LONG VALLEY EXPLORATORY WELL

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LONG VALLEY EXPLORATORY WELL - SUMMARY

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As was stated by the first presenter, the Long Valley Exploratory Well represents a vital linking of geothermal theory, technology and applications. The five presenters take us through that linking to the extent the current progress at the well makes that possible. The site is, of course, a geothermally rich resource, a "recently active" caldera. In many ways, the site has a wealth of data preceding the present work. It is a site which has excited the interest of the geothermal community for a long time. As is often the case in geothermal work, the prior data has raised as many questions as were answered. It is on this basis that the further exploration of a probable high temperature resource is being explored to great depths.

The first presentation represents the cooperation and coordination maintained between similar elements of the Basic Energy Sciences programs and those in the Geothermal programs of DOE'S Conservation and Renewable Energy activities. Similarly, the work exemplifies the close coordination of the DOE work with the U. S. Geological Survey, the National Science Foundation, and the U. S. Continental Scientific Drilling Program. The first presentation also represents the theoretical and modelling portion of the session.

Appropriate to geothermal technology, the central programmatic theme is geophysical and geochemical aspects of fluid flow and interaction in porous and fractured rocks. It was interesting to note that even the theoretical work and modelling addressed the applicability to earth-based energy resources, and as well their utilization in a manner such as to assure environmental acceptability. Topics addressed included: 1) fundamental properties and interactions of rocks, mineral, and fluids; 2) transport and flow of fluids in rocks; and 3) structure of geologic units.

The session continued with the description of the Phase II operations at the Long Valley Exploratory Well. The drilling operations were described as relatively trouble free, with some hole deviation near the bottom in basement rock that is hard and abrasive. This phase was drilled to 7588 ft., with 13-3/8" casing set to 6825 ft. The ultimate depth of the well is planned to be 20,000 feet, or at a bottomhole temperature of 500°C, whichever comes first.

Downhole science in the Long Valley Exploratory Well was presented by a representative of the U. S. Geological Survey. It is expected that the well will provide critical information on the structure and evolution of a young volcanic system. During the Phase II work, sidewall cores and coring were emphasized, and borehole televiewer images and measurements of temperature provided significant data on the state of stress and the hydrologic and thermal state of the central part of the caldera. Indications are that cold water is penetrating to considerable depths. During the rest of the fiscal year, hydrologic and stress data will be focused on, as well as obtaining further data relating to the source of earthquakes and as to whether molten rock is still present in a significant volume within 6 to 8 km of the surface.

Personnel from the University of Alaska presented geologic results for this session's third presentation. The relationship of hydrothermal circulation to a large crustal magma chamber is being examined. Further, the well is providing an important test of the models for the subsurface structure of active continental calderas.

Results thus far, primarily from cuttings and cores, generally support the classical view of large intracontinental calderas as piston-cylinder-like structures. Analogy to other caldera systems suggests that the still-cooling crystalline carapace of the caldera magma chamber could be encountered in the next phase of drilling to 13780 ft. When considered with geophysical and downhole measurements, the Long Valley Exploratory Well is expected to provide an improved three-dimensional view of the caldera and its hydrothermal system.

Coming full circle on the session, Sandia personnel concluded with their presentation of "A Model for Large-Scale Thermal Convection in the Long Valley Geothermal Region." Utilization of the model resulted in the inference that, during the early stages of drilling, the vertical temperature distribution may not be a reliable indicator of the presence or absence of the relatively shallow magma body which has been predicted to underlie the geothermal region.

It would seem, in summary, that the planning for the Long Valley Exploratory Well has resulted, already, in obtaining data which furthers the theoretical studies of both generalized and specific caldera systems, and support not only the study of calderas and magma bodies, but also support our ability to predict the existence and location of such resources with increasing accuracy.
Abstract:

Phase II of the Long Valley Exploratory Well was completed to a depth of 7588 feet in November 1991. The drilling comprised two sub-phases: (1) drilling 17-1/2 inch hole from the Phase I casing shoe at 2558 feet to a depth of 7130 feet, plugging back to 6826 feet, and setting 13-3/8 inch casing at 6825 feet, all during August-September 1991; and (2) returning in November to drill a 3.85-inch core hole deviated out of the previous wellbore at 6808 feet and extending to 7588 feet. Ultimate depth of the well is planned to be 20,000 feet, or at a bottomhole temperature of 500°C, whichever comes first.

Total cost of this drilling phase was approximately $2.3 million, and funding was shared about equally between the California Energy Commission and the Department of Energy. Phase II scientific work will commence in July 1992 and will be supported by DOE Office of Basic Energy Sciences, DOE Geothermal Division, and other funding sources.

Drilling Operations:

The first task, which went relatively smoothly, in Phase II drilling was to fish a string of core rod stuck in the core hole since Phase I. Approximately 230 feet of the fish came out in one piece, and the remaining 10 feet was milled up and pulled out with magnets. Rotary drilling then continued in the same Bishop Tuff entered at 2040 feet during Phase I. This formation, with some rhyolite intrusions, extended to 5900 feet, and progress in it was excellent, with more than 300 feet drilled on some days.

At 5900 feet, the borehole intersected the top of a highly mixed breccia. This rock includes fragments of both its neighbors: the Bishop Tuff above it and the Mount Morrison roof pendant below it. Although a 30-foot spot core was taken in this formation, the mechanism of the breccia's origin is still not clear. This is a significant stratum, extending from 5900 to 6645 feet. It is also a considerably harder rock than the Bishop Tuff; rate of penetration dropped and hole deviation increased in this interval.

True "basement" rock starts at 6645 feet; this is the metamorphic rock (hornfels) of the Mount Morrison roof pendant, so named because it outcrops near Mount Morrison north-west of the drill site. This unit was originally sedimentary rock, but was metamorphosed by the heat from a large granitic intrusion approximately 90 million years ago. It is hard and abrasive, with severe bit wear and rates of penetration frequently under 10 feet per hour. Hole deviation also increased in this interval, reaching almost 5° from vertical at a depth of 7130 feet. Deviation this large would present a problem at the beginning of Phase III drilling, but directional re-drilling at the bottom of this hole would have been very expensive. To avoid both of these scenarios, the well was plugged back to 6825 feet, where deviation was under 2-1/2°.

Before casing was set at this depth, 26 sidewall cores were taken in the interval between 3000 and 6700 feet, and the open hole was logged with conventional wireline tools (oriented caliper, gamma ray, sonic, dual induction) and a borehole televiwer. Following casing, preparations were made for approximately 700 feet of continuous wireline coring below the casing shoe. A 6-1/8 inch rathole was drilled approximately 50 feet below the shoe, and a string of Ocean Drilling Program drill pipe with an orienting wedge at the bottom was run into the hole and hung there with the wedge in the rathole. The drill pipe/wedge assembly guides the coring string out the side of the plugged-back wellbore and also forms a relatively small annulus around the core rods to reduce vibration and improve cuttings transport.

