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MEMORANDUM

TO: Robert Gray

FROM: Robert Blackett and Duncan Foley

SUBJECT: Effects of Solar and Geothermal Energy on ground water temperatures

Introduction

Ground water temperatures are derived from two principal sources: 1) Heat energy from the earth's interior is transferred to ground water by conduction through the surrounding rocks. 2) Heat energy from the sun is also transferred to ground water by conduction through the surrounding rocks.

The influence of solar heating diminishes downward from the ground surface in such rapid fashion that the effect is not detectable within a few meters of the surface. Therefore at depths below the level of solar influence, heat energy, above average annual air temperature, contained in ground water is due to energy generated within the interior of the earth.

Geothermal Gradient

Heat generated within the earth rises and is dissipated through the surrounding rocks. This dissipation of heat is referred to as the geothermal gradient and is usually expressed as degrees Centigrade per kilometer or degrees Farenheit per hundred feet. The gradient varies with different local or regional heat sources and type of rocks present in a given area. Figure 1 illustrates an example of a high heat flow area and corresponding high geothermal gradient versus an area of normal heat flow.

The relationship to the quantity of heat (q) that flows from a heat source to the surface for unit area is expressed as, $q = k\left(\frac{\partial T}{\partial Z}\right)$ where $\frac{\partial T}{\partial Z}$ is the geothermal gradient and k is the thermal conductivity for the surrounding rock type. The geothermal gradient will change inversely by passing from rock types of varying thermal conductivities, although the quantity of heat flowing will remain the same. The rise in temperature per unit volume produced by a given quantity of heat, however is inversely proportional to the specific heat (c) and the density (ρ) of the material and directly proportional to the thermal conductivity; these relations are combined into the diffusivity constant α where $\alpha = {}^{k}/c\rho$ (Lovering and Goode, p. 5).

Thermal Diffusivity

Thermal diffusivity, as defined above, is the only pertinent property of earth materials for measuring the effect of fluxuating heat from the sun. Table 1 shows ranges of diffusivity for some typical rock types. In general, those materials with high SiO_2 content and low porosities (such as quartzite) typically have high thermal diffusivity. In contrast, dry materials having high porosity (such as shales or soil) have low thermal diffusivity (Lovering and Goode, p. 7).

Solar Heating Effects

Temperatures within a few meters of the earth's surface are controlled almost entirely by the sun's heat. Cooling takes place in the form of evaporation and radiation. Heat derived from the sun fluxuates between maximum and minimum values on a daily and yearly basis. These heat fluxuations are termed diurnal and annual "waves" respectively, and propogate downward on a periodic basis. All such periodic waves decrease in amplitude with depth. The diurnal wave dissipates rapidly and is generally negligible below 1.5 meters (Lovering and Goode, p. 2). Non-periodic hot or cold waves of one or two weeks duration seldom penetrate below 5 meters. The annual wave can be detected in rocks of low diffusivity to a depth of at least 20 meters and can reach depths of up to 50 meters through material of high diffusitiy but does not affect subsurface conditions below this point and therefore can be omitted from consideration (Kappelmeyer and Haenel, p. 84). The boundary conditions defined at the earth's surface for geothermal problems below the depth of influence is the mean annual surface temperature. The mean annual surface temperature changes by 45^{o}C from poles to equator and varies by as much as 17^{o}C (30^{o}F) within the boundaries of the continental United States (see Figure 2).

The annual wave attenuates downward and approaches a sinusoildal form that can be asymmetric in regions where soil moisture becomes frozen and snow covered during winter months. Figure 3, as calculated by Lovering and Goode, shows theoretical depth versus temperature curves for average rock material of α =0.010 read shortly after the summer maximum and winter minimum. The outside envelope curves show the diminishing annual range in temperature from the surface downward for material of low ($\alpha = 0.0036$) and average ($\alpha = 0.010$) thermal diffusivity assuming a geothermal gradient of zero. If the effects of a normal geothermal gradient are considered, the envelope becomes asymmetric to the right as shown in Figure 4.

