UNIVERSITY OF CALIFORNIA, RIVERSIDE

BERKELEY • DAVIS • IRVINE • LOS ANGELES • RIVERSIDE • SAN DIEGO • SAN FRANCISCO 1868 SANTA BARBARA • SANTA CRUZ

INSTITUTE OF GEOPHYSICS
AND PLANETARY PHYSICS

RIVERSIDE, CALIFORNIA 92521

May 27, 1983

Ms. Susan M. Prestwich
Energy and Technology Division
U.S. Department of Energy
Idaho Operations Office
550 Second Street
Idaho Falls, ID 83401

RE: Final Report
Contract No. DE-FC07-80ID12145

Dear Ms. Prestwich:

As you recall, the above-mentioned contract had two essential elements: (1) Understanding of water/rock reaction with respect to improving the theoretical basis for geochemical prospecting of geothermal resources; and (2) Modelling of heat and mass transfer in geothermal fields. As a result of the funding provided under the contract we have written the following four reports:

(a) Elders, W. A., Bird, D. K., Williams, A. E., Schiffman, P. and Cox, B., "A Model for the Heat Source of the Cerro Prieto Magma-Hydrothermal System, Baja California, Mexico", published in the Proceedings of the Fourth Symposium on the Cerro Prieto Geothermal Field, 1983.

(b) Elders, W. A., Williams, A. E., Bird, D. K. and Schiffman, P., "Hydrothermal Flow Regime and Magmatic Heat Source of the Cerro Prieto Geothermal System, Baja California, Mexico", in press, Geothermics, anticipated publication date - Fall of 1983.

(c) Schiffman, P., Elders, W. A., Williams, A. E., McDowell, S. D. and Bird, D. K., "Active Metasomatism in the Cerro Prieto Geothermal System, Baja California, Mexico: A Telescoped Low Pressure/Temperature Metamorphic Facies Series", submitted to Geology.

(d) Bird, D. K., Schiffman, P., Elders, W. A., Williams, A. E. and McDowell, S. D., "Calc-Silicate Mineralization in Active Geothermal Systems", submitted to Economic Geology.

Enclosed are copies of these four reports which we would like to offer as the basis of the final report under the above-mentioned contract. When you have had a chance to read them perhaps you could tell us what changes would be necessary to put them into the required format, if any, for such a final report.

As you see, we have tried to give our research findings the widest possible dissemination by publication in the scientific literature as rapidly as possible, rather than waiting for publication as a DOE final report. I trust that this approach will meet with your approval. Many thanks for your consideration.

Sincerely,

W. A. Elders
Professor of Geology

WAE/lp

Enc

cc: P. Dingman, IGPP, UCR
Research Office, UCR
D. Nielson, UURI
C. Bufe, DOE

DOE # 004

FORMAT FOR DOE SCAP PROPOSAL COVER PAGE

Proposal Copy #4 / of 5

Submitted to the Department of Energy
Idaho Operations Office

SOLICITATION FOR COOPERATIVE AGREEMENT PROPOSALS
SCAP No. DE-SC07-80ID12145

CHARACTERISTICS OF WATER-ROCK INTERACTION IN GEOTHERMAL SYSTEMS

The Regents, University of California
Institute of Geophysics and Planetary Physics
University of California, Riverside
Name of Organization (including Branch, Title, if any)

University of California, Riverside
Riverside, CA 92521
Address of Organization | Zip Code

"Investigation of the Thermodynamic Constraints on Water/Rock Reaction and their Relationship to Fluid Flow Patterns in the Cerro Prieto Geothermal System, Mexico"
Title of Proposed Project

Funding Requested from DOE $99,991.00 Total Project Cost $112,655.00

Proposed Duration (in weeks) 52 Proposed Starting Date 1/1/81

Name of Principal Investigator Wilfred A. Elders

Position and Title Research Geologist/Professor of Geology

Telephone (with area code) (714) 787-3439/4500

Approval M. Jeanne Thornburg Manager, Contracts and Grants
Signature Title

M. Jeanne Thornburg August 5, 1980
Name (Typed) Date

OMB Approval No. 29-R0218

FEDERAL ASSISTANCE

1. TYPE OF ACTION (Mark appropriate box)
☐ PREAPPLICATION
☒ APPLICATION
☐ NOTIFICATION OF INTENT (Opt.)
☐ REPORT OF FEDERAL ACTION

2. APPLICANT'S APPLICATION
a. NUMBER UCR/IGPP-80/J
b. DATE Year month day 1980/08/04

3. STATE APPLICATION IDENTIFIER
a. NUMBER
b. DATE ASSIGNED Year month day 19

Leave Blank

SECTION I—APPLICANT/RECIPIENT DATA

4. LEGAL APPLICANT/RECIPIENT
a. Applicant Name : Regents of the University of California
b. Organization Unit : Institute of Geophysics & Planetary Physics
c. Street/P.O. Box : University of CA, Riverside
d. City : Riverside
e. County : Riverside
f. State : California
g. ZIP Code: 92521
h. Contact Person (Name & telephone No.) : Scientific-W. A. Elders (714)787-3439
Contract-Jeanne Thornburg (714)787-5535

5. FEDERAL EMPLOYER IDENTIFICATION NO. 956006142W

6. PROGRAM (From Federal Catalog) N/A
a. NUMBER
b. TITLE

7. TITLE AND DESCRIPTION OF APPLICANT'S PROJECT
"Investigation of the Thermodynamic Constraints on Water/Rock Reaction and their Relationship to Fluid Flow Patterns in the Cerro Prieto Geothermal System, Mexico"

8. TYPE OF APPLICANT/RECIPIENT
A-State
B-Interstate
C-Substate District
D-County
E-City
F-School District
G-Special Purpose District
H-Community Action Agency
I-Higher Educational Institution
J-Indian Tribe
K-Other (Specify):
Enter appropriate letter I/A

9. TYPE OF ASSISTANCE
A-Basic Grant
B-Supplemental Grant
C-Loan
D-Insurance
E-Other
Enter appropriate letter(s) Cooperative Agreement

10. AREA OF PROJECT IMPACT (Names of cities, counties, States, etc.)
Not site specific

11. ESTIMATED NUMBER OF PERSONS BENEFITING
N/A

12. TYPE OF APPLICATION
A-New
B-Renewal
C-Revision
D-Continuation
E-Augmentation
Enter appropriate letter A

13. PROPOSED FUNDING

a. FEDERAL	$ 99,991	.00
b. APPLICANT	12,664	.00
c. STATE		.00
d. LOCAL		.00
e. OTHER		.00
f. TOTAL	$ 112,655	.00

14. CONGRESSIONAL DISTRICTS OF:
a. APPLICANT 36
b. PROJECT

15. TYPE OF CHANGE (For 12c or 12e)
A-Increase Dollars
B-Decrease Dollars
C-Increase Duration
D-Decrease Duration
E-Cancellation
F-Other (Specify): N/A
Enter appropriate letter(s)

16. PROJECT START DATE Year month day 19 81/01/01

17. PROJECT DURATION 12 Months

18. ESTIMATED DATE TO BE SUBMITTED TO FEDERAL AGENCY ▶ Year month day 19 80/08/07

19. EXISTING FEDERAL IDENTIFICATION NUMBER N/A

20. FEDERAL AGENCY TO RECEIVE REQUEST (Name, City, State, ZIP code)
DOE, Idaho Operations Office, Idaho Falls, Idaho 83401

21. REMARKS ADDED ☐ Yes ☒ No

SECTION II—CERTIFICATION

22. THE APPLICANT CERTIFIES THAT ▶
a. To the best of my knowledge and belief, data in this preapplication/application are true and correct, the document has been duly authorized by the governing body of the applicant and the applicant will comply with the attached assurances if the assistance is approved.
b. If required by OMB Circular A-95 this application was submitted, pursuant to instructions therein, to appropriate clearinghouses and all responses are attached:

	No response	Response attached
(1)	☐	☐
(2)	☐	☐
(3)	☐	☐

23. CERTIFYING REPRESENTATIVE
a. TYPED NAME AND TITLE M. Jeanne Thornburg, Manager Contracts and Grants
b. SIGNATURE
c. DATE SIGNED Year month day 19 80 08 05

SECTION III—FEDERAL AGENCY ACTION

24. AGENCY NAME

25. APPLICATION RECEIVED Year month day 19

26. ORGANIZATIONAL UNIT

27. ADMINISTRATIVE OFFICE

28. FEDERAL APPLICATION IDENTIFICATION

29. ADDRESS

30. FEDERAL GRANT IDENTIFICATION

31. ACTION TAKEN
☐ a. AWARDED
☐ b. REJECTED
☐ c. RETURNED FOR AMENDMENT
☐ d. DEFERRED
☐ e. WITHDRAWN

32. FUNDING

a. FEDERAL	$	.00
b. APPLICANT		.00
c. STATE		.00
d. LOCAL		.00
e. OTHER		.00
f. TOTAL	$	.00

33. ACTION DATE ▶ Year month day 19

34. STARTING DATE Year month day 19

35. CONTACT FOR ADDITIONAL INFORMATION (Name and telephone number)

36. ENDING DATE Year month day 19

37. REMARKS ADDED ☐ Yes ☐ No

38. FEDERAL AGENCY A-95 ACTION
a. In taking above action, any comments received from clearinghouses were considered. If agency response is due under provisions of Part 1, OMB Circular A-95, it has been or is being made.
b. FEDERAL AGENCY A-95 OFFICIAL (Name and telephone no.)

SECTION IV–REMARKS *(Please reference the proper item number from Sections I, II or III, if applicable)*

UCR/IGPP-80/J

A Research Proposal

Submitted to

The Department of Energy

In Response To

Solicitation Number DE-SC07-80ID12145

from

THE REGENTS OF THE UNIVERSITY OF CALIFORNIA
Institute of Geophysics and Planetary Physics
University of California
Riverside, California 92521

August 1, 1980

Type of Institution: Public, State supported Educational

Title: Investigation of the Thermodynamic Constraints on Water/Rock Reaction and their Relationship to Fluid Flow Patterns in the Cerro Prieto Geothermal System, Mexico

Starting Date: January 1, 1981 Amount: $99,991

Duration: One Year

Principal Investigator and Coordinator: W. A. Elders
SS# 385-36-4597
Telephone: (714) 787-3439
787-4500
787-4501

Associate Investigator: Dennis K. Bird
SS# 564-70-0470
Telephone: (602) 626-5609

RESEARCH OBJECTIVES

1. APPLICANT ORGANIZATION:	The Regents of The University of California University of California, Riverside Riverside, California 92521

2. NAME, OFFICIAL TITLE AND DEPARTMENT OF ALL PROFESSIONAL PERSONNEL ENGAGED ON PROJECT, BEGINNING WITH PRINCIPAL INVESTIGATOR:

Name and Title	Department
Wilfred A. Elders, Research Geologist and Professor of Geology	Institute of Geophysics & Planetary Physics and Department of Earth Sciences, UCR
Alan E. Williams, Assistant Research Geochemist	Institute of Geophysics & Planetary Physics, UCR
Dennis K. Bird, Associate Investigator	Department of Geosciences, University of Arizona, Tucson, AZ

3. TITLE OF PROJECT "Investigation of the Thermodynamic Constraints on Water/Rock Reaction and their Relationship to Fluid Flow Patterns in the Cerro Prieto Geothermal System, Mexico"

4. ABSTRACT OF PROPOSED RESEARCH: (Outline Objectives and Methods in 200 Words or Less)

Hydrothermal minerals are the visible record of heat and mass transfer through rocks. Use of hydrothermal mineral assemblages in geothermal resource investigations, however, has hitherto been often neglected because of difficulties in interpreting the genetic significance of given assemblages which are affected by a number of physicochemical variables in natural systems. Recent advances in theoretical geochemistry and heat and mass transfer models now permit calculations of the controlling thermodynamic relationships between natural aqueous solutions and minerals at various spatial locations within dynamic geothermal reservoirs.

We propose to use these techniques of thermochemical and fluid flow analyses to derive a quantitative description of the pressure-temperature-composition controls responsible for observed compositional relations among minerals and aqueous species in a well-explored geothermal system. We believe that the Cerro Prieto field, where a series of prograde metamorphic minerals is being formed in response to temperatures as high as 350°C at 1.8 km depth, is the best candidate for this type of investigation. This field is the object of an intense and comprehensive scientific study which has produced an extensive data base on mineral distribution, mineral and fluid chemistry, and temperature distribution.

The application of rigorous theoretical analysis of mineral stabilities within a well-studied geothermal system will allow the development of quantitatively-based predictive models of mineral distribution and fluid flow applicable to future exploration and development of other fields.

TABLE OF CONTENTS

STATEMENT OF WORK

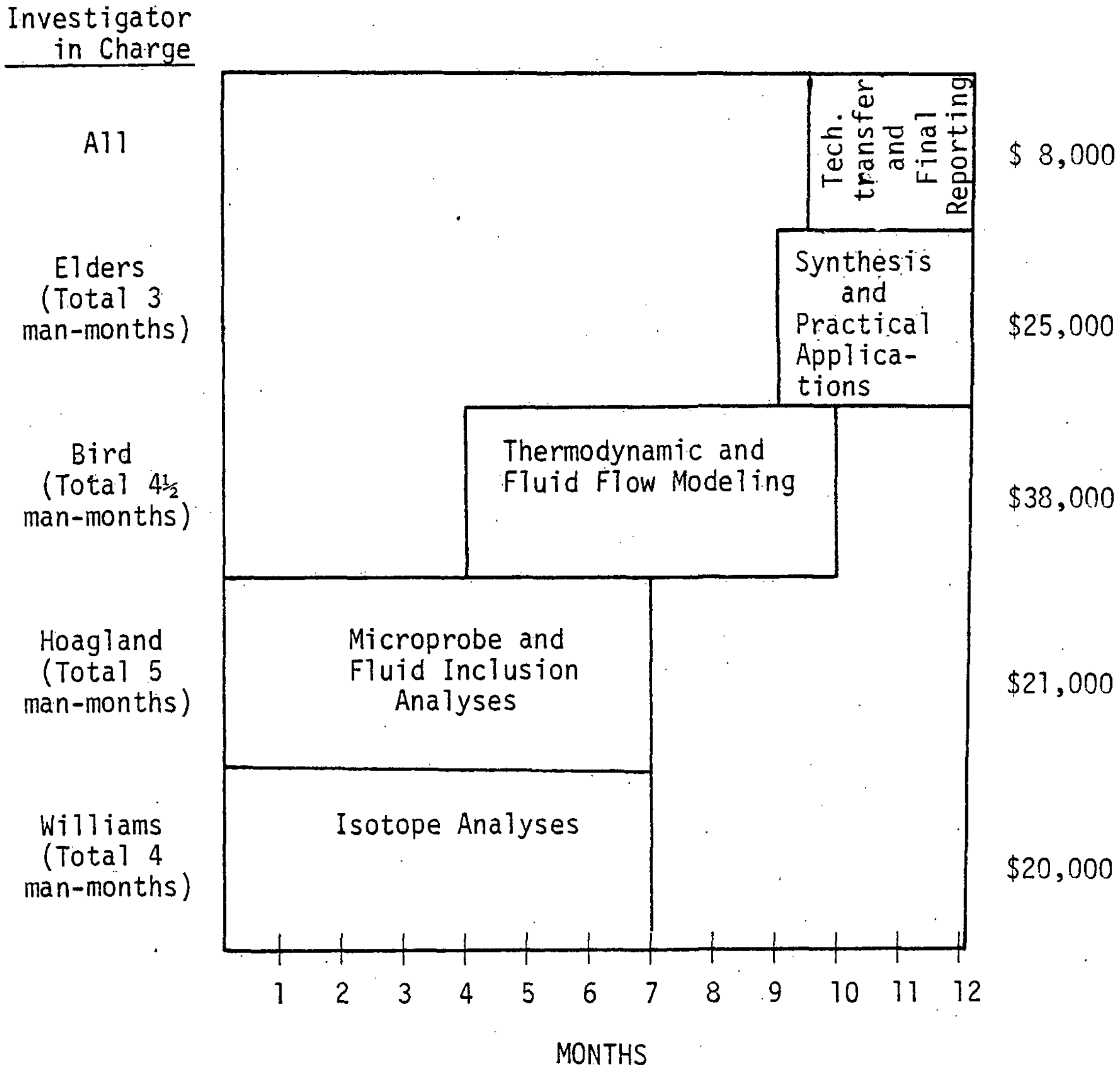
Our proposed project is a collaborative effort between personnel of IGPP at UCR and of the Department of Geosciences at the University of Arizona, Tucson (UA). Work to be performed at UA will be administered through a subcontract from IGPP. The critical new data required for accomplishment of our goals are extensive additional information on the chemistry of coexisting mineral phases in the Cerro Prieto system, supporting fluid inclusion homogenization temperatures, and stable isotope analyses of whole rock samples from the reservoir and surrounding environs. These data will be obtained by UCR utilizing the election microprobe and associated software at the California Institute of Technology, Pasadena, and the fluid inclusion and stable isotope facilities at UCR. Results of this work will include field-wide maps of variations in key mineral chemistry and water/rock ratios derived from stable isotope data and additional control on the ranges of temperature associated with various mineral assemblages. These data will serve as input and boundary conditions for the subsequent thermochemical and fluid flow models.

