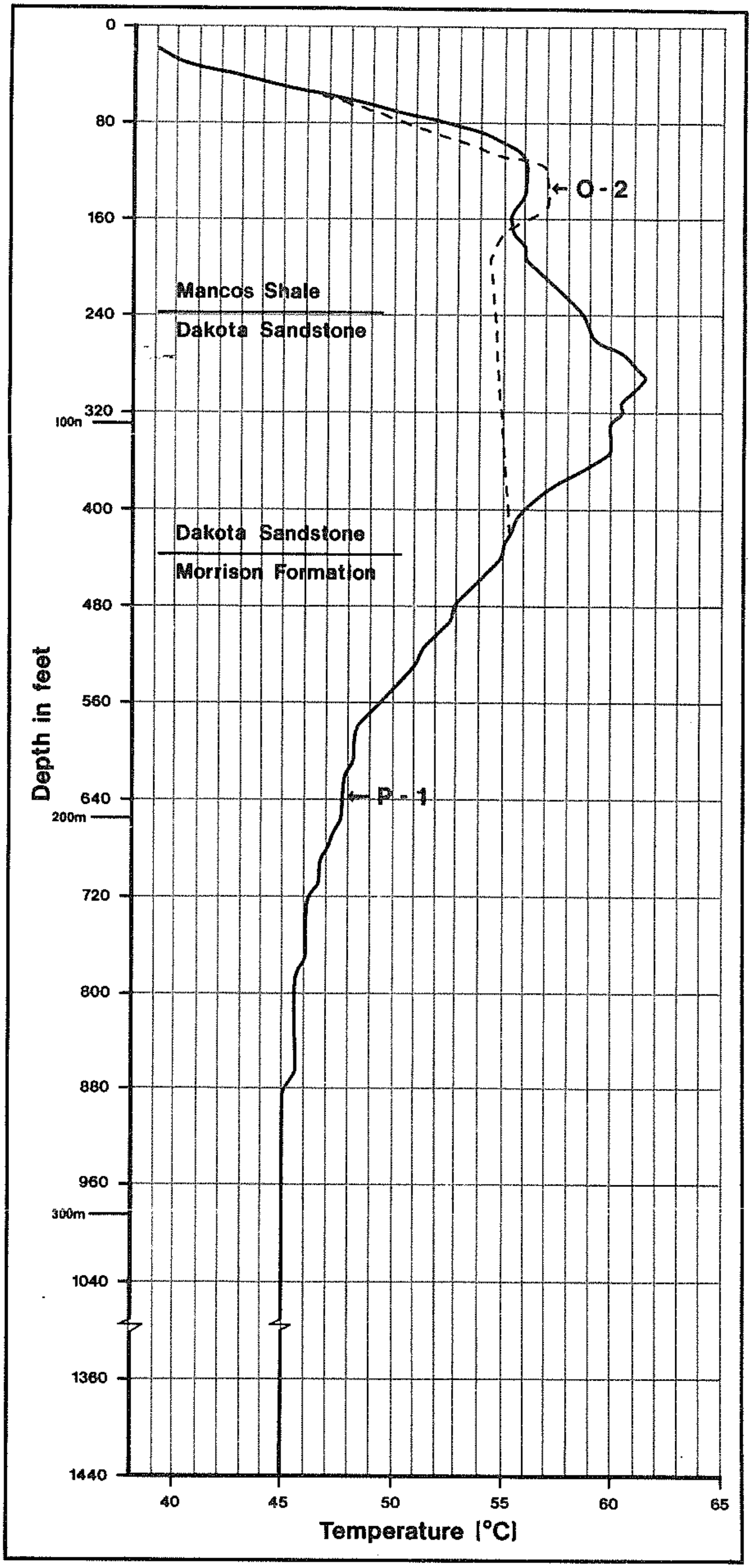


Figure 13 - Temperature Profiles of P-1 and O-2

TABLE 12. Summary Table of Physical Parameters from P-1

DEPTH (ft)	TEMP. (°C)	CONDUCTIVITY (mmhos)	Ph	FLOW (gpm)	COMMENTS
101	56			610	stabilized at 410
145	60			410	
180				410	
240	60	3900	6.5	550	
255	60	3900	6.5	810	
270	60			1500	2000 during drilling casing set
337				500	
380				600	
585	57			700	casing set
590	30			10	injected water
869	47	3250	6.5	260	
889	47	3400	6.4	340	
910	46			150	330 during drilling
970	47			200	
1030	47			310	
1070	46			470	
1090	46			515	
1116	46			435	
1205				350	
1245	45			650	
1270				890	
1290	45	3300	6.5		
1310				890	
1330				890	
1370	45			1015	
1370	45	3250	6.5	1400	after heavy mud washed from hole
1370	45			1400	next day
1385				40	casing set
1475	44	3300	6.5	190	

Natural Gamma: The gamma log shows the alternating sandstone, siltstone, shale sequences of the Morrison Formation (Fig. 12). A section of this curve between 1020 and 1070 ft (310-325 m) correlates very well with the increasing dolomite content, as described in Table 13. The gamma curve also correlates well with limestone-anhydrite of the Wanakah Formation (Fig. 12).

Neutron/Bulk Density: The alternating nature of the Morrison Formation is depicted by these logs (Fig. 12). The sharp contacts of the Wanakah Formation are also easily seen in those curves. At the base of the Morrison and the contact between the Entrada Formation and the Precambrian basement, these curves show definite porosity increases, which correlate well with producing zones.

Resistivity: The resistivity curve correlates well with the logs discussed above and the lithology.

Sonic: The primary features of this curve are fractures between 1200 and 1250 ft (365-380 m) in the Entrada Formation and the cycle skipping at the top of the Wanakah Formation (Fig. 12). The cycle skipping usually indicates fractures; however, there were no other fracture indicators at this depth. They may be due to the sharp interface between the Morrison and Wanakah Formations.

Quantitative interpretation of these logs was attempted, but the results were inconclusive and will not be reported.

Temperature Logs: Numerous temperature logs were run at various stages of the drilling to delineate producing zones and distinguish between thermal and nonthermal zones. Selected profiles are shown in Figure 13.

The profiles in Figure 13 were run under shut-in conditions after the hole was allowed to stabilize for several weeks.

The P-1 profile shows two distinct thermal zones which correlate with hot water encountered in the Mancos Shale and Dakota Sandstone. The temperature decreases to 45°C after reaching a peak of 61°C opposite the fault zone in the Dakota Sandstone and becomes isothermal by about 800 ft (243 m). Isothermal conditions continue through the Wanakah and Entrada Formations and into the Precambrian basement. Unfortunately, slight doglegs in the hole at about 1455 ft (442 m) prevented temperature measurements to the total depth.

In contrast, the O-2 profile, taken July 29, 1978, shows only one thermal zone between the surface and 572 ft (174 m), which is in the Mancos Shale at about 85-95 ft (26-29 m).

Well Pressure Changes During Drilling

Four-inch 0-60 psi and 0-120 psi Marshalltown pressure gauges were installed on the courthouse well (13 CADC1), Buhlers well (13 CADB1), and O-2 (while drilling P-1) (Fig. 7). A fourth gauge was used to measure shut-in pressure of P-1 whenever possible. A calibrated rod was used to monitor approximate water levels in the main spring vent, A.

Although the data were not recorded continuously, the pressure fluctuations give a good indication of the response of various wells and the spring (Fig. 14). As can be seen in Figure 14, Buhler's well and the courthouse well respond rapidly to the opening and closing of the 10-inch gate valve on O-2; one 12-hour shift was used for drilling, allowing the well to be shut-in for 12 hours.

On August 16, the high flow within the Mancos Shale was encountered at 100 ft (31 m) in P-1 affecting the pressures on O-2, Buhler's and the courthouse well (Fig. 14). Pressure in the courthouse well dropped to zero by the 17th. Unfortunately, the gauge on Buhler's well jammed sometime on the 16th. O-2 showed minimal pressure drop, from 60 to 52 psi, due to flow from this upper zone, but dropped drastically, to 38 psi, when the fault zone at 255 ft (80 m) was encountered. The pressure of the courthouse remained near zero and the spring level dropped 26 in. (22.5 cm), a maximum drop (Fig. 14). The pressure of other wells in town, as far away as 1000 ft (300 m), also went to zero. The courthouse well, O-2, and the spring level began to recover when the hole was cased, but the pressure of O-2 dropped to a minimum of 32 psi as drilling continued in the Dakota Sandstone and the Morrison Formation (Fig. 14). Pressures and the spring level recovered and stabilized after casing was installed, and lower zones were encountered and the drilling continued into the Precambrian basement.

