The most efficacious system for the quantity and quality of dilution water may then be selected for the site.

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The Occurrence of Thermal Ground-water in the Basin and Range Province of Arizona

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INTRODUCTION

Purpose

The principal object of this report is to examine on a regional basis the occurrence of ground-water having temperature considered to be higher than normal. Water emitted from natural springs and that produced by pumping for irrigation and industrial purposes is included in this study.

Location

The area included in this report is that portion of Arizona which lies within the Great Basin, (Basin and Range) Physiographic Province, (Fenneman, 1931, pp. 326-395) and comprises approximately 51,000 square miles of the state's surface area. The term "Desert Region" is also used in some reports for describing the subject area, (Halpenny, 1952).

Previous Investigations

Other than the brief compilation by Haigler (1969), no detailed work has been devoted entirely to a study of the occurrence of thermal ground-water in Arizona. Early workers such as Gilbert (1875) compiled a list of hot springs in the United States which included those springs whose water temperature exceeds the mean annual air temperature by 15° Fahrenheit. Peale (1883) further expanded the previous work in his report. Stearns et al (1937) and Waring (1965) compiled comprehensive sets of data on thermal springs in the United States. They reviewed the previous literature on the subject and their reports include extensive bibliographies. Included in their works were some springs whose water temperature may not exceed 10°F. above the mean annual air temperature of the locality but are appreciably warmer than normal for the area. White (1957) considers 10°F. above air temperature as significant and characteristic of thermal springs. For the purpose of this regional study, water must be 15°F. over the mean annual air temperature at their localities. (Waring, 1965, p.4)

Feth et al (1954) investigated the occurrence of springs in the Mogollon Rim area of Arizona; however, only a few of the many spring phenomena listed emit water with temperatures which can be classified as thermal. Several of the many studies made through the cooperative effort of the U.S. Geological Survey and the Arizona State Land Department which deal with the ground-water resources of particular areas in southern Arizona, contain statistical data on thermal springs and wells producing water of higher than normal temperature. Detailed work on most of the springs in the region is scanty to non-existant.

The general literature concerning hot springs and the occurrence of thermal water in other areas of the world is quite extensive (Waring, 1965). The scope of this study precludes a review of this material.

Acknowledgements and Method

The original investigation upon which this report is based was made possible through support granted by the Ground Water Branch, Water Resources Division, United States Geological Survey. Much of the work has been done by searching the literature and examining the records kept in the Tucson and Phoenix offices of the Ground Water Branch, U.S.G.S. The aid rendered by the personnel of these

offices is gratefully acknowledged. Visits to the sites of some of the more important thermal springs have been made intermittently since 1961.

Land Forms

The Basin and Range portion of Arizona is a region of numerous, broad intermontane valleys or basins and sharply rising mountain ranges of variable height and areal extent. Within particular belts the basins and ranges trend parallel with one another. Although a northwest-north trend is commonly ascribed to them, many depart from this orientation and lie in a transverse direction (Wilson and Moore, 1959). In the southeastern part of the state the valleys and mountain areas are approximately equal whereas in the central and western areas the basins have a much greater areal extent than the mountains (Heindl and DeCook, 1952).

GEOLOGY

A detailed discussion of current theories pertaining to the geology and geologic history of the Basin and Range Province of Arizona is not considered necessary for the purpose of this study. Most of the thermal water produced in the area is obtained from wells penetrating the Tertiary, Quaternary, and Recent alluvial fill in the structural basins. Deposition of the fill in the basins was accomplished under varying conditions causing great discontinuity of the lenses of gravel, sand, and silt that constitute most of the section. A general exception to the irregular strata sequence of the older valley fill is the occurrence of variable thicknesses of lake-bed clay in the upper portion of the stratigraphic section in several basin areas. The presence of the clay and the lens-like character of the aquifers tend to create artesian conditions both within and below the sealing zones in some areas. Water table conditions generally prevail above the clay zones (Heindl and DeCook, 1952).

Igneous Activity

Igneous activity was extensive during the Tertiary-Quaternary time with a wide range of rock types having been intruded into existing sediments or emitted as lava flows. The Quaternary volcanic rocks consist almost entirely of basalt flows and are found over wide areas within the Basin and Range region (Heindl and DeCook, 1952).

Structure

Structural disturbances resulting in faulting, flexing, erosion, deposition of sediments, and volcanic activity have taken place intermittently and with variable intensity throughout the geologic history of southern Arizona (Wilson and Moore, 1959). The alternating mountains and valleys of the Basin and Range province are the result of large scale faulting. The depression of some blocks and subsequent deposition of detritus derived from the adjacent uplifted blocks gave rise to the land forms as we see them today. These structural events occurred over a long period of geologic time and were not necessarily uniform over the entire region. The upper parts of the alluvial fill in many basins exhibit some apparent continuity from basin to basin (Heindl and DeCook, 1952).

