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DEEP BOREHOLE MEASUREMENTS FOR CHARACTERIZING THE MAGMA/HYDROTHERMAL SYSTEM AT LONG VALLEY CALDERA, CA

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ABSTRACT

The Magma Energy Program of the Geothermal Technology Division is scheduled to begin drilling a deep (6 km) exploration well in Long Valley Caldera, California in 1989. The drilling site is near the center of the caldera which is associated with numerous shallow (5-7 km) geophysical anomalies. This deep well will present an unparalleled opportunity to test and validate geophysical techniques for locating magma as well as a test of the theory that magma is still present at drillable depths within the central portion of the caldera. If, indeed, drilling indicates magma, the geothermal community will then be afforded the unique possibility of examining the coupling between magmatic and hydrothermal regimes in a major volcanic system. Goals of planned seismic experiments that involve the well include the investigation of local crustal structure down to depths of 10 km as well as the determination of mechanisms for local seismicity and deformation. Borehole electrical and electromagnetic surveys will increase the volume and depth of rock investigated by the well through consideration of the conductive structure of the hydrothermal and underlying regimes. Currently active processes involving magma injection will be studied through observation of changes in pore pressure and strain. Measurements of in situ stress from recovered cores and hydraulic fracture tests will be used in conjunction with uplift data to distinguish between those models for magmatic injection and inflation that are most applicable. Finally, studies of the thermal regime will be directed toward elucidating the coupling between the magmatic source region and the more shallow hydrothermal system in the caldera fill. To achieve this will require careful logging of borehole fluid temperature and chemistry. In addition, studies of rock/fluid interactions through core and fluid samples will allow physical characterization of the transition zone between hydrothermal and magmatic regimes.

INTRODUCTION

The Magma Energy Program exploratory well provides direct access to the physical, thermal and chemical regimes of a volcanic system that will provide invaluable information for validating magma location techniques. It is the purpose of the science plan for the Long Valley

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well to augment direct observations of the physical regime with experiments that will greatly increase the effective volume sampled by the well. As a result, data gathered from borehole experiments will significantly reduce the nonuniqueness of models of the caldera heat source that are based upon surface studies or wells that tap only the hydrothermal regime in the caldera fill.

Formed about 0.7 My ago by an eruption of rhyolitic magma that gave rise to the widespread Bishop Tuff, the Long Valley Caldera is a 17 by 32 km depression residing on the tectonic boundary separating the Sierra Nevada range from the Basin and Range extensional province. Since the caldera forming eruption, several episodes of volcanism have occurred. The most recent volcanic activity to give rise to surface flows within the caldera took place about 600 years ago forming the Inyo chain of domes in the northwestern quadrant of the caldera.

The presence of a hydrothermal system, ongoing seismicity and the occurrence of topographic uplift show that Long Valley remains an active system. However, the activity, which suggests periodic magmatic transport and emplacement, is now principally confined to depths somewhat below the caldera fill and down dropped crustal basement of the caldera. A detailed overview, which is briefly summarized here, of the kinds and degrees of activity associated with ongoing dynamical processes is given in Rundle and Hill (1988).

The location of the pad for the exploratory well is indicated by the "●" symbol on the resurgent dome in Figure 1. The asterisks and swarm of dots on the southern side of the caldera show the relationship of the pad to local seismicity. At least seven earthquakes, with magnitude greater than 5.5 (asterisks), have occurred in the vicinity of the resurgent dome since 1978. Lying on the resurgent dome, the drill site is also in a region of continuing elevation change. Leveling data obtained periodically over the past 80 years indicates that the site is near the maximum rate of uplift observed in the general area. Since 1975, the site has risen nearly 0.5 m.

