SANDIA REPORT SAND83- 1361 Unlimited Release UC-66 Printed October 1984

T; Shallow Magma Targets in the Western US.

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Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550 for the United States Department of Energy
under Contract DE-AC04-76DP00789
SF29000(8-81I

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Printed in the llnited States of America Availahle from
Naticinal Technical Inf'<~rmniot n Service US. Ijepartment(if Cnmmerce
6286 Port Royal Road Springfield, VA 22161
NTIS price codes Printed copy: A03 Mirrol'irhe ciipy: A01

S.4NPJ83-1361 Unlimted Release
Printed Oct,ober 1984

SHALLOW MAGMA TARGETS I N THE VESTERN U.S.

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Abstract
Within the next few years a hole w i l l be drilled into a shallow magma body in the western U.S. for the purpose of evaluating the eqgineering feasibility of magma energy. This paper examines potential d r i l l i n g s i t e s for these engineering feasibility experiments. Target sites high on the list are ones that currently exhibit good geophysical and geological data f o r shallow magma and a l s o have reasonable operatioqal requirements. Top ranked sites for the first magma energy well are Long Valley, CA, and Coso/Indian Wells, CA. Kilauea, HI, also in the top group, is an attractive site for some limited field experiments. A number of additional sites offer promise as eventual magma energy s i t e s , but sparsity of geophysical data presently prevents these sites from being considered for the first magma energy well.
*This work was supported by the U.S. Department of Energy under Contract number DE-AC04-76DP00789.

Distribution uc-66

SHALLOW MAGMA TARGETS I N THE WESTERN U.S.

Within the next few years a hole w i l l be drilled into a shallow, per- haps small, magma body in the western U.S. for the purpose of evaluating the engineering feasibility of magma energy. This paper summarizes results of a site selection process for these engineering feasibility field experiments. A suitable magma target must be relatively shallow and the logistical and environmental factors at the drill site must be favorable. The word "shallow" in this context varies with the site, but ideally means magma bodies at depths of 5 km or less. The word llshallow" implies that the site should be relatively easy and inexpensive t o d r i l l . A magma site in a harsh environment might be difficult to drill to depths of more than 1 ltm. Magma targets at sites with very favorable environments might be seriously con- sidered initially at depths as great as 6 or 7 km and eventually at depths as great as 10 t o 15 km. Although the eventual commercial application of magma energy w i l l depend on large magma bodies, much smaller magma targets will be acceptable for the first engineering feasibility field experiments. The site assessment process considered the geophysical and geological data for the existence of acceptable shallow magma targets at promising sites and, to a limited extent, considered major logistical and environmental factors at the sites. The site assessment conclusions apply only to targets of value to the magma energy engineering-feasibility field experiments.

The first step in selecting a shallow magma target for a future f i e l d experiment was to prepare a full list of sites and then use various criteria to reduce the full list to a workable list where the sites could be analyzed and ranked in detail. Table 1 presents a general list of all potential shallow magma sites that have been previously mentioned in major Magma Energy Research reports [Colp (1982), Hardee et al. (1982), Goldstein and Flexser (198411 and Continental Scientific Drilling Program reports [Continental Drilling (1975), Varnado and Colp (19781, Continental Scientific Drilling Program (1979), Luth and Hardee (1980)l. These shallow magma sites are a subset of the larger list of magma sites in the upper 10 km that were covered in USGS magma resource assessments [Smith and Shaw (1975,1979)]. Many of the sites in Table 1 do not meet the basic: require- ments for the magma energy field experiments, yet t h i s f u l l list includes most of the sites that have been thought at one time or another to contain shallow magma targets.

Although many criteria can be proposed to rank sites, primary criteria consistent with the engineering emphasis of the current Magma Energy Project are: (1) techni cal factors such as documented geophysical and geological. data supporting the existence of shallow magma, and (2) major operational factors such as logistics, and environmental and legal questions. Using these primary criteria, the f u l l list of sites i n Table 1 was first arranged into a coarse grouping of sites in three categories: prime sites, important future sites, and currently impractical sites. These groupings are l i s t e d in Table 2. Within each group the listing is alphabetical at this point. The last category was eliminated from serious consideration as early ex- perimental sites although these sites may have some later value in the program.

Data were gathered on the Category 1 and 2 sites and these sites were visited during the past year while the site assessment was in progress. Discussions were held with some of the main advocates of these individual sites. Limits on time and money constrain serious consideration primarily to the Catagory 1 sites.

After gathering additional technical data on the sites, talking to advocates, visiting the sites where possible, and considering operational factors, the Category I and 2 sites were rank ordered. The rank order is shown i n Table 3. A detailed discussion of the Category 1 and 2 s i t e data used in the ranking process is given in the appendix. The following is a brief summary of the major reasons for the rank of each site:

1 . Long Valley, CA -- This site is the first choice because the prospect of encountering small magma bodies at depths as shallow as 4 t o 5 km is good. The shallow magma bodies at Long Valley have been detected and studied by a number of different investigators. Recent seismic data

strongly suggests the presence of a small body of magma at a depth as shal- low as 4 to 5 km. The magma body beneath Long Valley represents a significant class of magma resource. Environmental and drilling factors look reasonably favorable and commerical geothermal companies are currently active i n the Long Valley area.

2. Coso/Indian Wells, C4 -- This s i t e i s a good second choice. Most data suggests that the magma body at Cos0 is 5 to 8 km deep while some data suggests the magma body is as deep as 10 km. The suspected magma body represents a significant class of magma resource. A commercial geothermal field is currently being developed at Coso. Environmental and drilling permit factors are very favorable because' the site is on~Navyland and the Navy is enthusiastic about the project. Acceptable weather exists year- round and the site is near major drilling supply centers. Some very interesting, but preliminary data, indicates the presence of a very shallow (1 to 3 km deep) magma body just south of Cos0 at Indian Wells.

3. Kilauea Volcano upper East Rift Zone, HI The possibility of finding shallow magma (1 to 3 km depth) at the upper East Rift Zone is excellent and drilling logistics look good for sites on private land outside the Park. The disadvantage is that this target is not a continental magma body although t h i s type magma is similar t o some useful continental magmas.