In-situ soil and rock temperatures were measured over a period of eight months by Fugro National, Inc. at a study site in Nevada to determine thermal properties of subsurface materials. Temperature measurements were obtained at various depths in drill holes to a maximum depth of 125 feet (38 m). Figure 5 illustrates the results of their studies. The effect of the annual wave becomes extremely dampened at a depth of eight feet (2.4 m) and is not detectable by 50 feet (15.2 m) where the geothermal gradient predominates thermal conditions.

Air and subsurface temperatures were monitored over a 24 hour period during the same study at one-half hour intervals to determine the effect of the diurnal wave on subusrface temperatures (Table 2). Figuro's findings show that while surface (air) temperatures varied by as much as 50 degrees ($^{\circ}$F), subsurface temperature variations at two feet below ground surface diminished to 0.5 degrees ($^{\circ}$F).

The net effect of the annual wave downward from the earth's surface regardless of thermal diffusivity is that the influence of the wave for all practical purposes, diminishes and rapidly approaches the average annual surface temperature at depths below 15 meters. Therefore, increases in temperature beyond the average annual surface temperature below the depth of influence of the annual wave can be attributed to heat generated from the earth's interior, the geothermal gradient.

REFERENCES

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Table 1. Thermal diffusivities of some common rocks, in cgs units

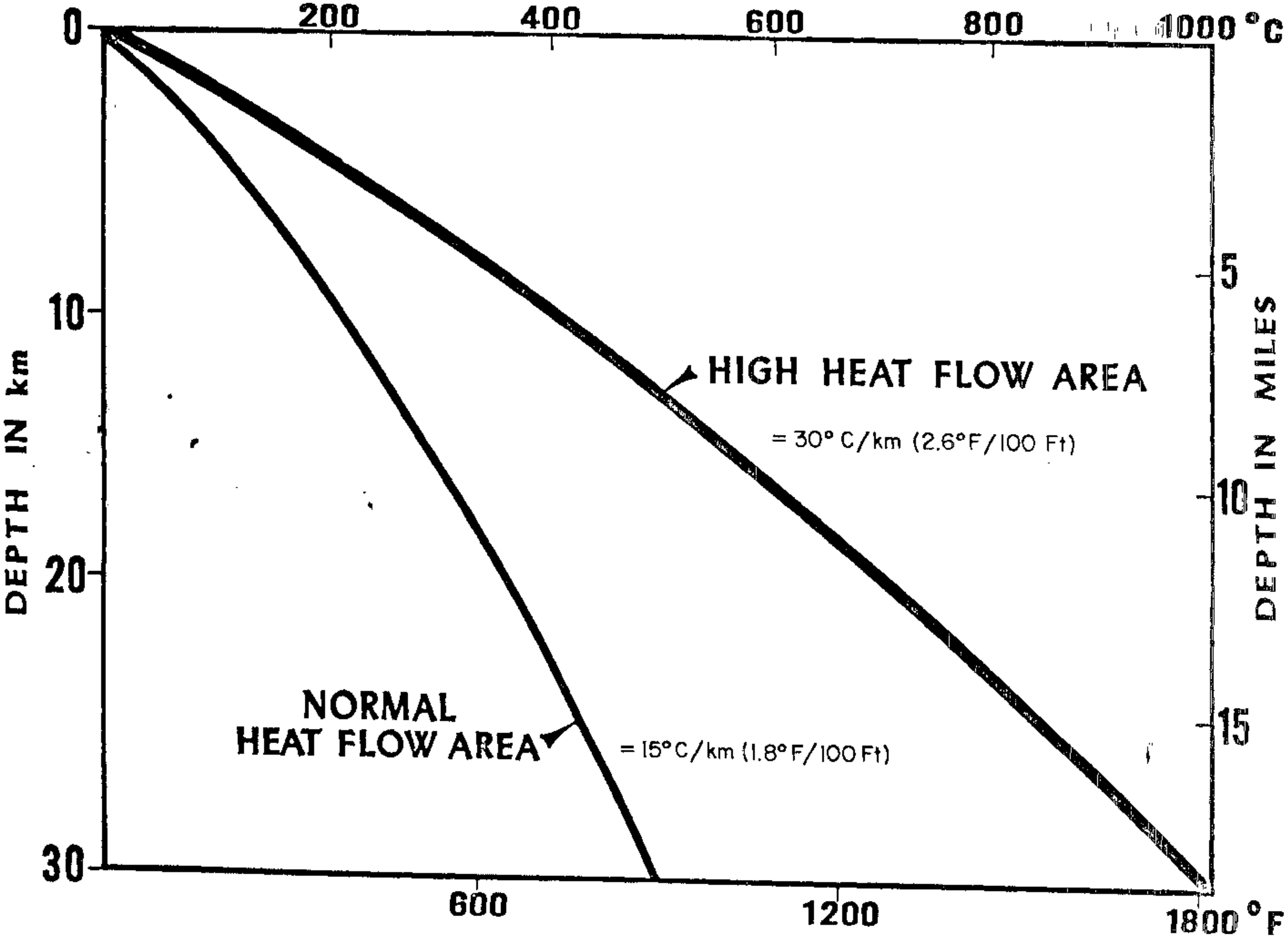
	1	2	3
Quartz sand, dry	0.0020	. . . . . .	. . . . . .
Quartz sand, 8.3 percent moisture	.0033	. . . . . .	. . . . . .
Sandy clay, 15 percent moisture	.0037	. . . . . .	. . . . . .
Gravel	. . . .	. . . . . .	0.0057-0.0062
Shale	. . . .	0.004	. . . . . .
Andesite	. . . .	0.005- .006	. . . . . .
Tuff	. . . .	.004- .009	. . . . . .
Basalt	. . . .	.007	. . . . . .
Traprock	.0075	. . . . . .	. . . . . .
Rhyolite	. . . .	.008	. . . . . .
Quartz latite porphyry	. . . .	. . . . . .	.007 - .011
Dolomite	. . . .	.008	. . . . . .
Limestone	.0081	.005- .011	.0095
Granite	.0127	.006- .013	. . . . . .
Marble	.0097	.0106- .011	. . . . . .
Sandstone	.0113	.012- .014	. . . . . .
Schist	. . . .	.008- .027	. . . . . .
Quartzite	. . . .	.023- .031	. . . . . .

