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GEOLOGIC AND ENGINEERING ASPECTS OF IDAHO'S GEOTHERMAL POTENTIAL

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ABSTRACT

Preliminary investigations of geothermal occurrences in Idaho have established the basic geologic, thermodynamic, hydrologic and chemical conditions which will be encountered in the exploitation of the geothermal resource. These conditions will impose definite restrictions on the range of possible engineering applications. Utilization for space heating and other low enthalpy uses appear most favored. The generation of electricity by a "magma-max" type process will become economically feasible as energy costs soar and the extractive technology is refined.

The total geothermal energy available in southern Idaho is significant, but its exploitation will be dependent on the rate at which the low temperature heat-extraction technology advances and the rate at which conventional energy costs increase.

INTRODUCTION

The attention of both the public and private sectors involved in the examination of the geothermal resource has been focused on one rather limited aspect of the total resource, that of the power production from the dry steam or medium to high temperature wet systems. The designation of Known Geothermal Resource Areas by the federal government and exploration leasing activity within the private industry has been centered on this type of geothermal system, which accounts for a small percentage of the total energy potentially available. White (1969) has estimated that the "dry steam" systems may only constitute one out of twenty natural geothermal systems, and exploratory drilling in the western United States seems to be substantiating his prediction (Koenig, 1970). The drilling of 37 geothermal fields or prospects as of October, 1969, had encountered only six areas with temperatures higher than 200°C (392°F). Only two U.S. areas of predominately dry steam are known--Yellowstone Park and the Geysers, Sonoma Co., California.

In spite of a marked lack of success in locating additional large dry steam areas, the interest in geothermal energy has continued to grow. This interest stems in part from a very speculative hope of discovering additional hidden dry steam zones. A second motivation for the current level of geothermal interest is provided by improving technology and rapidly changing economic conditions. There is a growing awareness that the added cost involved in energy extraction from relatively low enthalpy fluids or dry, hot-rock areas will be more than offset as energy demands grow and the energy crisis intensifies.

The present paper deals with some of the geologic and engineering problems which will be encountered as Idaho's geothermal development proceeds. Emphasis will be placed on the predictable parameters such as temperature and heat flow, associated water quality and geologic distribution, which will ultimately determine the best use for the geothermal resources.

PREVIOUS INVESTIGATIONS

Tabulations of thermal water data for Idaho have been compiled by Waring (1965) and Ross (1971). These studies provide data on Idaho's hot spring and well locations, including temperature and some water chemistry. A study by Nichols, Brockway and Warnick (1972) considers geologic factors relevant to hot water distribution in Idaho, the economics of its present utilization and the potential for additional geothermal development. Predictions made on the basis of SiO_2 analysis during this investigation indicate that the maximum temperatures in the Idaho geothermal systems fall in the 100^0- 160^0C range at depth. A joint investigation by the USGS and State of Idaho Water Administration (Young, in press, 1973) has involved a compilation of detailed water quality data for the state's thermal water and the application of sophisticated geochemical thermometers to the data.

In view of the more common occurrence of relatively low temperature "wet" geothermal systems, the status of low temperature heat exchange technology is especially relevant to Idaho. Recent translations of Russian technical papers as reported in the Bulletin of the Geothermal Resources Council (Vol. 2, No. 1, pp. 5-9, Feb., 1973) indicate that the Soviet Union may be significantly ahead of the United States in the technology of low temperature energy extraction. The Paratunka geothermal electric station in Siberia became the first electric station in the world driven by freon. Thermal water at 83^0C is utilized in heating freon which is flashed to steam at a temperature of 65^0C in the radial freon turbine. Effluent water from the Paratunka plant is utilized in neighboring greenhouse facilities.

A second geothermal electric power station in the Pauzhatka River Valley began operation in July, 1967. A steam-water mixture with a temperature of 170^0C and a pressure of two atmospheres is produced from 22 wells with an average depth of 300 meters. Current output of the station is 5,000 KW, with ultimate plans to expand the facility to a 20,000 KW capacity. The 1970 cost of electricity is given as 7.2 mills per KW/hr. The first American installation of this type is presently under construction (1973) at Beowawe, Nevada, utilizing the "magma-max" isobutane heat exchange process.