After a hiatus of about a month, a small coring rig was mobilized and placed on the floor of the big drill rig in such a position that it could run the core string through the string of hanging drill pipe. (This is the same coring technique used at the end of Phase I.) The core rig was used to rotate the core rods and provide fluid circulation through the core string, while the big rig provided hoisting capability for tripping the core string, as well as electrical power to operate both rigs. The core hole entered the formation from the wellbore at 6686 feet.
and reached 7588 feet. All the cored interval was in the same rock (hornfels) as the lower part of the 17-1/2 inch hole. Coring was fairly slow (average rate-of-penetration about 3 feet/hour), but obtained more than 99 percent core recovery. Several temperature logs have been done in the core hole since the completion of coring; bottomhole temperature has stabilized at approximately 104°C.

The information available from this well now includes: drilling contractor’s daily reports; Sandia daily reports; mudlogger’s daily reports; suite of open-hole wireline logs; 30’ of spot core from 6030’ depth; 26 side-wall cores between 3000’ and 6700’; approximately 700’ continuous core between 6868’ and 7588’; hole trajectory surveys; records of all drilling fluids and additives; and repeated temperature logs in the well since completion of the coring.

Proposed Scientific Work:

The well is available for scientific investigation and still has the drill pipe hanging in the wellbore for access to the core hole. Several experiments have been proposed for the summer of 1992, including hydrofracture, fluid sampling, injection/permeability tests, gravity measurements, wireline logs in the core hole, vertical seismic profiling in the cased hole, and, finally, a passive seismic monitor fixed semi-permanently in place. If the proposed program is completely funded, some of the experiments will require pulling the drill string out of the hole; in this event, further access to the core hole will be lost.
GEOLOGIC RESULTS FROM THE LONG VALLEY EXPLORATORY WELL

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ABSTRACT

As a deep well in the center of a major Quaternary caldera, the Long Valley Exploratory Well (LVEW) provides a new perspective on the relationship between hydrothermal circulation and a large crustal magma chamber. It also provides an important test of models for the subsurface structure of active continental calderas. Results will impact geothermal exploration, assessment, and management of the Long Valley resource and should be applicable to other igneous-related geothermal systems. Our task is to use the cuttings and core from LVEW to interpret the evolution of the central caldera region, with emphasis on evidence of current hydrothermal conditions and circulation.

LVEW has reached a depth of 2313 m, passing through post-caldera extrusives and the intracaldera Bishop Tuff to bottom in the Mt. Morrison roof pendant of the Sierran basement. The base of the section of Quaternary volcanic rocks related to Long Valley Caldera was encountered at 1800 m, of which 1178 m is Bishop Tuff. The lithologies sampled generally support the classic view of large intercontinental calderas as piston-cylinder-like structures. In this model, the roof of the huge magma chamber, like an ill-fitting piston, broke and sank 2 km along a ring fracture system that simultaneously and explosively leaked magma as Bishop Tuff. Results from LVEW, which support this model, are the presence of intact basement at depth at the center of the caldera, the presence of a thick Bishop Tuff section, and textural evidence that the tuff encountered is not near-vent despite its central caldera location. An unexpected observation was the presence of rhyolite intrusions within the tuff with a cumulative apparent thickness in excess of 300 m. Chemical analyses indicate that these are high-silica, high-barium rhyolites. Preliminary ⁴⁰Ar/³⁹Ar analyses determined an age of 626 ± 38 ka (this paper): These observations would indicate that the intrusions belong to the early post-collapse episode of volcanism and are contemporaneous with resurgence of the caldera floor. They are extensive sills rather than dikes, a possibility being investigated through relogging of core from neighboring wells, they were responsible for resurgence. A ⁴⁰Ar/³⁹Ar age of 769 ± 14 ka from Bishop Tuff at 820 m depth conforms with tuff ages from outside the caldera and indicates an absence of shallow hydrothermal activity (>300°C) persisting after emplacement. Work is proceeding on investigating hydrothermal alteration deeper in the well. This alteration includes sulfide+quartz fracture fillings, calcite+quartz replacement of feldspars, and disseminated pyrite in both the tuff and basement. Electron microprobe analysis of phases are being conducted to determine initial magmatic and subsequent hydrothermal conditions.

BACKGROUND

The Long Valley Caldera is one of three large-volume silicic continental eruptive centers in North America of Quaternary age. The others are the Yellowstone volcanic field and the Valles Caldera in north-central New Mexico. Of these systems, only Long Valley has exhibited volcanic activity into Holocene time.

The 17 x 32 km east-west elongate Long Valley Caldera formed between 760 and 780 ka ² astride contemporaneously active frontal faults of the eastern Sierran Nevada. (Figure 1).
temperature unit flowed to the south and east and has a calculated eruptive temperature of 720 to 737°C. The later high-temperature unit, with a calculated eruptive temperature range of 737 to 790°C, capped the southern flows and inundated an area to the north. This increase in eruptive temperature and the associated variation in chemical composition and phenocryst mineralogy are believed to reflect a pre-eruptive vertical zonation in a high-level rhyolitic magma chamber. Evacuation of the magma chamber during the eruption allowed collapse of the roof of an estimated 2-3 km.6 Up to 500 km³ of the pyroclastic material ponded within the subsiding caldron to an estimated average thickness of 1500 m.7

From 730 to 600 ka intrusive and volcanic activity within the caldera formed a resurgent dome and covered the floor of the caldera with rhyolitic lava flows, ash, and tuff. During the interval from 500 to 100 ka, phenocryst-rich rhyolites erupted around the dome blanketing areas to the north, southeast, and west. Later activity along a north-trending fissure system approximately 8 km west of the present day resurgent dome spilled basaltic lava to an accumulated thickness of 250 m. This lava ponded in the south and west moat.6 Rhyolitic volcanic activity in the area of the Long Valley Caldera resumed about 6 ka and culminated 0.55 ka with the emplacement of the Inyo chain rhyolite domes and craters in the west most of the caldera.8 The central and western caldera area and south of the caldera continues to display seismic activity that would indicate the movement of a shallow magmatic body. Since the early 1980’s the resurgent dome has had total measurable inflation exceeding 0.5 m and extension measured across the dome of up to 3-5 microstrain/year.9 This has led to the conclusion by Rundle and Hill10 and others that 0.15 to 0.2 km³ of magma has been injected beneath the resurgent dome at a depth of 4-6 km.

