ıajor importance to relate
the northern sub-province
-province. It seems clear
:ks must constitute an impor-
southern sub-province.
f the same age as the Ubendian
y the Mozambique Belt south
:n and Snelling, 1966, p. 159)
possible to identify structural
wo older belts throughout the
lt. It is tempting to speculate
ıes of southern Malawi (absent
rn sub-province) represent
same age as the Mafingi Group
in a different sedimentary
owever, preliminary work
to establish an unconformity
ıestones and the surrounding
er, the deformation and meta-
: limestones (plastic and high-
:ed contrast to the episodes of
in the north. It is of interest to
ıre no geosynclinal deposits in
-province of Malawi but they
nted by the limestones and
ıthern sub-province.

Research Inst. Africa Geol. Ann.
14.
, The sequence of Precambrian
s in south and central Africa:
ol. Congr. 18, London, 1948,
54–269.
les of physical geology: London,
).
, and **MacDonald, R.**, 1966,
s of the northern Uganda base-
v. 210, p. 726–727.
1965, The influence of basement
the evolution of the coastal
Tertiary) basins of Africa: p.
basins around Africa: London,
troleum, 122 p.
nd **Weiss, L. E.**, 1968, Experi-
ation and folding in phyllite:
erica Bull., v. 77, p. 343–373.
Some recent advances in our
of the controls of meta-
22–45, *in* Pitcher, W. S., and
Editors, Controls of meta-
ıburgh and London, Oliver and

, **N. J.**, and **Tex, D. C.**, 1968,
eochronology of Zambia and
of Central Africa: Canadian
v. 5, p. 621–628.

ED BY THE SOCIETY JUNE 5,

259

3/62

MERCADO *Comisión Federal de Electricidad, Comisión de Energía Geotérmica, Proyecto Cerro Prieto, Justo Sierra 2098, Mexicali, B.Cfa., Mexico*

Chemical Changes in Geothermal Well M-20, Cerro Prieto, Mexico

ABSTRACT

Following the initial discharge of well M-20, large variations took place in the pressure and enthalpy of the steam mixture. Results of chemical calculations showed possible causes of this variation, and indicated important limits on the capacity of the hydrothermal reservoir. The principal basis for the calculations were the ratio Na/K and the silica content of the flow.

INTRODUCTION

Geothermal well M-20 is one of a group of wells drilled in the geothermal zone of Cerro Prieto for the purpose of utilizing deep sources of hydrothermal energy to generate electric power (Fig. 1).

Well M-20, with a total depth of 1385 m, discharges a steam-water mixture through a casing $11\frac{3}{4}$ inches in diameter at a maximum rate of up to 680 tons per hour, 470 Btu/lb at 16 kg/cm^2 of pressure. At the present time it is the largest natural steam-well discharge in the world.

The construction of this well called for cementing the first casing to a depth of 1100 m; however, circulation and drilling mud were lost at 810 m, which indicated high porosity or fractured zones which could be good steam producers; (this was also indicated by the high temperature of the drilling muds). After the casing was cemented to 810 m, drilling was resumed to 1385 m, where once again there was a complete loss of the drilling mud. The well was finished by placing a $8\frac{5}{8}$ inch casing 575 m long at the bottom of the well, the lower portion of which was slotted from 1180 to 1385 m. When valving and other superficial installation were completed, the well started flowing without induction through a small drain line. The development was accomplished by controlling the discharge with orifices that were gradually increased in diameter. Thereby, slumping of the well walls was limited and helped in the control of sand erosion of the valves and discharge lines.

During the development of the well, chemical and physical changes occurred in the well water and provided information about the superheated waters in the deep-seated reservoir. For this purpose the basic parameters utilized were the chemical indices of Na/K variations and the silica content of the flow. The index Na/K was obtained by dividing mg/l. of sodium by mg/l. of potassium after dividing each by its respective molecular weight. Variations in the proportion Na/K depend upon the temperature, water-rock, and water-sediment interactions, and the depth at which the water is stored and at which it is produced. There is a relationship between temperature and the Na/K proportion which has been verified experimentally in several geothermal zones. (Ellis and Mahon, 1967). Underground water temperatures can be obtained by use of the Na/K indices of different waters.