OCCURRENCE OF THERMAL WATER

Geographic Distribution

Arizona

Thermal ground-water occurs in many places in the subject area. By far the greatest number of these occurrences is the result of wells which have been drilled for irrigation and industrial purposes. In order to reduce the element of confusion only wells producing water over 90°F. are shown on the figures in

this report. Although there are many natural springs within the region, only a small percentage of them can qualify as true thermal phenomena. The thermal springs listed by Stearns et al (1937) are widely scattered in southern Arizona with the only semblance of a concentration occurring in Graham and Greenlee counties. Although a part of this specific locality is located a short distance north of the Basin and Range boundary, as defined by the U.S.G.S., its importance precludes omission from this study.

Rates of flow from the springs in the Basin and Range region are generally small, some being little more than seeps. Temperatures range from 67°-184°F. Stearns et al (1937) associate most of the thermal springs with Late Tertiary and Quaternary lava flows and/or nearness to well recognized faults. None of the springs are of the eruptive type.

Sources of Heat and Water

Stearns et al (1937) state that the heat of thermal springs may be derived from:

1. The natural increase in temperature of the earth with depth.
2. An underlying body of hot or possibly molten rock.
3. Zones where there has been faulting of the rocks with the resultant development of heat.
4. Chemical reactions beneath the surface.
5. The energy derived by the disentegration of radioactive elements.

Plummer and Sargent (1931) contend that younger Tertiary beds might contain unaltered organic matter which would give rise to exothermic chemical activity, No.4 above. They also include the oxidation of sulphide minerals to limonites, hematites and other minerals as a possible heat source. Lovering (1948) discusses the oxidation of pyrite as a heat source in his study of geothermal gradients.

The association of the higher temperature ground-water in southern Arizona with Tertiary lava flows and intrusive rocks would suggest that there is a definite connection between them. This manifestation is apparent in the vicinity of Clifton and would include the area to the south and west in Graham county. The occurrence of thermal springs in Grant and Catron counties, New Mexico, east of Clifton, would also be included in this general area.

The literature on the occurrence of thermal water contains many theories as to the source of heat for particular areas. It was found that the categories as stated above will cover most of them satisfactorily.

The question of the source of water for the thermal phenomena has been the point of a great deal of speculation among investigators in the field. Meinzer (1924), in his discussion of certain thermal features in Nevada, states that the water may be of meteoric origin or it may be juvenile water given off by magmas. White (1957), in two studies, considers volcanic, magmatic, connate, and metamorphic waters and their association with thermal features. He has approached the problem by using the chemical analysis and isotope technique and presents a tentative criterion for recognizing the major types of ground-water of different origins.

In the Clifton area the thermal water emitted by springs is high in sodium and calcium chloride. Hem (Feth et al, 1954) states that this water may be of deep-seated origin and in part juvenile. Other springs and wells in the immediate area vary as to the degree of salinity. Gillard Hot Springs, Fig. 4, no. 11, located a few miles south of Clifton, emits high temperature water low in chlor-

ides. This suggests that the two areas draw their water from different sources or that the water flows through different types of rock on its way to the surface.

Relation to Structure

Stearns et al (1937) summarize this aspect of thermal occurrences. They state that in regions where warm rocks lie near the surface it is not difficult to explain how meteoric water may reach the heat source and be recirculated back to the surface combined with some magmatic water. However, when the heat source lies at depth meteoric water may not reach it unless favorable conditions exist. The agent which heats this shallow water could be magmatic steam under high pressure. It has been found that thermal water is closely associated with major fault zones (Waring, 1915; Meinzer, 1924; White and Brannock, 1950; and many others). Stearns et al (1937) are of the opinion that thermal springs throughout the entire Basin and Range Province are closely associated with major fault lines. Plummer and Sargent (1931) summarize work which indicates that the temperature of fluids in the subsurface decreases outward, away from fault zones.

The close association of tectonic distrubance and the occurrence of thermal water in southern Arizona is illustrated in the figures in this report. The structural elements shown are taken from Mayo (1958), Wilson et al (1960), USGS and AAPG (1961), Feth (1954), Wertz (1968), some selected open file reports (USGS), and many theses and dissertations on file in the University of Arizona library. Most of the minor lines of faulting have been excluded from the map in order to keep the density to a minimum.