Regarding caldera heat flow, conductive measurements obtained within the upper 300 m of sedimentary fill indicate values of 4 HFU near the western rim and 2 HFU near the the eastern rim of the caldera (Lachenbruch et al., 1976). For comparison, the regional background heat flow is 1.5 to 2 HFU. However, conductive heat flow to the surface of the caldera represents the least important pathway for heat to leave the caldera. Groundwater flows within the caldera appear to be the dominant mode of thermal transport. High permeability fractures and faults as well as a west-to-east groundwater flow from the Sierra Nevada range strongly affects the character of the presently observable geothermal regime within the two km layer of caldera fill. If convective heat transport to creeks, hot springs and lakes by the hydrothermal regime is taken into account, then the rate of heat loss is equivalent to a conductive rate of from 10-16 HFU over the area of the caldera (Lachenbruch et al., 1976; Sorey and Lewis, 1976).

Because of the complicated nature of hydrothermal transport in the caldera, it is unlikely that test wells limited to only the convection dominated regime of the fill can be used as a means of locating magma. It is anticipated that the new hole will penetrate well into conductively dominated basement rock. Temperature profiles obtained from a conduction dominated regime can be used to argue for or against the presence of magma.

Figure 2 illustrates the relationship of the planned well, designated 51-20, to several others in east-west and north-south cross sections. We anticipate that the well will be almost three times deeper than 66-29 and about four times as deep as M-1. The ring fracture system, indicating the boundary of subsidence, suggests that 51-20 is centrally positioned with respect to the main magma chamber. If the resurgent dome results from the high level intrusion of magma, it is conceivable that the well could pass from Bishop Tuff into an intrusive regime at depths as shallow as 1-2 km. Seismic reflection studies do suggest basement under the resurgent dome at 1-2 km although it is unlikely that the data can distinguish between granitic basement and a granitic intrusive (Science Guide for Long Valley Caldera Deep Hole, 1989).

PLANS FOR BOREHOLE EXPERIEMENTS

A primary purpose of the Magma Energy Workshop in June of 1988 was to identify those scientific questions associated with the exploratory well that have bearing on the success of the program. Several discussion groups, formed along disciplinary lines, considered critical scientific issues and experiments that relate to scientific and engineering goals of the program. A detailed summary of the sessions is presented in the Science Guide for the Long Valley Caldera Deep Hole and only a brief review is attempted here.

GEOPHYSICAL EXPERIMENTS

From a geophysical perspective, issues identified as being critical were: 1) determination of local crustal structure down to depths of 10 km; 2) determination of the driving mechanism for seismicity and deformation from borehole data and the application of borehole data for testing dynamical models of uplift; 3) ascertaining the relationship of pore pressure changes to seismicity, deformation and temperature changes. A suite of seismic, electrical, gravity and hydrologic experiments were proposed as having the potential to address these issues.

Surface seismic studies of the crustal structure at Long Valley have been hampered to some extent by the attenuation of seismic energy through the near-surface caldera fill. Using borehole seismometers will permit observation of seismic signals below the near-surface caldera fill. Vertical seismic profiling (VSP) will allow the information obtained from borehole geology to be extended to the surrounding environment. With downhole seismometers and surface sources, the technique allows acquistion of both up and down going seismic waves (Fig. 3). Information about the overlying fill and major interfaces is obtainable from VSP. Reflected wavefield observations will also permit investigation beyond the total depth of the hole. Borehole seismic recorders could also be used in tomographic experiments to map local seismic noise in a hole array related to fluid flow or rapid strain changes. Local earthquakes could also be recorded without the interference of the seismic "clutter" of the overlying layer. Most important, the recovered core and cuttings will permit validation of the tomographic models that have already been developed using surface observations (Kissling, 1988).

Borehole electrical measurements will also increase the volume of rock investigated by the well. Lateral conductivity structure could be investigated using a transmitter array located on the surface away from downhole receiver electrodes. Another experiment would attempt to "look ahead" of the drill hole at the conductivity distribution. Using an array of magnetometers and the earth's field or an artificial source, it may be possible to estimate the in-situ resistivity of magma. This borehole data should prove useful in evaluating the body of surface measurements that have already been obtained.

