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**Caldera Processes and Magma-Hydrothermal Systems
Continental Scientific Drilling Program—
Thermal Regimes, Valles Caldera Research,
Scientific and Management Plan**

Prepared by
The Valles Caldera Scientific Drilling Team

Edited by
Fraser Goff
Dennis L. Nielson*

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DE86 013628

*Earth Science Laboratory, University of Utah Research Institute, Salt Lake City, UT
84108-1295.

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Los Alamos Los Alamos National Laboratory
Los Alamos, New Mexico 87545

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PREFACE

The earth's continents have formed partly by plate tectonic interactions and the injection of magma from the upper mantle through geologic time. Magma injections and associated processes, such as hydrothermal system development and ore mineral formation, have occurred in the continental crust of the United States at Valles caldera and the Jemez Mountain region during the last 15 million years and are, in part, still under way as active present-day processes. Advances in our basic understanding of such processes can be achieved at Valles caldera using the same investigative techniques that proved so successful in the ocean basins: core drilling, deep fluid sampling, and borehole geophysical logging. This is the only way to obtain in situ data and avoid the ambiguities that commonly occur when surface surveys alone are used.

This document is the long-range plan for scientific drilling in Valles caldera. It explains the goals, uniqueness, and promise of scientific drilling in Valles and the specific objectives at individual sites. The research outlined is intended as a contribution to the US Continental Scientific Drilling Program, a collaborative effort among the US Department of Energy (DOE), US Geological Survey (USGS), and National Science Foundation (NSF).

This document has three purposes: 1) to present the long-range goals for scientific drilling in Valles; 2) to provide a background and act as a supporting document for future drilling proposals to be submitted to funding agencies; 3) to provide a framework of scientific goals that scientists (government, university, or industry) interested in Valles research might find helpful in using to explain their proposed research in the context of a long-range research plan.

This document will be updated periodically to reflect new information, such as that from VC-1. VC-1 was the first scientific core hole in the Valles and was funded by the US Department of Energy, Office of Basic Energy Sciences. Comments or suggestions regarding information in this document should be sent to

Dr. Fraser Goff
ESS-1, MS D462
Los Alamos National Laboratory
Los Alamos, New Mexico 87545 (Ph. 505-667-8060)

or

Dr. Dennis L. Nielson
University of Utah Research Institute
Earth Science Laboratory
391 Chipeta Way, Suite C
Salt Lake City, Utah 84108-1295 (Ph. 801-524-3422)

Recent results from VC-1 and other Valles caldera research are contained in EOS, v. 66, No. 46, Nov. 12, 1985, pp. 1080-1082 and in the February 1986 issue of the Journal of Geophysical Research.

CONTENTS

LIST OF CONTRIBUTING AUTHORS	1
ABSTRACT	2
I. EXECUTIVE SUMMARY	3
A. Introduction	3
B. Scientific Plan Summary	3
C. Management, Schedule, and Cost Summary	6
II. INTRODUCTION	7
A. History	7
B. Previous Work	12
C. Summary of VC-1	22
D. Objectives and Justification of CSDP at Valles Caldera	29
III. LONG-TERM SCIENTIFIC DRILLING PLAN AND SITE CHARACTERIZATION . .	31
A. Introduction	31
B. Sulphur Springs Site (VC-2)	35
1. Objectives	35
2. Background	35
3. Drilling/Coring Program	39
4. Statement of Work	43
C. Baca-12 Reopening and Deepening (VC-3)	47
1. Objectives	47
2. Background	47
3. Drilling/Coring Program	50
4. Statement of Work	50
D. Valle Grande Site Characterization and Drilling Program (VC-4)	52
1. Objectives	52
2. Background	52
3. Drilling/Coring Program	55
4. Statement of Work	56
E. Summary of the Scientific Plan	56

IV.	MANAGEMENT PLAN	57
A.	Management	57
1.	Introduction	57
2.	Organization	59
3.	Key Responsibilities and Authorities	59
4.	Key Documents and Records	63
5.	Periodic Reports	63
6.	Communication Interfaces	63
7.	Procedures	64
B.	Core Curation	64
V.	SCHEDULE AND BUDGET	65
A.	Schedule	65
1.	FY86	65
2.	FY87	65
3.	FY88	68
4.	FY89 and Beyond	68
5.	Core-Hole Research	68
B.	Budget	68
	REFERENCES	72
	VITAE OF PRINCIPAL INVESTIGATORS AND SUPPORTING STAFF	78
	APPENDIX: SCIENTIFIC PROPOSALS TO AUGMENT DRILLING PROGRAM	99
I.	GEOHERMAL SYSTEMS AND ROCK-WATER INTERACTIONS (Panel 1)	100
1.	Characterization of the Conductive-Convective Zone	101
2.	Characterization of Alteration Mineralogy and Zoning; Comparison with Fossil Epithermal Ore Systems	105
3.	Characterization of Water-Rock Interaction	108
4.	Chemical Characterization of the Boiling Zone	110
5.	Hydrogeochemical Systematics	111
6.	Origin of Fluids and Components	113
7.	Gas Geochemistry and Geochronology of Geothermal Fluids	115
8.	Natural Radionuclides of Uranium and Thorium Series in Groundwaters from Valles Caldera, New Mexico	117
9.	Measurement of Flow and Transport Characteristics	120

10. System Evolution: Phase Assemblages and Fluid Compositions .	121
11. Development of Predictive and Retrospective Numerical Models	123
References for Panel 1	124
 II. VOLCANOLOGY AND STRUCTURAL FRAMEWORK OF THE JEMEZ VOLCANIC FIELD (Panel 2)	126
1. Evolution of Magmatic Systems in the Jemez Mountains from 3 Ma to the Present	127
2. Studies of Precaldera Volcanic Rocks	129
3. Intracaldera Stratigraphy in the Sulphur Creek Area	131
4. Intracaldera Stratigraphy	133
5. Facies Models for the Location of Intracaldera Ore Bodies . .	135
6. Intracaldera Volcanism and Sedimentation, Toledo and Valles Calderas	137
7. The Toledo Embayment	138
8. Three-Dimensional Stress State at the Valles Caldera	139
9. Geometry and Internal Structure of the Valles Caldera	141
10. Development of Resurgent Doming	143
11. Development of Fracture Permeability	145
12. Seismic Surveys of the Valles Caldera	146
13. Lacustrine Sedimentation in the Valle Grande and Valle Toledo	148
References for Panel 2	151
 III. DETERMINING THE PRESENCE (OR ABSENCE) OF MELT BELOW THE VALLES CALDERA (Panel 3)	154
1. Detailed Analysis of Existing Subsurface Temperature Data from the Jemez Mountains	156
2. Numerical Simulation of Caldera Evolution	157
3. Depth and Temperature of Magma: Evidence Based on Recent Eruptives	158
4. Thermochronology of the Valles Caldera	161
5. Geophysical Investigations to Locate Magma or Position Boreholes	162
References for Panel 3	163

CALDERA PROCESSES AND MAGMA-HYDROTHERMAL SYSTEMS
CONTINENTAL SCIENTIFIC DRILLING PROGRAM--
THERMAL REGIMES, VALLES CALDERA RESEARCH,
SCIENTIFIC AND MANAGEMENT PLAN

Prepared by
The Valles Caldera Scientific Drilling Team

Edited by
Fraser Goff and Dennis L. Nielson

Collaborating Authors

Los Alamos
National Laboratory

M. J. Aldrich
W. S. Baldrige
L. F. Brown
P. Carpenter
R. Charles
T. N. Dey
J. N. Gardner
S. J. Goff
C. O. Grigsby
W. L. Hawkins
G. Heiken
D. Janecky
M. A. Mathews
K. H. Olsen
J. C. Rowley
D. T. Vaniman
G. A. Zyvoloski

P. Bethke
J. P. Bradbury
W. Elston
M. Harrison
J. Hulen
C. Janik
M. Kennedy
J. C. Laul
P. Morgan
F. Phillips
S. Self
B. Sibbitt
C. L. Smith
H. Stockman
C. Swanberg
A. White
J. A. Wolff
H. Wollenberg
J. V. Wright
P. M. Wright

US Geological Survey
US Geological Survey
University of New Mexico
State University of New York, Albany
University of Utah Research Institute
US Geological Survey
University of California, Berkeley
Battelle Northwest
Purdue University
New Mexico Institute of Mining and
Technology
University of Texas, Arlington
University of Utah Research Institute
US Geological Survey
Sandia National Laboratories
GEO Operator Corp.
Lawrence Berkeley Laboratory
University of Texas, Arlington
Lawrence Berkeley Laboratory
University of Texas, Arlington
University of Utah Research Institute

ABSTRACT

Long-range core-drilling operations and initial scientific investigations are described for four sites in the Valles caldera, New Mexico. This work is planned as part of the emerging Continental Scientific Drilling Program (CSDP), which is a collaborative effort among the US Department of Energy (DOE), US Geological Survey (USGS), and National Science Foundation (NSF). This plan builds on the success of the first CSDP core hole in Valles caldera VC-1, funded by the Department of Energy, Office of Basic Energy Sciences (DOE/OBES). The plan concentrates on the period 1986 to 1993 and has six primary objectives: 1) study the origin, evolution, physical/chemical dynamics of the vapor-dominated portion of the Valles geothermal system; 2) investigate the characteristics of caldera fill and mechanisms of caldera collapse and resurgence; 3) determine the physical/chemical conditions in the heat transfer zone between crystallizing plutons and the hydrothermal system; 4) study the mechanism of ore deposition in the caldera environment; 5) develop and test high-temperature drilling techniques and logging tools; and 6) evaluate the geothermal resource within a large silicic caldera.

Core holes VC-2a (500 m) and VC-2b (2000 m) are planned in the Sulphur Springs area; these core holes will probe the vapor-dominated zone, the underlying hot-water-dominated zone, the boiling interface and probable ore deposition between the two zones, and the deep structure and stratigraphy along the western part of the Valles caldera fracture zone and resurgent dome. Core hole VC-3 will involve reopening existing well Baca #12 and deepening it from 3.2 km (present total depth) to 5.5 km; this core hole will penetrate the deep-crystallized silicic pluton, investigate conductive heat transfer in that zone, and study the evolution of the central resurgent dome. Core hole VC-4 is designed to penetrate deep into the presumably thick caldera fill in eastern Valles caldera and examine the relationship between caldera formation, sedimentation, tectonics, and volcanism. Core hole VC-5 is to test structure, stratigraphy, and magmatic evolution of pre-Valles caldera rocks, their relations to Valles caldera, and the influences of regional structure on volcanism and caldera formation.

This Valles CSDP plan includes joint management by the Los Alamos National Laboratory and the University of Utah Research Institute. Each coring site will have a Principal Investigator, Chief Scientist, and Chief Engineer responsible for the scientific and technical operations. The estimated costs for core drilling and related scientific and technical support are included. This estimate does not cover costs of scientific research beyond the preliminary examinations and data reports.

This plan is current as of August 1985. It will be updated periodically to reflect new scientific results and prospects for funding the proposed research.

I. EXECUTIVE SUMMARY

A. Introduction

Core-drilling operations and initial scientific investigation are planned at four sites in the Valles caldera of north-central New Mexico. This work will be performed as part of the continuing Continental Scientific Drilling Program (CSDP), a collaborative effort of the Department of Energy (DOE), US Geological Survey (USGS), and National Science Foundation (NSF) (initiated in 1984). The work, as planned, would extend over a seven-year period from 1986 to 1993 and would have seven primary objectives:

- 1) Study the origin, evolution, and physical and chemical dynamics of the vapor-dominated portions of the geothermal system; map the hot-water-dominated portions of the geothermal system to understand the recharge, heat transfer, convective upflow, and outflow characteristics of the system.
- 2) Investigate the characteristics of caldera fill and mechanisms of caldera collapse and resurgence.
- 3) Determine the physical/chemical conditions in the heat-transfer zone between crystallized plutons and the hydrothermal system.
- 4) Evaluate the geothermal energy resources present within and adjacent to a large silicic caldera.
- 5) Study the mechanism of ore deposition within the caldera environment as it relates to the hydrothermal system processes and evolution.
- 6) Develop and test high-temperature well-drilling techniques and logging tools.
- 7) Serve as a natural laboratory for the testing and calibration of high-temperature geophysical techniques.

Scientific drilling in the Valles caldera will expand our knowledge of the heat- and mass-transfer processes associated with magmatic and volcanic phenomena and their role in the evolution of the Earth's continental crust. Application of the basic scientific knowledge gained will enhance discovery and definition of mineral and energy resources associated with hydrothermal systems.

B. Scientific Plan Summary

The Jemez Mountains volcanic field in New Mexico is one of the best-known volcanic centers in the world. It is a complex field, consisting of a large number of vents, but it is most famous for its large caldera complex, the

Valles-Toledo calderas. The Valles-Toledo calderas have been the object of scientific study and industrial development because of their youth and high-temperature geothermal systems. Previous work and drilling have revealed a thick, complex caldera fill and temperatures as high as 341°C. There is the possibility of untested "blind" hydrothermal systems within the thick caldera fill. The geophysical interpretation of the calderas has never been integrated; much of the subsurface structural interpretation is based on a detailed gravity survey. There have been no detailed seismic reflection or refraction surveys.

Since the earliest planning phases of the CSDP, the Valles caldera has been a high-priority site. It is an ideal natural laboratory for the investigation of magmatic processes, active hydrothermal and ore-forming systems. The many planning workshops for the CSDP, including those sponsored by the Carnegie Institution at Ghost Ranch in 1974, the National Academy of Sciences at Los Alamos in 1978, and the Thermal Regimes Panel and Mineral Resources Panel of the Geodynamics Committee of the National Science Foundation in 1984, have all concluded that the Valles caldera should be a prime CSDP candidate site.

A modest CSDP effort began in late summer of 1984 when a shallow core hole, Valles Caldera #1 (VC-1), was drilled inside the southwestern rim of the caldera. Not only was VC-1 the first CSDP hole in Valles caldera, but it was also the first continuously cored hole in the region. Core recovery from the 856-m-deep hole was over 95%. The primary objectives were all met, including: 1) core through the youngest rhyolite flow within the caldera, 2) obtain structural and stratigraphic information near the intersection of the ring-fracture zone and the precaldern Jemez fault zone, and 3) penetrate a high-temperature hydrothermal outflow plume near its source.

The success of VC-1 stimulated further interest in deep coring as a scientific tool to investigate calderas. This led to a workshop held at Los Alamos in the fall of 1984 (Heiken, 1985), attended by members of the national laboratories, universities, the US Geological Survey, and industry. The participants recognized that new insights and major advances in our understanding of hydrothermal systems, ore-deposition mechanisms, heat transfer processes, and caldera evolution in young silicic calderas could be achieved by further probing of the Valles complex. The participants at the workshop formulated 7 primary objectives (listed above) and also prepared 29

"preproposals" for research that would, collectively, achieve these objectives. These 29 preproposals, summarized in this long-range plan, are divided into three categories: 1) geothermal systems and rock-water interactions, 2) volcanology and structural framework of the Jemez volcanic field, and 3) presence or absence of melt below the Valles caldera. The workshop participants also decided that rock and fluid samples, core-hole logs, and *in situ* measurements required to perform the research described in the 29 preproposals could be acquired by drilling a minimum of six core holes at four sites. The four sites and the core holes to be drilled at each site are described below (Fig. 1).

1. VC-2a and VC-2b. This pair of wells will be at Sulphur Springs, within the western caldera moat. They will be drilled to penetrate the interface between vapor-dominated and hot-water-dominated systems and will provide information on the structure of the western ring-fracture system. VC-2a will be 500 m deep and will penetrate the vapor-dominated system. VC-2b has a targeted depth of 2000 m in impermeable Precambrian rock below

Figure 1.
Schematic diagram across Valles caldera showing the locations of proposed CSDP holes and their environments; hole VC-5 not shown.

the liquid-dominated system. We would expect to learn much about ore-depositional mechanisms from this pair of core holes.

2. VC-3. The deepest drill hole within the Valles caldera (Baca) geothermal field is Baca-12 (3243 m deep and 341°C). Until it is deepened, the hole can serve as a laboratory for testing high-temperature logging tools that are vital to all CSDP projects. We propose to deepen Baca-12 to a depth of 5500 m (estimated temperature of 500°C), where we hope to penetrate the crystallized roof of a pluton that produced the voluminous tuffaceous rocks associated with Valles caldera. Within this well we will also study stratigraphy and structure for evaluating models of structural resurgence. If a deeper hydrothermal system is penetrated by VC-3, there will be investigations of thermal/physical/mineralogical properties of rock units beneath the hydrothermal system.

3. VC-4a and VC-4b. This site is in the Valle Grande, within the eastern ring-fracture zone, where the caldera fill may be over 3 km thick. In these wells, we will investigate the structural relationship of the thick wedge of caldera fill, the Jemez lineament, and the Rio Grande rift. Intracaldera tuffs, lacustrine rocks and lavas will provide information on eruption processes, intracaldera sedimentation, structural resurgence, and resurgent volcanism. There will also be information on the presence or absence of a blind hydrothermal system below or within the caldera fill. The first well will be mainly for the purpose of investigating caldera moat sediments and will have a total depth of 1000 m. The second well will penetrate through caldera fill into precaldern rock units and will have a depth of 6000 m.

4. VC-5. The final CSDP well will be within the Toledo embayment (not shown on Fig. 1). Little is understood about this crescent-shaped structure, located immediately northeast of the Valles-Toledo calderas. Our purpose will be to penetrate the floor of the embayment, investigate the relationship of the Jemez lineament to Jemez volcanism and the Valles-Toledo caldera complex, and investigate recharge into the hydrothermal system.

C. Management, Schedule, and Cost Summary

The Valles CSDP plan that we have outlined will be jointly managed by the Los Alamos National Laboratory and the University of Utah Research Institute. Each coring site will have a Principal Investigator, Chief Scientist, and Chief Engineer responsible for the scientific and technical

operations. The proposed schedule calls for coring VC-2a in FY86; coring VC-2b and opening, evaluating, and deepening VC-3 (Baca-12) from FY87 through FY89; and coring the first VC-4 hole in FY87. The estimated costs of coring/drilling and related scientific and technical support are \$11,310,000 from FY86 through FY88. Costs broken down by years are

FY86: \$ 350,000

FY87: \$5,310,000

FY88: \$5,650,000.

These estimates do not cover costs of scientific research beyond the preliminary sample examinations and data reports. These funds will be requested by collaborating investigators through appropriate funding agencies.

II. INTRODUCTION

A. History

The Valles caldera (Fig. 2) has been a high-priority site since the earliest planning phases of continental scientific drilling. Because of the size, youth, and excellent preservation of this caldera complex, its high-temperature hydrothermal system, and its available geothermal data base, Valles caldera has appealed to both the thermal regimes and the mineral deposits communities as an ideal laboratory for the study of magmatic processes and active hydrothermal systems.

At the Ghost Ranch Workshop on Continental Drilling (Shoemaker, 1974), it was recommended that the CSDP drill into an active magmatic-hydrothermal system for the purpose of improving exploration techniques within geothermal systems and hydrothermal mineral deposits. Scientific problems that require drilling include 1) crystallization of magma, 2) rock-water interactions, 3) distribution and evolution of volatiles in igneous systems, 4) migration of H₂O and other volatiles into magma, 5) mechanisms of heat transfer, 6) convective circulation of pore waters around magma bodies, 7) state of stress and strain, and 8) a better means of evaluating volcanic hazards and development of ore-forming fluids. The Ghost Ranch group chose the Valles caldera as one of 11 potential sites for a scientific drilling program.

A more comprehensive planning workshop on continental scientific drilling was held at Los Alamos in July 1978 (US Geodynamics Committee, 1979). One of the six workshop panels recommended drilling in the Valles caldera ("Thermal regimes of the crust, particularly those related to hydrothermal and magmatic

Figure 2.
Map showing (a) location of Jemez Mountains with respect to the Jemez lineament and Rio Grande rift and (b) sketch of Valles caldera region.

systems," R. W. Decker). This panel, the Thermal Regimes Panel, examined in more detail questions put forth by the Ghost Ranch group. Their main point, however, was that there is no soundly based understanding of any hydrothermal system, below the depth of 3 km, with regard to chemical processes occurring there and to the means of heat transfer. A comprehensive understanding of these systems requires drilling (as far as technology allows) down to and into the solidified but still hot magma body. The panel recommended two areas for investigation of "hot-water hydrothermal convection systems driven by high-level igneous intrusions"--the Salton Sea and the Valles caldera.

The Geodynamics Committee, Thermal Regimes Panel report listed the following advantages of a drilling program in the Valles caldera:

- 1) Scientific significance includes information on the nature of large silicic magma bodies and caldera structure and the characterization of a modestly saline hydrothermal system.
- 2) Practical importance includes exploration at depth of models of thermal state, ore deposition, and geothermal resource base. It also includes determination of hydrothermal reservoir properties and information on the longevity of a hot-water system.
- 3) Availability of surface geologic maps and geophysical surveys.
- 4) Information from geothermal wells drilled within the caldera.

Since the Los Alamos workshop, the Continental Scientific Drilling Committee (CSDC) Panel on Thermal Regimes has been examining in some detail the problems to be addressed and site characterization. An initial investigation of specific CSDP drilling targets in Valles caldera was undertaken by an ad hoc task group consisting of researchers who had personal experience at the caldera (Taschek, 1981). Additional support for the panel was provided in part by the Department of Energy who prepared a "Comparative Assessment of Five Potential Sites for Hydrothermal-Magma Systems" (Luth and Hardee, 1980); the Valles caldera was one of these sites.

The Panel on Thermal Regimes' final report was recently published (CSDC, 1984a). They recommend that "... the United States should, therefore, initiate a new, highly focused scientific drilling program aimed at understanding the roots of hydrothermal systems related to young magmatic systems." The program would last 10 years and would involve a number of shallow- and intermediate-depth drill holes in several major geothermal areas. The program would culminate in several deep holes that reach as high

a temperature as possible before the limits of technology are exceeded. Silicic volcanic complexes and spreading centers are the targets of highest priority. The panel's recommendation includes

"Valles Caldera

The Valles caldera was the classic type-example on which geologists developed their concepts of resurgent calderas. Because of its relatively recent volcanism (less than 100,000 years ago), its well-developed physiographic and geological features, and the presence of a well-documented, high-temperature hydrothermal system, which has been drilled extensively by industry, we recommend that the Valles caldera be considered one of the prime targets for deep scientific drilling."

Table I (from the Thermal Regimes report) summarizes criteria for rating the Valles caldera as a prime CSDP site. Yellowstone had a higher rating on a scientific basis, but it had a very low probability as a drilling site because of political and environmental considerations.

The report of the Mineral Resources Panel of the CSDC recommends that the magma-hydrothermal system of the Valles caldera be a candidate site for scientific drilling within active hydrothermal systems (CSDC, 1984b). "The Valles caldera is considered to be an excellent target to gain information about depth-temperature-pressure-salinity conditions in a relatively simple hydrothermal system that has evolved above a shallow silicic magma. A comparison between the active system at Valles and the fossil hydrothermal system at Creede will yield interpretations that are beneficial to the understanding of both systems."

As a result of this widespread interest in drilling Valles caldera for the CSDP, a workshop was held in Los Alamos in October 1982 (EOS, June 28, 1983) to bring together interested parties from the national laboratories, the US Geological Survey, universities, and industry. A set of recommendations on drilling targets and supporting science was obtained for shallow, intermediate, and deep wells, and from these recommendations the general location of the first CSDP well, VC-1, was picked and a proposal written (Eichelberger et al., 1983).

Because of the success of VC-1 (Goff et al., 1984; Section IIC) and the continuing desire to pursue CSDP goals at Valles caldera with deeper research boreholes, a third workshop was held in Los Alamos in October 1984 (Heiken, 1985). The objectives of this meeting were to prepare a dedicated volume in

TABLE I

PRELIMINARY EVALUATION OF YOUNG SILICIC CALDERA SYSTEMS FOR DRILLING
TO THE ROOTS OF THEIR ASSOCIATED HYDROTHERMAL SYSTEMS
(from CSDC, 1984a)

Selection Criteria	Caldera Complex Systems		
	Yellowstone	Valles	Long Valley (including Inyo and Mono areas) and Coso
1. At least 400°C at 5 km	Very likely	Likely*	Unknown
2. Representative of fossil calderas	Likely	Likely	Likely
3. Presence of a well-defined magma body	Very likely	Unlikely in large amounts	Probable beneath western part of Long Valley
4. Availability	Low--owing to environmental sensitivity of National Park	Good	Good
5. Potential for using holes of opportunity	None	High because of large** industry and government activity	Moderate; low level of industrial activity
6. Geographical separation of evolutionary stages	Yes--on a time scale of 5 Ma; no--on finer scale with overlap of 3 calderas in 1.8 Ma	Poor; geographical overlap of 2 calderas and subsequent volcanism	Likely, if target includes Mono, Inyo, and Coso areas
7. Availability of site-selection data	Good	Good	Good for Long Valley and Coso; poor for Inyo-Mono
8. Feasibility of deep drilling	Good to fair, depending on location	Poor in the principal*** hydrothermal reservoir because of under-pressured hydrologic regime; good in other areas	Good on the basis of present evidence, but a high-temperature reservoir has not yet been penetrated

Addenda

* The expected temperature at 5 km is about 500°C based on the conductive thermal gradient in the bottom of well Baca-12 (Hulen and Nielson, in press).

** Data from approximately 35 geothermal wells are in public domain (see Fig. 4).

*** Almost all large calderas that are of interest as a source of energy and metallic resources demonstrate multiple episodes of formation. We view overlapping evolutionary stages as an opportunity to study active economically important processes that are represented in deposits of some old calderas.

**** Union Oil Company has drilled successfully in the underpressured reservoir of Redondo Creek. Thus the technology is available for drilling in these environments. In addition, the only hole scheduled for the Redondo Creek area is the deepening of Baca-12. This hole has already been completed through zones of most severe lost circulation.

a professional journal (Journal of Geophysical Research, early 1986) summarizing recent research in the Valles caldera and to prepare this long-range plan for continued CSDP drilling efforts.

For over 10 years, the continuum of workshops, panels, and studies for the purpose of continental scientific drilling has consistently selected the characterization of active magma-hydrothermal systems as a major program goal. The Valles caldera has always been considered one of the prime sites for a drilling program aimed at answering many of the questions that we have about those systems. This plan outlines a program of intermediate, deep, and very deep wells designed to probe the roots of the Valles caldera hydrothermal system. It should be considered as one element of the broader long-range DOE plan (DOE, 1985) for a comprehensive investigation of thermal regime processes by scientific drilling.

B. Previous Work

The Jemez Mountains volcanic field, New Mexico (Fig. 3), is one of the best-studied volcanic centers in the world because of pioneering efforts by C. S. Ross, R. L. Smith, R. A. Bailey, and their co-workers in the US Geological Survey (Ross et al., 1961; Bailey et al., 1969; Smith et al., 1970). Although the field contains roughly 2000 km³ of basaltic through rhyolitic rocks dominated volumetrically by andesites, the most significant recent activity was the formation of the Toledo and Valles calderas during eruption of over 600 km³ of rhyolitic ash-flow tuffs, the Bandelier Tuff, in two phases 1.45 and 1.09 Ma ago (Smith and Bailey, 1966; Doell et al., 1968; Izett et al., 1980). Caldera formation during eruption of large volumes of silicic ash implies the presence of underlying shallow magma chambers (Smith and Bailey, 1968; Eaton et al., 1975; Smith, 1979; Lipman, 1984). Drilling by geothermal companies inside and near the caldera depression and by Los Alamos National Laboratory on the western caldera margin verifies that the region is very hot at relatively shallow depths (Dondanville, 1978; Sibbitt et al., 1979; Laughlin, 1981). Maximum bottom-hole temperatures are 341°C at 3.2 km depth inside the caldera (Baca #12) and 325°C at 4.5 km on the western caldera flank (EE-2) (Heiken and Goff, 1983; Nielson and Hulen, 1984). The present distribution of isotherms and thermal gradients is easily modeled by cooling of a crystallizing silicic pluton emplaced under the caldera 1.1 Ma ago (Kolstad and McGetchin, 1978).

Figure 3.

Generalized stratigraphic column and map showing relations of major faults in the Jemez volcanic field; JFZ = Jemez fault zone, SFZ = Santa Ana Mesa fault zone, CFZ = Canada de Cochiti fault zone, PFZ = Pajarito fault zone, VC = Valles caldera, R = resurgent dome, T = Toledo Embayment, and SPD = St. Peter's Dome (from Gardner and Goff, 1984).