The coincidence of thermal water and fault zone is marked in several localities throughout the region. The highest temperature springs (120°-184°F.) in the state are found in the vicinity of Clifton, Fig.4, nos. 11 & 12. This area is the focal point for the intersection of several major lines of faulting. Southwest of Clifton, in the area around Safford, the Indian Hot Springs, Fig.4, no. 10, produce water at 119°F. Deep wells in this vicinity also produce considerable amounts of hot water ranging from 100°-120°F. One of the wells located a short distance north of Thatcher is artesian, flowing 500-600 gpm., temperature 118°F. The reported total depth of this well is 2162 feet. Several deep wells drilled for industrial purposes in this area have been reported as having water temperatures up to 138°F. but due to their being held confidential, little data is available on them. It will be noted that the Safford area lies directly in line with or adjacent to major structural trends. Hooker Hot Springs, Fig.4, no. 8, in northwestern Cochise county, follows the suggested pattern by being located upon a major structural trend. Other high temperature springs and wells located adjacent to the major trend are apparently being influenced by its proximity or possibly by minor parallel or branch faults. The coincidence of fault and thermal occurrence is not apparent in all cases. Irrigation wells which produce high temperature water in a number of areas were drilled in that part of the basin where the sediments are thickest, well away from the mountain front and at some distance from the line of faulting which generally outlines the uplift area. It is suggested that faults in the basin floor beneath the alluvium might act as conduits for circulating the high temperature water upward where it can be mixed with water of lower temperature (Meinzer, 1924; Armstrong and Yost, 1958). There is no positive way of proving this except the anomalous occurrence of unusually hot water in some of the older alluvium wells. The explanation for the occurrence of anamolous, high temperature water in alluvium-

filled basins is usually explained by the presence of local, abnormally high geothermal gradients. This is obvious but the explanation for the actual cause of the increased gradient is in most cases unknown. Whether the high temperature water rises from sufficient depths to be affected by heating through release of pressure or porous plug expansion (Adams, 1924) is conjectural.

Geothermal Gradients

Wilson (1929) defines the geothermal gradient as being the number of degrees of temperature increase per unit of distance of depth through the earth's crust and the reciprocal geothermal gradient or reciprocal gradient as the depth per degree increase in temperature calculated between the 100 foot depth and the bottom of the hole.

In this study the increase in depth per one degree Fahrenheit is used as the geothermal gradient. The value is obtained by dividing the well depth by the difference between the mean annual air temperature for the locality and the observed water temperature at the well.

Darton (1920) states that the factors which may influence the rate of temperature increase include variation in rock conductivity, underground tension, mineralization, volcanic influences, movement of underground waters and variation in radioactivity. The geothermal gradient varies widely from place to place in the United States, Arizona being no exception. At Phoenix the gradient ranges from 13 to 64 feet per degree. At the Congress mine near Prescott the gradient ranges between 63 to 186 feet per degree.

In this study geothermal gradient computations were made on many wells throughout the region. Gradients for some representative areas are included in Table 1. It was assumed that the highest temperature water came from the greatest depth in a well. Certain errors are incorporated into the computations because of the difficulty in knowing how much cooler water is being pumped from shallower depths. Well perforations or open hole completions generally cover considerable intervals of water bearing section; consequently, the empirical value of the geothermal gradients obtained under such conditions is apparent. Kister and Hardt (1961) comment on the difficulties of making quality of water determinations under such conditions.

In some isolated cases it was found that the gradients in neighboring wells checked quite closely. The high gradients obtained in the Buckhorn area, Table 1, could possibly be associated with local areas of rock of low thermal conductivity close to the surface, by the confluence of faults as suggested in Figure 3, or by a combination of the two factors. Studies made by Plummer and Sargent (1931) indicate that local or abnormal gradients are due to structural features which interrupt the continuity of the strata. The features which they describe might be a volcanic plug, saltdome or sharply folded anticline, all of which would change the rate of conductivity and possibly introduce other factors such as opening up channels for upward migration of warm waters or retarding downward movement of fresh, cooler water. Local chemical activity might also be increased by such a feature.

There is a paucity of data concerning the nature of the rocks making up the basin floors. Irrigation or industrial wells are rarely drilled to the basement in the region. Maps drawn on "bedrock" are in many cases very difficult to reconcile and data for such maps are somewhat empirical.

Quality of Thermal Water

During the course of this study several attempts to compare the concentration of particular minerals in hot spring and well water were made with no

tangible results. Plots using Fluoride, Sulphate (SO_4), Bicarbonate (HCO_3), and total dissolved solids content versus temperature produced graphs with widely scattered points and no reasonable correlations. Armstrong and Yost (1958) state that in the area they investigated there is no apparent relationship between the water temperature and the amount of dissolved solids in it.

