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July 1987

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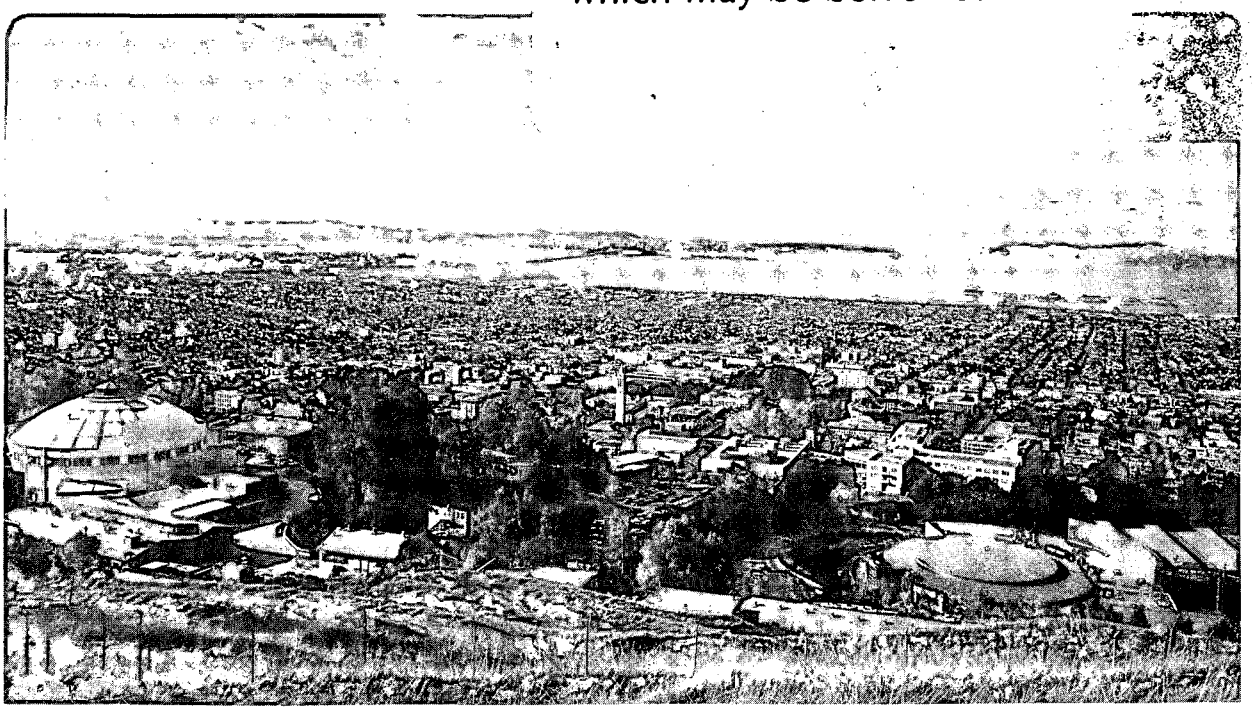

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Prepared for the U.S. Department of Energy under Contract DE-AC03-76SF00098

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AN ANALYSIS OF THE HYDROLOGIC EFFECTS OF PROPOSED TEST DRILLING IN THE WINEMA NATIONAL FOREST NEAR CRATER LAKE, OREGON

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ABSTRACT

This paper describes the results of a preliminary study on the hydrologic regime underlying the Crater Lake Caldera, Oregon. The study was performed to provide a basis for evaluating the potential for polluting Crater Lake by drilling exploratory boreholes on the flanks of the mountain. A simple conceptual model of the hydrologic regime was developed by synthesizing the data from the region surrounding the Caldera. Based on the conceptual model, a series of numerical simulations aimed at establishing the basic groundwater flow patterns under and surrounding the lake were performed. In addition to the numerical simulations, we used simple volumetric techniques for estimating the distance that drilling mud would migrate away from the borehole if drilling proceeded without drilling fluid returns.

Based on our calculations that show the regional flow of groundwater will oppose the flow of drilling mud toward the lake, and based on our volumetric estimate of drilling mud migration, our study concludes that drilling without returns will not pollute Crater Lake, nor will it affect the hydrologic regime in the immediate vicinity of the Crater Lake Caldera.

INTRODUCTION

The investigation described in this report was undertaken at the request of the Oregon State Office of the Bureau of Land Management, the United States Department of the Interior, and the United States Department of Energy. The purpose of the study is to provide the hydrologic basis for an amended Environmental Assessment of the consequences of exploratory test drilling for geothermal resources within the Winema National Forest adjacent to Crater Lake National Park, Oregon. The specific objective is to analyze impacts due to drilling about 1700-m deep geothermal gradient holes without maintaining circulation of drilling fluid.

In addition to the published data on the geology and geophysics of Mount Mazama and the limnology of Crater Lake, useful background information was obtained from a two day conference on Crater Lake sponsored by the Geothermal Resources Council, held in Portland, Oregon on February 24 and 25, 1987. Many of the workers who have done pioneering studies of Mount Mazama and Crater Lake presented their findings. This conference provided a synthesis of old and new scientific data on the area, much of which has been incorporated in the conceptual and numerical models described below.

APPROACH AND METHODOLOGY

Crater Lake has been the object of geological, limnological, and hydrological studies over the years. However, in general, there is a lack of much of the data that is usually considered to be a prerequisite for the type of analysis that needs to be performed in order to predict migration of potential contaminants in a groundwater system. For instance:

1. The hydrologic system at Crater Lake is not well known, and there are few constraints on the boundary conditions of the flow system.
2. No data are available on the permeabilities of rocks beneath the Crater Lake Caldera.
3. The temperature distribution in the rocks beneath Crater Lake and elsewhere in the volcano is unknown. The history of volcanism at Mt. Mazama supports the belief that temperatures are higher than normal in the upper few kilometers of the crust beneath the volcano.

Our study utilizes the results of numerical simulation modeling as the primary basis for our conclusions. The numerical code used for the simulations was developed at the Lawrence Berkeley Laboratories by G. S. Bodvarsson (1981). The code, PT, employs an integral finite-difference method for solving coupled equations of mass and energy transport. PT has been extensively tested and used by numerous investigators to solve a variety of hydrothermal flow problems. In the light of the above deficiencies of data, our approach has been to perform a series of modeling computations that would establish the general characteristics of the flow system in and around the Crater National Park with reasonable certainty.