Development of the thermochemical and fluid flow models will be accomplished primarily by our colleagues at UA using the computational facilities and software at UA, although UCR personnel will be closely involved in this segment of the project. The models will make explicit provisions for mineral solid-solution effects, reaction kinetics, and diverse patterns of fluid flow. Existing data on pressure, temperature, porosity, permeability, and time of reaction will be utilized as boundary conditions for these models. The results of this segment of the project will include quantitative descriptions of the critical thermochemical controls on water/rock reaction in this system and the effects of fluid flow patterns on mineral distribution.

Synthesis of the empirical and theoretical information generated during this project will allow the development and elucidation of methods of practical application of petrologic and mineralogic studies to geothermal developments. The proposed sequence of tasks is outlined in Figure 1. All of the investigators will share in each of the tasks; however, each will have a primary area of responsibility as shown in the Figure.

Figure 1

PROPOSED
PROGRESSION OF RESEARCH BY TASK
(Including cost approximation)



TECHNICAL DISCUSSION

STATEMENT OF THE APPROACH

Although geothermal reservoirs differ in some important ways from hydrocarbon reservoirs, most of the technology of exploration, assessment and characterization of geothermal resources has been derived directly from the petroleum industry. One consequence is that water/rock interactions have been relatively neglected in the characterization of geothermal resources in favor of more traditional approaches, such as those involving surface and subsurface geophysics. However, geothermal reservoirs exist in a temperature-pressure-composition regime in which water/rock interaction is of crucial importance. Such interactions occur rapidly and can result in dramatic changes in the physical properties of both fluids and rocks. They often, for example, lead to marked reduction in the porosity and permeability of the reservoirs (Elders, 1977a).

The only aspect of water/rock interaction which has received much attention is the use of geochemical geothermometers based on the analysis of surface samples of fluids (Ellis and Mahon, 1977; Fournier and Truesdell, 1973; Truesdell, 1976). This approach using silica and Na-K-Ca geothermometers, and the like, has had considerable success to the point where it has become a standard practice to utilize these techniques in any broadscale exploration program. These geothermometers are useful, cost-effective exploration tools; however, they are relatively poorly understood by some users and are therefore sometimes misapplied. There is a need, therefore, for better understanding of the chemical thermodynamic controls of this general class of fluid geothermometers.

Samples of geothermal fluids have usually reacted with some large and unknown volume of rock within a reservoir. Thus the temperatures they record apply to some unspecified location in the hydrothermal system. However, hydrothermal minerals are the visible records of heat and mass transfer at specific locations in geothermal systems. Yet relationships between such important parameters as fluid chemistry, enthalpy, alteration mineralogy and permeability in geothermal fields have been explored relatively little, apart from a few pioneering studies (Helgeson, 1968; Muffler and White, 1969; Browne and Ellis, 1970; Kristmannsdottir, 1976; and Bird and Norton, 1979). Thus, in contrast to the more extensive experience gained in the use of fluid geothermometers, the practical application of geochemical and petrological studes of rocks from geothermal systems has been relatively limited (Browne, 1970, 1978; Elders, 1977a).

Reliable prediction of intensive properties of geothermal reservoirs from measured compositions of fluids and/or minerals is crucial to the development of cost effective exploration and exploitation technology. The dependence of metasomatic mineral zoning on temperature, depth, and permeability is documented for many geothermal systems. However, spatial and temporal variations in the chemical characteristics of contiguous geothermal fluids are poorly understood.

We propose to conduct a thermodynamic analysis of compositional relations among mineral and aqueous solutions recovered from the Cerro Prieto hydrothermal system in Baja California, Mexico. Our primary goal is to provide a quantitative and internally consistent description of processes responsible for the formation of observed reservoir mineralogy and fluid chemistry. Such a description will, in turn, supply important boundary conditions for future mathematical models of heat and mass transfer of this and other geothermal systems. Equally important, we expect that this study will put existing chemical indicators of subsurface temperature on a better theoretical footing and may also potentially develop new or improved chemical geothermometers.

CONCEPTS, ASSUMPTIONS, AND LIMITATIONS

Recent advances in theoretical geochemistry and transport phenomena allow quantitative description and interpretation of compositional characteristics of aqeuous solutions and minerals and their dependence on temperature, pressure, porosity, and permeability in geothermal environments. These advances permit:

I. Calculation of thermodynamic properties of aqueous solutions, gases, and minerals at high pressures and temperatures from equations and data given by Helgeson and Kirkham (1974a,b,1976), Walther and Helgeson (1977), Helgeson, Delany, Nesbitt, and Bird (1978), Flowers (1979), Bird and Helgeson (1980), Aagaard, Helgeson, and Benson (1980), and Helgeson, Kirkham, and Flowers (1980), and

II. Calcuation of heat and mass transfer within magma-hydrothermal systems and quantitative description of fluid pathlines, source lines, and source regions from numerical analogs, equations, and data reported by Norton and Knight (1977), Norton and Knapp (1977), Norton (1978, 1979, 1980), and Norton and Taylor (1979). The confirmation of the credibility of these thermodynamic and transport calucations is, in part, dependent on the extent to which they replicate geologic, geochemical, and geophysical observations of active geothermal systems. This confirmation is necessary for the development of any reliable chemical geothermometer based on theoretical calucations or on empirical observations of natural hydrothermal phenomena.

To date, major element solute geothermometers are based primarily on empirical observations and assumptions of local equilibrium at depth within geothermal reservoirs. The latter assumption, together with the approximation that standard molal enthalpies of reaction between geothermal reservoir fluids and minerals are essentially independent of temperature, are fundamental to geothermometers based on linear regressions of fluid compositions and temperature (Fournier and Truesdell, 1973; Fournier and Potter, 1979; Fournier, 1979; Arnorsson, 1978). Critical evaluation of these approximations, and of others employed in contemporary solute geothermometers, is afforded by comparison of thermodynamic and transport calculations of hydrothermal processes with empirical geologic, geochemical, and geophysical characterstics of geothermal systems.

Theory and Applications

Description and interpretation of phase relations in geothermal systems requires simultaneous consideration of the extent to which the transient changes in pressure, temperature, porosity, permeability, reaction kinetics, and fluid flow affect the compositions and compatibilities of a wide variety of minerals and coexisting aqueous solutions. Analysis of equilibrium phase relations among minerals and geothermal fluids affords a convenient point of departure for later consideration of the consequences of metastable phase relations, reaction kinetics, and variable mass flux of the fluid phase.

Equilibrium constraints:

Equilibrium among mineral components and an aqueous solution can be written as

$$0 = \sum_{\underline{i}}^{\hat{\underline{i}}} \underline{n}_{\underline{i},\underline{r}} \psi_{\underline{i}} + \sum_{l}^{\hat{l}} \underline{n}_{l,\underline{r}} \phi_{l}, \tag{1}$$

where the subscripts $\underline{i}$ and ℓ respectively denote the mineral components (ψ) and the species in the coexisting fluid (Φ). In this equation $\underline{n}$ is the stoichiometric reaction coeffecient for the $\underline{r}^{th}$ reaction which is positive for products and negative for reactants. The logarithm of the law of mass action equation for reaction (1) allows the thermodynamic activities of aqueous species to be written as

$$\sum_{\ell}^{\hat{\ell}} \underline{n}_{\ell,\underline{r}} \log\left(\frac{\underline{a}_{\Phi_{\ell}}}{a^{z}_{H^{+}}}\right) = \log K_{P,T,\underline{r}} - \sum_{\underline{i}}^{\hat{\underline{i}}} \underline{n}_{\underline{i},\underline{r}} \log \underline{a}_{\psi_{\underline{i}}} . \qquad (2)$$

$K_{P,T,\underline{r}}$ in equation (2) is the equilibrium constant for the $\underline{r}^{th}$ statement of reaction (1) at the subscripted pressure (P) and temperature (T); $\underline{a}$ is the activity of the subscripted reaction component; and z is the charge of the ℓ^{th} aqueous species.

Differential changes in activity of the ℓ^{th} aqueous species along fluid flow path lines in geothermal systems are represented by

$$\frac{d \log\left(\frac{\underline{a}_{\Phi_{\ell}}}{\underline{a}^{z}_{H^{+}}}\right)}{dZ} = \left(\frac{\partial \log\left(\frac{\underline{a}_{\Phi_{\ell}}}{\underline{a}^{z}_{H^{+}}}\right)}{\partial T}\right)_{P,\hat{\phi}} + \left(\frac{\partial \log\left(\frac{\underline{a}_{\Phi_{\ell}}}{\underline{a}^{z}_{H^{+}}}\right)}{\partial P}\right)_{T,\hat{\phi}} , \qquad (3)$$

where $\hat{\phi}$ denotes constant activities of all aqueous species other than the ℓ^{th} and Z is unit distance along a fluid pathline which can be calculated using equations and data given by Norton and Knight (1977) and Norton (1978, 1979). Writing the total differential represented by equation (3) in terms of equation (2) gives

$$\sum_{l}^{\hat{l}} \underline{n}_{l,\underline{r}} \frac{d \log\left(\frac{\underline{a}_{\phi_l}}{\underline{a}^{z}_{H^+}}\right)}{dZ} = \frac{\Delta H^{\circ}_{P,T,\underline{r}}}{2.303RT^{2}} - \frac{\Delta V^{\circ}_{P,T,\underline{r}}}{2.303RT}$$

$$- \sum_{\underline{i}}^{\hat{\underline{i}}} \underline{n}_{\underline{i},\underline{r}} \left[\left(\frac{\partial \log \underline{a}_{\psi_{\underline{i}}}}{\partial T} \right)_{P,\hat{\psi},\phi_l} + \left(\frac{\partial \log \underline{a}_{\psi_{\underline{i}}}}{\partial P} \right)_{T,\hat{\psi},\phi_l} \right] , \qquad (4)$$

where $\Delta H^{\circ}_{P,T,\underline{r}}$ and $\Delta V^{\circ}_{P,T,\underline{r}}$ are the standard molal enthalpy and volume for the $\underline{r}^{th}$ statement of reaction (1) and $\hat{\psi}$ refers to constant activities of all mineral components exluding the $\underline{i}^{th}$. Equation (4) describes differential changes in the activities of aqueous species in equilibrium with their mineralogic environment as a function of distance along fluid pathlines. This differential change is a function of standard state thermodynamic properties of reaction and partial differential changes in activities of coexisting mineral components.

Explicit statements of reaction (1) and equations (2) and (4) permit calculation of activities of aqueous species in geothermal fluids and their pressure-temperature derivatives from standard state thermodynamic data and the activities of mineral components in coexisting solid solutions. Z in equations (3) and (4) can represent distance from the surface measured in geothermal drillholes or distance from some fixed point along a fluid flow pathline. Measured pressures, temperatures, and mineralogic phase realtions are required in this analysis. Compositional variations and substitutional ordering in authigenic minerals are explicity accounted for in equations (2) and (4) by thermodynamic activities of ideal mineral components. The effects of nonstoichiometry in minerals on the activities of components in solid solution can be approximated by any of a number of mixing and exchange relations reported in the literature (for example, see Mueller, 1962; Matsui and Banno, 1964; Thompson, 1967, 1969; Blander, 1970; Saxena, 1969, 1973; Grover and Orville, 1969; Kerrick and Darken, 1975; Powell, 1977; Bird and Helgeson, 1980; Aagaard, Helgeson, and Benson, 1980).

Application to drillhole samples:

Detailed analysis of mineralogic phase relations to solid samples recovered from geothermal drillholes at measured temperatures and pressures permits calculation of the activities of aqueous species in the coexisting fluid phase (eqt. 2). It has been shown (see fig. 2, A through C) that systematic vertical gradients in activity ratios of alkali and alkaline earth cations to hydrogen ions and in $f_{CO_{2(\underline{g})}}$ occur in the upper 2.5 km of the Salton Sea geothermal system (Bird and Helgeson, 1977; Bird and Norton, 1979, 1980). These gradients are predicted from measured metasomatic mineral zoning reported by McDowell and McCurry (1977) and McDowell and Elders (1978) and standard molal enthalpies and volumes of reactions among minerals and aqueous solutions represented by reaction 1 and equations (2) through (4). Measured concentrations of Na^+, K^+, SiO_2, and $CO_{2(\underline{g})}$ in fluids produced from drillholes near the Salton Sea are in close agreement with the results of these calculations (for example, see fig. 2, B and C). Similar correlations are found among measured and calculated fluid composition for a wide variety of active geothermal systems in Quaternary silicic volcanic piles near the Circum- Pacific margin as shown in figure 2D.

Figure 2. Diagrams A through C: Calculated temperature dependence of $\underline{a}_{Ca^{++}}/\underline{a}^2_{H^+}$, $\underline{f}_{CO_{2(g)}}$, and $\underline{a}_{Na^+}/\underline{a}_{K^+}$ in geothermal fluids compatible with observed mineral zoning reported by McDowell and Elders (1980) in sandstones penetrated by Elmore #1, Salton Sea geothermal system. In diagram A, the solid and open symbols represent alternate calculations using the same mineralogic data but various ordering states for $KAlSi_3O_8$ and $NaAlSi_3O_8$. The lengths of the ellipses and boxes represent the range in activity ratios compatible with the measured compositional variations in epidote and tremolite solid solutions. The curves in diagram B are calculated, the solid symbols denote measured epidote compositions coexisting with calcite, quartz, muscovite solid solution, and sanidine, and the hachured box is the measured value of $\underline{f}_{CO_{2(g)}}$. The solid curve in diagram C denotes equilibrium values of $\underline{a}_{Na^+}/\underline{a}_{K^+}$ in an aqueous solution compatible with albite and K-feldspar but the broken curves depict fluid compositions coexisting with alkali feldspars with nonequilibrium tetrahedral ordering of Al^{3+} and Si^{4+}. The solid symbols in diagram C are fluid compositions compatible with analyses of illite-phengite, sanidine, and albite from the Salton Sea geothermal system represented, and the hachured symbol is the measured composition and temperature of geothermal fluid.

Diagram D: Calculated (curves) and measured (symbols) values of $\underline{a}_{Na^+}^{3}\ \underline{a}_{K^+}^{5}\ \underline{a}_{Ca^{++}}^{-4}$ in geothermal systems near the Circum-Pacific margin. (Diagrams A and C from Bird and Norton, 1979, 1980; diagrams B and D from Bird and Helgeson, 1977, 1980).