Much further down the list are the Category 2 sites and their ranking is as f01lows:

4. Salton Trough, CA -- This s i t e is a distant fourth choice. There is no identified shallow magma target although there clearly is a magmatic heat source of some kind here. Limited data suggests that melt may exist as shallow as 6 km. Cold dikes are frequently encountered at depths as shallow as 1 to 2 km.

5. Geysers/Clear Lake, CA -- Drilling/logistical/environmental factors are reasonable but evidence for shallow magma is weak. Early geophysical

data suggested the presence of magma at depths of 7 to 12 km. Recent geophysical surveys have yielded inconclusive to negative results for the existence of a shallow magma chamber. The magma appears to be deeper than desirable for a first hole experiment.

6. Medicine Lake, CA -- Geological data suggests that this is a l i k e l y s i t e for magma. Geophysical data indicates that an intrusive complex un- derlies the site but the data fails to show the presence of melt. The case for the existence of shallow magma at Medicine Lake is based on geological arguments. Geophysical evidence f o r shallow magma a t Medicine Lake i s inconclusive. Weather and logistical factors are acceptable but less at- tractive than at other sites higher on this list.

7. Newberry Volcano, OR -- This is a promising site for shallow magma but geophysical data for the position and depth of the magma is almost totally lacking. Weather can make operations difficult for much of the year. Enrivonmental concerns have been aserious problem in the past but seem to have improved recently. Private land is available in the center of the caldera for a drill site.

8. Socorro, NM -- There is a good b i t of geophysical data supporting the existence of some shallow magma bodies here. The data includes the position and configuration of the magma. One of the small, but shallow, magma bodies may be as shallow as4to 5 km. Geological supporting data for shallow magma is lacking. Good year-round weather is an attractive factor ?or drilling. There is a potential problem with land access a t one of the shallow magma sites.

9. Augustine Volcano, AK -- There is ample data, both geological and geophysical, supporting the existence of shallow magma. The geophysical data here is largely from a single source. The drilling permit situation looks favorable but logistical problems are a significant concern because of distance and weather.

10. Kilauea Volcano, Lower East Rift or Southwest Rift, HI --- Magma is occasionally intruded into these portions of the rift system at depths as

c

shallow as 1 km. There is a reasonable doubt about being able to encounter molten magma here except after infrequent eruptions in these areas. Logistics and good year-round weather are favorable factors.

11. Mt . St. Helens, WA -- The prospect for encountering shallow molten magma here is excellent but environmental/logistical problems are overwhe- lmingly bad.

The three Category 1 sites discussed earlier all have extensive geophysical data suggesting the existence of shallow magma. More geophysi- cal data w i l l be obtained to help improve target definition and aid further i n the target selection process, however, no amount of geophysical data w i l l ever guarantee success! There w i l l always be an element of r i s k i n picking the final site for the first magma energy field experiment. Downhole geophysics and confirmation drilling w i l l be a necessary part of the ex- ploration for magma. The sites with the best probability of encountering
molten magma at shallow depth are active volcanoes but such sites are also the least likely ones for eventual commercial magma energy plants.

Geophysical exploration work is currently in progress at Long Valley, CA, and at Coso/Indian Wells, CA, i n preparation for an engineering-type magma energy f i e l d experiment i n three years. This geophysical work con- sists of active and passive, surface and downhole, seismic exploration work and, surf ace and downhole, thermal measurements. Because of limited resources, the magma energy field experimental work should concentrate on the Long Valley or Coso/Indian Wells sites with possibly some limited spe- cialized experiments at Kilauea.

Alaska Sites Augustine
Katmai Coso, CA
Geysers/Clear Lake, CA
H i st o r i c a l l y- Ac t i ve , Cascade Volcanos
Mt . Baker, WA (erupted 1870,1975)
Mt . Hood, OR (erupted 1801)
Mt . Lassen, CA (erupted 1914)
Mt . St. Helens, WA (erupted 1854,1980) Mt . Shasta, CA (erupted 1855)
Mt . Rainier, WA (erupted 1882) Kilauea Volcano, HI
Cal der a
East Rift Zone Southwest R i f t Zone
Long Valley/Mono Craters, CA Medicine Lake, CA
Newberry Caldera, OR
Rio Grande Rift, NM
Socorro
Valles Caldera
Roosevelt Hot Springs, UT Salton Sea/Imperial Valley, CA San Francisco Peaks, AZ Steamboat Springs, NV Yellowstone, WY

TABLE 1
FULL LIST OF POTENTIAL SITES

TABLE 2
CATEGORY GROUPING OF SITES
Cateaorv 1 Sites
Prime Sites: Shallow magma targets exist and are at least roughly characterized. Only refining geophysical data are needed. There are no serious drilling restrictions.
Coso, CA - Indian Wells, South Sugarloaf Kilauea Volcano, HI - Upper East R i f t Zone Long Valley, C4 - Inyo Domes, Casa Diablo
Cateaorv 2 Sites
Important Future Sites. Evidence for a shallow target is limited. Considerable additional geophysical data is needed. Serious logistical or environmental problems may e x i s t .
Augustine, AK
Geysers/Clear Lake, CA - Mt . Hanna
Kilauea, HI - Lower East Rift Zone, Southwest R i f t Zone, Puhimau Medicine Lake, CA
Mt. St. Helens, WA
Newberry V olcano, OR
Salton Trough, CA - Salton Sea, Imperial Valley
Socorro, NM - Sevilleta
Category 3 Sites
Currently Impractical Shallow Magma Sites. In many eases it is doubtful that a shallow, molten, magma target exists. Where such targets may exist, overwhelming adverse logistical or environmental problems make the s i t e currently impractical.
Active Cascade Volcanoes (other than Mt . St. Helens) Mt. Baker
Mt. Hood Mt. Lassen Mt . Shasta Mt . Rainier
Katmai, AK
Roosevelt Hot Springs, UT San Francisco Peaks, AZ Steamboat Springs, NV Valles Caldera, NM Yellowstone, WY