STRESS\ROCK MECHANICS EXPERIMENTS

Critical questions involving rock mechanics have focused on determination of the state of stress at depth in the caldera. In particular, it is important to learn if measurements of stress can be related to the regional tectonic and volcanic history of the area. It would also be helpful in understanding the present dynamics of the Long Valley system if changes in observed stress can be related to observations of seismicity and crustal strain. Engineering concerns cited included the need for instrumentation that can make the required in situ stress measurements at temperatures in excess of 300°C.

Simple elastic models of the interaction between a lithostatic stress field and spherical magma chambers show that stress gradients in the regime above the magma chamber increase with chamber radius (Wu and Wang, 1988). Where the temperature is well below 500°C in the hole, it is possible that stress data could be used as a diagnostic for the presence of a chamber a couple of kilometers below the drill. Furthermore, borehole stress data used in conjunction with already available surface uplift data should aid in constraining predictions of the size and location of any magma chamber (inflation center) beneath the resurgent dome. Several methods have been proposed for measuring the stress field including hydraulic fracturing, anelastic strain recovery (Warpinski and Teufel, 1987) and analysis of stress induced wellbore breakouts using an acoustic televiewer. In the lower temperature hydrologic regime of the caldera fill it is expected that any of these methods can provide useful information about the local stress distribution. At the higher temperatures likely to be encountered in the basement, operation of equipment and direct interpretation of wellbore data can be problematic. The thermal and stress regimes encountered by the borehole below two to three kilometers should provide an excellent test bed for both comparison and development of advanced stress measurement techniques.

THERMAL\FLUID REGIMES EXPERIMENTS

The hydrothermal system, because of its complexity, contributes to the problem of locating magma using thermal data. By penetrating a conductive regime beneath the caldera fill, we will have a unique opportunity to probe the roots of a hydrothermal system as well as its relationship, i.e., the thermal, physical and chemical coupling, to a heat source. We can really begin to understand the convective hydrothermal regime, itself, when we know what thermal and hydrologic boundary conditions to assign to its bottom boundary. Then progress can be made in understanding how caldera fill temperature profiles relate to an underlying heat source (Fig. 4).

The lack of curvature in borehole temperature profiles at some depths within the caldera has been used in the past to argue that conduction is the dominant mode of heat transfer within the hydrothermal system. Borehole temperature gradients would therefore provide realistic estimates of conductive heat flow through the caldera fill. If this hypothesis is correct, then the heat flow from the basement is small indicating at best only a weak heat source under the resurgent dome. However, the conduction dominated model overlooks the important fact that in a forced or natural convective system, heat is transferred by the formation of a boundary layer (Fig. 5). The boundary layer may form along a vertical surface or it may detach from a horizontal surface and convect vertically as a thermal plume. In such systems, virtually all the measurable temperature variation is in the thermal boundary layer. Little if any temperature difference exists outside the boundary layer. Since the bulk of geothermal temperature gradient measurements will be outside any thin thermal boundary layer structure (5 to 50 m thick), the value of interpreting gradient measurements in such systems as indications of total heat flow is questionable.

A transition from a convective to a conductive regime can be determined by observations of rapid steepening of the temperature gradient occurring in conjunction with large changes in fracture and/or matrix permeability. Such transitions will provide a basis for assessing the role of boundary layer heat transfer in the system. Thus borehole temperature logging along with estimates of permeability from core studies and borehole logs will be important for elucidating hydrothermal heat transfer.

SUMMARY

The Long Valley Caldera is the surface expression of a major volcanic system that may have ejected almost 600 cubic km of material. Seismic, thermal and uplift observations all suggest that activity continues at depth within the caldera. The Magma Energy borehole, sited on the resurgent dome of the caldera, will penetrate to a depth of 6 km or 500°C, whichever comes first. Because of its depth, the exploration borehole will provide a unique opportunity to probe a magma/hydrothermal system. In addition, it represents an ideal test bed for validating techniques applied to locating magma. To fully realize the potential of the well for achieving the programmatic goals of the Magma Energy Project, a series of borehole experiments is being planned. Only several of the many proposed at the Magma Energy Workshop have been discussed here.