1. From Ingersoll, Zobel, and Ingersoll (1948, p.244).
2. From International Critical Tables of the National Research Council (1927, p.55, 56).
3. Lovering and Goode (1954, p.7).

DATE	TIME	TEMPERATURE,* °F					
		AIR	DEPTH BELOW GROUND SURFACE				
			2 ft (0.6m)	4 ft (1.2m)	8 ft (2.4m)	50 ft (15.2m)	125 ft (38.1m)
10 JULY 1979	5:30 AM	53.3	76.0	70.2	61.3	59.1	61.3
	6:30	62.3	76.1	70.3	61.4	59.1	61.3
	7:30	73.6	76.1	70.4	61.5	59.2	61.4
	8:30	84.0	76.0	70.4	61.5	59.2	61.4
	9:30	84.0	76.0	70.2	61.3	59.1	61.3
	10:30	87.9	76.1	70.2	61.4	59.0	61.3
	11:30	91.4	75.9	70.1	61.3	58.9	61.3
	12:30	97.2	75.8	70.1	61.2	58.8	61.3
	13:30 PM	99.2	75.8	70.0	61.1	58.8	61.2
	14:30	98.3	75.8	70.0	61.1	58.6	61.2
	15:30	103.6	75.7	69.9	61.0	58.7	61.0
	16:30	97.2	75.7	69.9	61.0	58.5	60.9
	17:30	94.6	75.7	70.0	61.0	58.6	61.0
	18:30	93.5	75.8	70.0	61.1	58.6	61.0
	19:30	89.2	75.9	70.0	61.2	58.7	61.0
	20:30	78.8	76.0	70.1	61.3	58.8	61.1
	21:30	72.8	76.1	70.2	61.3	58.9	61.2
	22:30	68.0	76.2	70.3	61.4	59.0	61.3
	23:30	72.4	76.3	70.4	61.4	59.0	61.3
11 JULY 1979	00:30 AM	63.0	76.3	70.4	61.5	59.1	61.3
	1:30	62.0	76.4	70.4	61.6	59.1	61.4
	2:30	59.9	76.3	70.4	61.6	59.2	61.3
	3:30	64.7	76.3	70.4	61.5	59.1	61.3
	4:30	61.1	76.3	70.4	61.5	59.1	61.3
	5:30	58.2	76.3	70.4	61.5	59.0	61.3

* AVERAGE OF THREE THERMOCOUPLES AT EACH DEPTH

Table 2. 24-hour soil temperatures by Fugro National, Inc. at a Nevada study site.