CONCEPTUAL FRAMEWORK

The conceptual basis for the numerical models relies heavily on geological studies of Mount Mazama by Howel Williams (1942) and Charles Bacon (1983) and the hydrologic study by Phillips and VanDenburgh (1968). Recent limnological and geophysical studies of Crater Lake have also contributed to the development of the conceptual model. Several fundamental assumptions underlie the model. Briefly, these are as follows:

1. The hydrologic flow system is assumed to be generally radially symmetrical in conformity with the overall radial symmetry of the volcano. Nonsymmetric topography on the flanks of the volcano is recognized and differences between the east and south flanks are incorporated into the models.
2. The present shallow hydrologic regime was established at least 1000 years B.P. (Phillips and VanDenburgh, 1968). A further assumption is that long-term average precipitation and seepage loss from the lake are represented with accuracy sufficient for our purpose by the estimates of Phillips and VanDenburgh (1968).
3. A central magma body was present at shallow crustal depths approximately 7000 years B.P., and more recent eruptions give evidence of continued high heat supply to this body (Bacon, 1983).
4. The evolution of silicic magma and the ultimate collapse of the summit of Mount Mazama to form a large caldera are evidence for the location of the silicic magma chamber at shallow depths, possibly near the upper margin of a dense intrusive mass inferred from gravity data at a depth of about 2.5 km (Williams and Finn, 1985). It is expected, therefore, that temperatures may still be high in rocks of the collapsed block beneath the caldera.

Each of the foregoing assumptions applies equally well to Newberry, a large volcanic feature located about 95 km NE of Crater Lake, whose structure is similar in most important respects to Mount Mazama. At Newberry, extensive geological and geophysical studies, shallow test drilling, and recently completed numerical simulations offer insights that are useful in evaluating some less well documented aspects of Mount Mazama.

In the design of the numerical models, we make no assumptions regarding the location, size, or present condition of a magma chamber at Mt. Mazama. However, we accept the data presented by H. Nelson, R. Collier, and J. Dymond in three papers read at the GRC Technical Workshop on Crater Lake (Portland, Oregon, February 24 and 25, 1987) as evidence that high pressures and temperatures existed at shallow depths below the volcano as recently as 4000 years B.P.

Hydraulic heads at the surface of Crater Lake and in the adjacent rim rocks provide the principal driving force in the upper part of the hydrologic system at Mt. Mazama. We assume that the lake forms a recharge mound that forces a constant flux of water downward and radially outward. Thus, the amounts of precipitation and the subsurface leakage from the lake, both of which are known with reasonable accuracy, provide a known boundary condition at the upper surface of the model. For the boundary conditions at the outer edge of our model, we assume that temperatures and pressures are constant at a distance of about 30 km from the center of the caldera.

Many of the springs on the east and south flanks of Mt. Mazama emerge above lake levels at altitudes of more than 2100 m (7000 ft). Most of the remainder occur between altitudes of 1830 and 1890 m (6000 to 6200 ft). The presence of these springs indicates that vertical ground-water flow is impeded by low permeability rock units. We have assumed that the high apparent water tables east and south of the lake are, to a large extent, perched and that a true water table, related both to lake levels and to local base levels, lies at lower altitudes.

Below altitudes of about 1800 m on the east flank of Mt. Scott, the rocks are highly altered, dense, and poorly permeable. These rocks, which are predominantly rhyodacitic in composition, probably overlie hornblende andesites which may have similar hydrologic properties (Charles Bacon, oral commun., 1987). This rock assemblage appears to represent a barrier to downward percolation of meteoric water and is the probable cause of the large volumes of spring flow.

A rough estimate of the water budget for the east and south flanks of Mt. Mazama indicates that the water available from precipitation exceeds both the spring flows in this area and the total estimated seepage from Crater Lake. Average annual spring discharge to the east of Mt. Mazama may be about 1.1×10^8 m^3/yr and discharge to the south may be about 6.3×10^7 m^3/yr (from estimates provided by Garwin Carlsen, USFS, and published records of the USGS). If annual precipitation is assumed to average 45 in (1,143 mm) within a radius of 15 km from the lake center (above an altitude of about 1372 m), and if evapotranspiration is about 13 in (330 mm) (J. E. Vaughn, Deschutes National Forest, estimate for a lodgepole pine forest at Newberry Volcano, 1983), the net meteoric water available is about 810 mm, or 5.73×10^8 m^3/yr. Total spring flow is about 1.6×10^8 m^3/yr. Thus, there is no need to invoke seepage from the lake (approx. 8×10^7 m^3/yr; Phillip and van Denburgh, 1968) as a source of spring flow on the flanks of the mountain.

To the east of Mt. Scott, lake sediments of low permeability may underlie the lower slopes and extend beneath the Klamath Marsh. The sediments are assumed to be similar to those exposed in a road cut along Rte. 97 north of the Williamson River. Wells drilled through these sediments on the west margin of the Klamath Marsh penetrate permeable rocks and tap ground water under artesian pressure.

We have not attempted to model subsurface conditions related to the large domes and volcanic vents in the highlands east of the lake. The large volcanic features in this area, which include Pothole Butte, Mt. Scott, and Dry Butte, predate most of the construction of Mt. Mazama and show no evidence of recent volcanism or high heat flow. Mt. Scott, for example, is more than 400,000 years old and would not be expected to retain significant amounts of residual heat (Charles Bacon, oral commun., 1987). In the absence of reliable clues to the probable structure and rock properties at depth beneath these features, we model this region in the same way as the other areas surrounding the caldera.

Two cross-sections of the the hydrologic regime underneath and surrounding the caldera are modeled in this study, one trending approximately E-W (Model 1) and one trending approximately N-S (Model 2). In the following paragraphs, these models are described.

MODEL 1: E-W Cross Section

The first area modeled lies to the east of the lake and includes a wedge of terrain with its origin at midlake and its outer boundary at a radial distance of 28 km. The model is intended to represent hydrologic conditions that apply to the cross section A-B, shown in Figure 1. A cross-sectional profile of the model lies along an azimuth of 105 degrees from the lake center, passing close to the top of Cloud Cap and crossing the north flank of Mt. Scott (Figure 2). Below the lake, the sunken caldera block is given a diameter of 6 km in accordance with seismic data from the lake bottom reported by Nelson (GRC meeting, Portland, Feb. 24, 25, 1987). The profile extends to the Klamath Marsh near the confluence of Big Spring Creek and the Williamson River.

From the eastern boundary of the model, the water table was projected inward with a slope of 0.0015 to a point near the bottom of drill hole I-11A. This hole, bottomed at an altitude of approximately 1431 m, reportedly did not penetrate the water table. From this point to the surface of Crater Lake, the height of the water table, and consequently, the elevation of the top boundary of the computational mesh, was adjusted as a function of observed pressures in the upper row of nodes.