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CAPTIONS

FIGURE 1

Geologic and tectonic setting of Long Valley caldera. Blackened circle on resurgent dome indicated location of Magma Energy drilling site. Asterisks to south indicate earthquakes exceeding M=5.5 since 1978. Adapted from Rundle and Hill (1988).

FIGURE 2

Cartoon cross sections, west to east and north to south, through Long Valley caldera indicating position and depth of drill holes. From the Science Guide (1989).

FIGURE 3

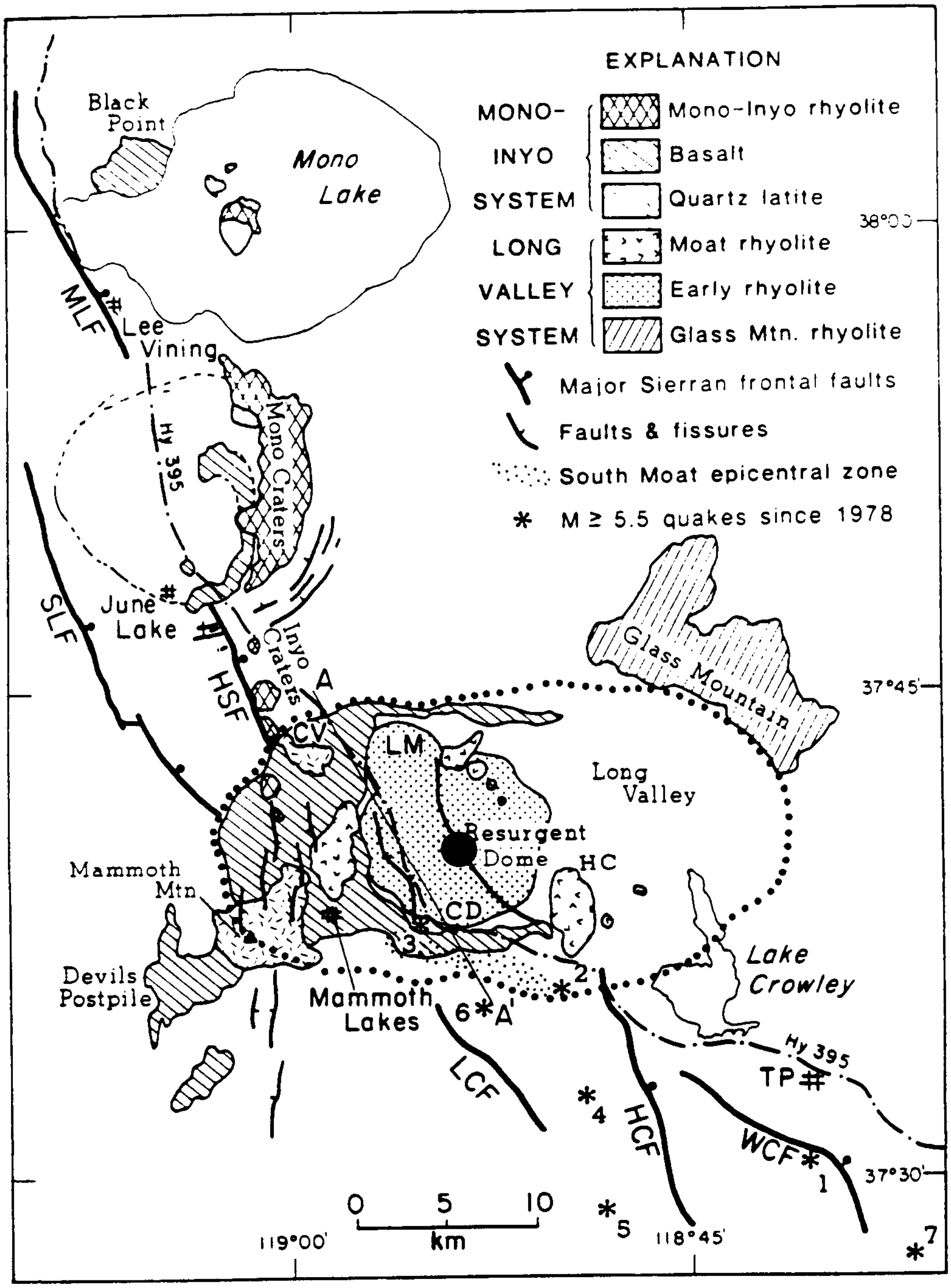
Cartoon illustrating VSP technique. Data can be obtained from both up and down going seismic waves. From Stewart (1984).

