THE HYDROTHERMAL SYSTEM ASSOCIATED WITH THE KILAUEA EAST RIFT ZONE, HAWAII

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Abstract

During the last twenty years drilling and fluid production on the Kilauea East Rift Zone (KERZ) has shown that an active hydrothermal system is associated with much of the rift. Well logging and fluid geochemistry indicate that reservoir temperatures exceed 360°C but are highly variable. Although neither well testing nor pressure decline data have clearly demonstrated the lateral limits of the reservoir, divergent fluid compositions over short distances suggest that the larger hydrothermal system is strongly compartmentalized across the rift zone. The chemical compositions of production fluids indicate that recharge is derived from ocean water and meteoric recharge and isotopic data suggest that the latter may be derived from subsurface inflow from the flanks of Mauna Loa.

Introduction

Results from ore than a dozen exploration wells drilled along the Kilauea East Rift Zone (KERZ) since the discovery of a geothermal resource there in 1976 has demonstrated that a significant high temperature reservoir is present along the KERZ and that production of electrical power from the resource is technically feasible. Economic and regulatory impediments delayed commercial development of the resource until seventeen years after the completion of the initial discovery well but electrical power generation from geothermal steam now supplies about 25 % of Hawaii Island's electrical demand. Early plans for much larger amounts of geothermal power have not been realized due to both the declining cost of fossil fuel generation and the continuing regulatory climate for geothermal power production in Hawaii. We present here a brief history of this effort along with a summary of resource data that has been gathered for the high temperature geothermal field present on the KERZ.

History

Exploration for geothermal resources in Hawaii started in 1962 with the drilling of four shallow (<300 m deep) wells along the East Rift Zone of Kilauea volcano. Elevated temperatures were encountered by all four wells but subsurface rocks were so porous that steam pressures were not adequate to drive a turbine and further efforts to develop the resource were abandoned. In 1972, a more intensive evaluation of the subsurface thermal conditions of this ocean-island volcano were initiated by the Hawaii Geothermal Project under National Science Foundation funding. This research effort surveyed the island of Hawaii for evidence of thermal discharges both on the ground surface as well as in coastal springs.

These early surveys again indicated that the KERZ showed strong

Table 1. Names, Depths and Temperatures for KERZ geothermal exploration and assessment wells

Well Name	Date Drilled	Depth (m)	T Max (°C)
HGP-A	1976	1966	358
Ashida	1981	2530	288
Lanipuna 1	1981	2557	363
KS-1	1981	2222	343
KS-2	1982	2440	354
Lanipuna 1-ST	1983	1911	221
Lanipuna 6	1984	1511	352
KS-1A	1985	1983	354
SOH-4	1990	2000	302
KMERZ-A1	1990	2637	335
KMERZ-A2-4	1990	2664	351
KS-3	1991	2257	209
SOH-1	1991	1684	349
SOH-2	1991	2073	260+
KS-7	1991	511	332+
KS-8	1991	1063	325+
KS-4	1992	2046	325+
KS-9	1992	1349	325+
KS-10	1993	1549	325+

evidence for elevated subsurface temperatures and, in 1975, a site was chosen on the Lower East Rift Zone (LERZ) of Kilauea for a deep research well with which to assess temperature and hydrologic conditions at depth (Sh
upe et al., 1978). The well, named HGP-A (Abbot) was completed in early 1976 to a depth of 1966 m. Bottom hole temperatures in excess of 350°C were measured in the well soon after completion, making the HGP-A well the hottest geothermal well that had been drilled in the world to that date, but production of fluids were limited by mud damage (caking) to the wellbore. Subsequent testing showed a progressive increase in pro-ductivity as drilling mud was purged from the formation and, at peak output, the well was capable of producing ~50 metric tons of fluid per hour (Kihara et al., 1976). After extensive tests were conducted on the production decline curves and fluid chemistry of the well, a 3 MWe wellhead steam-turbine generator was installed in 1981 to demonstrate the feasibility of producing electrical power from the reservoir discovered by the well. After an extended start-up and shake-down period, power production began in early 1982 that continued for nearly eight years until late 1989 (Baughman et al., 1985; Thomas, 1990).