The subsurface data base of Valles caldera is the best of any active caldera system in the United States (Fig. 4). Much of this information has been generated by DOE support of both the Baca Demonstration Project inside the caldera and the Hot Dry Rock Project outside. Stratigraphic information and practically all other data obtained from the 36 wells shown in Fig. 4 are in the public domain (Laughlin et al., 1983; Spencer and Tsang, 1984). The cumulative, known stratigraphic section for the Valles caldera region is nearly 7 km (Baca #12 and EE-2) consisting of 1950 m of Quaternary caldera fill, 300+ m of Tertiary precaldern rocks, 800 m of Paleozoic sedimentary

Figure 4.

Map showing locations of geothermal wells in the Valles caldera region; dots indicate that all information is in the public domain, whereas open circles indicate that only partial information is available; short-dashed line represents the outline of the resurgent dome, and long-dashed line represents the ring-fracture zone.

rocks, and 3700 m of Precambrian basement (Laughlin et al., 1983; Nielson and Hulen, 1984).

The Jemez Mountains volcanic field (Fig. 2) is located at the intersection of the north-south-trending Rio Grande rift and the northeast-trending Jemez volcanic lineament (Laughlin, 1981). Although Miocene through Holocene volcanic activity occurs along the entire Jemez lineament, by far the largest volume of volcanic rocks was erupted in the Jemez Mountains. The Rio Grande rift is a major crustal structure stretching from Colorado to northern Mexico and is characterized by thin crust (35 km), high heat flow (>2.5 HFU), extensional tectonics, and late Cenozoic basaltic volcanism (Riecker, 1979). Structural analyses of the region include maps by Kelley (1978) and Baldrige et al. (1983) and a tectonic model by Aldrich and Laughlin (1984). The Jemez Mountains overlie Paleozoic and Precambrian rocks in the west and Tertiary sediments of the Española Basin in the east.

Because of recent private and DOE-sponsored geothermal efforts in the caldera region and DOE-OBES-sponsored research directed toward the CSDP, many geologic and related investigations have been recently published on the Jemez Mountains and Valles caldera, which have greatly enhanced our previous knowledge (Mills et al., 1984). For example, it is now known that the Jemez Mountains have been continuously active for the last 13 Ma and that peaks of volcanic activity occurred in the intervals 10 to 7 Ma and 3 Ma to present (Fig. 3; Gardner and Goff, 1984). Volcanism and hydrothermal activity have been intimately associated with rift-related tectonism along several fault zones (Golembek, 1983; Goff et al., 1981; Gardner and Goff, 1984). These combined effects have produced widespread hydrothermal alteration observable in early-Jemez volcanic rocks. An excellent example is the ore deposits of the Cochiti Mining District, southeast of Valles caldera, where 6-Ma-old, gold-bearing quartz veins cut monzonite stocks and associated volcanic rocks (Paliza Canyon Formation) of early Jemez origin (Wronkiewicz et al., 1984).

The most spectacular events in the history of the field were eruptions of large-volume rhyolitic tephras over the last 3 Ma. At least two and possibly more ash-flow deposits were erupted from source areas now obliterated by Valles caldera; these were not previously recognized (Kite et al., 1982; Self et al., 1984; Nielson and Hulen, 1984). It is also now recognized that the 1.45-Ma-old Toledo caldera, the source of the lower Bandelier Tuff, is buried by and is nearly coincident with the younger Valles caldera rather than

located northeast of Valles (Goff et al., 1984; Heiken et al., 1985). The circular structure previously called Toledo caldera has been renamed the Toledo embayment (Fig. 5), and its origin is now the subject of reinterpretation. Locations of the Valles and Toledo calderas, the Toledo embayment and the swarm of rhyolite domes within it, and the postulated vents for earlier ash flows define a northeast trend coincident with the Jemez lineament (Self et al., 1984).

The Valles caldera was formed during eruption of the upper member of Bandelier Tuff at 1.09 Ma. This major event has been studied by many geologists and is considered to be one of the world's "type" calderas (Ross et al., 1961; Smith and Bailey, 1966; 1968). Valles caldera is the largest visible volcanic structure in the Jemez volcanic field, having a diameter of 22 km between topographic rims (Fig. 5). The inferred ring fracture indicated by a ring of intracaldera rhyolites has a diameter of 13 km. These rhyolites range in age from about 1.0 to 0.1 Ma (Doell et al., 1968). The

Figure 5.

Map showing locations of proposed CSDP holes; VC-1 is already complete; VC-5 will be located in Toledo Embayment; RCG = Redondo Creek graben, VRF = Valles ring-fracture zone, TRF = Toledo ring-fracture zone.

resurgent (structural) dome, composed primarily of uplifted Bandelier Tuff, is located just west of center in the caldera and rises nearly 1 km above the moat surface. The dome crest is cut by the Redondo Creek graben, which has been reactivated along the Jemez lineament.

In their classic paper on resurgent cauldrons, Smith and Bailey (1968) state that the resurgent dome grew soon after caldera collapse by shallow tumescence of volatile-poor "Bandelier" magma. However, on the basis of the gravity interpretation of Segar (1974) (Fig. 6) and available drill hole stratigraphy, Goff (1983) noted that the subsurface structure of the caldera

Figure 6.

Residual Bouguer gravity map of the Valles caldera; solid line shows topographic margin of the caldera, long-dashed line shows Valles ring-fracture zone, short-dashed line shows margin of the resurgent dome, and dotted line shows the outline of the Toledo embayment. Cross-section AB compares the present gravity signature (dots) with the gravity signature that the caldera is postulated to have immediately following the eruption of the upper Bandelier Tuff (dashed line) (from Nielson and Hulen, 1984).

is very asymmetric, being considerably deeper on the eastern side, and that basement structure beneath the west segment of the resurgent dome does not obviously show evidence of resurgence (Fig. 7). This is also suggested by the increasing thickness of upper and lower Bandelier Tuffs to the east (Fig. 8). From their detailed stratigraphic work on the Baca wells, Nielson and Hulen (1984) have concluded that resurgence certainly occurred after caldera collapse, but that Valles is possibly an example of a "trap-door" caldera. Nielson and Hulen (1984) have also modeled the resurgent dome as a deformed plate above a laccolithic intrusion and have concluded that the top of the Valles pluton may lie 4.7 km below the dome surface.

In the same way that Valles caldera is considered a "type" resurgent caldera, it must also be considered a "type" example of a volcanically driven hydrothermal system because it contains a potent magmatic heat source, a convecting hydrothermal fluid, an outflow plume, and meteoric recharge (compare model of Goff and Grigsby, 1982, with Henley and Ellis, 1983). The few hot springs that discharge from the caldera region fall into three unique categories based on geologic and geochemical criteria (Trainer, 1974; Goff and Grigsby, 1982). These are 1) acid-sulfate waters that issue primarily at Sulphur Springs along the western edge of the resurgent dome, 2) thermal meteoric waters that issue primarily from caldera-fill rhyolites around the

Figure 7.

Schematic cross section roughly parallel to line AB (Fig. 6) across Valles caldera based on gravity interpretation of Segar (1974) and available drilling data (from Goff, 1983).

Figure 8.
Isopach map of Bandelier Tuff and associated pyroclastic and caldera-fill rocks in vicinity of Redondo Creek graben.

western moat zone, and 3) deep geothermal waters and derivatives that circulate at depth within the caldera and flow outward to the southwest down the Jemez fault zone (Fig. 2). A fourth type of geothermal fluid occurs at depths of 3 km and more in impermeable Precambrian basement rocks flanking the caldera at Fenton Hill (Grigsby et al., 1984). This pore fluid displays subtle chemical differences from the hydrothermal waters inside the caldera but is believed to be representative of pore fluids in the heat transfer zone above a crystallizing pluton.

The hydrothermal system within Valles is controlled primarily by fracture and subordinate stratigraphic permeability along northeast-trending faults cutting the resurgent dome (Dondanville, 1978; Hulen and Nielson, 1982).

From numerical analysis of thermal gradient data obtained by Union Oil Co., Swanberg (1983) has identified two high-temperature convection cells within the caldera at Sulphur Springs and in the Redondo Creek graben (Fig. 9), but it is not clear if these cells are separate or connected at depth. Top of the geothermal system lies at a depth of approximately 550 m and has a temperature of 200°C both at Sulphur Springs and at Redondo Creek (Dondanville, 1971). Above this boiling interface is a vapor zone of low-formation pressure best documented in the Sulphur Springs area (Goff et al., 1985).

Figure 9.
Low-order polynomial fit (trend surface) to temperature gradient data and principal tectonic features, Valles caldera, New Mexico (from Swanberg, 1984).

No chemical data are yet available from deep fluids beneath the Sulphur Springs area, but fluid chemistry from five geothermal wells drilled in the Redondo Creek area was recently published by White et al. (1984). The produced fluid ranges from 250 to 300°C and from 5000 to 7000 mg/l TDS, is Na-Cl in character, and contains significant concentrations of Li, Cs, As, Br, and B. According to White et al. (1984), the reservoir is derived from one parent fluid that has thermally equilibrated at 330°C and has undergone various chemical changes by boiling and conductive cooling. Recharge to the geothermal system apparently occurs by deep circulation of meteoric water from the northeastern caldera moat zone and the overlying resurgent dome (Bodvarsson et al., 1980; Goff et al., 1985). Based on ³⁶Cl concentrations in Baca #13 fluid, the geothermal system is in secular equilibrium with its tuffaceous host rocks and does not contain young meteoric water (Phillips et al., 1984).

Outflow of the geothermal system down the Jemez fault zone was first suspected by Trainer (1974) and later documented by Goff et al. (1981) and Pearson and Goff (1981) using geologic, geochemical, geophysical, and drill hole data. Supporting evidence, strengthening this hydrologic model, was recently provided by Trainer (1984) and White et al. (1984). Although primary flow of the hydrothermal plume is focused in shattered limestone along the Jemez fault zone, additional flow occurs in permeable stratigraphic horizons above Precambrian basement on either side of the fault zone just outside the caldera (Goff and Grigsby, 1982). It is also recognized that the outflow plume consists of at least two discrete aquifers that have slightly different histories (Goff et al., 1981; Trainer, 1984; White et al., 1984).

The geophysical picture of Valles caldera has never been integrated although many different studies have been conducted. Much shallow geophysical information has been rendered unnecessary because of the great number of deep drill holes with available data (Fig. 4). Swanberg (1983) has presented the most recent interpretation of the abundant thermal gradient data as mentioned above (Fig. 9). Gradients above the two major convection cells exceed 500°C/km but become nearly isothermal well before the reservoir is encountered. The conductive gradient beneath the reservoir at a depth of 3 km as measured in Baca #12 is about 80°C/km (Hulen and Nielson, in press) suggesting that the temperature at the top of the crystallized "Bandelier" pluton (4.7 km depth) is roughly 500°C.

The gravity model of Segar (1974), based on over 700 gravity stations and the stratigraphy of Baca #4, indicates a very asymmetric caldera fill with a strong northeast grain parallel to the Jemez lineament (Fig. 6). Because the caldera is now known to deepen dramatically to the east, it appears that distribution of caldera fill and the caldera shape are controlled, in part, by precaldern structures associated with the Rio Grande rift and Jemez lineament (Goff, 1983; Nielson and Hulen, 1984).

Present microseismic activity is concentrated along fault zones around the flanks of the caldera but is glaringly absent beneath, indicating that a hot, plastic body of large size underlies Valles.* A study of P-wave and S-wave behavior beneath the caldera was performed by Suhr (1982) using explosive events from mines in the Four Corners area as energy sources. Suhr found that P-waves were delayed and S-waves attenuated beneath the caldera, again suggesting the presence of a hot, plastic body at depth. A seismic time-term analysis of local earthquake and six artificial explosion events by Ankeny (1985) verifies that a 10% reduction in P-wave velocity exists beneath Valles caldera to a depth of at least 10 km. Further work by Ankeny et al. (in press) using a simultaneous inversion of earthquake and refraction travel-time data revealed a 15-km diameter low-velocity anomaly beneath Valles caldera interpreted to be caused by elevated temperature and silicic intrusion effects, possibly but not necessarily a partial melt.

A deep magnetotelluric study of the Jemez Mountains-Rio Grande rift region by Hermance and Pedersen (1980) found that a widespread conductor occurs regionally at a depth of 15 km, but a separate higher level source was not detected directly beneath Valles.

No seismic reflection or refraction surveys have been run across Valles caldera. Although interpretation of these data might be complicated by the complex volcanic stratigraphy and more recent collapse structures, seismic methods could yield valuable information about the structure of the deep eastern side of the caldera and thus contribute to future CSDP well site selection.

C. Summary of VC-1

Valles Caldera #1 is the first CSDP well in Valles caldera and the first continuously cored well in the Valles region. VC-1 is discussed here to

* This information was provided by D. Cash and K. Olsen, Los Alamos National Laboratory, 1985.

highlight the scientific results obtained from CSDP coring and to preserve continuity in our overall CSDP at Valles caldera. The entire history of this coring effort is summarized in Table II. The Banco Bonito obsidian-southwest ring-fracture-zone target area was originally chosen during the Valles Caldera Workshop held at Los Alamos in October 1982 (EOS, June 28, 1983). Soon after, representatives of Lawrence Berkeley, Lawrence Livermore, Sandia, and Los Alamos National Laboratories gathered to formulate a "Four-Lab" proposal to initiate shallow drilling at Long Valley, Valles, and Salton Sea magma-hydrothermal systems (Eichelberger et al., 1983). The site chosen at Valles was the Banco Bonito obsidian vent on Baca Land and Cattle Co. land leased to Union Oil Co. Primary objectives were to obtain a continuous 650-m core down a young obsidian vent and to intersect the hydrothermal system in a region where outflow was suspected.

Table II lists concisely the great number of steps that go into the preparation and execution of a (modest!) CSDP coring project. During these preparations, the Banco Bonito vent site was moved to an alternate second site on Forest Service land because Union Oil Co. and Baca Land and Cattle Co. were conducting sensitive negotiations that precluded our original objectives. As summarized below, our alternate site was certainly as scientifically rewarding as the original site. Otherwise, no unusual events occurred in the planning or execution of the well. Although the coring rig arrived on July 31, 1984, and was released on September 3, 1984, after only 35 days of rig time, the total time involved from conception of the project to reporting of preliminary results was a little over two years. The project was a complete success (Goff et al., 1984; GEOTIMES, Feb., 1985).

A comprehensive drilling report documenting all activities and costs (Rowley et al., in prep.) will soon be available. Core recovery from the 856-m-deep well was over 95%, and core was curated according to procedures outlined by S. Goff (1986). Core first resided at Los Alamos but was shipped to a DOE/CSDP core repository in Grand Junction, Colorado, in the summer of 1985. A full suite of geophysical logs was obtained before completing the well. Additional measurements will be acquired and the well perforated to sample fluids. VC-1 is available for scientific use for the next five years thanks to the permit negotiated with the US Forest Service.

Primary scientific objectives at the second coring site (Fig. 10) were 1) to core the youngest intracaldera rhyolite (Banco Bonito obsidian, age

TABLE II
HISTORICAL DEVELOPMENT OF THE FIRST VALLES CALDERA,
CSDP-THERMAL REGIMES RESEARCH CORING PROJECT, VC-1
(from Rowley et al., 1985)

Date(s)	Activity
October 1982	Valles Caldera Workshop (EOS June, 1983) Choose Banco Bonito obsidian-southwest ring-fracture zone as high priority site.
November 1982	Initiate preparation of "Four-Laboratory" proposal. Begin discussions with Union Oil Co. and landowner for access to first Banco Bonito site.
December 1982	Informal discussions with core-rig contractors; decided on top-to-bottom core; preliminary cost estimates. Union Oil Co. gives verbal approval to core first Banco Bonito site.
March-April 1983	Submit "Four-Lab" proposal to DOE/OBES.
October 1983	"Four-Lab" proposal approved by DOE/OBES.
November 1983	Alert Los Alamos Support Groups (legal, safety, fire protection, procurement, environmental surveillance, etc.).
January-February 1984	Informal discussions with US Forest Service for second Banco Bonito site.
March 11, 1984	DOE Davis-Bacon determination.
April 1984	US DOE, DOI (USGS) and NSF accord signed. Forward draft procurement package (competitive solicitation with selection based on technical evaluation).
April 10, 1984	"Four-Lab" Principal Investigators and DOE/OBES approve second Banco Bonito site.
April 20, 1984	Final procurement package submitted.
April 26, 1984	Approval from Union Oil to core first Banco Bonito site received.
June, 1984	On-site management team, core curation procedures, and well sitters are organized.
June 7, 1984	Action Description Memo (ADM) approved by Los Alamos.
June 8, 1984	Baca landowner finally indicates lack of immediate interest in Banco Bonito project due to private reasons.
June 20, 1984	Responses to core rig RFQ received and evaluated.
July 3, 1984	Forest Service permit approved.
July 20, 1984	Core rig subcontract initiated with Tonto Drilling Services (Salt Lake City, Utah).
July 31, 1984	Rig arrives at VC-1 site.
September 3, 1984	Rig released at 1:15 p.m., T.D. at 856 m (2809 ft).
October 15-18, 1984	Workshop on recent research at Valles Caldera held at Los Alamos.
December 3-7, 1984	VC-1 preliminary results presented at Fall AGU, San Francisco (Geotimes, Feb., 1985).

Figure 10.

Location map of the Valles caldera showing the VC-1 core-hole site on the Banco Bonito obsidian flow; dotted pattern indicates zone of most intense intracaldera acid-sulfate alteration while stars denote postcaldera rhyolite vents.

approximately 0.1 Ma), 2) to obtain structural and stratigraphic information near the intersection of the ring-fracture zone and the precaldra Jemez fault zone, and 3) to penetrate a high-temperature hydrothermal outflow plume near its source. The location of VC-1 in the southwest caldera moat and a scant 5 km from the known hydrothermal system in Redondo Creek optimized the success of these three objectives.

VC-1 (Fig. 11) penetrates 300 m of intracaldera volcanic rocks, 35 m of Tertiary volcanoclastic breccia predating caldera formation, 91 m of Permian Abo Formation (red sandstones and shales), 381 m of Pennsylvanian Madera Limestone, and 49 m of Pennsylvanian Sandia Formation (clastic rocks). These rock types correlate well with cuttings from the Jemez Springs geothermal well (JS-1, Fig. 4) and outcrops exposed in San Diego Canyon southwest of the caldera (Goff and Kron, 1980). Based on stratigraphic comparisons, VC-1

Figure 11.
Stratigraphy of VC-1.

stopped roughly 20 m short of Precambrian basement. The Madera Limestone is approximately 400 m thicker than expected partly due to a 25° dip of the Paleozoic section. Detailed examination of the Madera limestone* has not revealed a repeated section due to reverse faulting.

The volcanic section in VC-1 also yielded some surprises. The Banco Bonito obsidian is four times thicker (149 m) than its nearest exposure 0.3 km away in San Diego Canyon, suggesting that it filled a paleovalley in the Valles caldera moat. In contrast, the Battleship Rock Tuff, which is over 100 m thick in San Diego Canyon, is only 12 m thick in VC-1. A previously unknown obsidian flow, 19 m thick, underlies Battleship Rock Tuff. The lower volcanic sequence consists of extremely lithic-rich, very densely welded upper and lower Bandelier Tuffs interpreted as probable intracauldron facies and a pre-Bandelier pyroclastic flow deposit that was probably erupted from a nearby vent (Kite et al., 1982; Self et al., 1984).

A volcanoclastic clay-rich breccia, 35 m thick, underlies the main volcanic sequence. This breccia contains about 1 m of black to brown andesitic soil at the top and grades downward into poorly sorted rock containing angular andesite and subordinate dacite, rhyolite, and basalt fragments in a variegated-clay matrix. A prominent clay seam occurs at about 305 m depth. This unit, which fills a paleo-San Diego Canyon, is now interpreted to be an altered colluvium shed from surrounding volcanoes of Tertiary Paliza Canyon Formation. The unit predates volcanic events associated with the Valles and Toledo calderas.

The volcanoclastic breccia and underlying Paleozoic rocks are faulted, sheared, and mineralized. Oriented cores of Madera Limestone, at 476 m depth, indicate that the limestone strikes approximately N35°E and dips 25°SE as opposed to the gentle NE dip seen in Paleozoic rocks in San Diego Canyon. We believe this deformation is caused by proximity of VC-1 to a buried strand(s) of the northeast-trending Jemez fault zone.

Thermal aquifers were encountered in several horizons (Fig. 12). Apparently the volcanoclastic breccia acts as a relatively impermeable barrier between cool aquifers in the volcanic sequence and thermal aquifers in Paleozoic rocks. The average thermal gradient from 350 to 750 m is 210°C/km, in agreement with the recently published thermal gradient data from the Valles caldera (Swanberg, 1983). The high bottom-hole temperature (BHT)

* This information was provided by D. Wachs, Israeli Geol. Survey, 1985.

Figure 12.
Thermal gradient of VC-1 (24 hours after completion).

of 160°C and the location of thermal fluids at the intersection of the ring-fracture zone and the Jemez fault zone (JFZ) verify that a hydrothermal plume leaks from the caldera down the JFZ and adjacent strata toward Jemez Springs and Soda Dam (Trainer, 1974; Goff et al., 1981).

Mineralization is most intense along shears, fractures, and faults from the volcanoclastic breccia on down. Although the alteration has not been examined in detail, it consists primarily of clays, calcite, pyrite, quartz, and chlorite. There is a general increase in the intensity and rank of alteration mineral assemblages with depth. Calcite veins occur from the Abo Formation on down while quartz veins occur only in Sandia Formation. A fracture from a sample of green, brecciated sandstone at 847 m contains

molybdenite (MoS_2) and anomalous concentrations of Cu, Pb, and Zn* while chalcopyrite (CuFeS_2) was identified in a Sandia quartz vein.** The ages of mineralization and their possible relationship to existing VC-1 thermal aquifers and the Valles hydrothermal system are problems now being addressed.

A cross section that runs E-W from the Jemez Plateau through VC-1 into the Valles moat zone and then bends northeast into the Redondo Creek graben area is shown in Fig. 13. The section is based on data from wells EE-2, VC-1, and Baca #12. Also shown in Fig. 13 are temperature isotherms based on the thermal gradient logs from these wells. VC-1 is located at a critical point for understanding the abrupt structural and stratigraphic changes that are associated with the collapse of Valles caldera. But VC-1 is also located at a critical point for understanding the change in the thermal regime from convective hydrothermal flow inside the Valles caldera to conductive heat flow outside. In all aspects, VC-1 has provided and will continue to provide fundamental data to our knowledge of this active magma-hydrothermal system.

D. Objectives and Justification of CSDP at Valles Caldera

In previous sections we have discussed both the objectives of CSDP and the known geology of the Valles caldera. We have demonstrated that research within the Valles caldera fulfills the stated objectives of the CSDP and is, in fact, mentioned as a prime candidate by several committees that have performed extensive reviews of potential drilling sites. We have also demonstrated that the existing subsurface data base at the Valles is large, and that the Valles is the best researched and documented young silicic caldera in the United States. In relation to other CSDP sites, Valles has both the largest suite of drill holes of opportunity and the deepest holes (B-12, 3237 m; EE-2, 4500 m). It is also the site of VC-1, one of the first holes to be completed under the CSDP. This extensive data base provides a critical foundation for the successful drilling of scientific holes, the development of new technologies, and the advancement of our understanding of important continental geologic processes.

As scientists, we are principally concerned with results of the drilling of holes for scientific purposes. However, the actual drilling process

*This information was supplied by J. Hulen, UURI, and R. Hagan, Los Alamos National Laboratory, 1985.

**This information was supplied by L. Maassen, Los Alamos National Laboratory, 1985.

Figure 13.

Schematic cross section of southwestern Valles caldera based on the known stratigraphy and thermal gradients of VC-1, EE-3 (Los Alamos National Laboratory), and Baca #12 (Union Oil Co.).

itself is risky, and extensive planning is required to ensure the successful completion of each scientific drill hole. For this reason, the Valles is an ideal candidate because drilling problems have been well documented (Molloy and Laughlin, 1982) and because the team assembled for this proposal has experience with drilling in the area.

One of the objectives of the CSDP is development of technology for performing measurements in the deep crust. As will be discussed in the following section, a hole of opportunity (Baca-12) can be reopened to provide a natural high-temperature laboratory for development and testing of logging tools that will be required in all subsequent Continental Scientific Drilling Projects.

Finally, from a technical standpoint, Valles is a prime choice for CSDP because it contains a well-defined magmatic system, a high-temperature hydrothermal system, and similarities to many fossil hydrothermal metal-depositing systems.

The following section outlines, in detail, the plan for Continental Scientific Drilling in the Valles caldera. The specific objectives to be accomplished through the drilling of each hole will be discussed along with the proposed locations and drilling plans. However, we can summarize some of the specific CSDP objectives that will be accomplished through this proposal:

- 1) Determination of the physical/chemical conditions in the heat-transfer zone between the crystallized pluton and the overlying hydrothermal system.
- 2) Determination of the mechanisms of caldera collapse and resurgence.
- 3) Determination of the stratification, differentiation, and heat-transfer processes of the Valles pluton.
- 4) Mapping of the dynamics of recharge, heat transfer, convective upflow, and outflow of the hot-water-dominated geothermal system.
- 5) Tracing the origin and evolution and the physical/chemical dynamics of the vapor-dominated portion of the geothermal system.
- 6) Determination of the mechanisms of ore deposit formation in the caldera environment.
- 7) Development of technology for drilling in high-temperature environments.
- 8) Development and testing of high-temperature geophysical logging tools.

III. LONG-TERM SCIENTIFIC DRILLING PLAN AND SITE CHARACTERIZATION

A. Introduction

Union Oil Co. (Santa Rosa, CA) has drilled about 20 deep wells into the NE-trending Redondo Creek graben in its search for intermediate-depth geothermal resources (Fig. 4). The company's wells have provided insight into only one of the many intriguing scientific targets within Valles caldera. New CSDP efforts outlined in this section are designed to yield valuable information about the complex mechanisms of caldera collapse and resurgence, the physical/chemical properties of country rock above the crystallized pluton, the evolution of vapor-dominated hydrothermal systems, the dynamics of hydrothermal convection cells, and the formation of ore deposits.

The most recent Valles caldera workshop (October 1984) led to panel discussions of sites for deep scientific drilling within the Valles caldera and resulted in recommendations for a series of holes in different locations within the caldera. These holes are shown in Table III and Fig. 5 and are numbered in order of the priorities that were established during a meeting of the panel chairmen and co-chairmen. Investigation of the southwestern ring-fracture zone is under way now that VC-1 is complete. Sites VC-2 through VC-4 (Fig. 5) are discussed in detail in following sections as the three sites that would best probe the depths of Valles caldera and best serve CSDP Thermal Regimes objectives. These three sites are Sulphur Springs, Baca-12 (reopening and deepening), and Valle Grande. Because Sulphur Springs is projected to be an intermediate-depth well of comparatively modest cost, with appeal to a wide variety of geoscientists, we plan to core this site first. Thus, the justification, coring program, and scientific plan in Section IIIC stress the Sulphur Springs site before the other two.

The Sulphur Springs area (VC-2a and VC-2b) will provide data for the scientific investigation of a number of important problems. Specifically, it will answer questions concerning the character of the interface between vapor-dominated and hot-water-dominated systems and will provide information on the character of the western ring-fracture system. It will also provide important information on the stratigraphy of the Bandelier Tuff and pre-Bandelier Tuffs on the west margin of the resurgent dome and, thus, on the mechanisms of resurgence and magmatic evolution of the caldera complex. Because a boiling interface occurs about 550 m beneath Sulphur Springs, we anticipate that much may be learned about ore deposit mechanisms. Predicted temperature and proposed depth of VC-2b are 300°C and 2 km.