The caldera has an active hydrothermal system with hot springs and fumaroles located in the vicinity of the resurgent dome. Although the caldera has been the center of several years of commercial hydrothermal exploration, the heat source for the present-day hydrothermal system has not been delineated. Temperature logs taken in wells drilled in the caldera have either shown a temperature inversion at the base of the intracaldera Bishop Tuff or have not displayed the geothermal gradient of 100°C/km expected from thermal modeling of the caldera.11 Recent work analyzing the isotopic geochemistry of the identified paleo- and present-day hot spring deposits has shown that the caldera has had varying intensities of hydrothermal activity since its formation. There have been two main cycles of thermal activity. The first one peaked about 300 ka and another extends from 60 ka to the present. Geothermometer-temperature estimates for the source reservoir for the present day system range from 214 to 248°C.12

A much better understanding of the hydrothermal and magmatic systems operating in the Long Valley Caldera can be derived from sampling the geology of the still-active resurgent dome. This is the opportunity drilling a deep well at a central position on the resurgent dome provides. It is at this location geological and geophysical evidence indicate the main heat source for the Long Valley magma/hydrothermal system. The LVEW Drilling Program is revealing the current conditions within the caldera and volcanic and hydrothermal history of the system. A detailed petrographic, geologic, and geochemical investigation has been designed to analyze core and cuttings retrieved from the well. Analysis of these samples and interpretation of the geologic observations are of critical importance to accomplishing the scientific objectives of the drilling plan. The objectives of this study are to elucidate the mechanics of caldera collapse and resurgence, define the character of the hydrothermal systems, identify recent intrusions and their extrusive equivalents, define and describe the condition of the underlying basement rocks, and provide better constraints on the magma chamber geometry and evolution.13

Drilling began with Phase I of the LVEW in the summer of 1989. The hole reached a depth of 839.4 m with recovery of 56.7 m of continuous core at the bottom of the hole. Drilling resumed in 1991 with Phase II. The hole was successfully deepened to 2313 m. Phases III and IV are planned to further deepen the hole toward contacting the crystalline carapace of the magma chamber.

CORE AND SAMPLE RECOVERY

During the rotary drilling of each phase of the LVEW, drill cuttings were collected at regular intervals, catalogued and bagged for later analysis. At the end of each phase the well was diamond cored to obtain continuous core for petrologic and geochemical analysis as well as determination of thermal conductivity, density, and rock strength.14 The core was field logged and shipped to the DOE Core Repository, Grand Junction, CO. In addition, during the rotary drilling of Phase II, a 10 m spot core was collected over the interval 1838 to 1848 m. This sample core has been invaluable for identifying an important breccia unit and revealing the need for caution in interpreting the cuttings. The exercise in recovering the spot core also provided a test of the feasibility of routine spot core collection during the critical deeper drilling of Phases III and IV. At the termination of the rotary drilling and prior to commencing with diamond coring, a suite of sidewall cores was collected. The selection of the depth intervals for core collection was based on field logged locations of hydrothermal alteration and hole condition. The recovered cores have been an valuable addition to the sample inventory of cuttings from the rotary drilled interval. Extrusive samples from the pre- and post-intracaldera fill, the outflow sheets of the Bishop Tuff, and the pre-existing basement rock have also been collected for analysis. Further field mapping and sample collection to complete the correlative extra-caldera sample suites are planned for the summer of 1992.

GEOLOGIC AND PETROGRAPHIC WORK TO DATE

Study of petrographic thin sections and scanning electron microscopy of samples prepared from the recovered cuttings and core of the 2313 m deep well reveal three major stratigraphic units with several thinner interleaved units. These major units are the post-caldera resurgent dome rhyolites named the Early Rhyolite (Qer); the caldera-forming pyroclastic unit, the Bishop Tuff (Qbt); and the pre-caldera basement rock, the Mt. Morrison roof pendant metasediments (Pzms). The Qbt contains multiple intrusive units that have been identified as intrusive equivalents of the Qer.1 (Figures 2 and 3).

The top 622 m of the well consists of rhyolite lava flows and tephas of the Qer. The tephra units make up more than 80% of the total interval. These tephas are glassy, aphyric, and generally perlitic, pumiceous, and lithic-poor.14 The lavas are flow-banded, aphyric rhyolite with margins of perlitic obsidian. The obsidian displays flow-
banded zones of microlitic glass and zones of dense, perlitic obsidian. Overall, the condition of these volcanic rocks is not exceptionally weathered, altered, or oxidized. This sub-unit is identified as Qer15 on the basis of the proximity to the extrusive domes of this unit and similar petrology. Qer1 is the earliest of the post-caldera eruptive volcanic units with K-Ar ages of $675 \pm 16$ ka.$^3$ Outcrops of Qer1 appear on the north end of the resurgent dome (Lookout Mtn) and along the north-south trending graben at the south end of the dome including the LVEW drill site. Comparison to the Qer sections logged from pre-existing wells within an 8 km radius of LVEW indicate similarities in the petrology of the rhyolite, but these units are not easily correlated stratigraphically. The Qer in the wells logged along the east and west wall of the resurgent dome graben show considerably more hydrothermal alteration than that encountered at LVEW. The section in the well does not appear to include the lithic-rich lower tephra section nor the basal ash fall found in the surrounding wells.

Figure 3. LVEW Stratigraphy

Qbt underlies the Qer flows and tephras. The depth of the Qer/Qbt contact is variable across the caldera. At the LVEW location the basement elevation of the contact is about 600 m deeper than in the western and southern moat holes (44-16 and M-1, respectively) and at least 200 m shallower than in the eastern moat hole (66-29) which did not reach the base of the Qbt. Also the Qbt unit is 4.7 times as thick as in holes in the western moat, 1.2 times as thick as holes in the southern moat, and <0.8 times as thick as holes in the eastern moat.$^{16}$ It is crystal- and lithic-rich throughout its 1178 m thickness at this location. The phenocrysts consist of dipyramidal quartz crystals up to 4 mm in length that are
characteristic of the Qbt, euhedral-to-anhedral sanidine crystals which vary in freshness and size from 1-3 mm, euhedral plagioclase crystals, and small, dark-reddish brown pseudohexagonal biotite crystals. The biotite phenocrysts decrease with depth until they occur only rarely after 1340 m. The densely welded matrix of the tuff is strongly overprinted by devitrification recrystallization. Axiolitic and spherulitic recrystallization textures nucleating from glass shards are themselves overprinted by coarser quartz recrystallization. This texture is likely associated with late vapor phase or supergene hydrothermal activity. Igneous biotites show limited alteration to chlorite, muscovite, and pyrite. The poorly sorted lithic fragments are angular-to-subangular, ranging in size from less than 1 mm to 10 cm. The abundance of these fragments increases with depth. The primary rock type represented in the lithics is the pelitic hornfels of the basement rock sequence. Metaquartzite/metatuff and metavolcanics are also found, and rarely granodiorite from the Sierra Nevada batholith. This suite of rock types matches the lithics identified in the southern lobe of the Qbt outflow sheet. The vent(s) for this lobe has been suggested to lie the south of the present day resurgent dome along the ring fractures of the caldera. Although the overall suite of lithics in the Qbt of LVEW and the southern outflow sheet is similar, the percentage of granodiorite lithics in Qbt is quite small. There is a possibility that the source vent is inboard of the vent for the outflow sheet.