5. Geysers/Clear Lake, CA - Mt . Hanna 6. Medicine Lake, CA
7. Newberry Volcano, OR
TABLE 3 RANKING OF SITES

1. Long Valley, CA -Casa Diablo, Inyo Domes 2. Coso, CA - south Sugarloaf, Indian Wells 3. Kilauea Volcano, HI - upper East Rift Zone 4. Salton Trough, CA - SE Salton Sea
- Sevilleta
8. Socorro, NM
9. Augustine V olcano, AK
10. Kilauea Volcano, HI - lower East R i f t or Southwest Rift 11. Mt. St. Helens, WA

APPEND1X

1. Long Valley, CA

Geophysical data for magma beneath Long Valley prior t o 1980 was summarized well by Kasameyer (1980). The best evidence came from t h e teleseismic data of Steeples and Iyer (1976 b) and the seismic refraction profile of H i l l (1976). These data suggest that the magma body beneath Long Valley caldera has a vertical extent of 12 km and exists at a depth of 7 to 19 km. High heat flow values in the caldera indicate the presence of a magmatic heat source, but temperature measurements in three moderately deep (1550 - 2100 m) holes have failed to show the high temperatures expected if the main magma body is as shallow as 7 km. Gravity data by Kane et al. (1976) is consistent with the existence of a large magma body at a depth of 8 t o 16 km. The Kasameyer (1980) report concluded that while considerable geophysical data suggested the main silicic magma body was as shallow as 7 km, the temperature data from recent d r i l l holes suggested that the magma body might be as deep as 15 km. Of course, aquifers f e d by snow melt off the Sierras certainly must mask much of the subsurface temperature and heat flow.

Since the Kasameyer (1980) report was published, tectonic activity has begun which suggests the existence of shallow magma. The recent geophysical data on Long Valley has been summarized by Goldstein and Flexser (1984). Currently, the seismic data is consistent with two possible sites in the caldera for this shallow tongue of magma. One site is beneath the Inyo Domes and the other site is beneath Casa Diablo [Rundle (1983), Rundle and Whitcomb (1983). Sanders (1984)l. Eruptions have occurred along the Inyo domes every 250 years for the last 1500 years [Bailey (1982)l. Recent work by Miller (1983) indicates that the material from Obsidian Dome to Inyo Craters erupted 550 years ago. Other data recently discussed by Sieh et al. (1983) indicates that the northern half of the Mono Craters erupted at about the same time. Starting in May 1980 a series of earthquake swarms including four ML> 6 events on May 25-27, 1980, and two M > 5 events on January 7, L 1983, have signaled the onset of renewed tectonic activity. Analysis of the 11

seismic data by Ryall and Ryall (1981, 1983) and more recently by Sanders (1984), has revealed the probable existence of magma at shallow depths (4.5 km) beneath t h e resurgent dome i n the central part of the caldera. Recent work by Kissling et al. (1984) using P-wave tomography, and by Cockerham [Cockerham and P i t t (1984), Cockerham (1984)l using one of the extremely few earthquakes in the northeastern part of the caldera t o observe S-wave ab- sorption beneath the resurgent dome, have confirmed the existence of the magma chamber in essentially the form shown by Sanders (1984). Moreover, analysis of the leveling, trilateration terrameter and gravity data by Rundle and Whitcomb (1984) and Whitcomb and Rundle (1983) suggests t h a t a l l of the data can be explained well by renewed inflation of the central magma chamber by injection of magma at depths as shallow as 5 km. The horizontal location of t h i s shallow magma is north and east of the Casa Diablo Hot Spring area.

In addition t o renewed seismic activity and crustal deformation, there has also been an increase in thermal activity and steam venting, along with locations of very recent tree kill due to increase in ground temperature. Much of this activity has been associated with Casa D ablo, although hot mud geysering to several tens of meters occurred at the time of the 1983 earthquakes in the Hot Creek bathing area [M. Clark (983)]. Gas analyses

performed on steam vents near Casa Diablo indicate CO2 of magmatic origin [Gerlach (1 983)
3.
Taken together, these data strongly suggest the existence of shallow magma beneath the resurgent dome at drillable depths (5 km). Further studies are currently underway t o better locate and define t h i s source.
In addition to the resurgent dome, other bodies of molten or partially molten rock probably exist at shallow depth inside and outside the caldera [Sanders and Ryall (1983), Sanders (19841, Ryall (1984)l. Shown i n Figure 1, from Sanders (1984), are the locations of the central resurgent dome magma body, the magma body to the northwest, and a possible one underneath Lake Crowley. The northwest body agrees in location with anomalous signals
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seen on seismic refraction profiles by H i l l (1976) and more recently by H i l l et al. (1984). The location of the Lake Crowley magma body is based on an incomplete data set and needs further refinement. Another possible location for shallow magma is the Adobe Hills area, to the northeast of Long Valley,
where swarms of earthquakes have recently occurred [Ryall (1984)]. Finally, magma may also be present at depths exceeding 8 km in a 3 meter thick dike beneath the Inyo Domes - Mono Craters chain [Whitcomb a n d Rundle (198311. Although at the present time weakly constrained, this location and configuration is at least consistent with recent gravity change observations from 1982 to 1983 [Whitcomb and Rundle (198311, and the recent, extremely young (500 years old), silicic eruptions associated with the Mono Craters [Sieh et al. (1983)l and the Inyo Domes [Miller (198411.
the existence of the body and its depth.
The magma reservoir inferred from geologic data rests on a model

products, mainly lava flows and domes [Smith and Shaw (1973)l. Important implications of this model are that basaltic magmas originate in the mantle or lower crust, rise to the surface to form flows fed by narrow pipes and dikes, and do not form large shallow storage chambers - with the possible exception of oceanic volcanoes that may have a large summit reservoir. The model predicts that large magma chambers formed in the upper 10 km of the continental crust will be silicic; thus, silicic volcanic systems of suffi- ciently young age provide the most attractive site for geothermal and magma energy exploration. This model is still the basis for igneous-related geothermal resource estimates within the U. S. Geological Survey [Smith and Shaw (1979), Bacon et al. (1980)l.