We also plan reopening and deepening Baca-12 (VC-3) in the southern Redondo Creek area. Although this site will not be deepened until the third year of this plan, the hole can serve as a valuable laboratory for the development, testing, and modification of high-temperature logging tools, which will be vital to all CSDP projects. This is the deepest hole in the Baca geothermal field at 3243 m and has the highest bottom-hole temperature, measured at 341°C. Major objectives at VC-3 are to penetrate the crystallized pluton roof beneath the caldera, to investigate the heat-transfer zone in country rock between the pluton and the hydrothermal system,

TABLE III

PROPOSED CSDP WELLS TO INVESTIGATE THE VALLES CALDERA MAGMA-HYDROTHERMAL SYSTEM; VC-1 WAS COMPLETED IN SEPTEMBER 1984

Well No.	Type*	Estimated Depth, m	Estimated BHT, °C	Primary Objectives
1. VC-1	C	650 (856)**	120 (160)**	<ul style="list-style-type: none"> a. Penetrate hydrothermal outflow plume b. Investigate intracaldera structure and stratigraphy c. Core youngest intracaldera rhyolite
2. VC-2a	C	500	200	<ul style="list-style-type: none"> a. Penetrate vapor-dominated zone
3. VC-2b	R/C	2000	300	<ul style="list-style-type: none"> a. Penetrate interface between vapor-dominated and hot-water-dominated zones at 550 to 600 m b. Investigate structure and stratigraphy of western resurgent dome c. Investigate thermal/physical/mineralogical properties of conductive basement beneath hydrothermal system
4. VC-3	R/C	5500	500	<ul style="list-style-type: none"> a. Penetrate crystallized roof of pluton that produced Valles caldera b. Acquire structural and stratigraphic data necessary to investigate the mechanism and evolution of resurgence c. Investigate heat transfer/metamorphic zone between crystallized magma below and hydrothermal system above
5. VC-4a	C	1000	100?	<ul style="list-style-type: none"> a. Investigate lacustrine-rich caldera fill b. Penetrate northeastern Valles ring fracture
6. VC-4b	R/C	6000?	400?	<ul style="list-style-type: none"> a. Penetrate possible buried hydrothermal system in Valles/Toledo caldera complex b. Investigate structural and stratigraphic relation of earlier Toledo caldera and Rio Grande rift to present Valles caldera c. Investigate recharge zone to hydrothermal system
7. VC-5	C	2000	150?	<ul style="list-style-type: none"> a. Penetrate floor of Toledo embayment b. Investigate relationship of Jemez lineament and precaldern volcanism to Valles/Toledo calderas c. Investigate recharge zone to hydrothermal system.

* C = core hole; R/C = combined rotary and core hole.

** Numbers in parentheses show completed depth and temperature of VC-1.

and to study the evolution of the central resurgent dome. Anticipated temperature and depth of VC-3 are 500°C and 5.5 km.

The third priority site lies in the Valle Grande area (VC-4a and VC-4b). A deep well at this location would penetrate the deep eastern floor of the Valles/Toledo caldera complex and would investigate structural relationships between the calderas and the earlier Jemez lineament and Rio Grande rift. Core from intracaldera lacustrine deposits (VC-4a) would yield much information on postcaldera development and climatic variations during the last 1.1 Ma. Additional information would be obtained on recharge to the deep hydrothermal system. Anticipated temperature and depth of VC-4b are 400°C(?) and 6 km(?).

The final priority well is VC-5, which is located within the Toledo embayment. The hole will test stratigraphy, structure, and magmatic evolution preceding formation of the Valles caldera. It will also investigate the influence of the Jemez lineament in the northern portion of the caldera structure and will possibly provide input into models of the hydrologic recharge of the geothermal system. Although no detailed drilling plan is discussed in Section III for VC-5, it is not a difficult drilling target from either the planning or the execution standpoint. The anticipated temperature and depth would be 150°C(?) and 2 km. Details for this coring effort are not discussed in this proposal because coring would not occur until several years into the program.

All the sites were selected with specific scientific objectives in mind. They were then prioritized with consideration given to both their costs and their short- and long-range scientific benefits. It is recognized that, as the investigations proceed, priorities may change as a result of what we have learned from our previous work or as a result of funding constraints.

In addition to the holes proposed here, there are other holes of opportunity within the caldera and its environment, which complement the information to be produced in this scientific program. The well data at and near Fenton Hill (Los Alamos) and inside Valles (Union Oil Co.) have already been mentioned (Fig. 4). In addition, stratigraphic and hydrogeochemical data from the WC#23-4 well drilled by Geothermal Resources International near the western margin of the caldera are available under a cooperative agreement with Los Alamos. The 1.3-km-deep AET-4 well drilled by Sunedco south of the Valles and east of San Diego Canyon soon will be made available to the

scientific community because the well has been given to Los Alamos. Information from the Fenton Hill area, the Baca project and GEO, VC-2, VC-3, and VC-4 will form an east-west cross section across a young silicic caldera and associated hydrothermal system in a young tectonic environment. VC-1, VC-3, VC-4, and VC-5 will form a longitudinal section parallel to the trend of the Jemez lineament. Taken as a whole, our CSDP is designed to develop a three-dimensional picture of one of the classic silicic volcanic centers in the world. The project will answer important questions concerning its magmatic and structural evolution and the important hydrothermal and mineralization processes that are presently active within the structure.

B. Sulphur Springs Site (VC-2)

1. Objectives. To demonstrate cost effectiveness to the scientific community, Continental Scientific Drilling Program sites should be designed so that each hole investigates several important problems. VC-2, at Sulphur Springs, satisfies this criterion. The principal objective will be to investigate physical and chemical characteristics of vapor- and hot-water-dominated geothermal systems and the boiling interface between these zones. VC-2 will also investigate the process of vapor zone formation, which has probably evolved from a hot-water system. The hole will investigate intracaldera stratigraphy and greatly improve our understanding of eruption and depositional processes of catastrophic ash-flow eruptions. The hole will be located near the structural interface between the ring fracture system and the resurgent dome and will allow an evaluation of structural processes in the development of fracture permeability. Drilling information from six nearby wells, a detailed 1:5000 scale geologic map, and very detailed geochemical studies are already available for the Sulphur Springs area (Goff and Gardner, 1980; Goff et al., 1985; Charles et al., in press).

2. Background. Sulphur Springs (Fig. 14) is the hottest, most active zone of hot springs and fumarole discharge within Valles caldera. On the basis of its acid-sulfate springs, both Renner et al. (1975) and Goff and Grigsby (1982) suggested that Sulphur Springs may be the surface expression of a small vapor-dominated geothermal system. The boiling interface will be intersected at a depth of about 550 m in caldera fill at an expected temperature of about 200°C (Goff et al., 1985). Temperatures of 100°C and fractures containing steam, CO₂, and H₂S are expected at depths of 50 m or less. The temperature gradient below 550 m is expected to be relatively

Figure 14.

Fault map of Sulphur Springs area from geologic map of Goff and Gardner (1980).

low because of near-isothermal conditions in the convecting hydrothermal system. On the other hand, the gradient is expected to rise conductively once Precambrian rocks are encountered; we intend to penetrate as much as 300 m of Precambrian in order to study the heat-transfer zone and associated metamorphic reactions.

The thermal anomaly of Sulphur Springs is displayed in Figure 9, a temperature gradient map of the caldera reproduced from Swanberg (1984). Sulphur Springs is one of two major high-temperature convection cells within the caldera, suggesting that a deeper zone of upwelling fluids underlies this area. We do not presently know how the convecting cell at Sulphur Springs is connected to the greater hydrothermal system of the caldera and to the convecting cell in the Redondo Creek graben.

Vapor-dominated systems, as exemplified by Sulphur Springs, are important to the geothermal industry because they may yield dry steam, which is the most economically desirable geothermal resource (Truesdell and White, 1973).

Famous examples of vapor-dominated systems include The Geysers, California, Larderello, Italy, and Matsukawa, Japan, which all produce electricity. According to White et al. (1971), vapor-dominated systems require a high-temperature boiling interface at depth between vapor- and liquid-dominated zones. The boiling interface is documented at most vapor-dominated geothermal systems, although The Geysers is a notable exception (Thomas et al., 1981). If a boiling interface does occur, its existence has important implications for ore genesis because loss of gases such as CO_2 and H_2S , turbulence due to boiling, and concentration of residual species in solution caused by loss of steam and volatiles may form precious and base-metal ore deposits. The famous Ag-Pb-Zn-Cu-Au ores of the Creede Mining District, Colorado, were deposited in a caldera environment that has postulated similarities to the Sulphur Springs reservoir configuration at Valles caldera (Steven and Eaton, 1975; Bethke and Rye, 1979).

A detailed geochemical study of the Sulphur Springs area by Goff et al. (1985) shows that acid-sulfate springs and argillic-to-advanced-argillic alterations are concentrated along intersections of subsidiary faults with the NE-trending Sulphur Creek fault. Noncondensable gases consist of roughly 99% CO_2 and 1% H_2S with minor quantities of H_2 , CH_4 , NH_3 , and He. Empirical gas geothermometry suggests a deep reservoir temperature of 215 to 280°C. Comparison of ^{13}C and ^{18}O between CaCO_3 from well cuttings and CO_2 from fumarole steam suggests a fractionation temperature of 200 to 300°C by thermal decarbonation of hydrothermally altered Paleozoic limestone and vein calcite in the reservoir rocks.

A plot of δD versus $\delta^{18}\text{O}$ for surface fluids at Sulphur Springs and deep reservoir fluid represented by Baca #13 is shown in Fig. 15. We first note that D contents of fumarole steam, nearby surface cold springs, and deep reservoir fluid are approximately the same, suggesting that recharge to the total geothermal system originates from nearby sources. We also note that the surface features at Sulphur Springs display a rather classic evaporation trend toward greater concentrations of δD and $\delta^{18}\text{O}$. Interestingly, the steam at Sulphur Springs denoted by the Main Fumarole is lighter in $\delta^{18}\text{O}$ than is meteoric water. In a rather elaborate discussion, Goff et al. (1985) have shown that such "light" steam must originate either by vaporizing relatively shallow groundwater at 200°C or by means of a two-stage boiling process through an intermediate-level reservoir at roughly 200°C.

Figure 15.

Plot of deuterium versus oxygen-18 for thermal and nonthermal waters of the Sulphur Springs area (from Goff et al., 1985).

Thus, both drilling and geochemical data indicate that a high-temperature boiling interface occurs beneath Sulphur Springs, probably 200°C at 550 m. Drilling and geochemical data also indicate that liquid water as hot as 300°C may exist in stacked reservoirs (Fig. 16), filling fractures and porous horizons at depths greater than 550 m. Because of these high subsurface temperatures, the existence of a boiling interface, the high-Cl nature of the deep hydrothermal fluid that exists elsewhere in Valles, and the existence of some metal anomalies in the fluid (White et al., 1984) and solid phases (Hulen and Nielson, in press), we believe that Sulphur Springs is a valuable choice for CSDP. It will yield important information on the interface between vapor-dominated and hot-water-dominated zones and related ore deposition mechanisms in an active environment.

The structural and stratigraphic model shown in Fig. 16 is based on drilling data (Fig. 17), detailed 1:5000 scale geologic mapping by Goff and Gardner (1980), and the gravity interpretation of Segar (1974). Although Sulphur Springs occurs in a localized graben-like feature, on the western

Figure 16.
Schematic cross section of Sulphur Springs area showing vapor zone and underlying liquid-dominated zones (from Goff et al., 1985).

edge of the resurgent dome, drilling results over the western half of the caldera and the gravity interpretation indicate the caldera is asymmetric and steps eastward toward the precaldern Rio Grande Rift (Goff, 1983). Detailed examination of cuttings in the Redondo Creek area of the caldera (Hulen and Nielson, 1982; Nielson and Hulen, 1984) shows that both the Upper and the Lower Bandelier Tuffs thicken eastward as well. Because it is now recognized that the earlier Toledo caldera is nearly coincident with present Valles caldera (Goff et al., 1984; Heiken et al., 1985), a core hole at Sulphur Springs would tell us much about the stratigraphy of tuffs in the western (shallow) collapse zone of the caldera, enable us to recreate the pre-Valles structure, and allow us to document some of the mechanisms of resurgence, in this "type" resurgent caldera.

3. Drilling/Coring Program. Seven wells have already been drilled in the Sulphur Springs area (Figs. 4 and 14; Table IV), and two of these wells (Baca #1 and Baca #3) are located approximately 1 km from the site proposed for VC-2 (the WC #23-4 well data are proprietary until January 1986). These should be similar to the proposed hole in terms of geologic formations

Figure 17.

Stratigraphy of existing deep wells in the Sulphur Springs area; locations on Figs. 4 and 14 (from Goff et al., 1985).

penetrated. The deepest of these two nearby holes reached a total depth of 790 m, or 1210 m short of the target depth of 2000 m. Both were drilled with air as the circulating fluid. Both encountered steam at depths of ≥ 450 m and temperatures $\geq 160^\circ\text{C}$ (Table IV). With the limited historical information available on the drilling in this area, it seems that a two-phase approach consisting of two wells would be the most likely to succeed (Fig. 18).

a. Phase One, VC-2a. The first coring effort should be designed to penetrate the upper, vapor-dominated zone down to approximately 500 m. In this harsh drilling environment, it will be necessary to relocate a well quickly and easily should insurmountable drilling problems be encountered. That means a portable (truck-mounted) coring rig should be used. Pressure control equipment (BOP) will also be required because one of our objectives

TABLE IV

SOME GEOTHERMAL WELLS OF THE SULPHUR SPRINGS AREA, VALLES CALDERA, NEW MEXICO; LOCATIONS ON FIGS. 3 AND 13. DATA OBTAINED FROM DONDANVILLE (1971), LAMBERT AND EPSTEIN (1980), AND UNION OIL COMPANY OPEN FILES.

Well	Depth (m)	Formation pressure (MPa)	Maximum temperature (°C)	Comments
Westates-Bond #1	1130	0.76	199 @ 740 m	Permeable zones filled with liquid water
Baca #1	790	0.52	157 @ 446 m	Well encounters steam zones @ 450 m with less than 5% liquid water
Baca #2	1740	2.14	220 @ 430 m	Well contains liquid water; no steam zones
Baca #3	680	0.76	199 @ 555 m	Well initially flowed 89% water from zones below 585 m; 50% water 1 day later
Baca #7	1687	9.7	240 @ 1675 m	Well contains liquid water; low permeability
Baca #8	1350	7.9	283 @ 1290 m	Well contains liquid water; low permeability; pressure = 0.76 MPa @ 300 m
WC#23-4				Well data proprietary until January 1986.

Figure 18.
Preliminary well-completion diagram of VC-2 core holes.

is to encounter superheated steam. The equipment must be able to operate at downhole temperatures of $\sim 200^{\circ}\text{C}$. A drilling fluids program will be needed to accommodate the high temperature as well as the potentially acid environment.

To begin VC-2a, a shallow surface conductor will be emplaced (3-10 m), and then continuous coring will begin with an HQ size bit (~ 96 -mm-diameter hole, 63.5-mm-diameter core). Coring should proceed to approximately 100 m. Following geophysical logging the hole will be reamed and cased with a suitable liner, probably 114.3 mm in diameter. After reaching the planned total depth of approximately 500 m at HQ size, a final set of geophysical logs will be obtained, and the hole will be completely lined to make it available for later re-entry. Upon completion of Phase One a preliminary site characterization report will be prepared to assist in the planning of Phase Two.

b. Phase Two, VC-2b. Planning of Phase Two will be heavily influenced by the results from Phase One. VC-2b will be spudded as close as possible to the Phase One hole to avoid stratigraphic and structural surprises and still hydrologically isolate vapor-dominated and liquid-dominated regimes. A fairly large-diameter surface casing (perhaps 250.8 mm) will be set in a 311.1-mm hole down to the same depth as the TD of VC-2a. The casing must be securely anchored (cemented) to avoid problems during later activities. This initial section will be drilled with a rotary rig following the emplacement of a shallow surface conductor and installation of a BOP. The rig should then switch to a dual drill pipe string (pipe within a pipe). With this dual string the drilling fluid circulation is contained entirely within the outer pipe and therefore protected from the formation, providing much more controllable drilling. A large-diameter (~ 215.9 -mm) core bit would then be run in the hole and the cement cored to confirm the quality of the cementing job. As the success of core drilling is highly dependent on control, another item to help provide this control will be a hydraulic top-hole drive assembly. Rotary coring in this fashion should proceed as deep as possible.

If the large-diameter coring is stopped because of problems in the well, a small NQ coring string should be run. This will consist of a 75.7-mm-diameter bit followed by a core barrel (perhaps as long as 20 m) and will utilize a positive displacement downhole motor on an appropriately sized drill string (N-size rods). This assembly will run inside the large core bit and pipe. Many trips will have to be made to retrieve this smaller diameter

core barrel. Coring will continue at this size as deep as possible. When it becomes necessary, both the small- and the large-diameter coring strings will be pulled from the hole, and then the hole will be rotary-drilled to the depth of the last core. The large coring string will again be run in the hole and coring resumed following the above procedure. This sequence will be continued until the target depth is reached.

The Phase Two configuration described above provides many opportunities to overcome drilling obstacles such as setting large casings and switching to other coring techniques. The dual string will allow controlled drilling fluid circulation in both forward and reverse modes. This plan is designed to be flexible enough to achieve success even with the adverse temperature and permeability conditions expected at this complicated site.

4. Statement of Work

a. Planning and Coordination. The successful completion of this project will require efficient management and coordination between the Principal Investigators, Chief Scientist, Chief Engineer, funding agency, and contracting staff. The responsibilities of these groups and individuals will be described in the management section of this proposal. Several planning and coordination meetings will be held during the period between funding and the initiation of the drilling operation. During these meetings, the progress of the various components of the project will be reviewed and work assignments made.

b. Permits. The necessary permits and land access agreements for drilling of the well will be completed. This will include establishing safety requirements, preparing environmental impact statements, and securing permits from the cognizant state and Federal agencies.

c. Contracting. Specifications for the drilling operation will be established and RFQs prepared and released to the public. Responses to procurements will be reviewed by both business and technical staff. A contract will be negotiated and signed with the successful bidder.

d. Drilling. To maximize the recovery of core, sampling of fluids, and recording of temperature-pressure data in both the liquid- and vapor-dominated zones, we propose that two wells be sunk as described in the drilling/coring program above. The first well will be cored to a depth of about 500 m to study the vapor-dominated zone while the second nearby well will be rotary-drilled and cased to this depth and then cored to a depth of 2

km to study the interface between the two zones, the liquid-dominated zone proper and the underlying heat-transfer zone. The advantage of this scheme is that it isolates vapor-dominated from liquid-dominated conditions so that they can be studied separately as a function of time.

During drilling, the Chief Engineer will maintain a staff on the rig. In addition, a team of scientists will be present to monitor collection of samples and to ensure proper documentation of these samples.

e. Preliminary Examination. Besides the major scientific proposals that are outlined in the Appendix, a specific set of scientific needs is required during and soon after the coring/drilling of VC-2a and VC-2b at Sulphur Springs. These needs include lithologic and geophysical logging, hydrothermal alteration studies, fluid and gas sampling, and state-of-stress measurements. Funding for these important activities is included in the proposal under preliminary examination.

1) Lithologic Logging. Careful lithologic logging of the core is required for basic documentation and characterization. This descriptive process is needed both to provide background for studies associated with the drilling process, such as geophysical logging and fluid sampling, and to provide documentation required for the curation process. The lithologic log can be widely circulated among interested researchers and will greatly aid them in formulating their scientific proposals and will expedite their requests for research samples.

2) Geophysical Logging. Because the wells VC-2a and VC-2b will investigate the vapor- and liquid-dominated zones at Sulphur Springs, the geophysical logging can be separated into two parts. In VC-2a the following logs are proposed:

- Caliper (0 - TD) - measure borehole size for condition and log corrections,
- Natural Gamma Ray (0 - TD) - lithology determination,
- Spectral Gamma Ray (0 - TD) - identification of fluid movement and zones of anomalous rare earth concentrations,
- Thermal and Epithermal Neutron (0 - TD) - identification of zones of bound water (generally clay-rich zones),
- Density (0 - TD) - rock density variations in well,
- Temperature (0 - TD) - temperature gradient,

- Spinner (intervals of interest) - fluid entries,
- Directional Survey (0 - TD) - well orientation.

For VC-2b, in the liquid-dominated zone, we propose to acquire the same logs as above plus the following logs:

- Sonic (static water level to TD) - acquire sonic velocity of rock formation and locate fractures, and
- Resistivity (static water level to TD) - acquire electrical resistivity of rock formations and locate fractures.

All logs will be acquired in analog and digital form. All logs will be calibrated immediately before and after logging, and a 60-m repeat run will be acquired. Copies of all logs will be filed with Petroleum Information Service, Denver, Colorado, where interested researchers may obtain them for reproduction costs only. A preliminary interpretation of the logs with respect to borehole lithology and other parameters forms part of the preliminary examination report.

3) Hydrothermal Alteration. Following the lithologic logging, selected samples will be analyzed by x-ray diffraction and petrographic techniques in order to characterize the hydrothermal alteration assemblages. Again, this study will not be exhaustive, but it will provide an initial identification of hydrothermal alteration mineralogy encountered in VC-2. This information will provide needed background for the interpretation of geophysical well logs and the design of fluid sampling programs. In addition, the results will provide information that can be distributed to other researchers to allow them to develop research proposals for detailed work on the VC-2 core.

4) Fluid and Gas Sampling. Because we propose that two wells be drilled in the Sulphur Springs area that focus on the vapor- and liquid-dominated zones respectively, fluid and gas sampling procedures will differ. VC-2a (vapor zone) can probably best be sampled for gases and fluid at the wellhead using a portable steam separator. Water samples come off one side and gases the other. A slim downhole sampler will be used only if the well does not emit gas, but we believe this situation to be highly unlikely given the known well histories in the area.

VC-2b (liquid zone) will be sampled in situ using an appropriate downhole sampler or samplers. Specific intervals of interest will be identified based on the coring history of the well and subsequent geophysical logs. The solid liner will be perforated and hot water entries sampled using packers as

necessary. If VC-2b is capable of flowing, either naturally or induced, wellhead samples will be obtained using a portable steam separator as described above.

All water samples will be analyzed for major/minor/trace element chemistry, stable isotopes of water, and ^{13}C , ^{34}S isotopes and tritium. All gas samples will be analyzed for bulk composition; gas/steam ratio; and ^{13}C , ^{18}O , and ^2H isotopes of appropriate gas species. Samples for more specialized analytical work will be provided either as outlined in the scientific proposal package (Appendix) or as new requests arrive.

5) Stress Measurements. Stress measurements will be made using the strain-relief technique on oriented cores taken from the Abo Formation and the Precambrian rocks. A heat shield will be required on the coring device since the bottom-hole temperature is anticipated to be about 300°C . Each oriented core will be short (approximately 0.5 m long) to keep the downhole time of the orienting device to a minimum. At a depth of 2 km the total time to core (round-trip time in and out of the hole and coring time) would be about 5.5 to 6 hours. Existing oriented coring devices will, with minor modifications, be able to perform the job. Some modest amount of development funds (about \$5 K) will be required to increase the chance of success in obtaining an oriented core in the Precambrian section of the anticipated 300°C temperature. There is little doubt that a core can be taken in the Abo Formation. Strain measurements and analysis of the data will be performed with the same equipment and techniques that were successfully used on the oriented core taken at VC-1.

f. Information Dissemination. The data acquired through the drilling of the VC-2 site will be made available to the scientific community as rapidly as possible to encourage widespread use of the data and to stimulate submission of proposals for work on the hole. The most effective means of bringing this about is to sponsor a workshop on the results of the drilling and the preliminary examination. We will organize such a workshop at Los Alamos soon after the completion of the drilling and preliminary examination of cores. In addition, a report on the preliminary examination will be prepared within two months to document project results.

g. Curation. Core and fluid samples collected during this program will be curated according to established DOE/OBES procedures (S. Goff, 1986).

This aspect of the project is described in greater detail in Section IV of this proposal.

C. Baca-12 Reopening and Deepening (VC-3)

1. Objectives. Baca-12 represents a hole of opportunity that can be utilized to satisfy one of the principal objectives of CSDP: penetration of the hot crystallized pluton of a major caldera. Since this hole is already more than 3 km deep, the deepening of Baca-12 can satisfy this objective more cost effectively than any other location we are aware of. The hole will also accomplish the following objectives. It will define the processes of heat and mass transfer in the conductive regime, which separates the Valles pluton from the overlying convective hydrothermal system. The hole will determine the depth and chemical composition and depth variation of the Valles pluton, in order to refine models of the formation of resurgent cauldrons and chemically zoned magma chambers. It will sample the upper portions of the Valles pluton to define differentiation processes. It will also allow us to map the fault and fracture pattern as a function of depth within the conductive regime and into the Valles pluton. In addition, it will allow us to investigate processes in an active contact-metamorphic system. Prior to deepening, the hole can be used as a natural laboratory for the development and testing of geophysical logging tools in a high-temperature environment.

2. Background. Baca-12 is the deepest well drilled in the Baca geothermal project area (Figs. 4 and 19). This hole was originally drilled to a depth of 2808 m and then subsequently deepened to test the potential for deep geothermal production within the field. The hole presently bottoms in Precambrian granite at a depth of 3242 m. A schematic of the well is shown in Fig. 19. The hole is preserved with 7 in. casing to a depth of 2711 m near the bottom of the Abo Formation.

Although Baca-12 is in the cooler portion of the field, where hydrothermal fluids flow toward the southwest, its great depth achieves a bottom-hole temperature (341°C) that is the highest measured at Valles caldera to date. The temperature log of the hole is shown in Fig. 20. Survey 47 was run prior to deepening, and survey 51 was run following the deepening. The behavior of survey 51 suggests that the hole had not achieved thermal equilibrium, so the actual temperatures can be expected to be higher than those shown. Except for these temperature surveys, no other geophysical logs have been run in the lower part of this hole. In addition, 0.96 m of

Figure 19.
Schematic diagram of Baca #12.

granite core was recovered from the well bottom. The cored granite is Precambrian and lithologically similar to that drilled at Fenton Hill.*

The intersection of Precambrian basement in the bottom of Baca-12 rather than the pluton of the Valles caldera has led to questioning of Smith and Bailey's (1968) model for the formation of resurgent domes (Goff, 1983). However, Nielson and Hulen (1984) and Hulen and Nielson (in press) have

*This information was supplied by A. W. Laughlin, Los Alamos National Laboratory, 1985.

Figure 20.

Temperature gradients of Baca #12 compared with stratigraphy: CF = caldera fill sediments, Ts = Upper Bandelier Tuff, Ot = Lower Bandelier Tuff, Lt = lower tuffs, Tpc = Paliza Canyon Formation, Pa = Abo Formation, Pm = Madera Limestone and Sandia Formation, Pcg = Precambrian basement.

applied a model of dome formation which suggests that the magmatic body which produced the doming lies at a depth of 4700 to 4900 m or approximately 1500 to 1700 m beneath the bottom of Baca-12. Thus, if these estimates are correct, the crystallized pluton beneath the Valles caldera is within accessible drilling depths.

At this time, Baca-12 has been plugged and abandoned by Union Oil Company. We propose to reopen this hole, perform appropriate scientific measurements, and eventually deepen Baca-12 to between 5000 and 5500 m, where we believe the silicic pluton of the Valles caldera will be intersected.

3. Drilling/Coring Program. A careful review of previous activities in the hole will help us know how to proceed with the proposed second deepening. After achieving access to the hole and cleaning it out, considerable effort must be expended to determine its condition. With downhole temperatures expected to reach and possibly exceed 500°C, the opportunity exists to develop technology and test drilling hardware and logging tools.

The abandoned, buried wellhead must be located and excavated and a new wellhead installed. Since the hole has been deepened once beyond the original significant depth, it will be necessary to determine whether the casing is worn out. Various casing investigation logs must be run. The status of the cement behind the casing will also be established. At the expected high temperatures, weak casing or cement could jeopardize the project's success. It may be prudent to use a retrievable casing string within the existing pipe to avoid problems.

This project would lend itself nicely to a two-phase approach. In Phase One, a workover rig should be used to re-enter the hole and clean it out for the logging and other preliminary operations. This rig would be used to drill out the cement plug and fill material and to run additional casing if necessary. Various technology development efforts could also be accomplished. There would be an opportunity to test various deep coring techniques in preparation for the actual deepening, which will require a much larger rig.

Upon completion of the initial phase, the data will be analyzed, and the actual deepening (Phase Two) will be planned with this information. The deepening should be a continuous coring operation, if possible, to maximize lithologic and structural data. Upon reaching the target depth, geophysical logging and fluid testing will be accomplished; methods to be used will depend on what high-temperature tools are available. The lower part of the hole will then be cased, if necessary, to provide access for future activities.

4. Statement of Work.

a. Planning and Coordination. This component of the work statement will provide for the planning and coordination effort between the Principal Investigators, the Chief Scientist, the Chief Engineer, the funding agency, and the contracting staff.

b. Permits. Both the reopening and deepening of Baca-12 will require permits from the appropriate state and Federal agencies. In addition, safety documents and environmental assessments will be prepared.

c. Contracting. Specifications for contracts required to reopen Baca-12 and to deepen the hole to 5.5 km will be established. RFQs for the work will be prepared and released to the public. Responses to the procurement will be reviewed by both the business and the technical staff, and a contract will be negotiated and signed with the successful bidders.

d. Drilling.