TYPES OF GEOTHERMAL DEVELOPMENT PROJECTED FOR IDAHO

The potential for development of the geothermal resource and the problems anticipated during development will depend to a large extent on the type of geothermal system(s) present. For the purposes of this discussion, geothermal systems are categorized as: (1) high-temperature systems, either "wet" or "dry" with reservoir temperatures above 200°C, (2) low-temperature geothermal systems with reservoir temperatures of 100°-200°C, (3) hot water zones with temperatures less than 100°C, and (4) "dry, hot rock zones" which have a geothermal gradient above 30°/KM but lack a convective water circulation system.

<u>High Temperature Systems</u>

The initial geothermal rush centered on the search for potent, high-temperature dry steam geothermal systems of the Geysers type. After several years of extensive oil company exploration, the outlook for finding additional dry steam systems in Idaho or elsewhere in the United States is not particularly promising. An initial appraisal of published geochemical data for the major hot springs of the United States reveals the scarcity of high-temperature geothermal systems. Silica contents of greater than 260 ppm are indicative of the 200°C temperatures required for "conventional" geothermal steam turbine generation. Silica-predicted temperatures to 160°C are relatively common in Idaho and the other western states, whereas predicted temperatures above 200°C are extremely rare. High temperature geothermal systems, either wet or dry, apparently require a unique coincidence of geologic conditions for their development.

High temperature geothermal zones are symptomatic of an intense heat flow anomoly within the crust. The heat flow may be associated with a spreading axis (Iceland and Imperial Valley) or with convective heat loss from a cooling near-surface, magma chamber (Yellowstone Park and the Geysers).

The probability of near-surface plutonic emplacement is much higher with viscuous silicic magmas which originate within the crust as opposed to fluid basaltic lava. Basalt and andesite volcanism have deep-seated, mantle sources and may or may not form magma chambers in the crust during their eruption. Indications of extensive magmatic differentiation within a volcanic sequence may thus assume an important role in the evaluation of the volcanic activity as a potential heat source. The establishment of differentiation trends may indicate that crustal ponding of a basalt or andesite magma has occurred, thus providing the required heat source. Evidence of volcanism in itself is not a sufficient guarantee of geothermal zone development. The volcanism should be of relatively recent age (less than 1 my), or associated magmatic rocks may have already cooled.

An application of geochemical evaluation techniques and an examination of the geologic setting both indicate that Idaho's high-temperature geothermal potential is not great. The dominant volcanism within the Snake River Plain during the Holocene has been basaltic. A higher than normal heat flow associated with this basaltic volcanism is undoubtedly present; but the high volume, cold water flow of the Snake River Plain aquifer is sufficient to mask the high heat flow at depth. The age of rhyolitic volcanism becomes progressively younger from west to east across southern Idaho (Armstrong, 1971). The possibility of "hidden" dry steam geothermal zones in eastern Idaho cannot be ruled out entirely but must be considered unlikely.

Low Temperature Systems

The majority of the geothermal occurrences of Idaho appear related simply to deep water circulation in areas with a higher than normal heat flow. Measurements of heat flow by Blackwell (1969) and Sass, et.al. (1971) indicate that extensive areas of the western states have regional heat values significantly in excess of the continental average of 1.5 heat flow units (one heat flow unit = 1 HFU = 1 u calorie/cm^2/sec). Blackwell referred to the broad zone of high heat flow in the Basin and Range, Northern Rocky Mountain and Columbia Plateau Provinces as "the Cordilleran Thermal Anomaly Zone." Heat flow data from the Wallace district in northern Idaho yielded an average value of 2.3 HFU (Blackwell, 1969). Measurements south of Murphy Hot Springs, Owyhee County, in northernmost Nevada by Sass, et.al., (1971), yielded a value of 3.76 HFU and a calculated thermal gradient of 43^{0}C/Km. Otherwise, there is an absence of heat flow data for southern and central Idaho.

Some of Idaho's higher temperature geothermal occurrences are shown in Figure 1. The observed temperatures and specific conductivities of these springs are listed in Table I. These thermal waters occur in a variety of geologic environments, including zones along the margins of the Snake River Plain, within the Idaho Batholith and within the Basin and Range Province of eastern Idaho. The widespread distribution of these occurrences supports the theory that they are related to regional heat flow conditions rather than localized "hot spots."