High temperatures are associated with the highest K content and with solutions having lower Na/K indices:

High Temperature — Low Na/K ratio
Low Temperature — High Na/K ratio

The Na/K index has been extensively utilized in New Zealand (Ellis, 1961; Mahon, 1961, 1967; Ellis and Mahon, 1967) to study hydrothermal water movement and to locate productive geothermal zones.

At Cerro Prieto similar studies have been made with very good results (Mercado 1967, 1968).

SAMPLING

The well-head arrangements of the drill

Geological Society of America Bulletin, v. 80, p. 2623–2630, 6 figs., December 1969

holes at Cerro Prieto are similar to those used on oil wells. Samples of the steam-water mixture were collected during all stages of development. They were taken from valves located on the well head. Water samples were collected on the separated water line from a pilot separator or in the weir box of the twin silencer. (This latter method was used when the discharge was small.) The samples were collected in polyethylene bottles of 1.0 l capacity. The techniques used in the collection of steam-water mixture and separated water were similar to those described by Mahon (1961) for the geothermal wells at Wairakei, New Zealand.

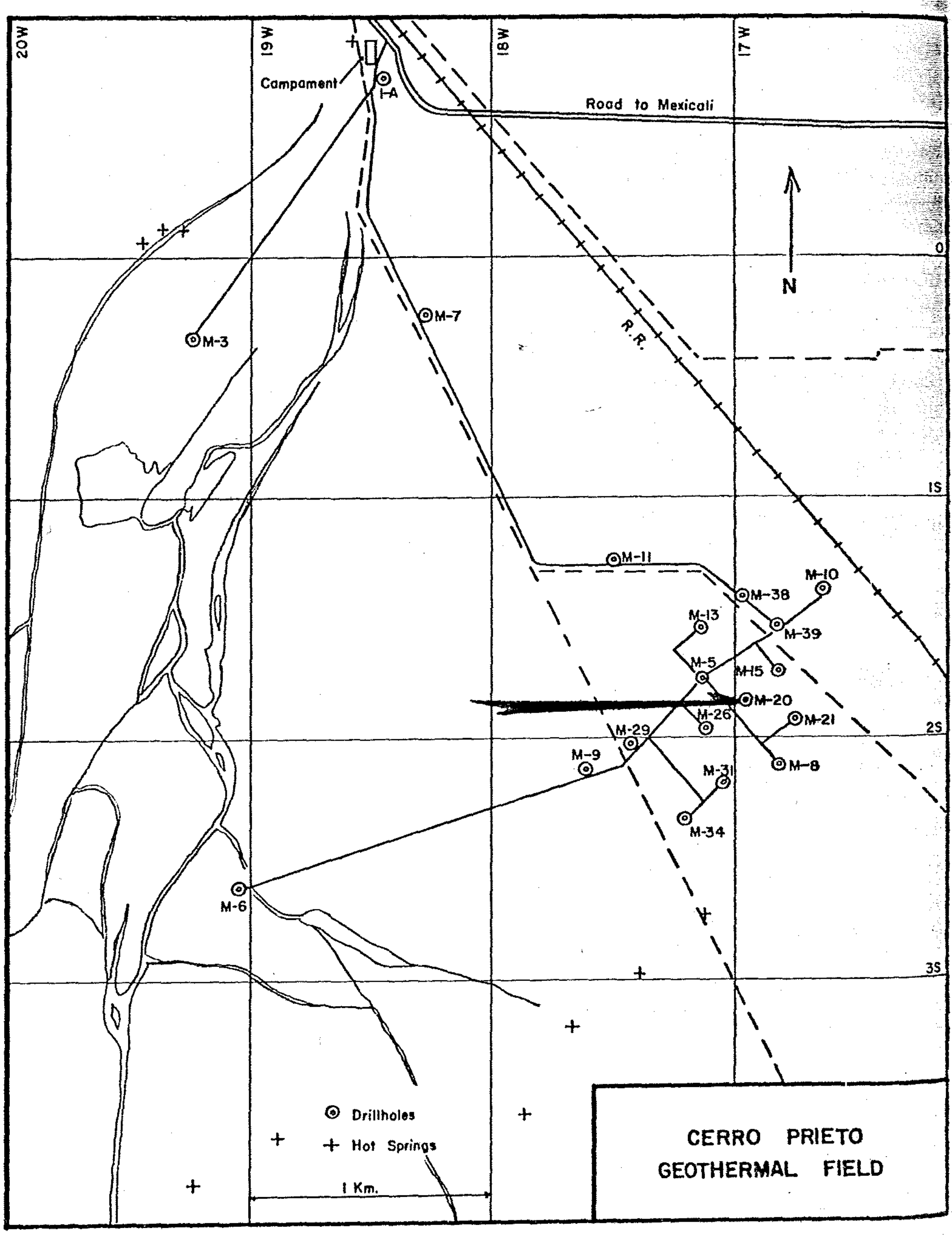


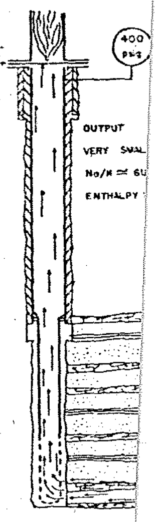
Figure 1. Location of drillholes, Cerro Prieto geothermal field.

METHODS OF

For this work,
for all samples we
spectrophotometry
for Na and 770
spectrophotometer
and photomultipl
Dilutions of 1:20
original samples
determinations w
using HCl as the

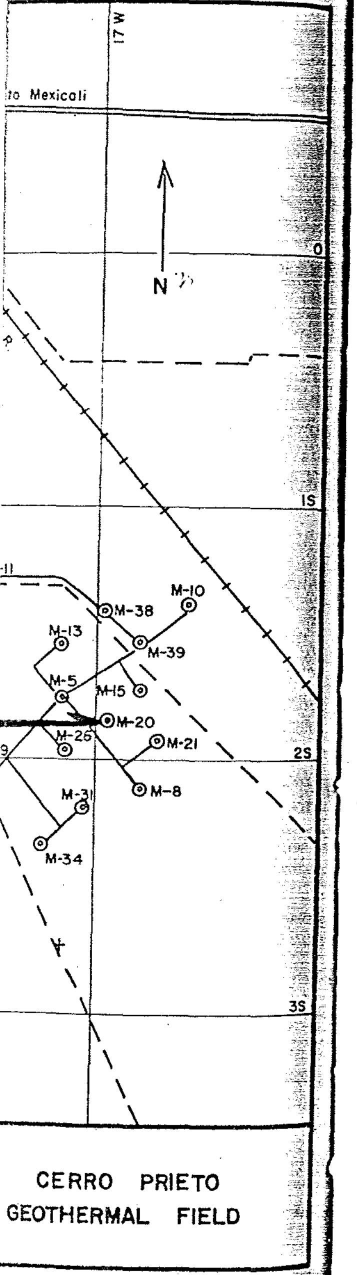
DISCUSSION

With the initia
which had a smal
high pressure a
noted, which was
the greatest heat
production more
well M-20 by the
high enthalpy (F
diameter was inc
steam and water
from the high-ter
immediately bro
the drilling mud
to the surface. I
was changing at
charge was incr
well was discharg
immediate sand
sociation with a
When this occur
tled through a



A

latter method was used when the
small.) The samples were col-
thylene bottles of 1.0 l capacity,
s used in the collection of steam
e and separated water were
c described by Mahon (1961) for
l wells at Wairakei, New Zealand.