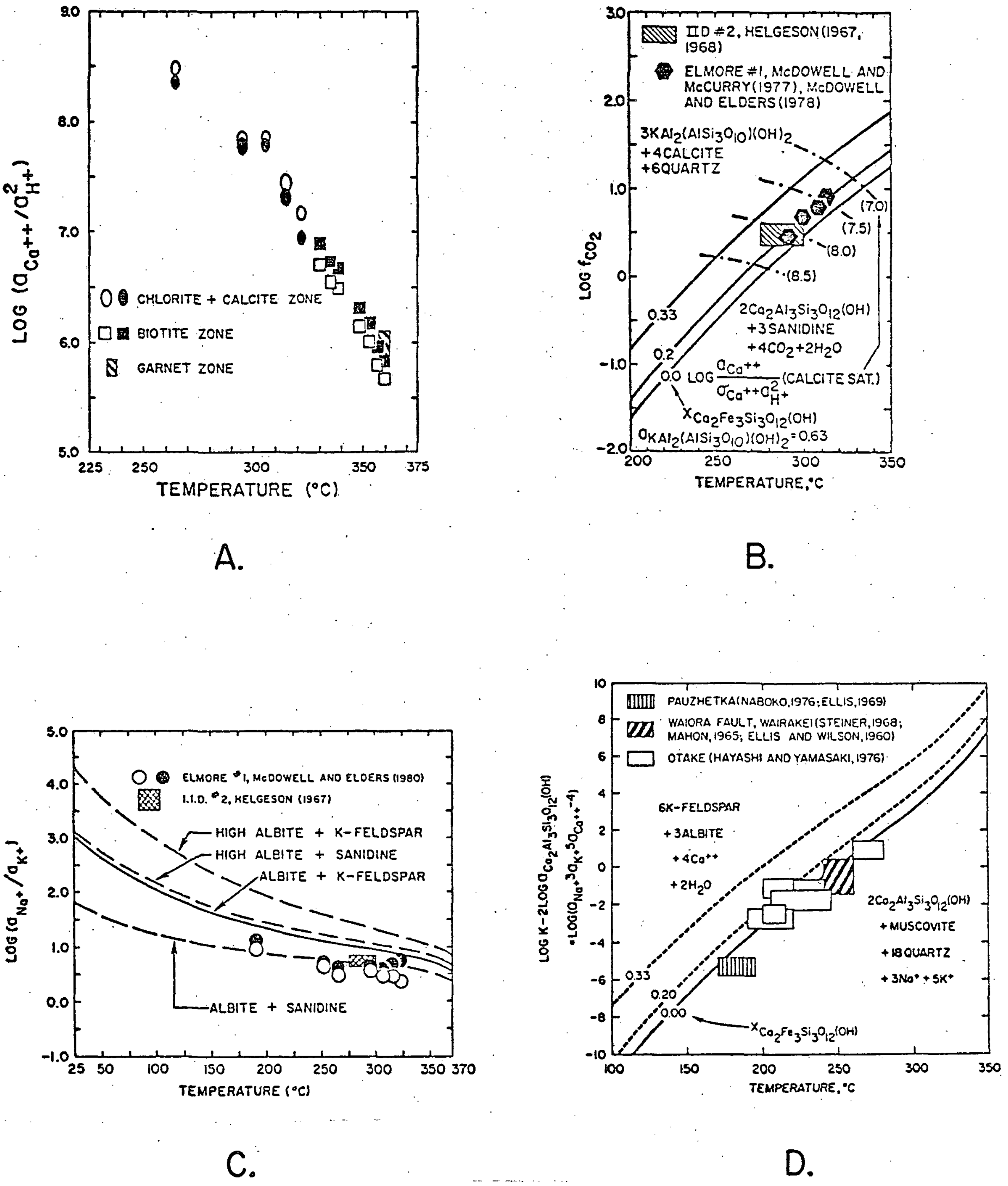

9.0
8.0
7.0
6.0
5.0
LOG ($a_{Ca^{++}}/a^2_{H^+}$)
CHLORITE + CALCITE ZONE
BIOTITE ZONE
GARNET ZONE
225
250
300
350
375
TEMPERATURE (°C)
A.
3.0
2.0
1.0
0
-1.0
-2.0
LOG f_{CO_2}
II D #2, HELGESON (1967, 1968)
ELMORE #1, McDOWELL AND McCURRY (1977), McDOWELL AND ELDERS (1978)
$3KAl_2(AlSi_3O_{10})(OH)_2$ +4CALCITE +6QUARTZ
(7.0)
(7.5)
(8.0)
(8.5)
0.33
0.2
0.0
$2Ca_2Al_3Si_3O_{12}(OH)$ +3SANIDINE +$4CO_2+2H_2O$
LOG $\frac{a_{Ca^{++}}}{\sigma_{Ca^{++}}+a^2_{H^+}}$ (CALCITE SAT.)
$X_{Ca_2Fe_3Si_3O_{12}(OH)}$
$a_{KAl_2(AlSi_3O_{10})(OH)_2}=0.63$
200
250
300
350
TEMPERATURE, °C
B.
5.0
4.0
3.0
2.0
1.0
0.0
-1.0
LOG (a_{Na^+}/a_{K^+})
ELMORE #1, McDOWELL AND ELDERS (1980)
I.I.D. #2, HELGESON (1967)
HIGH ALBITE + K-FELDSPAR
HIGH ALBITE + SANIDINE
ALBITE + K-FELDSPAR
ALBITE + SANIDINE
25
50
100
150
200
250
300
350
370
TEMPERATURE (°C)
C.
10
8
6
4
2
0
-2
-4
-6
-8
-10
LOG K -2LOG $a_{Ca_2Al_3Si_3O_{12}(OH)}$
$=$LOG($a_{Na^+}{}^3a_{K^+}{}^5a_{Ca^{++}}{}^{-4}$)
PAUZHETKA (NABOKO, 1976; ELLIS, 1969)
WAIORA FAULT, WAIRAKEI (STEINER, 1968; MAHON, 1965; ELLIS AND WILSON, 1960)
OTAKE (HAYASHI AND YAMASAKI, 1976)
6K-FELDSPAR
+3ALBITE
+$4Ca^{++}$
+$2H_2O$
$2Ca_2Al_3Si_3O_{12}(OH)$
+MUSCOVITE
+18QUARTZ
+$3Na^+$ + $5K^+$
0.33
0.20
0.00
$X_{Ca_2Fe_3Si_3O_{12}(OH)}$
100
150
200
250
300
350
TEMPERATURE, °C
D.

Figure 2.

Applications to fluid flow pathlines:

Processes that form geothermal deposits are summarized by the theories of mass, momentum, and energy transport. Numerical approximations of partial differential equations describing these theories permit simulation of the processes using modern computer methods (Norton and Knight, 1977). Transport theory then provides a basis for developing predictive methods to assist in the quantitative description of subsurface conditions in geothermal systems.

Compositional variations of fluids and rocks in geothermal systems can be viewed in both a conceptual and a mathematical sense by two different perspectives: (1) Monitoring compositional changes in a fluid packet as it moves along its flow path. This framework can be used to predict the environment through which a fluid flowed before emerging from a thermal spring or well bore. Mathematically, this corresponds to the Lagrangian viewpoint and to the concept of fluid pathlines, sourcelines, and streaklines developed by Norton (1978). (2) Monitoring compositional changes at a fixed position within the system. In studies of active and fossil geothermal systems this corresponds to deducing the time-integrated paragenesis of a particular rock sample. Mathematically, this corresponds to the Eulerian viewpoint and to the concept of integrated values over a constant volume portion of the system at a fixed position.

Fluids circulate through hydrothermal systems along pathlines defined by

$$d\overline{Z}_i = \overline{v}_i dt, \qquad (5)$$

where $\overline{v}_i$ is the Darcy velocity of the i^{th} fluid packet, and $\overline{Z}_i$ is the position vector of the packet at some time (t). From an Eulerian viewpoint, the composition of fluid in equilibrium with its mineralogic environment is defined throughout the system by equation (2). Consequently, the pathline for fluid components can also be calculated by combining the total derivative of equation (2) with equation (5), which gives

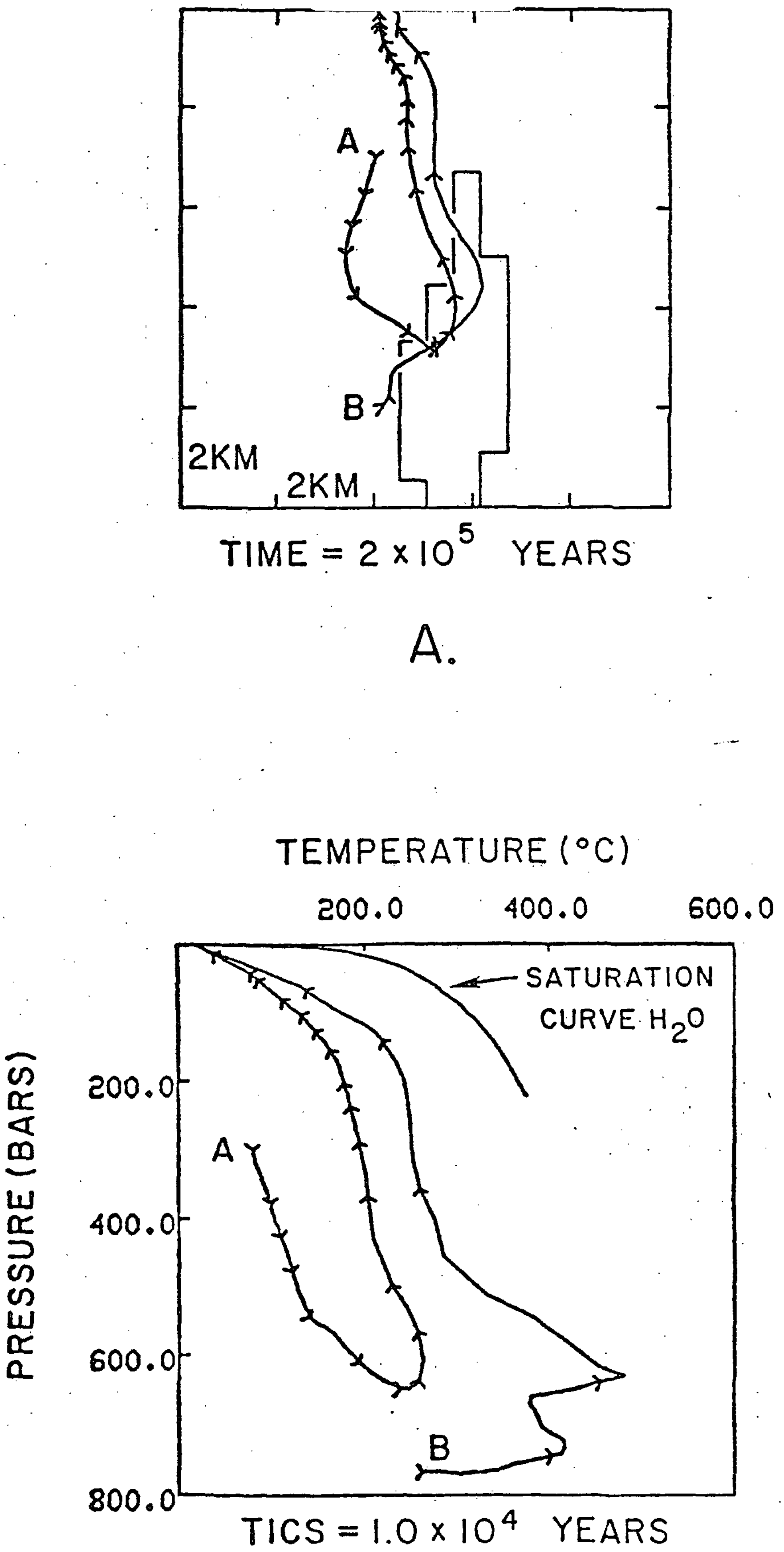
$$\sum_{l}^{\hat{l}} \underline{n}_{l,\underline{r}} \frac{d \log\left(\dfrac{a_{\phi_l}}{\underline{a}^{z}_{H^+}}\right)}{dt} = \bar{V}_i \sum_{l}^{\hat{l}} \underline{n}_{l,\underline{r}} \frac{d \log\left(\dfrac{a_{\phi_l}}{\underline{a}^{z}_{H^+}}\right)}{d\bar{Z}_i} \qquad (6)$$

It is apparent from equations (4) through (6) that the time rate change in activities of aqueous species within a fluid packet flowing through a geothermal system is proportional to the standard molal volumes and enthalpies of reactions between this fluid and its mineralogic environments and the partial differential changes in the compositions of the coexisting minerals.

Practical application of these concepts to geothermal systems is apparent if we consider fluid samples collected from flowing springs. The composition of this fluid is the integrated result of water/rock reactions "upstream" along its pathline. It is not possible to explicity integrate the equations back through time. However, the concept of source lines and source regions together with solutions to a set of initial value problems permits quantitative predictions to be made of the temperature, pressure, and composition of the "upstream" environment.

Figure 3 shows two typical pathlines resulting from a high level igneous intrusion associated with calc-alkaline volcanism as reported by Norton (1978, 1980). The initial and boundary conditions of this numerical analog are similar in many respects to the geothermal systems represented

Figure 3. Fluid pathlines for two fluid packets computed from a numerical transport model for a high level igneous intrusion (represented by the box in diagram A) after 2 x 10^5 years since the initial implacement. Diagram A illustrates the fluid paths in a geologic cross section and Diagram B is the pressure-temperature projections for the pathlines. Initial and boundary conditions for the numerical calculations are given in Norton (1979, 1980). (Modified after Norton, 1979 and 1980, and unpublished calculations).


A
B
2KM
2KM
TIME = 2 x 10^5 YEARS
TEMPERATURE (°C)
200.0
400.0
600.0
SATURATION CURVE H2O
PRESSURE (BARS)
200.0
400.0
600.0
800.0
A
B
TICS = 1.0 x 10^4 YEARS

A.

B.