Areas of the cross section shown in Figure 2 are labeled with Roman numerals designating the hydrologic units differentiated within the model. Values of material and fluid properties are shown in Table 1. Our knowledge of the subsurface conditions at Mt. Mazama is not sufficient to permit meaningful use of fine distinctions in rock density, porosity, heat capacity, thermal conductivity, and compressibility; hence, these properties were given constant values representative of volcanic rocks. Ranges of permeability were used in the models to represent probable differences in permeability among the units. The permeabilities chosen are based on field measurements in volcanic terrains reported in the literature, primarily those from Brace (1980, 1984), Hardee (1982), Henley and Ellis (1983), Sammel (1980), and Sammel and Craig (1981). For each of the models, numerous simulations were performed using a range of permeability (k) and anisotropy ($k_{vertical}/k_{horizontal}$ ranging from 0.01 to 1) values for each of the rock units. In this report, we discuss the results of the simulations with the horizontal permeabilities listed in Table 2.

The permeability in unit I is relatively high, in keeping with indications from eruptive centers such as Newberry Volcano and several centers in the vicinity of Klamath Falls. Unit VII is given a lower permeability on the basis of hydrologic indications (see above) and core from drill hole I-11A. Unit IV is given a low permeability on the basis of the presence of the lake perched above it and the likelihood that rock alteration and mineral deposition would have occurred at the low-temperature upper boundary of a former hydrothermal system. Permeabilities in the remaining units are intermediate to low on the assumption that the rocks are late Tertiary basalt flows overlying strata of unknown composition.

MODEL 2: N-S Cross Section

The cross section A-C shown in Figure 1 which is used for Model 2 (Figure 3) follows the high ground between Sun Creek Valley and Munson Valley, passes through Crater Peak, and heads toward the South Entrance Station on an azimuth of approximately 162 degrees. The profile ends near Fort Klamath at a lineal distance of 30 km (about 18 mi.) from the lake center.

The occurrence of many springs, including Annie Spring, at altitudes above 1800 m suggests that ground water is at least partly perched at levels similar to those in Model 1. Model 2 was constructed accordingly. The estimated water table, which descends from the level of Crater Lake, is constrained at a distance of about 15.5 km by the level of Annie Creek, at about 17 km by data from drill hole II-1, and at its maximum distance in Model 2 (30 km) by the level of Agency Lake. This base level is about 113 m lower than the Klamath Marsh in Model 1, thus imposing a significantly steeper gradient on the shallow flow of Model 2 as compared to Model 1.

We have not attempted to model the roots of Crater Peak for the same reasons given above regarding Mt. Scott. The rocks below an altitude of about 1300 m are assumed to be basalt flows similar to those logged at a depth of 60 m in drill hole II-1. These rocks extend to large but unknown depths. In general, with the exception of unit I, the permeability values used for Model 2 are similar to those in Model 1. Higher permeabilities are needed in unit I to match the water table distribution for Model 2. The values for the horizontal permeability of the various rock units used in the simulation runs for Model 2 that are reviewed in this report are listed in Table 2.

Heat Flow and Boundary Conditions

In the cases reported here, the lake surface is treated as a constant-flux boundary, with a seepage rate of 1250 kg/s. (Several simulations were performed using the full recharge rate of 2500 kg/s (about 8×10^7 m^3/yr), but, as discussed later, it is unlikely that the full recharge enters that regional groundwater flow system.) At the vertical outer boundary, water is free to flow in or out of the system but maintains a constant temperature and pressure profile. Along the bottom boundary of the system, we impose a constant heat flow of 105 mW/m^2, which is equal to the minimum value estimated by Blackwell and others (1982) for the main trend of the Cascade Range. No mass is allowed to enter or leave the system across the bottom boundary. The ground surface is treated as a constant temperature boundary, with a temperature of 3.9 °C.

To simulate the influence of the magma body on the local heat flow, we assume that the temperature remains at 350 °C at a depth of approximately 1.5 to 2.5 km below the lake surface (see hydrologic unit VI in Figures 2 and 3). In one of the Cases (Model 2, Case 2), hot water recharge is imposed at a rate of 125 kg/s of 350 °C water at the bottom boundary in rock unit VI in order to simulate the effects of heated fluids upwelling from a great depth directly underneath the caldera.

Initial Conditions

The initial temperature distribution in our model (Figure 4) was obtained from a similar but much more detailed numerical modeling of the hydrothermal system at Newberry Volcano. Basically, the initial conditions were

developed by considering the thermal regime surrounding a convectively cooling magma chamber (Sammel and others, 1987). In this transfer, we rely on similarities between Mt. Mazama and Newberry Volcano in size, construction, and the recency of silicic volcanism. We have assumed that the two volcanoes supported similar thermal regimes during the past few thousand years. At Newberry Volcano, maximum temperatures at a depth of 2.5 km below the caldera rim were estimated to be greater than 300 °C and perhaps as high as 400 °C after 4000 years of convective cooling.

RESULTS

The results from four numerical simulations, describing two cases each from Model 1 and Model 2 are discussed in the following paragraphs. In general, the results from Model 1 and Model 2 are similar, and inferences about the general flow directions and magnitudes, lake levels and seepage, and heat flow are transferable from one model to the other.

Lake levels and seepage

The simulated levels of Crater Lake are highly sensitive to the amount of seepage and the permeability of adjacent rocks. Early attempts to simulate the full recharge (2500 kg/s) estimated by Phillips and VanDenburgh (1968) showed that unexpectedly high permeabilities are required for the hydrologic units adjacent to the lake in order to keep it from rising to unacceptably high levels.

As an alternative to increasing the overall permeabilities in units I and II to unrealitically high values, we assume that much of the seepage from the lake is conveyed in a few highly permeable zones that are not part of the regional flow system. Evidence for one such permeable zone is found at the northeast margin of the lake (Charles Bacon, oral commun., 1987). To account for these channels, we assume that only one-half the recharge estimated by Phillips and VanDenburgh actually seeps into the bulk of the rock mass that is modeled.

With a recharge of 1250 kg/s, the lake level for Model 1 (Case 1) remained within a few meters of its present day elevation of 1882 m. In other cases, the lake declined to levels as low as 1728 m or rose as high as 2356 m from its initial level of 1882 m, depending primarily on changes in the permeability of units I, II and III. In all of the cases, small adjustments in the permeability distribution could have been used to achieve better agreement between the predicted and measured lake level. However, because the changes in lake level had little effect on the direction and rate of flow, we did not attempt to achieve an exact match in each case.

Vertical seepage through the lake bottom is directed both upward and downward in the various models, and, in most models, upward and downward seepage occur in adjacent nodes in response to small differences in pressure. The vertical seepage is never greater than 4 percent of the total outflow from the lake, and overall, it did not have a significant impact on the results of the models. Clearly, increased permeability in the unit directly underlying the lake could strongly affect seepage rates and temperatures beneath the lake, but the general flow pattern could not be significantly changed.