Secondary mineralization has deposited silicia, sulfides, and calcite along fractures and increasing calcite mineralization in the matrix as the well deepens. Euhedral pyrite and rare chalcopyrite also appear as disseminated crystals throughout the matrix of the tuff. In addition, the interval of 1676 to 1737 m displays a marked increase in chlorite mineralization. The timing of the deposition of the secondary mineral phases may be related to either the cycles of hydrothermal activity within the caldera or early post-emplacement mineralization. Shearer et al.17 and Connolly et al.18 have investigated the relationship of the sulfides in the veins and fractures to the disseminated crystals. The pyrite and chalcopyrite show limited textural zoning, most likely representing a single hydrothermal episode. This is substantiated by sulfur isotope measurements across pyrite crystals in the Bishop Tuff.

Finally, elemental analysis of the tuff indicates depletion of alkali and alkaline earths and enrichment of S, Fe, Zn, As, and Cu. The former reflects the devitrification recrystallization and the latter the hydrothermal alteration.1

In order to constrain the timing and magnitude of the thermal events that have affected the texture of the intracaldera tuff, 40Ar/39Ar ages were determined. Two relatively unaltered sanidine separates from a Qbt section at 820 m depth were selected for 40Ar/39Ar dating by the bulk-sample step-heating technique. The plateau ages from the sanidines average 769 ± 14 ka. This is the same as sanidine ages of 762 ± 12 ka determined from analysis of samples from surface exposures of the tuff.2 As the sanidines in the core do not reflect a reset age, it is unlikely that any hydrothermal activity in the excess of 300° C occurred in the upper 1 km of the central caldera since emplacement. It appears that the inferred11 current condition of deep fluid circulation suppressing high vertical magmatic heat flow has existed since caldera formation.

The Qbt intersected by LVEW is invaded by multiple rhyolitic dikes or sills.14 These intrusions vary from over 100 m to less than 10 m in thickness and comprise 28% or about 300 m of the total intracaldera tuff section at this location. The intrusions are aphyric and aphaniitic, although a coarse mosaic quartz phase overprints the primary texture much the same as in the tuff. This mosaic crystallization tends to occur in lenticular zones throughout the microcrystalline matrix and most likely represents secondary mineral deposition in vesicles. Generally, the edge of the vesicle is quartz and the center consists of massive calcite suggesting a progressive mineralization as temperature decreased. Calcite also occurs as pseudomorphs after feldspar crystals in intrusions at depths of 926 and 1222 m. However, few distinct phenocrysts have been identified in the intrusive sequences. This is surprising as the extrusive Qer, although phenocryst-poor in relation to the Qbt, does contain up to 5% phenocrysts of plagioclase, magnetite-ilmenite, hypersthene, and biotite.10 The intrusives display some aspects of hydrothermal alteration such as silica-pyrite vein fill and hematite-rutile replacement of primary magnetites and ilmenites. Whole rock major and trace element compositional analytic samples from the intrusive sequence at 783 to 810 m match analyses from the extrusive obsidian from the Qer. Both are high silica (76.0 and 75.4 wt. % respectively) and contain abundant Ba (up to 1254 ppm). 40Ar/39Ar dating of whole rock samples of the intrusion located at 802 m depth yield a date of 626 ± 38 ka. This age is consistent with K-Ar ages derived from samples of extrusive Qer. The unit that most nearly matches the intrusive age is the Qer3. This unit outcrops on the resurgent dome 5 km north of LVEW.3,15

Because the intrusives make up such a large percentage of the total intracaldera tuff thickness it is possible that they may account for the structural resurgence on the dome. This hypothesis would be supported if the intrusions were identified in surrounding wells located on the dome. Examination of cores and samples from these wells to date has not located additional Qer intrusions into intracaldera tuff. This line on study will continue until all available core and cuttings form previous wells have been logged.

The Qbt directly overlies a well-indurated epilastic breccia unit of 90 m thickness and of undetermined age and origin. The breccia is poorly sorted and graded and consists of angular clasts of Pzms and unidentified volcanic rocks. At several intervals within the unit the breccia has been disturbed. The matrix is very fine grained clastic material and interstitial calcite. The matrix also contains traces of anhedral, fresh volcanic quartz crystals. A similar, thinner unit has been identified in core from well 68-28, located 4.2 km to the south south-east of LVEW. Here the unit sharply contacts the basal ashfall unit of the Qer at a depth of 493 m and the top of the Qbt at 495 m. It is likely these types of breccia were deposited rapidly during the onslaught of volcanic and associated tectonic activity and deposited in water. If the apparent similarity of the breccias above and below the Qbt holds up under close scrutiny, the breccias are probably related to caldera collapse.

Beneath the breccia is a 135.6 m section of epidotized altered rock. The protolith is not readily identified but appears to be volcanic on the basis of petrographic textural analysis. It likely represents Mesozoic metavolcanic rocks of the roof pendant. Neither the breccia nor the altered zone in the well is intruded by post-caldera volcanics.
At 2025.4 m, the metasedimentary basement rock, Pzms, is encountered. The primary rock type is a very fine grained, color banded pelitic hornfels with abundant graphite. This unit also contains euhedral, disseminated pyrite crystals. Several layers up to 15 m thick of metachert and marble are interleaved within the hornfels at irregular intervals. The basement rock has undergone several cycles of fracturing and deformation. The color banding of the pelitic rock allows fracturing and offset to be mapped and correlated. The fracturing can be grouped into 4 generations with associated fracture dip and fill mineralogy. In sequence of oldest to youngest, the generations of fractures are: 1) a plane of weakness associated with the primary banding of the rock, measured at 50° to the vertical plane of the core, 2) pyrite filled fractures at 48° to the vertical plane of the core and frequently offsetting the primary banding, 3) fractures measured at 10° off the vertical plane of the core and filled with massive-to-crystalline calcite and quartz, and 4) calcite, quartz, and pyrite filled fractures at 30° to vertical plane of the core and frequently offsetting the older fractures by as much as 2 cm. The chemical, isotopic, and petrographic characteristics of the Fe-sulfides in this rock are being investigated. It is hoped a chemical pattern will be identified that will aid in distinguishing the effects of caldera formation and post-caldera hydrothermal activity. Phase II drilling ceased at a depth of 2313 m still within the Pzms unit.

SUMMARY

Phases I and II of the LVEW drilling project have provided important new data and samples to a depth of 2.3 km in the resurgent dome of the Long Valley caldera. Work to date has centered on defining the petrology of the volcanic and hydrothermal systems as well as constraining the geochemistry of these systems.

The stratigraphy of the well passes through the post-caldera rhyolites, identified as Qer1, contacting the caldera-forming Qbt at 622 m. The basement rock consists of Mt. Morrison roof pendant metasediments. This stratigraphic sequence in the center of the caldera supports the model of piston-cylinder collapse. Encountering the top of the Qbt 200 m deeper than anticipated and the continual thickening of the intracaldera tuff from west to east argue strongly for syn-tectonic activity along the prevailing Sierran fault system such as the Laurel-Convict Fault or the Hilton Creek Fault.