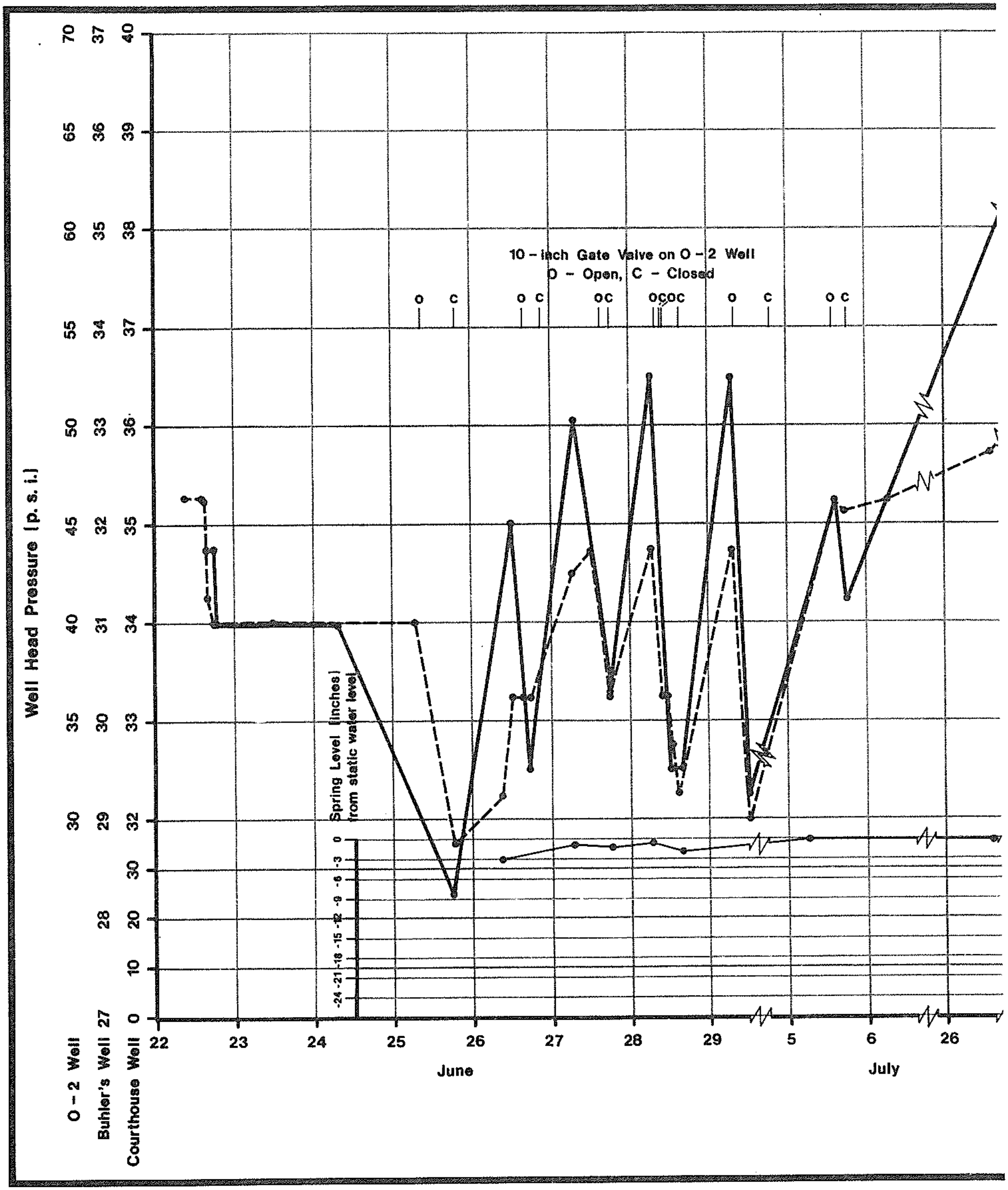
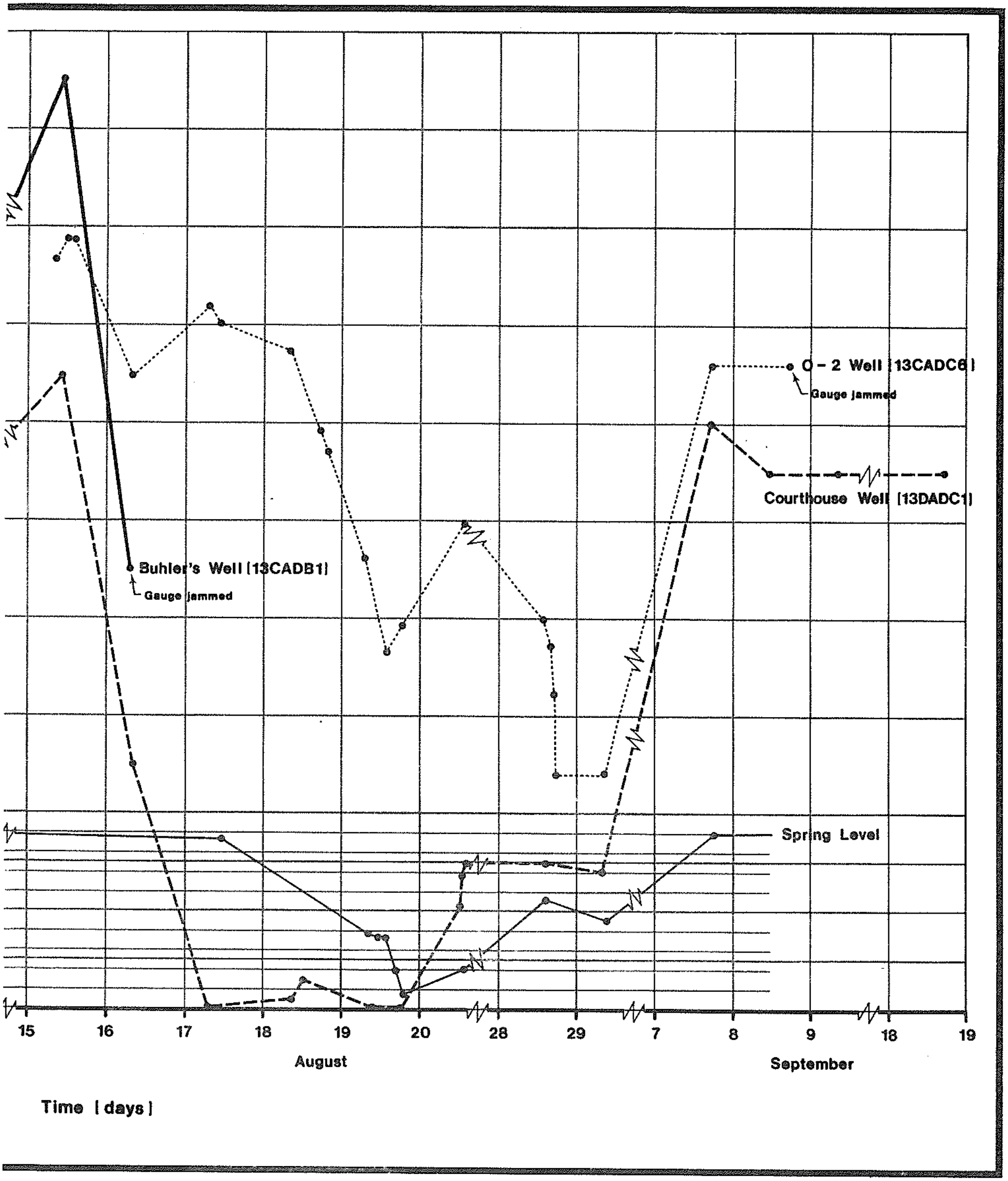


Figure 14 - Hydrographs of Thermal Wells



and Springs, Pagosa Springs, Colorado

DISCUSSION AND CONCLUSION

General Nature of the Pagosa Springs Geothermal System

There are no geologic indications of intrusives providing heat to the Pagosa geothermal system. The youngest known intrusives are the latest Miocene dikes of the Archuleta dike swarm and the 26-28 m.y. old subvolcanic batholith postulated by Lipman and others (1978). The lack of adequately young intrusives suggests that heat is provided to the geothermal system by a slightly enhanced regional geothermal gradient.

Assuming a twice normal geothermal gradient of 60°C/km in the Pagosa area (Barrett and others, 1976; and Edwards and others, 1978), meteoric water would have to circulate down 1 to 2 kilometers (6500 ft) to acquire either the observed or calculated temperature. This required depth of circulation suggests that the crystalline rock of the Precambrian basement is the primary geothermal reservoir.

An argument often used against such deep circulation of meteoric water is that fractures close with depth and, therefore, permeabilities and porosities approach zero. However, numerous tunnel, mine, and drilling operations have shown the existence of permeable zones at depths of several thousand meters, most of which are associated with faulting (Davis and Turk, 1964). In one example, Batzle and others (1978) show that porosity increases with depth from 5×10^{-4} to 25×10^{-4} in core from the Marysville, Montana, geothermal test well. Also, they show matrix permeability increases as much as 2 orders of magnitude below 1200 meters. Galloway (1977) postulated that in most cases, deep circulation and subsequent heating requires the intersection of major structures with crystalline rocks, such as batholiths or Precambrian complexes. In the northern Rocky Mountains, hot springs are overwhelmingly associated with crystalline rocks (Galloway, 1977).

The water chemistry, including isotope analyses, support the idea of meteoric water circulation. It is unlikely that water originating within the crystalline rocks would have such high total dissolved solids, particularly high sulfates. Also, it is unlikely that water flowing entirely within the sedimentary units would have high lithium, boron, and fluoride, as do these geothermal fluids. The most probable flow regime would include significant contributions of various parameters to meteoric water by both sedimentary and crystalline rocks. The oxygen 18-deuterium ratios also support the idea of a completely meteoric water source.

Description of Circulation System

One of the major questions regarding the nature of this sytem is whether the thermal water is flowing laterally through the Dakota Sandstone or is fed vertically to the Dakota Sandstone by a vertical feature. Information collected during this study supports the latter concept.

The configuration and locations of known hot water wells indicate the lateral extent of the thermal water is limited (Plate 2). Wells which have encountered cold to warm water have been drilled on the periphery of the downtown area. One of these wells (13 CBDC) completely penetrates the Dakota Sandstone. Other wells completed in the Dakota Sandstone in the Pagosa area have encountered cold groundwater.

The two resistivity maps (Figs. 5 and 6) mimic the limited area of known hot water. Lateral flows would have been well within the depth range of the dipole-bipole survey and with its contrasting water chemistry, should have been detected.

The pressure response of wells completed in various units and changes in the spring level indicate a high degree of interconnection between all the units, except the basement rocks (at least within the time frame of the drilling). However, the potentiometric pressure of the thermal water increases from 35 psi in the Mancos Shale to 85 psi in the Precambrian basement, suggesting this is a discharge area for the thermal water system, which includes all the rock units beneath Pagosa Springs.

The high degree of interconnectivity of the rock units is supported by the thermal water chemistry. Analyses from various wells, springs, and the test holes, from all depths, are very nearly the same (Tables 3, 5, and 8). The only difference, relative calcium and sodium percentages, shows a linear relationship with respect to depth (Fig. 9) without any significant changes in total dissolved solids, suggesting the waters are the same.

Another strong argument for a system controlled by a vertical feature is the high flow encountered in the Dakota Sandstone in P-1, but not in O-2, 93 feet (28 m) from P-1. The vertical feature encountered in P-1 is probably a small displacement vertical fault which may be either the major conduit, as suggested by its strong control over pressures in all thermal wells and springs, or is one of many related, interconnected vertical faults. If this type of fault were to continue well into the basement, it would explain why high, hot flows were not encountered in basement rocks. The high volume, hot water might be restricted to fault zone(s) and mixes with cold groundwater over larger volumes of the aquifers. This is supported by the lack of hydrothermal mineralization and alteration noted in the Precambrian rocks, whereas alteration and mineralization becomes more intense closer to the fault zone at 255 ft (77 m).

Age of the Thermal System

No clean-cut answer is available concerning the age of this system. Atkinson suggests a calculable minimum age if erosion data were available, assuming 800-1000 ft (241-301 m) of overburden have been stripped off since the system reached a maximum temperature of about 230°C. However, a good estimate of erosion rates is not known at this time.

MINERALOGICAL AND PETROGRAPHIC INVESTIGATION OF SAMPLES FROM GEOTHERMAL WELLS O-1 AND P-1, PAGOSA SPRINGS, COLORADO

by

W.W. Atkinson, Jr.

Introduction

Samples of cuttings and drill core were subjected to several types of examination: visual study, x-ray diffraction, thin sections and fluid inclusion observations. This work provided information on the nature of the rocks within the geothermal system, as well as on minerals deposited by the system, and temperatures it attained during deposition.

Mr. Paul Boni assisted with the x-ray studies. Mr. Gary Mitch carried out thin section studies on the sedimentary rocks. This assistance is gratefully acknowledged.

Visual Examination

Each of the 110 samples of cuttings recovered was examined under a binocular microscope. Characteristics of the cuttings such as color, grain size, roundness, sorting and mineral proportions were estimated visually. Samples were washed and examined wet for clarity, and the disintegration of clays in water could be observed. Each sample was tested for calcite with dilute hydrochloric acid. Results of this study are summarized in Table 13. In general, most of the samples appeared to consist primarily of cuttings taken from the sample interval, with only small proportions of caved cuttings from higher in the hole. Where some doubt existed as to the depth of origin, each lithology in a sample and its approximate percentage of cuttings is given.

Eight ft of core from the bottom of the hole were examined with a hand lens and microscopically. These results are summarized in Table 14.

Table 13

Visual Descriptions of Well Cuttings

A. Well O-1

Depth of samples (feet)	Description
0-160	Shale, soft, very dark brownish gray, fissile. Locally contains some detrital sand, flakes of biotite. Pyrite in tiny (0.2 mm or less) clusters of cubes at 105 and 120. Shale calcareous at 120, and white calcite veinlets 120 to 160.
241-284	Shale, soft, medium brownish gray, noncalcerous, with sandstone laminate 1-5 mm thick, and beds of unknown thickness. Sandstone is f.g. to m.g., well-sorted, arkosic, and with clots and streaks of carbonaceous matter. Some shale shows slicken-sides.
	Hydrothermal euhedral quartz and pyrite crusts up to 1 mm thick coat many fragments of sandstone and some shale. Barite clots occur with pyrite and euhedral quartz crystals up to 1 mm long on one fragment. Material for fluid inclusion study came from this interval.
299-402	Sandstone, quartzitic, light gray, medium to coarse-grained, slightly arkosic. Sparse carbonaceous and shaly laminations. A little pyrite on fractures 399-402.
419-422	Shale, black, with abundant quartz silt and sand.
459-464	70% cuttings caved from above. 30% sandstone, light greenish gray, very poorly sorted (0.1 to 3 mm), poorly rounded, frosted grains. Some light brown chalcedony grains. Some white clay clots 2-3 mm. 10-40% light greenish clay. Sparse disseminated pyrite cubes.
479-484	Shale, medium gray and medium greenish gray, soapy, swells and disintegrates in water. 10-2% clear quartz sand, poorly sorted, poorly rounded.
	A little sandstone, coarse grained (2-3 mm), poorly sorted, poorly rounded, with clay matrix.
499-504	Sandstone, white, well-rounded, frosted grains 0.3-0.5 mm in diameter, high porosity. About 10% very fine grained material between grains.
	Common to abundant euhedral pyrite on fracture surfaces. A little euhedral quartz.