Hem (1954) states that the Clifton spring water is essentially a solution of sodium and calcium chloride. He suggests that the dissolved minerals in this water might be derived by leaching of the igneous and metamorphic rocks occurring at or near the springs and at depth.

Some comparisons between the analyses of thermal spring water from nearby irrigation wells presented fairly close correlations, on an individual basis. The analysis of water from Agua Caliente Spring in western Maricopa county, Fig. 2, no. 4, agreed quite well with the analysis of high temperature water from an irrigation well located in the same section. This might indicate a common source of supply for them and further substantiate the reason for the gradual decline of flow from the spring. Wells located at a distance from the spring and producing cool water contain substantially higher amounts of dissolved minerals. In several cases it is not possible to make a comparison because of the lack of wells in the immediate vicinity of the spring.

The study of the mineral constituents in the ground-water of the many basins of southern Arizona is complex and requires a great deal of specialized effort. In order to arrive at well founded conclusions pertaining to the origin of thermal waters by the analysis method much more time and work than this study permitted would be required.

Utilization of Thermal Water

In this region where water is highly prized the natural flow of springs is used for all purposes, dependent of course upon its physical and chemical properties. It has long been believed that high temperature spring waters possess medicinal properties. Following up on that idea, hot bath facilities have been constructed at several locations. A brief discussion of this phase of water utilization follows.

Springs

Radium Hot Springs in Yuma county, Fig. 2, no. 3, was developed as a small bathing facility. A pump installed on a shallow well transferred the water to a storage tank from where it was piped to the private bathing cubicles. When this location was visited several years ago, there was no one in attendance and it appeared that the facility was seldom used.

Agua Caliente Springs, located a few miles north of Sentinel in western Maricopa county, Fig. 2, no. 4, could well be called a "ghost resort". For many years this site was a favorite of winter visitors despite the rather uninviting countryside. Extensive facilities were provided including a hotel, cabins, restaurant, school, garage, and numerous private bathing cubicles. During World War II a large swimming pool was constructed for the principal use of the troops from the nearby Desert Training Center. During the past several years the flow of water from the springs steadily declined, with the loss of water being blamed on the pumping of high capacity irrigation wells located a short distance to the north and east of the spring area.

To the writer's knowledge no other thermal springs, located in the western half of the region, are the subjects of commercial development.

Indian Hot Springs, Fig. 4, no. 10, near Pima in Graham county was, until a few years ago, a hot bath and resort establishment. All of the required facilities were provided, including a fully equipped hotel and restaurant. At the present time the property is privately owned and the hot springs are not being exploited.

The hot saline water of Clifton Hot Springs, Fig. 4, no. 12,which is located within the city, is presently used to supply partially a municipal swimming pool. The water no longer emits at the surface, therefore it is pumped through a spray system where it is cooled. Fresh, cool water is mixed with the spring water. Attempts to utilize the hot water for medicinal baths have not been successful.

Gillard Hot Springs, Fig. 4, no. 11, located near the confluence of the San Francisco and Gila Rivers, occupies a site which is too inaccessible for exploitation. Previous attempts to use the water for bathing purposes have been unsuccessful.

The remaining thermal springs in the region are used as sources of private water supplies.

Wells

At Buckhorn, east of Mesa, the high temperature water pumped from drilled wells is being used for hot baths on a rather large scale. The investment in housing and entertainment facilities for the clientele is apparently quite large. It is probably the largest establishment of its kind in the state. A few miles south of Safford, Fig. 4, deep wells producing water at 109°F. supply hot bath facilities.

At several locations deep wells drilled to provide water for power plants and other industrial purposes have encountered hot water. In some instances the expense of providing cooling equipment has caused the abandonment of the hot water producing aquifers. As previously stated, many irrigation wells produce high temperature water. Whether this water is detrimental to plant growth would depend upon its dissolved mineral content. It was found that in some cases hot water of fairly high salinity was mixed with fresher water for farming purposes.

Conclusions

1. The occurrence of thermal water in the Basin and Range Province of Arizona is closely allied to structural elements.

2. The amount of influence "bedrock" may have on thermal water occurrence is difficult to ascertain. Perhaps future geophysical studies will aid in answering this question.

3. In most of the areas of southern Arizona where thermal water occurs it seems reasonable to expect that we are dealing dominantly with meteoric water. Wherever possible, detailed studies of the local geology and quality of water should be made.