rmal field.

METHODS OF CHEMICAL ANALYSIS

For this work, determinations of Na and K for all samples were made quantitatively by spectrophotometry at a wave length of 589μ for Na and 770μ for K. A Beckman DU spectrophotometer with flame photometry and photomultiplier attachments was used. Dilutions of 1:20–25 were made from the original samples using distilled water. Silica determinations were made gravimetrically using HCl as the principal reagent.

DISCUSSION

With the initial discharge from well M-20 which had a small orifice to control the flow, high pressure and high temperature were noted, which was expected, because strata with the greatest heat content and pressure go into production more easily. This was indicated in well M-20 by the lower Na/K index and the high enthalpy (Figs. 2, 3 and 4). As the orifice diameter was increased, greater quantities of steam and water flowed to the surface. Water from the high-temperature–high-pressure strata immediately broke the mud cake formed by the drilling muds on the well walls and moved to the surface. In this way the chemical index was changing at the same time that the discharge was increasing (*see* Fig. 5). When the well was discharging through a 5-inch pipe, an immediate sand discharge was noted in association with an increase in the Na/K index. When this occurred, the flow was again throttled through a 3-inch opening (to prevent valve erosion), but the initial pressure was not realized (*see* Fig. 4; Table 1). This phenomenon suggests possible production from overlying strata. As development was continued by gradually increasing the diameter of the opening, the Na/K index did not change appreciably with different discharges, but remained at high values. This indicated that overlying strata were producing greater quantities of water because the higher density associated with lower temperatures caused the water to flow down the annular space between the well wall and the casing, after which it ascended to the surface. The total flow from the well was made up of contributions from the different producing strata and included small contributions of steam from the deeper zone. This condition is shown in Figure 2.