FIGURE 4

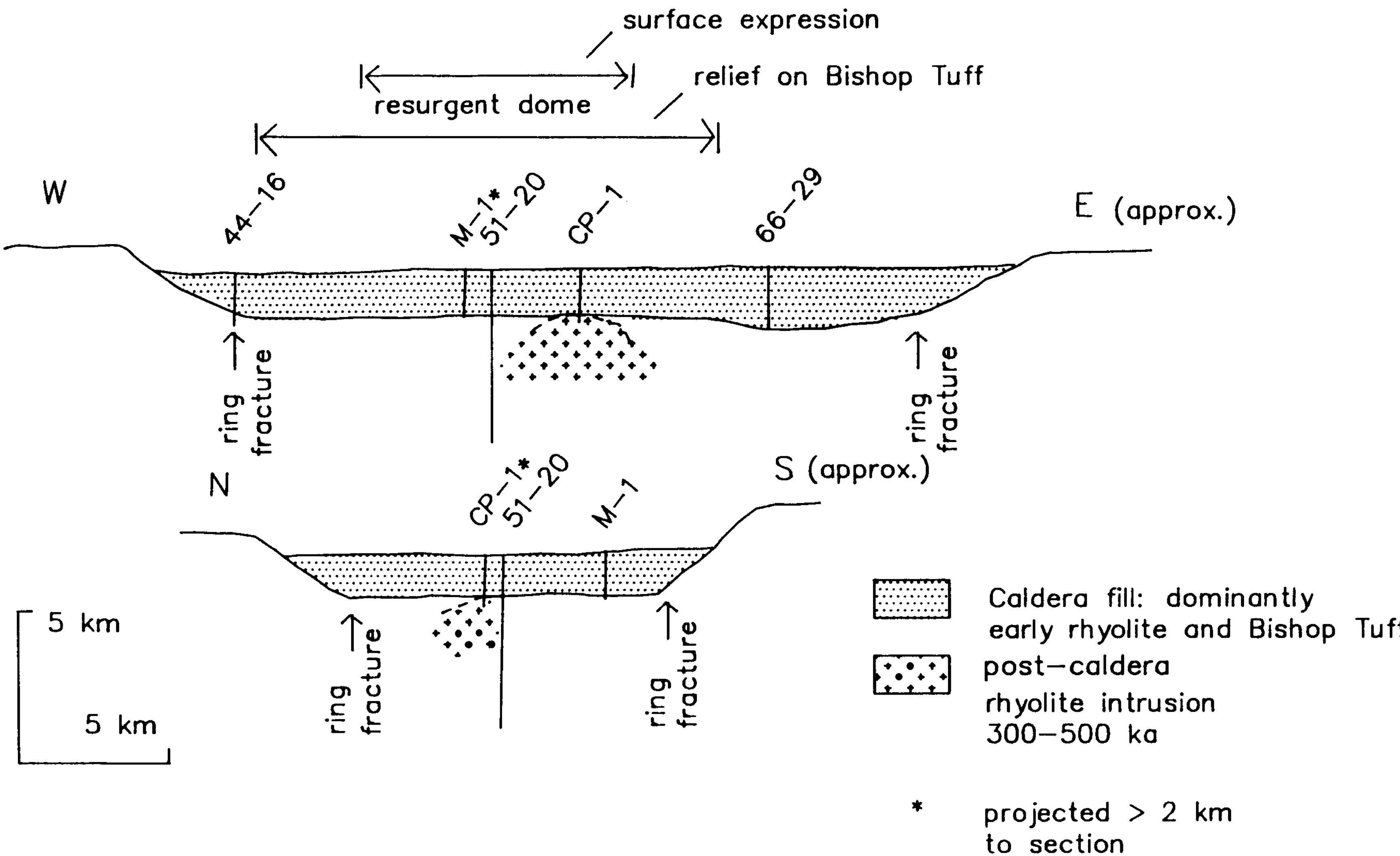
Caldera fill temperature profiles appear to be the result of a complicated hydrothermal regime. In the absence of detailed information about this regime it will be most difficult to determine the nature of any underlying magmatic heat source. Profiles adapted from Suemnicht, 1987.