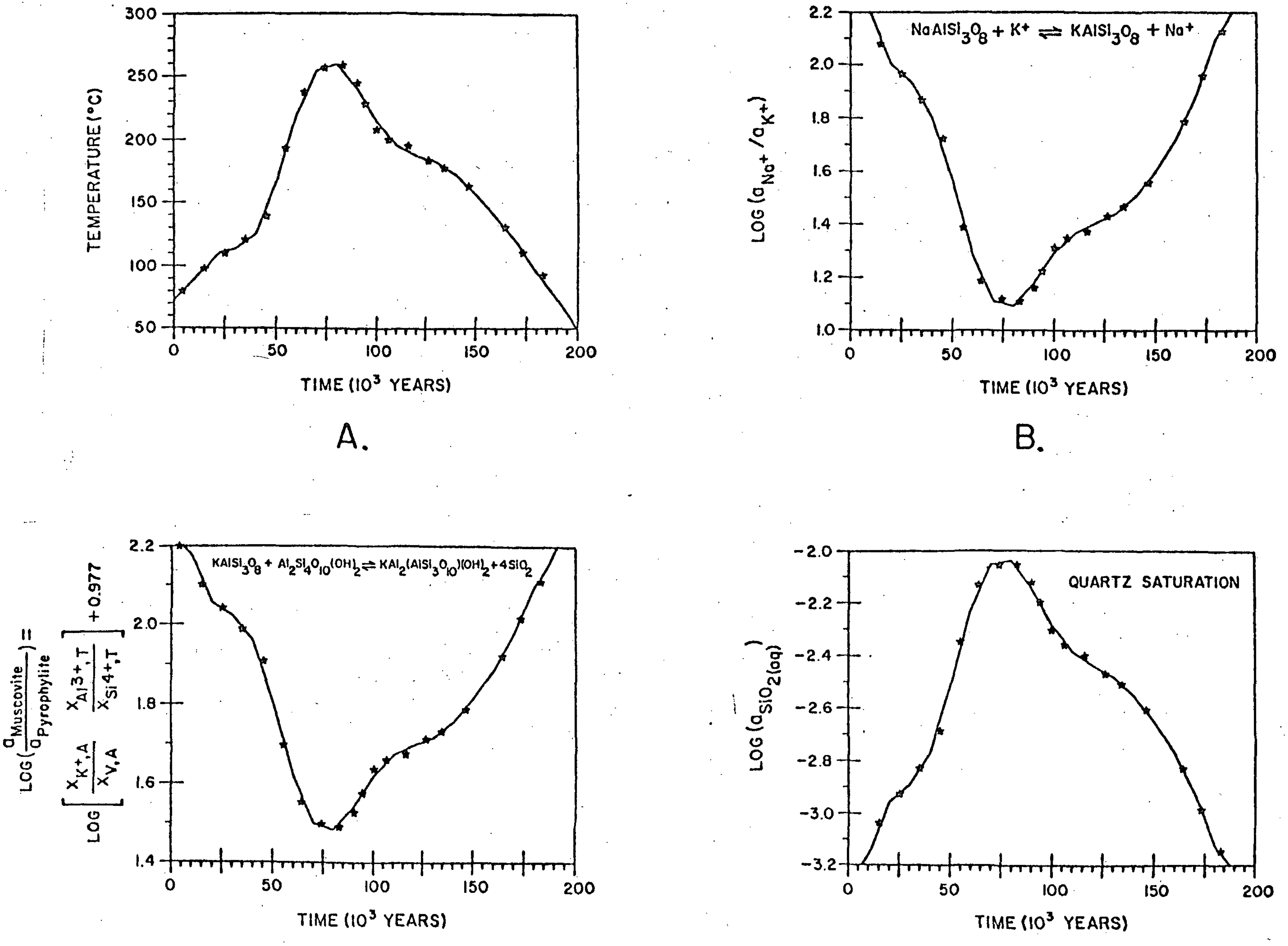
Figure 3.

in figure 2D. Fluid and mineral compositions characteristic of pathline A are shown in figure 4 in accord with specific statements of equations (2), (4), and (5), and equilibrium betweeen this fluid and albite, K-feldspar, dioctahedral layer silicates, and quartz. As shown in this figure, fluid compositions and layer silicate compositions vary dramatically along this flow path (fig. 2, B,C,D).

Pathlines A and B shown in Figure 3 demonstrate that the initial fluid sourceregion has a significant effect on subsequent fluid paths and resident time within geothermal systems. For example, the travel time of these two packets from the geothermal reservoir at 1 to 2 km deep and at temperatures of 200 to 250°C is 10^5 years for fluid A and 2.5 x 10^4 years for fluid B.

Figure 4C shows the relationship between the activity of muscovite and the pyrophyllite components in dioctahedral layer silicates and a fluid in equilibrium with quartz and a partially disordered potassium feldspar along a pathline taken from Norton (1979, 1980). Note that as temperature increases (Fig. 4A), that the activity ratio shown in Fig. 4C decreases. This is contrary to the trends reported for active geothermal systems (Muffler and White, 1969; Reed, 1976; McDowell and Elders, 1980). A similar relationship is shown in Figure 5 where the measured values of $m_{SiO_{2(aq)}}$ for selected geothermal fluids are plotted as a function of measured temperature. Fluids chosen are from well studied geothermal systems containing alkali feldspar and diotahedral layer silicate mineral assemblages. The solid lines represent fluid saturation with various silica polymorphs, while the broken lines denote isopleths of the cation site distributions in the layer silicates as specified in the figure for a fluid in equilibrium with a partially disordered potassium feldspar. Note that as a

Figure 4. Time rate of change in the temperature (diagram A), the activity of $SiO_{2(aq)}$ (diagram D), and the activity ratio of Na^+ to K^+ (diagram B) in the fluid packet for pathline A in Figure 2 in accord with equilibrium of this fluid and albite, K-feldspar, quartz, and a dioctahedral layer-silicate solid solution. Diagram C shows the composition of the dioctahedral-layer silicate solid solution in the wall rock in equilibrium with this fluid. Bird and Trembly, unpublished calculations).


TEMPERATURE (°C)
300
250
200
150
100
50
0
50
100
150
200
TIME (10^3 YEARS)
A.
$NaAlSi_3O_8 + K^+ \rightleftharpoons KAlSi_3O_8 + Na^+$
LOG (a_{Na^+}/a_{K^+})
2.2
2.0
1.8
1.6
1.4
1.2
1.0
TIME (10^3 YEARS)
B.
$KAlSi_3O_8 + Al_2Si_4O_{10}(OH)_2 \rightleftharpoons KAl_2(AlSi_3O_{10})(OH)_2 + 4SiO_2$
$LOG(\frac{a_{Muscovite}}{a_{Pyrophylite}}) = \left[LOG \frac{X_{K^+,A}}{X_{V,A}} \frac{X_{Al^{3+},T}}{X_{Si^{4+},T}}\right] + 0.977$
2.2
2.0
1.8
1.6
1.4
TIME (10^3 YEARS)
C.
QUARTZ SATURATION
LOG ($a_{SiO_2(aq)}$)
-2.0
-2.2
-2.4
-2.6
-2.8
-3.0
-3.2
TIME (10^3 YEARS)
D.

C.

D.

Figure 4.

Figure 5. *Measured values of* $m_{SiO_{2(aq)}}$ *for fluids from well studied* geothermal systems containing both alkali feldspar and layered silicate mineral assemblages plotted as a function of measured temperature. The solid lines represent saturation of various silica phases while broken lines denote isopleths of the ratio of the mole fraction of the K^+ cation to vacancies in the A *interlayer site times the ratio of the mole fractions* of tetrahedral Al^{3+} to Si^{4+} for dioctahedral layer silicates in equilibrium with a fluid phase and a partially disordered potassium feldspar. The dotted hexagons represent fluids from the Broadlands geothermal system (Mahon and Finlayson, 1972); the striped boxes Cerro Prieto (Reed, 1976); the striped circles, Kawerau (Mahon, 1962); the open rectangles, Otake (Hayashi and Yamasake, 1974); the solid circles, Wariakei (Mahon, 1966); the open triangle, Waiotapu (Wilson, 1963); and the solid triangle, Pauzhetsk (Vakin and others, 1970).

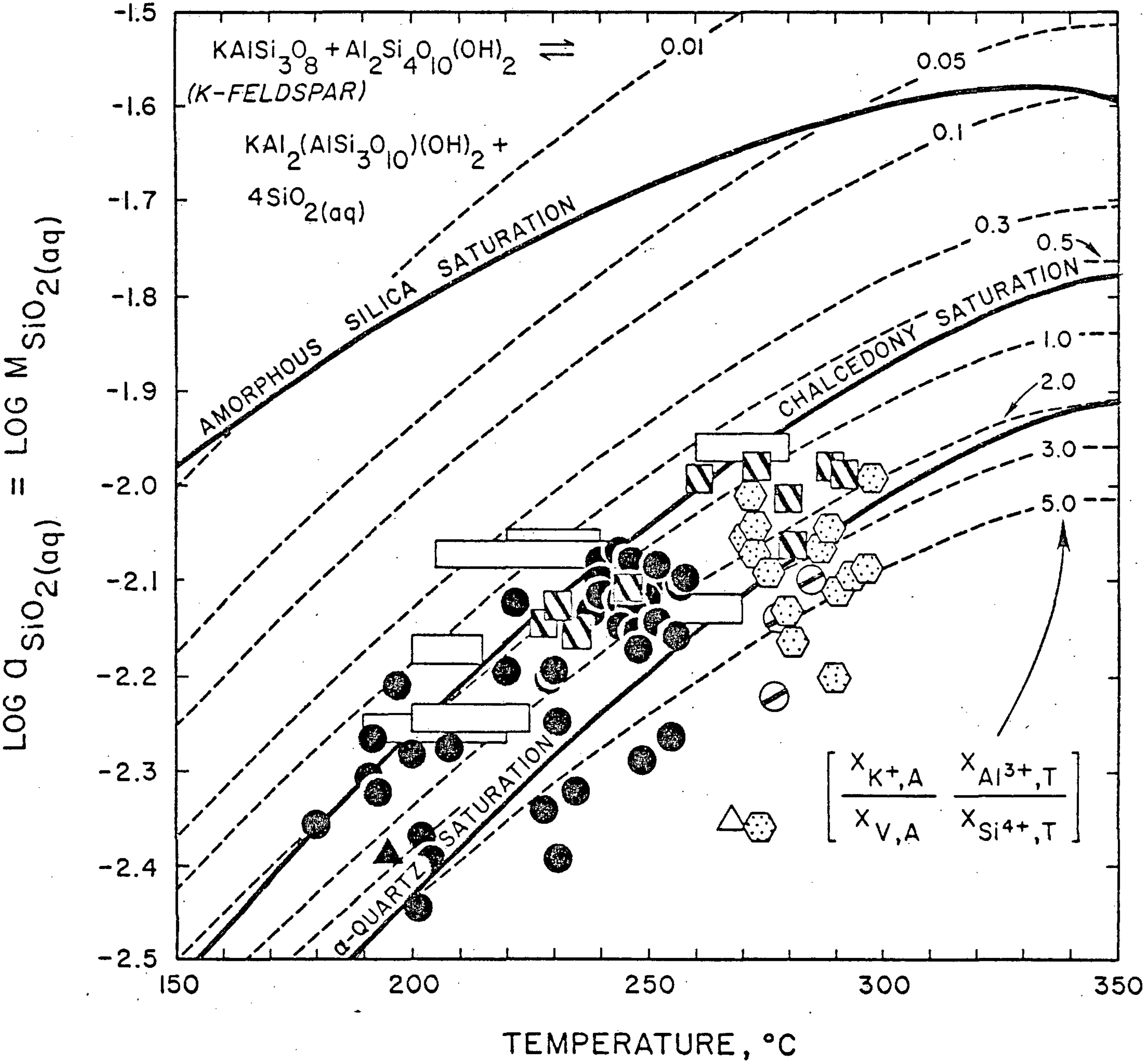

$KAlSi_3O_8 + Al_2Si_4O_{10}(OH)_2 \rightleftarrows$
(K-FELDSPAR)
$KAl_2(AlSi_3O_{10})(OH)_2 +$
$4SiO_{2(aq)}$
AMORPHOUS SILICA SATURATION
CHALCEDONY SATURATION
α-QUARTZ SATURATION
0.01
0.05
0.1
0.3
0.5
1.0
2.0
3.0
5.0
$\left[\frac{X_{K^+,A}}{X_{V,A}}\;\frac{X_{Al^{3+},T}}{X_{Si^{4+},T}}\right]$
$LOG\ a_{SiO_2(aq)} = LOG\ M_{SiO_2(aq)}$
-1.5
-1.6
-1.7
-1.8
-1.9
-2.0
-2.1
-2.2
-2.3
-2.4
-2.5
150
200
250
300
350
TEMPERATURE, °C

Figure 5.

fluid moves up in temperature along the quartz saturation curve, the activity ratio of the muscovite to the pyrophyllite component decreases. The general trend of the fluids plotted in the figure closely approximates increasing values of the ratio of the activity of the muscovite to the pyrophyllite component with increasing temperature and does not appear to follow or even parallel the saturation curve for quartz.

It is apparent from these diagrams that more work is needed to accurately determine the relationships among layered silicates, alkali feldspars, quartz, and geothermal fluids. A detailed study of layered silicate compositions measured in geothermal systems and calculated along pathlines will be undertaken as part of the overall proposal.

Non-equilibrium constraints:

The redistribution of chemical components during geothermal processes is a consequence of relaxation of a complex geologic system toward overall chemical, thermal, and mechanical equilibrium. Temporal variations in the concentrations of a chemical component within the system are due to: 1). the rate of advection of the component in the fluid phase; 2). the rate of diffusion of the component both in the fluid and in the solid phases; 3). the irreversible or nonequilibrium reaction rates among aqueous solutions and minerals; 4). and the reversible equilibrium reaction rates (Norton, 1979). Equilibrium reaction rates of change in activities of aqueous species are represented by equations (4) and (6) for the Lagrangian reference state. Similar equations are presented for the Eulerian fixed reference state by Norton (1979). Advective and diffusion rates depend upon the local fluid velocity and concentration gradients for the former rate, and on the Laplacian of concentration and the corresponding temperature dependent diffusion constants in the latter rate. Irreversible reaction rates of change in the concentration of the i th component in the r th phase can be written as

$$\frac{2C_{i,r}}{2t} = \frac{\nu_{i,r}\, k_r\, S_r\, a_j^{w}}{\phi_f} \qquad (7)$$

where $\nu_{i,r}$, k_r and S_r are the stoichiometric coefficient, intrinsic reaction rate constant, and the surface area of the r th phase, a_j is the activity of the j th species, w is the order of the reaction, and ϕ_f is the volume fraction of the fluid.

In equation (7) k_r is related to temperature (T), the activation energy (E*), and a frequency factor (A_r) by

$$k_r = A_r \exp\,(-\Delta E^*/RT) \qquad (8)$$

(Helgeson, 1971; Bailey, 1974; Aagaard and Helgeson, 1977, 1980; Norton, 1979; Norton and Taylor, 1980). Values of k_r are available for only a few of the common rock forming silicates (see summary in Norton and Taylor, 1980). Nevertheless there is sufficient data on alkali feldspar and quartz transfer rate constants to afford a preliminary evaluation of the irreversible rate of change of Na^+/K^+ and $SiO_{2(aq)}$ in the fluid flow pathlines such as those shown in figure 3B and D. Calculations of this type have been presented by Norton and Taylor (1979) and Helgeson (1979). Although calculations of mass transfer of chemical components are severely restricted due to the limited data base of the thermodynamic properties of aqueous complexes and transfer rate functions, preliminary calculations permit evaluation of the extent to which the surface composition of a fluid packet, such as that for pathline A in figure 3, will refect the subsurface temperatures in a geothermal system. This analysis affords preliminary evaluation of thermodynamic based solute geothermometers and the consequences of the rate limiting reaction processes which appear to be governed by surface chemical reactions as proposed by Lagache (1965, 1976), Helgeson (1971), Paces (1973), Petrovic (1976), Petrovic, Bernor, and Goldhaber (1976), Aagaard and Helgeson (1977, 1980), and Berner (1978).

Stable Isotope Constraints

The reaction of sedimentary rock in response to circulating geothermal fluid is not limited to the mineralogic chemical reactions discussed above. In addition, the minerals exchange oxygen, hydrogen and carbon with a geothermal fluid composed primarily of water. The study of stable isotopic exchange between various minerals and the geothermal fluid can, in principle, provide accurate constraints on the temperature distribution and thermal history of the geothermal reservoir. Stable isotope geochemical analysis is also capable of indicating the source and history of the water in the circulation system. Of particular interest in this proposal is the use of data on the exchange of oxygen between the fluid and the reservoir rock in order to quantify the water/rock ratio involved in the geothermal interaction.