- 1) Reopen Baca-12 and clean the well out to its total depth.
- 2) Run a complete suite of geophysical well logs in the hole to evaluate hole conditions and plan the deepening effort.
- 3) Collect a fluid sample from the lower portion of the hole.
- 4) Deepen Baca-12 to 5.5 km and probable temperature of 500°C and preserve the hole for additional scientific measurements. A large portion of this deepening effort should be planned to maximize core recovery.
- 5) Maintain the hole for appropriate experiments such as testing the survivability of geophysical logging tools in the high-temperature environments, logging, fluid sampling, and alteration studies.
- 6) During the deepening of Baca-12, the Chief Engineer will maintain a staff to monitor the drilling. In addition, scientists will be present at all times to monitor the collection of samples and to ensure the proper documentation of these samples.

e. Preliminary Examination. As described in the Statement of Work for VC-2, the preliminary examination will include lithologic and geophysical logging, hydrothermal alteration studies, fluid and gas sampling, and state-of-stress measurements.

f. Information Dissemination. The data acquired through the reopening and deepening of Baca-12 (VC-3) will be made available to the scientific community as rapidly as possible. This data transfer will be implemented through workshops and published reports.

g. Curation. Sample curation will be performed as outlined in Section IV.

D. Valle Grande Site Characterization and Drilling Program (VC-4)

1. Objectives. No deep drilling has been done in the eastern part of the caldera complex. Deep core holes here would test the hypothesis of a trap-door caldera (Nielson and Hulen, 1984; Heiken et al., 1985), test the proposed stratigraphic sequence, examine the caldera moat deposits, and examine a postulated recharge area to the deep hydrothermal system associated with the downdropped part of the trap-door caldera. Smith and Varga (1984) have presented evidence that most hydrothermal activity in the Bonanza caldera, a trap-door caldera, was along the downthrown part and not along the hinge line. Thus, it is possible that an unrecognized hydrothermal system or cell exists within the caldera complex below the Valle Grande, capped by one of the densely welded members of the Bandelier Tuff. This hole will also investigate the ring-fracture system that has served to control magmatic processes since the formation of the Valles caldera.

2. Background. The Valle Grande area makes up the southeastern third of the Toledo-Valles caldera complex (Fig. 21); it is bounded on the east by the Sierra de Los Valles, which are composed mainly of precaldern dacite domes and andesitic composite cones of the Tschicoma Formation. The northwestern side of the valley is Redondo Peak, the eastern segment of the Valles resurgent dome, composed mainly of Bandelier Tuff. The Valle Grande itself is part of the eastern moat of Valles caldera.

Rocks mapped within the moat include exposures of lacustrine sediments near the valley center and gravels and sands of alluvial fans on the caldera wall and resurgent dome (Griggs, 1964; Smith et al., 1970). Water wells drilled in the center of the Valle Grande penetrate 360+ m of caldera fill, including sands, gravels, and diatomaceous silt (Griggs, 1964). Overlying (and interbedded with?) the moat sequence are Valles intracaldern rhyolite domes. These include Cerro del Medio, one of the oldest and largest rhyolitic domes, at 1.1 Ma (Doell et al., 1968) and South Mountain and Cerro la Jara, two of the younger domes, erupted at 0.5 Ma. The inferred position of the Toledo and Valles ring fractures, and the structural line along which these rhyolite domes were erupted, runs from South Mountain and Cerro la Jara through the middle of the Valle Grande and across Cerro del Medio.

The thickness of caldera fill in the eastern half of the caldera complex is unknown. Other than a few shallow water wells, the only basis for interpretation of this thickness is the gravity survey of Segar (1974). On

LEGEND

0 1 2 km

Geology compiled from Griggs (1964) and Smith et al. (1970)
Gravity compiled from Sagar (1974)

Figure 21.
Diagram of Valle Grande area showing potential hole sites.

the basis of those data (Figs. 6 and 7), it is believed that caldera fill may be up to 3400 m thick. If the stratigraphic sequence is similar to that of the western half of the caldera, where there are many deep wells, the caldera fill should include 1) lower tuffs--silicic-welded and nonwelded tuffs older than the Bandelier Tuff; 2) the Otowi member of the Bandelier Tuff; 3) Cerro Toledo rhyolitic tuffs, moat sediments, and rhyolite lavas of Toledo caldera; 4) Tshirege member of the Bandelier Tuff; and 5) intracaldera rhyolitic tuffs, lavas, and moat sediments of the Valles caldera. If the caldera fill thickens greatly toward the east, as suggested by the stratigraphic work of Nielson and Hulen (1984) and as interpreted on the basis of gravity data, then it is possible that both the Toledo and Valles calderas are trap-door calderas, with the greatest subsidence along the trend of the Jemez lineament and the precaldern Tschicoma volcanoes.

Seismic refraction and reflection lines, as proposed by Olsen in the Appendix, Panel 2, would be useful for identifying the structural form of the Valle Grande area: Are the large gravity lows caused by prevolcanic grabens or by a thick caldera-fill sequence within a trap-door caldera complex? The seismic data would also be useful in identifying major reflectors, such as those that may exist at the boundaries between the upper and lower members of the Bandelier Tuffs, the pre-Bandelier Tuff, and precaldern rocks. These seismic studies are not budgeted in this proposal.

Testing scientific problems within the Valle Grande area can be done at several candidate sites (Fig. 21).

Site A) This proposed site is adjacent to the rhyolite flows of Cerro del Medio and about halfway between the inferred ring fracture and the base of the resurgent dome. It is in the middle of one of the deepest gravity lows (Fig. 21). The site is far enough from Baca Ranch headquarters and the highway to be unobtrusive, but it is also close to a graded ranch road.

Site B) This proposed coring site is within the second deepest gravity low, inside the inferred ring fracture. It is, however, visible from Ranch headquarters and the highway and probably would not be selected for this reason. This site is probably ideal for examining the thickest caldera fill.

Site C) This site is located at the edge of the resurgent dome, 3 km inside the inferred ring fracture. Although the site is not ideal on a scientific basis, it is behind Cerro Piñon, out of sight of all housing and thoroughfares.

Cerro del Medio is located over the deepest gravity low, but there would be over 400 m of rhyolitic lava to drill through before reaching any of the caldera fill, which is the primary objective of this coring site.

3. Drilling/Coring Program. Previous drilling in the eastern moat of the Valles caldera has been limited to shallow water wells. Most of these wells are outside the ring-fracture zone, and the deepest well (360 m) penetrated only moat sediments. Nearby relevant deep drilling experience is nonexistent. In a similar setting in the Timber Mountain caldera in southern Nevada, an exploratory hole was cored in moat sediments and debris flows as well as in nonwelded to densely welded ash-flow tuffs (Byers, Hawkins, and Muller, 1981). Although the total depth (~800 m) was much less than that proposed for this site (6 km) there should be many similarities, at least in the upper units. The lithologic sequence of moat sediments, welded and nonwelded tuffs, and lavas should be repeated if the hole is deep enough. Temperatures at depth in the eastern moat of the Valles caldera are not well known, but if this is a trap-door caldera, major hydrothermal activity could be encountered, with temperatures as high as 400°C.

The hole should follow all the established practices for drilling in hydrothermal areas. Blowout preventers (BOP) should be utilized on well-cemented casing. A large-diameter (508-mm) surface conductor should be installed to 60 or 70 m. Following rotary/coring (HQ) down to at least 500 m, the hole diameter should be wide enough to set a 346-mm-diameter casing, so subsequent step-downs in size will still provide sufficient room for flexibility in future operations. A BOP will then be installed on this well-anchored casing. Coring will continue at as large a diameter as is operationally prudent. Step-downs in size will be determined based on the progress of the operation. Drilling fluids will have to provide the usual features of cuttings removal, subsurface pressure control, lubricity, and hole cleaning as well as survive high temperatures.

Ideally, drilling should be done in stages with an interval between each stage to examine data and plan the next stage. The initial stage should be the coring of the upper sediments and tuffs down to approximately 2 km. This

should provide sufficient data to plan the next stage(s) of drilling to the target depth of 6 km.

4. Statement of Work. Target depth for this VC-4 site is 6 km in order to penetrate the entire caldera-fill sequence, older rocks of the Tschicoma Formation, and pre-Jemez Mountains volcanic rocks. Based on thermal gradient data obtained by Union Oil Co. in the area (Dondanville, 1971), we expect the BHT at this site to be as high as 400°C; thus, it is likely that we will penetrate the deeper zone of recharge to the hydrothermal system and, possibly, a separate hydrothermal cell.

In addition to the intriguing deep targets at VC-4, the intracaldera lacustrine deposits and interbedded rhyolite domes and flows could tell us much about the geologic and hydrologic evolution of the caldera moat zone and climatic changes during the last 1.1 Ma.

We plan, then, two wells in the Valle Grande area: a 1000-m core hole (VC-4a) and a 6-km well (VC-4b). The sequence of events for this effort will be patterned after that planned for the other site. The work statement components will be described later in more detail, but they will include the following:

- 1) Planning and Coordination
- 2) Permits
- 3) Contracting
- 4) Drilling
- 5) Preliminary Examination
- 6) Information Dissemination
- 7) Curation

E. Summary of the Scientific Plan

Preceding sections of this plan have described a program of scientific drilling in Valles caldera. Figure 1 illustrates schematically the environments that will be sampled by the proposed holes. VC-2a will evaluate processes that are active in a vapor zone that overlies a high-temperature hydrothermal convective system. VC-2b will investigate the boiling interface and dynamics of the underlying hot-water-dominated convective system, zones important for understanding producing geothermal systems and formation of hydrothermal ore deposits. The opening of VC-3 (Baca-12) will provide a facility for testing logging tools in a high-temperature environment. VC-3 has already been drilled through a hydrothermal convective zone and is now in

a conductive regime that we believe to be controlled by the structural style of the resurgent doming process. We estimate that this hole is presently within 2 km of the top of the Valles pluton. Deepening of the hole into the pluton will provide important information on conductive regime, intrusive processes, and differentiation processes at the top of a young felsic pluton. We expect that it will intersect a hydrothermal convective zone, possibly beneath the upper member of the Bandelier Tuff. This hole will also investigate the geologic processes along the ring-fracture zone of the calderas. An understanding of processes active along the ring-fracture system is critical to understanding the evolution of calderas and the eruptive products associated with them.

In addition to the above objectives, we point out that the Valles has an exceptional data base which is composed of existing mapping, surveys, and holes of opportunity that will serve to complement data to be gathered by this proposed effort.

IV. MANAGEMENT PLAN

A. Management

1. Introduction. A CSDP-Thermal Regimes Project Team for Valles caldera will be managed jointly by the Earth and Space Sciences Division at Los Alamos National Laboratory and by the University of Utah Research Institute (UURI). The team will operate according to the policies and procedures of both organizations. This project team will be interdisciplinary and will include scientists and engineers. Positions on the project team will be staffed primarily by investigators from these two organizations.

Except for nomenclature differences, the planned organization is generally consistent with the organizational framework for Thermal Regimes-CSD described in Appendix 5 of the draft DOE Long-Range Plan for CSD (DOE, 1985). For example, the Chief Scientist (Fig. 22) is equivalent to the Nth Hole On-Site Science Manager, and the Chief Engineer (Fig. 22) is equivalent to the Nth Hole Drilling Manager in the DOE Long-Range Plan (DOE, 1985). Similarly, the authors of this document, the Valles Caldera Scientific Drilling Team, represent a consortia proposing a specific drilling project and could, in whole or in part, become the Nth Hole Working Group of the DOE Plan. Future updates of this document can incorporate as necessary

Figure 22.

Valles caldera CSDP management plan. This chart is current as of August 1985. It will be modified as necessary in updates of the plan.

any needed organizational modifications in order to be consistent with the final DOE Long-Range Plan.

2. Organization. The CSDP Thermal Regimes Project Team for Valles caldera will be organized to reflect the complexity of the project and to guarantee the acquisition of high-quality scientific data through drilling in a complex geologic environment. The personnel who staff the positions described here will change as work progresses.

Organization of the CSDP Thermal Regimes Project Team during the drilling phases is shown in Fig. 22. The team will consist of four key members: Project Manager, Principal Investigator, Chief Scientist, and Chief Engineer. Collectively, these individuals will be responsible for all planning, procurement, operations, and other activities necessary to meet the scientific objectives at each of the four Valles CSDP sites. The project team will be supported by technical and administrative specialists primarily at the Laboratory and UURI, by advisory panels and consultants, and by the OBES/CSDP drilling office at Sandia National Laboratories.

Our intent is to have a different Chief Scientist and Chief Engineer for each of the proposed drill sites. This arrangement will allow these individuals to concentrate on specific portions of the project while the Principal Investigator and Project Manager are concerned with both the specific drill site and the overall project objectives. A more detailed description of the responsibilities and authorities of the various members of the project team appears below.

Figure 22 also shows the key contractual relationships of the Valles caldera CSDP. We suggest that DOE/OBES contract separately with the Los Alamos National Laboratory and the UURI. It is more cost effective and logistically efficient if Los Alamos handles all subsequent subcontracting, the most significant of which will be the drilling subcontract.

3. Key Responsibilities and Authorities. (This section was current as of August 1985, but it might require modifications in updates of this plan.)

a. Project Manager. If the subcontracting functions are carried out through Los Alamos, the Project Manager should be a member of the Los Alamos Earth and Space Sciences Division. He or she will serve as the interface between UURI management, Los Alamos management, DOE/OBES, the DOE/OBES drilling office, and the Principal Investigators. As the single point of

accountability for the project, he or she will be responsible for the following:

- 1) Expediting and facilitating subcontracting
- 2) Assuring proper documentation of project plans
- 3) Controlling project costs
- 4) Controlling project schedule
- 5) Assuring the high quality of scientific output

The Project Manager, with the Principal Investigators, will be responsible for updating and maintaining this scientific drilling plan. In addition, the Project Manager will approve the Scientific Plan (see below) and Drilling Operations Plan (see below) prepared by the Principal Investigators, Chief Scientist, and Chief Engineer for each of the four sites.

b. Principal Investigator. The Principal Investigators will have the responsibility for assuring that scientific objectives at each site are met and for maintaining the technical planning required to meet the proposed project schedule. It is anticipated that each of the two Principal Investigators (Goff and Nielson) will alternately serve as Chief Scientist, and that at transition time the duties of one Principal Investigator will be largely assumed by the other Principal Investigator. The Principal Investigator will assist the Project Manager in cost and schedule control and give general guidance and direction to the Chief Scientist and Chief Engineer. In the event of disagreement between the Chief Scientist and Chief Engineer concerning the conduct of the project, it will be the responsibility of the Principal Investigator to resolve the conflict. The Principal Investigator will assist in the preparation and maintenance of the Scientific Plan for each site and modify it as necessary as drilling operations proceed. The Principal Investigator will approve the Drilling Operation Plans for each site, which are prepared by the Chief Engineer at that site, in direct consultation with the Principal Investigator. The Principal Investigator will convene the Science Advisory Panel and Drilling Technology Panel to review the Science Plan and Drilling Operations Plan, respectively, at each site, and will have the panels review and advise on other aspects of the project as needed. The Principal Investigator will negotiate land access at each site. The Principal Investigator will serve as the point of contact for the external flow of data and as such inspect core boxes and fluid

samples received from the Chief Scientist, to assure their integrity before delivery to the CSDP curator.

c. Chief Scientist. The Chief Scientist will be directly responsible for the scientific planning and success of each of the proposed sites. The Chief Scientist will supervise and coordinate activities of drill-site geologists/hydrologists, the Preliminary Scientific Report Team, and the Long-Term Experiments Team. During drilling operations, the Chief Scientist will assure that all required rock and fluid samples are collected, handled, and stored at the drill site as per the "CSDP Sample Management Policy and Procedures." The Chief Scientist will create and supervise a Preliminary Scientific Report Team to publish preliminary results at each site on 1) the scientific findings, 2) lithologic logs, 3) borehole logs and surveys, 4) fluid samples and hydraulic tests, and 5) the drilling history. The Chief Scientist will plan and monitor fluid sampling, hydraulic tests, and logging operations. The Chief Scientist will assist the Principal Investigator with the Scientific Plan and, in turn, will be able to call upon the Principal Investigator if assistance is needed in the performance of the Chief Scientist's responsibilities.

d. Chief Engineer. The Chief Engineer or his delegated representative will have responsibility for and authority over the activities of all coring and drilling subcontractors. In addition, the Chief Engineer will develop and maintain the Drilling Operation Plan for each site and will have this plan reviewed by the DOE/OBES Drilling Office. The Chief Engineer should work through the Laboratory procurement organization to negotiate contracts for drilling, coring, casing, cementing, and logging. The Chief Engineer will assist the Principal Investigator with land access, will acquire permits, and will prepare the Environmental Assessment. He will supervise all logging, surveying, and other downhole services and have a log analyst witness these activities. In addition, he will assure that records of all drilling-related activities, including subcontractor records, are maintained in the Drill-Site Record File. Safety of all personnel at the drill site is the responsibility of the Chief Engineer. The Chief Engineer will consult with the Chief Scientist to ensure optimum scientific data from the project while staying within prescribed budgets and schedules.

e. Drill-Site Geologist/Hydrologist. Site geologists are responsible for 1) preliminary descriptions (lithologic logs) of core and cuttings; 2)

record keeping; 3) marking, tagging, and boxing of cores according to curatorial protocol; 4) visitors to the site; and 5) cooperative work with investigators with regard to special cores and experiments. All site geologists are responsible for transfer of information to the next shift and for remaining on site until that information is understood.

f. Sample Curator. With the cooperation of the Principal Investigators, the Curator will evaluate and respond to all requests for samples from the core holes. The Curator will spot-check curation protocol and techniques during drilling and assure that core and other samples are transferred to the USDOE Thermal Regimes curation facility. The Curator will keep a record of all sample materials used for nondestructive and destructive experiments and analyses.

g. Scientific Advisory Panel. An overview committee will be organized to review scientific plans and progress of the Valles caldera drilling program. It will also evaluate the overlap of scientific proposals and recommend cooperative projects. It will work to review, annually, the scientific goals and progress of the program. The committee will consist of six members, representing the national laboratories, universities, industry, and government agencies. If possible, at least several members will be from CSDP committees other than Thermal Regimes.

h. Drilling Technology Advisory Panel. This panel will review the scientific goals of the coring program and recommend the most effective means of achieving those goals. It will consist of six members, drawn from industry and government.

i. Preliminary Scientific Report Team. The Preliminary Scientific Report Team will be made up of the Chief Scientist, two drill-site geologists, a well-log analyst, a hydrologist or hydrogeochemist, a geophysicist, and a technical editor. After completion of each core hole, a preliminary report on the geology, geochemistry, and geophysics must be prepared quickly, to be circulated to the scientific community; this report will serve as the basis for new studies and sample requests. The report must be a brief (less than 100 pages) but comprehensive overview and will be published 2 months after completion of the core hole. This report will be released at a workshop. The purpose of the workshop will be to expedite the transfer of information to the scientific community. The meeting will also

serve as a forum for establishing working groups and encouraging proposal writing.

j. Long-Term Experiments Team. In situ experiments as well as other experiments in and near the core hole must be reviewed and coordinated with the drilling effort. The Long-Term Experiment Team will be established to carry out this effort. The team will be headed by the Chief Scientist and will be staffed according to need.

k. SNL Drilling Office. Our drilling and subcontract plans will be reviewed by the DOE/OBES Drilling Office at Sandia National Laboratories as necessary.

l. Safety Engineer. The Chief Engineer is responsible for the safety of all personnel and for the enforcement of safety rules and precautions. He will be advised from time to time by professional safety engineers from Los Alamos.

4. Key Documents and Records. Listed below are the key documents and records that will be maintained during this project. Also listed is the person who bears the principal responsibility for generating and maintaining these documents. (This section was current as of August 1985, but it might require modification in updates of this plan.)

a. Project Plan (this document) - CSDP Thermal Regime Drilling, Valles caldera - Project Manager and Principal Investigators

b. Scientific Plan (for each core hole) - Chief Scientist in collaboration with Principal Investigators

c. Drilling Operations Plan (for each core hole) - Chief Engineer

d. Drill Site Records File (for each core hole) - well-site geologists under the supervision of the Chief Scientist

e. Curation Records (for each core hole) - Curator

f. Project Records File (for each core hole) - Project Manager with the assistance of Principal Investigators, Chief Scientist, and Chief Engineer

5. Periodic Reports. Monthly reports will be prepared by the Principal Investigators. During the drilling operation, written reports will be delivered to DOE/OBES on a weekly basis.

6. Communication Interfaces. The Principal Investigators will be responsible for external communications concerning the project. It will be their responsibility to keep DOE/OBES and other members of the scientific community informed concerning the progress of this project. The Principal

Investigators have a special obligation to keep the Collaborating Investigators informed about drilling and experiment schedules as well as availability of data.

7. Procedures. When deemed necessary, standardized procedures will be formalized. These will include, at a minimum, procedures for the well-site geologists and procedures for emergencies.

B. Core Curation

Cores, cuttings, liquids, gases, and other samples and data from the proposed research drill holes in Valles caldera will be handled in accordance with established DOE/OBES curation policy and procedures (S. Goff, 1986). With the experience gained from DOE/OBES shallow drilling at Long Valley and Valles calderas, coupled with the ambitious nature of the proposed work, a professional field curatorial team will be a necessity. This team and their procedures are presently being developed as a separate DOE/OBES activity. This team will work under the direction of the Principal Investigators and the Chief Scientist for the project in conjunction with a curation facility representative.

All personnel handling core at the drill site will be familiar with CSDP curation procedures and will be responsible for round-the-clock sample handling that will include completing detailed field records, as well as labeling, numbering, boxing, and photographing the cores.

All sample requests will be reviewed by the Chief Scientist(s) to allow coordination of the sampling program. Principal Investigators and other scientists may take sample splits of recovered materials or "subsamples" only after the preliminary investigation has been completed, but before the samples are sent to the interim curation facility at Grand Junction, Colorado. Preliminary investigations, which must be completed first, include logging in the materials and completing the field description. The amount of subsample that a Principal Investigator or other scientist takes must be consistent with the amount specified in the proposal detailing scientific investigations to be performed. Responsibilities for subsample collection in the field will reside with the curation facility representative. After field descriptions and initial work are completed to the Chief Scientist's satisfaction, the cores and cuttings will be shipped to the Grand Junction repository.

V. SCHEDULE AND BUDGET

A. Schedule

The schedule shown in Fig. 23 and in Table V and described below begins with coring/drilling at the Sulphur Springs site (VC-2). At the same time (1986) initial preparations for workover operations and later, deeper drilling/coring at the Baca-12 (VC-3), Valle Grande (VC-4), and Toledo Embayment sites (VC-5) will be made.

1. FY86. Because preliminary surface work has been completed at both the Sulphur Springs (VC-2a) and the Redondo Creek area, where Baca-12 (VC-3) is located, negotiations, permits, and subcontracts will be prepared to complete well VC-2a early in FY86; preliminary planning for VC-2b and for reopening Baca-12 will begin at the same time. Coring of VC-2a will be performed during spring or summer FY86.

2. FY87. Activities in FY87 will be concerned with negotiations, permits, subcontracts, and coring of VC-2b and finishing operations at the VC-2a site. (This schedule will be changed in the next update of this plan. The earliest start for VC-2b is FY87.) Workover operations will be performed at the VC-3 site while making plans for deepening and coring the 1000-m hole at the VC-4 site.

After completion of VC-2a and VC-2b (Sulphur Springs), a team of scientists will conduct a preliminary scientific investigation and then will prepare reports on the lithology, geophysical logs, hydrothermal alterations, fluid and gas samples (if any), and physical properties of oriented core (Section III.5). In addition the core will be curated and distributed to other researchers as outlined in Section IVB. Finally, preparations must be made to perforate the two wells at selected horizons to sample geothermal fluids and gases.

At VC-3 (Baca-12) the well will be located, the site prepared, and a workover rig brought on (April to September FY87) to clean out Baca-12 and evaluate the condition of the well. From this information, a plan will be formulated to deepen the well.

Seismic lines will be run across the Valle Grande area during summer FY87 in preparation for a coring plan for VC-4a and later VC-4b. Based on results of the seismic survey and existing geologic information, a plan for coring a 1000-m hole at the VC-4 site (Valle Grande) will be prepared. The core hole will be completed by July 1987. A scientific team will perform a preliminary examination, and the core will be curated, etc., as described for the VC-2 site above.

* NOTE: VC-1 SCIENCE IS PRESENTLY FUNDED BY "FOUR-LAB" PROPOSAL.

Figure 23.
Valles caldera CSDP drilling/coring schedule (August 1985).
The schedule will be changed in the next update to reflect slippages
in earliest start dates.

TABLE V

ESTIMATED DRILLING* AND RELATED SUPPORT BUDGET BY FISCAL YEAR
(Dates will be changed in the next update to reflect slippages in earliest start dates.)

FY86

VC-2a, 500-m core hole Sulphur Springs**	\$ 150 K
VC-2a, planning, subcontract preparation, well sitting, etc.	<u>200</u>
Total	\$ 350 K

FY87

VC-2b, 2000-m core hole Sulphur Springs**	\$1,800 K
VC-2b, planning, subcontract preparation, well sitting, etc.	500
VC-2a and 2b, curation and preliminary scientific examination, perforation of wells for fluid sampling	300
VC-3, preliminary plan for workover operations	180
VC-3, workover operations and interpretation Baca#12***	1,600
VC-3, workover management; plan and subcontract preparation for deepening	320
VC-4a, 1000-m core hole Valle Grande**	270
VC-4a, planning, subcontract preparation, well sitting, etc.	215
VC-4a, curation and preliminary scientific examination	<u>125</u>
Total	\$5,310 K

FY88

VC-3, deepen Baca#12 to 5 km	5,000 K
VC-3, planning, management, and well sitting	450
VC-4b, planning and subcontract preparation for 6-km well	<u>200</u>
Total	\$5,650 K

* Note: These are initial, preliminary scoping cost estimates.

** Estimate includes mobilization/demobilization, casing and liner, cement, mud and additives, site preparation, bits, wellhead, rig time, geophysical logs, and 50% contingency.

*** Estimate includes site preparation and well relocation, mobilization/demobilization, workover rig, geophysical logs, and 50% contingency.

3. FY88. The major activities in FY88 are to deepen Baca-12 (VC-3) to 5.5 km and to begin planning the 6-km well in Valle Grande (VC-4b). Core-hole science will continue, using data and core obtained from VC-2a, VC-2b, and VC-4a through individual research proposals not budgeted in this proposal.

Based on results of the workover operations in FY87, a plan will be finalized for conditioning Baca-12 if needed and for a large rotary core-drilling rig to deepen Baca-12 from 3.2 to 5.5 km. We estimate that deepening will take approximately 6 months (April to September FY88).

4. FY89 and Beyond. Although it is not covered in this proposal, funding will be required to carry out the preliminary scientific investigations on the Baca-12 deepening and to drill and core a 6-km well in the Valle Grande during FY89 and FY90 (Fig. 22). This subject will be addressed in a subsequent, updated version of this proposal. Activities and costs associated with VC-2a and VC-2b, VC-3, and VC-4a are summarized in Table VI; VC-3 is forecasted through FY89 in order to present a complete estimate for this very important well.

5. Core-Hole Research. After preliminary scientific investigations and curatorial functions are completed for each hole, the Chief Scientist will be responsible for coordinating outside scientific investigations. The core will remain at interim facilities at Los Alamos for a period of one year after completion of the individual holes, and then the core will be shipped to the DOE/OBES facility at Grand Junction, Colorado.

Table VII lists examples of research and the costs that funding agencies should anticipate from the CSDP program in Valles caldera. As discussed in the Appendix, these miniproposals were generated at a workshop at Los Alamos in October 1984. From our experience with VC-1, funding agencies should expect several times the number of proposals initially formulated and should expect most core-hole science to lag one to two years behind the coring and drilling activities.

B. BUDGET

The estimated budget for successfully accomplishing the drilling/coring, preliminary scientific, and curatorial tasks of this proposal are outlined in Tables V, VI, and VIII. Table V lists the estimated costs by fiscal year. As noted, the cost of coring or drilling an individual hole includes subcontractor, third-party contractors, materials, geophysical logs, and a

TABLE VI
ESTIMATED DRILLING AND RELATED SUPPORT BUDGET BY SITE
(Dates will be changed in the next update to reflect slippages in earliest start dates.)