Flow Directions and Magnitudes

The modeling studies indicate the distribution of fluid velocities within the various sub-surface rock units. For example, the arrows in Figures 5, 6, 7 and 8 show the directions and magnitudes of ground-water flow for the cases listed in Table 2. In evaluating the patterns of flow shown in Figure 5 and succeeding diagrams, it should be kept in mind that the illustrations have a 4 to 1 vertical exaggeration. The result is to distort perceptions of the geometric relations, particularly the vertical components of the flow vectors and the depths of the drill holes relative to their distances from the lake. In true perspective, the model would be seen to consist of thin layers that extend to four times the length shown. In addition, the vectors are based on a linear scale of the logarithms of the magnitudes, which makes order of magnitude differences appear small.

The direction of flow is, as expected, generally downward and outward away from the lake. Vertical components of the flow vectors are directed strongly downward near the lake in spite of the low vertical permeability imposed by the anisotropy ratio (the ratio of the vertical to the horizontal permeability). In each case a large convection cell dominates flow in hydrologic units IV, V and VI beneath the lake. The magnitude of the upward flow is enhanced for the case where fluid recharge occurs under the caldera (Model 2, Case 2; see Figure 8).

In one case (see Figure 5), flow is radially inward in the lowest row of nodes at distances up to 8.5 km from the lake center. For Model 1, increasing the permeability of the rock units II and III from 5×10^{-14} and 1×10^{-15} m^2, respectively, to 1.3×10^{-14} m^2 (Case 2) eliminates the inward flow and creates a more uniform flow field. This results from the rapid outward flow in unit III and a consequent decrease in pressure, which prevents flow into the high-pressure region beneath the caldera. For Model 2, inward directed flow is small and confined to within a radius of 3 km from the center of the lake.

Many prior and subsequent trial runs showed that the flow patterns pictured in Figures 5 through 8 are well established in a few hundred years after the start from the initial hydrostatic equilibrium conditions. Models simulating times as long as 6000 years showed slow decreases in flow velocities but no significant changes in the flow pattern as time progressed.

Heat flow and lake temperatures

Although modeling heat flow was not the primary objective in this work, an analysis of the heat flow calculated from the models provides some reassurance that the temperature distribution and rock properties chosen for the caldera region in our models are reasonable estimates. Heat flow through the lake bottom at simulation times of 1000 years ranged from 930 to 1500 mW/m^2. The heat flow is almost entirely conductive. The lower of the two values is about 11 percent greater than the maximum value actually measured at lake bottom and the higher is about 10 percent less than the maximum estimate of total heat flow given by Williams and Von Herzen (1983).

The models presented here make no attempt to reproduce measured temperatures in Crater Lake. Nevertheless, the model results show reasonable approximations of lake

temperatures and measured heat flows. In most of our simulations, lake temperature increased initially and then slowly decreased as cold recharge overcame high initial temperatures and convective upflow of warm water. From an initial temperature of 3.9 °C, lake temperatures quickly rose to approximately 8 °C and then slowly declined. We have not attempted to incorporate the effects of convective heat transfer between the lake and the atmosphere, which would tend to reduce the temperature of the lake.

Temperature data presented in this report are limited to the type of results described above. Unlike the fluid flow results, which after a period of several hundred years are not sensitive to initial conditions of pressures or temperature, temperature results are highly sensitive to initial temperatures and to the permeability distribution. In the absence of much additional data with which to constrain initial temperature distributions and boundary conditions, we have chosen to avoid presenting possibly misleading results.

Influence of Hot Water Recharge

The second case reported for Model 2 is designed to evaluate the influence of a significant amount of hot water recharge entering the system directly over the magma chamber. For this case, 350 °C water is injected into the lower part of unit VI at a rate of 125 kg/s (1/10 the rate of lake seepage) to simulate the upflow of hot water that might result from a hydrothermally driven convection cell. A previous trial with injection at 12.5 kg/s showed small effects of such injection by increased heat flows and vertical mass transport. Model 2; case 2 clearly demonstrates these effects.

Lake temperatures are slightly higher than in previous cases, and they continue to rise slowly through the 4000 year simulation period. Net mass flow into the lake is still dominantly conductive, but total heat flow has increased to 1500 mW/m^2 at 1000 years and is still rising at 4000 years. Clearly, hot water influx at depths of more than 2.5 km has a significant effect on the transport of both heat and mass beneath the caldera. However, as illustrated in Figure 8, the flow regime beyond the radius of the caldera is not greatly affected by the convective flows under the caldera.

DISCUSSION

The results from Model 1 and Model 2 lead to the conclusion that only major structural features such as faults or stratigraphic discontinuities could significantly alter the flow pattern on the flanks of Mt. Mazama as determined by the models. The following paragraphs review structural features that could potentially alter this conclusion.

A fault or dike that has a low permeability relative to the surrounding rock may or may not influence the flow pattern, depending on its orientation. If the structure lies in a vertical plane oriented along a radius to the lake, it would have little or no effect on the flow pattern. To the extent that such a structure cuts across the natural radial flow paths, and in the extreme case is perpendicular to the flow paths, it will act as a barrier to the flow. Nevertheless, on a regional scale, water will still flow from the high pressure area of the lake to the low pressure area of the local or regional base level. In such a case, there is virtually no possibility that fluid from beyond the barrier could be forced to flow toward the lake.

In the case of an impermeable sill or other horizontal structure or stratum of low permeability, water from the lake would flow above it, retaining much of its initial high hydraulic head. Fluids from outside the caldera area could neither move upward through the barrier against the overlying high hydraulic head nor flow on top of the barrier against the radially outward gradient that would exist there. As with the previous case, the large- scale flow field would be changed only locally by such a feature and could not be completely reversed.

Considering now cases in which structural features are more permeable than the surrounding rock, the consequences can be stated rather briefly. The flow in such features would in general simply be more rapid than in the surrounding rock, and the prevailing potential (head) differences between the lake area and the nearby base levels would govern the overall directions of flow in the same way as in the absence of permeable structures.

One special case deserves a separate description, however. This could be a permeable fault or fracture situated high on the flank of the mountain that would intercept ground-water recharge in the overlying perched water zone, shown in Figures 2 and 3. Water moving down this conduit could eventually mix with the underlying ground water, and if the hydraulic head in the fault or fracture were sufficiently high above lake level (greater than 1882 m), there would be a component of flow directed toward the lake. The concern here, of course, is whether or not such a flow component could carry any of the drilling fluid from proposed drill holes into the lake. In order for this to occur, two conditions must exist: (1) the drill hole must be located between the fault or fracture and the lake; and (2) the hydraulic head in the fault or fracture must be significantly higher than the lake level in order to produce a counter flow to the prevailing ground-water movement.