Temperature distribution:

The most convenient element for the stable isotopic study is oxygen since it is a major constituent of both the rock and the hydrothermal fluid. The natural fractionation of oxygen isotopes between a fluid and coexisting mineral phases is also a strong function of the temperature at which they equilibrate (Figure 6). It has been shown that pore filling calcite in sandstones of geothermal systems located in sedimentary terrain are quite susceptible to equilibration with the circulating fluid (Clayton

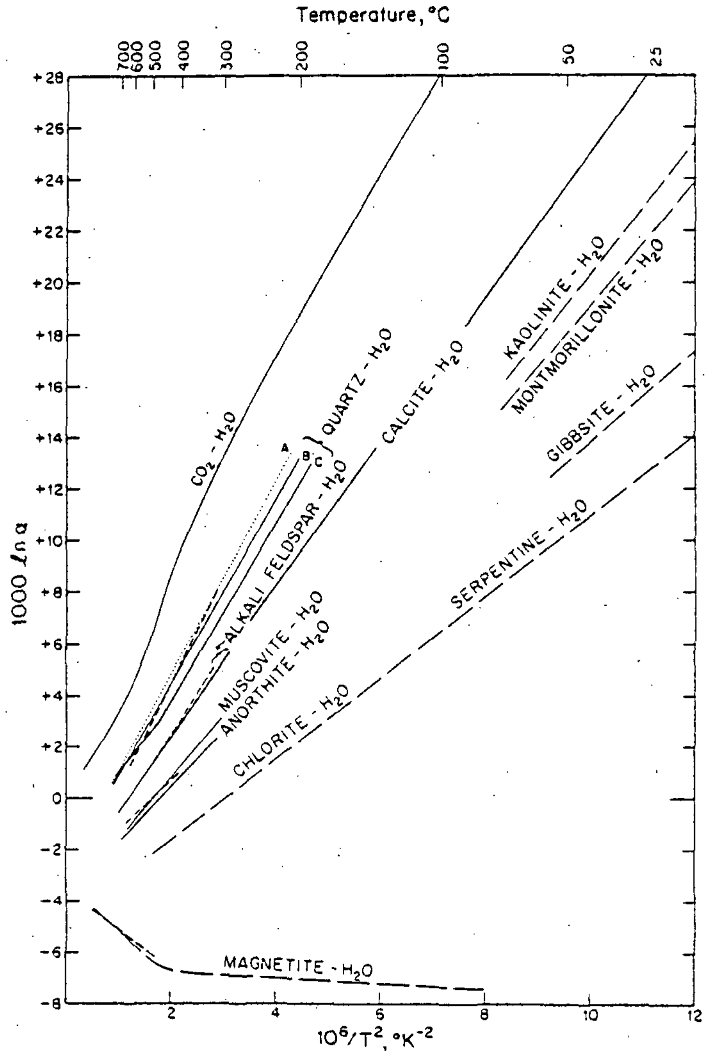


Figure 6. Compilation of equilibrium oxygen isotope fractionation curves for various mineral-water systems. Empirical, theoretical, and experimental data are included (after Taylor, 1979).

et al., 1968, Coplen et al., 1975; Kendall, 1976; Elders et al., 1977, 1978a). This ease of equilibration has been shown for calcites in sandstones at Cerro Prieto (Elders et al., 1977, 1978c; Olson, 1979) and has allowed the calculation of reservoir temperatures from the isotopic data on rock samples and that of the fluid. An accurate knowledge of the distribution of temperature in the stable reservoir is critical for the understanding of the other processes of water/rock interaction within the system.

Other minerals which coexist with calcite in the sedimentary rocks undergo oxygen isotopic exchange at different rates. Detrital quartz as well as other silicate phases have been shown to approach isotopic equilibrium with the hydrothermal fluid at a rate significantly slower than that of calcite in the same rocks (Clayton et al., 1968; Coplen et al., 1975; Kendall, 1976). The degree of isotopic exchange in these minerals appears to be a function of time, and so a careful study of disequilibrium isotopic relationships may serve as an indicator of the thermal history of the geothermal system.

Source of hydrothermal fluids:

The oxygen and hydrogen isotopic variations of water in the oceans, rain, streams, lakes and most ground waters are quite systematic and so such isotopic data on geothermal fluids can indicate the source of the water in the system. Meteoric waters have been shown to closely follow the equation (Craig, 1961):

$$\delta D = 8\,\delta^{18}O + 10$$

due to the equilibrium condensation of rain water from the atmosphere. River, lake, and low temperature ground waters are derived from a meteoric source and their isotopic composition is subsequently altered by evaporative processes. In any given locality, water sources can be accurately identified by their isotopic composition.

It has been shown that nearly all geothermal waters are of surface derivation (Craig, 1963), but have suffered oxygen isotopic exchange with the rock in the geothermal reservoir. This exchange is evidenced by an "isotopic shift" of the oxygen isotopic composition of the water toward equilibrium with the reservoir rock.

Quantification of water/rock interaction:

As mentioned above, water involved in nearly all geothermal circulation systems appears to be derived from meteoric or surface water sources. Waters of these types have been shown to be generally far lighter in their oxygen isotopic composition than would be in equilibrium with the rock present in the reservoir. The interaction of these two phases at relatively high temperatures is shown by the depletion of the rock in ^{18}O and the consequent enrichment of that isotope in the fluid phase. Since this is the case, a simple mass balance equation can be developed to show the relative amounts of each phase invovled in the interaction.

$$W\,\delta^{i}_{H_2O} + R\,\delta^{i}_{rock} = W\,\delta^{f}_{H_2O} + R\,\delta^{f}_{rock}$$

where (W) is the percent of oxygen involved with the fluid phase, (r) is the percent of the systems total oxygen located in the rock, (i) indicates initial conditions, and (f) indicates final values after hydrothermal interaction. This equation can then be written

$$W/R = \frac{\delta^{f}_{rock} - \delta^{i}_{rock}}{\delta^{f}_{H_2O} - \delta^{i}_{H_2O}}$$

where W/R is the oxygen mole ratio of water to rock involved in the high temperature circulation system.

In a "fossil" geothermal area or hydrothermal ore body, the final isotopic composition of the fluid phase is often difficult to determine. In that situation (Taylor, 1974), it must be assumed that the final fluid composition is determined by isotopic equilibrium with the rocks with which exchange occurred and the temperature of the interaction (see Figure 7). A hypothetical model of the fluid circulation must also be assumed since the calculated water/rock ratio is also dependent on the amount of fluid recirculation that takes place in the system (Figure 7).

In the case of an active geothermal system, however, this problem does not exist since the geothermal fluid is still present and can be analysed for its isotopic composition. The isotopic shift of the fluid phase, caused by the water/rock interaction, can be directly calculated by the difference between the source water and the final geothermal fluid. In a similar manner, the isotopic shift suffered by the rock in the reservoir calculated by the comparison of whole/rock $\delta^{18}O$ values of samples from within the geothermal system with those of unaltered rock samples of similar lithology taken outside of the hydrothermal circulation system. This information, when included in a mass balance calculation similar to that discussed above, can easily and accurately produce a value for the overall water/rock ratio involved in geothermal interaction integrated over the whole circulation history. The actual flow rate of hydrothermal fluid through the system is, however, not possible to calculate without an accurate measure of the time in which the observed water/rock interaction has taken place. Local variations in the water/rock ratio may be observable as deviations in the measured isotopic shift of the fluid or rock

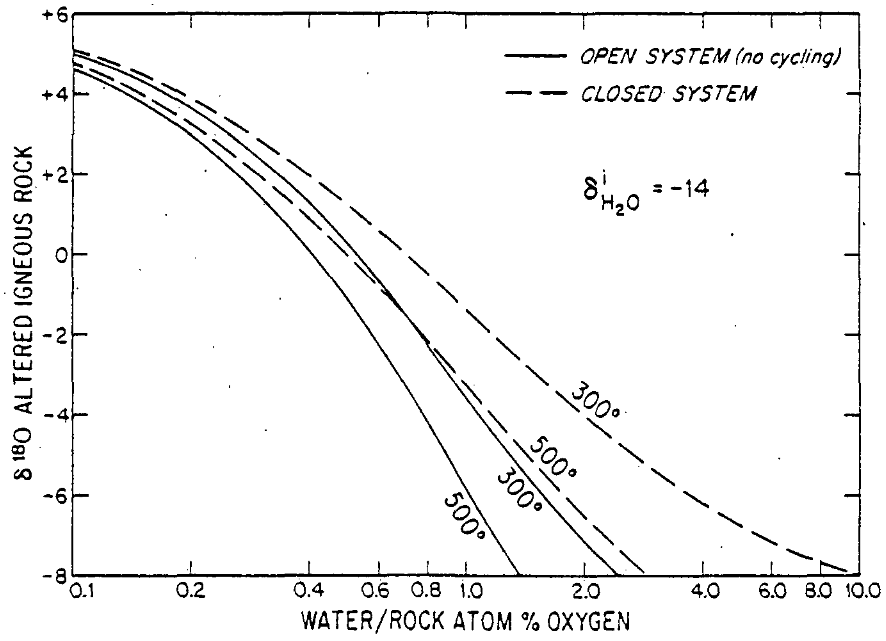


Figure 7. Plot of oxygen isotopic compositions of hydrothermally altered igneous rock vs. calculated water/rock ratio (after Taylor, 1979).

phases. It is therefore necessary to precisely analyse both geothermal water and reservoir rock samples to provide a complete three dimensional picture of the geothermal interaction.

Transport theory has been used to calculate the effects of hydrothermal circulation in a fossil geothermal system (Norton and Taylor, 1979). In that study, it was shown that such models of the mass and thermal transport can successfully be constrained by the observed isotopic exchange of oxygen between the reservoir rock and the circulating fluid. In an active geothermal environment, such as that at Cerro Prieto, actual measurements of parameters such as present temperture distribution, hydrothermal flow regime, permeabilities and fluid composition can be utilized instead of assumed or calculated conditions necessary in such a study in a fossil area. In addition, three dimensional sample coverage in the extensively drilled Cerro Prieto field is far superior to the sampling possible in an eroded fossil area such as the Skaergaard (Norton and Taylor, 1979; Taylor and Forester, 1979). Because of the additional constraints on hydrothermal circulation in the active Cerro Prieto geothermal system, a great deal may be learned about the interaction of rock and fluid in response to the chemical, thermal and fluid transport in such a system.

Transport calculations summarized above afford a new approach to the understanding of the transient characteristics of water/rock interaction in active magma-hydrothermal systems. Applications of transport theory and thermodynamic constraints to the vast data base for the Cerro Prieto geothermal system will contribute significantly to this knowledge. The concepts, principles, and methods developed during this study will then be applicable to other geothermal systems.

Procedure and Supporting Data

The thermodynamic approach to understanding water/rock interaction and characterizing geothermal systems is of general applicability, no matter what type of geology or fluid chemistry is involved. However, we feel that at this stage in development it would be inappropriate to attempt to apply it to poorly explored systems. The best chance to develop techniques and concepts of wide generality and practical applicability is to study systems which are well-explored and for which an adequate body of supporting data already exists.

We are therefore proposing to carry out a study of solution/mineral interactions in the Cerro Prieto geothermal field in Baja California, Mexico (Fig. 8) using the extensive data on mineral distribution and phase chemistry which already exist (Hoagland and McDowell, 1978); Hoagland and Elders, 1978; Elders et al., 1977, 1978b, 1979, 1980). Critical additional data on phase chemistry, mineral formation temperatures, and whole rock stable isotope compositions, will be obtained as part of this proposed research project, and interpreted using the computational methods developed by Bird and Norton (1980).

The choice of Cerro Prieto:

We believe that at the present time Cerro Prieto is the best studied geothermal field in the world. The Comision Federal de Electricidad of Mexico (CFE) has developed the first commerically viable geothermal power plant in North America to produce electricity from a water-dominated field. This plant, at Cerro Prieto in the Mexicali Valley of Baja California, Mexico, began producing 75 MWe in April 1973. By March 1979, it had 150 MWe of generating capacity and in 1982 a 30 MWe low pressure turbine will be added which will use existing production wells. At present, a major