As the capabilities of the geothermal reservoir on the KERZ were proven, interest in development of the resource led to commercial acquisition of development rights for the steam resource in several areas along the rift zone. Although electrical demand on the island of Hawaii was limited due to the island's sparse population, both Hawaii's high reliance on petroleum for power production (>90%), as well as the high cost of petroleum during the late 1970's and early 1980's, gave rise to plans for large scale development of the resource and installation of an inter-island cable (Bonnet, 1990; Fesmire and Richardson, 1990). It was hoped that the cable could economically transmit geothermal power to the much larger market on the island of Oahu where most of the state's population lived at that time.

Fifteen deep wells were drilled on these commercial leases during the two decades since completion of the HGP-A well. Testing of these wells has shown that the resource is strongly associated with the intrusive complex that forms the KERZ and that the conditions within the rift were highly variable both with respect to depth and with lateral distance; downhole temperatures, at depths of 1500 m or more, have ranged from 125°C to 365°C; dissolved salts concentrations in production fluids have varied by more than a factor of ten; and steam production rates from individual wells has varied by a factor of more than five (GeothermEx, 1992; ENEL, 1990; Thomas, unpub. data). Although many of the early wells drilled into the rift showed limited production capacity due to low permeabilities, the most recent wells drilled (KS-8, KS-9, and KS-10) intersected permeable structures that provided production rates as much as four times higher than the modestly productive wells of the early exploration effort (Thomas, unpub. data). Although the unexpected strength of the first of these (KS-8) resulted in an 30-hour episode of uncontrolled steam venting, it also demonstrated that extraordinary steam productivities could be found in this geothermal system and that, with a well-planned drilling program, the cost of field development for a generator facility would be substantially lower than that which was originally estimated.

At the present time, two of the above three wells (KS-9 and KS-10) are supplying steam to a 35 MWe geothermal generator facility that now provides about 25% of the electrical demand for the island of Hawaii. However, the remaining commercial interests which initially invested in geothermal exploration along the rift zone have abandoned further development programs for the foreseeable future: in some cases, exploratory drilling on their leases proved unsuccessful, but other projects were abandoned because of excessive costs (associated with regulatory delays) coupled with falling world prices for petroleum (and avoided electrical costs). Further, even though the technical feasibility of an undersea interisland cable was demonstrated (Bonnet, 1990), initial plans to link the islands' electrical grids have been abandoned for the present. Hence, further geothermal development in Hawaii will have to await a substantial increase in the cost of electrical power and an improvement in the regulatory climate within the state.

Reservoir Characteristics

The exploration and research wells drilled into the KERZ have demonstrated that subsurface temperatures within the rift zone are quite high. Maximum bottomhole temperatures on the lower rift varied from about 320°C up to (and beyond) the capabilities of the available instrumentation to make detailed downhole temperature measurements (>365°C). Similar temperatures were found in the middle of the East Rift Zone (MERZ) where temperatures in some drillholes were estimated to be in excess of 400°C on the basis of damage done to drilling equipment (True Geothermal Company, oral comm.). In general, the highest temperatures were found to be restricted to what is inferred to be the middle of the dike complex: wells that were drilled south of the surface expression of the rift (Lanipuna 6) as well as north of the rift (SOH-1) encountered temperatures that were substantially lower than those that lie clearly within the rift zone. Temperature profiles in these wells typically showed modest temperatures, that were elevated with respect to ambient groundwater but usually less than 50°C, down to depths of 1000 m or more. Below about 1000 m to 1500 m, temperatures were found to rise rapidly and approach a temperature that was equivalent to that of saturated steam at the equivalent hydrostatic pressure, (a boiling point with depth curve) (GeothermEx, 1992; Thomas, 1987). These temperature/depth relationships were often maintained to the bottom of the wells. Exceptions to this trend were found in the later series of KS wells: KS-8, KS-9, and KS-10 showed substantially higher pressures for their depths than could be accounted for by hydrostatic pressures (Puna Geothermal Venture, written communication). Because of the nearly constant pressures present in all three wells, which encountered the resource at three different depths, it was inferred that the productive zone was a steam-filled fracture, filled with boiling water at its base, and having a restricted steam discharge zone at its head; within the fracture, steam maintained temperatures and pressures consistent with the boiling feed zone and maintained a saturated steam pressure sufficient to displace the boiling zone to an equilibrium depth corresponding to hydrostatic pressure (Thomas, unpub. data).