When applied to the Cos0 Range, the model yielded a volume of 630 km3 for the magma reservoir [Smith and Shaw (1979)l. The magma body is rhyolitic in composition and has erupted at least 38 times in the last 1 m.y. The eruption products consist of about 2 km3 of remarkably constant composition rhyolites forming domes, flows, and pyroclastic deposits spread over 150 kmL of Sierra Nevada granitic and metamorphic rocks [Bacon et a l . (198O)l. A t least 19 vents of Pleistocene alkali basalts occur on the east, south, and west margins of the rhyolite field. Most of the rhyolite domes and a l l of the rhyolite flows are less than 0.3 m.y. The youngest rhyolite is 0.04 m.y., and the average rate of eruption of rhyolite has increased throughout the history of the field. Several detailed geologic and geochemical investigations of the Cos0 rhyolite field have been reported i n recent literature and contain the data used to constrain estimates of the magma body volume and composition [Duffield et al. (19801, Bacon et al. (1980), Bacon et al. (19811, and Bacon (1982)l. The longevity of silicic volcanism and the geothermal system it has supported require an external supply of heat [Duffield et al. (1980)l. The most feasible source inferred for the heat is mantle-derived basaltic magma intruding the crust in response to high rates of lithospheric extension in the Cos0region [Lachenbruch and Sass (1978)l. There is impressive petrographic and geochemical evidence for the intrusion of basalt into the silicic magma

chamber, with subsequent mixing [Duffield et al. (19801, Bacon et al, (198111.

Heat flow values from shallow boreholes indicate that at least a 100 km2 part of the Cos0 region is characterized by abnormally high subsurface temperatures and geothermal gradients [Combs (198011. Geothermal gradients range from 25.3 0 C/km t o 906 OC/km and arise from convecting hot water and convective heat transport from former feeder dikes to recent rhyolite domes and flows. Heat flow values range from 1.6 to 23. HFU. The higher values (>lo) are restricted to the rhyolite dome f i e l d and associated steam vent and hot spring manifestations. For example, the highest heat flows were measured near Sugarloaf Mountain, one of the most recent domes, and D e v i l ' s Kitchen, one of the major steam vent areas at present. Heat transferred by convection of water would be rapidly exhausted were it not for intermittent resupply from depth. The heat flow data at Cos0 substantiate the hypothesis that the hydrothermal activity and associated recent volcanic rocks are products of a long-lived magma system at 5-20 km depth that has periodically erupted lava during the past 0.3 - 1.0 m.y. and has provided the primary heat source for the Cos0 geothermal f i e l d [Combs (1980)l.

Teleseismic evidence has shown t h a t an intense, low-veloci t y body exists from 5 t o 20 km depth under the geothermal reservoir and is ap- proximately 5 km wide on top and becomes increasingly elongate in a N-S direction with depth [Reasonberg et al. (19801, Young and Ward (198011. The zone is 10 km wide at depths between 10 and 17.5 km [Reasonberg et al. (1980)]. The t o t a l volume of the zone that may contain melt is ap- (1980)l.

Not a l l geophysical surveys have resolved a magma reservoir under Coso. Those that have, often give different depths to the top of the body. For example, earthquake seismicity data suggest the absence of liquid at depths

. The low-velocity zone underlies the area of high heat
proximately 900 km3
flow, hot springs, steam vents, and recent volcanism. The shallowest part of the body is centered below the region of highest heat flow. The most plausible explanation for the delay shadow, based on consistency with ther- mal data, is that it is caused by the presence of magma [Reasonberg et al.

shallower than about 8 km [Walter and Weaver (1980)], unlike thermal [Hardee and Larson (198O)J and P wave delay data that suggest depths as shallow as 5 km. Reconnaissance telluric current, audiomagnetotelluric, and direct current surveys [Jackson and O'Donnell (1983)l show a resistivity low in the geothermal area, but the investigations were limited to the upper 3 km of the crust and are, therefore, not deep enough to fully evaluate the presence of magma. The effect of an underlying magma body is not identifiable in the gravity pattern at Coso. The presence of such a body, however, is not precluded by gravity because it may be too deeply buried, has too low a density contrast, or has too small a size to be revealed within the complex regional gravity background found at Cos0 [Plouff and Isherwood (198O)J. A magnetic low coincides with the heat flow high at Coso, but it is believed to be due to the low abundance of magnetite in the silicic plutonic rocks at depth and the destruction of magnetite in metamorphic rocks by hydrothermal fluids [Plouff and Isherwood (1980)l and not necessarily a reflection of shallow magma. Magma chamber models and recent geophysical data for Cos0 has been well summarized by Goldstein and Flexser (1984). Goldstein and
Flexser (1984) estimate the depth t o magma at Cos0t o be greater than 10 km. Some geophysical studies, however, place the magma body at a depth of 6 km [C. Austin, personal communication]. Recent S-wave attenuation measurements by Rinn et a1 (1984) indicate that any magma at Cos0is deeper than 5 km. The measurements by Rinn et al. (1984) surprisingly indicated the presence of a highly attenuating zone south of the Cos0Mountains at Indian Wells. The identified area at Indian Wells is a possible shallow magma body less than 3 km deep.
The Cos0 site has the advantage of being on a weapons base and it is easily accessed by available roads. Water and power are available at the site and the weather is suitable for drilling throughout the year. Geothermal drilling into the hydrothermal system at the site has been suc- cessful and full-scale development of the resource is anticipated over the next few years. These a c t i v i t i e s would provide useful information about drilling conditions at the potential magma site, and they offer the pos- s i b i l i t y of some direct involvement in the magma project by industry. Navy

personnel have indicated they would welcome a deep-drilling effort at Cos0 as a means for increasing their knowledge of the region. In addition t o the wealth of information already available at Cos0 compared t o most other possible s i t e s , there is a staff of geologists at the China Lake Base very familiar with the geology of the area. The recently identified site at Indian Wells shares many of the advantages of the main Cos0 site although the Indian Wells site is largely on private land.
3. Kilauea Volcano, HI -Upper East Rift Zone
Considerable data exists for a shallow (2 - 6 km) magma chamber beneath
t h e summit of Kilauea Volcano. Current environmental restrictions preclude this as a drill site, however, because the summit chamber is in the central part of the Hawaii Volcanoes National Park where deep drilling is not presently allowed. The rift zones of the volcano, fed by t h i s summit magam chamber, extend outside the park boundaries and are potential magma targets. Geodetic data and extrusion rates during sustained eruptions at Kilauea imply an average summit magma supply of 7 to 9 x 106 m3/month for the past 30 years [Swanson (19721, Dzurisin et al. (198411. Approximately 35 percent of the net magma supply was extruded, the remainder was stored in the East

Rift (55percent) and the Southwest Rift (IO percent) [Dzurisin et al. (1984)l. Summit magma intrudes the rift zones as nearby vertical dikes, based on seismic and geodetic data and comparisons with dikes exposed in eroded rift zones of older Hawaiian shield volcaons [Swanson et al. (1976), Macdonald and Abbot (1970)l. Dikes comprise 25 - 50 percent of the total rock i n r i f t zone complexes exposed by erosion i n older Hawaiian volcanos with wedges of intervening older lava flows accounting for the rest of the complex. Most of the dikes are less than 1.5 m thick, and occasionally they are as thick as 15 m [Macdonald (1977)l.