The intracaldera Qbt is densely welded and devitrified. Secondary mineralization occurs as Fe-sulfide, quartz, and calcite fracture fill, and alteration of Fe-Ti oxides. There are no vent or near-vent breccia units. Preliminary petrography of the Qbt failed to identify any pyroxenes in the tuff.18 The absence of pyroxene has been interpreted as representative of the earlier, lower temperature unit of the outflow sheet.5 This would suggest that only the lower unit of the pyroclastic tuff is represented at this near central location within the caldera. However, the post-eruptive mixing dynamics of intracaldera tuffs are not well constrained and more detailed petrology of the Qbt will be necessary to address this problem.

The Mt. Morrison roof pendant basement rocks were intersected at 2025 m, with the 225 m interval between the base of the Qbt and the top of the basement consisting of as yet unidentified breccia and altered metavolcanics.

Despite the relatively low temperatures measured at the bottom of the in the well (1030° C)11, the petrology indicates mass transport has occurred in the past. Nowhere is there evidence of lateral zones of transport but more a overall imprint of hydrothermal activity. In addition, the age determinations of the Qbt would indicate no high temperature (>300° C) activity has occurred in the top 1 km of the resurgent dome since emplacement.

The picture of the eruption, collapse, resurgence and alteration will continue to develop as work progresses on this important probe into the center of a major caldera. Analogy to other caldera systems suggests that the still-cooling crystalline carapace of the caldera magma chamber could be encountered in the next phase of drilling to 4.2 km. In concert with geophysical observations and downhole measurements, this project will provide an improved three-dimensional view of Long Valley Caldera and its contained hydrothermal system.

REFERENCES


A MODEL FOR LARGE-SCALE THERMAL CONVECTION IN THE LONG VALLEY GEOTHERMAL REGION

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Albuquerque, New Mexico

ABSTRACT

A numerical simulation is presented for a simplified model of the Long Valley geothermal system in order to elucidate the nature of the large-scale thermal structure within the system and to assess implications for the drilling program currently underway in the region. The two-dimensional model consists of three horizontal layers, the upper two of which are porous and saturated with a single phase fluid. The system is limited in horizontal extent and heated uniformly from below. An associated planar, natural convective flow is thus produced. The results of the simulation indicate the possibility of wide variations in vertical temperature profiles for the model system, depending on the locations of measurements relative to the convective cells within the layered medium. Thus it can be inferred that, during the early stages of drilling, the vertical temperature distribution may not be a reliable indicator of the presence or absence of the relatively shallow magma body which has been predicted to underlie the geothermal region.

NOMENCLATURE

- $A_L$: Aspect ratio of layered system
- $g$: Acceleration of gravity
- $H$: Thickness of layered system
- $H_A, H_B, H_C$: Thicknesses of layers A, B, and C, respectively
- $k$: Permeability
- $k_A, k_B$: Permeabilities of layers A and B, respectively
- $k_e$: Effective permeability of combined porous layers
- $k_r$: Reference permeability
- $L$: Width of layered system
- $Nu_e$: Effective Nusselt number for combined porous layers
- $N_u$: Nusselt number
- $P$: Pressure
- $P_{\text{max}}$: Maximum hydrostatic pressure
- $P_o$: Surface pressure
- $p$: Dimensionless pressure
- $q/a$: Heat flux
- $Ra_c$: Critical Rayleigh number ($= 4 \pi^2$)
- $Ra_e$: Effective Rayleigh number for combined porous layers
- $Ra_o$: Reference Rayleigh number
- $T$: Temperature
- $T_o$: Temperature of upper surface of layered system
- $T_m$: Temperature of magma
- $T_{sat}$: Saturation temperature for water
- $U, V$: Velocity components in X and Y coordinate directions, respectively
- $u, v$: Dimensionless velocity components
- $X, Y$: Horizontal and vertical coordinates, respectively
- $x, y$: Dimensionless coordinates
- $\alpha_e$: Effective, volume averaged, thermal diffusivity
- $\beta$: Coefficient of volumetric thermal expansion
- $\Delta T$: Overall temperature difference
- $\Delta T_C$: Temperature difference across conduction layer
- $\Delta T_e$: Effective temperature difference across combined porous layers
- $\theta$: Dimensionless temperature
- $\lambda_e$: Effective, volume averaged, thermal conductivity
- $\nu$: Kinematic viscosity
- $\rho$: Density of fluid
- $\rho_o$: Reference density

INTRODUCTION

The purpose of this study is to provide estimates of general features of the large-scale thermal structure within the Long Valley caldera geothermal region. The study is done in support of the drilling program which has been initiated within the Long Valley caldera near Mammoth Lakes, California, where seismological evidence suggests the presence of a relatively shallow magma body. The analysis described in this paper is, in large part, excerpted from a more detailed study reported previously by Hickox and Chu (1990).

Models of the geothermal region are useful aids to the interpretation of field data to be acquired during the drilling operation. For example, it would be particularly useful to be able to infer the presence of a magma body from the measured geothermal gradient. We have performed a numerical simulation for a model system in order to elucidate the nature of the large-scale thermal structure within the geothermal system of the Long Valley caldera. The results of this simulation include temperature and velocity distributions and overall heat transfer rates for a range of parameters typical of those anticipated in the physical system. The numerical results are shown to hold implications for the interpretation of field measurements to be made during the drilling operation.

MODEL OF THE GEOTHERMAL SYSTEM

Physical Model

A current estimate of the structure of the geothermal region within the Long Valley caldera is depicted in the cross-
sectional sketch in Figure 1, which was developed from seismological data acquired in the area (Rundle, et al., 1985). Based on Figure 1, it is hypothesized that, for our present purpose, the simplest representation of the geothermal region consists of three distinct horizontal layers overlying a magma chamber. The layered system is illustrated in Figure 2. The upper layer (A) is composed of postcaldera fill and Bishop tuff, the central layer (B) is composed of Sierran basement material, and the lower layer (C) is crystallized magma, where heat transfer occurs by conduction. Layers A and B are assumed to be permeable and saturated with liquid water. The assumption of saturation with a single-phase fluid is rather restrictive and will be verified after the numerical results have been presented. The associated permeabilities of the layers are denoted by $k_A$ and $k_B$. It is assumed that the thicknesses $H_A$, $H_B$, and $H_C$ of the various layers are such as to place the top of the magma chamber at a depth $H$ of 6 km. The effective width $L$ of the layered system is approximately 18 km, yielding an overall aspect ratio $A_L = L/H = 3$. The caldera is approximately elliptical in planform, but for our initial analysis, we have assumed that the region can be represented as a two-dimensional, planar, layered system. Following the assumption of Sorey, Lewis, and Olmsted (1978), a temperature difference of 790 °C is assumed to occur across the three-layer system, with the upper and lower boundaries maintained at the uniform temperatures $T_0 = 10 °C$ and $T_m = 800 °C$, respectively. A summary of the assumed values for the relevant physical properties and dimensions is given in Table 1, where we have taken the fluid properties to be those of liquid water and have neglected any temperature dependence.