The individual occurrences of thermal water are controlled by geologic conditions which allow the deep circulation of ground water. The thermal waters of northern Owyhee Co., the Boise area and the Mount Bennett Hills near Mt. Home in Elmore Co. appear related to the regional normal faults bordering the Snake River Plain. Hot springs within the Idaho Batholith such as Boiling Springs, Vulcan Hot Springs, Worswick Hot Springs and the thermal waters of Long Valley near Cascade are related to faulting which is best detected by its expression as linear drainage patterns.

The major hot springs of eastern Idaho are likewise related to regional faulting. Areas such as Vincent Hot Springs near Preston in Franklin County and hot water within the Raft River KGRA near Malta in Cassia Co. are related to north-south trending faults which are part of a regional fault pattern associated with the Basin and Range Province. As reported by Mundorff (1971), this same fault trend is thermally active throughout Utah. It coincides with the tectonically-active region referred to as the "Intermountain Seismic Belt." (Sbar, et.al., 1972)

The geothermal zone at Raft River may owe its origin to its unique geologic setting. Stone (1969) states that three major tectonic zones, the rift zones of the eastern and western Snake River Plain and the Raft River graben, intersect near the north end of the valley. Heat flow and/or deep water cirvulation near this intersection may be responsible for the presence of artesian water at the boiling point in the Raft River basin.

1 Raft River Basin, Cassia County
2 Worswick Hot Springs, Fairfield, Camas County
3 Walker Well, Mt. Bennet Hills, Elmore Co.
4 Blacks Well, northern Owyhee Co, Sec 9, T7SR6E
5 Boiling Springs, Valley County
6 Vincent Hot Springs, Preston, Franklin Co.
7 Lava Hot Springs, Bannock County
8 Alpine Hot Spring, Bonneville County
9 Green Canyon Hot Springs, Newdale, Madison County
10 Heise Hot Spring, Jefferson County
11 Sullivan Hot Spring, Custer County