The Kilauea East Rift is a 50 km long, 5 km high rift zone where basal- tic magma occurs at depths as shallow as 1 to 2 km [Swanson et al. (1976), Ryan et al. (1981)]. The active portion of the East Rift Zone is ap- proximately 2 km wide [Swanson et al. (1976)l. Eruptions along t h i s r i f t zone frequently bring molten basaltic magma to the surface where it is

erupted as lava. The upper 25 km of the East R i f t Zone is a good target for shallow magma. The portion outside the park boundary, for environmental and logistical reasons, is a particularly good target. The East R i f t Zone extends from the summit magma chamber of Kilauea Volcano down to the sea at Kipu Poing. The lower part of the East Rift, like all of the Southwest Rift Zone, is somewhat inactive. The upper part of the East R i f t Zone (upper 25 km) is very active. The lower East R i f t eruptions, however, are more voluminous than upper East R i f t eruptions, and there is an inverse relation- ship between the amount of summit deflation and the elevation at which eruptions occur on the East R i f t [Epp et al. (1983)l. This relation implies that East R i f t eruptions drain the summit magma chamber t o levels depending on the elevation at which rift zone dikes are tapped [Epp et al. (1983)l. Geophysical data and theoretical calculations indicate that portions of the upper East R i f t Zone contain molten or near molten magma i n a region roughly 0.1 to 1 km in diameter at depths as shallow as 1 to 2 km [Decker (1983), Hardee (1984)3. This geophysical data consists of inflatiorddeflation or tilt measurements and seismic data which are used to chart the underground flow of magma. The character of the seismic data from the upper East R i f t indicates that this portion of the magma conduit system is open and the magma in it is relatively fluid [Decker (1983)l. Theoretical calculations [Hardee (1982, 198411 based on a repeated magma injection model combined w i t h observed volumes of throughput in the upper East R i f t predict that the upper 25 km of the East Rift should be relatively open to flow and should contain molten or near molten magma while t h e lower portion of the East R i f t should be relatively closed to flow and only occasionally contain molten magma. Recent flow calculations indicate that the conduit in some cases is a roughly circular conduit 4 to 10 m in diameter and in other cases is a dike or sill typically 2 m thick and 40 m wide [Hardee (1984)l. Older exposed rift zones show no evidence for continuous conduits, and intrusions with thicknesses of several hundred meters have not been reported in studies of eroded rift zones. They may occur, however, in the lower levels of the rift zones that are not exposed by erosion. Most summit deflations are rapid (100 - 1000 m'/sec) and apparently related to new dike formation [Epp

et al. (1983)]. During the past nine years, however, there have been several aseismic "slow leak" deflations that were not accompanied by new dike formation and that suggest the existence of more or less continuous magma conduits within t h e East R i f t Zone [Epp e t a l . (198311. Observed magma intrusion rates and volumes of erupted lava over the last 300 years agree with this model and the related calculations [Decker (198313.

Kilauea Volcano is not in the continental U.S. and the basaltic magma from Kilauea is not typical of common continental magmas. Erupted examples of basaltic magma, however, are found throughout the continental U.S. and in t h i s sense experiments at Kilauea can be related t o some continental magmas. If these differences can be rationalized, the advantages of drilling for magma at Kilauea East Rift are significant. Magma clearly exists in the upper East R i f t Zone at shallow depths and its location is fairly well known. Magma frequently erupts along the East Rift Zone allowing geophysi- cal, thermal and geochemical experiments to be run in freshly erupted lava from the conduit. Several potential drill sites exist on the upper 25 km portion of the East R i f t Zone including sites on the private land of the Campbell Estates and possible sites on state land near Heiheiahulu. The Campbell Estate group already has plans and permits to drill the East Rift. In discussions with representatives of the Campbell Estate group, it appears likely that they will drill within the next two years and they are inter- ested in the Magma Energy Project and the possibility of joint cooperation [Trotter (1983), Kawada (1983)l.

An interesting target for drilling on the upper East R i f t is the Puhimau Hot Spot. This site formed in 1936 [Zablocki (1978), Jagger (1938)] when ground temperatures suddenly rose to 85 C and killed off the trees and vegatation. Ground temperatures are still high today and reach 90 - 95 C just below the surface. The heat source is either a shallow magma intrusion or a deep magma intrusion coupled t o a fracture-controlled steam f i e l d above which extends t o the surface. Heat flow measurements by Dunn i n 1983 indi- cate that the surface heat flow at Puhimau Hot Spot is the same magnitude as a t Kilauea I k i Lava Lake (q = 250 W/m2). Electrical geophysical measure- ments [Zablocki (1978)] indicate that there is a conductive zone at 50 m

depth. Thermal measurements by Dunn also indicate a thermal boundary at 50 m depth. A preliminary hole drilled to 100 m depth would be very useful to determine if the boundary at 50 m depth is the top of a magma intrusion. If so, the Puhimau Hot Spot would be a valuable location for magma energy field experiments -- particular1y experiments aimed at eva1uating geophysical techniques for locating magma. The main drawback is that this site is within the Hawaiian Volcanoes National Park and is burdened with environmen- tal restrictions.