TEMPERATURE VS DEPTH IN EARTH

FIGURE 1

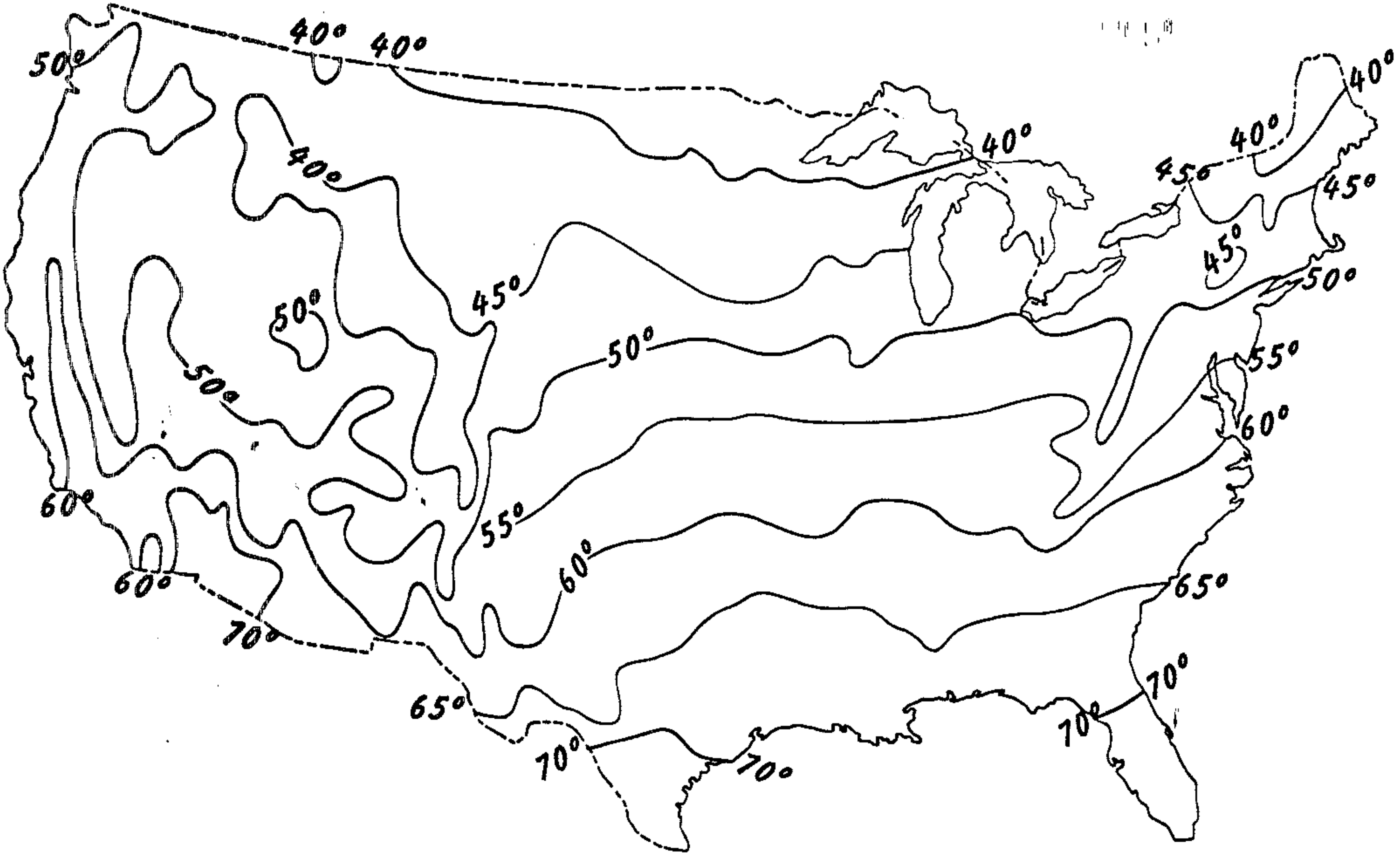


FIGURE 2 - Average annual surface temperatures for the United States. Temperatures in degrees Fahrenheit. After Visher, 1954.