The fluid productivity of the early test wells showed substantial differences within the reservoir. The HGP-A well, during initial flow tests was found to have a permeability that was on the order of 1 milliDarcy (md) and, even at this low value, the bulk of the productivity was found to come from a few (~3) thin production intervals (Kihara et al., 1976). Subsequent commercial drilling at the Lanipuna 1 site, located 1 km west of HGP-A, showed temperatures that were higher than those of HGP-A (>365°) but productivities that were lower still and that were unable to sustain steam flow from the well (Barnwell Geothermal Company, oral communication). The early KS series of wells (1, 1A, 2, and 3), located north east of HGP-A, found subsurface permeabilities that were in the same range as those of HGP-A and the wells produced steam flows of about 25 to 40 metric tons per hour (Iovenitti and D'Olier, 1984). As noted above, the later wells in the KS series encountered much higher productivities and, as a result, were able to sustain steam flows that exceeded 150 metric tons per hour. Toward the west, on the middle rift zone, a primary well with three deviated re-drills encountered high temperatures but moderate to very low permeabilities; limited flow testing for these wells found an estimated productivity of about 25 tons per hour (True Geothermal Energy Co., oral communication).

The low to moderate productivity of the formation, combined with hydrostatically controlled reservoir pressures resulted in extremely high pressure drops across the production faces of these wells. As a result, fluid boiling was occurring in the formation with the result that production fluids typically showed excess enthalpy: the steam to water ratio was higher than would be produced by a single-phase liquid boiling zone (Thomas, 1982). The HGP-A well, with a maximum temperature of 358°C, produced a steam quality of about 50% at a wellhead pressure of 620 kPa whereas an isoenthalpic flash of 358°C reservoir fluid should have produced approximately a 25% steam quality (Kihara et al., 1976). Other wells, which had even lower permeability, showed a tendency to initially produce a two-phase mixture of steam and water that would progressively "dry" to a single-phase steam-dominated flow (Iovenitti, and D'Olier, 1984).

The KS-9 and KS-10 wells, as noted above, initially produced single-phase steam from a steam-filled fracture; after an extended period of production, liquid levels in this fracture progressively rose to encounter the intake of the deeper of the two wells which began producing a saturated mixture of steam (Puna Geothermal Venture, oral communication).

The "durability" of production from the deep wells on the KERZ has, to date, been truly tested only by the HGP-A well which was maintained in continuous production for a period of eight years. Nearly all the productive wells that were tested showed high production rates during initial start-up, but, as the boiling zone moved from the wellbore into the formation, production dropped off rapidly (during several hours) by as much as 80% and then stabilized (Kihara et al., 1976). During the eight year production life of the HGP-A, the long-term decline in output (after the initial drop) amounted to about 2% to 3% per year (Thomas, unpub. data). However, this decline was later found to be the result of the formation of a partial obstruction within the wellbore where shallow, cooler fluids were leaking through casing perforations; during two brief intervals immediately after the obstruction was cleared, production again rose to near that observed soon after start-up of the plant. Hence, a truly accurate measurement of the well's productivity decline has not been made but can reasonably be estimated to be less than about 2% to 3% per year. The only other wells for which long-term production data is now available are those from the KS-9 and KS-10 wells: initial productivities of these wells exceeded 150 tons of steam each but, because these are commercial wells, more recent data for their productivity are not available.