519-524	Sandstone, white, well-rounded, frosted grains, medium- to coarse-grained cemented by soft white clay. About 20% chert pebbles 0.5-2 mm, white, gray, black, red. A little pyrite in clots and single euhedral crystals on some fragments.
539-564	20% white sandstone as in previous sample. Shale, light blue-greenish gray, soapy, soft, 10% very clear quartz sand. Swells in water.
564-584	80% shale as in previous sample. 5% shale, dark brownish red, slightly to very silty, swells in water. 15% caved cuttings from above.
599-604	75% sandstone, white, medium-grained, well-rounded, frosted grains, partly cemented by white clay. Abundant open pore spaces containing pyrite crystals. 10% siltstone, pale green, swells in water. 5% tiny disseminated euhedral pyrite cubes. 5% siltstone, dark brownish red argillaceous, and silty shale. Shale swells in water. 10% caved cuttings from above.
655-659	Sandstone, pale yellow, fine-grained, hard, about 30% clots of interstial white clay, with some bright green clots (possibly celadonite or chlorite).
658-664	90% shale, soft, soapy, pink, dark reddish brown and pale green, with 5% quartz sand. Some fragments appear to consist of sand-size lithic clasts, probably originally tuffaceous. 10% limestone, light gray, very fine grained.

B. Well P-1
Depths of samples (feet)

345	Shale, black, carbonaceous, with black waxy partings and lenses up to several mm thick. Fragments of elongated pyrite concretions up to about 5 mm diameter, with radial growth patterns.
598-601	85% sandstone, white, well sorted, medium grained. About 40% clear quartz and 60% opaque white quartz. Sparse red and green grains, part of which are soft clay. 10% shale, light blue green, with 10% clear quartz sand. Disintegrates in water. 5% caved cuttings from above.
601-608	70% sandstone, white to pale pink, as in previous sample. Red lithic grains more abundant. 20% siltstone to shale, medium to dark reddish brown. 10% lithic sandstone, medium reddish gray, medium grained, with 20 to 40% clear quartz grains. The remaining grains are white, pink, reddish brown, and rare green lithic fragments well-sorted, and which are partly altered to clay.

and rare green lithic fragments well-sorted, and which are partly altered to clay.

628	Sandstone, pale pink to medium reddish brown, with 20-70% clear quartz grains, and the remainder white, pink and reddish brown lithic grains. Medium-grained, well-sorted, except, for rare black to brown chert pebbles. Many cuttings disintegrate in water. Calcareous cement.
638	30% sandstone, medium pinkish gray, medium-grained, as in previous sample. 20% sandstone, white, hard, with chalcedonic (?) cement and altered white chalky lithic grains. Similar to white sandstone 598-608. 50% siltstone, medium dark brownish red. Fairly hard.
648-718	Arenaceous to lithic sandstone, pinkish to reddish gray, pale tan, and pale greenish to light green, and white. 10 to 80% clear quartz sand, average 33%. Remainder consists of white, pale gray, blue-green, red, pink, and black and lithic fragments altered to clay. Calcareous cement is common, sparse calcite veinlets.
728	Sandstone, medium tannish gray, medium-grained, well-sorted, arkosic with 30-40% blocky white feldspar grains.
	Hydrothermal minerals on fracture surfaces on some cuttings. Euhedral quartz, calcite and two tiny grains positively identified as chalcopyrite.
738-788	Lithic arenaceous sandstone, fine- to medium-grained, dominantly light- to medium-bluish-grayish green, with some gray and reddish brown. 10-60% clear quartz sand, average 33%. Remainder consists of pale to dark green, grayish green, purplish gray, white, red and black lithic grains altered to clay. Slightly to very calcareous. Well sorted.
798-808	Sandstone, arkosic, light gray, medium-grained, well-sorted. 30-40% sericitized feldspar and lithic grains.
	Euhedral pyrite on some fracture surfaces. Hydrothermal.
818	Siltstone, dark-purplish gray with pale green streaks.
828	Sandstone, arkosic light gray, medium-grained. About 20% feldspar, 5% multicolored lithic grains.
838	Siltstone to shale, 80% dark reddish brown, 20% light gray. Some finely laminated. Soft, disintegrates in water.

848	Lithic sandstone, 40% purplish gray and 60% light gray green, medium-grained, poorly sorted, 20-30% clear quartz grains, 70-80% lithic grains partly altered to clay.
858	Shale, silty, 90% dark brownish red with 10% pale greenish gray streaks.
868-878	Sandstone, white, medium-grained to fine-grained, hard, glassy. Sparse red, black and greenish grains. 10% chalky cement and clots (dolomite?). Slightly calcareous.
888	Shale, sandy, 50% dark purplish gray, 50% medium greenish gray, calcareous, about 30-40% quartz sand.
898	Sandstone, medium to light brown, fine-grained, well-sorted, very calcarous, abundant interstitial clay.
928	Shale, dark brownish purple with a few pale green streaks. Calcareous.
938	Sandstone, light tan to white, medium-grained to fine-grained, hard, calcareous, 10% white chalky grains.
948	Sandstone, purplish gray, medium-grained, very calcareous, very clay-rich. Speckled with greenish gray spots, which appear to have been volcani-clastic grains.
958-968	Shale, slightly greenish medium to dark gray. Very calcerous. 10% to 20% fine quartz sand. Some purplish streaks.
978-1068	Sandstone, white, fine-grained to medium-grained, poorly sorted, 10-30% white chalky cement and clots (dolomite?). At 998, very hard. Deeper sandstone is soft and friable or disaggregated. At 1068 ft, coarse poikilitic dolomite cements the rock.
1078-1108	Shale, medium- to dark-reddish brown, 10% silt to sand, slightly to very calcareous. Calcite veinlets present at top.
1118-1198	Limestone-anhydrite. White crystalline anhydrite in nodules 2-5 mm diameter with fetid medium to dark gray, finely crystalline limestone between. Average 40% anhydrite nodules. 1128-1138, 60-70% anhydrite.
1208	Limestone, platy, laminated, 1-2 mm, black, with 5% gypsum nodules. A few coarse (1 cm) selenite (gypsum) cleavage fragments.

1218-1368	Sandstone, light gray, fine-grained to coarse-grained, very poorly sorted, well-rounded, high sphericity, frosted grains, calcareous. Mostly soft to disaggregated. At 1288, rock is pale pink, arkosic, very hard and non-calcareous. At 1218, rock is carbonaceous.
	Pyrite as tiny diseminated crystals, interstitial grains and 1-2 mm thick pyrite veinlets from 1288 to 1258. From 1258 to 1368, only rare tiny disseminated pyrite crystals.
1371-1475	Gneiss, 40% fine-grained foliated biotite, 40% feldspar porphyroblasts 0.5-1 mm, including 10% pink to orange to red microcline and 30% plagioclase, which is locally sericitized. 20% clear glassy quartz in small grains in biotite. Red aplite at 1390.

Table 14

Visual Log of Diamond Drill Core from

Well P-1, 1475-1483 Feet

	Description
1475-1475.3	Biotite-feldspar gneiss, fine-grained, as in interval 1371-1475.
1475-1477.6	Granite, fine-grained (0.5-1 mm), weak foliation. About 30% quartz, 50% white to red feldspar, 15% biotite, 5% epidate.
1477.6-1479	Migmatite, Lenses of pegmatitic orange microcline and quartz in biotite schist and gray granite gneiss.
1479-1483	Biotite gneiss, fine-grained. 80% biotite and 20% feldspar grains (1 mm or less) in disseminations and streaks in biotite.

X-Ray Diffraction Study

Seventy-nine of the samples were subjected to an x-ray diffraction examination. Representative portions of the cuttings were crushed to pass 200 mesh and loaded into an aluminum sample holder to obtain a sample approximately 1 x 2 cm x 2 mm thick. The samples were then run on a Norelco diffractometer. The following operating conditions were used: Cu radiation, 35 kV, 17 ma, scan 2° per minute, chart speed 1/2 in. per minute.

Charts of samples were compared with charts of standards for identification, which were compared with powder patterns listed in the ASTM X-ray Diffraction card file, to ensure that no extraneous peaks were present. All peaks could be identified from rocks in the sedimentary section. In the Precambrian rocks at the bottom of the hole, a few very minor peaks defied identification. In order to identify such minor components, other methods such as thin section studies are necessary. This is because the complex pattern of peaks from the five or more major minerals effectively masks most of the pattern of a minor constituent.

Results are summarized in Table 15. Only minerals which were postively identified are listed. Three categories of concentration are given: major, moderate to minor, and trace. Due to the characteristics of each mineral, these relative proportions are only very approximate. Proportions of clays in particular are difficult to estimate from diffractometer charts, since a poorly crystallized clay may show very low peaks even when pure. Some minerals, such as feldspars, have major peaks which are masked by quartz. When potassium feldspars are minor constituents, not enough of their patterns are visible to discriminate between orthoclase and microcline. Consequently, only "K-feldspar" was reported. Albite, on the other hand, can be easily distinguished. With the complex mixtures of patterns obtained, micas cannot be discriminated. Since biotite was visible in the samples at the bottom of the hole, peaks for mica were taken to indicate biotite. However, muscovite in addition was seen in the thin sections.

Clay minerals were given special attention. Illite is indicated in a large number of samples by a peak near 10A (angstroms). This peak varies considerably in quality, from a somewhat broad hump, to a fairly narrow one. Its intensity was usually less than 10% full scale deflection, although in a few samples it ranged up to 25%. In a few samples a faint rise at 14A indicates the presence of montmorillonite. Kaolinite was indicated by a fairly sharp peak at 7A, although the quantity present was usually small. Chlorite occurs in the Precambrian rocks. It has a very poor 14A peak, with a sharp, much higher 7A peak.

Thirteen samples were selected for glycolation and heating tests. In one, (0-1, 479-484), the montmorillonite peak clearly shifted from 14A to 17A. In other samples, the montmorillonite concentration was too low to observe peak shifts. The illite peaks did not shift, but dropped slightly in intensity and sharped somewhat. This suggests the presence of small concentrations of randomly interlayered montmorillonite. Glycolation did not affect 7A peaks for kaolinite. Heating to 550°C sharpened illite peaks and caused montmorillonite and kaolinite peaks to disappear. These tests, which are standard for clay minerals, provide support for the identifications of patterns on other charts.

Fluid Inclusion Study

In several samples, euhedral quartz and pyrite were observed on fracture surfaces. These minerals have an appearance typical of crystals deposited by hydrothermal fluids. Other minerals observed locally included calcite, barite and chalcopyrite.

Several rock fragments were recovered from 248 ft depth in well P-1. They were coated wtih drusy, euhedral quartz and pyrite, and one fragment had barite as well. The thickness of the quartz crust was about 1 mm or less. Two of the cobbles were selected for fluid inclusion study. Thin slices were cut, then ground on both sides to a thickness of 0.2 to 0.4 mm, polished on both sides, then carefully examined by microscope for fluid inclusions.