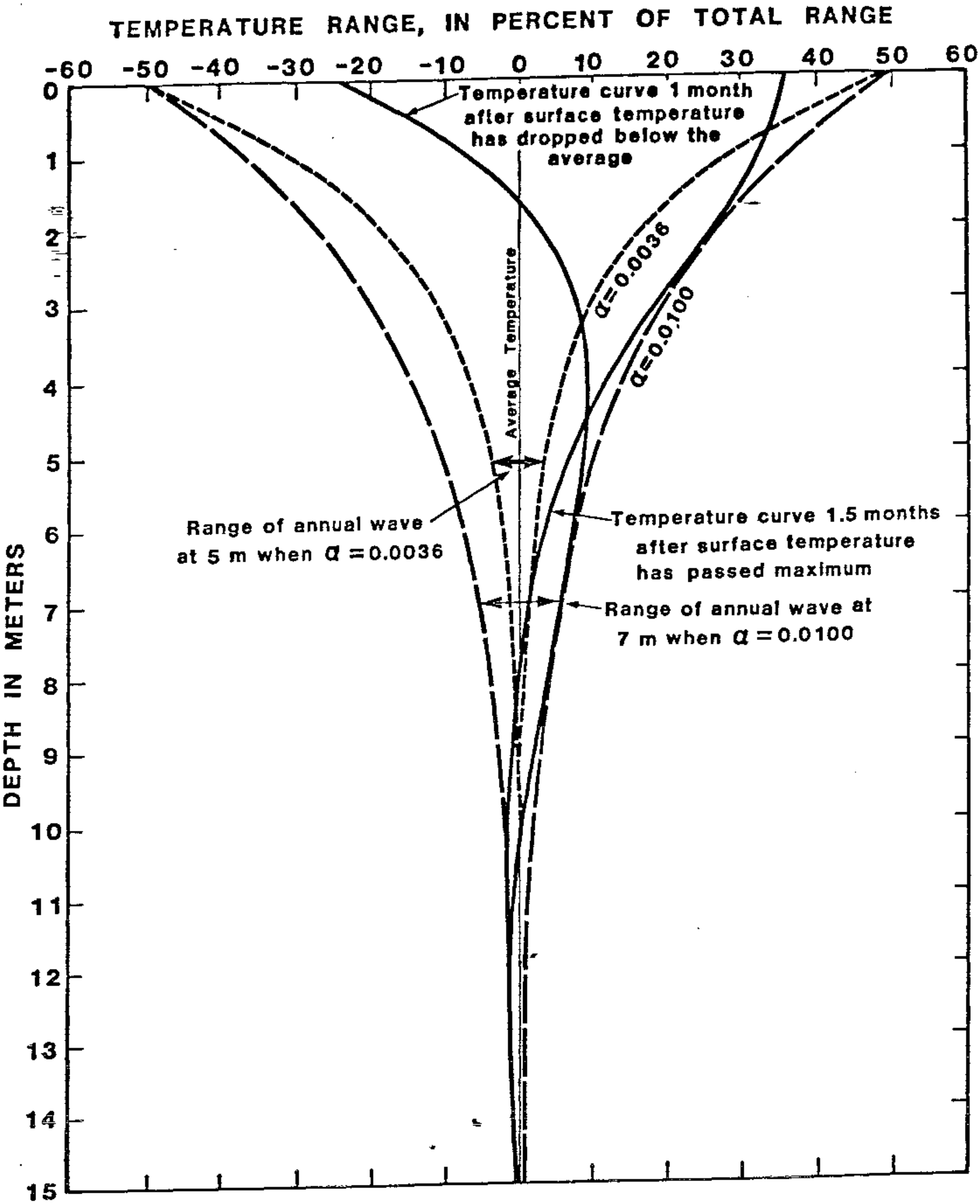


FIGURE 3 - Subsurface envelope curves showing attenuation with depth of effect of annual surface temperature in media having diffusivity (α) of 0.0036 and 0.0100. Theoretical depth temperature curves when α = 0.0100 are shown for dates 1.5 months after maximum, and for 1 month after annual average is passed in the fall. The envelope curves for diffusivity 0.0036 and 0.0100 show the temperature range at depth in percent of total temperature range at surface. (After Lovering & Goode, 1954)