4. Salton Trough, CA

The Salton Trough is a zone of crustal spreading that runs from the Gulf of California into southern California. This thin region of the crust is a possible location for shallow magma. The site most likely to contain shallow magma is at Cerro Prieto just across the southern border of California in Mexico. The Cerro Prieto site is impractical for magma energy field experiments because it is outside the U.S. The only apparent site for shallow magma on the U.S. portion of the Salton Trough is at the southeast end of the Salton Sea CKasameyer (1980), Goupillaud and McEuen (1983), Goldstein and Flexser (1984)l. There is young volcanism in the area at the Buttes (10,000 year old rhyolitic domes). On the basis of a magnetic anomaly, Griscom and Muffler (1971) estimate an average depth of 2.5 km t o the dike complex. Occassionally some of these dikes might be active and molten. Cold dikes have been encountered i n holes drilled in the area. Kasameyer (1980) estimates the depth to magma to be 6 km, however, he notes that there is no direct evidence about the location or extent of molten material and the molten targets, if present, are small. Goldstein and Flexser (1984) also note that there is considerable data suggesting melt may occur at depths as shallow as 6 km. They are not able to identify specific magma targets, only promising areas for siting a hole. Goupillaud and McEuen (1983) are pessimistic about finding shallow magma here. They con- clude that the Salton Sea geothermal field is the best target for shallow magma, but the chances of magma occurring at depths of 3 km (10,000 f t) are remote. The Kasameyer (1980) report concluded that although magma may

currently be intruding at depths as shallow as 5 km, the location of such shallow molten magma by geophysical methods is d i f f i c u l t .

5. Geysers/Clear Lake, CA

The magma heat source for The Geysers geothermal field is believed to be a crustal magma body near Clear Lake, specifically beneath Mt. Hannah, about 16 km northeast of The Geysers. This site was one of five evaluated for the DOE Continental Scientific Drilling Program site assessment study [Luth and Hardee (1980)l. The geophysical evidence for this magma body is well documented in Kasameyer (1980). The following is a brief summary of the documentation and conclusions in the report by Kasameyer (1980).

Gravity data by Chapman (1975) and Isherwood (1976) show a g r a v i t y low beneath the volcanic edifice of Mt. Hannah. This gravity anomaly is clearly associated with The Geysers geothermal field. The gravity low is inter- preted t o be a silicic magma chamber centered between 6 and 14 km depth [Isherwood (1976)l. The absence of magnetic sources beneath 6.5 km depth in t h i s region suggests that the body is above the Curie Temperature and hence molten [Kasameyer (1980)l. Teleseismic P-wave delay data by Steeples and Iyer (1976a) and Iyer et al. (1980) led Iyer and others to interpret this as a crustal magma chamber extending between 4 t o 30 km depth and centered between Mt . Hannah and The Geysers. Electrical resistivity and heat flow results at this site are currently somewhat ambiguous although the geother- mal field at The Geysers clearly implies the presence of a crustal heat source.

The conclusion of the Kasameyer (1980) report is that a large, partially-molten, magma body roughly 200 km2 i n area exists i n the Clear Lake area at a depth as shallow as 7 km. The report further concludes that t h i s is an attractive site for drilling toward magma although one drawback is that the geologic setting is somewhat unique and complex and the magma body may be atypical.

Goldstein and Flexser (1984) note that recent geophysical surveys have yielded inconclusive to negative results for the existence of a large shal- low magma chamber. In particular, compressional and shear wave seismic

surveys by Rossow et al. (1983) and electrical time domain measurements by Keller and Jacobson (1983) and Keller et al. (1984) failed to indicate the presence of melt in the suspected area of the magma body beneath Mt . Hanna.

6. Medicine Lake, CA

The Medicine Lake Highland i s a 25 km diameter s h i e l d volcano i n north-
ern California. It is one of the most active volcanic centers in the western United States. The field has a volume of IO3 km3 and was built in the la.st 106years. The general structure is a gently sloping shield of mafic lavas and t u f f s , surmounted by a 7 x 10 km caldera. Closely as- sociated with the caldera are a large number of silicic vents less than 104 years old. The greatest concentration of these is on the east rim of the caldera, where surface thermal activity persists in a one-acre area of hot ground. The most recent volcanic activity [Anderson (1933), Eichelberger (1975), Heiken (1978), and Fink et al. (1983)l consists of two large flank eruptions of basaltic andesite of young but undetermined age and a major eruption 1100 years ago. Geological data suggests that this erupted material came from a small s i l i c i c magma chamber 4 - 16 km deep [Heiken (1978)l. Gravity data can be fitted to a proposed model of a 2.5 km thick intrusion beneath the volcano [Finn and Williams (1982)l. Seismic refrac- tion studies by Zucca et al. (1981) and Catchings (1982) fail to show any large low-velocity zones that could be interpreted as molten magma [Finn and Williams (1982)l. Seismic refraction lines run by the USGS [Catchings et al. (1983)] show a high velocity body underlying the caldera with a top within 2 km of the surface and broadening with depth. The body is most likely a solidified intrusive complex. This intrusive complex is anomalous1y attenuating and a possible interpretation is that this attenua- tion is due to the presence of melt. The high seismic velocity, however, is inconsistent with the presence of large quantities of melt. Electrical studies [Stanley (1982)l f a i l t o show any conductive anomaly which could be interpreted as a partially molten magma body. A recent electrical survey by Frischknecht et al. (1983) shows a conductor within a few hundred meters depth beneath the caldera but this is likely a hydrothermal system at this

shallow depth. The conclusion, based on the geophysical data, is that the shallow intrusive complex beneath the caldera is mostly solidified [Finn and Williams (1982)l. The intrusion, even if solid, may still be hot since a fumarole with near boiling temperature water occurs near the caldera r i m [Finn and Williams (1982)l. A deeper magma reservoir in the 5 to 10 km depth range might exist. The spatial distribution of basalt and rhyolite eruptions around the caldera and the manner in which basalt mixes with
rhyolite suggest processes that would have occurred in a magma reservoir at depths on the order of 5 to 10 km. Goldstein and Flexser (1984) have recently reviewed the data on Medicine Lake and they conclude that geologi- cal data and indirect geophysical data supports the existence of a magma body at a depth of 7 to 10 km. They also conclude that more study is needed before one could be confident about reaching a magma body at any reasonable depth. Finally, site logistics for Medicine Lake are reasonably good al- though snow is a problem about four months of the year.