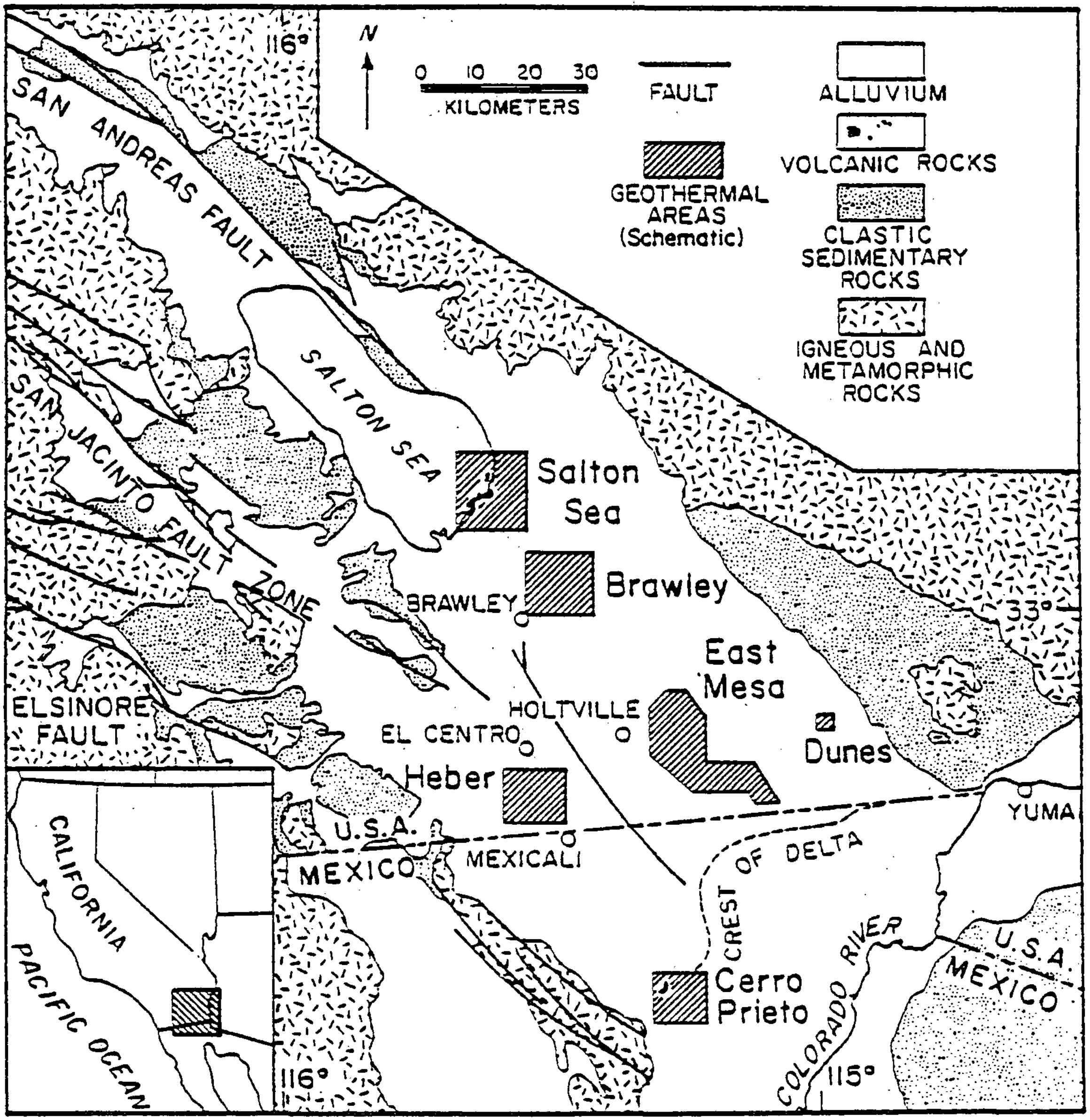


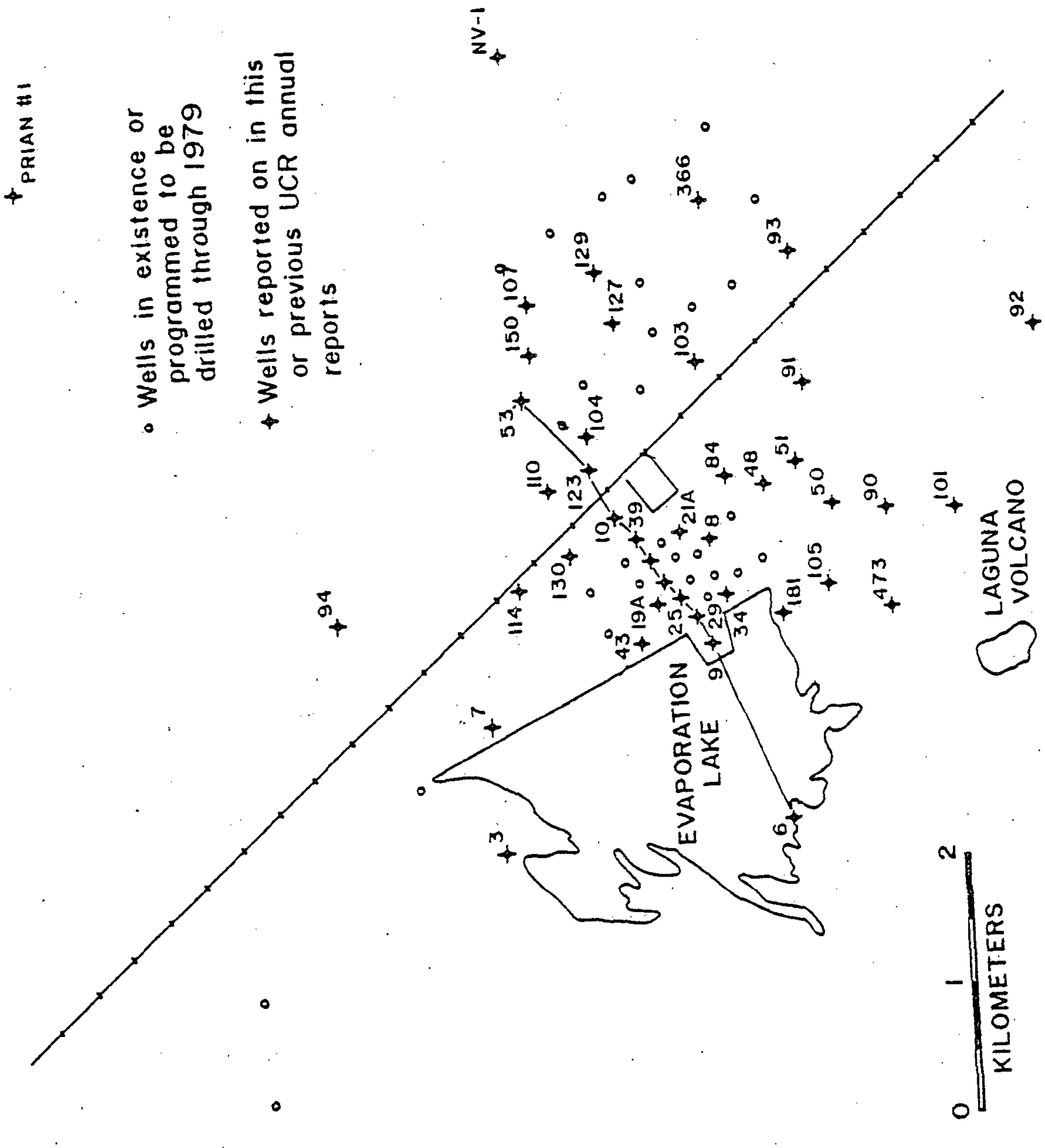
Figure 8. Generalized geologic map of the Imperial Valley and adjacent areas.

exploration and development drilling program is underway and construction plans call for expanding the installed capacity to 290 MWe by 1984.

A program of international scientific and technical collaboration was initiated in July 1977 as a result of a written agreement between CFE and the Department of Energy of the U.S.A. (DOE). Lawrence Berkeley Laboratory, of the University of California, is managing this program on behalf of DOE. This program, together with the earlier technical investigations of CFE, has produced a broad array of surface and subsurface geological, geophysical and geochemical data. In contrast to the usual situation in the U.S.A., all of these data are in the public domain. The early results of this collaboration have been reported at well-attended symposia in San Diego in 1978, and in Mexicali in 1979 (Anomymous, 1978, 1979). A wealth of subsurface lithological samples and water samples are available from the more than sixty-five wells drilled to date at Cerro Prieto (Fig. 9). This wells produce Na-K-Ca chloride brines of up to 18,000 mg/l total dissolved solids. A wide range of temperatures and temperature gradients have been encountered ranging from 350C° at 1.8 km, to 108°C at 3.2 km depth. The Plio-Pleistocene deltaic sediments of the reservoir exhibit prograde metamorphic mineral assemblages of greenschist facies (Reed, 1976; Elders _et al_., 1977, 1978a, b, c, 1979, 1980a,b); Hoagland and Elders, 1978; Hoagland and McDowell, 1978).

The work we are proposing is not site-specific, as the understanding of the controls of water/rock interaction we will develop should be widely applicable to other systems at similar temperatures. However, we believe that Cerro Prieto is the best candidate for the type of study proposed. No comparable body of data and samples is available for any geothermal field in the United States of America. Furthermore, the UCR

Figure 9. Map showing the location of Cerro Prieto wells.



investigators have already gained two years experience of working on the Cerro Prieto field.

Related previous work:

Since 1968 the Geothermal Resources Program of the Institute of Geophysics and Planetary Physics (IGPP) at the University of California, Riverside (UCR) has carried out a multifaceted investigation of the geothermal resources of the Salton Trough of California and Mexico (Fig. 8). A list of reports published by IGPP as a result of this work is included in the SUPPORTING DATA section. This research was aimed at investigating the nature and origin of water-dominated geothermal systems; a necessary prerequisite for intelligent exploration, characterization, assessment and utilization of geothermal resources.

Part of these investigations involved geochemical and petrological studies of rock and fluid samples recovered from deep drilling. These studies show that the nature of hydrothermal alteration depends not only on temperature but also upon the permeability of the rocks and upon fluid composition (Bird and Elders, 1976; Kendall, 1976; Elders, 1977b; Hoagland and Elders, 1977; McDowell and McCurry, 1978; McDowell and Elders, 1978, 1979; Hoagland and McDowell, 1978).

The recent rapid pace of drilling together with the other studies referred to above, made the Cerro Prieto system a particularly favorable site for detailed studies of water/rock interaction. Accordingly, following on the pioneering work of Reed (1976), we have concentrated our efforts there during the past two years. These studies have shown that a well-developed and systematic suite of prograde minerals occurs (Hoagland and Elders, 1978; Hoagland and McDowell, 1978; Elders et al., 1977, 1978a, b, c, 1979, 1980a,b), involving phyllosilicates, carbonates, feldspars, quartz and hydrous calc-aluminum silicates (Figures 10, 11). One immediate practical application of this finding has been our use of these hydrothermal mineral assemblages and associated supporting data on fluid inclusion and light stable isotopes to predict reservoir temperatures while exploration wells are being drilled, prior to well completion and testing (Elders,et al., 1978b). Similarly, our maps of the distribution of hydrothermal mineral zones in the subsurface are proving useful in interpreting gravity and electrical resistivity data and in formulating reservoir engineering mdoels (Elders et al., 1979; Vonder Haar and Puente, 1979). The zone of most intense hydrothermal alteration is a gravity and resistivity high because of the consequent reduction in porosity.

Our studies have also detected systematic variations in the chemical composition of several key minerals, similar to variations noted in other hydrothermal fields (Figures 12 and 13). Preliminary data on chemical compositions of important coexisting phases at Cerro Prieto have allowed us to make a reconnaissance study of the physiochemical controls over phase assemblages and mineral compositions. For example, we have noted a difference in the mineral assemblages which occur at the same temperature in wells M84 and M53, two wells which lie on opposite sides of a major fault (Fig. 14). Figure 15 shows the stability fields of these assemblages as a functin of CO_2 fugacity and silica activity, and suggests that there is a difference in the CO_2 fugacity prevailing in these two wells. This in turn implies that communication of gas between M84 and M53 may be restricted. Furthermore, our preliminary calculations suggest that the mineral assemblages in both of these wells have formed under conditions of supersaturation with respect to quartz (Fig. 16). This inference may also have important implications for reservoir models, as it suggests that both

Figure 10.

MINERAL ZONATION IN CERRO PRIETO SANDSTONES

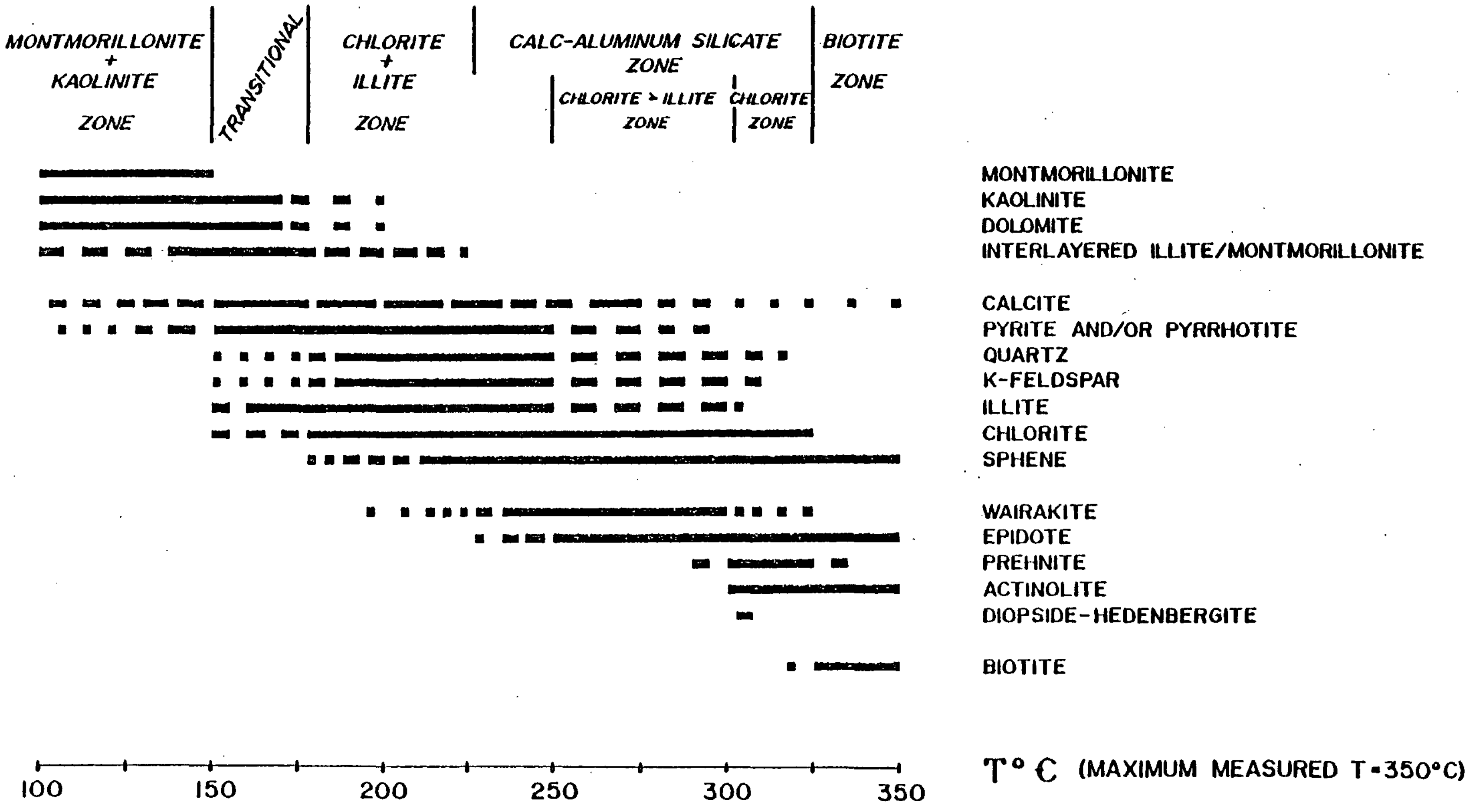


Figure 11. Occurrence of hydrothermal minerals in sandstones along the profile A-A'. Isotherms modified from Mercado (1976).

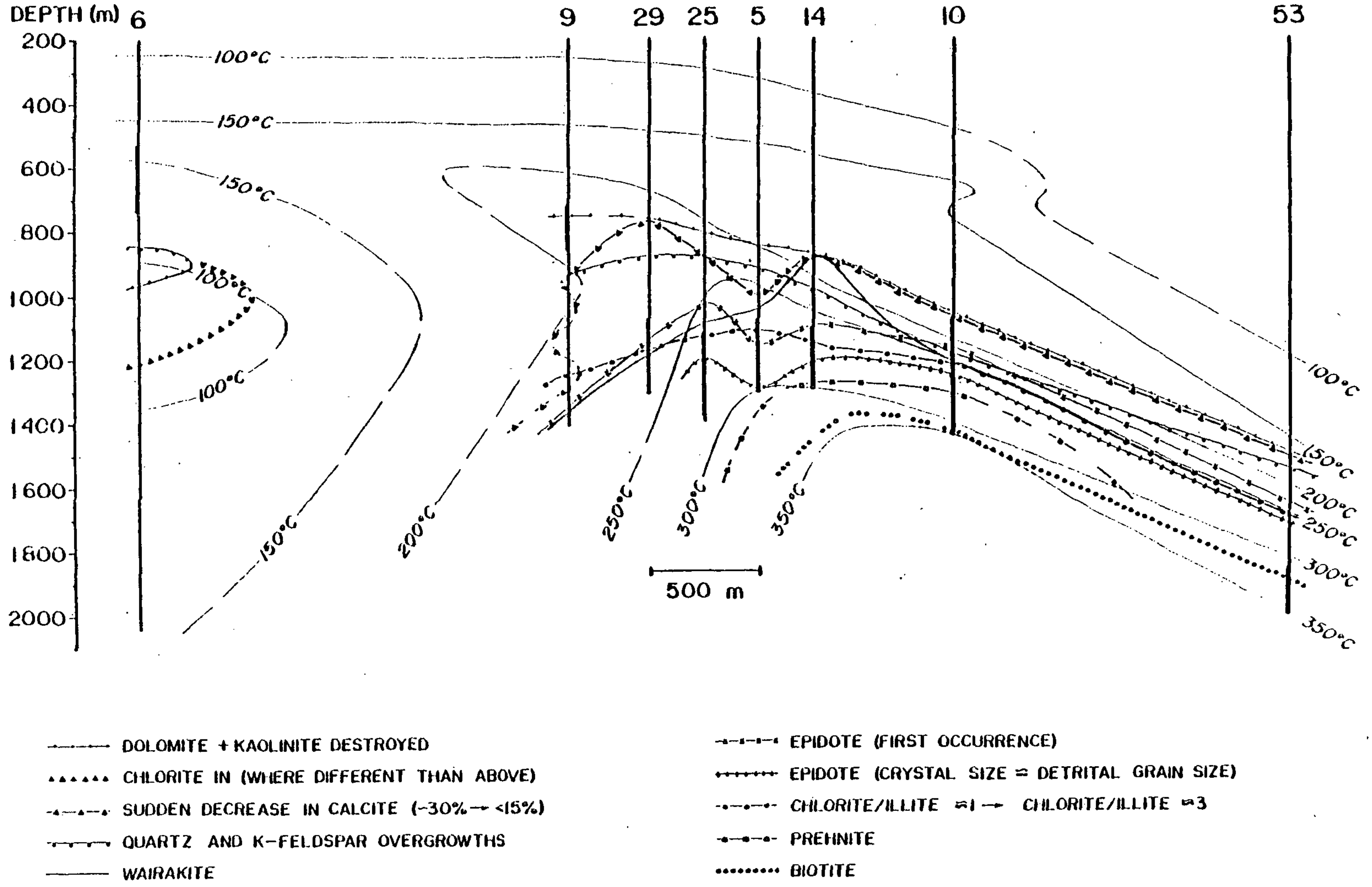


Figure 12. Compositions of hydrothermal epidote versus depth in Well M53 at Cerro Prieto. Inset shows temperature profile. Triangles show mean value for a given depth. (Elders *et al*., 1978c).