**Mathematical Representation**

In this section, we describe briefly the mathematical model which forms the basis for the numerical simulation. Within an individual porous layer, the nondimensional equations which represent conservation of mass, momentum, and energy are given, respectively, by

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0,$$

$$\left(\frac{k_v}{k}\right) u = -\frac{\partial p}{\partial x}, \quad \left(\frac{k_v}{k}\right) v = -\frac{\partial p}{\partial y} + \theta,$$

and

$$Ra_c \left( \frac{\partial \theta}{\partial x} + \frac{\partial \theta}{\partial y} \right) = \frac{\partial^2 \theta}{\partial x^2} + \frac{\partial^2 \theta}{\partial y^2},$$

where all quantities in these and subsequent equations are defined in the Nomenclature. The origin of coordinates is taken at the lower left hand corner of the layered system and gravity acts in the negative $y$-direction. In writing equations (1)–(3), we have assumed steady, incompressible flow, used Darcy's law as the basis of the momentum equation, and invoked the Boussinesq approximation whereby density changes are accommodated only in the body force. Density is assumed to be linearly related to the temperature by

$$\frac{\rho}{\rho_0} = 1 - \beta \Delta T \theta,$$

an expression which we have incorporated in the development of equation (2). Nondimensional quantities are related to dimensional quantities by the following relations:

$$(x, y) = (X, Y)/H, \quad (u, v) = (U, V)/(g\beta \Delta T k_c/\nu), \quad \rho = (P + \rho_0 g Y)/(\rho_0 g \beta \Delta T H), \quad \theta = (T - T_0)/\Delta T,$$

where $\Delta T = T_m - T_0$ and the Rayleigh number $Ra_c$ is given by

$$Ra_c = \frac{g \beta \Delta T k_c H}{\nu \sigma_c}.$$

For all variables except the temperature, we have used upper case letters to represent dimensional variables and the lower case for nondimensional variables. We have used $\theta$ for the nondimensional temperature. The reference Rayleigh number $Ra_c$ is based on the total thickness $H$ of the layered system and a reference permeability $k_c$, which we have taken equal to 1 darcys ($10^{-12}$ m$^2$), corresponding to the largest permeability anticipated for layer A. Within the lowest layer (C), heat transfer occurs by thermal conduction only and $\theta$ is determined from the solution of Laplace's equation which is obtained when the left hand side of equation (3) is set equal to zero.

All boundaries of the layered system depicted in Figure 2 are taken to be impermeable. The lower and upper horizontal boundaries are assumed to be maintained at uniform nondimensional temperatures $\theta(x,0) = 1$ and $\theta(x,1) = 0$, respectively. The two vertical boundaries are assumed to be perfectly insulated. Continuity of normal velocities and thermal flux is maintained along interfaces between layers. Taking $\Delta T = 790 °C, g = 9.8 m/s^2$, and using the parameters given in Table 1, a numerical value of 9290.4 is obtained for the reference Rayleigh number $Ra_c$, based on the total layer thickness $H$, overall temperature difference $\Delta T$, and reference permeability of the upper layer $k_c$. 

**Figure 1.** Cross-sectional schematic of the geological features of the Long Valley caldera, after Rundle, et al., (1985).
Basic notions regarding the structure of the flow field can be inferred from the work of McKibbin and O'Sullivan such that an integral number of cells will form within the given layered system of aspect ratio. Cellular convection, we have elected to analyze the convection times associated with obtaining converged solutions to multi-cases consistent in Table 2 for analysis. These cases cover the extremes of the anticipated parameter variations. So long as the effective Rayleigh number for the layered system is greater than some critical value, a multi-cellular convection pattern will form. Owing to the large computing times associated with obtaining converged solutions to multi-cellular convection, we have elected to analyze the convection by isolating individual convection cells with aspect ratios chosen such that an integral number of cells will form within the given layered system of aspect ratio 3, and which will also maximize the rate of heat transfer across the layered system. This procedure is described in the following subsection.

### Aspects Ratio of Convection Cells

Basic notions regarding the structure of the flow field can be inferred from the work of McKibbin and O'Sullivan (1980, 1981) and Masuoka, et al. (1979) who considered the stability of flow and heat transfer in multiple layered porous media, of infinite horizontal extent, heated from below. Of particular interest here are their considerations of systems consisting of two horizontal layers heated from below with uniform temperatures maintained on the lower and upper boundaries. When the Rayleigh number is defined in terms of the overall temperature difference, total combined layer thickness, and the permeability of the lower layer, their results indicate that, for the range of parameters in Table 1, the critical Rayleigh number \( Ra_c \) is very near \( 4 \pi^2 \); the value typically associated with a single layer system. Our geometry includes a lower conduction layer, so the lower boundary condition imposed in the cited references is not strictly enforced. Furthermore, the aspect ratio of our geometry is restricted to a value of 3. Nevertheless, we assume that the stability criterion \( Ra_c = 4 \pi^2 \) is approximately true provided that the temperature difference is taken as that which actually occurs over the two porous layers, excluding the conduction layer. It is thus likely that all of the cases in Table 2 result in effective Rayleigh numbers which exceed the minimum critical value for convection to occur. Based on the results of McKibbin and O'Sullivan and Masuoka, et al., we anticipate the formation of a multi-cellular convection pattern. For a single porous layer, the aspect ratio of a single cell is approximately unity for a layer of infinite extent. For a two layer system of large permeability contrast between the layers, the convection is concentrated in the layer of higher permeability and has a width which is approximately equal to the thickness of the more permeable layer. When the permeability contrast is not relatively large, the convection pattern tends toward that of a single layer. When the layered system is limited in horizontal extent, we anticipate behavior similar to that for an unbounded system but with the individual cell aspect ratio taking on only those values which result in the formation of an integral number of cells over the horizontal extent of the layers.

To analyze the convection pattern, we focus on a single cell and consider only those specific aspect ratios which result in the formation of an integral number of cells. Based on the studies of Combarnous and Bories (1975), we assume that the physically realizable cell aspect ratio is the one that maximizes the overall heat transfer rate. Results of this selection process are discussed in the following section.

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### Table 1: Numerical values for physical properties and dimensions.