The hydrothermal quartz is remarkably clear, and free of fluid inclusions. After an extensive search, only three were found which were large enough, about 10 to 15 microns in diameter, for determination of filling temperatures. A number of others (13) were found which could be measured roughly, and from which estimates of the ratio of volume of the bubble to volume of the incusion were made. This type of estimate yields rough figures, which are subject to errors. The main source of error arises from the fact that the three-dimensional shape of the entire inclusion cannot be seen. Usually, the inclusion is assumed to have a square or circular cross-section normal to the plane of the polished surface. If the inclusion is actually larger, the true bubble to inclusion ratio is smaller, and the estimated temperature of filling is too high. With these limitations in mind, volume ratios of bubble to entire inclusion were found to range from 0.021 to 0.18. Assuming that the liquid is pure water, these inclusions would fill at temperatures from 71 to 232°C. One inclusion which had a long tube-shaped form could be fairly accurately measured. It yielded an estimate of 198°C.

Filling temperatures of fluid inclusions were measured on a Chaix-Meca (Nancy, France) heating stage. The apparatus was calibrated with substances with known melting points. The calibration runs suggest an accuracy of ± 1°C.

Before filling temperatures were measured in hydrothermal quartz, two inclusions in heated fractures in sandstone grains were studied. The first filled at 171.2°C, with a precision of ± 1.0°C, using four measurements. The second filled at 161.8°C. Only one measurement was made.

Of the three inclusions in a hydrothermal quartz crystal, one leaked at 184°C. The second filled at 252.1°C. When an attempt was made to repeat the measurement, it, too, leaked. A third inclusion filled at 230.5°C. This was the lowest of four repeats, which gave results in sequence of 231.5, 234.5, 230.5, and 231.5. The second of the group appeared to be in error due to a poor observation. Another six measurements were made, which gave the following results in sequence: 236.5, 237.5, 236.5, 239.2, and 240.2. These results are significantly higher than the first four, and appeared to be systematically increasing with each cycle of heating and cooling. A leak was therefore suspected, and the first four measurements are probably the only valid ones.

The range of temperatures probably reflect different stages of development in the hot spring system. The heating measurements actually show fairly good agreement with the measurements of inclusion and bubble sizes, and subsequent estimated filling temperatures.

TABLE 15

Mineralogy of O-1 and P-1 Well Cuttings Determined by X-ray Diffractometer

Sample	quartz	illite	calcite	dolomite	albite	K-feld-spar	Kao-linite	pyrite	other
WELL O-1									
100	x	x	X				x	x	tr. mont.
105	x	x	X				x	x	tr. mont.
120	X	x	X	tr	x	tr	x		tr. mont.
140-160	X	x	x	x	tr		x	x	x mont.
241-244	X	x							
264	X	x							
284	X	x		x				x	tr. mont.
299-304	X	tr							
319-322	X	x							
339-342	X	tr							
399-402	X	x						tr	
419-422	X	x					X		
459-464	X	x							
479-484	X	X							tr. mont.
499-504	X	x						tr	
519-524	X	x						tr	
539-564	X	X						tr	
579-584	X	X						tr	
599-604	X	x						x	
655-659	X	x		x	tr		x		
658-664	X	x	tr	x	tr		tr	tr	
WELL P-1									
248-268									barite
345	X	tr					X		
598-601	X	x		x	X		x		
668	X	tr	tr	X	X				tr. mont.
678	X	X	tr	x	tr				
688	X	x	X	x	x				
708	X	x	x	x	tr				
718	X	x		x	x		tr		
728	X	tr		X	x				
738	X		tr	x	x		tr		
748	X	x	tr	x	tr	tr	tr		
758	X	x		x		tr			
768	X	x	x	X	tr		tr		
778	X	x	x	x	tr	tr		tr	
788	X	x		x	x	x	tr		
798	X	x	tr	X					
808	X	tr	x	x	x	x			
818	X	x	x	x	tr	tr			
828	X	tr	tr	x	x	x			
838	X	X		tr	x	x		tr	
848	X	x	tr	x	tr	tr			
858	X	x	x	x	tr	tr			
868	X	x	x	X	x		tr		
878	X		x	X	tr	tr	tr		
888	X	x	x	x	tr	tr			

Notes: X = major component x = moderate to minor component tr = trace mont. = montmorillonite

TABLE 15

Mineralogy of O-1 and P-1 Well Cuttings Determined by X-ray Diffractometer (continued)

Sample	quartz	illite	calcite	dolomite	albite	K-feld-spar	Kao-linite	pyrite	other
898	X	x	X	tr	tr	tr			
908	X	x	x	x	tr	tr		tr	
928	X	x	x	x					
948	X	x	x	x		tr			
968	X	x	X	x	tr				
988	X	x	x	x		tr			
1008	X	x	X	x					
1028	X	x		X	tr				
1048	X	tr	tr	X					
1068	X		tr	X					
1088	X	x	tr	x	tr	tr			
1108	X	x	tr	x	tr	tr			
1128			x						X anh.
1148			x						X anh.
1158	tr		x						X anh.
1168			x						X anh.
1188	tr		x						X anh.
1208	tr		X						{ x anh. X gypsum
1228	X	x	x			tr			
1248	X	tr	x	x		tr			
1268	X	x	x	tr		tr			
1288	X	x	x	x	tr	tr			
1308	X	x	x	x	tr	tr			
1328	X	x	tr	tr					
1338	X		tr	tr					
1348	X	tr	x	x	tr	tr			
1368	X	x	x	x		tr		x	x gypsum
1371	X				X	X			{ X bio. x gypsum
1385	X				X	x			{ X bio. tr. chl.
1405	X		x		X				{ X bio. tr. chl.
1425	X		tr		X				{ X bio. tr. chl.
1445	X		tr		X				X bio.
1465	X				X	X			{ x bio. tr. chl.
1475	X				X	X			{ x bio. tr. chl.

Notes: X = major component x = moderate to minor component tr = trace mont. = montmorillonite ahn. = anhydrite bio. = biotite chl. = chlorite.

Most samples from 1371 to 1475 contain traces to minor amounts of epidote. In most cases it was not possible to discriminate orthoclase from microcline, so that the presence of either is given as K-feldspar. In a few cases the x-ray pattern indicated microcline. Muscovite could not be discriminated from biotite in samples 1371-1475 due to interfering peaks. See sample descriptions for additional mineralogical information.

Thin Sections

Seventeen thin sections of sedimentary rocks, primarily sandstones, were studied by Gary Mitch. His results are given in detail in Table 16. Additional data on mineralogy is provided by this study. In some cases minerals which could not be detected in the x-ray study were found in thin section. The study also provides information on the diagenetic history of the sediments.

Three thin sections of Precambrian metamorphic and igneous rocks from the bottom of the hole were also studied. Data on these samples is summarized in Table 17.

Discussion of Results

Hydrothermal Activity

Information on hydrothermal activity of the geothermal system is the primary interest in the present work. Much of the information obtained is unfortunately not diagnostic of hydrothermal activity. This is primarily because diagenetic processes produce mineralogy and textures similar to those produced by hydrothermal fluids. Examples of these sorts of features include alteration of feldspars to kaolinite and sericite, quartz overgrowths on sand grains, and carbonate cement. Even the crusts of euhedral pyrite and quartz in veins are, by themselves, not conclusively indicative of hot water, but require proof in the form of fluid inclusions. Finally, diagenetic illite and kaolinite are identical with hydrothermal sericite and kaolinite.

The occurrence of barite and chalcopyrite are suggestive of hydrothermal activity. Barite occurs as a diagenetic mineral only very rarely, and in such cases forms spheroidal concretions of radially fibrous crystals. Chalcopyrite has been reported as a mineral produced by supergene processes in copper deposits, but the single, euhedral crystals observed in well P-1 at 728 ft depth must be regarded as hydrothermal. The habit of quartz crystals observed is elongated, with prominent prism faces. This is typical of hydrothermal veins, whereas quartz formed at low temperatures by surficial processes typically grow in radial clusters, with only rhombohedral faces exposed. This includes geodes and crusts on fractures. Such information is only qualitative, of course, and does not give much indication of how high temperatures may have been.

The most important information was obtained from fluid inclusions in the hydrothermal quartz from the sample at 248 ft. It is probable that the thermal history of the system is recorded in inclusions, with some trapped at the maximum temperature, and many during the period of cooling. Those trapped during rising temperatures might be expected to leak due to rising internal pressure and be sealed again later. When temperatures ceased rising, the tendency to rupture would stop, and fluid would be trapped at the maximum temperature, or during the cooling period.

The maximum temperature obtained, 252.1°C, may not be reliable, since the inclusion leaked afterward. The filling temperature of 230.5°C is probably good, since it was replicated four times before the inclusion may have begun to leak. The maximum temperature estimated from ratios of volumes of the bubble to total inclusion was 232°C. The agreement between the two data is welcome, but since so few inclusions were found which could be measured, this may not be representative of the maximum temperature attained by the system at the depth sampled.

Water at a temperature of 230°C must be confined by a pressure of at least 28 kg/cm^2, or it will boil. It is probable that the geothermal system at Pagosa Springs has been open to the surface for most of its history, so that this pressure was applied by a hydrostatic head alone. That is, the system was not subject to lithostatic pressure. If this is true, the minimum depth of formation of the fluid inclusions can be calculated. If the overlying column of water were all at 25°C, this would provide the maximum density to contain the pressure, and hence a minimum depth. A column of water 1087 ft above the inclusions would provide a pressure of 28 kg/cm^2. It is not too likely that the overlying water was entirely this cool, however. Another possibility is that from the surface to the site of inclusion entrapment, all the water is at the boiling temperature. This would provide the lowest possible water density. The depth from the surface would be about 1260 ft. Any amount of cooler water could be present, so that a column of water intermediate between 1087 and 1260 ft could provide the pressure. A third possibility is that the pressure was actually higher, and the depth is greater, but indeterminate. This last possibility is more probable, since no evidence of boiling was observed. The inclusions studied occurred at a depth of only 248 ft. Since the minimum possible depth of origin lies between 1087 and

1260 ft, this means that at least 800 to 1000 ft of overburden have eroded off since the inclusions were trapped. This further suggests a minimum age of the system, based on the rate of erosion.

The occurrence of pyrite and euhedral vein quartz shows a relation to lithology of the host rocks. All were sandstones, mostly with a low clay content. The rocks were therefore either permeable or brittle, capable of maintaining open fractures. Quartz and pyrite were observed in the Dakota Sandstone at 241, 264, 339, and 399 ft. In the Morrison Formation, which consists mostly of clay-rich beds, quartz and pyrite occur only in relatively thin sandstone beds, at depths of 499, 599, 655, 728 (chalcopyrite here), and 798 ft. The Wanakah consists of limestone and anhydrite, and apparently was impermeable. Below, a little pyrite was observed in the Entrada Sandstone at 1228 and 1308 ft. At 1258, pyrite occurred in 1-2 mm thick veinlets.

It appears that the wells O-1 and P-1 were not within the central part of the hydrothermal system at depth, although this location was within reach of the mineralizing water. Results will have to be obtained from other wells in the future to locate the central part of the system.

Lithology

Information obtained from visual logging, x-ray work, and thin section studies may be helpful to other workers regarding the lithologies and thicknesses of rocks drilled.

From the samples of cuttings, some limits may be placed on the depths of sedimentary contacts. At 284 ft, the rock is shale with sandy lenses, whereas at 299 ft the rock is sandstone. The base of the Dakota appears to lie between 422 and 459, the latter depth at which clay-rich sandy rocks first appear. The base of the Morrison occurs between 1108 and 1118, while the base of the limestone in the Wanakah was observed between 1208 and 1218. No strong lithologic difference was noted between the sandstone in the internal 1218-1278 and that below from 1298 to 1368. Both intervals may belong to the Entrada. At 1371, the top of the Precambrian was encountered.