Fluid Compositions

The compositions of the fluids produced by the test wells on the KERZ have been highly variable: some wells were found to have a total dissolved solids (TDS) concentrations that were equivalent to about 5% of seawater salinity whereas others were found to have concentrations that were nearly equivalent to seawater (ENEL, 1990; GeothermEx, 1992; Thomas, 1987). The significance of the low salinity fluids can be understood in the context of the expected groundwater compositions in an ocean island environment: accepted models of groundwater hydrology on Hawaii Island predict a thin "Ghyben Herzberg lens" of fresh water floating on seawater saturated rocks below. Hence, early exploration efforts anticipated a fresh water lens (at the HGP-A site) having a thickness of only about 70 m with a rapid transition to seawater salinity fluids below. Instead, the deep production fluids from the well were found to have TDS concentrations equivalent to a 5% seawater mixture (Thomas, 1982). Other wells that were drilled nearby, however, showed initial salinities that ranged from that of seawater to about 50% of seawater salinities (Thomas, 1987). The picture is further complicated by the fact that the fluid salinities typically did not remain constant: during the productive life of the HGP-A well, TDS values increased toward seawater concentrations and had reached levels equivalent to about 40% of seawater by the time the well was shut-in in 1989. The other wells, over short-term well tests showed an increase in salinity as the steam fraction in the total output increased; because of the separation of steam from residual brine in the formation, it was not possible to determine whether the changing salinity conditions were reflective of a change in the source fluids or simply the result of progressive depletion of the water fraction in the fluids. The other wells for which long-term production data are available are those from the KS-9 and KS-10 wells; available data indicate that the fluid salinities for these wells remained constant for up to a year after the onset of brine phase production (Novak and Thomas, 1995; Thomas, 1994).

Although it is clear that the source of the majority of the dissolved solids present in the high-salinity geothermal fluids is seawater, the chemical compositions of the seawater has been heavily modified by interactions with the reservoir rocks. The most commonly observed changes in the thermally modified seawater were the nearly complete depletions of magnesium, sulfate and carbonate ions, and an enrichment of potassium and calcium ions; sodium and chloride ions did not show substantial changes in their concentrations from expected seawater ratios. Because the relative concentrations of the alkali ions (sodium, potassium, magnesium and calcium) at equilibrium in the geothermal reservoir are controlled by the temperature of the reservoir fluids (Fournier, 1981; Giggenbach, 1987) we are able to determine the degree of equilibration of the reservoir fluids with production temperatues at different times during the well's production life. Figure 2 is a ternary plot of the relative concentrations of sodium, potassium, and magnesium in the geothermal fluids from several wells on the KERZ. It is evident that some of the wells' compositions plot within the highly equilibrated field of the figure and correspond to fluid temperatures encountered by the wells. However, other wells (e.g. KS-3) plot in the region of only partially equilibrated fluids where seawater had not fully equilibrated with the reservoir temperatures. The significance of this fact is that, during the reaction of seawater with reservoir rocks, the pH of the evolving seawater can fall to values as low as a pH of 2 resulting in highly aggressive geothermal fluids. Consistent with this was a measured pH of the residual brines from KS-3 of approximately 3.5 with iron concentrations of more than 2000 mg/kg (Thomas, unpub. data).

Also shown in Figure 2 are data from the HGP-A well for fluid samples taken through the life of the well. The early fluids plot along the K-Na axis at equilibrium temperatures of about 300°C but, with time, the compositions move up the K-Na axis toward lower equilibrium temperatures. Although production temperatures remained nearly constant during this interval, the changing compositions suggest that fluids from a lower temperature environment were being drawn into the production zone supplying the well. This suggests that HGP-A was located near the boundary of the reservoir and that continued production would, eventually, have produced a decline in temperature and productivity. Analysis of currently available data from the KS-9 and KS-10 wells have not shown any evidence of impending temperature decline.

Reservoir Model

The drilling and fluid production data that have been gathered to the present time allow us to describe a broad conceptual model of the relationship between the KERZ and the geothermal system associated with it. Geologic data on now-exhumed rift zones indicate that they consist of a complex of near-vertical tabular dikes that extend from depths of 3 km or more to near the surface (Walker, 1990). Interspersed between the dikes are subaerial lava flows (at shallow depths) and hyaloclastites and pillow basalts at depth. The dense, low permeability dikes are barriers to fluid flow and, hence, the geothermal system can be considered to be compartmentalized with minimal mixing of fluids between compartments. Seismic activity is high within the rift zone and results from lateral spreading of the rift (in response to dike injection) and from seaward gravitational failure of the southern flank of the island; these events are, therefore, the source of fracturing within the rift that provides fluid permeability in an otherwise low permeability environment. Hence, fluid flow is governed by fracture permeability and determines the source fluids within different portions of the geothermal reservoir.