FIGURE 5

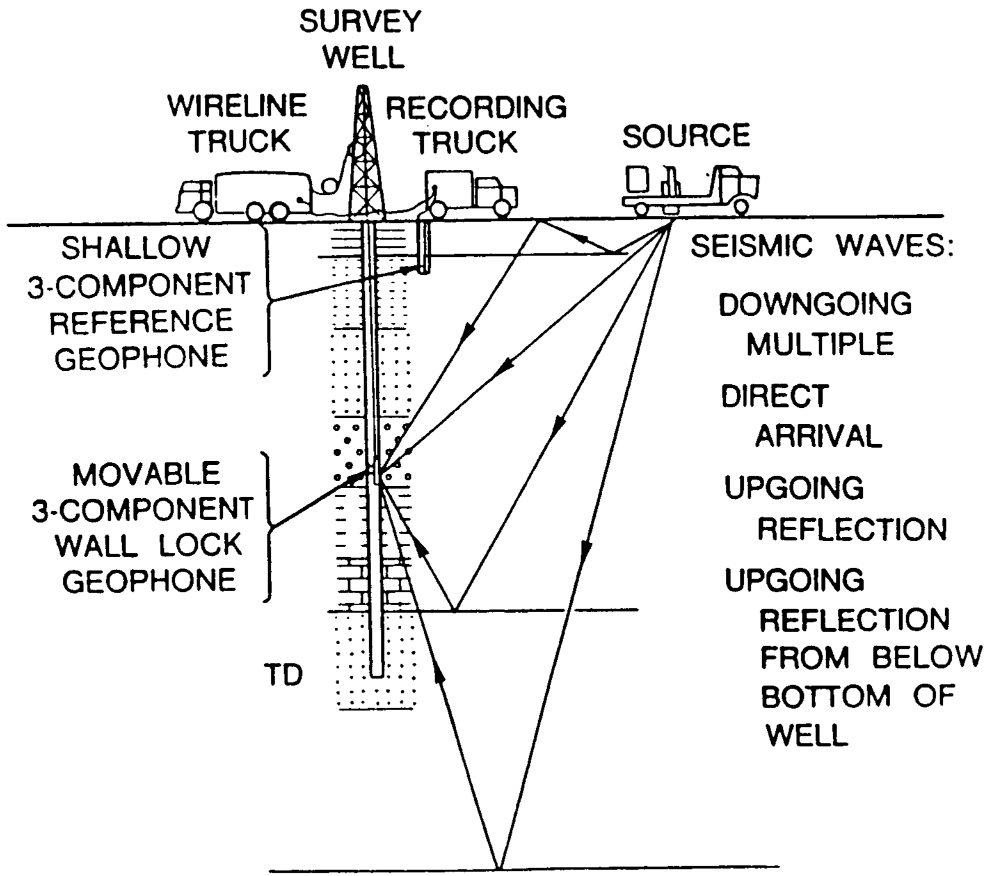
Thermal boundary layers form when flows over heated boundaries exist. Most of the heat is carried within the thin thermal boundary layer. Attempts to measure temperature gradients outside this boundary layer may not be meaningful.