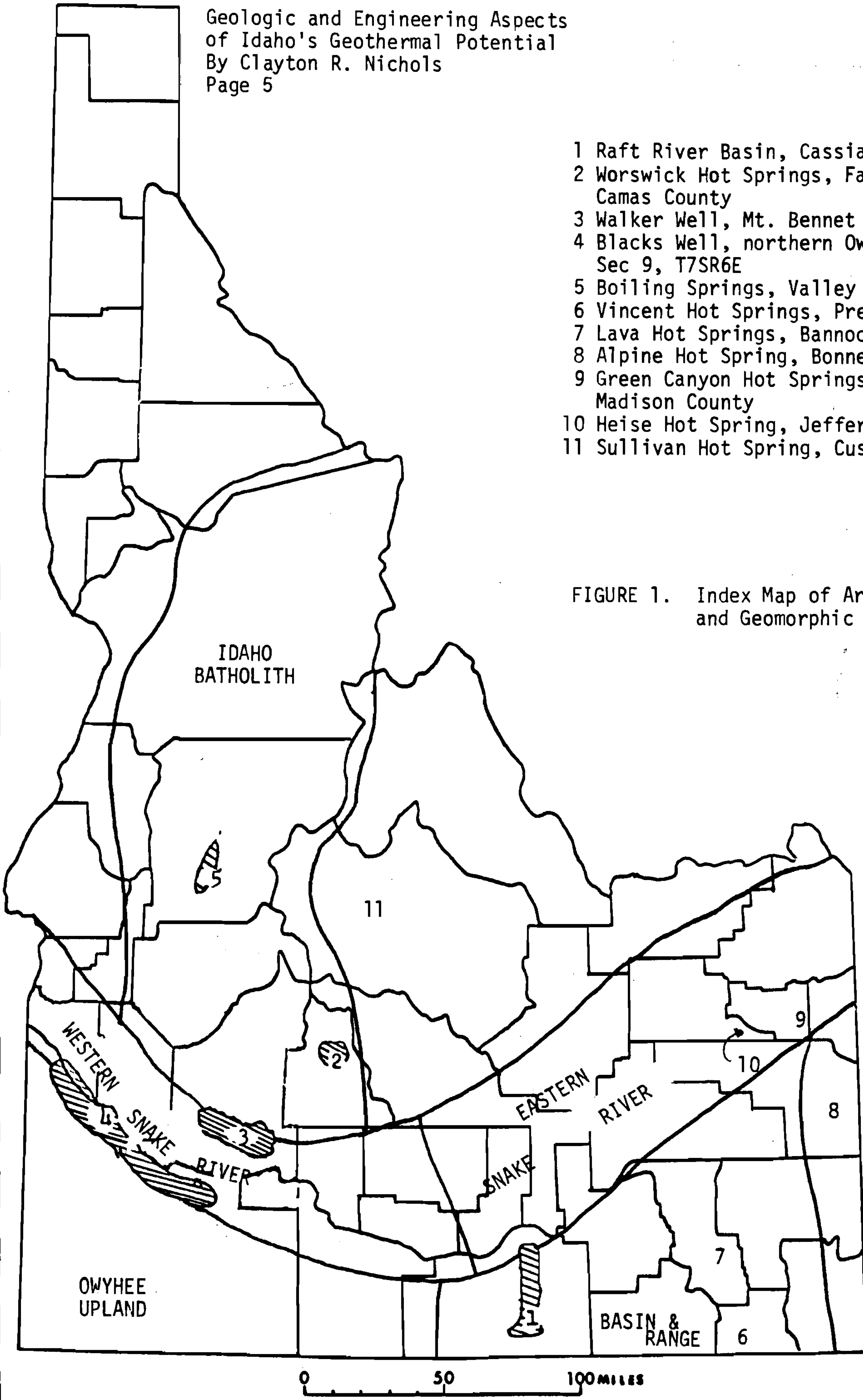

FIGURE 1. Index Map of Areas Investigated and Geomorphic Provinces.

TABLE 1

No. (Fig. 1)	Location	Probable Wallrock at depth	Observed Temperature ^{0}C	Specific Conductance u ohms at 25^0C
1	Raft River Basin Cassia County	Sedimentary	98^0	5,600
2	Worswick Hot Springs near Fairfield, Camas County	Granite	88^0	320
3	Walker Well, Mt. Bennet Hills, Elmore County	Acid volcanic rock, basalt and granite	63^0	350
4	Blacks Well, Northern Owyhee County Sec 9, T7SR6E	Acid volcanic rock, basalt and granite	49^0	455
5	Boiling Springs, Valley County	Granite	88^0	325
6*	Vincent Hot Springs near Preston, Franklin County	Sedimentary	82^0	18,500
7	Lava Hot Springs, Bannock County	Sedimentary	62^0	1,280
8	Alpine Hot Spring, Bonneville County	Sedimentary	56^0	6,404
9	Green Canyon Hot Springs near Newdale, Madison County	Basalt, acid volcanics, and sedimentary	46^0	700
10	Heise Hot Spring, Jefferson County	Sedimentary	50^0	5,500
11	Sullivan Hot Spring, Custer Co.	Sedimentary	41^0	1,120

* Specific conductance for No. 6 - 11 from Ross (1971).

Based on the silica-predicted temperature ranges, a number of Idaho areas should produce a super-heated hot water which will partially flash to steam on production. Wells drilled to date in many of these areas with predicted temperatures in the 100-160^{0}C range have failed to encounter temperatures above the boiling point.

This is especially true of the thermal zones along the north and south margins of the Snake River Plains. These wells are producing hot water from relatively shallow reservoirs where extensive mixing of the hot water with cooler surface water and heat loss have occurred. Production of the higher temperature fluids will require detailed geologic exploration in order to determine proper placement of the production wells.