MIGRATION OF DRILLING FLUID

A typical drilling fluid that might be used in a core hole is a light bentonite mud with added caustic soda. For the purpose of these calculations, the maximum loss-of-circulation rate is estimated to be 10,000 gpd (38 m^3/d). We have compared this rate with the flow rates computed by the models by means of the following simple calculations. If the average hole diameter in the 1500 m of cored drill hole is 5 inches (0.127 m), the area available for discharge is 600 m^2 and the maximum specific loss rate is 7.33×10^{-7} m^3/s per square meter of drill hole surface. With respect to the rock mass and the formation adjacent to the hole, the injected fluid may be regarded as a finite-width line source having an area perpendicular to the stream lines equal to 190 m^2. The specific loss rate calculated in this approach is 2.26×10^{-6} m^3/s per square meter of formation rock perpendicular to the flow field. This rate is approximately 75 times the maximum ground-water flow rate in the vicinity of the proposed drill hole (I-11A). From these facts, we conclude that the the drilling fluid loss will control pressures and dominate the flow regime in the close vicinity of the drill hole.

Tracer studies have amply demonstrated the complexities of volcanic terraines. For example, recent tracer tests in the geothermal aquifer at Klamath Falls showed that fluid velocities can be as high as 4×10^{-3} m/s in an aquifer

where overall mass flow velocity is probably in the range 1×10^{-7} to 1×10^{-9} m/s (Gudmundsson, 1984; Benson, and others, 1984). It is reasonable to assume that, at Crater Lake as elsewhere in volcanic aquifers, most ground-water flow occurs in fractures and permeable strata that represent only a small fraction of the total rock mass. Flow velocities in these features may be orders of magnitude greater than the velocities calculated by our models.

In spite of the lack of data on details of the permeability distribution within the fractured volcanic rocks, some simple calculations can lead to useful conclusions about the fate of drilling fluids in the rocks. Without regard to permeability, the volume of rock that could be invaded by injected fluid is commonly calculated as piston-flow displacement. For example, after 90 days of drilling, with loss-of-circulation at a rate of 10,000 gpd (4.38×10^{-4} m^3/s, the volume of injected fluid is 3400 m^3. Table 3 shows the maximum distance from the drill hole that would be occupied by drilling fluid injected into the specified thicknesses of permeable rocks. The porosity is assumed to be 10 percent. Two examples are shown: the first represents 360-degree radial flow and the second represents the result of injecting the entire amount of fluid into a 45-degree wedge of permeable rock. The assumption of piston flow is not unrealistic in cases where the injection pressure controls the flow regime in confined aquifers and where the injected fluid is cooler and more dense than the formation fluid. The calculations show that even in the extreme and highly unlikely case that the entire flow of drilling fluid entered a stratum 0.1 m thick and was confined to 1/8 of the surrounding volume, the fluid would spread to a radial distance of less than 1 km in the absence of regional groundwater flow.

In examining additional extreme cases, calculations like those above show, for example, that the assumed volume of drilling fluid could not reach the region of caldera fill beneath the lake if it were injected in a pipe-like lava tube 0.75 m in diameter, even if the drill rig pumps were capable of pumping it that far. Similarly, the drilling fluid would stop short of the caldera fill if all of it were injected into a single fissure 50 m high and 0.01 m wide (less than 1/2 inch).

The extreme cases outlined above are included primarily to demonstrate that even in the most unlikely circumstances, drilling fluids will not enter Crater Lake from the proposed drilling locations shown in Figure 1. When it is also considered that drilling mud is particulate matter, heavier than water, that will settle out at low velocities, it is concluded that, in all likelihood, the mud will not travel more than several hundred meters from the borehole.

Finally, the results of the modeling show that the regional ground-water flow field will transport fluids away from the lake and will oppose any travel toward the lake from the flanks of the mountain. This will be true regardless of the permeability of the rocks or the presence of high heat flows at depth.

Implicit in this study has been the assumption that the ground-water system in the vicinity of the lake is in hydraulic connection with ground water beneath the flanks of the mountain. Should this turn out not to be the case in any part of the area because of impermeable structural barriers, there could, of course, be no contamination of the lake by drilling fluids injected beyond these barriers. Parenthetically, the model results suggest that if high-temperature water is located at shallow depths beneath the flanks of the mountain, this finding would indicate that the hot water must be rising from a deeper hydrothermal system in faults and fractures that are, at least in part, isolated from the shallow ground-water body. Drill holes penetrating these features would also be isolated from the shallow ground-water body and, therefore, from the lake. In such cases, radially outward flow of hydrothermal fluids in the deep system would preclude the inward flow of drilling fluid in the same way as does the outward flow of seepage from the lake in the shallow groundwater system.

CONCLUSIONS

1. For the purpose of analyzing possible impacts of fluid injection from drill holes in the vicinity of Crater Lake, the ground-water flow system beneath Mt. Mazama can be represented by simple simulation models.

2. Two major driving forces are able to establish the fundamental nature of the ground-water flow. These forces are the hydraulic head imposed by the water level in Crater Lake and the high pressures generated at large depths beneath the lake by high-temperature rocks. Both of these forces tend to move ground-water radially outward under the flanks of the mountain. Each would operate in the way shown by this study independently of the other, although the vertical extent of mass flow from either is highly dependent on the vertical permeability.

3. Temperatures at depths of 2.5 km or more beneath the lake are probably high in view of the volcanic history of Mt. Mazama, which includes an eruption as recently as 4000 years B.P., and by analogy to Newberry Volcano, a Cascade Range volcano of similar size, characteristics, and eruptive history.

4. On the basis of temperatures measured in the lake and the hydrologic evidence provided by the models, the hydraulic head in the lake appears to be the dominant hydrologic force in the shallow (less than 1.5 km depth) ground-water regime. In the areas of concern for this report, the directions and magnitudes of ground-water flow are determined largely by the potential differences (hydraulic head differences) between the lake and the local base levels of the Klamath Marsh to the east and the upper Klamath Lake valley to the south of Crater Lake. Simply put, the uppermost ground water body is principally controlled by gravitational forces that cause it to flow from high elevations to lower elevations.

5. The general direction of ground-water movement under the flanks of the mountain is not sensitive to assumptions of permeability and anisotropy in the models, although the magnitudes of flow and the details of flow directions are sensitive to these factors. The principal flow directions could not be reversed by the presence of rocks that differed from those modeled or by the existence of major structural features that were not modeled. The reason is simply the dominating effect of high-altitude recharge of water from precipitation and snow melt and the consequent seepage from the lake.