The ultimate sources of the fluids recharging the geothermal system remain somewhat problematic. It is clear that seawater makes a significant, and in some areas a dominant, contribution to the reservoir fluids. In an otherwise uniformly permeable environment, seawater should provide the bulk of the fluids recharging the reservoir. However, the origin of the freshwater in the hydrothermal system is not as easily identified. Early models of the rift system suggested that a combination of nearly vertical fractures, formed by intrusive injections as well as lateral failure of the rift, would preferentially permit freshwater recharge to the deep reservoir; intensive hydrothermal alteration of the seaward-facing reservoir rocks was postulated to have resulted in deposition of secondary minerals which would obstruct fracture permeability and inhibit intrusion of seawater from the flanks of the rift (Thomas, 1987). The model also suggested that high temperatures would result in convective overturn of fluids present in the rift zone and would allow cold, fresh recharge to displace deeper thermal fluids and, thereby, sweep saline fluids from the rift. More recently, an alternative model has been suggested by the results of a deep drilling project on the flanks of Mauna Loa volcano where a soil horizon between an older volcanic surface (Mauna Kea) and younger, overlying (Mauna Loa) lava flows had forced freshwater to more than 300 m below sealevel (Thomas et al., 1996). Recent isotopic work on fluids and alteration products on the KERZ has suggested that a similar phenomenon may be occurring there: freshwater recharge from the upper slopes of Mauna Loa may be forced to flow down to substantial depths below the overlying Kilauea lavas and, in so doing, serve to recharge the deep hydrothermal system associated with the KERZ (Conrad et al., 1997).

Although further sampling and analysis of the isotopic and chemical compositions of the rocks and fluids within the KERZ hydrothermal system will be needed to confirm this latter model, it does serve to answer several persistent questions that the former model has been unable to address. In particular, the absence of altered saline discharge from the reservoir into the overlying groundwater system in the rift: although there is ample evidence of thermal fluid discharges in the local groundwater, none of the source fluids for these discharges appear to be the result of deep, high-temperature equilibrated fluids (Novak and Thomas, 1995; Thomas, 1994). South of the rift, however, there is evidence that high temperature fluids may be surfacing in warm coastal springs and suggest a generally southward migration of the deep groundwater flow (Novak and Thomas, 1995). In addition, analysis of carbon dioxide in the non-condensable gas fraction of the geothermal steam has indicated that significant amounts of "modern" carbon are present in the geothermal fluids: the apparent age of the CO_2 produced by the deep fluids is on the order of 10 ka to 15 ka (Thomas, unpub. data). The only realistic source for the radiocarbon fraction in the geothermal gases is atmospheric (or root-zone) carbon dioxide dissolved by shallow groundwater recharge (Thomas et al., 1996). The apparent age of the geothermal carbon dioxide is consistent with shallow recharge transiting through the hydrologic cycle to the rift where it is mixed with radiocarbon-free magmatic CO_2 (Thomas, et al., 1996).

Summary and Conclusions

During the last two decades, research and demonstration projects conducted on the KERZ have resulted in limited development of the geothermal system associated with the active dike complex that forms the rift zone. Analysis of the well testing data and geothermal fluid chemistry indicates that a substantial geothermal resource is associated with the KERZ and that the resource is highly compartmentalized. Fluid compositions demonstrate that freshwater recharge to the rift is an ongoing process and that the source of the fresh water may be from inflow of deep groundwater derived from the slopes of Mauna Loa. the resource is probably restricted to the most active portion of the rift zone and that the dike structure has resulted in a highly compartmentalized hydrothermal system. Nonetheless, commercial drilling has demonstrated that productive horizons can be found in the rift and that commercial production of electrical power is technically feasible. Further, more substantial, development of the geothermal resource for the production of electrical power for the island and state of Hawaii will, however, have to await an improving regulatory and economic environment.