In Figure 2A, the well is shown discharging a small quantity of fluid at 400 psi through a ½-inch-diameter orifice. Under these conditions, the Na/K ratio in the discharge of well M-20 was 6 units and similar to the indices of wells M-5 and M-26 in the immediate vicinity (*see* well location map, Fig. 1). It is possible under these conditions that the flow well is supplied only by strata of higher temperature near the bottom with an enthalpy of approximately 610 Btu/lb.

The well in Figure 2B flowed through a 1-inch orifice at a high pressure of 600 psi and the Na/K index was increased to 6.5 units, indicating that strata of slightly lower temperature are furnishing water to the flow. At

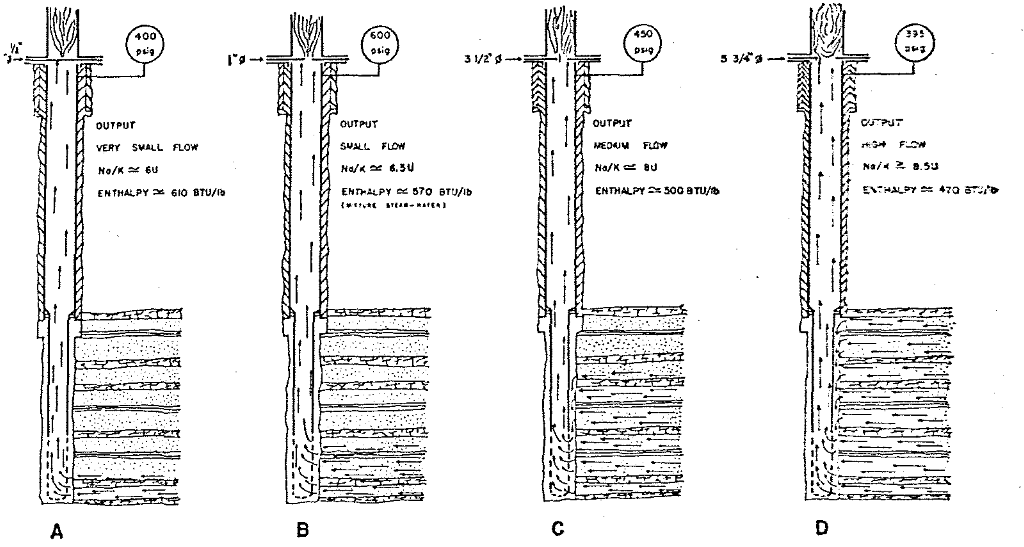


Figure 2. Production mechanism of well M-20.

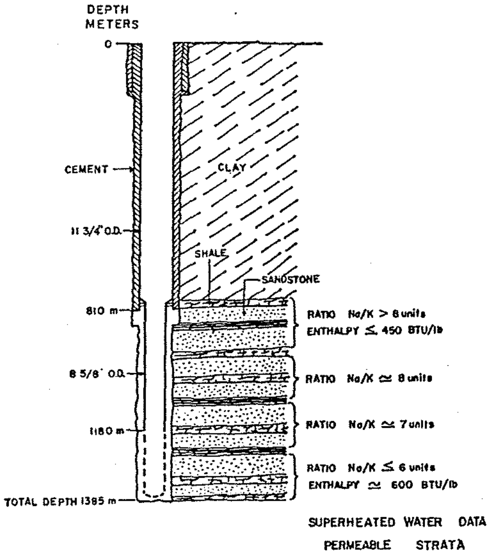


Figure 3. Na/K distribution, well M-20.

this point the enthalpy of the mixture calculated by the silica method was found to be about 570 Btu/lb.