VC-2 (Sulphur Springs)		VC-3 (Baca #12 reopen and deepen)		VC-4 (Valle Grande)	
<u>FY86</u>					
1. 500-m core hole (VC-2a)	\$ 150 K				
2. Management/Planning					
a. Principal Investigators, Chief Scientist	110				
b. Chief Engineer	50				
c. Well sitters	20				
d. Curation and distribution of samples	20				
<u>FY87</u>					
3. 2000-m core hole (VC-2b)	1800	1. Workover Operations and Interpretation	\$1780 K	1. 1000-m core hole (VC-4a)	\$ 270 K
4. Management/Planning (VC-2b)		2. Management/Planning		2. Management/Planning	
a. Principal Investigators, Chief Scientist	150	a. Principal Investigators, Chief Scientist	170	a. Principal Investigators, Chief Scientist	50
b. Chief Engineer	280	b. Chief Engineer	150	b. Chief Engineer	125
c. Well sitters	70			c. Well sitters	40
d. Curation and distribution of samples	100			3. Preliminary scientific examination	75
5. Preliminary scientific examination	145			4. Curation and distribution of samples	50
6. Perforate wells for fluid and gas sampling	55				
<u>FY88</u>					
		3. Deepening to 5.5 km	5000	5. Management/Planning (VC-4b)	
		4. Management/Planning		a. Principal Investigators, Chief Scientist	75
		a. Principal Investigators, Chief Scientist	175	b. Chief Engineer	125
		b. Chief Engineer	125		
		c. Well sitters	150		
<u>FY89 (Forecast)</u>					
		5. Preliminary scientific examination	150		
		6. Curation and distribution of samples	100		
Totals	<u>VC-2a and 2b: \$2950 K</u>	<u>VC-3: \$7800 K</u>		<u>VC-4a (only): \$ 810 K</u>	

50% contingency fund. The planning and management costs for each hole are estimated as a separate item for each fiscal year as are the preliminary scientific examination and curatorial costs.

Table VI lists the estimated drilling and support costs by site for FY86 through FY88. Because the Baca-12 reopening and deepening project is a very complicated and expensive--but a very important--task, its costs are forecasted through FY89 to obtain an estimated cost for the entire VC-3 project. Note that efforts at the VC-4 site (Valle Grande) will be well

TABLE VII

ESTIMATED SCIENTIFIC BUDGET FOR ONE FISCAL YEAR
(Based on preproposals in the Appendix)

Investigator(s)	Institution(s)	Cost
<u>Water-Rock Interactions</u>		
1. W. Elston, J. Grambling	Univ. New Mexico	\$ 40 K
2. R. Charles, J. Hulen, D. Nielson	Los Alamos/UURI	130
3. D. Janecky	Los Alamos	180
4. C.L. Smith	USGS	25
5. H. Wollenberg, A. White	LBL	150
6. C. Grigsby	Los Alamos	70
7. F. Goff, C. Janik, M. Kennedy, F. Phillips	Los Alamos/USGS/UC Berk./NMI	100
8. J.C. Laul	Battelle NW	120
9. L. Brown	Los Alamos	300
10. R. Charles, J. Hulen, F. Goff, D. Nielson	Los Alamos/UURI	100
11. L. Brown	Los Alamos	100
	Subtotal	\$1,315 K
<u>Volcanology and Structure</u>		
1. J. Wolff, J. Gardner	U. Texas, Arlington/Los Alamos	50 K
2. W. Baldrige, D. Vaniman	Los Alamos	300
3. J. Hulen	UURI	50
4. J. Wright, S. Self	B.P. Minerals/U. Texas, Arlington	100
5. J. Wright	B.P. Minerals	50
6. G. Heiken	Los Alamos	100
7. G. Heiken, D. Vaniman, F. Goff, S. Self, W. Wolfe	Los Alamos/U. Texas, Arlington	130
8. T. Dey, J. Aldrich	Los Alamos	35
9. J. Aldrich, K. Olsen	Los Alamos	140
10. D. Nielson	UURI	100
11. D. Nielson	UURI	100
12. K. Olsen	Los Alamos	180
13. J. Bradbury	USGS	100
	Subtotal	\$1,435 K
<u>Presence or Absence of Melt</u>		
1. P. Morgan	Purdue Univ.	30 K
2. G. Zyvoloski	Los Alamos	50
3. H. Stockman, S. Self	SNL/U. Texas, Arlington	75
4. M. Harrison	SUNY, Albany	30
5. P. Carpenter	Los Alamos	100
	Subtotal	\$ 285 K
	Grand Total	\$3,035 K

TABLE VIII

ESTIMATED DRILLING AND RELATED SUPPORT BUDGET BY INSTITUTION
(This table is current as of August 1985. It will be modified as necessary in updates of the plan.)

	<u>Los Alamos</u>	<u>UURI</u>
<u>FY86</u>		
1. Drilling subcontractor and third party	\$ 150 K	---
2. Staffing*	<u>100</u>	<u>\$ 100 K</u>
Totals	\$ 250 K	\$ 100 K
<u>FY87</u>		
1. Drilling subcontractor and third party	\$3,905 K	---
2. Staffing**	<u>940</u>	<u>\$ 465 K</u>
Totals	\$4,845 K	\$ 465 K
<u>FY88</u>		
1. Drilling subcontractor and third party	\$5,000 K	---
2. Staffing*	<u>400</u>	<u>\$ 250 K</u>
Totals	\$5,400 K	\$ 250 K
<hr/>		
* Includes:	Principal Investigators Chief Scientist and Staff Chief Engineer and Staff Well Sitters	
** Includes:	Principal Investigators Chief Scientist and Staff Well Sitters Log Interpretation Preliminary Scientific Examination (VC-2a, 2b, and 4a) Sample Curation and Distribution	

under way by the end of FY88 but that efforts do not include the 6-km hole (VC-4b). In terms of comparative costs, deepening Baca-12 is estimated to be three times more costly than completing the two core holes at Sulphur Springs (VC-2a and VC-2b); yet because Baca-12 is already 3.2 km deep, the overall cost of this ambitious and unique scientific undertaking is comparatively inexpensive.

Estimated drilling and support costs, by institution, are listed in Table VIII.

Table VII lists the estimated scientific budget to complement this drilling proposal based on the miniproposals in the Appendix. As mentioned

before, these costs are intended to give funding agencies an idea of what kinds of proposals and costs to expect. The table is not intended to be a complete list of the potential research that could be accomplished on the suite of CSDP holes at Valles caldera. Based on our experience with VC-1, funding agencies should expect research proposals to exceed the cost of drilling/coring each well. The cost (from Table VII) of research proposed for just the Sulphur Springs holes (VC-2a and VC-2b) is about \$1400 K in just one year.

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VITAE OF PRINCIPAL INVESTIGATORS AND SUPPORTING STAFF

Although many staff members from both Los Alamos and UURI will be involved in this project, the following paragraphs summarize the experience and education of key members of the project team.

C. W. Myers, Acting Program Manager

C. W. Myers received a B.S. (1966) and M.S. (1968) in geology from the University of Georgia and his Ph.D. (1972) from the University of California at Santa Cruz. He was a postdoctoral fellow at State University of New York, Stony Brook, from 1973 to 1974.

From 1976 to 1981 he managed the Repository Geology Unit of Rockwell's Hanford Operations where he supervised well-site geologists and drilling and coring operations. His responsibilities included preparation of drilling contracts and specifications, subsurface geologic mapping, and structural analysis and integrating geological and geophysical data. These data were used to select the candidate host rock for a proposed nuclear waste repository at Hanford, Washington.

From 1981 to the present he has been at the Los Alamos National Laboratory where he managed the Geology Group and is now the Associate Division Leader, Earth and Space Sciences Division. He is the former chairman of a committee to develop the test plan for the exploratory shaft for Nevada Nuclear Waste Storage Investigations.

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Fraser Goff - Principal Investigator, Chief Scientist (VC-2)

Fraser Goff received his B.S. in chemistry from San Jose State College in 1971 and his Ph.D. in Earth Science from the University of California at Santa Cruz in 1977, where his dissertation dealt with formation and chemistry of segregation pipes and veins in basalt flows. During his Ph.D. program, he was employed by the U.S. Geological Survey as a chemist and geologist in connection with The Geysers-Clear Lake geothermal region, California. Upon completion of his Ph.D., he spent a year as Senior Geologist at Rockwell Hanford Operations working on the Basalt Waste Isolation Project. In 1978 he joined Los Alamos National Laboratory where he is currently a staff member in the Geology-Geochemistry Group. His major research efforts at Los Alamos have been evaluation of both conventional and Hot Dry Rock geothermal resources through integration of geological, geophysical, and hydrogeochemical data; field-oriented geologic, petrologic, and hydrogeochemical studies of the Valles caldera region; and application of hydrogeochemical techniques in geothermal exploration. He has worked on geothermal systems in the U.S., St. Lucia, New Zealand, and China. He also has worked on the nuclear waste project and as a Laboratory consultant to the NRC on reactor site geology. He was Task Manager of the U.S. Hot Dry Rock resource evaluation and site assessment team (1980-1982) and acted as P.I. and Chief Scientist during coring of VC-1, the first CSDP hole in Valles caldera.

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Dennis L. Nielson - Principal Investigator, Chief Scientist (VC-3)

Dennis Nielson received his B.A. in geology from Beloit College in 1970. In 1972 he received an M.A. in geology and in 1974 a Ph.D. in geology both from Dartmouth College. Following completion of his Ph.D. he was employed as a Staff Geologist for the Anaconda Company where he was responsible for uranium exploration in frontier environments in the United States. During this period of time he planned and supervised several exploration drilling programs using both coring and rotary methods. In 1978 he joined the University of Utah Research Institute and presently serves as the manager of the geology section. At UURI he has specialized in the study of high-temperature geothermal systems and the exploration techniques that can be used in their discovery and assessment. He served as Project Manager for DOE's Industry-Coupled Program, which cost-shared with industry exploration and deep drilling at eleven geothermal sites in the northern Basin and Range. He also served as Project Manager for DOE's Geothermal Exploration and Assessment Technology Program, which included program design, formulation and technical review of procurements, and assisting DOE in the monitoring of outside contracts. He presently serves as Principal Investigator for the geothermal exploration of Ascension Island, South Atlantic Ocean, under contract to the U.S. DOE and the U.S. Air Force. As part of this program he has planned and supervised the completion of about 2000 m of core drilling on Ascension Island. He served on the DOE Review Panel for the Baca Geothermal Power Plant Project and is thus very familiar with Union Oil Company's operation in the Valles caldera. For the past three years he has directed UURI's research effort in the Valles caldera. Nielson is also a candidate for the MBA degree at the University of Utah and thus has a strong formal background in management techniques.

Selected Publications

Nielson, D. L., 1973, Silica diffusion at Ascutney Mountain, Vermont: Contrib. Min. Pet. 40, 141-148.

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Grant H. Heiken - Chief Scientist (VC-4)

Grant Heiken received a B.A. in geology from the University of California, Berkeley, in 1964, an M.A. from the University of Texas, Austin, in 1966, and a Ph.D. from the University of California, Santa Barbara, in 1972. From 1964 to 1968, he was involved with field work in Colorado (U.S.G.S.), northern Chihuahua, Mexico, and south-central Oregon. From 1969-1975 he was a geologist with the Planetary and Earth Sciences Division, NASA-Johnson Space Center where he was a member of the Lunar Sample Preliminary Examination Team and conducted research on Lunar and Terrestrial volcanism and Lunar regolith.

From 1975 to present he has been a staff member, Los Alamos National Laboratory, where he has applied research in volcanology to geothermal exploration and resource evaluation, isolation of radioactive waste in tuffs, volcanic hazards, and effects on the atmosphere. For four years he was project leader, hot dry rock geothermal resource evaluation. Field studies have been in volcanic fields in New Mexico, Colorado, the Caribbean, Central America, Hawaii, and Greece.

Selected Publications

Heiken, G., 1979. Pyroclastic flow deposits: Am. Scientist 67, 654-571.

Heiken, G., and Goff, S., 1980. Continental Scientific Drilling Program - Curatorial Needs: Los Alamos Scientific Laboratory Report LA-8725, 294 pp.

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- Heiken, G., and Wohletz, K., 1985. Tephra deposits associated with silicic domes and lava flows. Submitted to a *Geol. Soc. Spec. Paper on silicic domes*.

Jamie N. Gardner - Chief Scientist's Staff

Jamie N. Gardner received his B.S. in Earth Science from the University of California (Santa Cruz) in 1976 and his Ph.D. in Geology from the University of California (Davis) in 1985. His dissertation dealt with the tectonics and petrogenesis of the Jemez Mountains volcanic field. From 1975 to 1979, he worked for Atlantic Richfield Hanford Co., Rockwell Hanford Co., and the U.S. Geological Survey as a field geologist and petrologist on the Basalt Waste Isolation Project on the Columbia River Plateau in Washington state. When he first came to Los Alamos in 1979, Jamie worked as a field geologist on the Off-site Tuff Project in central Nevada and acted as a consultant to the NRC on reactor site safety. In 1980, he performed a field mapping and petrologic study of the Mountain Home, Idaho, hot dry rock site. In 1984, he was made Program Manager of a seismic hazards project to investigate active faulting in the Los Alamos-Pajarito Plateau area. He was actively involved as Chief Scientist's Staff with the planning and execution of VC-1, the first CSDP corehole in Valles caldera. He has been involved in several field mapping, petrologic, tectonic, and hydrogeochemical studies of the Jemez Mountains-Valles caldera region.

Selected Publications

- Swanson, D. A., Wright, T. L., Camp, V. E., Gardner, J. N., Helz, R. T., Price, S. M., Reidel, S. P., and Ross, M. E., 1980, Reconnaissance geologic map of the Columbia River Basalt Group, Pullman and Walla Walla Quadrangles, Washington and Idaho: U.S. Geol. Surv. Misc. Geol. Invest. Map I-1139.
- Gardner, J. N., Eddy, A. C., Goff, F. E., and Grafft, K. S., 1980, Reconnaissance geologic map of Northern Kawich and Southern Reveille Ranges, Nye County, Nevada: Los Alamos Scientific Laboratory Report LA-8390-MAP, scale 1:62,500, 6 sheets with discussion of geology, structure, economics, geohydrology, and water chemistry.
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- Goff, Fraser, Gardner, Jamie, Grigsby, C. O., Vidale, Rosemary, and Charles, Robert, in press, Isotope geochemistry of Sulphur Springs, Valles caldera, New Mexico, and a model of the underlying geothermal system: J. Volc. Geotherm. Res.

Jeffrey B. Hulen - Chief Scientist's Staff

After receiving his B.S. in geology from the University of Utah in 1969, Jeff Hulen began a long association with Kennecott Copper Corporation as an exploration geologist with its subsidiary, Bear Creek Mining Company. His initial work involved geologic interpretation of the Flambeau massive sulfide deposits near Ladysmith, Wisconsin, but most of his tenure with Bear Creek focused on porphyry copper/molybdenum exploration in western Nevada. In 1977, after a little more than a year at Kennecott Exploration, Inc., where he worked on developing new geochemical and geological techniques for locating concealed porphyry orebodies, he joined the Earth Science Laboratory (ESL) Division of the University of Utah Research Institute. At ESL, his principal research efforts have been three-dimensional interpretation of subsurface structural and stratigraphic controls of fluid flow in geothermal systems, and hydrothermal alteration and zoning in these systems, particularly as an analogue of ancient systems responsible for depositing precious metal ores.

Selected Publications

- Hulen, J. B., and Sibbett, B. S., 1982, Sampling and interpretation of drill cuttings from geothermal wells: Soc. Prof. Well Log Analysts, Reprint Vol., p. IV 3-54.
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Robert W. Charles - Chief Scientist's Staff

Robert Charles received his B.S. in physics from Bucknell University in 1967 and his Ph.D. in geology (Experimental Petrology) from MIT in 1972. His dissertation was an experimental and chemigraphic investigation of mineral stabilities in the amphibole series richterite-ferrorichterite. His principal thesis advisor was D. R. Wones. Much of the experimental work was done at the Carnegie Institution of Washington Geophysical Laboratory where he had a predoctoral fellowship under H. S. Yoder, Jr. After branch training in the U.S. Army Corps of Engineers, he moved to the University of British Columbia for a postdoctoral fellowship under H. J. Greenwood. During these years, he developed an interest in computational as well as experimental aspects of geochemistry. He became a staff member at Los Alamos National Laboratory in July 1974 and became Project Leader for the Office of Basic Energy Sciences Geochemistry at Los Alamos in February 1982. Research at Los Alamos includes geochemical modeling of hydrothermal systems. Critical to this effort has been the development of experimental systems and fluid samplers as well as computational methods to deal with complex multi-component systems.

Selected Publications

- Charles, R. W., 1977, The phase equilibria of intermediate compositions on the pseudobinary richterite-ferrorichterite: *Am. J. Sci.* 5, 594-625.
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- Charles, R. W., and Vidale, R. J., 1982, Temperature calibration of a new rapid quench pressure vessel: *Am. Mineral.* 67, 175-179.
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- Goff, F. E., Vidale, R. J., Charles, R. W., and Gardner, J., 1986, in press, Gas and isotope geochemistry of Sulphur Springs, Valles Caldera, New Mexico, and a model of the underlying geothermal system: *J. Volcanol. Geoth. Res.*

Mark Mathews - Chief Scientist's Staff

Mark Mathews obtained his B.S. in geophysical engineering from Colorado School of Mines (1965) where he also received M.S. and Ph.D. degrees in geophysics (1970, 1973). From 1965 through 1975, he worked with several private companies doing oil and geothermal exploration in Louisiana, Texas, California, Oregon, Alaska North Slope, and the North Sea. In 1975, he worked with Bendix Field Engineering on uranium well logging and exploration projects. Since 1977, he has been a member of the Geophysics Group of Los Alamos National Laboratory working on projects in geothermal well logging research, methane hydrates, and weapons testing/containment. His geothermal well logging research program gave him wide experience with innovative methods as well as access to the wells of a number of U.S. geothermal fields through collaborative DOE/private industry agreements. Because of his acknowledged expertise in well logging, he is not only a member of many professional organizations in this field but has also served as Vice President of Technology and of Publications for the Society of Professional Well Log Analysts. From 1980 through 1983, he was a member of the Downhole Measurements Advisory Panel of JOIDES and presently serves on the Science Experiments Committee for the Salton Sea Scientific Drilling Project. He provided advice and interpretation on the geophysical logs that were obtained from VC-1, first CSDP corehole in Valles caldera.

Selected Publications

- Mathews, M. A., 1980. Log interpretation techniques to identify production zones in geothermal wells: Proc. 6th Workshop on Geothermal Reservoir Engineering, Stanford Univ., Palo Alto, CA, SGP-TR-50, p. 303-309.
- Mathews, M., Pettitt, R. A., and Miles, D. J., 1981. Logging operations in a very hot geothermal well: The Log Analyst, V. XXII, No. 5, pp. 3-8.
- Mathews, M. A., 1981. Wireline well logging - an underutilized technique in reservoir evaluation: Geotherm. Res. Counc. Trans. 5, 295-298.
- Mathews, M. A., and LaDelfe, C. M., 1983. Lithology and log comparison of some boreholes in southern Yucca Flat: Proc. Second Symp. Containment of Underground Nuclear Explosions, p. 121-155.
- Mathews, M. A., and Von Huene, R., 1985. Site 570 Methane Hydrate Zone: printed in Initial Reports of the Deep Sea Drilling Project, V. LXXXIV.
- Mathews, M. A., 1985. Data collection - physical, Chapter in Engineering and economic assessment of geothermal resources: Steps toward a financial analysis: Geotherm. Res. Counc., Davis, CA.

John Rowley - Chief Engineer

John Rowley earned his B.S. degree in mathematics in 1950, an M.S. in physics, and a Ph.D. in applied mechanics in 1957, all at the University of Michigan. His doctoral dissertation presented a new method for theoretical analysis of thermo-elastic stresses in flat-plate separations. In 1957 he joined the Los Alamos National Laboratory to work on the nuclear rocket propulsion. For that project he completed projects and arrangements in reactor core thermal, fluid, and structural analysis; high-temperature thermal shock component testing; facilities design; refractory material development; high-temperature instrumentation; fuel element design; and physical chemistry of fuel corrosion. He was involved in reactor test planning, operations, data analysis, and post-test evaluations. In 1970 he became interested in advanced excavation technology and led an NSF-funded project to develop a drilling tunneling technology based on rock and soil melting. In 1974, he contributed to the development of and concepts for the extraction of geothermal energy from hot dry rocks. For that program he helped with technical planning, field operations, and advanced drilling and downhole hardware development; especially significant was his directing the development of a high-temperature turbodrill. Rig and drilling supervision for deviated wells to 5 km at 300+°C was included. He has held a variety of supervisory and management positions during the above assignments.

Currently he is a staff member in the Geology and Geochemistry group with interests in and contributions to high-level nuclear waste disposal, drilling technology, program development, and CSDP. This past year he directed the contracting for and supervised the technical aspects of the Valles caldera VC-1 core hole as a member of the team conducting that CSDP-Thermal Regimes project.

Selected Publications

- Rowley, J. C., and Naghdi, P. M., 1954, An experimental study of biaxial stress-strain relations in plasticity: J. Mech. Phys. Solids 3, 63-80.
- Rowley, J. C., Naghdi, P. M., and Beadle, C. W., 1955, Experiments concerning the yield surface and the assumption of linearity in the plastic stress-strain relations: J. Appl. Mech. 22(3), 416-420.
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- Rowley, J. C., Hanold, R. J., Bankston, C. A., and Neudecker, J. W., 1974, Rock Melting Subterrenes - their role in future excavation technology: Presented at the Rapid Excavation and Tunneling Conference, Am. Inst. of Mining Engineering, June 24-27, 1974.
- Rowley, J. C., 1974, Rock melting technology and geothermal drilling: Proceedings of Conference on Research for Development of Geothermal Energy Resources, Pasadena, CA, September 23, 1974.
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- Rowley, J. C., 1982, Worldwide Resources: In Handbook of Geothermal Energy, (Chapter 2), Gulf Publishing Co.
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- Brittenham, T. L., Neudecker, J. W., Rowley, J. C., Williams, R. E., 1982, Directional drilling equipment and techniques for deep, hot granite wells: J. Pet. Tech. June, 1421-1430.
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Bruce S. Sibbett - Chief Engineer's Staff

Bruce Sibbett received his B.S. in geology from Brigham Young University in 1972 and, after two years with the BLM, earned his M.S. in geology from the University of Idaho at Moscow in 1976, where his thesis involved mapping Challis Volcanic in central Idaho. He next worked for two years in Wyoming where he supervised uranium exploration drilling. In 1978 he joined the Earth Science Laboratory/University of Utah Research Institute, where he has had extensive involvement with geothermal resource evaluation programs. His major research efforts at ESL have been geologic mapping and drilling in volcanic terrains. He was site supervisor for 6,560 feet of core drilling on Ascension Island, South Atlantic Ocean. He has worked on mapping projects covering a total of 425 square miles, most of this in the Basin and Range.

Selected Publications

Sibbett, B. S., 1982, Geology of the Tuscarora Geothermal Prospect, Elko County, Nevada: Geol. Soc. Am. Bull. 93, 1264-1272.

Sibbett, B. S., 1983, Structural control and alteration at Beowawe KGRA, Nevada: Geotherm. Res. Council. Trans. 7, 187-191.

Hulen, J. B., and Sibbett, B. C., 1983, Sampling and interpretation of drill cuttings from geothermal wells: Soc. of Prof. Well Log Analysts, Geoth. Log Interp. Handbook, 2nd Edition, p. IV 5-54.

Sibbett, B. S., Nielson, D. L., and Adams, M. C., 1984, Geothermal gradient drilling and measurements, Ascension Island, South Atlantic Ocean: Earth Science Lab/UURI, Tech. Report prepared for U.S. Air Force, ESL #134, 72 p.

Ward Hawkins - Chief Engineer's Staff

Ward Hawkins received his B.S. in geology from the Mackey School of Mines at the University of Nevada-Reno in 1978. Following graduation he worked for Fenix and Scisson, Inc., at the Nevada Test Site (NTS) as a well-site geologist and then as group leader for the Los Alamos National Laboratory geologic support. In 1979 he joined the Laboratory as a staff member in the Containment group and is now Associate Group Leader in the Geology/Geochemistry group. His primary activities at the Laboratory have been related to the underground containment of nuclear explosions at the NTS including the development of detailed site characterizations of emplacement sites. This requires integration and compilation of geologic, geophysical, and hydrologic data, both surface and subsurface, into a prospectus that also addresses engineering concerns. Directing and monitoring drill-hole sampling and logging operations are a major part of this effort. Other involvements have been in Hot Dry Rock drilling and completion, MX deep basing, with minor participation in several projects requiring geologic site characterization support.

Selected Publications

- Byers, Frank M., and Hawkins, Ward L., 1981, Geology of drill hole Uel8t and Area 18, Timber Mountain Caldera Moat, Nevada Test Site, with a section on geophysical logging by D. C. Muller: USGS report USGS-474-312.
- Drellack, S. L., Jr., Davies, W. J., Gonzales, J. L., and Hawkins, W. L., Geologic investigations into drill hole sloughing problems, Nevada Test Site: 2nd Containment Symposium, Albuquerque, NM, Los Alamos National Laboratory document LA-UR-83-2281.
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Sue Goff - Curator

Sue Goff received her B.S. in Sociology from Cornell University in 1968 and M.S. in Geology from Michigan Technological University in 1978. She worked as an exploration geologist for U.S. Steel Corporation and Union Carbide Corporation before joining Los Alamos National Laboratory as a staff member in 1978. Her research interests at Los Alamos have centered around exploration geology and biogeochemistry. Since 1980 she has been working on the curatorial needs of the Continental Scientific Drilling Program. With Grant Heiken, she convened a workshop of core curators in 1981. Since returning from sabbatical leave in New Zealand she has been involved in initiating and developing policy guidelines and procedures for handling samples obtained from the CSDP and overseeing the establishment of a dedicated core repository. She has successfully applied these procedures to the VC-1 core at Valles caldera and the core obtained from the Inyo Drilling Project.

Selected Publications

- Goff, S., 1986, Curatorial Policy Guidelines and Procedures for the Continental Scientific Drilling Program, Los Alamos National Laboratory Report LA-10542-OBES, 23 pp.
- Goff, S., and Heiken, G., 1981, A report on the workshop on core and sample curation for the National Continental Scientific Drilling Program, May 5-8, 1981.
- Heiken, G., and Goff, S., 1981, Continental Scientific Drilling Program curatorial needs - a report to the National Academy of Sciences - National Research Council Continental Scientific Drilling Committee: Los Alamos National Laboratory Report LA-8726-MS, 294 pp.

John Whetten - Technical Advisory Committee

John T. Whetten received an A.B. in geology from Princeton University in 1957, an M.A. in 1959 from the University of California, Berkeley, and a Ph.D. in 1962 from Princeton University. From 1963-1980 he was a Professor of Oceanography and Geology; from 1968-1969, Associate Dean of the Graduate School, and from 1969-1974, Chairman of the Department of Geological Sciences at the University of Washington. From 1975 to 1980 he was a geologist for the U.S. Geological Survey, working primarily on regional tectonic and stratigraphic problems in western Washington. Since 1980 he has been at the Los Alamos National Laboratory in the Earth and Space Sciences Division Office; he has been Division Leader since 1984.

Selected Publications

- Whetten, J. T., 1966. The geology of St. Croix, U.S. Virgin Islands: Geol. Soc. Am. Mem. 98, 177-239.
- Whetten, J. T., Tabor, R. W., Frizzell, V. A., Jr., Swanson, D. A., Byerly, G. R., Booth, D. B., Hetherington, M. H., and Waitt, R. B., Jr., 1980. Preliminary geologic map of the Chelan 1:100,000 quadrangle, Washington: U.S. Geol. Surv. Open-File Map 80-841.
- Tabor, R. W., Frizzell, V. A., Booth, D. B., Whetten, J. T., Waitt, R. B., Jr., and Zartman, R. E., Preliminary geologic map of the Skykomish River 1:100,000 quadrangle, Washington: U.S. Geol. Surv. Open-File Map 82-747.
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- Whetten, J. T., 1983. Energy and Minerals Project: Report on Employment Generating Projects, OAS Mission Costa Rica, Documents of the Department of Social Affairs, Organization of American States, pp. 132-139.
- Whetten, J. R., 1984. Testimony on the Hot Dry Rock Geothermal Energy Program: Hearing before the Subcommittee on Energy Development and Applications, Committee on Science and Technology, House of Representatives, 98th Congress, Second Session, v. 3, pp. 510-525.
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Phillip M. Wright - Technical Advisory Committee

Phillip M. Wright received a B.S. in Geological Engineering in 1960 and a Ph.D. in 1966, both from the University of Utah. Following graduation, he worked for Kennecott Exploration and served eight years as Chief of the Geophysics Division. In 1977 he joined the University of Utah Research Institute and presently serves as Technical Vice President of UURI. At UURI he has been responsible for the overall technical supervision of all DOE-sponsored geothermal research and technical assistance.