7. Newberry Volcano, OR

Newberry Volcano in west central Oregon has been of interest as a
geothermal site for at least a decade. This site has been mentioned as a target site for shallow magma in the past [Shoemaker (19751, Varnado and Colp (1978)l. This volcano has active fumaroles, young rhyolitic deposits (one dated at 1300 years b.p.1, and a number of cinder cones and vents, all of which suggest the presence of magma. Newberry Volcano consists of both basaltic and rhyolitic material. The volcano has a well-developed caldera structure. A hole drilled through the caldera would be expected to encounter mixed basaltic and rhyolitic material. Below the base of the volcano, a d r i l l hole would encounter a sequence of Tertiary volcanic rocks. A molten or recently solidified rhyolitic magma chamber probably e x i s t s i n the crust and is likely underlain by a basaltic magma chamber [Varnado and Colp (1978)]. This volcano sits on crustal material consisting of Mesozoic plutons and metamorphic rocks or older rocks that were deformed during the Mesozoic.

Magneto-telluric data has failed to show evidence for a large magma chamber beneath the volcano [Stanley (1981) 1. Gravity data, however, does suggest the presence of a large intrusive body at shallow depth [Williams and Finn (198l)l. The most suggestive data for shallow magma comes from the 1981 drilling by the USGS in Newberry caldera. In this drilling operation, high temperatures (265OC) were encountered a t shallow depth (930 m) [Black (1982)l. Extrapolation of t h i s thermal data implies that a shallow magma source exists at a depth of 2 km or less [Sammel (1981)l. Better heat flow data would help t o define t h i s potential shallow magma source although Sarnmel (1981) notes that much of the heat flow at shallow depth is thought t o be masked by ground-water flow. In 1983 a hole drilled by Sandia National Laboratories near the s i t e of the USGS hole encountered high tem- peratures (180°C) when a hot aquifer was penetrated at a depth of 400 m. The main problems with this site are weather and environmental
concerns. Newberry caldera is i n a State Recreational Area and Oregon, i n particular, is sensitive about geothermal drilling in such areas. A small portion of the land in the center of the caldera is privately owned and the present owners are interested i n encouraging a magma energy well on t h e i r property. The Oregon Department of Geology and Mineral Industries (DOGAMI) is currently encouraging a proposal for scientific drilling activities i n Oregon. Altogether, the environmental concerns may not be as severe today as they were a few years ago.

8. Socorro, NM

The magma at Socorro is interpreted to be a large area (1700 km2) sill-
like intrusion at a depth of 20 km with smaller sill-like intrusions at shallower depths [Kasameyer (1980)l. Chapin et al. (1979) notes that some of the smaller sills appear to occur at depths as shallow as 4 km. Jaksha (1982) has some preliminary microearthquake data that indicates possible shallow magma dikes and sills near Ladron Peak at depths as shallow as 2 to 3 km. Recent microearthquake activity indicates the existence of magma in active dikes or

sills at a depth of 5 km near the Sevilleta refuge about 30 km north of Socorro [Sanford (1984)l. It is the smaller shallow magma
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intrusions at 3 to 7 km depth that are potentially useful for magma energy f i e l d experiments. The geophysical data for the shallow magma intrusions at Socorro come primarily from two sources: passive seismic measurements by Sanford and h i s colleagues, and active seismic measurements by COCORP. Three passive seis- mic techniques have been used t o identify these shallow magma bodies: (1) screening of SV waves, (2) spatial distribution of Poisson's ratio (ratio of
S to P velocities), and (3) spatial distribution of microearthquake hypocenters [Sanford and Schlue (1980)l. For instance, microearthquake foci around the suspected shallow magma intrusions are never deeper than 2.5 km whereas i n adjacent areas activity extends t o 8 km depth. This absence of microearthquake activity is interpreted to be due to the presence of liquid
magma. The active seismic techniques such as Vibroseis P-wave reflection seismic surveys conducted by COCORP also show the presence of shallow magma intrusions. One COCORP survey northwest of Socorro for instance, detected a bright reflector less than 3 km wide at a depth of 6.4 km [Brown et al. (1980)]. This bright spot is interpreted t o be a small shallow magma body [Kasameyer (1980) 1.
Microearthquake swarm activity occurred in March 1983 at a depth of 5.5 km (+- 1/2 km) near the Sevilleta refuge about 30 km north of Socorro. This svJarm activity suggests the presence of shallow magma at 5 to 6 km depth. This location is at the center of the Socorro uplift. Another area just south of Socorro has had swarm activity suggesting the presence of shallow magma at depths around 7 km. The swarms are thought to be a result of the movement of magma in dikes and sills. Additional suggestions that the swarms are related to magma are: (1) swarms appear to line up in radial patterns from the center of the uplift in a manner similar t o the r i f t zones on Hawaiian volcanos, (2) the pattern of swarming (many hours of activity but with no aftershocks) suggests that the swarms are associated with the movement of fluid underground and are not due t o dry fracturing, (3) the swarms appear t o be triggered by tidal cycles again suggesting the swarms are due to the movement of fluid at depth, (4) the swarms tend to be restricted t o a narrow depth range. The amount of uplift in the Socorro
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area times the area of the uplift is on the order of the volume rate of magma supply t o Kilauea Volcano i n Hawaii. Sanford (1984) points out t h a t a reasonable amount of magma injection in shallow dikes and sills beneath the Socorro u p l i f t could easily be accounted for in the observed uplift. The case for shallow magma at Socorro is based primarily on seismic data. There is some supporting heat flow evidence. Heat flow values as high as 11.7 HFU have been observed i n t,he Socorro area [Reiter and Smith (1977), Sanford (1977)]. There are reports of hot water ponds near Socorro. The southward flow of the Rio Grande, however, tends to mask much of the heat flow anomaly. The major drawback of the 5 km deep suspected magma body north of Socorro is a possible land problem. This land is on the Sevilleta bird refuge.
At Socorro we have an abundance of seismic data, both passive and active, supporting the existence of small shallow magma intrusions. Heat flow measurements show a small heat flow high associated with the main 20 km deep magma body at Socorro, but there is presently no heat flow momaly identified for the shallow magma intrusions. There is no recent eruptive activity, however, such as occurs at other magma sites. The closest recent eruptive activity is the 1000 year old basaltic lava flow at Valley of Fires, 100 km east of Socorro. The lack of nearby recent eruptive activity at Socorro is not necessarily a drawback. As Bullard (1971) point,s out, there are places like Larderello with obvious magmatic heat sources but no nearby recent eruptive history (The nearest volcanic craters are 100 km from Larderello). What all this data suggests is that the Socorro area might be a young magma system which has not yet evolved i n t o a volcanic system.