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Well and Location		Depth (ft.)	Water Temp.°F.	Gradient ft./1°F.
4 wells near Ajo, Pima Co.	a/ (average)	1021	98.5	39
3 wells in Palomas Plain Yuma & Maricopa Co's.	a/	443	108	13
6 wells, Harquahala Plain Yuma & Maricopa Co's	a/	1150	93	49
Deep test for oil, South of Yuma	a/	6015±	125	120
3 wells, T3N:R1W, NW of Phoenix	a/	524-1468	87-92	44
2 wells, T1N:R2W	a/	925	90-95	12
3 wells in Buckhorn area east of Mesa.	a/	325	107	8
4 wells, Casa-Grande-Eloy	a/	708	89	39
Saguaro Power Plant Well #1 near Redrock		1950	108	49
" " " " #2		680	82	48
Tucson City well B-6 Randolph Park		1183	100	36
Tucson City Well SC-15		1715	104	43
Tucson City Well SC-19		832	88	40
Tucson G & E. well, SE of Tucson		2500	126+	42
" " " " well #8		975	93	37
5 wells in Safford area	a/	1095	99	30
Safford Golf Crse. well		2180-2420	99-100	30
5 wells, San Simon V. (Darton)	a/	920	103	26
Phelps Dodge well-Clifton		220-498	121-130	31
" " " "		140-500	132-143	33

Table 1. Geothermal Gradients for selected locations in So. Arizona

Map No.	Name & Location	Geology	Temp. °F.	Disch. gpm.	Use, Remarks.
	Mohave Co.				
1	Cofers Hot Springs. NW,Sec.36,T16:Ri3W	Faulting in lake beds?	95	20	Domestic, irrig., bath.
	Yavapai Co.				
2	Castle Hot Springs. Sec.3,T7N:R1W.	Tert. lavas.	115-122	280±	Resort, bath.
	Yuma Co.				
3	Radium Hot Springs. Sec.12,T8N:R18W.	Tert. vol-canics.,Alluv.	122	Pump	Hot baths.
	Maricopa Co.				
4	Agua Caliente Sprgs. Sec.19,T5S:R10W.	Quat. lava, alluv.	100	Seep	Abandoned resort.
	Pima Co.				
5	Aguajito Sprg., at Quitoquibrito nr.Mex.	Schist hills alluv.	85	50±	Bathing & stock.
6	Agua Caliente Sprg. Sec.20,T13S:R16E.	Alluv. over faulting.	86	150±	Domestic & bathing.
	Santa Cruz Co.				
7	Agua Caliente Sprg. Sec.13,T20S:R13E.	K?,sh.,over Quat. granite.	82-90	10±	Not used.
	Cochise Co.				
8	Hookers Hot Sprig. Sec.6,T13S:R21E.	Alluv. over granitic rx.	122	20-30	Domestic,bathing
	Graham Co.				
9.	Hot Sprg.-Aravaipa Sec.35,T5S:R19E.	Tert. lava	90	6	Bathing
10	Indian Hot Springs 8 mi. NW.of Pima	Plio. lake beds, alluv.	119	300	Resort private.
	Greenlee Co.				
11	Gillard Hot Sprgs. Sec.27,T5N:R29E.	Alluv.,cglt. over Tert. volcs.	184	100±	Not used
12	Clifton Hot Sprgs. City of Clifton	Alluv., Tert volcs.	127-160	Pump	Bathing