When discharging through a larger diameter orifice of 3½ inches (Fig. 2C), the well-head

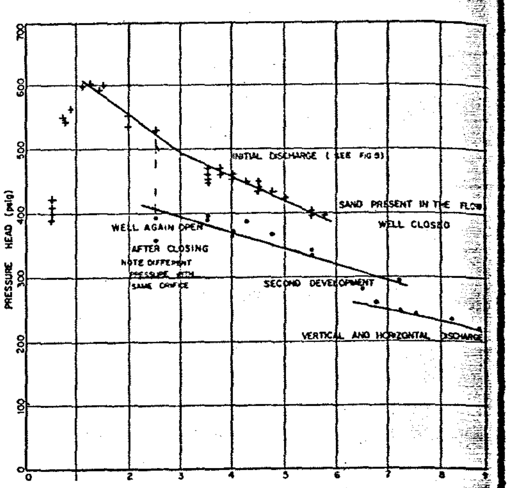


Figure 4. Pressure variations, well M-20.

pressure decreases and, consequently, so does the pressure at the bottom of the well. When the flow began to draw on the upper strata, a small quantity of sand was captured by the fluid, and the Na/K ratio was increased to 8 units. In this figure we can visualize the fluid as probably coming from strata lying above the

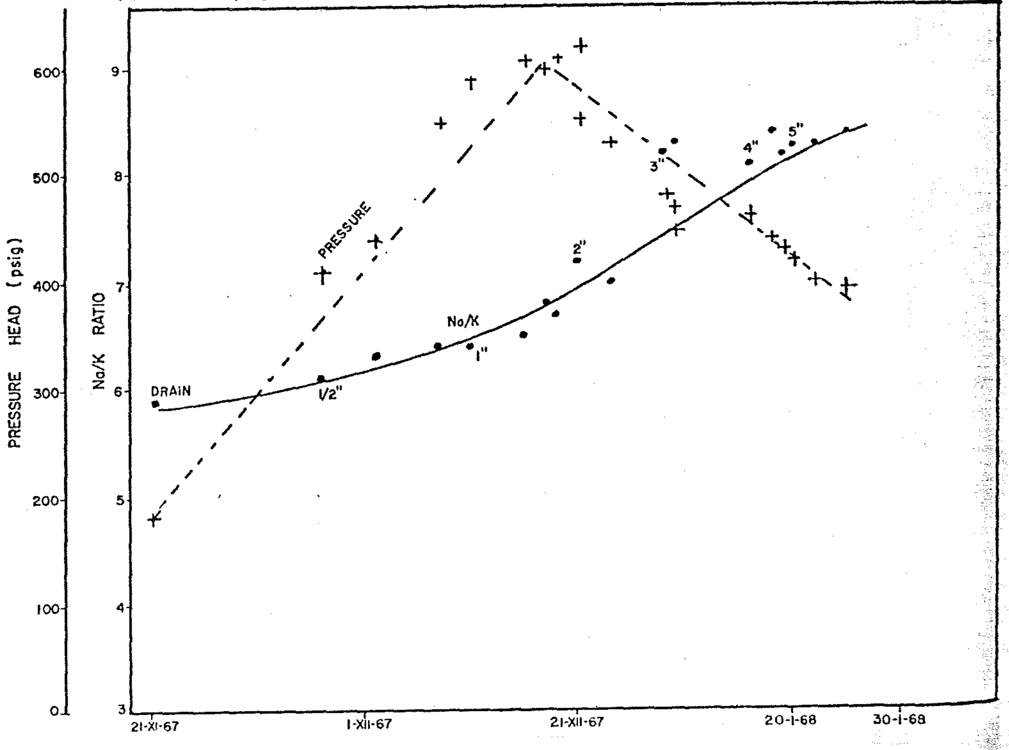
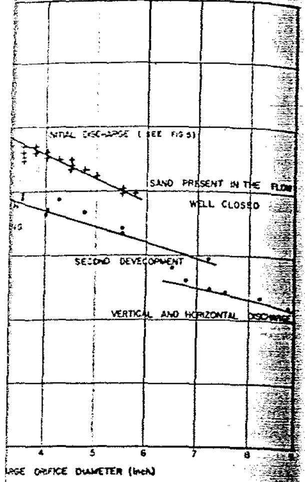
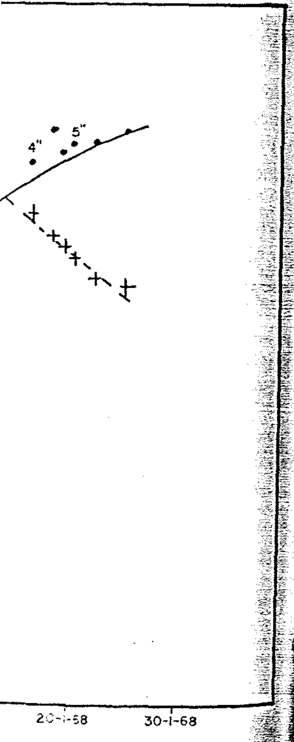