EXPLANATION
MONO-INYO SYSTEM
Mono-Inyo rhyolite
Basalt
Quartz latite
LONG VALLEY SYSTEM
Moat rhyolite
Early rhyolite
Glass Mtn. rhyolite
Major Sierran frontal faults
Faults & fissures
South Moat epicentral zone
M ≥ 5.5 quakes since 1978
Black Point
Mono Lake
MLF
Lee Vining
Hy 395
Mono Craters
SLF
June Lake
HSF
Inyo Craters
A
CV
LM
Glass Mountain
Long Valley
Resurgent Dome
HC
CD
Mammoth Mtn
Devils Postpile
Mammoth Lakes
6
A'
2
3
Lake Crowley
LCF
HCF
WCF
TP
4
5
1
7
38°00'
37°45'
37°30'
119°00'
118°45'
0 5 10
km



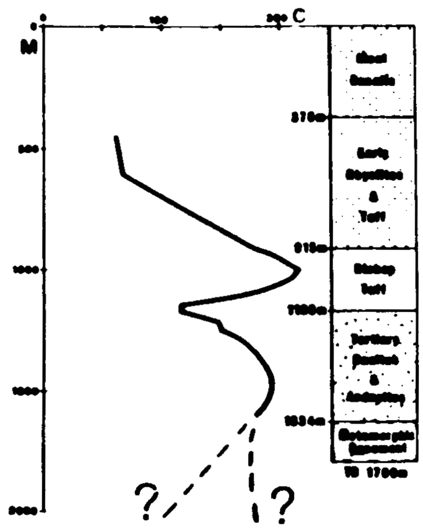
surface expression
resurgent dome
relief on Bishop Tuff
W
44–16
M–1*
51–20
CP–1
66–29
E (approx.)
ring fracture
ring fracture
N
CP–1*
51–20
M–1
S (approx.)
ring fracture
ring fracture
5 km
5 km
Caldera fill: dominantly early rhyolite and Bishop Tuff
post–caldera rhyolite intrusion 300–500 ka
* projected > 2 km to section


SURVEY
WELL
WIRELINE
TRUCK
RECORDING
TRUCK
SOURCE
SHALLOW
3-COMPONENT
REFERENCE
GEOPHONE
SEISMIC WAVES:
DOWNGOING
MULTIPLE
DIRECT
ARRIVAL
UPGOING
REFLECTION
UPGOING
REFLECTION
FROM BELOW
BOTTOM OF
WELL
MOVABLE
3-COMPONENT
WALL LOCK
GEOPHONE
TD

3

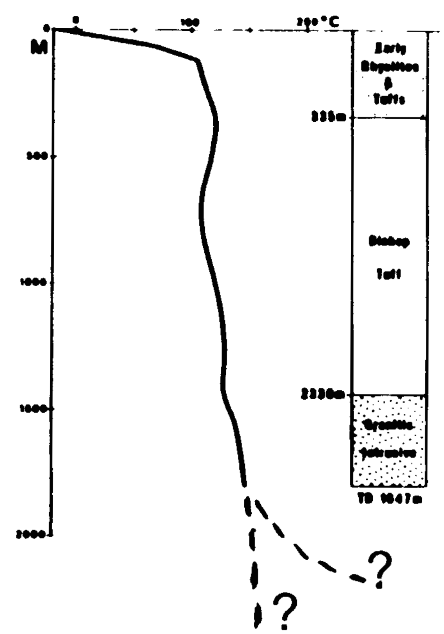
What Do Hydrothermal Temperature Profiles Really Mean For Location of Magmatic Regime???