Selected Publications

Costain, J. K., and Wright, P. J., 1973, Heat flow at Spor Mountain, Jordan Valley, Bingham, and LaSal, Utah: J. Geophys. Res. 78/35, 8367.

Wright, P. M., 1981, Gravity and magnetic methods in mineral exploration: Seventy-Fifth Anniversary Volume, Economic Geology, Society of Economic Geologists, p. 829-839.

Wright, P. M., 1981, Seismic methods in mineral exploration: Seventy-Fifth Anniversary Volume, Economic Geology, Society of Economic Geologists, p. 863-870.

Capuano, R. M., Adams, M. C., and Wright, P. M., 1983, Tracer recovery and mixing from two geothermal injection-backflow studies: Proceedings, Ninth Workshop on Geothermal Reservoir Engineering, Stanford University, California, December.

Wright, P. M., Capuano, R. M., Adams, M. C., and Moore, J. N., 1984, Uses of geochemistry with injection-backflow testing in geothermal reservoir studies: Geotherm. Res. Counc. Trans., vol. 8.

APPENDIX
SCIENTIFIC PROPOSALS TO AUGMENT DRILLING PROGRAM

Much of the scientific rationale for a Valles Drilling Program was established during the October 1984 Los Alamos Workshop. The attendees were organized into three panels whose objectives are described under the following titles: Panel 1 - Geothermal Systems and Rock-Water Interactions; Panel 2 - Volcanology and Structural Framework of the Jemez Volcanic Field; and Panel 3 - Determining the Presence (or Absence) of Melt Below the Valles Caldera. The proposals listed in this section cover a wide range of research topics designed to address many of the fundamental questions relating to CSDP (Thermal Regimes). Attendees were given one day during which they were to write preproposals with budget estimates. These proposals are for planning purposes only and are not included in the budget estimates for management and drilling (Sections IV through V), although they are listed separately in Table VII. The actual, full-scale proposals will be submitted to the appropriate funding agencies for consideration after the drilling proposals have been funded or after preliminary examination of samples collected during the program. However, our experience with VC-1 indicates that the number of unsolicited proposals will be several times greater than the number of preproposals listed here.

I. GEOTHERMAL SYSTEMS AND ROCK-WATER INTERACTIONS (PANEL 1)

Hole No.

- VC-2,VC-3, 1. Characterization of the Conductive-Convective Zone -
VC-4 W. Elston and J. Grambling
- VC-2 2. Characterization of Alteration Mineralogy and Zoning;
Comparison with Fossil Epithermal Ore Systems -
R. Charles, J. Hulen, and D. Nielson
- All 3. Characterization of Water-Rock Interaction - D. Janecky
- VC-2 4. Chemical Characterization of the Boiling Zone - C. L. Smith
- VC-2,VC-3, 5. Hydrogeochemical Systematics - H. Wollenberg and A. White
VC-4
- VC-2,VC-3, 6. Origin of Fluids and Components - C. Grigsby
VC-4
- VC-2,VC-3, 7. Gas Geochemistry and Geochronology of Geothermal Fluids -
VC-4 F. Goff, C. Janik, M. Kennedy, and F. Phillips
- VC-2,VC-3, 8. Natural Radionuclides of Uranium and Thorium Series in
VC-4 Groundwaters from Valles Caldera, New Mexico - J. C. Lau
- VC-2 9. Measurement of Flow and Transport Characteristics - L. Brown
- All 10. System Evolution: Phase Assemblages and Fluid Compositions -
R. Charles, J. Hulen, and D. Nielson
- All 11. Development of Predictive and Retrospective Numerical Models -
L. Brown

CHARACTERIZATION OF THE CONDUCTIVE-CONVECTIVE ZONE

Wolfgang E. Elston and Jeffrey A. Grambling

Background: The conductive-convective zone (heat-transfer zone) occupies the region of heat transfer between a heat source (crystallizing magma) and a convecting hydrothermal system. It includes the low-pressure/high-temperature facies of contact metamorphism and the regime of metasomatic effects long recognized in skarns and other contact zones around siliceous igneous bodies.

Statement of Problem: Geologic relations at contacts of siliceous igneous bodies suggest the following sequence of overlapping paragenetic stages:

1. Contact metamorphism, essentially isochemical, involving heat transfer, principally by conduction.
2. Metasomatism, involving some form of fluid transfer of materials.
3. Hydrothermal processes, which tend to overprint the earlier stages as the heat source decays and temperature falls.

This proposal is focused on the metasomatic stage and on the transition from the contact metamorphic stage to the metasomatic stage.

Previous Work: The two investigators have previously supervised a thesis (Maggiore, 1981) on metamorphism of carbonate rocks located beneath the floor of a "fossil" Valles-type caldera (the Oligocene Emory Cauldron, Black Range, southwestern New Mexico) and an underlying pluton. Temperature and X_{CO_2} can be constrained by the stability fields of metamorphic phases present in these rocks.

Statement of work: Core samples obtained from the metamorphosed rocks overlying a young crystallized magma body beneath the Valles caldera can be expected to yield the following information:

1. The paragenetic stage prevailing at present at varying depths and under present conditions of temperature, pressure, and fluid regimes.
2. Metamorphic reactions in a variety of rock types (e.g., Pennsylvanian limestone, Precambrian crystalline rocks).
3. The chemical and isotopic compositions of fluids and solutes, including pore fluids, fluids circulating through fractures, and fluid inclusions trapped in minerals, especially minerals in equilibrium with the present environment.

4. The state of fluids - subcritical or supercritical.
5. Partitioning of elements during fluid-rock reactions and the nature and rates of metasomatic processes.

Science Program: The proposed characterization of the conductive-convective zone can be used to calibrate previous field and laboratory studies of phase relations under contact metamorphic and metasomatic conditions. It has already been proved from cuttings recovered from Baca-12 that high-temperature metamorphic phases (tremolite, etc.) exist in Pennsylvanian carbonate rocks beneath the volcanic sequence filling Valles caldera. It is expected that samples recovered by drilling/coring the deeper parts of Valles caldera will lack the low-temperature post-magmatic overprint invariably found in ancient geologic systems.

The proposed program can be carried out at the University of New Mexico. It would involve two graduate students working on, respectively, rocks and fluids, supervised by two faculty members familiar with metamorphic and metasomatic reactions and with "fossil" calderas, such as Emory Cauldron. The University of New Mexico has the necessary laboratory facilities and is within a 30-minute flight or 2-hour drive of Los Alamos.

Studies of Rocks: The graduate student assigned to rocks will determine from core samples:

1. The premetamorphic protolith of each rock sample.
2. Isochemical contact metamorphic reactions.
3. Nonisochemical (metasomatic) changes and theoretical prediction of the composition of the metasomatic fluid.
4. Relationships of observed phase relations to actual temperatures and pressure.
5. Comparison of observed phases with those of "fossil" systems.

Studies of Fluids: The graduate student assigned to fluids will determine:

1. Phase relations in fluid inclusions, including ratios of components (H_2O , CO_2 , etc.), salinities, and solid phases.
2. If possible, fluids obtained from the hole during and after drilling/coring operations.
3. Comparison of these actual fluids to the composition of fluids calculated by theoretical methods.

4. The origin of fluids, including components of magmatic and meteoric origin and pore fluids derived by metamorphic (dehydration or decarbonation) reactions.

Both studies can be integrated with studies of "fossil" geothermal systems.

Budget Estimate: A 3-year budget is proposed, involving 2 graduate students half-time during the 9-month academic year and fulltime at \$1,100/mo for 2-1/2 summer months and 2 faculty members at 1 summer month each. The total, including travel to drilling and field sites, use of laboratory facilities, publications costs, and indirect costs would be about \$60,000/year.

Estimated Budget, Per Year

1. Salaries and Wages:

a. W. E. Elston, Professor, 1 mo. @ \$5,000/mo.	\$ 5,000
b. J. A. Grambling, Assoc. Professor, 1 mo. @ \$3,000/mo.	3,000
c. Two graduate students, 9 mo. @ 0.5 FTE and 2.5 mo. @ 1.0 FTE @ \$1,200/mo.	16,800
d. Secretarial and technician services, 400 hrs. @ \$5/hr.	<u>2,000</u>

Total, Salaries and Wages \$26,800

2. Travel and Field Expenses:

a. Travel, University vehicle, 2,000 mi. @ \$0.30/mi.	1,800
b. Per diem, 4 persons, 30 days @ \$26/day	1,560
c. Professional meetings, 2 persons @ \$800	<u>1,600</u>
Total, travel and field expenses	\$ 4,960

3. Laboratory Expenses:

a. Electron microprobe, 80 hrs @ \$35/hr	2,800
b. Thin sections, 100 @ \$5	500
c. Microprobe sections, 40 @ \$10	400
d. Chemical analyses, 40 @ \$35	1,400
e. Miscellaneous, equipment use and supplies	<u>500</u>
Total, laboratory expenses	\$ 5,600

4. Publications costs 1,000

5. Computer costs 500

TOTAL, 1 year \$38,860

TOTAL, 3 years \$116,580

Note: If grant is to be administered by the University of New Mexico, please add 20% to salaries and wages (fringe benefits) and 47% to total (indirect costs).

CHARACTERIZATION OF ALTERATION MINERALOGY AND ZONING; COMPARISON WITH FOSSIL EPITHERMAL ORE SYSTEMS

Robert Charles, Jeff Hulen, and Dennis Nielson

Background: The nature and distribution of hydrothermal alteration can be extremely useful in characterizing such critical features of an active geothermal system as size, potential permeability, and thermal history. Hulen and Nielson (in press), for example, have shown that the active system beneath the Redondo Creek area of the Valles caldera has been hotter in the past, and that permeable pathways in this system are commonly associated with intense phyllic alteration. Redondo Creek, however, represents only a portion of the area in the caldera known to host convecting hydrothermal systems. The Sulphur Springs area, intensely acid-sulfate leached at the surface (Goff and Gardner, 1980; Charles et al., 1984), is another vigorously active intracaldera hydrothermal center worthy of investigation by deep scientific drilling. Careful study of alteration in core from a deep Sulphur Springs drill hole would allow comparison with broad-scale and detailed alteration zoning at Redondo Creek, resulting in a clearer understanding of thermal fluid circulation and fluid-rock interaction throughout the Valles caldera.

The proposed Sulphur Springs borehole, in addition, would permit further investigation of the relationship, apparent in the Redondo Creek area (Hulen and Nielson, in press), between the active Baca geothermal system(s?) and fossil systems responsible for deposition of silver-base metal epithermal vein deposits such as those at Creede, Colorado (Barton et al., 1982). Core from the Sulphur Springs borehole would also allow characterization, among ore and alteration minerals, of detailed paragenetic relationships possibly obscured or obliterated during production of cuttings from the Redondo Creek wells.

Statement of the Problem: Deep scientific drilling in the Sulphur Springs area would provide answers to the following questions concerning hydrothermal alteration mineralogy and zoning in the Valles caldera:

1. How are alteration assemblages zoned, vertically and laterally, and how do these zones reflect system evolution?

2. How do alteration zoning characteristics at Sulphur Springs compare with those in the Redondo Creek area and how do differences, if any, reflect differences in host rock and in geochemistry of thermal fluids presently circulating in the two areas?
3. Can certain alteration assemblages be used to help locate active thermal fluid conduits?
4. Which assemblages delineate the zone of boiling?
5. What metal-complexing mechanisms are active in the deep fluid?
4. Are active or recently active hydrothermally altered conduits enriched in silver (or other ore metals), as they are at Redondo Creek?
7. What is the analogy between the active hydrothermal system(s) beneath Redondo Creek and Sulphur Springs and the systems believed to be responsible for the formation of silver-base metal epithermal veins and stockworks?

Statement of Work: We propose to characterize alteration mineralogy and zoning in the Sulphur Springs borehole using a variety of methods designed to investigate progressively more detailed aspects. Careful visual examination and logging with the assistance of the binocular microscope will precede petrographic examination, x-ray diffraction (bulk and 5- μ m fraction), whole-rock geochemistry, microprobe chemical analysis of discrete minerals, fluid inclusion studies, and scanning electron microscopy. A minimum of 100 thin sections, 100 bulk plus clay-fraction XRD analyses, perhaps 20 SEM samples, and 100 whole-rock geochemical analyses would be required. The data acquired through these studies would allow confident thermomechanical modeling of the Sulphur Springs system.

Budget:

	<u>FY1</u>	<u>FY2</u>
R. Charles	\$30.0 K	\$40.0 K
J. Hulen	30.0	40.0
D. Nielson	15.0	20.0
Thin Sections	1.5	0.5
XRD Analysis (bulk)	20.0	7.0
Electron Microprobe	5.0	5.0
SEM Analysis	10.0	2.0
XRF Analysis	10.0	2.0
Nuclear Microprobe	10.0	5.0
Equipment	5.0	---
Computation Costs	5.0	5.0
Travel (meetings)	1.0	2.0
Publication Costs	<u>2.0</u>	<u>7.0</u>
	\$144.5 K	\$135.5 K

Includes fringe, salary, burden

CHARACTERIZATION OF WATER-ROCK INTERACTION

David Janecky

Background: The occurrence of significant hydrothermal activity in the Valles caldera is well demonstrated, both as hot spring activity at Sulphur Springs and as a result of geothermal exploration drilling. Solutions sampled within the caldera, Jemez fault zone, and adjacent Fenton Hill boreholes indicate that at least three distinct hydrothermal solution compositions exist: acid-sulfate solutions at Sulphur Springs, "deep geothermal fluid" in the caldera and Jemez fault zone, and solutions in the Precambrian rocks at Fenton Hill. An intermediate depth scientific borehole in the Sulphur Springs area will provide important new information on the relationships between solution types and alteration patterns in this system. The resulting improvement of our understanding of the Valles caldera hydrothermal system will form a basis for examining other hydrothermal systems related to calderas, for example, the hydrothermal system active in the Yellowstone caldera and the fossil hydrothermal ore deposits of the Creede caldera.

Statement of Problem: Understanding the mechanisms of water-rock interaction in the Valles caldera hydrothermal system is critical to deciphering hydrogeochemical systematics, origins of solutions and solutes, chemical evolution of dissolved inorganic and gas components, isotopic systematics, and the distribution and interrelation of alteration zones and assemblages. Various researchers will be involved in characterizing solution and solid samples from the proposed borehole; however, the results of those investigations cannot explicitly define the mechanisms and pathways of alteration, or the influence of disequilibrium and kinetics on the reactions.

Statement of Work: Hydrothermal alteration of rock types present in the Valles caldera will be experimentally investigated to determine reaction mechanisms and the influence of kinetics and equilibria on reaction pathway. Dickson-type hydrothermal apparatus and facilities for characterization of solutions and solids at Los Alamos National Laboratory will be used for this effort. In addition to characterizing major element chemistry of solutions, composition and abundance of major mineral components, and the redox state of the system, particular attention will be focused on characterizing the solubility and fate of minor and trace elements and the minor alteration

minerals formed. The experimental results will be integrated with reaction pathway modeling using EQ3/6, and other codes, to provide a framework that can be used to examine the sensitivity of the results of water-rock interaction to variations in rock, solution, and hydrologic characteristics of the Valles caldera. These models can also be used predictively for similar hydrothermal systems where detailed information is not available.

<u>Budget Estimate (2 year):</u>	<u>Year 1</u>	<u>Year 2</u>
Hydrothermal Experimentation	\$115,000	\$ 50,000
Data Reduction	30,000	75,000
Modeling	30,000	75,000
Publications and Presentations	<u>5,000</u>	<u>5,000</u>
	\$180,000	\$205,000

CHEMICAL CHARACTERIZATION OF THE BOILING ZONE

Cole L. Smith

Background: Current models of geothermal systems that formed epithermal ore deposits suggest that boiling is an important process in controlling the deposition and transport of elements characterizing epithermal ore deposits. Fluid inclusion studies of fossil geothermal systems that formed epithermal ore deposits indicate boiling is an important process in the formation of these deposits at temperatures between approximately 180° and 320°C.

Statement of Problem: The trace metal chemistry of fluids between 180° and 320°C has not been adequately investigated in active geothermal systems, but has only been inferred from studies of fossil geothermal systems. Most wells that are used for geothermal power generation produce composite geothermal fluids from several sources, such as fractures that intercept the drill hole at different depths and orientations. Fluids produced from different sources could be introduced into the drill hole at different temperatures and with differing chemistry.

Statement of Work: The chemistry of fluid samples that are well characterized with respect to temperature, depth, gas concentration, and source fracture orientation might give valuable information that could be used to test various models of epithermal ore deposit formation.

Scientific Program: It is proposed that fluid samples in and below a boiling zone or zones at temperatures between 180° and 320°C be collected and analyzed for all major elements and gases as well as some trace elements such as As and Sb. The analyses of the fluids will be compared with the mineralogy and chemistry of the associated rocks. If possible, each major fluid entry should be packed off and sampled separately. High gas concentrations promote boiling at depths greater than those indicated by depth to boiling curves for pure water. Drilling in areas known to contain high gas concentrations may allow a study of the effect of removing gas from a high-temperature fluid and may have a greater chance of intercepting a zone of high-temperature boiling. The best drilling site for this project would probably be between Fenton Hill, where drilling encountered high CO₂ concentrations, and Sulphur Springs, which discharges significant quantities of H₂S.

Budget Estimate: Travel, purchase of a downhole sampling device, and collection and analyses of samples should cost no more than \$40,000.

HYDROGEOCHEMICAL SYSTEMATICS

Harold Wollenberg and Art White

Background: The circulating hydrothermal system of the Valles caldera is being characterized by hydrogeochemical investigations encompassing the meteoric recharge, hot-spring and geothermal well waters from within the caldera, and warm and hot waters of springs of the outflow zone. Stable-isotope ratios and major and trace element abundances of these waters are being compared with chemical compositions of altered and relatively fresh rocks, along with measured and calculated chemical geothermometer temperatures, to furnish input for reaction-path models. These models help to trace the chemical evolution of fluids and minerals in the circulating system and the pathways that the water follows into, through, and out from the system.

Statement of Problem: Most samples collected from Valles geothermal wells (predominantly from the Redondo Creek area) are of the total wellhead product and may not originate from specific hydrostratigraphic horizons. Samples and analyses of fluids and altered rocks from discrete intervals in a hole penetrating the complete lithologic section of the caldera (including well into the Precambrian) will furnish a considerably better base than what now exists of rock-water chemical data for entry into appropriate reaction-path and transport codes.

Statement of Work: Samples of fluids from specific zones, determined primarily by examination of drill logs, will be obtained from packed-off and/or perforated intervals, following initial flowing of the hole to assure access to uncontaminated formation fluids. Samples of cuttings and ores from these zones will also be selected and preserved for detailed mineralogical and chemical analyses, emphasizing major and trace element concentrations and stable isotope concentrations.

Scientific Program: Besides furnishing a base for reaction-path models that help define the evolution of the hydrothermal system, the data obtained will help form the basis for determining the system's age. In these respects, a hole in the Sulphur Springs area, penetrating deep into the Precambrian, will encounter fluids and altered rock of the upper vapor zone, high-temperature water in the relatively permeable caldera fill, and pore fluids in the thermally conductive zone that is believed to underlie the

area. The results of the analyses and their interpretations will then provide significant terms for entry into predictive and retrospective models.

Budget Estimate: \$150 K for each of 2 years.

ORIGIN OF FLUIDS AND COMPONENTS

Charles O. Grigsby

Background: On the basis of ion ratios, two neutral chloride waters have been identified in the Valles caldera region: 1) the so-called "deep geothermal fluids," which circulate in the fractured volcanic and sedimentary rocks within the caldera and along the Jemez fault zone, and 2) the pore fluid observed in the Precambrian rocks at Fenton Hill. Understanding the origins of these fluids — meteoric, magmatic, etc., — may provide important clues about hydrogeochemical processes associated with the emplacement of a caldera. In particular, these fluids act as indicators of fluid flow, heat transport, and chemical reactions between fluids and rocks.

Problem Statement: Because the pore fluid in the Precambrian rocks has, to date, only been observed in the four deep wells at Fenton Hill, observation of this fluid in one or more deep wells drilled into Precambrian rocks beneath the caldera would be important in establishing the origin of this fluid.

Statement of Work: This work requires the ability to identify and sample fluid entries in a deep and hot well. Core or cuttings are required to evaluate the equilibrium conditions among the fluid phases and the primary, alteration, and fracture-filling mineral phases. Comparisons of the major, minor, and trace element geochemistry, stable isotope geochemistry, and gas geochemistry between Fenton Hill and the new CSDP well(s) would be used to study the spatial and temporal evolution of deep convective heat and mass-transport processes in the caldera.

Scientific Program: One or more wells drilled into Precambrian rocks beneath the Sulphur Springs area would allow the comparison of the "deep geothermal fluid" and the Precambrian fluid within a single well. In order to observe the Precambrian fluid, the well should be drilled as far as possible (and a minimum of 1000 ft) into the Precambrian. Samples would be collected from intervals of interest using downhole fluid samplers and from the wellhead if the well is capable of flowing.

Budget Estimate:

0.25 FTE Total	\$30 K
Field Support	30 K
20 Chemical Analyses of Water (major/trace) Los Alamos	5 K
20 Stable Isotope Analyses of Water (contract)	1 K
20- ¹³ C and Other Specialized Analyses (by contract or arrangement)	
Equipment	<u>5 K</u>
Total	\$71 K

GAS GEOCHEMISTRY AND GEOCHRONOLOGY OF GEOTHERMAL FLUIDS

F. Goff, C. Janik, M. Kennedy, and F. Phillips

Background: The objective of this work is to determine the age and origin of the thermal fluids beneath the Sulphur Springs area and relate these data to the Valles caldera geothermal system. The chemical and isotopic compositions of gases can be used to infer equilibrium temperatures and sources for the geothermal fluids. Measurements of radioactive element abundances in the fluids are used to trace fluid flow and to estimate both relative and absolute ages of the fluids and therefore the geothermal system.

Statement of Problem: Presently, the origin of Valles geothermal gases is not obvious. C. Janik is investigating carbon-13 content of CO_2 , HCO_3^- and CO_3 -bearing rocks along a transect across the western half of the caldera to determine the origins of CO_2 and the reactions controlling carbon species. Carbon-13 studies at Sulphur Springs (Goff et al., 1986) suggest that the CO_2 originates partly from thermal decomposition of Paleozoic carbonate strata that underlie the caldera. A large magmatic component to the CO_2 is not indicated. On the other hand, helium studies by Smith and Kennedy (in press) indicate that some deep mantle or magmatic source is degassing into the overlying geothermal system. Analyses of gases and their isotopic compositions including noble gases may help resolve some of these problems of origin.

Investigations of ^3H and ^{36}Cl at Valles caldera (Vuataz and Goff, in press; Phillips et al., 1984) indicate that the deep geothermal fluids are probably more than several thousand years old. However, we do not have enough information on the relative abundances of these isotopes in various parts of the geothermal system and therefore do not have relative ages of subsystems or stacked reservoir horizons. We need this information to understand reservoir dynamics.

Statement of Work: From previous reports released by Union Oil Co. (Goff et al., 1986), we know that a well at Sulphur Springs will penetrate vapor-dominated and liquid-dominated zones having a variety of gas and fluid compositions. We plan to obtain gas samples (using both flowthrough- and caustic-soda-type gas bottles) and water samples for ^3H and ^{36}Cl analysis from downhole sampling of individual fluid entries and from wellhead sampling if the well or wells flow. We have observed chemical and isotopic

differences in the various aquifers penetrated by some geothermal wells in the Valles caldera area and therefore would stress the importance of downhole sampling. Chemistry and isotopes of gases will be analyzed jointly by Los Alamos, the USGS, and U.C. Berkeley. Analyses of ^{36}Cl will be performed by the New Mexico Institute of Mining and Technology in collaboration with researchers at the TAMS facility in Rochester, New York. Analyses of tritium will be contracted to the University of Miami (H. G. Ostlund).

Budget Estimate: \$100 K/yr for 3 years.

NATURAL RADIONUCLIDES OF URANIUM AND THORIUM SERIES IN GROUNDWATERS
FROM VALLES CALDERA, NEW MEXICO

J. C. Lau

Background: Investigations of natural radionuclides of the uranium and thorium decay chains in groundwaters at various temperatures provide very important information about the behavior of their analog radionuclides in high-level radwastes in a breached repository.

Statement of Work: The objective of this work is to address the overall issue of radionuclide transport parameters as a function of temperature by studying the disequilibrium of natural radionuclides in hot geothermal areas of Valles Caldera, New Mexico. The natural radionuclides in the ^{238}U and ^{232}Th decay series are ^{238}U - ^{234}Th - ^{234}U - ^{230}Th - ^{226}Ra - ^{210}Pb - ^{210}Bi - ^{210}Po ; ^{232}Th - ^{228}Ra - ^{228}Th - ^{224}Ra (see Table 1). These radionuclide data would enable us to determine 1) retardation factors relative to soluble components (e.g., Rn); 2) in situ sorption and desorption coefficients; 3) rate of sorption and desorption; 4) "solubility limits" under natural conditions; 5) evaluation of the above parameters as a function of increasing temperature; 6) approximate or minimum age of water; and 7) nature of source region. The radionuclide disequilibrium results will enable us to predict the near- and far-field behavior of radwaste radionuclides over a wide range of temperatures in a repository.

TABLE 1. Radionuclide Relationship in ^{238}U and ^{232}Th Chains.

^{238}U Chain

^{238}U	→	^{234}Th	---	^{234}U	→	^{230}Th	→	^{226}Ra	→
$4.4 \times 10^9 \text{ yr}$		24.1 d		$2.44 \times 10^5 \text{ yr}$		$7.5 \times 10^4 \text{ yr}$		1600 yr	
^{222}Rn	---	^{210}Pb	→	^{210}Bi	→	^{210}Po			
3.82 d		22.3 yr		5.0 d		138.4 d			

^{232}Th Chain

^{232}Th	→	^{228}Ra	---	^{228}Th	→	^{224}Ra	
$1.4 \times 10^{10} \text{ yr}$		5.76 yr		1.91 yr		3.66 d	

SAMPLING PLAN FOR GROUNDWATER

We will sample groundwaters from shallow, intermediate, and deep aquifers from at least four different temperature ranges: 1) 50°C, 2) 50-100°C, 3) 100-200°C, 4) 200-300°C. We can work with a few samples from each temperature regime. Our sample plan is as follows.

- a) Rn^{222} gas is collected in an evacuated chamber and measured by the alpha scintillation method. Sample requirement is about 0.5 l.
- b) 1- to 4-l aliquots are taken for the analysis of the following radionuclides by carrier-free radiochemical separations.
 - ^{238}U , ^{235}U , ^{234}U ---BY MASS SPECTROMETRY---(^{233}U AS TRACER)
 - ^{234}Th , ^{232}Th , ^{230}Th , ^{228}Th ---BY ALPHA AND BETA SPECTROMETRY---(^{229}Th AS TRACER)
 - ^{226}Ra , ^{228}Ra , ^{224}Ra ---BY GAMMA COUNTING---(^{133}Ba AS TRACER)
 - ^{210}Pb VIA ^{210}Po ---BY ALPHA SPECTROMETRY---(^{208}Po AS TRACER)
 - ^{210}Bi VIA ^{210}Po ---BY ALPHA SPECTROMETRY---(^{208}Po AS TRACER)
 - ^{210}Po BY ALPHA SPECTROMETRY---(^{208}Po AS TRACER)
- c) If volume is not a constraint, then we will pump a few gallons through our large-volume sampler containing several filters and two Al_2O_3 - BaSO_4 adsorption beds to concentrate ^{226}Ra , ^{228}Ra , and ^{224}Ra , and we will measure these radionuclides by direct gamma counting on our low-energy photon detector (LEPD). Otherwise, these radionuclides will be measured as outlined in (b) above.
- d) Barium, strontium, and the rare earths (Nd:Am:Cm) are measured by neutron activation analysis on 0.1-l aliquots. The rare earths along an inter-radionuclides spectrum will address the question of the nature of source region.

Solid Samples (Cores)

The levels of ^{238}U and ^{232}Th are usually high (ppm range) in rocks or core samplers. By instrumental counting using multidimensional coincidence/noncoincidence NaI(Tl) - NaI(Tl) and LEPD counting system, we will obtain data for ^{238}U , ^{226}Ra , ^{210}Pb , ^{232}Th , and ^{40}K . The sample requirement is about 30-100 g for instrumental counting.