6. The fundamental nature of the flow system appears to be well established by the models, and it is clear that natural hydraulic forces in the flow system will oppose the flow of drilling fluids toward the lake at any point in the proposed drilling areas. Nevertheless, the analysis of impacts from the injection of drilling fluid does not depend only on the presence of radial outward ground-water flow. Calculations of volume displacement show that drilling fluid could not reach Crater Lake from proposed drilling sites even in the most extreme and unlikely cases considered.
7. In view of the ground-water flow directions determined by the modeling, which would oppose the flow of drilling fluid toward the lake, and in view of calculations that show the volume of injected fluid to be too small to reach the lake by simple volume displacement, we conclude that the loss-of-circulation while drilling fluid does not pose a threat to Crater Lake or in any way affect the hydrologic system in the immediate vicinity of the Crater Lake caldera.

ACKNOWLEDGEMENTS

We are grateful for the contributions of a number of colleagues. In particular, we thank Charles Bacon and Manuel Natheson (USGS) for background information and discussions, Cindy Yates (LBL), who performed the data input and retrieval for much of the modeling, Garwin Carlson of Winema National Forest for a detailed description of streams and springs in the Crater Lake area, and personnel of the California Energy Company for making proprietary data available to us and sharing background information on the Crater Lake area. We are also grateful to Marcelo Lippmann and Manuel Natheson for reviewing this paper and providing valuable comments. This work was sponsored in part by the U. S. Department of Energy under contract number DE-AC03-76SF000098 by the Assistant Secretary for Conservation and Renewable Energy, Office of Renewable Technology, Division of Geothermal Technology.

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Table 1. Material and fluid properties used in all cases.

Rocks					Fluid
Density ($kg\ m^{-3}$)	Specific Heat ($J\ kg^{-1}\ K^{-1}$)	Thermal Conductivity ($W\ m^{-1}\ K^{-1}$)	Compressibility (Pa^{-1})	Porosity (-)	Density is calculated as a function of temperature and pressure. Viscosity and expansivity are calculated as functions of temperature. Compressibility is calculated as a function of pressure.
2200	2000	2.0	5×10^{-10}	0.1	Specific Heat: 4200 $Jkg^{-1}\ K^{-1}$

Table 2. Permeability distribution used for reported results from Models 1 and 2.

Hydrologic Units	Model 1 Case 1	Model 1 Case 2	Model 2 Case 1	Model 2 Case 2[1]
I	6×10^{-14}	6×10^{-14}	1×10^{-13}	1×10^{-13}
II	5×10^{-14}	1.3×10^{-14}	5×10^{-14}	5×10^{-14}
III	1×10^{-15}	1.3×10^{-14}	1×10^{-15}	1×10^{-15}
IV	2×10^{-16}	2×10^{-16}	1×10^{-16}	1×10^{-16}
V	1×10^{-15}	1×10^{-15}	1×10^{-15}	1×10^{-15}
VI	1×10^{-16}	1×10^{-16}	1×10^{-15}	1×10^{-15}
VII	1×10^{-17}	1×10^{-14}	-	-

[1] Assuming a recharge of 125 kg/s of 350 ° C water from below the caldera

Table 3. Distance that drilling fluid would migrate in formations of various thicknesses.

Thickness of permeable formation	Maximum Distance from Drillhole Radial (m)	45 °-Wedge (m)
1500	2.7	7.6
500	4.7	13
100	10.4	29
10	33	93
1	104	295
0.1	329	931

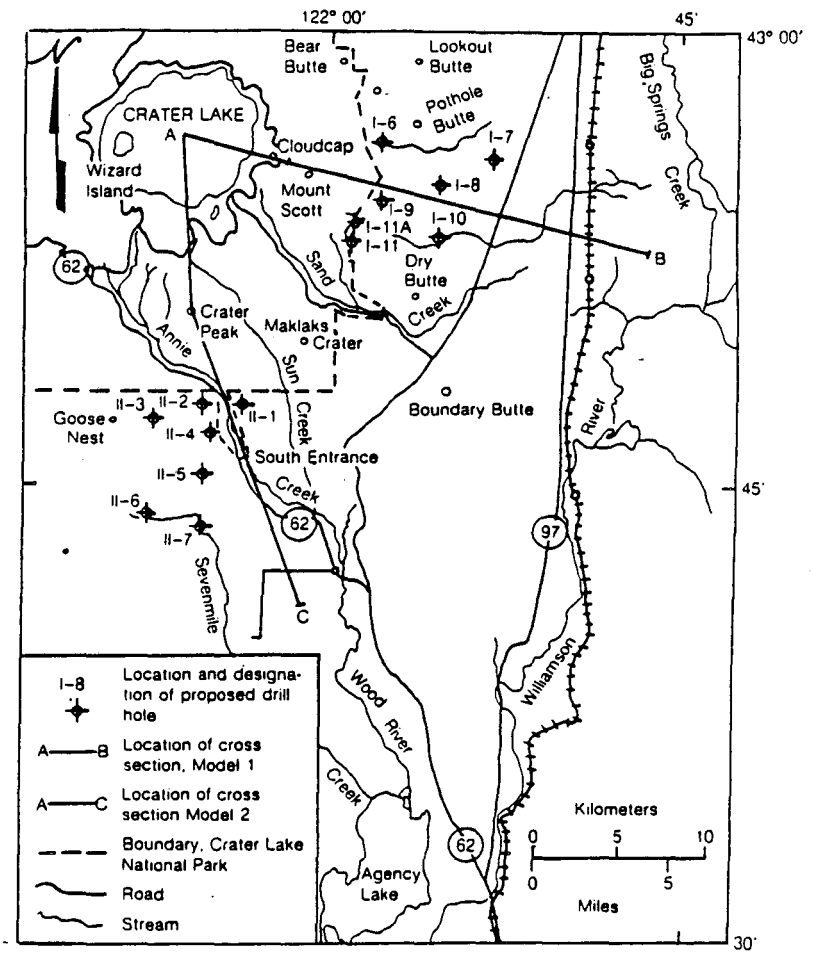

Figure 1. Map showing locations of model cross sections, proposed drilling sites, and selected geographic features.

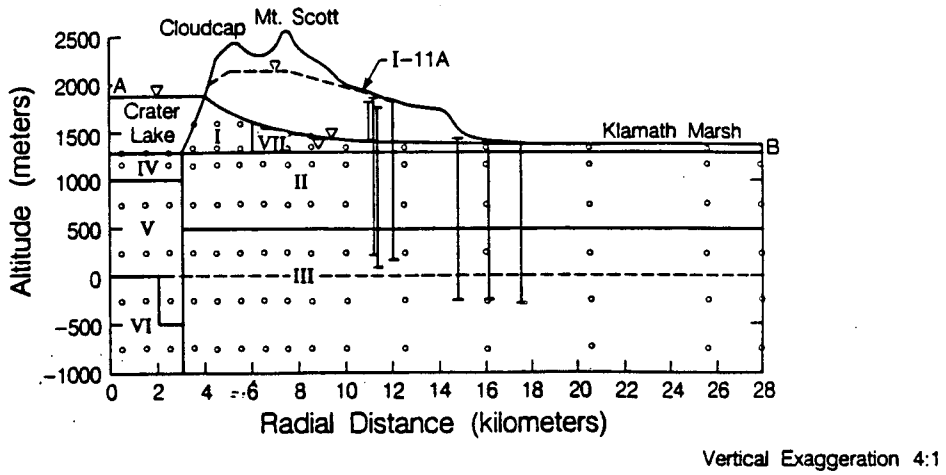

Figure 2. Computational mesh for Model 1.