Figure 5. Pressure and Na/K variation *versus* time, well M-20 (initial discharge).



ssure variations, well M-20.

and, consequently, so does
e bottom of the well. When
draw on the upper strata, a
sand was captured by the
/K ratio was increased to 8
re we can visualize the fluid
g from strata lying above the



itial discharge).

TABLE 1. CHEMICAL RESULTS

Date	Discharge Diameter (inches)	Pressure (psig)	Sodium (ppm)	Potassium (ppm)	Na/K ratio	SiO_2 (ppm)	E Btu/lb.
Initial discharges (Fig. 4)							
21XI67	Drain	180	5760	1650	5.9		
7XII67	½	405	6593	1825	6.1	702	610
12XII67	½	420	6350	1707	6.3		
S.W. 18XII67	¾	550	7575	2000	6.4		
S.W. 21XII67	1	593	7650	2025	6.4	1116	568
26XII67	1⅛	610	6437	1672	6.5	675	572
28XII67	1¼	600	6594	1650	6.8		
S.W. 29XII67	1½	605	7968	2017	6.7	1131	572
31XII67	2	610	6093	1431	7.2		
3I68	2½	531	6500	1569	7.0		
8I68	3	480	6250	1294	8.2		
9I68	3½	450	6406	1306	8.3		
16I68	4	462	5250	1100	8.1	581	500
S.W. 18I68	4½	442	7625	1530	8.4	776	480
19I68	4¾	432	6219	1294	8.2		
20I68	5	426	6469	1325	8.3		
22I68	5½	404	6375	1300	8.3		
25I68	5¾	397	6250	1263	8.4	500	468
25I68	5¾	390	6750	1181	9.0		
Sand in the flow (closed well)							
Well open again. Discharge by several diameters.							
30I68	4	438	6437	1225	8.9		
1II68	3	465	6187	1205	8.7		
1II68	3	430	5937	1050	9.6		
6III68	5	375	5781	1006	9.7	516	473
Sand present in the flow. Return to small diameter (start second development, Fig. 4).							
15III68	2½	400	5187	950	9.3	476	464
16III68	3	400	5312	944	9.5	476	458
18III68	3½	390				481	460
19III68	4	395	5512	1005	9.3		
20III68	4½	393	6093	1081	9.5		
27III68	4¾	385	5906	1012	9.9		
30III68	5¼	370	6125	1069	9.7		
3IV68	6	360	5562	994	9.5		
17IV68	6½	280	6000	1094	9.3	506	470
24IV68	6 + 4 *	225	5500	1031	8.8		
26IV68	6 + 5 *	240	5906	1140	8.8		
3V68	6 + 5½ *	235	6375	1175	9.2		
Recent values low output							
8VI68	3	384	5594	1145	8.3		
3VII68	3½	382	6531	1275	8.5	523	475
Chlorides ±10,000 ppm in mixture							

S.W. Separate water
* Two discharges

slotted portion of the pipe. This is feasible because between the well walls and the center pipe there is considerable annular space by which water of lower temperatures can go down once the overlying strata have gone into production.

With a 5¾ inch orifice (Fig. 2D), the discharge increased accompanied by a consequent decrease in well-head pressure and an increase in the Na/K index to 9 units. Enthalpy calculated by the silica method was about 470 Btu/lb, which indicated that large temperature variations existed in different producing strata. When the discharge of the well was controlled by a small orifice, only water from hotter strata contributed to the well discharge. When the discharge is increased by increasing the size of the orifice, the bottom pressure decreases, and strata of higher elevation and lower temperature begin to contribute to the flow. Once the upper strata go into production, the cooler water flowing above the hotter water near the bottom of the well partially displaces the hot water.