Within the Morrison Formation many samples consisted of clay with variable amounts of quartz sand. Close examination of these samples revealed a granular structure in the clay, on the same scale as the quartz grains. It appears that the clay originally consisted of lithic fragments, probably of volcanic origin. The abundance of feldspar in the clay is also suggestive of such origin. These rocks have been termed "lithic sandstones" in the logging notes, but might also be called "diagenetic shales", in accordance with their present properties.

Precambrian rocks at the bottom of the hole exhibit normal mineralogy for rocks of this age in the Rocky Mountain area. Weak alteration observed in thin section of 1479 and 1481 is typical of metamorphic effects, and not that associated with hydrothermal alteration. The latter is typically guided by fractures, and destroys feldspars, particularly plagioclase, and biotite.

The very strong alteration at 1371 may be due to pre-Entrada weathering. This is particularly suggested by the replacement of biotite by hematite. Elsewhere in the well, where hydrothermal minerals occurred, hematite was not observed. The most prevalent hydrothermal mineral, pyrite, does not occur at 1371. It appears, then, that the alteration at this depth is not hydrothermal, and that the geothermal system did not reach this point in the well.

Potassium-Argon Date on Precambrian Rocks

A potassium-Argon date was obtained on biotite from the granite cored in Well P-1 between 1475.3 and 1477.6 feet. The entire granite interval was split and half was submitted to Geochron Laboratories Division of Krueger Enterprises, Inc., in Cambridge, Mass. There, the rock was crushed and biotite separated for the determination. The age obtained was 1152 ± 39 million years. It is Precambrian, as expected from the lithology.

Precambrian rocks from the southern Rocky Mountains region typically reflect a history of folding, metamorphism and intrusion by granitic rocks about 1700 million years ago, and a second event characterized by granitic intrusions about 1400 m.y. Locally, later events, such as the intrusion of Pike's Peak granite (1015 m.y.) lowered the mica ages or rocks (Hedge, et al., 1968; Hansen and Peterman, 1968). Giffin and Kulp (1960) determined potassium-argon ages of

Precambrian rocks in south-central Colorado, obtaining numbers from 980 to 1540 m.y. One specimen, a biotite gneiss, yielded a date of 1130 m.y., very close to the age of the Pagosa Springs granite sample. The biotite gneiss was collected between Cimarron and Sapinero, just west of Gunnison, and about 85 miles north of Pagosa Springs. Hansen and Peterman (1968) obtained Rb-Sr dates of 1190 $\pm$ 60 m.y. on two quartz monzonites from the Black Canyon of the Gunnison, although a K-Ar date on one of the specimens was 1220 $\pm$ 40 m.y. These results suggest that the date on the Pagosa Springs sample is not anomalous, and has not been re-set by hydrothermal activity from the hot springs. This is the opinion of Carl Hedge, U.S. Geological Survey, Denver (personal communication), with whom the writer concurs.

Table 16

Thin Section Studies of Sedimentary Rocks

by Gary Mitch

Sample No.: 0-1, 0-20' ("A")

Rock Name: Shaly siltstone

Composition: Too fine-grained for accurate point counting. Estimated mode is 70% silicate silt, 30% matrix clay. Silicates are mostly quartz, some feldspars and shreds of biotitec. Matrix is a network of mixed layer clays and spotty chloritic patches all laced with sericite. Small amounts of relatively pure kaolinite are derived from in-situ alteration of plagioclase (?). Matrix is shrouded in an iron-rich veil of decomposition products. Disseminated pyrite is present as scattered euhedra (to .003 mm) and botryoidal clusters.

Texture: No bedding laminations seen in thin section. Silt ranges up to .06 mm, averages = .03 mm, and is subrounded to angular. Sorting is good.

Alterations: Much overgrowth silica is altering to chert and can be traced through many transitional stages.

Sample No.: 0-1, 241-244

Rock Name: silty shale with sandy laminae

Composition: Too fine-grained for modal analysis. Silt generally looks quartzose. Matrix clays are heavily coated with iron oxides and an aggregate extinction is present. Matrix is peppered with pyrite which, except for veins (see below), shows a weak alinement within bedding or no site preference at all.

Texture: Laminae in the sample are about 1/4 mm thick and are apparent from concentrations of fine sand, coarse silt or layers unusually rich in iron oxides or carbonaceous (?) matter. Fractures, fairly consistent at 50' to bedding are present and filled with euhedral quartz and pyrite.

Alterations: Other than vein fillings, the silicate silt is peripherally altering to matrix clays. Alteration of pyrite likely contributes much of the matrix iron oxides.

Sample No.: 0-1, 264

Rock Name: quartz wacke

Composition: Frameworks 70 matrix 28 other 2 (rock fragments, pyrite). Framework fraction is virtually all quartz. These grains are variably strained and contain plutonic accessory minerals. Rock fragments are usually chert. Pyrite is scattered throughout and is occasionally in streaky laminea-like layers. Matrix is composed of mixed layer clay assemblages laced with sericite or illite.

Texture: Amount of matrix alternates between crude layers. Matrix-poor zones show early compaction effects of long and sutured grain contacts and many quartz overgrowths. Matrix-rich zones generally retain a grain support fabric and still show significant overgrowth rims and suturing between grains. Quartz grains are quite variable in shape (angular to round) but fairly consistent in size, averaging 1/10 mm (very fine sand).

Alterations: Framework grain-matrix borders in the matrix poor zones are complex, with peripheral alteration to the matrix clays. Sutured aggregates of grains in these areas are undergoing dissegregation from clays working in along internal grain contacts. These alterations are more advanced in the matrix rich areas, which accounts for the increased amount of clays. Matrix supported, sutured grain aggregates also support a diagenetic origin for this clay product. Thus the matrix rich and matrix poor zones likely reflect different stages of diagenesis.

Sample No.: 0-1, 319-322

Rock Name: quartz alrenite cemented with quartz

Composition: Quartz 95 grains 80 cement 15 other 5 (rock fragments feldspar, opaques). Mineralogically quite simple in that virtually all grains are quartz sand. Remainder is quantitatively minor rock fragments and a few feldspar grains. Trace amounts of ilmenite (altered to leucoxene) and pyrite at present. Quartz cement is present as syntaxial overgrowths on grains.

Texture: Quartz grains are tight and interlocking reflecting a porosity decrease during initial compaction with resulting pressure welding and precipitation of the overgrowths. Quartz grains are in the fine sand fraction (1/8 - 1/4 mm). Original grain boundaries at the base of the overgrowths show the quartz to have been well rounded and well sorted. Feldspars and rock fragments were compacted and sutured with the quartz. Some of these grains were also apparently squashed between compacting quartz grains.

Alterations: Virtually all the feldspar and rock fragments have altered to clays and sericite. These products are observed occupying dispersed grain positions. Relict plagioclase twins and alteration product inhomogeneities indicate the former presence of feldspar and rock fragments respectively. Dark colored material bearing opaques (pyrite, hematite) occurs along some grain borders.

Sample No.: 0-1, 399-402

Rock Name: quartz arenite

Composition: Quartz 90 other 10 (chert, clay, pyrite, rock fragments, voids). Quartz grains show variable strain and inherited inclusions and are cemented from pressure welding and optically continuous overgrowths. Rock fragments are largely altered to mixed layer clay assemblages. Pyrite fills voids, lines chert and clay pseudomorphs of framework grains, replaces into them and occurs along intact grain boundaries.

Texture: Grain fabric is tight and interlocking from pressure solution resulting in suturing of grains and precipitation of overgrowths. The voids present could be from flushing of post-depositional clay pseudomorphs of unstable frameworks. Original quartz borders below overgrowths show that the grains, before compaction, were generally very round, ranged from 1/3-1/2 mm in size (medium sand) and were well sorted.

Alterations: Unstable framework grains have altered to clays which corroded adjacent quartz grains. Many quartz overgrowths and grains are degrading to chert. These processes have produced clay and chert pseudomorphs of frameworks. Pyrite has moved in along fractures and grain boundaries, filled voids (from flushing of pseudomorphs (?) and localized around pseudomorphs.

Sample No.: 0-1, 499-504

Rock Name: feldspathic wacke

Composition: Quartz and feldpsar 58 clays 28 carbonate 13 other 1 (muscovite, pyrite, rock fragments). Distinguishing feldspar and quartz was not attempted as much of the plagioclase as untwinned. Both microline and plagiocalse are present. Quartz is typically clear, somewhat strained, and bears sytnaxial overgrowths. A small amount of pyrite - no specific distribution - is present, as are some shreds of detrital muscovite clays are kaolinitic and authigenic. The carbonate (calcite ?) appears to be a late cement.

Texture: Major framework grains average 0.2 mm (fine sand) in diameter. Sorting and grain roundness have been degraded by diagenetic alterations. The presence of syntaxial overgrowths and sutures on floating grains alludes to an early compaction history. The grain dispersal we see now is due to clay production through alteration of grains.

Alterations: The clay present is derived from alteration of framework grains, particularly feldspars, rock fragments and syntaxial overgrowths. The clay production disaggregates grains and disperses the framework. The carbonate present is believed to be a late introduced cement as it appears to transect all the textures and embays all sample constituents.

Sample No.: O-1, 655-659

Rock Name: feldspathic wacke

Composition: Frameworks 46 carbonate 28 clays 26 tr. opaques, tourmaline. Owing to difficulty in distinguishing untwinned plagioclase, feldspars were not tabulated separately but combined with quartz in the framework count. This fraction is estimated at 85% quartz, 15% feldspars. Frameworks are all variably altered. Clay is probably all authigenic and contains some areas of relatively pure kaolinite but includes much mixed layer types and illite or sercite. In light of the alterations, modal feldspar has diminished through time. Dolomite is present as a late (?) cement.

Texture: Frameworks appear moderately sorted and of very fine sand (1/10 mm) size. Grain shapes vary widely (angular to round) but this is partially due to the wholesale grain alterations (to clays) that are tending to disperse the framework. Precipitated syntaxial overgrowths and welded grain contacts are still present and their distribution and occurrence indicate a tightly welded framework following initial compaction.

Alterations: Virtually all grains, but particularly feldspars, are altering to clays - some to near obliteration. Grains are found in all stages of alteration from peripheral degradation to minute remnant grain shreds in grain-sized clay patches. Clay pseudomorphs are present. Carbonate appears to be a late cement, post-dating much of the alteration - but this is unclear as carbonate cement patches are turbid and veiled.

Sample No.: P-1, 728

Rock Name: sub feldspathic arenite

Composition: Quartz 67 feldspar 9 cement (silica) 8 cement (carbonate) 16. Quartz grains are variably strained and commonly bear syntaxial overgrowths. Feldspars include both plagioclase and microcline and show some alterations but are generally intact. Some of this alteration is likely to be source area weathering. Carbonate cement is dolomite.

Texture: Framework quartz is subrounded and averaging 1/4 mm grain diameters (fine sand). Feldspars are similary sized but are more angular owing to cleavage. The sample is well sorted and the carbonate cement poikilotopically encloses framework grains.

Alterations: Frameworks are all relatively intact but undergoing peripheral etching by the carbonate cement. In some instances almost entire grains have been obliterated. Syntaxial overgrowths show more extensive replacement by the carbonate.

Sample No.: P-1, 828

Rock Name: feldspathic wacke

Composition: Quartz 46 feldspar 19 clays 15 carbonbate 20. Quartz grains are variabley strained and commonly have syntaxial overgrowths. Trace amounts of detrital opaques are present along with some disseminated authogenic hematite. Carbonate cement cross cuts most grains.