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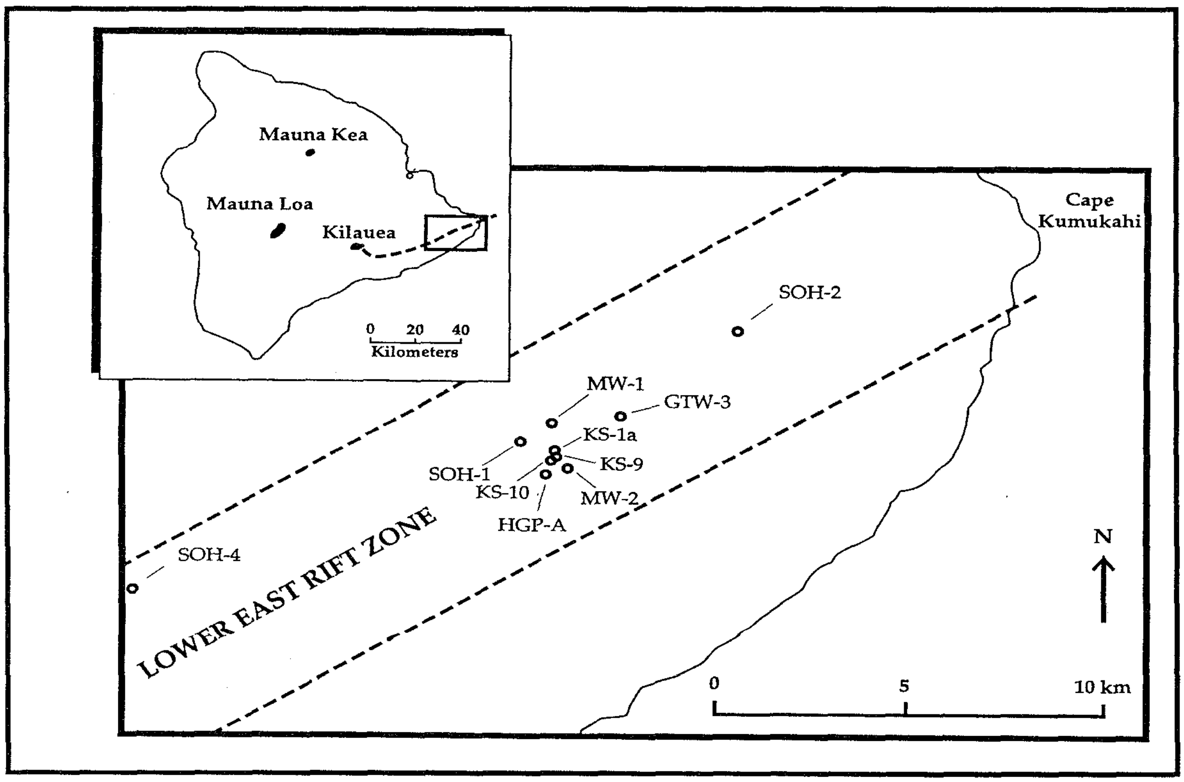

Figure 1. Map of the Kilauea East Rift Zone showing locations of geothermal exploration wells.