<table>
<thead>
<tr>
<th>Layer</th>
<th>( H_{A,B,C} ) (km)</th>
<th>( k ) (darcy)</th>
<th>( \lambda ) (( \frac{W}{mK} ))</th>
<th>( \rho_o ) (( \frac{kg}{m^3} ))</th>
<th>( \alpha_o ) (( \frac{m^2}{s} ))</th>
<th>( \nu ) (( \frac{m^3}{s} ))</th>
<th>( \beta )</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>2 ( \times ) 10^{-1} - 1</td>
<td>2 ( \times ) 10^{3}</td>
<td>5 \times 10^{7}</td>
<td>10^{-6}</td>
<td>10^{-4}</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>2 - 3.5 ( \times ) 10^{-3} - 10^{-2}</td>
<td>2 ( \times ) 10^{3}</td>
<td>5 \times 10^{7}</td>
<td>10^{-6}</td>
<td>10^{-4}</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>0.5 - 2</td>
<td>2</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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### Table 2: Cases chosen for numerical simulation.

<table>
<thead>
<tr>
<th>Case Number</th>
<th>( L/H )</th>
<th>( Ra_c )</th>
<th>( H_{a,H} )</th>
<th>( H_{b,H} )</th>
<th>( H_{c,H} )</th>
<th>( k_{a}/k_o )</th>
<th>( k_{b}/k_o )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3</td>
<td>9290.4</td>
<td>1/3</td>
<td>1/3</td>
<td>1/3</td>
<td>1.0</td>
<td>0.010</td>
</tr>
<tr>
<td>2</td>
<td>&quot;</td>
<td>&quot;</td>
<td>1/3</td>
<td>1/3</td>
<td>1/3</td>
<td>&quot;</td>
<td>&quot;</td>
</tr>
<tr>
<td>3</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>1/3</td>
<td>1/3</td>
<td>0.1</td>
<td>0.010</td>
</tr>
<tr>
<td>4</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>1/3</td>
<td>&quot;</td>
<td>&quot;</td>
</tr>
<tr>
<td>5</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>1/3</td>
<td>1/3</td>
<td>0.1</td>
<td>0.010</td>
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<td>&quot;</td>
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<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
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</tr>
</tbody>
</table>

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**Figure 2.** Three-layer, planar, representation of the Long Valley caldera used in the analysis.
NUMERICAL RESULTS

Nusselt Numbers and Aspect Ratios for Convection Cells

In order to apply the cell selection criteria described in the previous section, we calculated the Nusselt number $\text{Nu}$ for several cell aspect ratios, corresponding to integral numbers of cells in the layered system, for each of the eight cases chosen for investigation. The Nusselt number is defined as the ratio of the rate of heat transfer across the entire system divided by the rate at which heat is transferred by thermal conduction. Recalling that the overall aspect ratio of the system is denoted by $A_L$, the Nusselt number is then given by

$$Nu = \frac{1}{A_L} \int_0^{A_L} \left( \frac{\partial \theta}{\partial y} \right)_{y=0} \, dx,$$

where $A_L = 3$ for the geometry under consideration. The results of these calculations are summarized in Table 3.

Based on the results of the numerical simulations, the heat flux ranges from 8 to 17 $\text{HFU}$ ($1 \text{ HFU} = 10^{-6} \text{ cal/cm}^2s$). We note that Sorey, Lewis, and Olmsted (1978) estimated an average heat flux of $15 \text{ HFU}$ for the entire caldera, including the eastern portion which is not thought to overlie the magma chamber. Hence, our results are in essential agreement with the estimate of Sorey, et al. A true heat flux nearer the high end of the calculated range of values suggests that Cases 5 or 7 may be more representative of the actual, large-scale, thermal process.

<table>
<thead>
<tr>
<th>Case</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. Cells</td>
<td>5</td>
<td>9</td>
<td>5</td>
<td>8</td>
<td>6</td>
<td>9</td>
<td>5</td>
<td>8</td>
</tr>
<tr>
<td>Nusselt No.</td>
<td>1.45</td>
<td>1.37</td>
<td>1.48</td>
<td>1.22</td>
<td>2.55</td>
<td>1.37</td>
<td>2.68</td>
<td>1.22</td>
</tr>
</tbody>
</table>

Table 3. Number of cells and Nusselt number calculated for the eight cases identified in Table 2.

Typical Convection Patterns

As an illustration of the range of convection patterns encountered among the eight cases considered, we have included streamline and isotherm plots for Cases 2 and 7 in Figure 3. These two cases are representative of the extremes of the parameter variations given in Table 2. Case 2 involves layers of equal thickness with the largest permeability contrast between the permeable layers and illustrates the behavior anticipated when the convection cell is concentrated within the upper layer. This geometry results in nine convection cells. In the figure, the cell rotation is clockwise. In the multi-cellular pattern, which would exist in the complete system, adjacent cells would have opposite circulations, with the particular direction resulting from naturally occurring perturbations to the flow. The streamlines for Case 2 consist of ten streamlines spaced in nine equal increments between nondimensional stream function values of $1 \times 10^{-4}$ and $10 \times 10^{-4}$ and three additional stream function values of $1 \times 10^{-5}$, $1 \times 10^{-6}$, and $1 \times 10^{-7}$ included to show the relatively weak penetration of the flow into layer B. Isotherms are spaced in twenty equal increments between the maximum and minimum values for $\theta$ of 1 and 0, respectively. Case 7 involves a conduction layer of minimum thickness and the smallest contrast in permeabilities. This choice of parameters results in five convection cells. To illustrate the flow field, eight streamlines in equally spaced increments between values of $1 \times 10^{-4}$ and $8 \times 10^{-4}$ for the nondimensional stream function were chosen. Since the chosen values for the stream function correspond to some of those selected for Case 2, the relatively strong penetration of flow into layer B is evident. As for Case 2, the isotherms for Case 7 correspond to increments of 0.05 in the nondimensional temperature $\theta$. Upon comparing the temperature distributions for Cases 2 and 7, it is evident that thermal conduction is dominant in layer B for Case 2, while the effects of convection are significant in this layer in Case 7.

Temperature Profiles

Representative vertical temperature profiles for each of the eight cases considered are given in Figure 4. For each case, three temperature profiles were computed at the following locations: (1) along the boundary of the convection cell where
Figure 4. Vertical temperature profiles for Cases 1-8. Profiles are computed along vertical lines corresponding to (1) upward flow, (2) the center of the convective cell, and (3) downward flow.
the flow is upward, (2) through the center of circulation of the cell, and (3) along the boundary of the cell where the flow is downward.

Although the magnitudes of the effects vary, several common features are apparent among the eight cases. In regions of upward flow, the temperature profile exhibits a boundary layer behavior, with a relatively strong gradient, adjacent to the upper boundary. With increasing depth, a region of relatively constant temperature is encountered, followed by a region of steadily increasing temperature with an essentially constant gradient. In regions of downward flow, a thick layer involving only a small thermal gradient exists adjacent to the upper surface. This is followed by a region of steadily increasing temperature with a reasonably constant gradient. Profiles taken through the center of a cell exhibit an inflection as a result of the horizontal, reversing, flow encountered, and lie between the two profiles discussed previously. The inflection involves a region with a positive thermal gradient adjacent to the upper surface followed by a region with a negative gradient which is caused by the flow reversal. As the depth increases, a region with a positive thermal gradient is established. The temperature in this last region lies between those values associated with upward and downward flows.