Texture: Frameworks range fromn silt to 1/2 mm but average in the fine sand grade (1/8-14 mm). Grains are subangular to subrounded and the sample looks well sorted. Grains shapes are modified by peripheral alterations. Modal feldspar is being decreased by alteration to clay and this increases the amount of matrix present as grains are replaced and disaggregated.

Alterations: The feldspar grain interiors preserve what might be minor source area weathering. Borders of these and quartz grains and overgrowths are being replaced, in-situ, by clays. All stages of alteration can be seen. Trace opaques have oxidized. Carbonate-clay relations are unclear; the carbonate appears to postdate major clay alterations.

Sample No.: P-1, 878

Rock Name: quartz arenite

Composition: Frameworks 63 carbonate 21 clays, mica 12 other 4 (pyroxene, opaques). Framework feldspar are often untwinned fragments or whole grains difficult to segregate from quartz except for microcline. Clay matrix includes some kaolinite and much mixed layer types with micromicas (chlorite, sericite ?) in a network around grains. Matrix contains much disseminated hematite. Carbonate cement is cloudy.

Texture: Frameworks are well sorted and grain sizes range from silt to 1/8 mm, averaging about 1/10 mm (very fine sand). These are subangular to subrounded. Carbonate cement is patchy but encloses these and their clay pseudomorphs. A more extensive mixed-layer clay assemblage and micormica network pervade the framework and appear to enclose carbonate patches too. Sporadically preserved grain overgrowths and sutured and long grain contacts indicate an early compaction.

Alterations: Early feldspar alteration is preserved as kaolinitic patches. Carbonate cement appears to have been introduced later and has etched and embayed framework grains. Later development of mixed layer clay assemblages appear to corrode all constituents and the late micromica network follows manmy intergrain borders and appears to even surround some carbonate cement patches.

Sample No.: P-1, 888

Rock Name: quartzose siltstone

Composition: Silt 70 matrix 30 (visual estimation). Silt consists largely of quartz; microcline and plagioclase are present also and show as twinned grains and cleaved fragments. Some chert fragments and detrital heavy minerals are present. Matrix appears to be largely a mixed-layer clay assemblage with portions which have much micromica (chlorite, sericite). Matrix contains much disseminated hematite. Some carbonate occurs in the matrix.

Texture: Textural relations are largely veiled by the matrix impurities. Silt averages 1/25 mm in grain diameter (medium-coarse silt) and is subrounded to angular in shape; many grains are cleavage fragments. Sorting in the silt is poor to moderate.

Alterations: Silt is being perhipherally altered to matrix clays but this is not likely to be extensive. The carbonate may be reconstituted detritus, but is quantitatively minor.

Sample No.: P-1, 908

Rock Name: feldspathic arenite

Composition: Quartz 51 fed 14 carb 28 clay 5 other 2 (rock fragments, 2 iron). Quartz occurs as single grains, variably strained and rutilated,and polycrystalline grains, chert, and meta-quartz rock fragments. Feldspar fraction includes both microcline (75%) and plagioclase (25%). Clay includes kaolinate and mixed layer assemblages. The carbonate occurs as a cement and hematite is disseminated throughout.

Texture: Carbonate cement poikilotopically encloses framework grains. Frameworks range from fine silt to 1/8 mm in grain diameters (very fine sand) and are well sorted. Grain shapes vary from subangular to angular with few larger subrounded quartz grains. Grain size and shape has been altered somewhat by the carbonate cement etching peripheries.

Alterations: The carbonate cement, an early void filler, has etched and corroded the framework grains it encloses. Subsequent kaolinization of feldspars has left cement enclosed clay patches. These have etched back into the carbonate along with mixed layer clays which may represent altered rock fragments. Late peripheral alteration has produced micromica networks along grain boundaries and these appear to enclose some carbonate cement also.

Sample No.: P-1, 988

Rock Name: Sub feldspathic to quartz arenite

Composition: Quartz 43 carbonate 40 f eldspar 10 clay 5-8 other 1 (rock fragments). Quartz is variably strained and corroded by the carbonate, which is the major binder in the sample. Overgrowths on grains are not extensive. Clays include kaolinitic and mixed-layer assemblages. Feldspars include both plagioclase and microcline.

Texture: Carbonate dominates the sample. Its texture is granoblastic and it embays most grains and is tending to disperse the framework. Frameworks are in the fine sand range (1/8-1/4 mm) but grain size and shape are effectively altered from peripheral replacement by carbonate.

Alterations: The high modal per cent (40) of carbonate cement and its granoblastic texture suggest it to be a late replacement. It corrodes, embays, and has fairly extensively replaced many framework grains. It is as likely, though less clear, that the carbonate is also engulfing clays produced from alteration of a once greater feldspar fraction.

Sample No.: P-1, 1018

Rock Name: feldspathic wacke

Composition: Frameworks 70 mica & clay 15 carbonate 12 other 3 (chert, rock fragments, hornblende, zireon). Quartz feldspar are distinguished with difficulty, owing to untwinned plagioclase. Much of the feldspar is more altered and cleaved relative to quartz and a visual estimation places felspar in excess of 10% rock volume. This may be all plagioclase. No microcline was seen. Matrix clays are authigenic and have kaolinitic patches but are strongly illitic (?). Many frameworks have mica envelopes which, owing to the long flake dimensions, it judged to be sericitic muscovite. The carbonate is late cement.

Texture: Framework grains range 1/4 - 1/10 mm and average within the fine sand fraction (1/5 - 1/10 mm). The sample is well sorted and grain shapes are subrounded to subangular, excluding obvious cleavage fragments which are distinctly angular. Grain boundary sutures and overgrowths attest to early compaction but the texture is dominated by the authigenic clays, micas and carbonate cement.

Alterations: Matrix clays can be seen to accumulate from in-situ breakdown of feldspars. The carbonate cement corrodes and embays most framework grains and appears to be encroaching on the authigenic clays but this cannot be determined with certainty. Late recrystallization has produced the mica envelopes on frameworks and this does appear to enclose carbonate also.

Sample No.: P-1, 1078A

Rock Name: Silty shale, some scattered sand

Composition: Sample is too fine grained for modal analysis but visual estimation places the sand/silt fraction at 30%. This sand and silt is largely quartz with lesser feldspar and is enclosed in a brownish clay matrix that is heavily oxidized but can be seen to still contain disseminated pyrite in descrete euhedra and small clusters. Disseminated and blebby hematite account for the reddish brown color. Trace amounts of other silicates (e.g., tourmaline) are present. Some carbonate is present.

Texture: No obvious stratification is present in thin section. Carbonate occurs as vein filler and in discrete patches that may be reconstituted detritus.

Alterations: Matrix clays are oxidized, silt and sand grains are peripherally altered to matrix clays but the extent of this cannot be determined.

Sample No.: P-1, 1078B

Rock Name: shaly siltstone, quartzose

Composition: Too fine-grained for modal analysis. Silt fraction comprises over 50% of the sample and contains virtually all quartz and feldspar. This is bound in a heterogeneous clay matrix carrying small amounts of detrital biotite, dispersed hematite, sericite, illite and stringers and patches of turbid hematitic carbonate cement.

Texture: Silt grains are subangular to subrounded and are moderately-to-well-sorted. Textural reations are generally clouded by dispersed oxides and other impurities in the binders.

Alterations: Most silt is corroded and embayed by the binding material.

Sample No.: P-1, 1258

Rock Name: subfeldspathic arenite

Composition: Quartz 59 feldspar 7 carbonate 21 clay 8 other 5 (rock fragments, pyrite). Quartz is variable and includes single grains with optically continuous overgrowths and polycrystalline grains. Chert rock fragments are present. Feldspar includes significant plagioclase, much of which is untwinned. Clay is authigenic and occurs as grain size patches derived from altered framework grains (feldspars and rock fragments). Carbonate appears to be an early cement. Significant euhedral and subhedral pyrite is scattered about but except for a few concentrations on certain rock fragments, it shows no site preference.

Texture: Carbonate cement poikilotopically encloses many framework grains and is interpreted as an early void filling cement. Grain overgrowths and long grain contacts point to an early compaction event but again, the carbonate signifies preservation of significant void space following this. Grain diameters range from coarse silt to 3/4 mm and average about 1/4 mm (fine-medium sand). Sorting is moderate, grain shapes are subrounded, but etching by cement has increased angularity on many.

Alterations: The carbonate cement has extensively etched or corroded the framework grains. Kaolinite patches enclosed by this cement suggest that feldspar alteration followed cementation but subsequent clay-carbonate relations are problematical. In some cases, the carbonate appears to have later been corroded back by the authigenic clay. In other grains, the replacement clay appears to merely abut the cement fabric. Micromica envelopes around many grains are the result of a late recrystallization of matrix clays.

Sample No.: P-1, 1268

Rock Name: subfeldspathic arenite grading to subfeldspathic wacke

Composition: Quartz 53 feldspar 11 carbonate 15 clays 14-18 other 3 (rock fragments, pyrite)
Sample is essentially the same as P-1, 1258 but with the following differences:

1) modal feldspar includes significant microcline
2) there is less carbonate, more clay in this sample, more mixed layer clays
3) illite appears better developed here in the matrix and on feldspars

Textural relations and alterations are essentially the same.

Table 17

Thin Section Studies of Pre-Cambrian

Metamorphic and Igneous Rocks

P-1, 1371

Mineralogy:

- quartz, about 20%
- biotite, about 10%
- altered plagioclase, about 60%
- microcline, about 10%

Texture: equigranular, xenomorphic

Remarks:

Plagioclase is completely altered to a mixture of carbonate and sericite.

Biotite is partly altered to hematite.

Rock Type: granite gneiss, or gneissic granite.

P-1, 1479

Mineralogy:

quartz	47.1%
microcline	13.4%
plagioclase (An_{32})	24.7%
coarse muscovite	6.6%
epidote	2.7%
apatite	0.7%
chlorite	0.3%
biotite	4.5%
sericite	tr
zircon	tr
metamict allanite ?	tr
	100.0%

Texture: equigranular, xenomorphic

Remarks:

Quartz and coarse microcline occur in closts surrounded by a mixture of coarse plagioclase, biotite, fine-grained quartz and epidote.

Microline is slightly perthitic. It shows rare graphic intergrowths with quartz.

Plagioclase locally shows albite twinning, where it gives a composition of An_{32} based on extinction angles. Elsewhere it appears to have been replaced by a dirty-appearing, optically negative, untwinned feldspar; intergrown with biotite, sericite, coarse muscovite and locally by epidote. No clear difference in index occurs between the two, however.

1000 points counted

Rock Type: Granodiorite

P-1, 1481

Mineralogy:

plagioclase (An_{32})	37.3%
biotite	36.2%
coarse muscovite	3.8%
sericite	9.3%
carbonate	3.6%
epidote	7.8%
chlorite	2.0%
	100.0%

Texture: gneissic to schistose

Remarks:

Biotite is euhedral, with a strong foliation

Plagioclase is largely untwinned, optically negative, and gives a composition of An_{32} based on extinction angles. It is randomly replaced by epidote. Elsewhere it is randomly partly sericitized.

Epidote occurs in clots up to several mm diameter with coarse muscovite and carbonate, with placioclase mostly absent or replaced. Foliation is deflected around these clots, so it appears that deformation is partly post-alteration, and probably pre-Cambrian in age.

1000 points counted.

Rock Type: Biotite plagioclase schist.

Barrett, J.K., and Pearl, R.H., 1976, Hydrogeological data of thermal springs and wells in Colorado: Colo. Geol. Survey Inf. Series 6, 124 p.