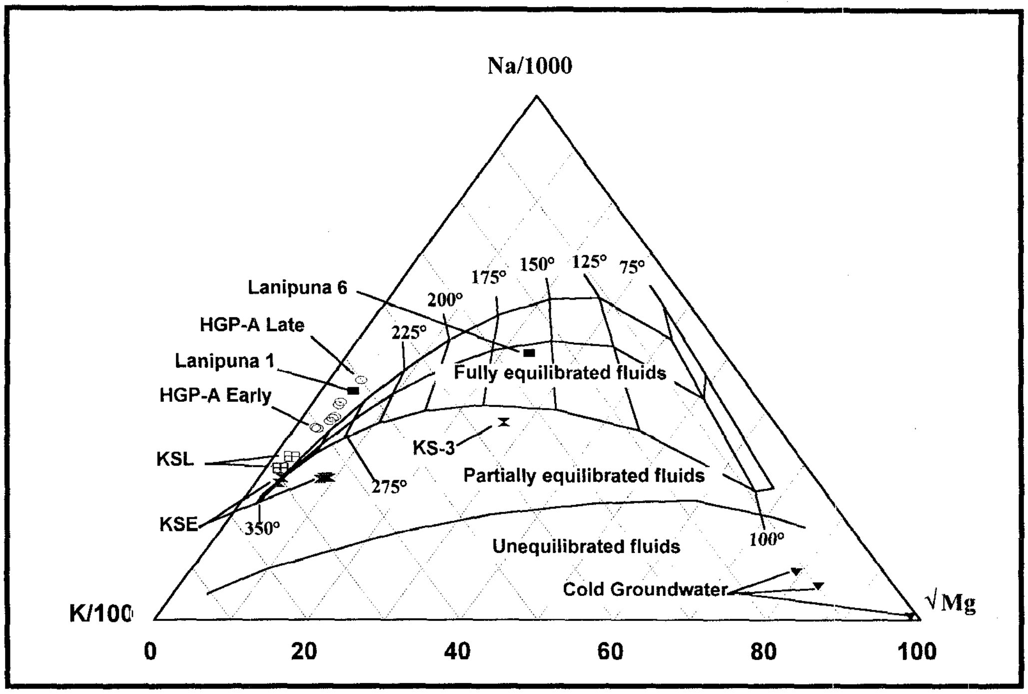

Figure 2. Ternary diagram of cation geochemistry for KERZ geothermal exploration wells. KSE and KSL are early and late wells, respectively, in the KS series.

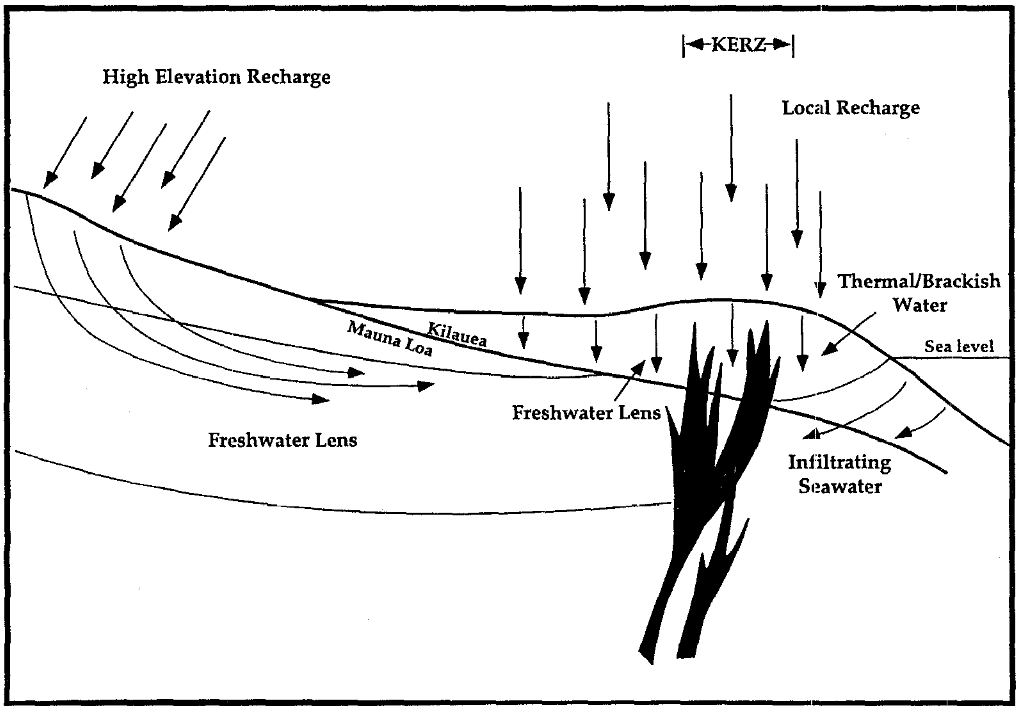

Figure 3. Conceptual model of fluid flow within the KERZ.