As an example, we have the same result when the well is "killed" for modifications and repairs. When cold water is put on top of the well flow, a hydrostatic column brings the bottom pressure into static equilibrium, and the cooler water of the lower strata absorbs the water that is continuously being added. It is possible that a similar effect would result if flow from mean- and high-temperature strata were mixed. At well M-20 there are producing strata with temperature differences on the order of 100° C, based on variations of the Na/K index. This well has provided valuable information for the approximation of well conditions and the contents of the upper strata in this area. Other wells in this area produce fluids only from the deeper strata of highest pressure and temperature.

In Figure 3 the data are used to illustrate the probable distribution of the Na/K ratio in the geothermal waters at several levels where permeable sands or fractured shales occur. It is possible that waters immediately underlying the clays at a depth of 800 m are superheated and have an enthalpy of 400 Btu/lb near the bottom of the well (±1380 m) waters have an enthalpy of 650 Btu/lb, or greater. It is also possible that free steam can be found at that depth which comes from still deeper strata of higher temperatures.

VARIATION OF NA/K INDEX VERSUS PRODUCTION DEPTH IN THE WELLS

In Figure 6 there is an approximate relationship between the Na/K ratio and depth. The curves which are formed by connecting the values from each well have a characteristic slope which passes through values obtained from several superficial manifestations near the wells. Well M-20 especially demonstrated this characteristic variation, because the discharge control and analytical procedures were most comprehensive and precise for this well.

Wells M-6 and M-10 are outside the values for the other wells shown in Figure 6 principally because the fluid follows an unusually long flow path (M-6), or the fluid chemistry is not in equilibrium with the temperature (M-10). However, the characteristic slope between maximum and minimum values can be noted

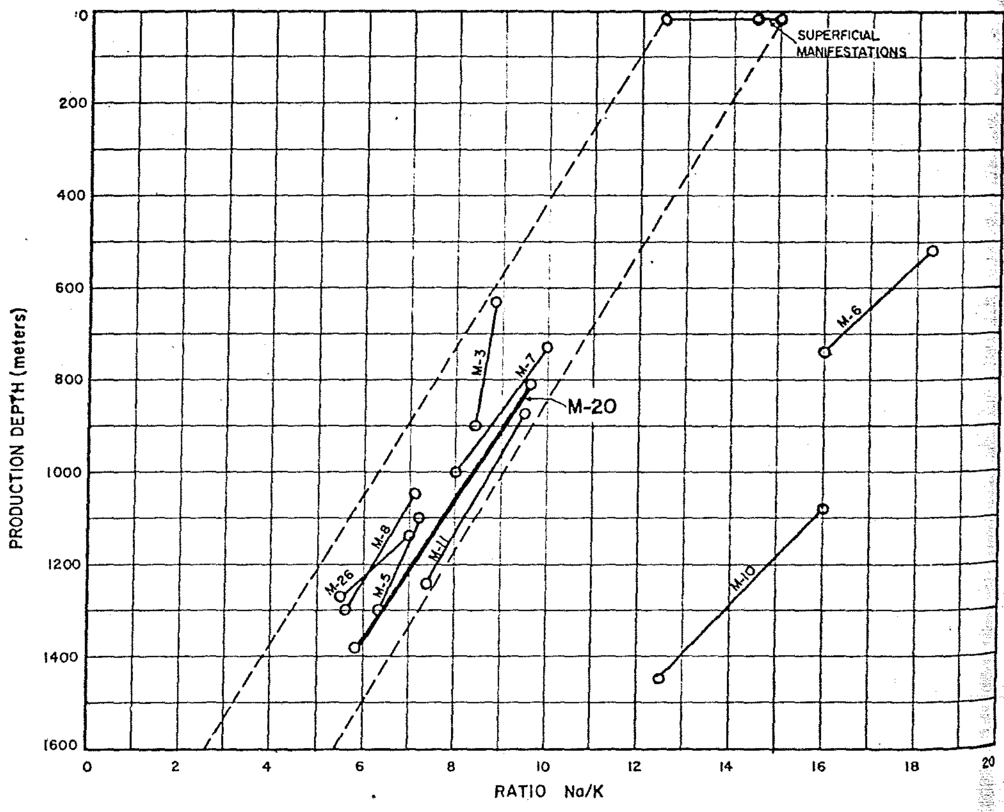


Figure 6. Na/K *versus* depth in several drillholes. Graph shows maximum and minimum values obtained for the several wells under different discharge conditions.