This is illustrated by the developmental history of the Pathe Geothermal Zone, Hidalgo, Mexico (Nichols, 1970). The difficulties encountered at Pathe by the Mexican government's Comision Federal de Electricidad are especially relevant to the geothermal situation in Idaho. The geologic setting of the area and the temperature range is similar to that of the majority of the Idaho occurrences. Twenty-two wells were drilled in attempts to obtain steam production from fissures bearing water with silica-predicted temperatures of 157^{0}C. The first well was drilled directly into the surface expression of the fault and "cratered" when steam was encountered at a depth of 200 meters. Four wells eventually were drilled which produced steam-water mixtures with usable temperatures and pressures. The other 18 wells were improperly placed in that they either were drilled on the wrong side of the fault zone or were drilled directly on the fault and encountered cooling due to shallow surface water encroachment. One of the wells which did intersect the fault at depth was unproductive, as it encountered a portion of the fault sealed by mineral deposition.

The Pathe venture should not be considered a failure, as it has provided electricity for a remote region in Mexico for the past 15 years. It also served as a pilot operation for the Mexican government's more successful development of the Cerro Prieto field south of Imperial Valley. The lesson to be learned from Pathe, however, is clear. In the massive high temperature geothermal zones, such as the Wairakie, New Zealand field, an improperly-placed development well will still produce usable thermal fluids. A well improperly placed in the reservoir will simply produce lower temperature fluids at lower pressures than wells completed in the fissures. In a lower temperature field such as Pathe or the majority of Idaho's thermal zones, a well which fails to intersect the fissure at the proper depth or misses it completely will probably be dry or produce only hot water.

The proper placement of development wells in Idaho's geothermal zones will require a much higher degree of precision than is normally required in oil and gas production. The target in drilling will normally involve the intersection of a steeply-inclined fault zone at a pre-determined depth in a geologic setting many times more complex than that normally present in petroleum reservoirs.

Dry Hot-Rock Zones

Thermal zones of the types considered previously are attractive in that their thermal energy may be converted to electrical energy with the technology already in hand or in the research and development stage. The total energy available in convective geothermal systems is dwarfed by the energy content of dry, hot-rock areas with above-average geothermal gradients.

Assuming a gradient of only 30°C per km (86°F per mile), Meidav (1973) calculated that the energy stored per square mile in continental areas to a depth of 7.5 km (4.8 miles) is equivalent to the energy in 53 million tons of oil. A cubic mile of rock with an initial temperature of 350°C (652°F) in cooling to 250°C (482°F) releases thermal energy equivalent to the heat content of 300 million barrels of oil (Gerber, 1972).

Two proposals for the "mining" of this heat energy are being considered. The Plowshare concept developed by the Atomic Energy Commission and affiliated organizations would utilize nuclear explosives to fracture a chamber within hot crystalline rock. Water would be piped into the bottom of the chamber, and steam would be produced through holes drilled into the top. A temperature of 350°C at a depth of 8000 feet is usually postulated in considerations of the feasibility of the concept.

The second concept would extract heat from hot, dry rock by hydrofracturing the rock with water under 7000 psi pressure. The combination of pressure and rock temperatures (300°C) would lead to the development of a complex fracture system which would then be utilized as the site for conversion of water to steam (Aamodt and Smith, 1972).

Both of these ideas depend on the location of hot, dry crystalline rock at depths which may be reached by drilling (8000 feet). Engineers are inclined to assume that these conditions exist; geologists are expected to be able to locate them. A geothermal gradient of 140°C/km would be required to reach the required temperature of 350°C at 8000 feet. This gradient, five times the normal, may or may not be common.

The extensive area of the Sierra Nevada batholith can be ruled out, as it has a lower than normal thermal gradient. The Idaho batholith must be considered a prime contender for possible application of the hot, dry-rock technology, as its numerous hot springs indicate a higher than normal heat flow. The question of just how high the batholithic heat flow may be will not be known until extensive heat flow surveys have been made.

The "base" of the Snake River Plain should also be considered as a possible site of deep heat exchange tests. The marginal fault zones are thermally active; but, as mentioned previously, heat flow from the center of the plain is dissipated by the Snake River Plain aquifer. Shallow heat flow measurements under these circumstances would probably be meaningless, and the suitability of the Snake River Plain for geothermal development will remain in question until deep test drilling is initiated.

GEOTHERMAL WATER QUALITY

Fluids produced during geothermal energy extraction from convective systems may constitute either a bonus or the main detriment to geothermal development. The high total dissolved solids content of geothermal brines produced from high temperature "wet" systems may lead to problems with precipitation, corrosion, and waste water disposal. On the positive side, the high chemical content of thermal water may allow the profitable recovery of valuable metals and salts. Corrosion problems may be minimized by utilization of a "magma max" type of heat exchange process.