For radiochemical separations of solid samples, we will need a 2-10-g sample. Following the individual element separations, ^{238}U , ^{235}U , and

^{234}U isotopes are measured by mass spectrometry. The precision of the results is about 1 to 3%. The isotopes ^{232}Th , ^{230}Th , and ^{228}Th are measured by alpha spectrometry with a precision of 2 to 10%. The ^{226}Ra and ^{228}Ra isotopes are measured by alpha and gamma spectroscopy, while ^{210}Pb and ^{210}Po are measured by alpha spectroscopy with a precision of 2 to 10% depending on the activity level.

Budget Estimate: \$120 K/yr (1 man year)

- Includes on-site sampling of four aquifers.
- Analysis of natural radionuclides of ^{238}U and ^{232}Th series (Table 1) in waters.
- Analysis of rare earth elements in waters.
- Instrumental counting of a few core samples for radionuclides.

MEASUREMENT OF FLOW AND TRANSPORT CHARACTERISTICS

Lee Brown

Background: Fluid flow, heat transfer, and mass transport within fluids and solids are processes whose significance in geologic occurrences is difficult to overstate. Flow and transport characteristics can be deduced from the history and evolution of the system and from potentials for various types of exploitation.

Statement of Problem: As stated above, it is important to know the flow and transport characteristics of the system being studied. The measurement of these is the goal of this portion of the study.

Statement of Work: Fluid flow is dependent primarily on fracture characteristics of the system, with a lesser dependency on the rock matrix properties. Thus, measurement of fracture characteristics can give insight into flow characteristics. Nonflow measurement of fracture characteristics can be made using analysis of oriented core, drill cuttings, downhole cameras, and sonic amplitude logs. Geophysical measurements also are helpful. The characteristics of the rock matrix are best obtained from core analysis. Experiments involving flow include pressure testing, interwell tracer flow experiments, and huff-puff tracer experiments. Numerical modeling of the results can give estimates of fracture permeability, matrix permeability, fracture dimensions, and porosity of different flow paths.

Mass transport within a fluid is best measured by tracer experiments, both interwell and huff-puff.

Heat transport can be estimated from temperature logs of the well and the measurement of thermal gradients within the rock.

Budget Estimate: \$300 K/yr (For tracer experiments only; other experiments are covered in other topics.)

SYSTEM EVOLUTION: PHASE ASSEMBLAGES AND FLUID COMPOSITIONS

Robert Charles, Jeff Hulen, and Dennis Nielson

Background: Sulphur Springs is but one of many hydrothermal expressions found in the Valles. Goff et al. (1982) and White et al. (1983) have tabulated geochemical data for well over one hundred thermal and nonthermal waters found in the Valles and its immediate environs. These waters include meteoric waters, acid-sulfate waters, thermal meteoric waters, deep geothermal waters, and mineralized waters as well as intermediate types.

Solid phase alterations correspondingly span a wide spectrum. Hulen and Nielson (1984), Nielson and Hulen (1984), Fox (1983), and Charles et al. (1984) have examined some of these alterations petrographically, stratigraphically, chemigraphically, and thermochemically. Types of assemblages are acid-sulfate assemblages at Sulphur Springs, pervasive propylitic alterations and structurally controlled phyllic alterations in the Baca, and zeolitic alterations in the Baca. The proposed deep wells, especially VC-2a, VC-2b, and VC-3, will determine the relationship between these varied hydrothermal systems that will have general application to less evolved hydrothermal systems and ancient, dissected systems resulting from the emplacement of a silicic magma body.

Statement of Problem:

1. How many stacked hydrothermal systems are there?
2. What structural and chemical connections exist between these?
3. What does the relict mineralization tell us about the evolution of the caldera?
4. What is the nature of the deep fluid underlying the known hydrothermal systems?
5. What metal transport is seen? What complexing is important?
6. Can these metals be used as tracers to help define hydrology?

Statement of Work: This project will build upon the alteration assemblages defined in the pre-CSDP work of Hulen and Nielson (1984), Nielson and Hulen (1984), Fox (1983), and Charles et al. (1984). VC-2a and b will clarify many of the relations between the surface acid-sulfate alterations and the pseudo-vapor-dominated zone. They will clarify the zone's connection with deep geothermal waters and allow us to compare our findings with the classical models of White et al. (1971) and Buchanan (1981). VC-3, the

deepening of Baca-12, will provide information about the deepest heat and chemical transfer zone as one penetrates the deepest metamorphic zones and the roof of the granitic pluton.

The presence of continuous core will define the petrogenetic sequence of mineralogy. Detailed examination of thin sections will be necessary. In detail, the bulk chemistry and mineralogy will be defined with respect to major, minor, and trace element composition. Trace element mobilization and transport will be defined by nuclear microprobe, which can detect spatially resolved elemental compositions to units of ppm without destruction of the rock. Thermomechanical calculations with computations in concentrated solutions after the method of Pitzer (1979) will allow us to completely model the hydrothermal systems with respect to solids, gases, and fluids.

Budget:

	<u>FY1</u>	<u>FY2</u>	<u>FY3</u>
R. Charles	\$30 K	\$40 K	\$40 K
J. Hulen	30	30	30
D. Nielson	20	20	20
Nuclear Microprobe	<u>---</u>	<u>30</u>	<u>---</u>
Total	\$80 K	\$120 K	\$90 K

These costs include analytical costs, publication, travel, computation, and salaries.

DEVELOPMENT OF PREDICTIVE AND RETROSPECTIVE NUMERICAL MODELS

Lee Brown

Background: Heat transfer, fluid flow, movement of solids, mass transport within fluids and solids, and chemical reaction are the processes that underlie the geologic occurrences that this study will investigate. These processes can be modeled mathematically; proposed sequences of events can be described by the appropriate partial differential and integral equations, and these equations can be solved to predict and explain what will be found by the experimental tests.

Statement of Problem: Experiments must be chosen and designed so as to yield the maximum information.

Statement of Work: Numerical models, based on present concepts of the Valles caldera system, will be used to identify tests that are the most sensitive judges of the models' realism. Differences between the predicted and observed results will be used to modify the models so as to predict the additional results of further tests, and again to design tests that are most sensitive for assessing the concepts embedded in the models. This iterative process will be continued throughout the study.

Many codes exist at Los Alamos and elsewhere that can be used with their boundary conditions to solve the equations of this study. Examples are Los Alamos' 2-dimensional WAFE code for combined heat and mass transport, 3-dimensional TRACR3D code for flow and sorption in porous and fractured media, and KRAK code for solid fracturing. Many others are available, so code development is not envisioned as a major part of the numerical modeling portion of this study. Rather, the existing codes will be used in the modeling program to maximize the information obtained from the investigation.

Budget Estimate: Approximately \$100 K/yr.

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II. VOLCANOLOGY AND STRUCTURAL FRAMEWORK OF THE JEMEZ VOLCANIC FIELD (PANEL 2)

<u>Hole No.</u>	<u>VOLCANOLOGY</u>
VC-3,VC-4 VC-5	1. Evolution of Magmatic Systems in the Jemez Mountains, from 3 Ma to the Present - J. Wolff and J. Gardner
VC-4,VC-5	2. Studies of Precaldera Volcanic Rocks - W. S. Baldrige and D. T. Vaniman
VC-2	3. Intracaldera Stratigraphy in the Sulphur Creek Area - J. B. Hulen
VC-3,VC-4	4. Intracaldera Stratigraphy - J. V. Wright and S. Self
VC-3,VC-4	5. Facies Models for the Location of Intracaldera Ore Bodies - J. V. Wright
VC-3,VC-4, VC-5	6. Intracaldera Volcanism and Sedimentation, Toledo and Valles Calderas - G. Heiken
VC-5	7. The Toledo Embayment - G. Heiken, D. Vaniman, F. Goff, S. Self, and W. Wolfe
VC-2,VC-5	8. Three-Dimensional Stress State at the Valles Caldera - T. Dey and M. J. Aldrich
VC-2,VC-4, VC-5	9. Geometry and Internal Structure of the Valles Caldera - M. J. Aldrich and K. H. Olsen
VC-2,VC-3	10. Development of Resurgent Doming - D. L. Nielson
VC-2,VC-3, VC-4	11. Development of Fracture Permeability - D. L. Nielson
VC-4	12. Seismic Surveys of the Valles Caldera - K. H. Olsen
VC-4	13. Lacustrine Sedimentation in the Valle Grande and Valle Toledo - J. P. Bradbury

EVOLUTION OF MAGMATIC SYSTEMS IN THE JEMEZ MOUNTAINS

FROM 3 Ma TO THE PRESENT

John Wolff and Jamie Gardner

Background and Problem: Processes in and evolution of silicic magma bodies are poorly understood and are the subject of controversy (Hildreth, 1979; 1981; Mahood, 1981; Cameron, 1984; Miller and Mittlefehldt, 1984). Despite the known compositional heterogeneity of the Tewa Group, the youngest volcanic rocks of the Jemez Mountains, and its potential value in these debates, there is only a small body of published petrologic data (Smith, 1979; Smith and Bailey, 1966). Rocks of the Tewa Group represent the culmination of greater than 13 Ma of volcanism in the Jemez Mountains. The Tewa Group includes dacitic domes and pyroclastic deposits, voluminous rhyolitic ash-flow tuffs (Bandelier Tuff), and post-Toledo and post-Valles caldera rhyolitic flows. Although there are data regarding the petrology and geochemistry of Pre-Tewa magmatic activity (Loeffler, 1984; Gardner, 1985) intensive petrologic and geochemical studies of the Tewa Group rocks are needed to understand their relation to earlier magmatic activity and to reveal information regarding physical, thermal, and geochemical evolution of this long-lived silicic magma system.

Scientific Program: The study will integrate data from core samples with concurrent investigation of Tewa Group rocks exposed at the surface. Detailed sampling of Tewa Group rocks on the basis of internal eruption stratigraphy and processes has already yielded a suite of 400 samples. Drill-core samples are crucial for two reasons. First, several Tewa Group eruptive units not found outside Valles are present in intracaldera fill (Nielson and Hulen, 1984); second, the probable initiation of caldera collapse after the onset of each Bandelier eruption means that both intracaldera and extracaldera samples are required for a complete study. While hydrothermal alteration will limit the usefulness of geochemical study of intracaldera rocks, many elements (e.g., Zr, Nb, REE) and isotopic systems (e.g., Nd) should be insensitive to alteration. Attention will be focused on these and on relict primary mineral phases. For this study, any core of Tewa Group rocks will be useful, but ultimately studies of core from a 4-km hole in the eastern part of the Valles caldera, where the intracaldera sequence is thickest and most complete, will yield the most significant information.

Subvolcanic intrusive rocks, which are the solidified representatives of erupted volcanic rocks, should be present at depth beneath Valles caldera. Nielson and Hulen (1984) suggest that the resurgent magma body beneath Redondo Dome penetrated 4 to 7 km beneath the surface. Core samples of such silicic intrusive bodies, co-magmatic with the volcanic rocks, would provide unique opportunities for tests of petrogenetic models and magmatic processes because such intrusive rocks may represent either a crystalline carapace of the pre-eruptive magma body or a solidified, degassed post-eruptive residual material. Reopening and coring of Baca-12 to 5 km offer the best chance of providing samples of the subvolcanic intrusive rocks.

Work Plan:

- 1) Collection of surface sample suite. (Already achieved)
- 2) Petrographic and electron microprobe study.
- 3) Whole-rock geochemical analyses for major and trace elements.
- 4) Trace element analyses of crystal/matrix separates.
- 5) Repeat 2 through 4 for drill-core samples.
- 6) Radiogenic and stable isotope studies.

Estimated Annual Budget: \$180 K per year for three years.

Personnel: J. Wolff 0.3 FTE
 J. Gardner 0.3 FTE
 3 graduate students

STUDIES OF PRECALDERA VOLCANIC ROCKS

W. S. Baldrige and D. T. Vaniman

Background: These studies will focus primarily on rocks of the Polvadera Group, especially the Tschicoma Formation, but will include rocks of the Keres Group. The purpose is to study the development of the magma system that immediately predated and led to the Bandelier magma system. Rocks of the Polvadera Group represent a continuous basalt-dacite-rhyolite magma system that developed from at least 11 Ma ago to 2 Ma ago and terminated in a rhyolite similar to that of the Bandelier tuff (Smith et al., 1970; Gardner and Goff, 1984.*

Statement of Problem: Rocks of the Polvadera Group represent a major volcanic edifice (500 km^3) centered approximately on the northern rim of the Toledo embayment. The Tschicoma Formation includes several domes of intermediate composition and probably also (based on pyroclastic rocks in the Puye Formation) at least one caldera or large crater. Field studies suggest that the central part of this Tschicoma volcanic field is now buried beneath the Valles and Toledo calderas.

Statement of Work: Studies of precaldern rocks must involve 1) field and geochemical work on exposures outside of the caldera rim as well as 2) petrographic and petrologic work on similar rocks encountered in cores. Item 1) is critical, not only to identifying precaldern rocks from cores and understanding their alteration, but also to understanding their importance to the Jemez volcanism as a whole.

Field work must be oriented toward delineating eruptive units (including vents) and characterizing these units petrologically and geochemically. It is also of key importance to conduct detailed mineralogic studies of these rocks. Item 2) must focus on recognizing and delineating eruptive units which possibly do not crop out on the surface. Drilling and coring, especially in the northeastern Valles caldera and/or Toledo embayment, are important for understanding the total extent and volcanogenic significance of the precaldern (Tschicoma?) volcanic fields.

*Information is also available from D. Vaniman and W. S. Baldrige, Los Alamos National Laboratory, 1986.

Scientific Program: Drilling is necessary to determine the distribution and nature of precaldern rocks. Since the geographic center of the Tschicoma vent field is probably near the northern rim of the Valles caldera (and may even be the Toledo embayment), core holes must be located as close as possible to this area. We favor a site located in either the northeastern Valles caldera or the Toledo embayment areas. Holes must of course penetrate through the Bandelier tuff, which is possibly as thick as 3 to 3.5 km in the northeastern Valles area. Two holes, one in each of the above areas, are strongly recommended.

<u>Budget Estimate:</u>	<u>First Year</u>	<u>Second Year</u>
Field mapping (1 FTE)	\$130 K	\$140 K
Core studies (petrography, chemistry, mineralogy)	130	140
Petrographic support, etc.	26	28
K-Ar age dates	11	12
Travel, publications	<u>3</u>	<u>3</u>
TOTAL	\$300 K	\$323 K

INTRACALDERA STRATIGRAPHY IN THE SULPHUR CREEK AREA

J. B. Hulen

Background: An intermediate depth borehole in the Sulphur Springs area not only would provide a wealth of new information about thermal fluid flow and hydrothermal alteration in an especially vigorous segment of the active Valles caldera hydrothermal system but also would help define intracaldera stratigraphy within a critical portion of the Valles-Toledo (and earlier?) caldera complex. Recent work by Self et al. (1984) has indicated that the approximately 3-Ma-old pre-Bandelier ignimbrites [the informally designated "Lower Tuffs" of Nielson and Hulen (1984)] may have been erupted from a small caldera complex that might be situated in part beneath the Bandelier Tuff in the Sulphur Springs area. The proposed borehole, therefore, would presumably penetrate and supply samples of this early caldera complex. Nielson and Hulen (1984) note that in the vicinity of a highly productive geothermal well B-4, in the Redondo Creek area, pronounced thickening of the permeable pre-Bandelier ignimbrite coincides with the hottest reservoir temperatures (up to 300°C) at commercially producible depths. Similar and perhaps greater thickening of these rocks in the pre-Bandelier caldera, together with strong fracturing (and brecciation?) associated with development of this caldera, might be partially responsible for localizing the Sulphur Springs hydrothermal system.

Statement of the Problem: The following aspects of intracaldera stratigraphy beneath the acid-sulfate (argillic) altered Sulphur Springs area could be usefully investigated by drilling and obtaining core from an intermediate-depth research well:

- 1) Is there evidence of a pre-Bandelier caldera and does such a caldera influence localization of the area's intense hydrothermal activity?
- 2) Can the stratigraphy of the Bandelier Tuff and associated underlying and overlying felsic tuffs and sediments in this area be correlated with the time-equivalent sequence penetrated in Union Oil Company boreholes in the Redondo Creek area?
- 3) Have intratuff sandstones and thin, nonwelded ash-flow tuffs (and air-fall tuffs) served as secondary thermal fluid conduits in the Sulphur Creek area, as they have at Redondo Creek?

- 4) To what extent do the original composition and texture of intracaldera units at Sulphur Creek influence superimposed hydrothermal alteration?

Statement of Work: Core from the proposed research borehole should be carefully logged using the binocular microscope, supplemented by petrographic and x-ray diffraction methods. Particular care should be taken to locate intratuff stratigraphic marker horizons as well as zones of welding and crystallization in ash-flow tuffs. Such marker horizons and welding/crystallization intervals should be correlated with hydrothermal alteration zones. Cross sections relating stratigraphy in the Sulphur Creek well to that of the Redondo Creek area (as well as in wells outside the caldera) should be prepared. Much of the petrographic and XRD work required for this study can also be applied to a parallel investigation of hydrothermal alteration mineralogy and zoning.

Projected Costs:

1. Detailed logging of core from a 1,000- to 3,000-m well	\$30 K
2. Petrography and x-ray diffraction analysis	15
3. Miscellaneous costs: chemical analysis, travel
supplies, illustration, etc.	5

Total \$50 K/yr for three years

INTRACALDERA STRATIGRAPHY

J. V. Wright and S. Self

Background: The two Bandelier Tuffs (1.4 and 1.1 Ma; Doell et al., 1968) and their calderas, the Valles and Toledo, are well-known examples of silicic explosive volcanic products (Smith and Bailey, 1966). Work on the out-flow (extracaldera) ash flow (or ignimbrite) sheets has been done by R. L. Smith and R. A. Bailey, and later by S. Self, J. V. Wright, and co-workers (e.g., Wright et al., 1981; Self and Wright, 1981).^{*} Also, studies of ignimbrite-forming events in the Jemez Mountains older and younger than those of the two Bandelier Tuffs are under way. On the intracaldera Redondo resurgent block within the Valles caldera (Smith and Bailey, 1968; Smith et al., 1970), the outcrop is dominated by Tshirege (1.1 Ma) Member Bandelier Tuff; it also contains uplifted lake sediments and has an apical faulted graben, supporting an origin by updoming. Recently, Nielson and Hulen (1984) have investigated the stratigraphy of the Redondo Creek (Baca Project) area of the resurgent block. They showed that both upper (Tshirege) and lower (Otowi) Bandelier Tuffs are present in the resurgent block, but they had no core to work with and thus could give no details of the internal textures and depositional histories of the intracaldera ignimbrite fill.

Apart from this paper and various reconnaissance studies of 30-Ma-old resurgent calderas of the San Juan Mountains (see Lipman, 1984, for review), almost nothing is known in detail about resurgent intracaldera sequences, as many of the best-described ones are not well exposed, e.g., Yellowstone, Toba, Cerro Galan, and Long Valley. Therefore, discussion on mechanisms of resurgent uplift (e.g., Smith and Bailey, 1968; Gephart and Parmentier, 1983; Marsh, 1984; Smith and Braile, 1984) has never been able to consider details of the internal features, stratigraphy, and rock types within the resurgent block.

Statement of Problem: Past studies (Lipman, 1984) have shown that up to two-thirds of the magma volume erupted in a major caldera-forming event is contained within the collapse depression as an intracaldera-welded ignimbrite. Hence, a significant proportion of the magma withdrawn from the chamber resides within the caldera. This material has never been included in

^{*}Information is also available from J. V. Wright, University of Texas, Arlington, 1986.

detailed studies of volcanology, stratigraphy and facies models, and petrology of ignimbrites and their magma reservoirs simply because the opportunity has never been available. Some features have been discovered, e.g., mega- and meso-breccias (Lipman, 1976), but the internal volcano-stratigraphic sequences and structures within resurgent blocks are virtually unknown. Specifically regarding the upper Bandelier Tuff eruption and the Redondo Dome, it will be essential to understand the details of the later erupted ignimbrite outflow units because these are more likely to represent the same units that ponded in the caldera (Kite and Self, 1984). Detailed knowledge of the intracaldera stratigraphy will lead to better understanding of the evolution of the Valles caldera and will help to unravel the problems of how many caldera collapse events have taken place in the Jemez Mountains.

Statement of Work: Drilling within the Valles caldera is essential because

- 1) Little surface is exposed within the caldera and more specifically on the Redondo Peak resurgent dome.
- 2) A continuous rock record is needed to determine the stratigraphy and lithological changes within the Bandelier tuffs and the stratigraphy of the intracaldera succession.

Scientific Program:

- 1) Examination of the core with detailed logging of the drilled succession and detailed studies of textural/lithological variations within the two Bandelier tuffs.
- 2) Detailed field mapping of the upper welded parts of both Bandelier tuffs in previous studies has suggested that they are equivalents of the intracaldera tuffs; however, more detailed studies of these are needed to understand the filling of calderas during eruption and caldera collapse.
- 3) Relationships of extracaldera geology to that inside for better understanding of general intracaldera stratigraphy.

Location of Well(s): SE of Cerro Piñon in Valle Grande (at least 4 km).
Others on resurgent Redondo Dome.

Budget Estimate: \$100,000/yr for three years.

FACIES MODELS FOR THE LOCATION OF INTRACALDERA ORE BODIES

J. V. Wright

Background: Intracaldera settings of large silicic volcanoes such as at the Valles caldera are known to be potential sites for the deposition of precious and other epithermal metals (e.g., Henley and Ellis, 1983). Epithermal deposits of gold, silver, lead, and zinc may be found associated with shallow-level hydrothermal systems inside the caldera margins. In addition, porphyry copper-gold deposits may be associated with deep-level intrusives. There is also the possibility that bedded massive sulphides deposited in a deep caldera lake may occur, although, as yet no substantial deposits of this type are known from continental rhyolitic centers.

Statement of Problem: Most exploration for volcanigenic ore bodies is within ancient volcanic successions (e.g., Canada and Australia), which are often discontinuously outcropping, variably deformed, and metamorphosed. Unlike hydrocarbon exploration, where predictive sedimentary facies models are used routinely and have been very successful in locating accumulations, very few facies models for volcanic successions in general and for intracaldera successions specifically have been produced; in the intracaldera case this is because of the paucity of data for modern intracaldera rocks. However, many of the problems encountered in hydrocarbon and mineral exploration are not too dissimilar (e.g., locating porous horizons and facies along which mineralizing fluids have moved and/or precipitated), and indeed mineralized zones/ore horizons and alteration zones can be considered as facies within the context of a facies model. Facies models derived from drilling the intracaldera succession at Valles are potentially very important in predicting the location of ore bodies in similar ancient settings.

Statement of Work: Drilling is necessary and is the only way to determine the intracaldera stratigraphy and hence develop facies models for the volcanic and volcanoclastic rocks and alteration zones and any mineralized zones/ore horizons encountered. The location of drill sites should be the same as those presented by Self and Wright (1981) to give the best stratigraphic results.

Scientific Program: The scientific program would involve

- 1) Construction of facies models for the complete intracaldera succession. This should be a development of studies of the intracaldera succession proposed by Self and Wright, and by Heiken.
- 2) Facies modeling should be coupled with hydrothermal and fluid-rock interaction studies to predict fluid migration pathways and thereby identify potential mineralized zones/ore horizons and significant alteration zones.

Results: The result of this study would be to produce predictive facies models for the location of ore bodies in intracaldera successions of large silicic volcanoes in ancient volcanic successions.

Budget Estimate: \$50,000/yr for three years.

INTRACALDERA VOLCANISM AND SEDIMENTATION, TOLEDO AND VALLES CALDERAS

G. Heiken

A complete record of intracaldera volcanism, which occurred after deposition of the upper and lower members of the Bandelier Tuff, structural resurgence, and possibly, surface hydrothermal activity, may be preserved within intracaldera sediments and tuffs. Within the Toledo and Valles calderas, we know little about the intracaldera stratigraphy except for lithologic logs of shallow water wells in Valle Grande and Valle Toledo (Griggs, 1964), a few thin surface exposures, and cuttings from Baca project wells that are located in the Redondo Creek area (Nielson and Hulen, 1984). A caldera lake may be present within the eastern Toledo caldera, on the basis of phreatomagmatic tuffs of the Cerro Toledo sequence that are exposed outside of the caldera complex. Interpretation of gravity surveys by Segar (1974) indicates that low-density rocks are present in the eastern half of the Valles-Toledo calderas to a depth of about 3 km; these may be a caldera-fill sequence. Intracaldera deposits may be part of that sequence and can be sampled only by drilling.

We propose to 1) prepare lithologic logs of all intracaldera deposits sampled by coring; 2) characterize all stratigraphic units by petrographic, chemical, and mineralogic analyses; 3) examine secondary mineralogy to identify permeable units that may have served as aquifers and conduits for hydrothermal fluids; 4) determine ages of significant volcanic ash horizons; 5) correlate ash deposits with intracaldera domes and deposits visible outside of the caldera; and 6) interpret source areas for epiclastic sediments and unconformities with regard to structural deformation by resurgence and/or continued caldera collapse.

Continuous coring within these sequences is required. The thickest sequence for both Toledo and Valles calderas may be near Cerro del Medio, but this area has never been cored or drilled. One 3-km-deep core hole would penetrate most of the caldera-fill sequence. Valles intracaldera rocks could be sampled and the extent and volume determined with a series of shallow wells. These would be located along a line from the Toledo embayment to the center of Valle Grande.

Budget Estimate: \$200 K (\$100 K/yr - 2 yr).

THE TOLEDO EMBAYMENT

G. Heiken, D. Vaniman, F. Goff, S. Self, and W. Wolfe

Background: The 10-km-diameter Toledo embayment has been one of the more enigmatic physiographic features of the Valles-Toledo caldera complex. It has been proposed as 1) a separate caldera associated with pre-Bandelier pyroclastic rocks that crop out within the Puye formation; 2) part of an elongate, NE-SW Toledo caldera; 3) a large slump into the Toledo caldera; or 4) part of a graben adjacent to the Rio Grande Rift. Much of the embayment has been filled with Toledo-age intracaldera rhyolitic domes.

Statement of Problem: The origin of the Toledo embayment is an important piece of the history of this caldera complex. It appears to be closely tied to the earliest voluminous pyroclastic eruptions in the Jemez Mountains. Unless the relationship between the Toledo embayment and the main caldera is understood, we have little chance of charting the volcanic evolution culminating in the Bandelier Tuff.

Statement of Work: Several shallow holes are needed within the embayment to determine 1) if the lower member of the Bandelier Tuff is thick (as it would be within a caldera) or part of a thinner outflow sheet; 2) if the caldera wall sequence is repeated as it would be in a slump; 3) if a sedimentary sequence is present; and 4) what types of down-dropped Tschicoma rocks occur within the Toledo embayment.

Scientific Program: A first hole, centrally located, would answer the questions of stratigraphic sequence and structure (slump features?) at depth. Subsequent holes can then be located to explore the shape of the Toledo embayment. Because of the present lack of knowledge of rocks that may occur at depth, the initial hole at least must be continuously cored. The scientific program should include logging, to define the rock properties necessary for geophysical studies and for future interpretation of uncored holes, and petrologic studies of core.

Budget Estimate: Approximately \$130 K/yr - 2 years.

THREE-DIMENSIONAL STRESS STATE AT THE VALLES CALDERA

T. Dey and M. J. Aldrich

Background: The Valles caldera sits in a transition zone between the stress states of the Rio Grande rift and the Colorado Plateau (Aldrich and Laughlin, 1982). This, together with the structural complications of the Jemez lineament make the stress state uncertain. Results from Valles Corehole #1 and from the Hot Dry Rock site at Fenton Hill indicate that normal faulting on the ring fracture dominates the stress state in that area. A magma body, since it cannot support shear stress, will redistribute the stress field around it. A three-dimensional picture of stresses will help unravel the contributions of the magma body, caldera collapse, and the Jemez lineament to the stress state and structural evolution of the area in and around the Valles caldera.

Statement of Problem: Find the most important structural features by measuring the stress state in and around the Valles caldera in three dimensions.

Statement of Work: Using the techniques of strain relaxation on freshly cut core samples and differential strain analysis measurements in the laboratory (Kowallis and Wang, 1983), we would estimate the three principal stress magnitudes and directions throughout the Valles region. The core samples need to be oriented and intact. Pieces 6 in. or longer are required. Samples should come from deeper than 1000 ft to insure that the stresses are large enough to give a good measurement. Ideally, samples will be taken at 500-ft intervals down to and into the Precambrian.

The maximum depth for applying these techniques will be limited by the highest temperature at which the orienting tool will work. Wireline coring is preferred since the core begins its strain relaxation as soon as it is cut, and we need to start measuring this relaxation as soon as practical.