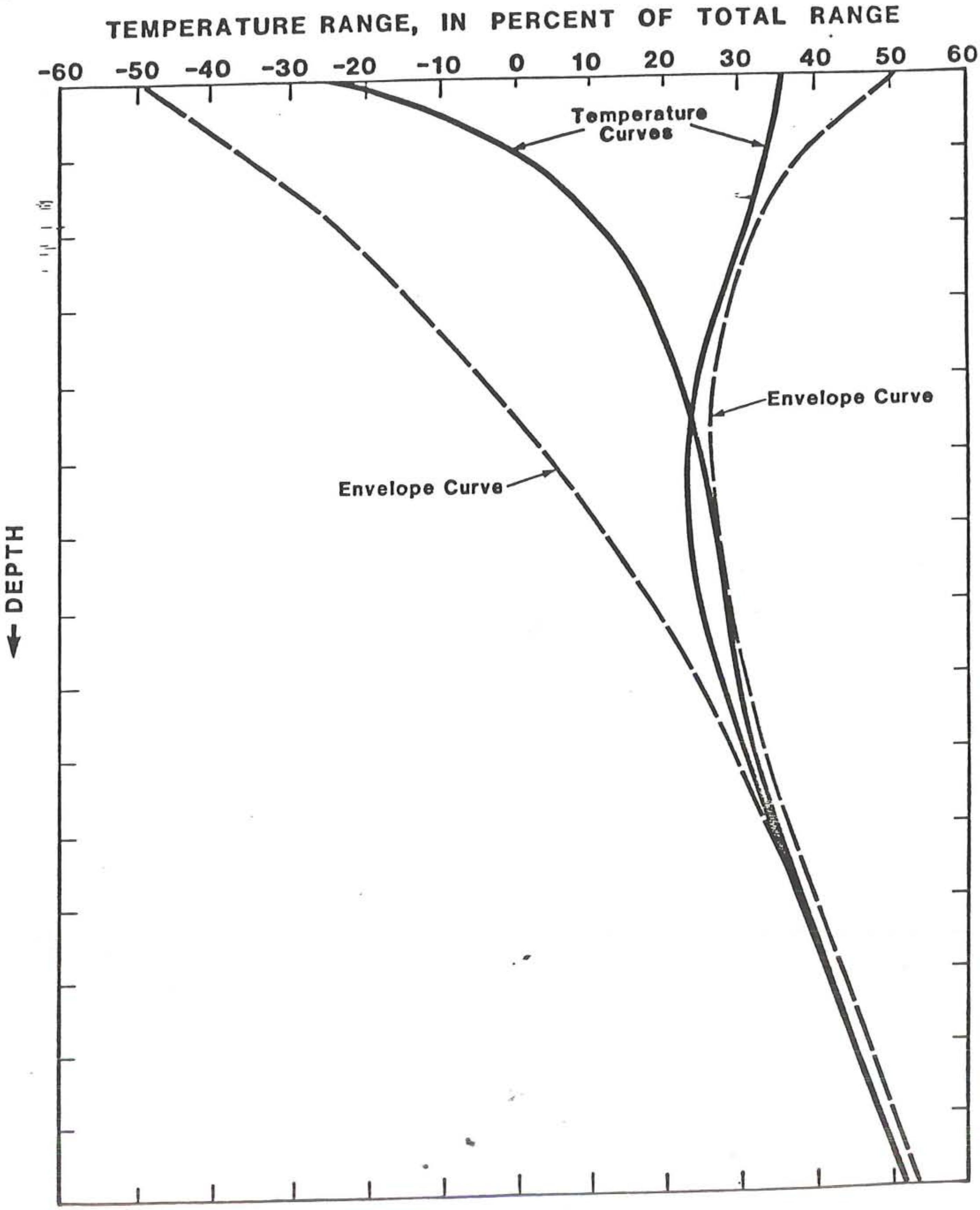


FIGURE 4 - Idealized diagram showing effect of a normal geothermal gradient upon subsurface envelope curves of Figure 3.