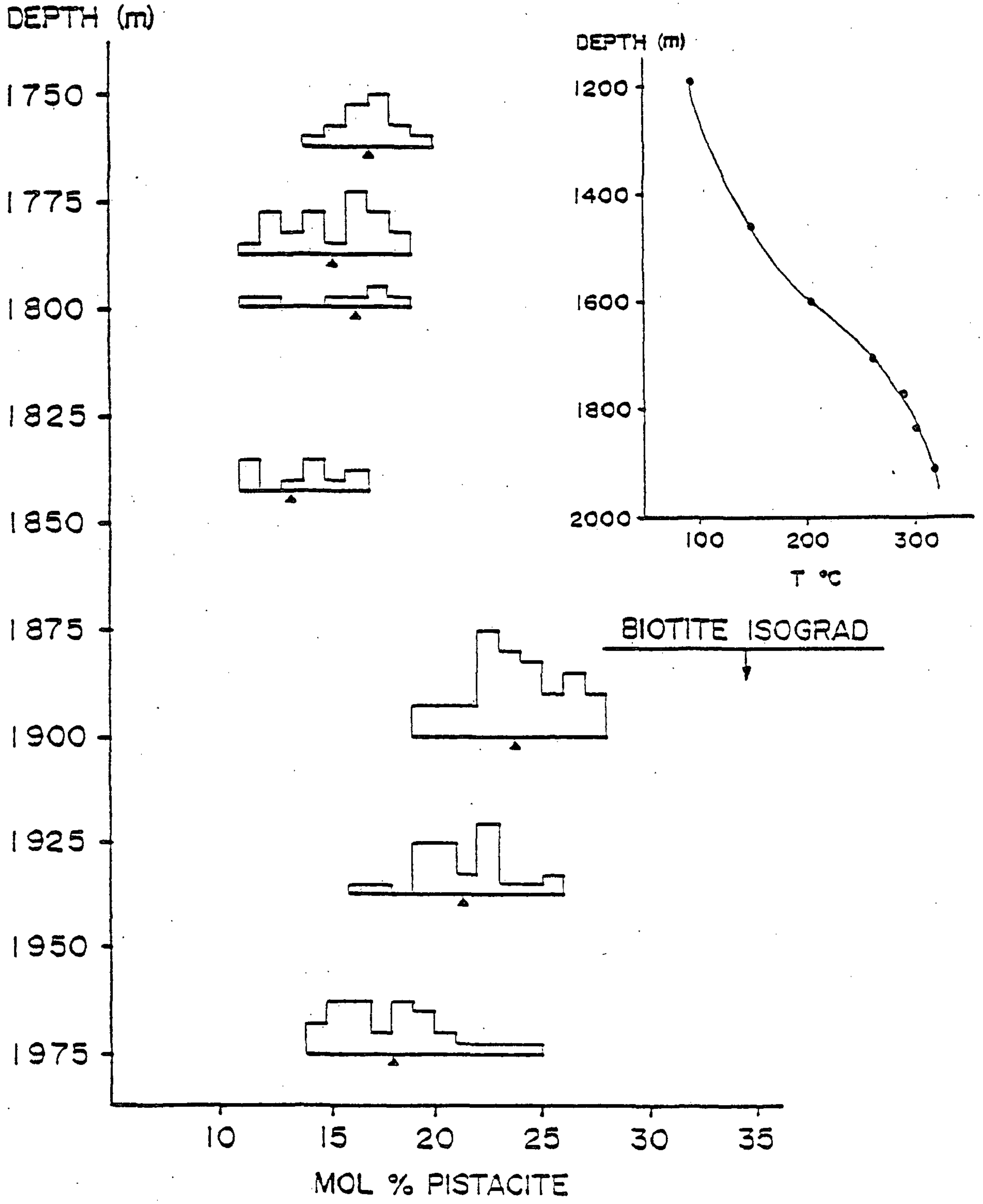


Figure 13. Composition of epidote with depth in well Elmore #1, Salton Sea geothermal field (McDowell and McCurry, 1977).

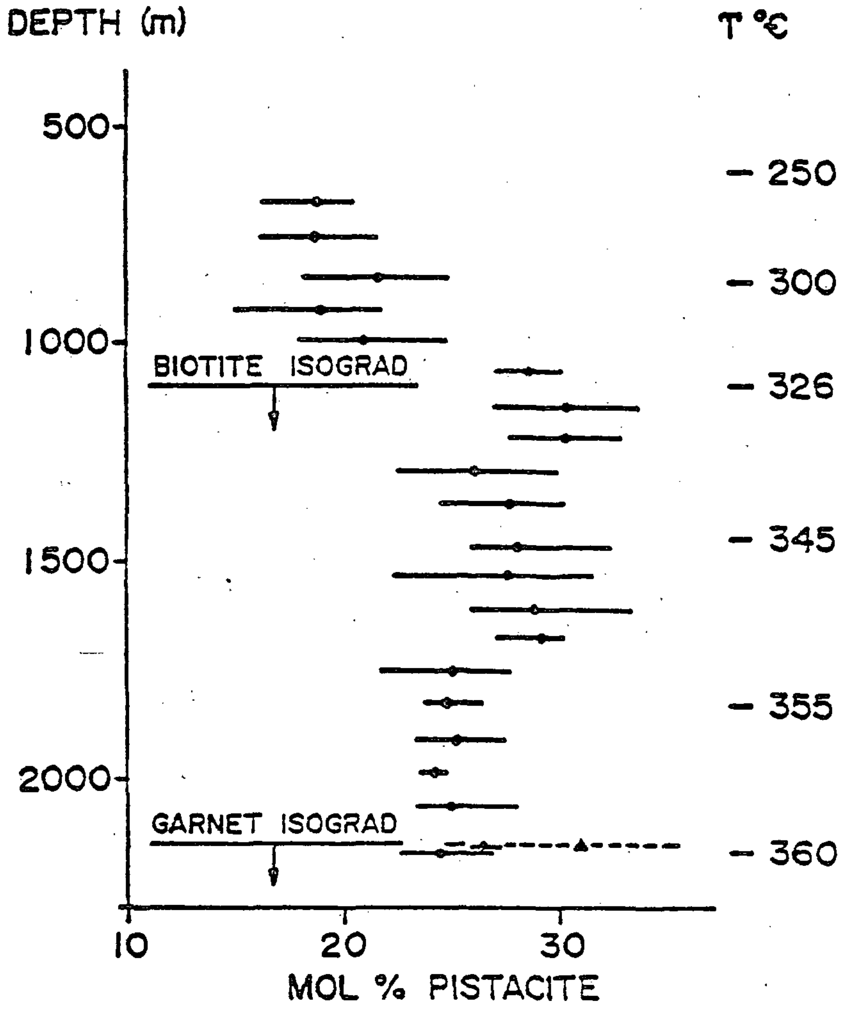
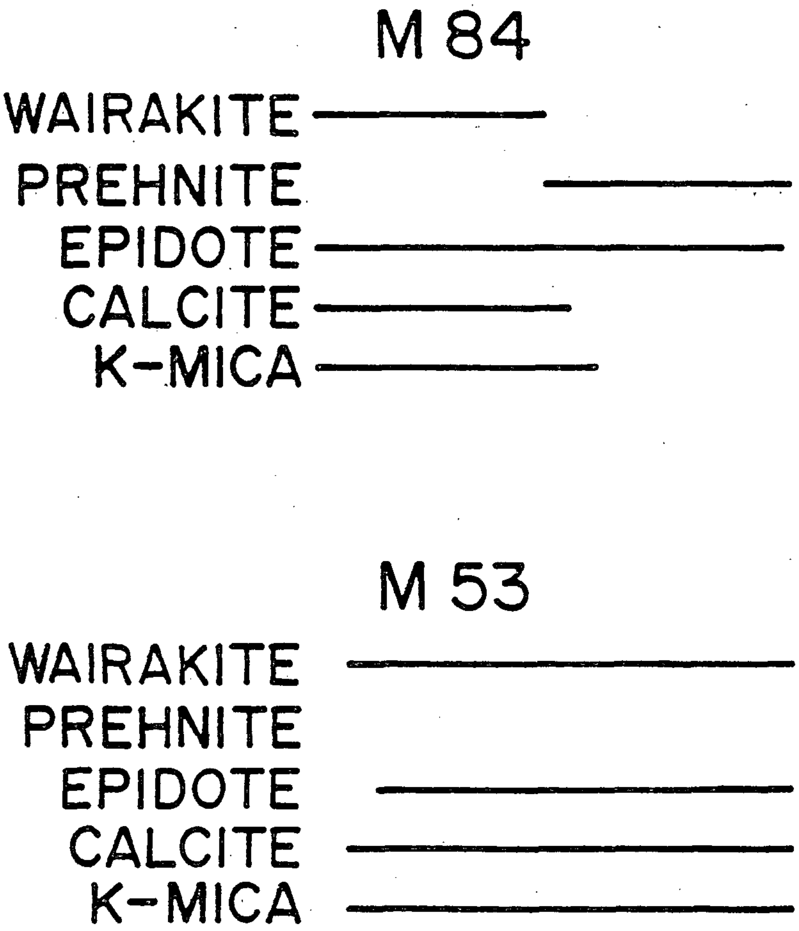


Figure 14. Mineral paragenesis in wells M84 and M53 at 300°C in sandstones from the Cerro Prieto geothermal field (Elders *et. al.*, 1979).



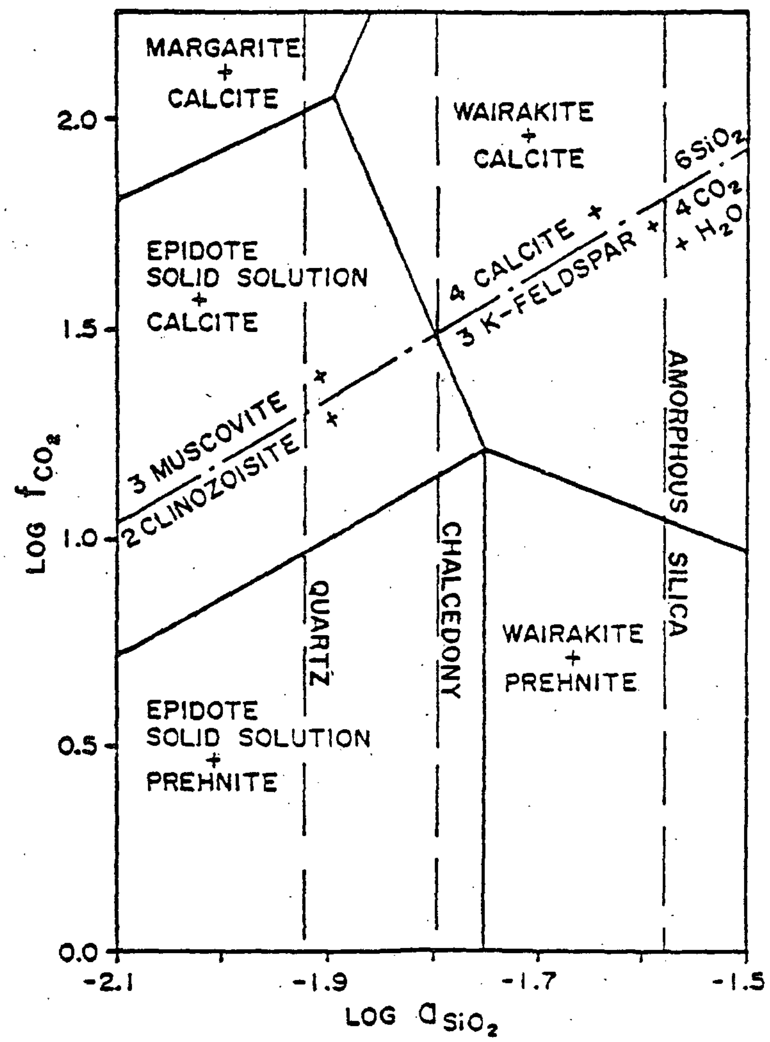


Figure 15. Calculated CO_2 fugacity and silica activity diagram for mineral assemblages in the Cerro Prieto geothermal field. The M84 assemblage (Fig. 8) occurs within the stability field of epidote + prehnite (log f $CO_2 \leq 1.2$). The M53 assemblage lies in the stability field of muscovite + calcite, along the boundary between the fields of epidote + calcite and of wairakite + calcite ($1.4 <$ log f $CO_2 \leq 2.0$) Elders _et al._, 1979).

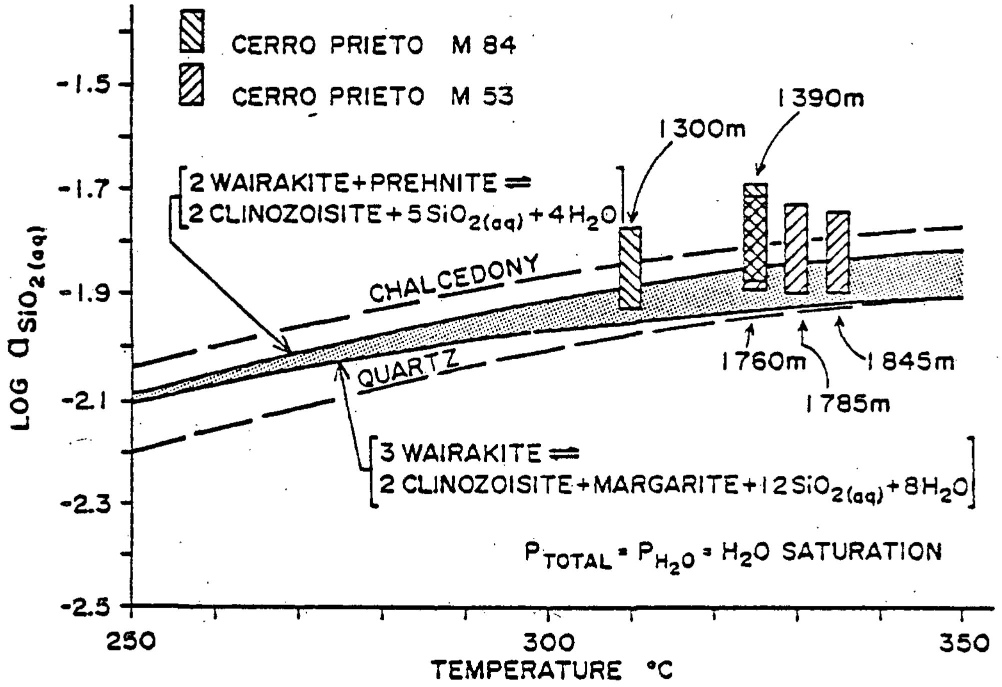


Figure 16. Calculated activity of SiO_2 versus temperature. The shaded area indicates the stability field of coexisting clinozoisite + wairakite. The ruled areas show the upper and lower boundaries of this field, when corrected for actual epidote compositions, measured in different parts of wells M84 and M53 at Cerro Prieto. Note the requirement for supersaturation of quartz at temperatures up to 340°C (Elders et al., 1979).

of these wells lie in parts of the reservoir being heated by influx of fluid from an even hotter source.

In our earlier studies at Cerro Prieto we made a tentative approach to defining the discharge and recharge volumes of the reservoir in terms of mineral abundances (Hoagland and Elders, 1978). We suggested that a quartz-adularia association was characteristic association was characteristic of an environment where hot water was being discharged into colder rocks, whereas a calcite-rich zone represented cold water entering hotter rocks or a region of boiling (Fig. 17). Development of the thermodynamic controls over minderal reactions will allow us to refine this crude, qualitative idea and hopefully perfect models of fluid flow and temperature change in the reservoir based on mineralogical and chemical criteria.

A large body of data has already been accumulated regarding the stable isotope geochemistry of the Cerro Prieto geothermal field. It has been shown (Truesdell _et al._, 1979) that the fluids extracted from Cerro Prieto geothermal wells have been derived from Colorado river ground waters. The water has apparently suffered an oxygen isotopic shift of the order of 2 to $4^{0}/00$ (parts per thousand) in response to exchange with the rocks in the heated geothermal reservoir. The observed oxygen isotopic composition of these geothermal fluids is supported by extensive work comparing isotopic compositions of calcite with temperature data from well logs, petrology and fluid inclusions. The fluid isotopic compositions calculated by these methods seem to agree quite well and a value on the order of $-8.3^{0}/00$ (relative to SMOW) has been concluded (Olson, 1979).