---

for the two wells. Figure 6 sh
consistent variation in the Na
dependent upon the depth
stratum unless influenced by
through normally confining
variation is approximately tw
each 300 m of depth, and it i
of potassium as the waters m
from their principal source to
shown is an orderly distrib
thermal fluid between int
meable and impermeable stra
thick clay sequence.

CONCLUSIONS

By considering the possibi
flow in well M-20 through
between the casing and the
of the bore), it is possible to
enthalpy and discharge p
which have been observed o
the other drilled wells.

The orderly distribution
in the various strata also sho
exist between them. These c
due to fracturing because c
impermeable shale are interc
sandstone.

Ellis, A. J., 1961, Geotherma
investigations: Un. Nat. C
of Energy Proc., G-42 R
Ellis, A. J., and Mahon, W.
hydrothermal systems a
water-rock interactions:
mochim. Acta, v. 31, p.
Mahon, W. A. J., 1961, San
drillholes discharges: Un.
Sources of Energy Pro
269–277.

Manuscript Received by T
10, 1969.

for the two wells. Figure 6 shows that there is a consistent variation in the Na/K ratio which is dependent upon the depth of the producing stratum unless influenced by vertical leakage through normally confining shale zones. This variation is approximately two Na/K units for each 300 m of depth, and it illustrated the loss of potassium as the waters migrated vertically from their principal source to the surface. Also shown is an orderly distribution of hydrothermal fluid between interconnected permeable and impermeable strata underlying the thick clay sequence.

CONCLUSIONS

By considering the possibility of descending flow in well M-20 through the annular space between the casing and the drilled hole (wall of the bore), it is possible to explain the great enthalpy and discharge pressure variations which have been observed on a lesser scale in the other drilled wells.

The orderly distribution of the Na/K index in the various strata also show that connections exist between them. These connections must be due to fracturing because continuous layers of impermeable shale are intercalated with porous sandstone.

An additional finding of this study was the existence in this area of an important water-bearing zone from a depth of 800 to 1000 m. This is of great importance because steam can be produced from different zones making it possible to drill and bring to production wells of shallow depth at the same location as the existing wells (M-5, M-8, M-15, M-21, M-26, and others) that derive fluid from the deeper strata at depths of 1100 to 1500 m. Naturally, pressures and temperatures of this water-bearing zone are lower than those of waters emanating from greater depths. However, utilization of these waters presents advantages and saving in drilling completion and exploitation. Similarly, there are fewer problems associated with the accumulation of salt deposits in the producing strata, a problem which is common to wells of greater depth in the field.

Finally, water-bearing zones between 800 and 1500 m (maximum depth reached in the field) greatly increase the field reserve where the maximum steam-well discharge pressure of 1040 psi, 73 kg/cm², bottom temperature of 730° F, 388° C, and discharge rate of steam-water mixture of 1,500,000 lb/hr 680 tons/hr, are the greatest known in the world.

REFERENCES CITED

Ellis, A. J., 1961, Geothermal drillholes chemical investigations: Un. Nat. Conf. on New Sources of Energy Proc., G-42 Rome, p. 208–217.

Ellis, A. J., and Mahon, W. A. J., 1967, Natural hydrothermal systems and experimental hot water-rock interactions: Geochim. et Cosmochim. Acta, v. 31, p. 519–538.

Mahon, W. A. J., 1961, Sampling of geothermal drillholes discharges: Un. Nat. Conf. on New Sources of Energy Proc., G-46, Rome, p. 269–277.

Mahon, W. A. J., 1967, Natural hydrothermal systems and the reaction of hot water in sedimentary rocks: New Zealand Jour. Sci., v. 10, no. 1, p. 206–221.

Mercado, S., 1967, Hydrothermal geochemistry in Cerro Prieto: 1 St. Cycle Conf. Geohydrology, Mexicali, B.Cfa. Mexico, Ag., p. 31.

——— 1968, Localization of hydrothermal highest activity zones by chemical proportions: 3rd Cong. Mexicano de Química Proc., p. 32.

MANUSCRIPT RECEIVED BY THE SOCIETY, MARCH 10, 1969.