Table 2. List of selected thermal springs in the Basin & Range of Arizona

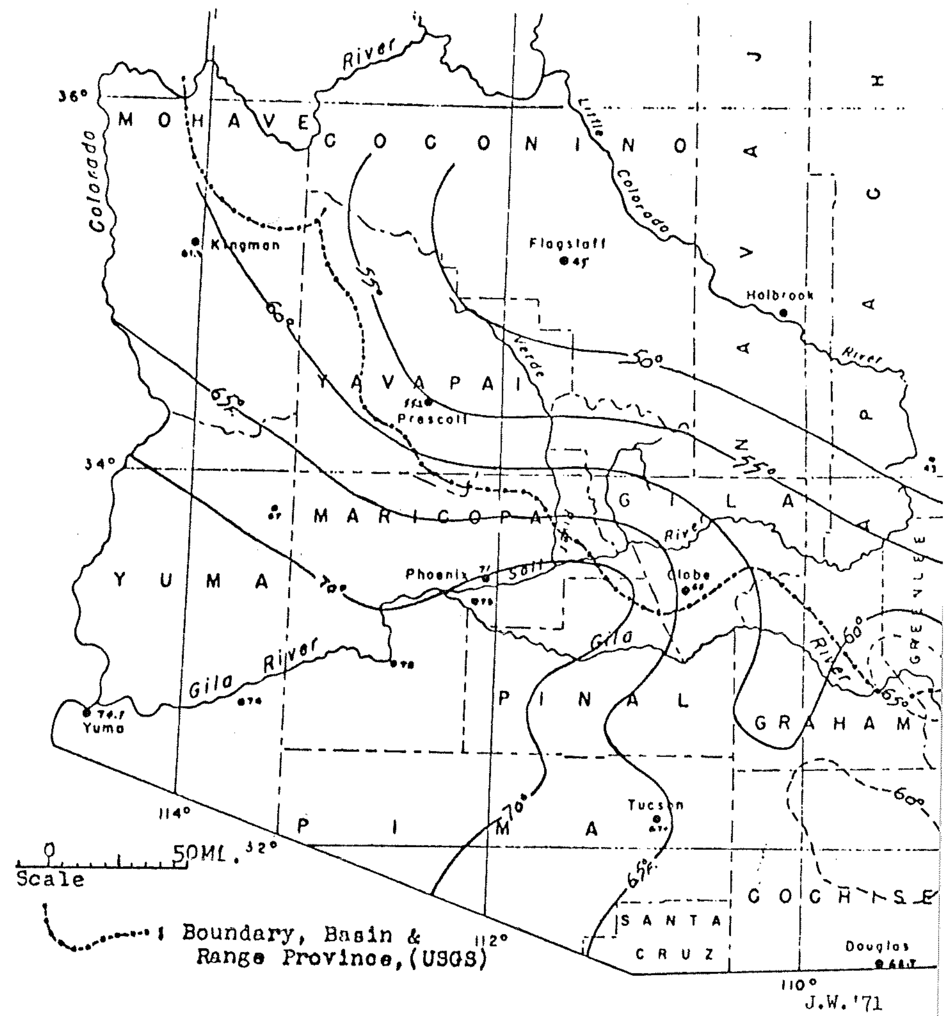

Figure 1 - Map of ARIZONA showing mean annual air temperature and area covered by this study.