___1978, An appraisal of Colorado's geothermal resources: Colorado Geol. Survey Bull. 39, 224 p.

Batzle, M.L., Shirey, S.B., Simmons, Gene, 1978, Correlation of physical properties with microfracture characteristics [abs.]: Geological Society of America Abstracts with program (Rocky Mountain Section), v. 10, no. 5, p. 210.

Craig, H., 1963, The isotopic geochemistry of water and carbon in geothermal areas, in E. Tongiogi, ed., Nuclear geology of geothermal areas: Spoleto, Italy, 284 p.

Davis, S.N., and Tuck, L.J., 1964, Optimum depth of wells in crystalline rocks: Groundwater, v. 2, p. 6-11.

Dunn, D.E., 1964, Evolution of the Chama basin and Archuleta anticlinorium, eastern Archuleta County, Colorado: Univ. of Texas Ph.D., thesis available from Univ. Microfilms Inc., Ann Arbor, Michigan, 114 p.

Galloway, M.J., 1977, Water circulation model for hot springs in fractured crystalline rock [abs.]: Geol. Soc. America Abstracts with Program (Rocky Mountain Section), v. 9, no. 6, p. 725.

Giffin, C.E., and Kulp, J.L., 1960, Potassium-argon ages in the Precambrian basement of Colorado: Bull. Geol. Soc. Am., v. 71, p. 219-222.

Hail, W.J., Jr., 1965, U.S. Geol. Survey unpub. reconn. map.

Hansen, W.R., and Peterman, Z.E., 1968, Basement-rock geochronology of the Black Canyon of the Gunnison, Colorado: U.S. Geol. Survey Prof. Paper 600-C, p. C80-C90.

Hedge, C.E., and others, 1968, Precambrian geochronology of the northwestern Uncompahgre Plateau, Utah and Colorado: U.S. Geol. Survey Prof. Paper 600-C, p. C-91-96.

Hem, J.D., 1970, Study and interpretation of the chemical characteristics of natural water: U.S. Geol. Survey Water-Supply Paper 1473, 363 p.

Iorns, W.V., Hembree, C.H., and Oakland, G.L., 1965, Water resources of the Colorado River Basin - Technical report: U.S. Geol. Survey Prof. Paper 441, 370 p.

Keller, G.V., 1977, Geophysical surveys at Pagosa Springs and Glenwood Springs: Unpub. report from Geophysics Fund, Inc., Colorado School of Mines.

Kelly, V.C., and Clinton, N.J., 1960, Fracture systems and tectonic elements of the Colorado Plateau: Univ. New Mexico Pub. Geology, no. 6, 104 p.

Koulet, K.G., and Armstrong, J.A., 1978, An environmental report on the drilling and production testing of an exploratory geothermal well in Pagosa Springs, Colorado: Report under contract by the Denver Research Institute, 69 p.

Kruseman, G.P., and de Ridder, N.A., 1970, Analysis and evaluation of pumping test data: Institute for Land Reclamation and Improvement, Wageningen, The Netherlands.

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, p. 2329-2352.

Lohman, S. W., 1972, Ground-water hydraulics: U.S. Geological Survey Prof. Paper 708, 70 p.

Pearl, R.H., 1972, unpublished groundwater report.

Pearl, R.H., Galloway, M.J., and Dick, J., 1970, The Pagosa Springs Project--the first permitted geothermal wells in Colorado: Geothermal Resources Council, Transactions, v. 2, p. 517-519.

Read, C.B., Wood, G.H., Wanek, A.A., and Mackee, P.V., 1949, Stratigraphy and geologic structure in the Piedra River canyon, Archuleta County, Colorado: U.S. Geol. Survey Oil and Gas Inv. Prelim. Map 96.

Ryder, R.T., 1977a, Oil and gas potential of the Chama-Southern San Juan Mountains wilderness study area, Mineral, Rio Grande, Archuleta, and Conejos Counties, Colorado, in Mineral resources of the Chama-Southern San Juan Mountain wilderness area, Mineral, Rio Grande, Archuleta, and Conejos Counties, Colorado: U.S. Geol. Survey open-file rept. 77-309, 210 p.

___1977b, Hydrocarbon potential of the Archuleta anticlinorium, Brazos uplift, Chama basin: v. 77, no. 49, The Oil and Gas Journal, Dec. 5, p. 163-170.

Steven, T.A., and others, 1974, Geologic map of the Durango quadrangle, southwestern Colorado: U.S. Geol. Survey Map I-764.

Vail, E.E., 1896, Pagosa Hot Springs, the Carlsbad of America, Archuleta County, Colorado: Pagosa Springs Herald.

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

Wood, G.H., and others, 1948, Geology of southern part of Archuleta County, Colorado: U.S. Geol. Survey Oil and Gas Prelim. Map OM-81.

DEPARTMENT OF NATURAL RESOURCES
COLORADO GEOLOGICAL SURVEY
JOHN W. ROLD, DIRECTOR

GEOLOGIC MAP OF THE PAGOSA SPRINGS AREA, COLORADO

by Michael J. Galloway

COLORADO GEOLOGICAL SURVEY
SPECIAL PUBLICATION 10
PLATE 1 OF 3

EXPLANATION

Holocene

Qal — **Alluvium**
Gravel, sand, and silt

Pleistocene

Qtr — **Travertine Deposits**
Calcium carbonate, deposited by hot springs

Qt — **Terrace Deposits**
Well-rounded gravel and sand

UNCONFORMITY

Miocene — Potosivolcanic Series

Tl — **Dikes**
Lamprophyre and diabase

Tcl — **Sills and Lacoliths of Conejos Age**
Chiefly granodiorite and syenite porphyry

Tpcu — **Upper Member**
Flow rock, flow breccia, and tuff, ranging from basalt to rhyolite

Tpcl — **Lower Member**
Gravel, sand, and silt; largely derived from volcanic rocks

UNCONFORMITY

Eocene and Oligocene

Tbb — **Blanco Basin Formation**
Sandstone and arkosic pebble conglomerate chiefly derived from Precambrian plutonic igneous and metamorphic rocks

UNCONFORMITY

Paleocene

Tka — **Animas Formation**
Shale and sandstone containing much volcanic debris

? UNCONFORMITY ?

Upper Cretaceous

Kl — **Lewis Shale**
Dark, bentonitic, marine shale

Kmv — **Mesaverde Group undivided**
Massive sandstone to interbedded sandstone and shale

Km — **Mancos Shale undivided**
Dark, marine shale with some sandstone and limestone

Kd — **Dakota Sandstone**
Quartz sandstone with some dark carbonaceous shale

UNCONFORMITY

Jurassic

Jmw — **Morrison and Wanakah Formations, Undifferentiated**
Variegated sandstone, siltstone, mudstone, and shale, and laminated brown to black gypsiferous limestone, respectively

Contact
Dashed where doubtful,
Dotted where concealed

Normal Fault
Dashed where doubtful,
Dotted where concealed
Bar and dot on downthrow side

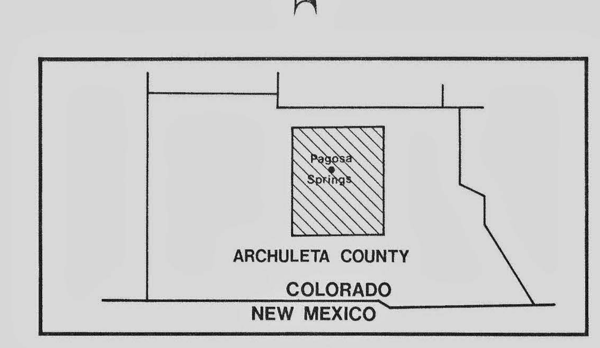
Dikes
Dashed where doubtful,
Dotted where concealed

Axis of Anticline

Axis of Syncline

Dip and Strike of Beds
Number indicates degree of dip

N



INDEX MAP

Base from U. S. Geological Survey

SCALE 1:24 000

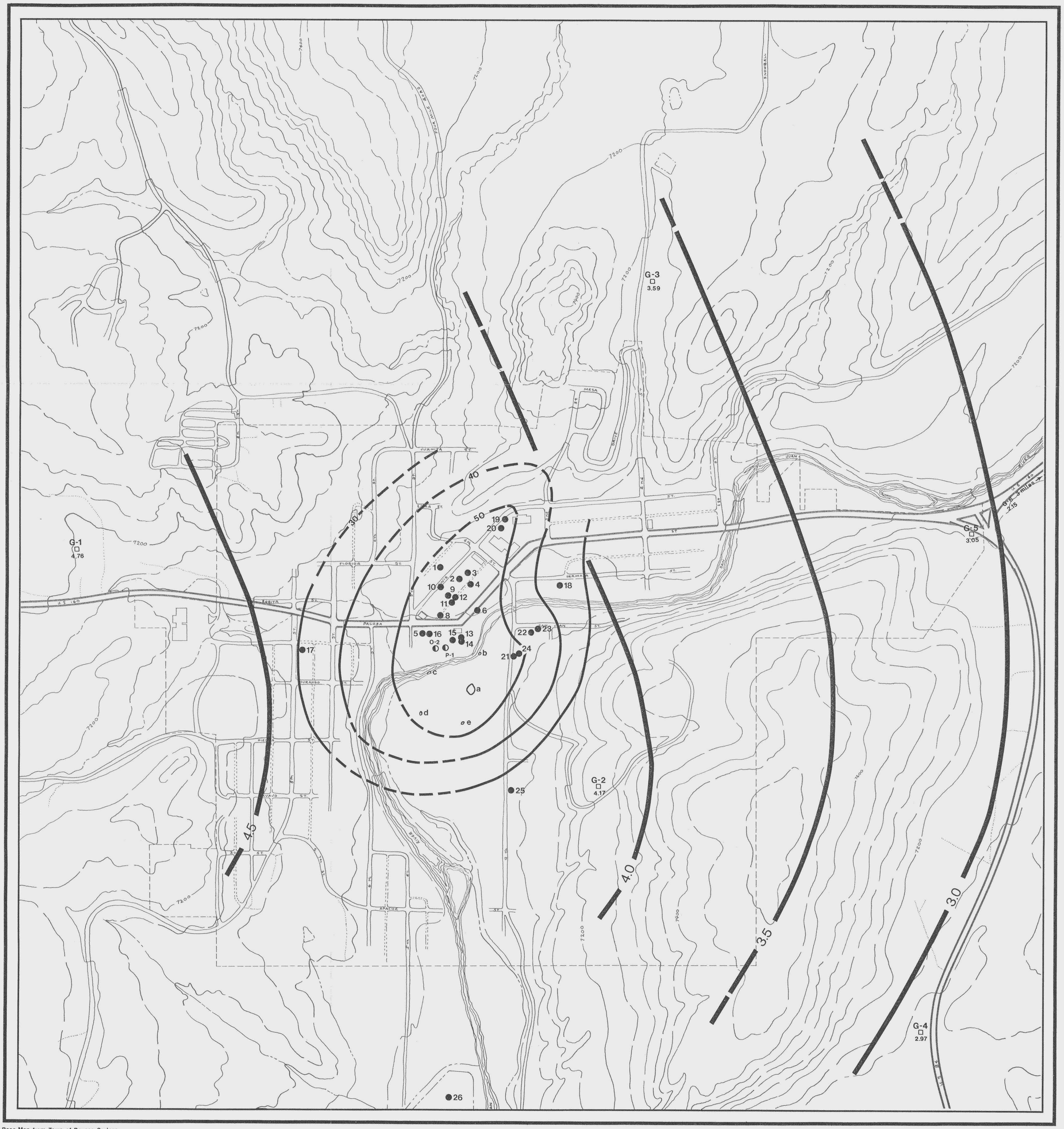
Drafted by M. V. Persichetti

DEPARTMENT OF NATURAL RESOURCES
COLORADO GEOLOGICAL SURVEY
JOHN W. ROLD, DIRECTOR

GEOTHERMAL MAP OF THE PAGOSA SPRINGS AREA, COLORADO

by Michael J. Galloway

COLORADO GEOLOGICAL SURVEY
SPECIAL PUBLICATION 10
PLATE 2 OF 3



Base Map from Town of Pagosa Springs

Drafted by M. V. Persichetti

SCALE
0 100 500 1000 FEET

EXPLANATION

Line of Equal Heat Flow (H. F. U.)