9. Augustine Volcmo, AK
Augustine Volcano, located on Augustine Island in Cook Inlet, Alaska,
is essentially an island volcano. This volcano has been very active and has had five major eruptions in the last 200 years (1312, 1883, 1935, 1964, and 1976) [Kienle and Swanson (1980)]. There are data suggesting the existence of a shallow magma chamber beneath the volcano and t h i s was the basis for seismic fan shooting experiments and other geophysical experiments in 1975.

The 1975 field experiments were part of a joint program of magma energy investigations by the University of Alaska and Sandia Laboratories. As part of these field investigations, a shallow (82 feet) hole was drilled near the summit of Augustine in 1975. The drilling logistics and field experiments are described in a progress report by Kienle et al. (1975).
Kienle (1984) has accumulated considerable seismic data indicating a shallow magma body beneath Augustine at a depth of about 900 m (+- 250 m) below sea level. From a drillable position on the volcano the depth to the magma body would be about 1500 m [Kienle (1984)l. The conduit and magma chamber appear t o be vertically plumbed and centered directly beneath the volcano. A drillhole to the magma chamber would require angle drilling at a steep angle of about 45 degrees. The technology for steep angle drilling of this type in hot zones is not developed and would be difficult for the depth required. A vertical drillhole from the 200 m high summit of Augustine
would expect to encounter the magma body at a total depth of 2.1 km, which is not an unreasonable drilling depth. Such a drilling operation, however, would have to be totally supplied by helicopt r since construction of a road
t o the summit would be impractical.
A second magma target at Augustine is the 600 m diameter dome at the
summit that formed after the 1975 eruption. This dome could be drilled from a suitable site outside the rim. Such a position exists near a known hot spot at the summit rim on part of the 1964 dome . An angled hole could be drilled here through the 1964 dome material into the 1976 dome. A hole 100 t o 300 m long could reach molten material inside the 1976 dome. An angled hole over this short distance might be feasible with present technology. The value of such a hole would be largely scientific and would be useful for geophysical and engineering experiments.
10. Kilauea Volcano, HI -- Lower East R i f t or Southwest Rift
The intrusion rate in the Lower East R i f t Zone (greater than 30 km from the summit) is low and this implies that the conduit only intermittently contains molten magma [Hardee (1984)l. The last eruptive activity in the

Lower East R i f t was in 1360. Several possible drill sites exist. One is near the HGP-1 well. The intrusion rate in the Southwest Rift Zone is similar to that of the Lower East Rift [Hardee (1984)l. Again, the implication is that the Southwest R i f t Zone only intermittently contains molten magma. The last eruptive activity on the Southwest Rift was in 1974, howsver, in 1981 about
40 x IO6 m3 of magma was intruded into the Southwest R i f t . None of the 1981 intruded magma reached the surface, but some of it came very near the sur- face presenting a possible shallow magma target for drilling. Modeling based on deformation data indicates that one of these 1981 intruded dikes is 4 km high, 1 m thick and comes to within 250 m of the surface [Okamura et al. (1981), Okamura (1984)l. This particular site is located near Cone Crater. The surrounding area is still steaming at present. This shallow intrusion is outside the tourist areas of the Park and can reasonably be considered as a possible d r i l l site. The disadvantage is that a dike 1 m wide would have solidified within days after its formation in 1981. It is unlikely that molten magma exists today at shallow depths at this location.
11. Mt. St. Helens, WA

The active dacitic lava dome at Mt. St. Helens is currently the shal-
lowest magma source in the continental U.S. The dacitiz magma at Mt. St. Helens is representative of a major class of magmas that are potentially usable for magma energy exploitation.

Potential targets at Mt . St. Helens include magma in the dome, the feeder conduit, and the inferred shallow reservoir at depth. Drilling into magma intruded into the dome would be risky because of exposure to small gas-ash eruptions that occur during phases of the present dome building activity [Swanson et al. (1983)l. Dangers from landslides off both the dome and steep crater walls would also be significant. There is evidence that the feeder conduit remains filled with viscous lava at all times [Chadwick et al. (198313, but the diameter of the conduit is likely to be no larger than 25 - 40 m, based on observations of the diameters of protodomes formed after explosive eruptions in 1980 [Swanson (198411. Seismic, deformation,

gas emission, and petrologic data suggests the existence of a shallow reser-
voir connected to the dome by the feeder conduit [Malone et al. (1983),
Weaver et al. (1983), Chadwick et al. (1983), Dzurisin and Westphal (1983), Casadevall t al. (1983), Cashman and Taggart (1983)]. The depth t o the inferred shallow reservoir is uncertain. Various investigators place it
from less than 1 km to as much as 3 km depth. At one time interpretations of seismic data indicated the reservoir was displaced north of the dome and resided under Goat. R0cl.c~[e.g. see Weaver e t al. (1983)l. Reinterpretations of the seismic data based on a new crustal model for the area, however, place the inferred reservoir directly under the dome.

Drilling to either the conduit or the inferred reservoir from inside the crater would require angled holes and present some d i f f i c u l t problem. With the conduit and reservoir targets now located directly beneath the dome, it would be necessary to drill from a site on the crater breach to the north within a kilometer or less from the dome. This raises serious con- cerns over hazards from gas-ash eruptions, landslides, snow avalanches, and floods. The shallow magma reservoir could conceivably be angled drilled from outside the crater. This would simplify some problems, but the greater distance would require drilling as much as5km at a very steep angle. In addition to the problems noted already, an attempted drilling at Mt. St. Helens would confront obstacles from environmentalist interests, weather, and lack of roads and readily available water supply.

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