Scientific Plan: We need coring at a number of sites in and around Valles. The best start would be one site each at the NW and SE parts of the caldera away from both the apparent location of the Jemez fault zone and the ring fracture. An additional site in the caldera in the fault zone will help determine the effects of the fault zone on the stress state. Two additional sites outside the ring fracture (one to the south-southeast of the caldera and

west of the Pajarito fault, the other in the north) will complete a good picture of the stress state of the Valles.

Budget Estimate: Cost of oriented core - \$20 K per hole for field and laboratory work. Total for five holes - \$100 K.

GEOMETRY AND INTERNAL STRUCTURE OF THE VALLES CALDERA

M. J. Aldrich and K. H. Olsen

Background: The ring-fracture system associated with the Valles caldera was first inferred to dip inward by Smith et al. (1961). They assumed that ring fractures formed during doming or "regional tumescence" (Smith and Bailey, 1968, p. 636), which caused the development of inward dipping fractures as described by Anderson (1936). Smith and Bailey (1968) proposed four mechanisms (continuous rise of magma, hydrostatic rebound, regional detumescence and centripetal pressure, and magmatic convection and related processes) that could cause resurgent doming and suggested that all of these processes may have been active in the Valles caldera. Evaluation of new drill hole and gravity data of the Valles caldera by Goff and Decker (1983) shows that the top of the Precambrian delineates a structural depression under the Valles resurgent dome (Redondo) and not a structural high as indicated by Smith et al. (1970). R. A. Bailey has suggested that this geometry developed over a collapsed regional dome such as that which presumably preceded development of the Valles caldera. Nielson and Hulen (1984) suggest that a laccolith may have caused the resurgence.

Problem: The basic geometry of the ring fractures of the Valles caldera has not been documented. There is no evidence to either substantiate or refute the Smith et al. (1961) model. Additionally, very little is known about the internal structure of the caldera. Hulen and Nielson (1984) have developed an interpretive cross section for the central graben of Redondo Peak, but data are not available to extend this cross section to the ring fractures. The Jemez lineament crosses through the caldera, but virtually nothing is known of its deep structure. Valles caldera has become a type model, and yet key aspects of its geometry and structural development are not known.

Statement of Work: The geometry of the Valles caldera ring-fracture system and internal structure will be determined. This will be accomplished through evaluating a combination of detailed gravity modeling, seismic reflection investigations, and data from deep drill holes. The drill hole and log data are critical to developing a realistic geometric model of the caldera as they will delineate the stratigraphy, provide acoustic velocities of the

various stratigraphic units for interpreting seismic reflection profiles, and provide fracture orientation and intensity information.

Three holes drilled within the Valles caldera into the Precambrian basement are required. One of these holes should penetrate 3 km of basement rock and be located on or near the ring fracture. Gamma-gamma, full-wave acoustics, spinner, televiewer, and caliper logs would be run in each hole. Vertical seismic profiling would also be performed. From this information, the geometric model of the caldera will be improved and a plan developed for locating seismic reflection (COCORP?) lines.

Budget Estimate: Logging - Vertical reflection profiling: \$150 K/yr for three years.

DEVELOPMENT OF RESURGENT DOMING

D. L. Nielson

Background: The resurgent dome of the Valles caldera (Redondo Dome) is historically the "type" location for the resurgent doming process (Smith and Bailey, 1968). However, the actual process involved in the formation of resurgent domes has been brought into question at Valles (Goff, 1983). Nielson and Hulen (1984) feel that the observed relationships are consistent with the structural uplift of the dome by resurgency of the pluton or plutons responsible for the Bandelier Tuff eruption. This magma is also the most obvious heat source for the hydrothermal system(s) presently active in the Redondo Creek area.

Statement of Problem: Understanding the evolution of major silicic centers requires knowledge of the resurgent doming process. At Valles, the older Jemez fault has had an obvious influence on the formation of the dome. The question remains whether the principal cause of the formation of Redondo is resurgence of the underlying magma or some other structural process. Calculations based on a theory of magma resurgence result in a suggestion that the magma lies at a depth of 4.7 km (Nielson and Hulen, 1984). Another implication of the model we have adopted is that fracturing in the lower portion of the domed sequence should be a result of compression stress. This should result in decreased permeability and low water-rock ratios in the region above the magma body.

The nature of interaction between the underlying magma and roof rocks is also open to speculation. Redondo Dome apparently acted as a relatively coherent block both during subsidence of the caldera and during subsequent doming. This is also suggested by the paucity of dikes intersected by drilling within the dome. It is therefore likely that the contact between the pluton and its roof will be relatively sharp. The contact could also be characterized by extensive cataclasis of the upper portion of the pluton. Once within the pluton we may find remnants of the layered stagnant upper portion of the pluton and may be able to pass into the convectively mixed lower portion of the igneous mass. In short, deep drilling can document the transition from a hydrothermal system through the conductive heat-transfer region into the underlying magmatic heat source and, at the same time, verify the postulated model for resurgent doming.

Statement of Work: Drill to the magma body underlying Redondo Peak by reopening and deepening Baca-12. The interaction between this body and the roof rocks can only be understood through the information from a deep hole. The core from the hole will be logged in detail. The logging will document the character and frequency of fractures, and alteration studies will be done to aid in quantifying the hydrothermal processes along those fractures. Samples of plutonic rock will be collected and analyzed chemically. Analyses will be compared to data from surface exposures of the Bandelier Tuff and will be interpreted in the context of evolution of the magmatic system. Samples from the crystallized magma will define the degree of stratification in the upper portion of the pluton and the amount of interaction of the magma fluids.

Budget Estimate: An estimated budget of \$100,000 is required to properly log the core from Baca-12 and investigate hydrothermal alteration, chemical variation in young plutonic rocks, and character of fracturing.

DEVELOPMENT OF FRACTURE PERMEABILITY

D. L. Nielson

Background: Calderas such as Valles are excellent targets for the discovery of high-temperature geothermal systems. Union Oil Company's exploration in the Valles was located within the resurgent dome of the caldera and was frustrated by low permeability, although temperatures were high. A model proposed by Nielson and Hulen (1984) suggests that resurgent domes are inherently impermeable. Observations in other caldera environments suggest that hydrothermal convection systems are more likely to be found in the ring-fracture systems.

Statement of Problem: The ring-fracture zone of the Valles caldera is the potential site of a high-temperature hydrothermal convection system. Subsidence of the Valles caldera presumably developed complex fracturing in the Otowi Member of the Bandelier Tuff. Following collapse, the emplacement of the Tshirege Member resulted in a nonfractured cap on a system. The possibility of this model has not been tested by drilling at Valles.

Statement of Work: Drill to a depth of 2000 m within the ring-fracture system of the Valles caldera. This hole should be drilled in the Sulphur Creek area with core to total depth. Additional holes of interest would then be prepared for drilling in the eastern portion of the caldera (VC-3 and VC-6). Once the hole has been completed, the following actions will be taken.

- 1) Core will be logged in detail to document the character of fracturing and provide a genetic interpretation of the formation of the fractures.
- 2) Hydrothermal mineral assemblages will be documented using x-ray diffraction, SEM, and electron microprobe techniques. These assemblages will be compared with measurements of present temperatures to determine whether the thermal region has changed with time. The assemblages will also help determine if the present vapor-dominated system in the Sulphur Creek area has been superimposed on a previous hot-water-dominated system.

Budget Estimate: A budget of \$100,000 is proposed for detailed logging of the core and documentation of fracturing as well as the characterization of hydrothermal alteration phases and their interpretation.

SEISMIC SURVEYS OF THE VALLES CALDERA

K. H. Olsen

Background: Interpretation of geological structure and testing of concepts and models for evolution of volcanic complexes and hydrothermal systems require geophysical data of high precision to determine densities and seismic velocities of formations from the immediate subsurface to mid-crustal levels (15-20 km), where residual magma may still be found in young systems. A few deep (and expensive) research drill holes cannot hope to solve all problems within a complex shallow crustal magma plumbing system; detailed seismic surveys are necessary to extend to a 3-dimensional "image" the highly localized and detailed borehole cores and logs. Seismic reflection and refraction ("wide-angle" profiling) may also be very useful before drilling in helping to optimize siting for specific or suspected targets.

Statement of Problem: Seismic reflection profiling techniques are familiar in the oil exploration industry. Yet there are three major shortcomings when they are applied to volcanic-hydrothermal structural problems: 1) standard industry equipment is massive and expensive and is not easily deployed in remote areas to answer localized problems; 2) much standard industry data processing is oriented mainly to near-horizontal sedimentary structures (more complex special processing schemes are required to interpret volcanic environments); and 3) standard reflection techniques provide an image of reflecting horizons but very little quantitative information on seismic velocities at specific levels, which can often be diagnostic of petrology and density. Precise velocity information can be obtained by supplementing the standard reflection profiling technique with an associated high-resolution refraction/wide-angle reflection survey, which partly uses some of the same recording equipment as the reflection spread (but it uses different explosion source energies and geometry.) Highly portable, small seismic spreads that can be used for small-scale research problems in volcanic areas are now available through a few university research groups. At a later stage when more details are known about localized "reconnaissance" areas, it may be advantageous to contract for a single larger survey from industry.

Statement of Work: We propose to use existing equipment:

- 1) 12-channel, 400-m-long CDP digital reflection recording system provided by the Purdue University members of our group.
- 2) Portable 30-component digital recording units and shothole drilling equipment provided by Los Alamos National Laboratory Geophysics Group.
- 3) A downhole geophone in any available borehole.

This equipment will be used to obtain information on the stratigraphy of volcanic rocks, to define subsurface fault traces, and to obtain precise seismic velocity values for several key geologic formations in the Jemez Mountain volcanic field. These data will be used to supplement existing data in interpretive models of deep seismic and density (gravimetric) structure as well as to address the problem of previously sparse data sets on ring fractures, intracaldera moat stratigraphy, etc., prior to siting future drill holes. Additional similar surveys will be done at postdrilling sites to extend known structure to surrounding regions. Vertical seismic profiling (VSP) techniques will be employed whenever drill holes are available.

Budget Estimate: Only initial stages (1 or 2 field seasons) are estimated here. After initial stages, we expect to revise the program to possibly use higher energy (or vibroseis) sources and/or industrial recording equipment.

A. Los Alamos National Laboratory (ESS-3 Geophysics Group):

1 man-year effort including supplies \$130 K
(6 staff members for 1 month, field equipment, explosives, shot hole drilling, etc., and 2 people, 1/4 time each for data processing and computer modeling)

B. Purdue University (Geosciences Department)

Field crew (3-4) and digital reflection equipment \$50 K
for field season, travel and living expenses, etc.

LACUSTRINE SEDIMENTATION IN THE VALLE GRANDE AND VALLE TOLEDO

J. P. Bradbury

Background: The presence of caldera moat lacustrine deposits in the fill of the Valles caldera has been determined by analysis of well cuttings and surface outcrops (Conover et al., 1963). The deposits occur in both the Valle Grande and the Valle Toledo and consist of pumiceous and rhyolitic conglomerates interbedded with lacustrine sands, silts, and clays. The fine-grained deposits contain freshwater diatoms (Conover et al., 1963) and pollen grains (Sears and Clisby, 1952), and possibly other lacustrine organisms such as ostracodes, cladocerans, and so forth. Lacustrine deposits predominate in the upper 100 m of caldera fill in the Valle Grande and are more widely distributed in the fill of Valle Toledo. Existing test wells through these deposits indicate the presence of a number of distinct layers of lacustrine deposits and probable facies changes from shallow to deeper water environments within the moat lake.

Statement of Problem: A geologic and paleontologic analysis of the caldera-fill lacustrine deposits will provide important regional paleoclimatic information and local paleoenvironmental data that specifically relate to the tectonic and hydrothermal evolution of the Valles caldera.

Paleoclimate: Sears and Clisby (1952) demonstrated that the uppermost lacustrine sediments of the Valle Grande contain abundant and well-preserved pollen, and that changes in the frequencies of spruce, fir, pine, and oak pollen at different stratigraphic levels probably are related to Pleistocene climatic changes. Because their samples were undated, meaningful comparison could not be made with other paleoclimatic histories in the Southwest. Nevertheless, radiocarbon dating of the upper part of the caldera-fill sequence is feasible if it is younger than 50,000 years old. If older, the lacustrine sediments may be dated by correlation of volcanic ashes (tephrachronology) or paleomagnetism. For example, if the moat were receiving sediments about 620,000 years ago, they should contain the Lava Creek tephra of that age from eruptions in Yellowstone National Park. In addition, the record should contain the Brunhes/Matuyama paleomagnetic boundary if the deposits are in the range of 700,000 years old.

Irrespective of the actual age of the moat lacustrine deposits, their paleoclimatic interpretation based on pollen, diatom, and possibly other

fossils and sediment characteristics, could, if datable, provide important information relevant to several Pleistocene paleoclimatic and paleoenvironmental studies in the western U.S. and to paleoclimatic studies of deep sea sediments of equivalent age.

The lacustrine sediments presumably began to form soon after the caldera collapsed, and the fine-grained organic sediments that are useful for paleoenvironmental reconstruction probably formed shortly after the caldera walls stabilized and became vegetated. The record could therefore have begun about 1 million years ago. Lacustrine deposition would have been terminated by the breaching of the moat by the Jemez and San Antonio creeks in response to tectonism, headward erosion, and (or) filling of the moat with sediments. The paleoclimatic potential of the moat sediments depends in large measure on the continuity and age range of the sediments. The most likely place to obtain a continuous record of lacustrine deposition would be near the center of the largest area of the moat lakes, presumably in the Valle Grande (e.g., Well 7, Conover et al., 1963) or along San Antonio Creek in the Valle Toledo. Before any drilling site is selected, existing well logs should be carefully examined. Seismic investigation of the thickness and extent of the moat deposits could also provide important information.

Paleolimnology and Local Paleoenvironment: The local paleolimnological record of the caldera moat sediments is also of considerable importance. The stratigraphic distribution of diatoms and ostracodes will reflect past water chemistry, salinity, depth, and perhaps temperature of the moat lakes. Because the hydrochemistry of the moat lakes will partly vary according to the character and amount of hot spring and (or) fumarolic emanations, the proxy paleolimnologic record of diatoms and other lacustrine organisms can record changes in the hydrothermal evolution of the caldera.

Another important aspect of a stratigraphic paleolimnological study of the moat sediments will be its potential for correlating both tectonic and depositional events within the caldera. Existing well logs show extensive interbedding of fine-grained lacustrine deposits and coarse-grained alluvial or colluvial gravels that may have been tectonically dislodged from the caldera walls. Biostratigraphic correlation of such units, as well as correlation of lake sediment outcrops and core in the Valle Grande and Valle Toledo calderas, will be essential for unraveling the collapse/resurgence history of the Valles caldera.

Statement of Work:

- 1) A paleolimnologist should participate in planning the drilling program to make certain that drill holes are located where maximal recovery of the lacustrine record is likely, and that additional cores are placed where facies of lacustrine deposits will be intersected if possible.
- 2) Once cores are extracted, a paleontologist and (or) sedimentologist should assist or advise core logging and sampling for paleontologic analysis.
- 3) One to two weeks of field work are required to investigate and sample outcrops of lacustrine sediment in the Valle Toledo and other pertinent areas within and on the flanks of the Jemez volcanic field.
- 4) Sample analysis of diatoms, pollen, and other lacustrine microfossils would take place in the laboratories of respective specialists under the direction and coordination of Bradbury.
- 5) Cores of lacustrine sediment will be ^{14}C dated, sampled, and analyzed for volcanic tephras, and for paleomagnetic character.

Results: The paleontological (pollen, diatoms, and perhaps ostracodes) and sedimentological study of the lacustrine deposits in the Valle Grande and Valle Toledo will produce a paleoclimatic history of the Valles caldera that can be compared to other such records in the Southwest (e.g., the San Agustin Plains, New Mexico; Markgraf et al., 1984) and elsewhere in western North America.

In addition, the local paleolimnological record will help document the tectonic and hydrothermal history of the caldera and aid in correlating the phases of collapse, resurgence, and erosion of the caldera.

Budget:

1. Palynologist (pollen analysis)	2 yr	\$ 70 K
2. Diatomist-stratigrapher	2 yr	80 K
3. Ostracode analysis (part time if appropriate)		30 K
4. Field work		5 K
5. Radiocarbon analysis (dating)		5 K
6. Miscellaneous		<u>10 K</u>
		\$200 K

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III. DETERMINING THE PRESENCE (OR ABSENCE) OF MELT BELOW THE VALLES CALDERA
(PANEL 3)

Hole No.

All	1. Detailed Analysis of Existing Subsurface Temperature Data from the Jemez Mountains - P. Morgan
All	2. Numerical Simulation of Caldera Evolution - G. Zyvoloski
None	3. Depth and Temperature of Magma: Evidence Based on Recent Eruptives - H. Stockman and S. Self
VC-2,VC-3
VC-4	4. Thermochronology of the Valles Caldera - M. Harrison
None	5. Geophysical Investigations to Locate Magma or Position Boreholes - P. Carpenter

Understanding the thermal and petrological evolution of the Valles caldera, and thus the class of features that it represents, could be considerably enhanced by in situ measurements and recovery of core from a deep drill hole intersecting recently crystallized granitoid rock. Actual magma tapping would have profound scientific and economic impact but may remain technologically unfeasible. To enhance the possibility of reaching this material or at least to assess whether a shallow-to-intermediate-depth magma body exists, we propose five avenues of research to determine the best site for the drill hole. These studies would use the petrology of the recent volcanic products and variations in isotopic age systems to obtain temperature-time-pressure constraints. These constraints could be utilized in simulations of caldera evolution to assess the likelihood of there being an active, shallow-level magma body beneath the caldera. Together with a comprehensive analysis of existing heat flow data to establish an energy budget for the caldera, these studies would maximize the opportunity for access and contribute significantly to our understanding of volcanic processes.

DETAILED ANALYSIS OF EXISTING SUBSURFACE TEMPERATURE DATA FROM THE JEMEZ MOUNTAINS

Paul Morgan

Background and Statement of Problem: Subsurface temperature data from a number of sites in the Jemez Mountains have been collected as part of the Union Oil/DOE Geothermal Exploration Program within the Valles Caldera, as part of the Los Alamos National Laboratory hot dry rock drilling experiment outside the western margin of the caldera and as part of other geothermal and heat flow studies around the caldera. These data indicate a complex thermal regime associated with the caldera, with shallow heat transfer commonly dominated by convective and/or transient thermal regimes. Although a regional analysis of these data has been attempted using filtering and continuation techniques, no coherent detailed study of the convective systems and their implications for caldera evolution has yet been attempted. Such a study should be attempted prior to intermediate depth drilling within the caldera to provide information for site selection for the drilling.

Statement of Work: A program of detailed analysis of the subsurface temperature data from the Jemez Mountains is proposed, with special reference to the hydrothermal convective systems within this region. The first stage of this analysis will be a compilation of all available subsurface temperature data and preparation of isotherm maps and cross sections. Lithologic and hydraulic cross sections and maps corresponding to the temperature compilations will also be prepared. These compilations will be used to identify hydrothermal systems associated with the Valles caldera and to identify free and forced convection systems within the caldera and its margins.

Results: The characteristics of these systems will be analyzed using numerical and analytic modeling techniques to constrain the total heat loss through the systems, the driving forces behind the hydrothermal convection, and where possible, the ages of the convecting systems. The final stage in this analysis will be to use the modeling results to attempt to define any magmatic heat sources within the caldera. All data required for this study are currently in the public domain, and analysis techniques are fully developed. The results of this study will be coordinated with subsurface temperature information and thermal history information from other geological, geophysical, and geochemical techniques.

Budget Estimate: \$30 K/yr for three years.

NUMERICAL SIMULATION OF CALDERA EVOLUTION

George Zyvoloski

Background: Numerical models can be useful tools for locating magma bodies and evaluating the thermal history of calderas. Computer models now exist that can follow the collapse and resurgence of caldera complexes. This representation of the material movement as well as the incorporation of hydrothermal convection near the magma body makes accurate estimates of the position of magma body possible. However, it is necessary to have accurate temperature data, both in past time and present time, to provide input and constraints on the computer model.

Statement of Problem and Approach: The past time thermal data can be obtained from geological evidence, but this data may not be accurate enough (in both temperature and time) to provide a primary check for the computer model. For example, the modeling of the collapse and resurgence produces differences in the order of only 10-20°C in a system like the Valles caldera over that same model without incorporating the collapse and resurgence effects. Accurate present-day temperature measurements (i.e., logs in deep holes) are therefore necessary. Several holes spaced from near the center of the caldera to the outer edge would be beneficial. These holes would also provide valuable thermal property data as well as fracture zone mapping necessary to fully utilize the computer models available.

Results: Three-dimensional models of the thermal state, through time, will be produced for the Toledo and Valles calderas. These results will be compared with the present-day geothermal system as observed by drilling.

Budget Estimate: \$50 K/yr for three years.

DEPTH AND TEMPERATURE OF MAGMA: EVIDENCE BASED ON RECENT ERUPTIVES

Harlan Stockman and Steve Self

Background: The Banco Bonito obsidian flow and associated pyroclastics comprise the youngest ($\sim 10^5$ years) materials erupted within the Valles caldera. A determination of the pressure and temperature of the source of these volcanics would serve as a constraint on thermal modeling (e.g., Zyvoloski, this proposal) and would provide a strong base point for estimating the present-day depth to magma. Such information would be invaluable in guiding any deep-drilling program within the caldera.

The Banco Bonito has not been studied as extensively as the older volcanics of the Jemez Mountains. An approximate age of 10^5 years has been suggested for the flow (Doell et al., 1968), though it may be much younger;* a more accurate age determination is currently under way.** Petrographic studies and a limited number of magnetite-ilmenite temperature determinations have been reported (McCormack, 1980; Prigmore, 1978), but little is known of the extent of variations in bulk chemistry and phenocryst assemblages, the depth of origin, or the accuracy of temperature estimates.

Statement of Problem: 1) Temperature estimates of glassy rhyolites, such as the Banco Bonito, are not adequately constrained by traditional geothermometers. There is a need to corroborate magnetite-ilmenite temperatures by other pressure-independent techniques, such as zircon/melt and apatite/melt geothermometers (Green and Watson, 1982; Watson and Harrison, 1983).

2) Most conventional geobarometers, based on equilibria between two crystalline phases, are not applicable to glassy rhyolites. Reasonable alternative geobarometers involve a) estimation of volatile pressures from H_2O and CO_2 contents of glass inclusions, using solubility-pressure relationships (Burnham, 1979; Holloway, 1976), and b) experimental replication of liquidus phenocryst assemblages as a function of pressure.

3) P and T estimates are likely to vary, perhaps as a function of stratigraphic position in the Banco Bonito and associated pyroclastics. It is

*This information was supplied by D. Miller, U.S. Geological Survey, 1983.

**This information was supplied by F. Goff, Los Alamos National Laboratory, 1984.

important to determine if this variability reflects a real P,T heterogeneity in the source or is due to error in estimation techniques, as the range in P and T could be used to constrain the size and thermal boundary conditions of the magma chamber. Hence, it is necessary to correlate P,T estimates with independent indicators of source heterogeneity, such as whole rock and phenocryst compositions.

Statement of Work: We propose the following program to obtain P,T estimates for the Banco Bonito and associated pyroclastics:

- 1) Sampling. Appropriate samples have been obtained from the VC-1 core hole, and additional samples can be obtained from surface exposures.
- 2) Geochemical survey. A broad geochemical survey, consisting of whole-rock major and trace element analyses and electron microprobe analyses of phenocrysts, is a prerequisite to this study, both to assess source heterogeneity and to determine the suitability of various geothermometers and geobarometers as functions of stratigraphic position in the flows and pyroclastics. Such a survey is already under way as part of Sandia's involvement in the VC-1 drilling project.
- 3) Detailed microanalyses. Included are laser Raman microprobe analyses of H_2O and CO_2 in glass inclusions in phenocrysts and in fluid inclusions; ion microprobe analyses of H_2O and CO_2 in glass inclusions; high-sensitivity analyses of Zr and P_2O_5 in matrix glass by electron microprobe; and high-quality analyses of accessory mineral phenocrysts for zircon/melt and apatite/melt geothermometry. A laser Raman probe is available at Sandia and has been used successfully for nondestructive analyses of fluid inclusions in halite and for analyses of synthetic glasses. Ion probe analyses will be made in cooperation with R. Ryerson of Lawrence Livermore National Laboratory. Electron microprobe analyses will be made at Sandia, using a Cameca MBX microprobe equipped with advanced software for matrix corrections and data reduction and possessing light element capabilities.
- 4) Replication of liquidus assemblages. Experimental replication of liquidus phenocryst assemblages can be made at Sandia, using a combination of cold seal bombs and large-volume internally heated pressure vessels, up to temperatures of 1100°C and pressures of 3 kbars.

Upon completion of the experimental and analytical program, the appropriate geobarometric and geothermometric techniques will be used to

estimate pre-eruption P and T as a function of stratigraphic position in the eruptive sequence.

Relationship to Other DOE Programs. Similar studies are under way for CSDP coreholes in the Inyo Chain of Long Valley. Comparison of results from Long Valley and the Valles will provide invaluable insights on the evolution of magma chambers in resurgent calderas. In addition, the Magma Energy Program at Sandia involves the use of recent eruptives to estimate magmatic conditions (P, T, and volatile content) at depth; experimental techniques being developed as part of the Magma Energy Program are directly applicable to the work proposed here.

Budget Estimate: \$75 K/yr for three years.

THERMOCHRONOLOGY OF THE VALLES CALDERA

Mark Harrison

Background and Statement of Problem: The Precambrian basement encompassing the volcanic rocks of the Valles caldera can potentially reveal a detailed record of the temperature history of the region of the past 10 Ma. The constituent minerals of the basement rocks, including biotite, muscovite, and K-feldspar, cooled below their respective K-Ar closure temperatures (the temperature at which daughter product loss by diffusion ceases) between about 900 and 1300 Ma. They remained closed systems until recently when elevated temperatures may have caused ^{40}Ar loss to occur. As the $^{40}\text{Ar}/^{39}\text{Ar}$ age system technique has the demonstrated ability to resolve the internal distribution of ^{40}Ar within crystals, their age and the thermal intensity of this later heating can be determined by imaging the diffusion loss profiles within these minerals.

This approach has been successfully applied to K-feldspars obtained from cores recovered from the Fenton Hill drill holes and should yield estimates of the age of heating in basement cores obtained from within the resurgent dome. These three phases (K-feldspar, biotite, and muscovite) can monitor the duration of thermal events in the temperature range 200°C to 400°C for the time scales appropriate to caldera formation.

Approach and Results: Analysis of samples from the bottom of the 3.2-km-deep Baca-12 hole, currently at a temperature of 341°C, should provide a temperature-time datum that could be used in conjunction with sample thermal models to assess the height of this sample above the cooling magma body. For example, if the Baca-12 hole is extended, a program of sample analyses could be established to continually feed back information regarding the duration of the transient heating at depth and to re-establish the likelihood of contacting the pluton aureole at the predicted depth.

Budget Estimate: \$20 K/yr for three years.

GEOPHYSICAL INVESTIGATIONS TO LOCATE MAGMA OR POSITION BOREHOLES

P. Carpenter

It is important to investigate sites for an intermediate depth well using seismic imaging techniques. Magmatic regions generally exhibit a decrease in seismic wave velocity and an increase in attenuation. Determining a crustal velocity and attenuation should be the focus of new experiments.

An example of such an experiment was the CARDEX 81 seismic refraction/reflection profiles. The data from the CARDEX shots revealed two anomalous low velocity areas, one just northeast of the caldera rim and one on the southern rim. These regions could be investigated further with a similar experiment; a closer shotpoint-receiver spacing would enhance resolution (e.g., 0.5 km). However, to fully interpret the CARDEX and any new wide-angle data, it is necessary to obtain velocities for shallow (~ 3 km) rocks in the Valles area. A conventional common depth point reflection survey over a typical volcanic section would help in this regard. One possibility would be to do a vertical seismic profile using well VC-1.

In addition to velocity and attenuation measurements from explosions, earthquakes in the area may provide velocity, attenuation, and earthquake source information from considerable depth (10-15 km). Analysis of fault plane solutions from local microearthquakes would allow us to determine if magma/water injection is playing a role in generating these earthquakes.

Finally, mining explosions in the area can provide useful information if stations are positioned in a fan configuration. The work of Gerhard Suhr (1981?) could be expanded using different fan configurations to delineate the shape of any large coherent magma bodies.

Budget Estimate: \$50-100 K/yr

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