Thermal water quality is primarily a function of two variables (1) the temperature of the thermal fluids at depth and (2) the chemical nature of the wallrock encountered during underground circulation. A consideration of Idaho's thermal water quality indicates that the nature of the wallrock at depth is the dominant factor responsible for the variation. Water quality from various Idaho localities is shown in Table 1 in terms of observed temperature and measured specific conductivity, an indicator of the total dissolved solids content of the water. The silica-predicted temperatures for all of the samples listed are in the 100°C to 160°C range. This predicted temperature range should be considered minimal, as the "maximum base level temperature at depth," predicted by the silica thermometer may be lowered by dilution of the water with shallow ground water.

A comparison of these analyses with the geologic setting (Figure 1) indicates that the water quality in the western portion of the state is much superior to that in the eastern half. Thermal waters associated with the Idaho batholith, the margins of the western Snake River Plain, and the Owyhee Uplands are remarkably pure. The total dissolved solids values reported by Ralston and Chapman (1969) and Ross (1971) indicate average values of approximately 300 ppm for the warmer wells in northern Owyhee Co. Ross (1971, p. 23) estimates that the total dissolved solids values for hot spring water from granitic rocks north of the Snake River Plain averages only 224 ppm.

The thermal water associated with the Idaho batholith and the Owyhee Upland are thus exceptions in terms of normal thermal fluid composition. The byproduct water produced during energy extraction here may be considered a valuable side benefit of the geothermal exploitation rather than a pollutant as is normally the case. Reinjection of the cooled waters would be required only if it was deemed necessary in order to preserve fluid pressures within the system. None of the waters are acid and corrosion problems should be minimal. Carbonate saturation is not approached in any of the reported analyses and calcite buildup has not been encountered during production of the water.

The water quality of thermal fluids produced in eastern Idaho is "normal" in that it has the potential for most of the engineering problems usually associated with the production of hot brines. The relatively high total dissolved solids contents of these wells are still low in comparison to brines produced at Wairakie, New Zealand and Imperial Valley, California. They are sufficiently high, however, to require prior planning and constant monitoring of the equipment and effluent.

Ellis (1970) has shown that extensive calcite deposition in pipes may occur when carbonate-saturated solutions lose CO_2 during the boiling which accompanies production. Calcite buildup has occurred during the utilization of carbonate-rich thermal waters in eastern Idaho, and plans for the development of these fluids should consider regular programs of carbonate removal.

A potentially more serious problem, that of amorphous silica deposition in production casing, does not appear to be a major threat in any of the known Idaho thermal occurrences. Silica solubility as a function of temperature increases markedly above 200°C. The rapid deposition of amorphous silica during production usually results from the cooling of silica-rich fluids originally heated considerably above 200°C. Reported silica analyses do not indicate any waters with silica contents approaching the problem concentration level, and no silica buildup problems have been encountered.

CONCLUSIONS

A consideration of reported water-chemistry data, known geologic conditions, and observed water temperatures supports the conclusion that Idaho's geothermal potential lies in the development of its abundant low temperature geothermal zones. The probability of encountering intense, high temperature geothermal zones of the Geysers type is not great, as silica predicted temperatures are in the 100-160°C range for Idaho's hot springs and wells.

The recent technological progress in the field of heat extraction from low enthalpy fluids will make economical power generation a reality in numerous geothermal zones with a 100-200°C temperature range. The wide distribution of these thermal zones in terms of geologic setting and their rather narrow predicted temperature range indicate that Idaho's geothermal occurrences are related to a regional zone of above average heat flow. Individual hot springs are localized by convective water circulation in major fracture zones. The primary geologic problem facing the developer of low temperature geothermal zone will be the requirement for pinpoint accuracy in well placement. Wells incorrectly completed in aquifers rather than the fissures will lack sufficient temperature and pressure for utilization.

The technology for "mining the heat" from hot dry rock is rapidly being developed. Idaho has two regions, the Idaho batholith and the "base" of the Snake River Plain, where this technique might be applied. The prime obstacle for the successful application of these techniques is the need for detailed heat flow data. The Idaho batholith and Snake River Plain constitute critical "holes" in the rapidly growing heat flow data base.