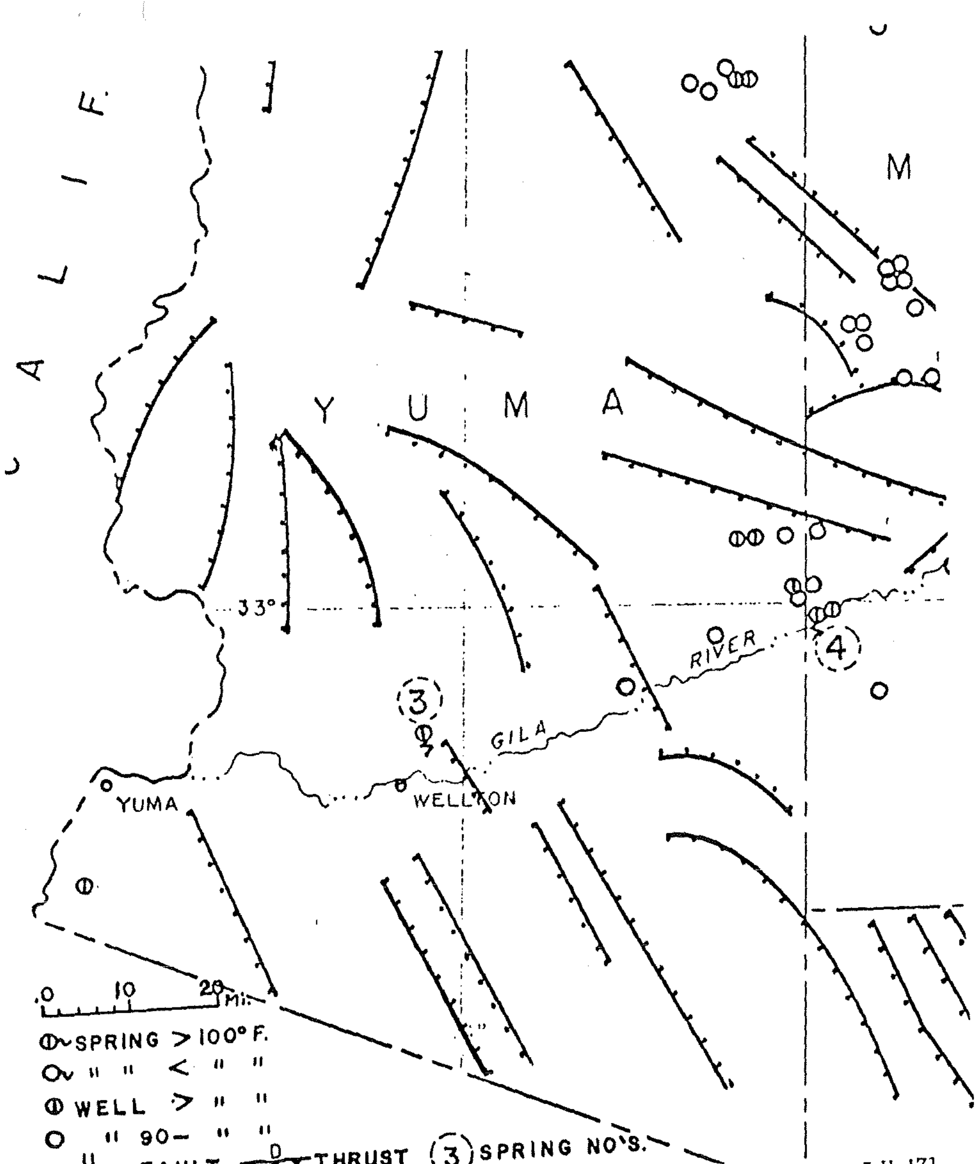

Figure 2

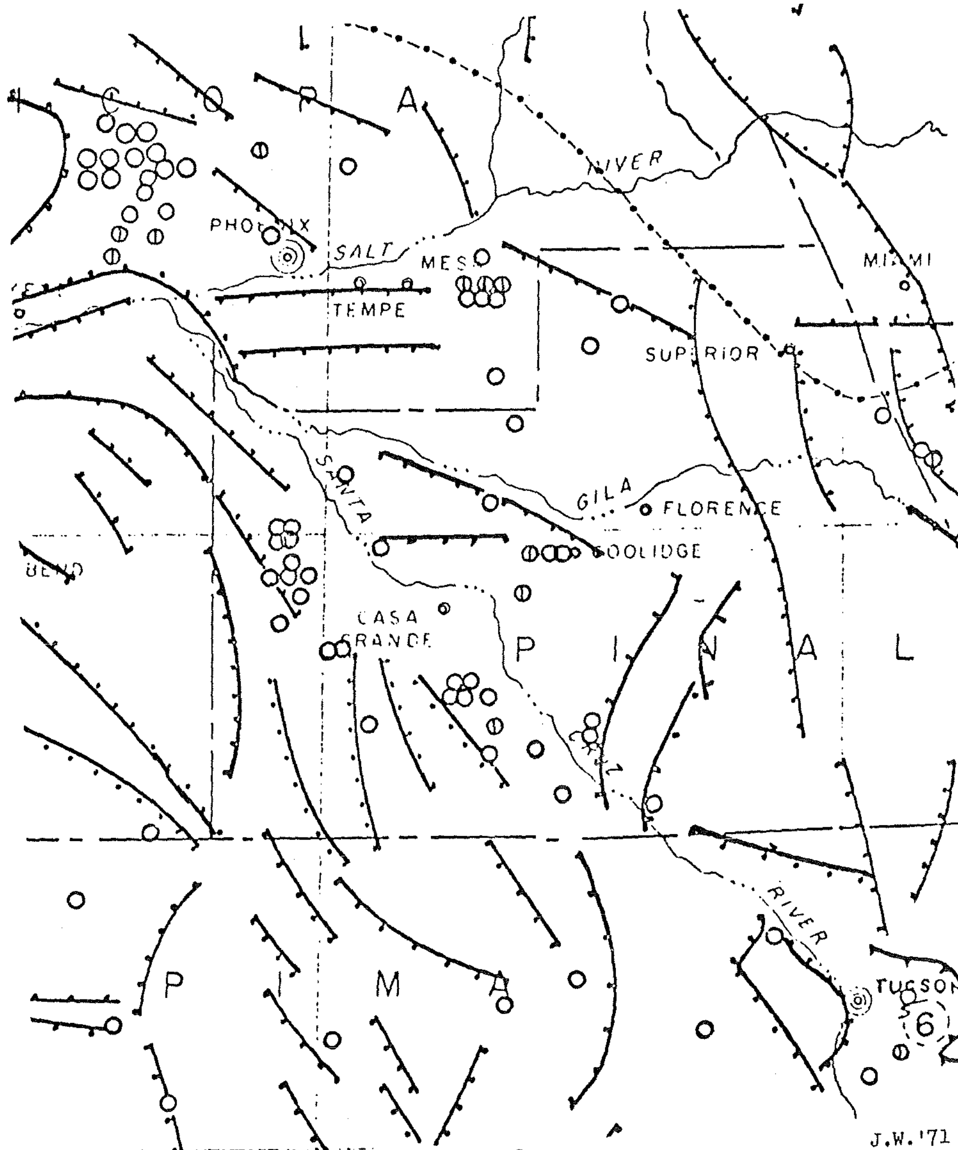

Figure 3

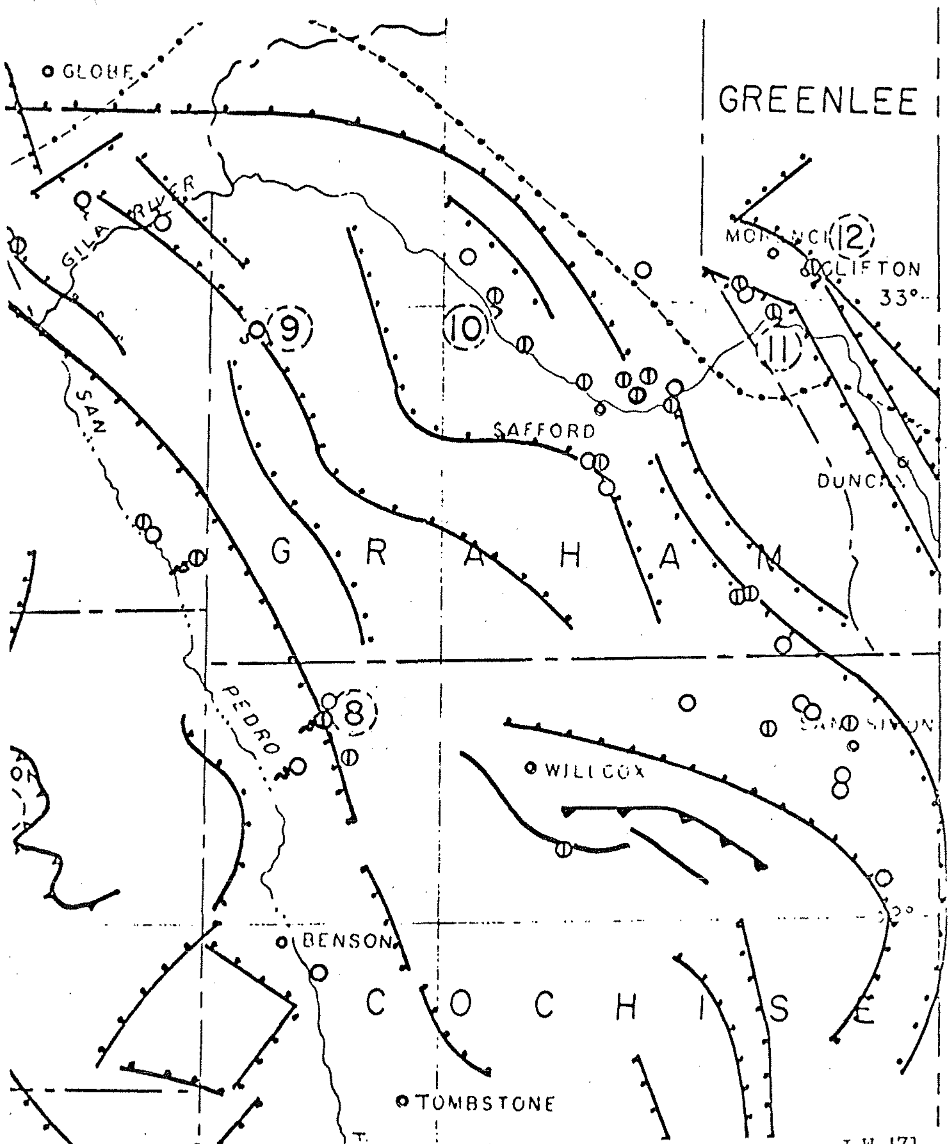

Figure 4

PROGRESS IN DEVELOPING FOREST MANAGEMENT GUIDELINES FOR INCREASING SNOWPACK WATER YIELDS

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INTRODUCTION

Snowmelt is a major source of runoff and water yield for the reservoir systems in Arizona, and it also contributes to the recharge of groundwater aquifers. Much of the snowmelt runoff occurs in the ponderosa pine forest. This suggests the possibility of using forest management methods to enhance sn melt water yield if trees and their spatial arrangements affect the snow regim Basic research indicates that forest management does affect the snowpack (Anderson, 1963; Berndt, 1961; Goodell, 1965; Packer, 1962), and can cause in creases in snowmelt runoff (Hoover and Leaf, 1967).

Another aspect of these encouraging water yield results supports the feas bility of their ultimate application in operational management programs. Ther is reason to believe that thinning and clearing of timber overstories can be made compatible with wood, forage, and wildlife production, and recreational us of forest lands.

The goal of the research project discussed in this progress report is the preparation of forest management guidelines for increasing water yields from snowpacks in the ponderosa pine type on the Salt-Verde River Basins. These Basins yield runoff for the municipal, agricultural, and industrial developments in the Phoenix and central Arizona area. Since this area is so important