Line of Equal Groundwater Temperature (°C)

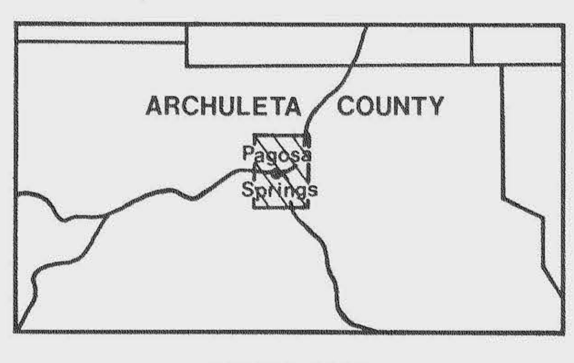
G-1 3.00 Heat Flow Hole Location, Number, and Heat Flow (See Table 6)

●20 Hot Well Location and Number (See Table 4)

◐P-1 C. G. S. Test Well Location and Number (See Table 4)

⬭a Hot Spring Vent and Letter (See Table 2)

N



INDEX MAP

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HYDROLOGIC MAP OF THE PAGOSA SPRINGS AREA, COLORADO

by Michael J. Galloway

COLORADO GEOLOGICAL SURVEY
SPECIAL PUBLICATION 10
PLATE 3 OF 3

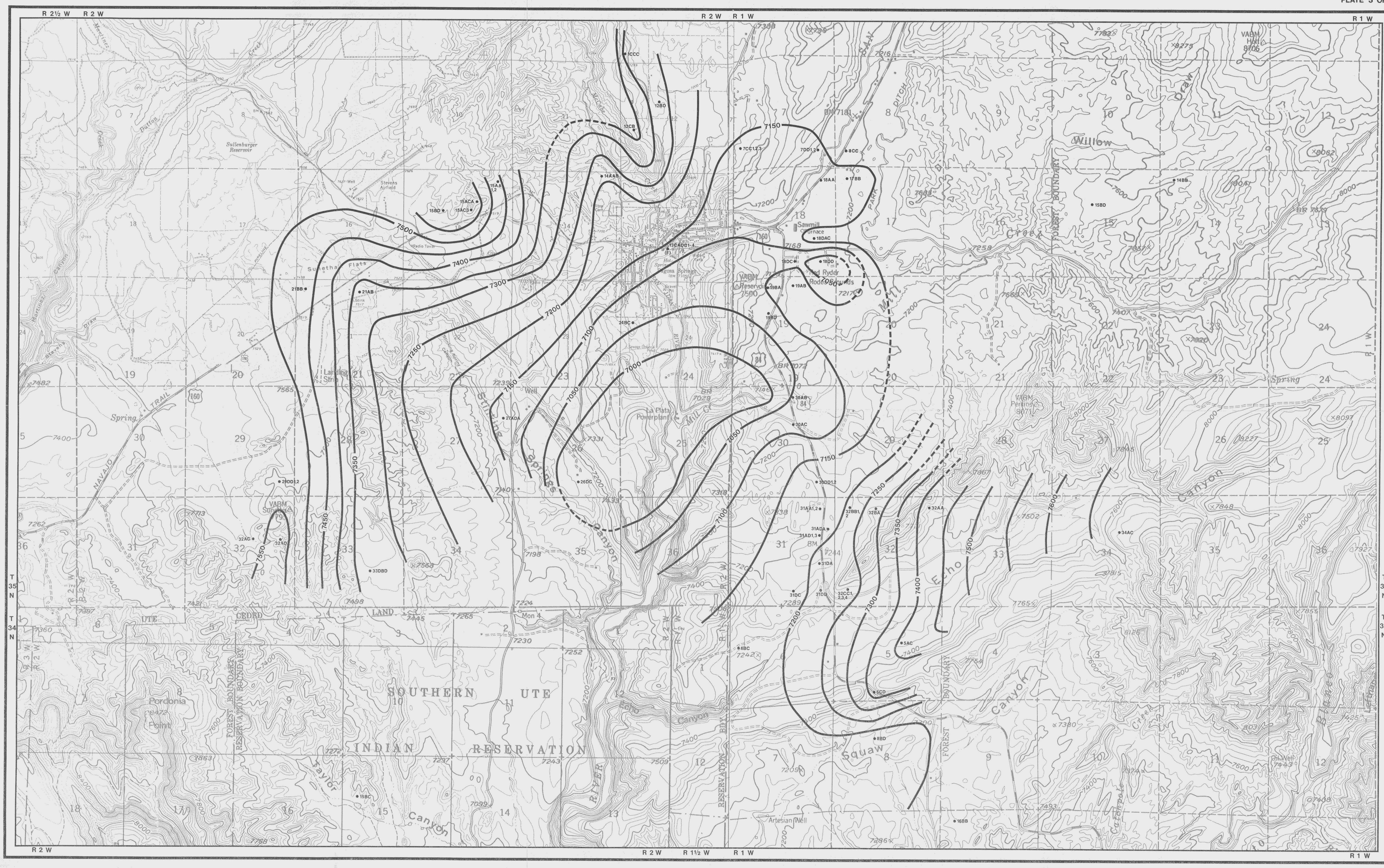


Figure 1 - Elevation of the Water Surface, Mancos Shale, Pagosa Springs Area, Colorado

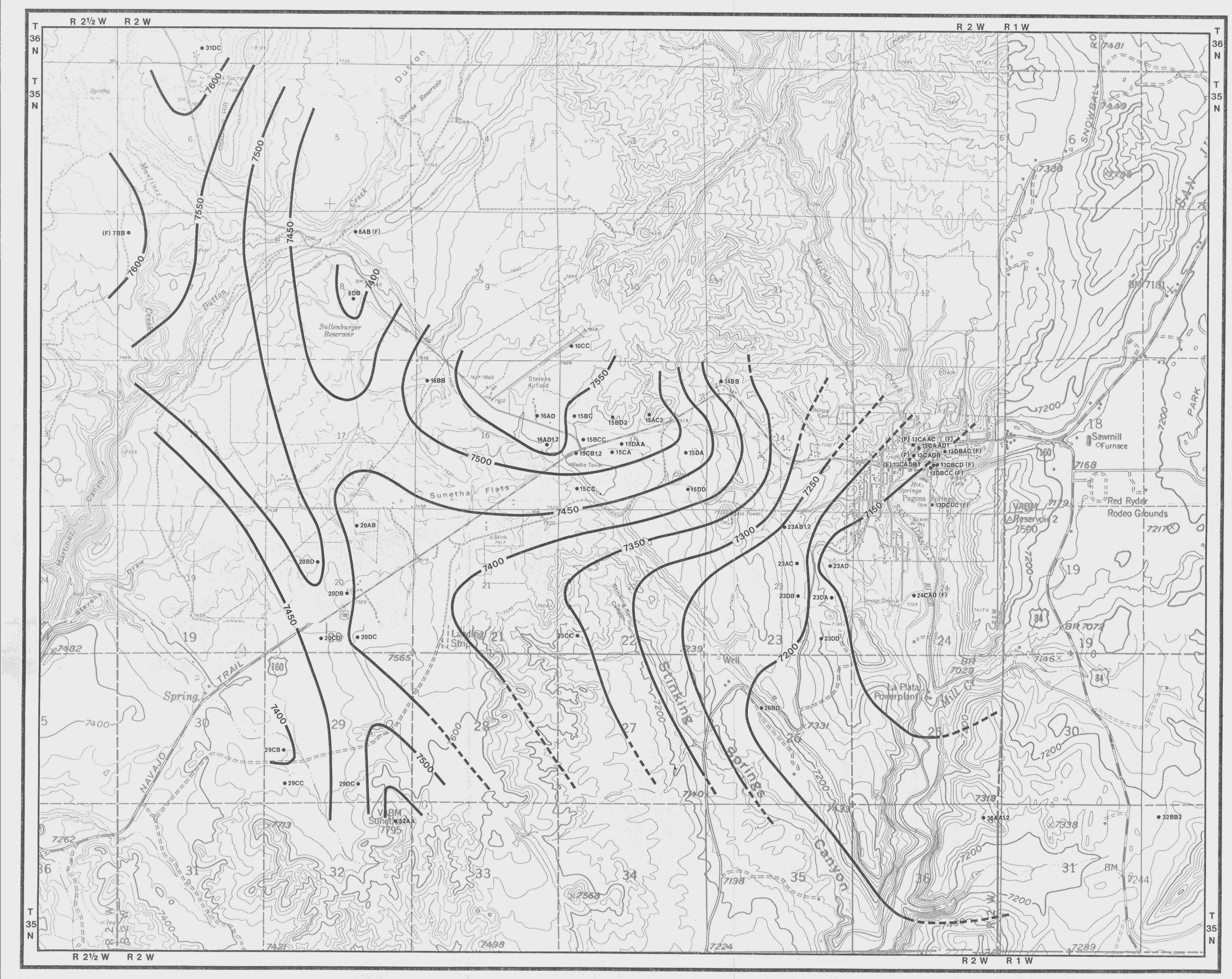


Figure 2 - Elevation of the Potentiometric Surface, Dakota Sandstone, Pagosa Springs Area, Colorado

EXPLANATION

• 20CAD (F) — **Well Location and Number**
Number identifies Section and location within Section;
(F) indicates well is flowing at the surface

Line of Equal Elevation of the Water Surface, Mancos Shale
Dashed where approximately located

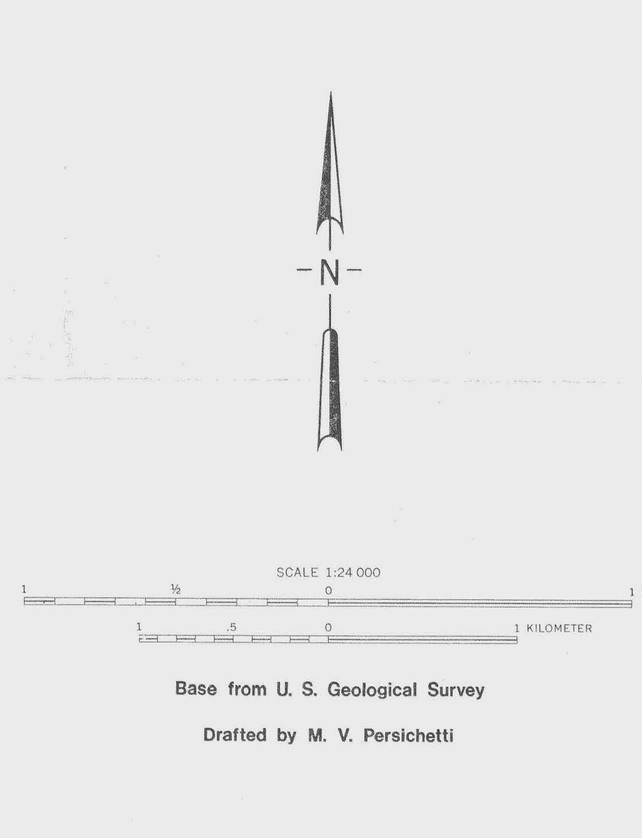
Line of Equal Elevation of the Potentiometric Surface, Dakota Sandstone
Dashed where approximately located

N

SCALE 1:24 000

Base from U. S. Geological Survey

Drafted by M. V. Persichetti



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