Water quality of the thermal fluids reflects the differences in the chemistry of the wallrock encountered during circulation within two differing geologic environments. The water quality of thermal fluids within the western half of the state is generally excellent. The effluent from geothermal development would be usable for irrigation purposes (< 500 PPM TDS) and would not present a serious pollution problem.

Geothermal zones in the eastern half of the state are characterized by fluids with high total dissolved solids, thus reflecting the dominantly sedimentary wallrock encountered during circulation. Calcite deposition will be encountered during production but silica deposition problems will not be serious. Production plans for eastern Idaho should include waste water disposal by means of reinjection.

The low temperature range (< 200°C) and water quality problems will favor a heat exchange process and numerous individual smaller power generation facilities. Western Idaho particularly has regions suitable for a multiple use of the geothermal resource. Power generation, space heating, and warm water agricultural use of effluent water appear a reality within the next decade.

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REFERENCES

Aamodt, Lee, and Morton Smith, 1972. Induction and Growth of Fractures in Hot Rock (Abstract): Trans. Amer. Nuc. Soc., v. 15, no. 1, pp. 21-22.

Armstrong, R. L., 1971. K-AR Chronology of Snake River Plain, Idaho (Abstract): Geological Society of America Abstracts with Programs, Rocky Mountain Section, 24th Annual Meeting, v. 3, no. 6, 366 p.

Blackwell, D. D., 1969. Heat Flow Determinations in the Northwestern U. S., Journal of Geophysical Research, v. 74, no. 4, pp. 992-1007.

Ellis, A. J., 1970. Quantitative Interpretation of Chemical Characteristics of Hydrothermal Systems. U.N. Symposium on the Development and Utilization of Geothermal Resources, Pisa.

Gerber, C. R., 1972. Stimulation Concepts for Geothermal Energy Production (Abstract): Trans. Amer. Nuc. Soc., v. 15, no. 1, 19 p.

Koenig, J. F., 1970. Geothermal Exploration in the Western United States. Geothermics, U.N. Symposium on the Development and Utilization of Geothermal Resources, Pisa, Italy, v. 2, Part I, pp. 1-13.

Meidav, H. T., 1973. Global Geothermal Energy Estimates, (preprint), Geothermal Resources Seminar, United Nations, January, 1973, 3 p.

Mundorff, J. C., 1970. Major Thermal Springs of Utah. Utah Geological and Min. Survey, Water-Resources Bulletin, no. 13, 59 p.

Nichols, C. R., 1970. The geology and geochemistry of the Pathe Geothermal Field, Hidalgo, Mexico. Dissertation, University of Oklahoma, 178 p.

__________, Brockway, C. E., and Warnick, C. C., 1972. Geothermal Water and Power Resource Exploration and Development for Idaho. Research Report NSF-Geothermal 47-514, Water Resource Research Institute, University of Idaho, 47 p.

Ralston, D. R., and S. L. Chapman, 1969. Ground-water Resources of Northern Owyhee County, Idaho. Idaho Department of Water Administration Bull. No. 14, 85 p.

Ross, Sylvia H., 1971. Geothermal Potential of Idaho. Idaho Bureau of Mines and Geology, Pamphlet No. 150.

Sass, J. H., Arthur H. Lachenbruch, Robert J. Munroe, G. W. Greene, Thomas H. Moses, Jr., 1971. Heat Flow in the Western United States. Journal of Geophysical Research, v. 76, no. 26, pp. 6376-6413.

Stone, G. T., 1969. Structural Implications of Quaternary Lava-dome Distribution in the Snake River Plain, Idaho (Abstract). Abs. with Program for 1969, part 7, Annual Meeting of Geol. Soc. of Amer., Nov., pp. 217-218.

Waring, G. A., 1965. Thermal Springs of the United States and Other Countries of the World: A Summary. Geol. Surv. Prof. Paper 492, revised by R. R. Blankenship and Ray Bentall, 383 p.

White, D. E., 1969. Geothermal Energy. Geological Survey, Circular 519, 17 p.