In those cases with the largest contrast in permeabilities, convective effects are concentrated in the upper layer and the thermal gradients throughout this region are small. A linear thermal gradient, indicative of thermal transport by conduction, exists in the two lower layers of the multi-layer system. When the permeability contrast is least, the effects of convection are apparent in both of the porous layers, leading to a wide variation in thermal profiles. This effect is enhanced further when the thickness of the conduction layer is reduced.

Comment on the Assumption of a Single-Phase Fluid

In the analysis, we have assumed that the porous layers are saturated with a single-phase fluid. Here, we wish to comment on the validity of this assumption by comparing the local temperature within a convective cell with the local saturation temperature. The local saturation temperature is determined from the empirical relation

$$T_{sat} = \frac{P}{10^3} \cdot 10^2.2235 - 17.778,$$

where $P$ is the local pressure in $Pa$ and the saturation temperature $T_{sat}$ is in degrees Celsius. Since the convection is relatively weak, the pressure distribution differs only slightly from hydrostatic. We thus determine the pressure as a function of depth from an integration of the hydrostatic pressure gradient. The approximate local density is given in terms of the local temperature by equation (4) and the local temperature is determined from the results of our numerical simulations, as illustrated in Figure 4.

Except for Case 7, the local temperature was found to be always substantially lower than the local saturation temperature. For Case 7, the temperature profile associated with the upward-flowing fluid closely approaches the saturation temperature in a limited region of the upper part of the convective cell. Since the local temperature is near the saturation temperature in the upper region of the convection cell, we conclude that there may be a slight tendency toward the local production of two-phase flow. However, this condition obtains only for the upward flow region of Case 7. All other cases were found to be well within the subcooled region for subcritical pressures.

**DISCUSSION**

We have shown that a rather wide variation in two-dimensional, cellular, convection patterns can exist in the multi-layered system selected to represent the geothermal region of the Long Valley caldera. Associated with the convective patterns is a correspondingly large variation in temperature distributions. When the permeability contrast is large and the convective cell is concentrated in the uppermost layer, the vertical temperature profile is, on average, rather uncomplicated and consists of an essentially isothermal layer adjacent to the upper surface followed by a region of constant gradient. On the other hand, when the permeability contrast between the upper layers and thickness of the conduction layer are both reduced, the thermal structure can be quite varied, with a range of vertical thermal profiles possible, depending on their location relative to the cellular convection pattern.

The results of our studies appear to have strong implications for the interpretation of temperature profiles which are to be monitored during the drilling of the exploratory well in the Long Valley caldera. The main implication is that, during the early stages of the drilling, the temperature distribution may not be a strong indicator of the presence or absence of a magma body at depth. Depending on the location of the well relative to any existing convection cell, the temperature distribution encountered initially may: (1) exhibit a strong initial gradient followed by an isothermal region, (2) exhibit essentially isothermal behavior, or (3) exhibit an initial positive gradient which becomes negative and then positive as the depth increases. These regions of anticipated complex thermal structure can occupy as much as 40-50% of the total thickness of the three-layer system. Following the variations in the upper regions associated with the cellular convection, are regions of monotonically increasing temperature with relatively constant gradients. However, the magnitude of the gradient is still influenced by the structure of the system and the location of the profile relative to any convective motion that may be present.

Certain of our assumptions restrict the generality of our results and influence, to varying degrees, the conclusions of our study. Here we wish to comment briefly on several of the more important assumptions and their possible consequences with regard to our initial effort to describe the overall features of the thermal structure which may exist in the Long Valley caldera geothermal region.

Since the Long Valley caldera is approximately elliptical in planform and the ratio of major axes is on the order of only two, the convective flow may well exhibit three-dimensional aspects which differ from the strictly two-dimensional "rolls" of our analysis. Hence, some regions of the layered system could be dominated by three-dimensional convective cells of
polygons. There would then be local, columnar, regions of ascending and descending flow accompanied by an increase in the local and, possibly, overall heat transfer rates. The vertical temperature profiles would still, however, be expected to exhibit variations similar to those associated with two-dimensional, planar, flow. In comparison with our planar model, a three-dimensional convective flow would be considerably more complex in structure and would pose additional computational difficulties for numerical simulations.

In our model, we assumed that the layered model system was limited in horizontal extent and confined between impermeable vertical boundaries. This is obviously a simplifying assumption that may not reflect adequately the in situ conditions. For example, under in situ conditions, lateral infusion of flow across the vertical boundaries may occur. It would then be worthwhile to consider the effects of permeable vertical boundaries in future simulations. Inflow, from the surrounding region, would tend to destroy the cellular nature of the convective flow predicted for the original model system. This effect would be most pronounced at the edges of the layered system. The extent to which the influence of end conditions would penetrate into the flow field would depend on the layer aspect ratio, the permeabilities, and the pressure boundary conditions imposed on the vertical boundaries.

The multi-cellular convection pattern is also influenced, to a large degree, by the assumption of uniform heating from below and the relative uniformity of the geological structure assumed. Nonuniform heating and variations in the geological structure can have a pronounced effect on the convective pattern and should be considered in future studies. For example, the nonuniformities mentioned could restrict the formation of uniform, multi-cellular convection and, under favorable circumstances, lead to the formation of single or dual convective cells within the geothermal region. The location of the exploratory well relative to the induced, convective flow field thus becomes problematical.

We have made a preliminary attempt to represent heterogeneities, which are prevalent in geothermal systems, by incorporating three distinct layers in our model. Since geothermal regions are often dominated by smaller scale heterogeneities such as fractures, there are other considerations which could form the basis for future studies. In this regard, it would be informative to study the effects of various models for liquid phase dispersion and the effects of local perturbations to the transport processes associated with fractures.

Finally, the existence of steady flow should be considered. For a bottom-heated single layer system with prescribed aspect ratio, there is an upper limit for the Rayleigh number above which natural convective flow is always unsteady. Based on considerations of previously published studies for single layer systems, we believe our simulations fall within the limits of steady flow. However, it would be in order to perform studies which would define the limits of steady flow for layered systems.

Based on our results and subsequent discussion, it is apparent that care must be exercised in the interpretation of temperature profiles measured in geothermal regions which are thought to overlie a magma body. The presence or absence of strong thermal gradients in the upper layers of the region are not, of themselves, sufficient to imply the existence or absence of a magma body at depth. Since the various physical, geometrical, and geological parameters are not known accurately at this time and the simulations incorporate a number of simplifying assumptions, our work must be regarded as preliminary. Certainly additional studies are needed to develop a more complete understanding of the thermal aspects of the complex geothermal region which exists in the Long Valley caldera.

ACKNOWLEDGMENTS

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