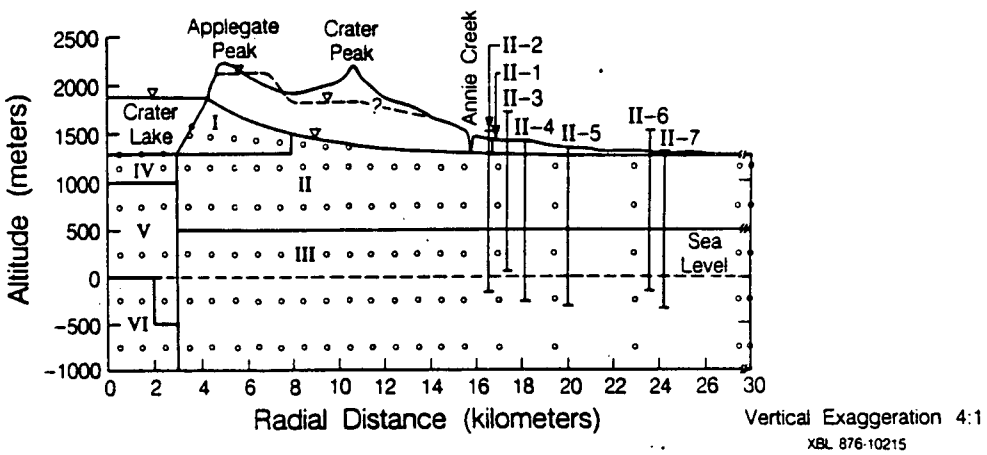

Figure 3. Model 2 boundaries are treated as in Model 1. Seven proposed drill holes in the Masama II area are projected on the cross section. Drill hole II-1 is shown to drilled depth.

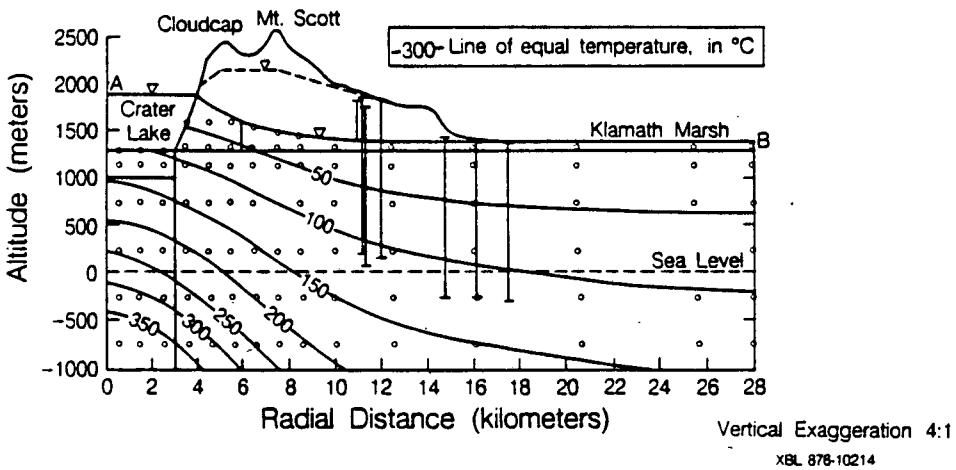

Figure 4. Initial temperature distribution used in all models. The temperatures are taken from a simulation model of Newberry Volcano for a time 4000 years after cessation of volcanic activity (see text for explanation). The cross section represents Model 1, Case 1.

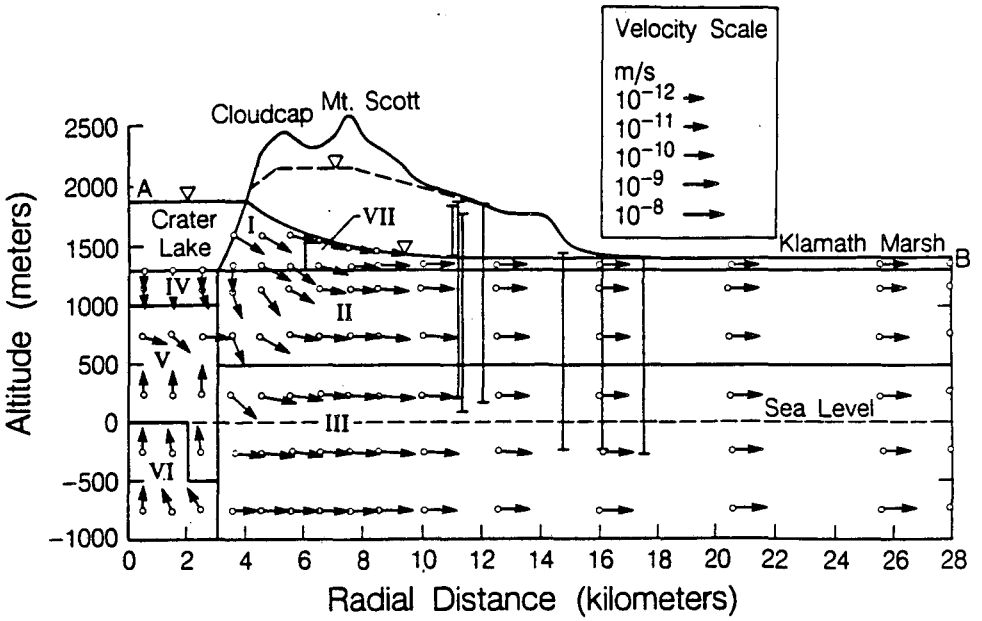

Figure 5. Directions and magnitudes of ground-water flow in Model 1, Case 1.