-5 HFU?



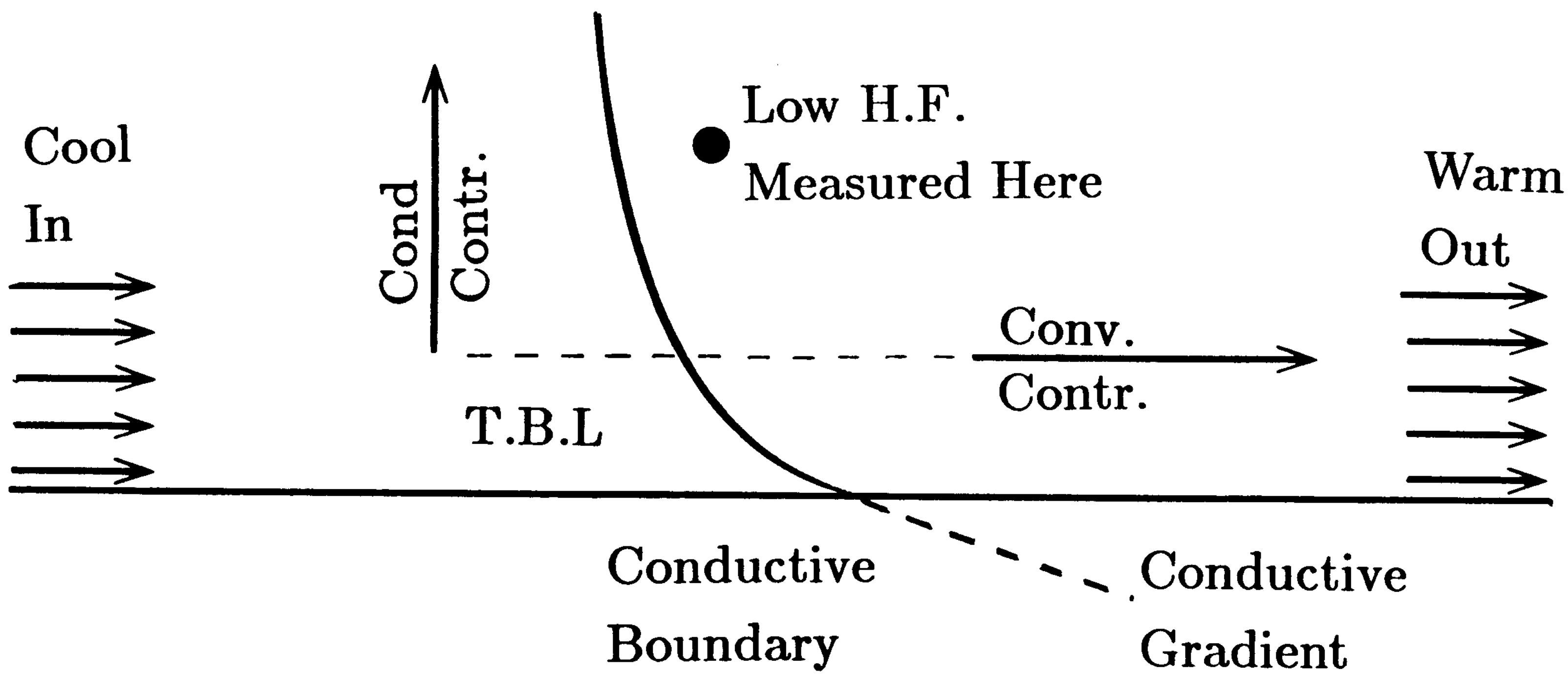
44-16

+2 HFU?



Claypit

Measuring Heat Flow In Moving Fluid Near Boundary



T.B.L Thickness is 5-50 Meters