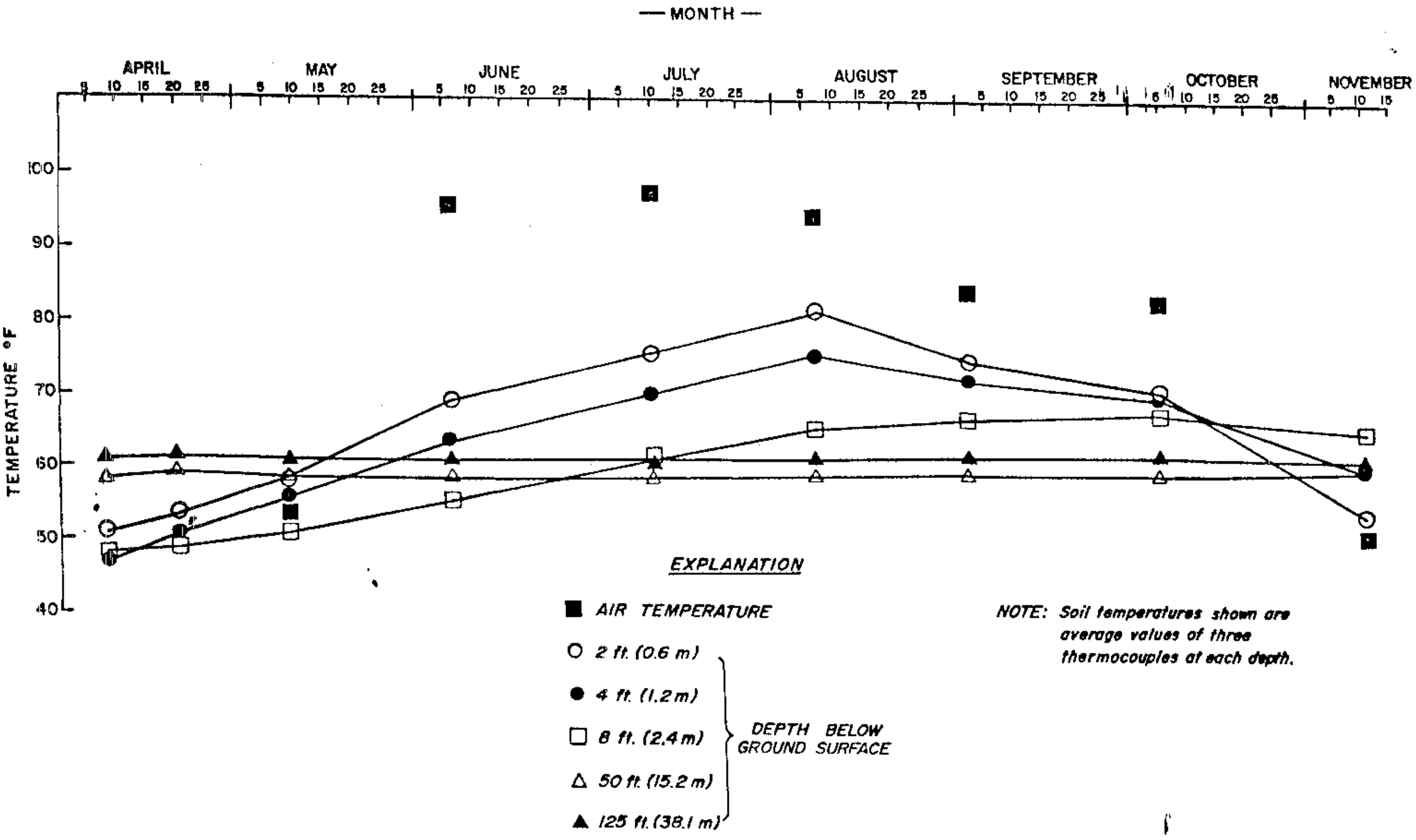


FIGURE 5 - Soil temperature plot by Fugro National, Inc. at a Nevada study site.