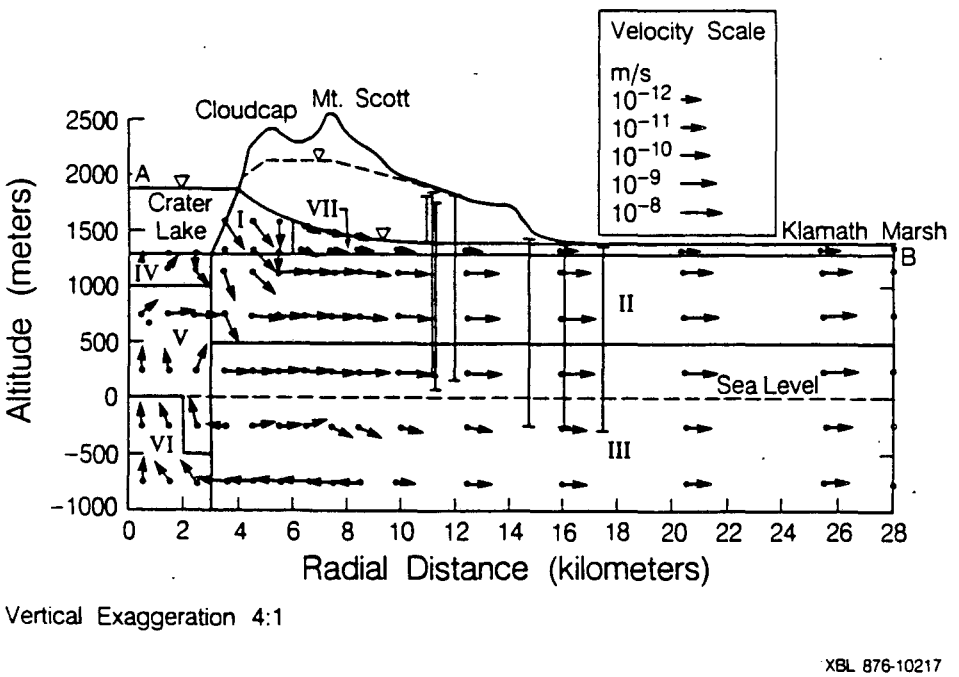

Figure 6. Directions and magnitudes of ground-water flow in Model 1, Case 2.

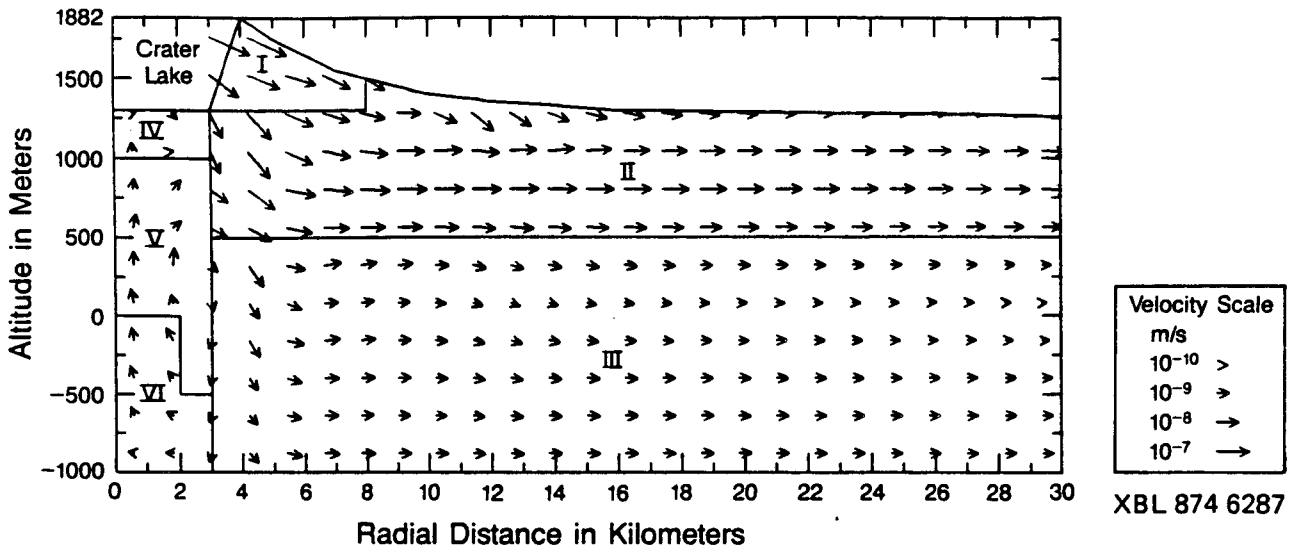

Figure 7. Directions and magnitudes of ground-water flow in Model 2, Case 1.

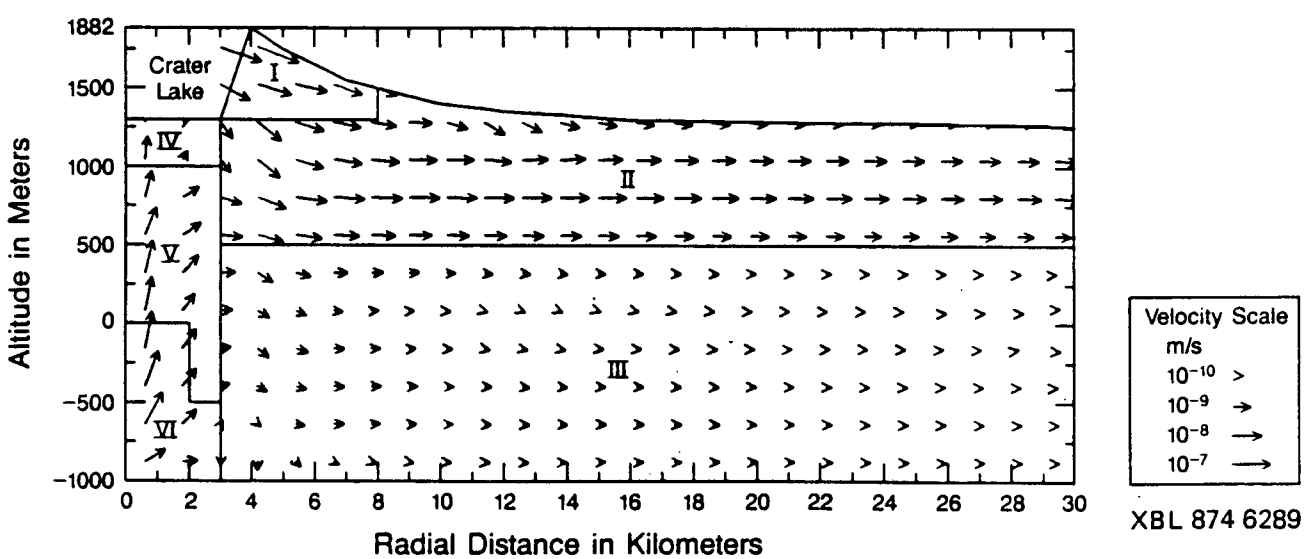

Figure 8. Directions and magnitudes of ground-water flow in Model 2, Case 2.

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