	FLUID TEMPERATURE	
	← FALLING	RISING →
	QUARTZ-ADULARIA ZONE	CARBONATE ZONE
PRECIPITATION	Quartz and Feldspar	Calcite and Anhydrite
SOLUTION	Calcite and Anhydrite	Quartz and Feldspar
	DISCHARGE	RECHARGE

Figure 17. Hydrologic environments of formation of pore cements at Cerro Prieto (Hoagland and Elders, 1978).

The isotopic compositions of calcite in sandstones have been shown to be a reliable indicator of the stable reservoir temperature (Olson, 1979) and an excellent data collection (Elders et al., 1977, 1978, 1980a, 1980b) of such analyses has been accumulated. From this data, a reliable picture of the thermal distribution can be calculated (Elders et al., 1980b) (Figure 18). Calcite isotopic compositions measured in shales are often out of equilibrium with the present reservoir fluid, a result of the lower permeabilities of the finer grained sediments (Olson, 1979; Elders et al., 1977, 1978c). The observed differences in the degree of approach of these shale values to equilibrium are likely indicators of differences in the overall flow hydrothermal fluid through different regions of the geothermal system.

Oxygen isotopic measurements in the silicate phases of Cerro Prieto have only begun recently, but results appear rather interesting. In particular, it has been shown that detrital quartz can remain nearly inert to isotopic exchange with the hydrothermal fluid at temperatures as high as 200°C (Elders et al., 1980b). The overall isotopic shift suffered by the sedimentary rocks is, therefore, much smaller than that indicated by the easily equilibatred calcite. Hence, the calculated water/rock ratio may be far smaller than previously thought (Olson, 1979; Elders et al., 1978c).

The large amount of isotopic data presently available and the quantity of reservoir rock material available for future analysis make the Cerro Prieto geothermal area an ideal location for developing our understanding of isotopic relationships indicative of geothermal water-rock interactions.

Such models can be also improved by allied studies involving other types of geothermometry which we currently have underway. These include fluid inclusion measurements (Elders, 1977b; Freckman, 1978); vitrinite

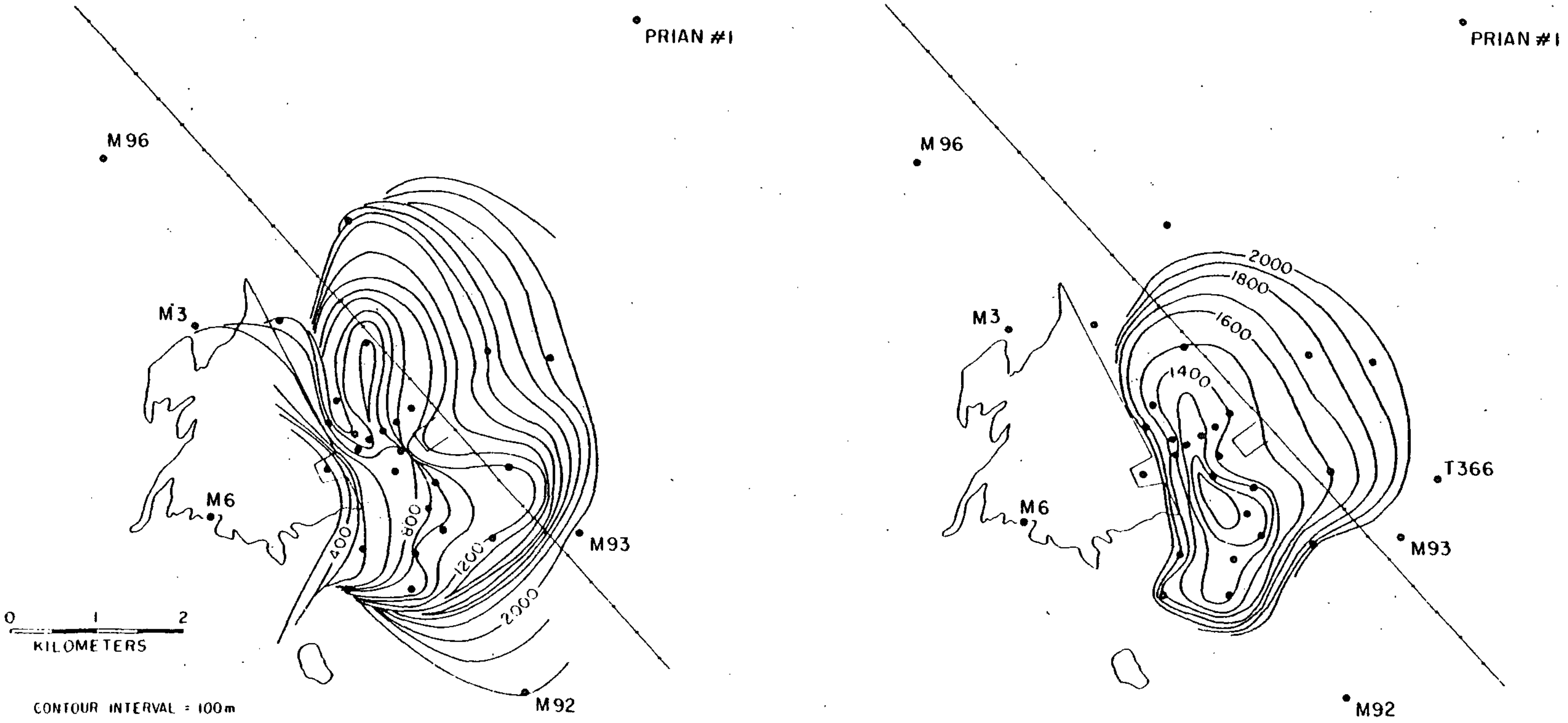


Figure 18. Depth in meters of the 200°C (left) and the 300°C (right) isotherms as determined by $\delta^{18}O$ in calcite from sandstones (after Elders et. al., 1980). Some contour lines intersect due to temperature inversions.

reflectance geothermometry (Barker, 1979, Barker and Elders, 1979) and unpublished work on fission track annealing as a method of dating thermal events at Cerro Prieto. These allied studies are also aimed at understanding temperature history, fluid flow, water/rock ratios, changes in porosity and permeability, and ultimately, mass and heat transfer in the system.

We believe that a fundamental understanding of water/rock interaction in active hydrothermal systems is emerging as a result of such detailed studies. The thermochemical study proposed at Cerro Prieto will contribute significantly to this knowledge. The concepts, principles and methods thus developed will then be applicable to other geothermal fields.

Expected Accomplishments:

As a result of the proposed project, we expect to develop a detailed knowledge of the variations in phase chemistry in the Cerro Prieto reservoir and the relationship of these variations to present and past reservoir temperatures. Particular emphasis will be placed in determining the compositions of phyllosilicates. The analyses of whole rock stable isotope compositions, when combined with existing data on the isotopic compositions of various carbonate and silicate minerals, will allow us to calculate the water/rock ratios involved in hydrothermal alteration at various locations wtihin the reservoir. We will hence be capable of producing maps of total fluid flow in the reservoir and surrounding environs. The fluid inclusion data to be acquired in this project will be integrated with existing geothermometry data and existing data on the duration of heating at Cerro Prieto to provide constraints on the time-temperature history of the system.

Evaluation of all the above data within a thermochemical and mass transfer framework will allow us to quantitatively describe the critical parameters governing alteration of geothermal reservoirs. We anticipate that this quantitiative description of the process of water/rock reaction at Cerro Prieto will enable us to develop effective predictive exploration and assessment models based on petrologic data which will be applicable to other geothermal systems.

FEASIBILITY AND COST-EFFECTIVENESS

The combination of experience and facilities at UCR and UA provides a unique opportunity for a collaborative study addressing the topics outlined in the technical discussion section.

The methodology and facilities for acquiring and analyzing the necessary data for this project already exist at one or the other of the institutions, and the personnel who will participate in this proposed research have all acquired extensive experience in applying these techniques to geothermal problems. The extant sample and data base from the Cerro Prieto field is unequalled anywhere in the world and is already possessed or is readily available to the investigators. Hence, no costs for sample acquisition, equipment procurement, or personnel training are necessary for completing this project. Additionally, no problems involving proprietory information will be encountered.

The potential cost benefits of employing petrologic and geochemical studient of subsurface samples during the exploration and development of geothermal areas are great. The necessary samples automatically become available whenever a well is drilled, hence no sample acquisition costs are involved. The cost of drilling a deep geothermal well in the Imperial Valley is presently between 1-2 million dollars, hence any petrologic input to well-siting which results in avoiding the drilling of only one unproductive well can pay for itself many times over. Several cases where the most basic petrologic examination of geothermal well samples could have saved substantial drilling expenditures are known to the investigators. In a more positive vein, our work at Cerro Prieto has illustrated that petrologic studies can enhance the probability of siting productive wells (Elders, *et al.*, 1978b); as well as provide a good indication of subsurface temperatures encountered while actually drilling a well. We intend to use the information generated by this research to help categorize the various mineralogic techniques as a function of cost-effectiveness at three levels of sophistication:

I. Methods applicable at the drillsite;

II. Methods attainable by a field laboratory;

III. Methods obtainable by a well-equipped research laboratory.

REFERENCES CITED

Aagaard, P., & Helgeson, H. C., 1977, Thermodynamic and kinetic constraints on the dissolution of feldspars: Abstr. Progrm. Geol. Soc. Am. 9, 873.

Aagaard, P., and Helgeson, H.C., 1980, Thermodynamic and kinetic constraints on reaction rates among minerals and aqueous solutions. I. Theoretical considerations: Am. J. Sci., 280 (in press).

Anomymous, 1978, Proceedings: First symposium on the Cerro Prieto geothermal field, Baja California, Mexico, Sept. 20-22, 1978, San Diego, California: Lawrence Berkeley Laboratory rept. LBL-7098, 456 p.

Anomymous, 1978, Program and abstracts: Second symposium on the Cerro Prieto geothermal field, Baja California, Mexico, Oct. 17-19, 1979, Mexicali, Baja California, Mexico (in press).

Arnorrson, S., 1978, Major element chemistry of the geothermal sea-water at Reykjanes and Svartsegi, Iceland: Mineralogical Magazine, v. 42, p. 209-220.

Bailey, A., 1974, Effect of temperature on the reactions of silicates with aqueous solutions in the low temperature range. In Proc. Intl. Symp. Water-Rock Interaction, Prague, 375-80.

Barker, C. E., 1979, Vitrinite reflectance geothermometry in the Cerro Prieto geothermal field, Baja California, Mexico: M.S. thesis, University of California, Riverside, Institute of Geophysics and Planetary Physics (UCR/IGPP) rept. 79/10, 135 p.

Barker, C. E., and Elders, W. A., 1979, Vitrinite reflectance geothermometry in the Cerro Prieto geothermal field: Transactions, Geothermal Resouces Council, 3, p. 27-30.

Berner, R. A., 1978, Rate control of mineral dissolution under earth sciences conditions: Am. Jour. Sci., v. 278, p. 1235-1252.

Bird, D. K., and Elders, W. A., 1976, Hydrothermal alteration and mass transfer in the discharge portion of the Dunes geothermal system, Imperial Valley of California, U.S.A.: Proceedings of the Second United Nations Geothermal Symposium, San Francisco, May, 1975, 1, p. 285-295.

Bird, D. K., and Helgeson, H. C., 1977, Prediction of the chemical characteristics of geothermal reservoir fluids from authigenic mineral assemblages [abs.]: Geol. Soc. America Abs. with Programs, v. 9, p. 898-899.

Bird, D. K., and Helgeson, H. C., 1979, Chemical interaction of aqueous solutions with epidote-feldspar mineral assemblages in geologic systems. II. Equilibrium constraints in metamorphic/geothermal processes: Am. Jour. Sci., v. 279, in press.

Bird, D. K., and Helgeson, H. C., 1980, Chemical interaction of aqueous solutions with epidote-feldspar mineral assemblages in geologic systems. I. Thermodynamic analysis of phase relations in the system $CaO-FeO-Fe_2O_3-SiO_2-H_2O-CO_2$: Am. Jour. Sci., in press.

Bird, D. K., and Norton, D., 1979, Correlation of the spatial variations in the composition of geothermal reservoir fluids from petrochemical observations and thermodynamic calculations in the Salton Sea geothermal system [abs.]: Geol. Soc. America Abs. with Programs, v. 11, p. 388.

Bird, D. K., and Norton, D., 1980, Theoretical prediction of phase relations among aqueous solutions and minerals in the Salton Sea geothermal system: Geochimica et Cosmochimica Acta, in review.

Blander, M., 1970, The partitioning of cations between co-existing one-site-two-site phases: Geochim. et Cosmochim. Acta., v. 34, p. 515-518.

Browne, P. R. L., 1970, Hydrothermal alteration as an aid in investigating geothermal fields: Geothermics, Spec. Issue 2, p. 564-570.

Browne, P. R. L., 1978, Hydrothermal alteration in active geothermal fields: Ann. Rev. Earth Planet. Sci., 6, p. 229-250.

Browne, P. R. L., and Ellis, A. J., 1970, The Ohaki-Broadlands hydrothermal area, New Zealand: Mineralogy and related geochemistry: Am. Jour. Sci., 269, p. 97-131.

Clayton, R. N., Muffler, L. J. P., and White, D. E., 1968, Oxygen isotope study of calcite and silicates of the River Ranch No. 1 Well, Salton Sea geothermal fields, California: American Journal of Science, v. 266, p. 968-979.

Coplen, T. B., Koesar, P., Taylor, R. E., Kendall, C., Mooser, C., 1975, Investigation of the Dunes geothermal anomaly, Imperial Valley, California: Part IV. Geochemical studies of water, calcite, and silicates. IGPP/UCR Report No. 75-20 43 p.

Craig, H., 1961, Isotopic variations in meteoric waters: Science, v. 133, p. 1702-1703.

Craig, H., 1973. The isotopic geochemistry of water and carbon in geothermal areas; in Nuclear Geology in Geothermal Areas, Tonqiorgi, E., ed., Consiglio Nazional delle Richerche, Pisa, p. 17-53.

Elders, W. A., 1977a, Petrology as a practical tool in geothermal studies: Geothermal Resources Council, Transactions, 1, p. 143-145.

Elders, W. A., 1977b, Rock-water interaction and temperature distribution in the Salton Sea geothermal field, Imperial Valley, California, U.S.A. (abs.): Abs. with Programs, Geol. Soc. America, 9, p. 965.

Elders, W. A., Olson, E., Hoagland, J. R., Barker, C., Johnson, P., and Collier, P., 1977, A comprehensive study of samples from geothermal reservoirs: Petrology and light stable isotope geochemistry of wells M48, M84, M90, M91 and Prian No. 1: Final report to the Dept. of Energy/Lawrence Berkeley Laboratory, UCR/IGPP rept. 77/37, 153 p.

Elders, W. A., Hoagland, J. R., McDowell, D., and Cobo, J. M., 1978a, Hydrothermal mineral zones in the geothermal reservoir of Cerro Prieto, B.C., Mexico: Proceedings of the First symposium on the Cerro Prieto geothermal field, Baja California, Mexico; Lawrence Berkeley Laboratory, rept. LBL-7098, p. 68-75.

Elders, W. A., Hoagland, J. R., and Olson, E., 1978b, Hydrothermal mineralogy and isotopic geochemistry in the Cerro Prieto geothermal field, Mexico. III. Practical applications: Geothermal Resources Council, Transactions, 2, p. 177-180.

Elders, W. A., Hoagland, J. R., Olson, E. R., McDowell, S. D., and Collier, P., 1978c, A comprehensive study of samples from geothermal reservoirs: Petrology and light stable isotope geochemistry of twenty-three wells in the Cerro Prieto geothermal field, Baja California, Mexico: UCR/IGPP rept. 78/26, 264 p.

Elders, W. A., Hoagland, J. H., Valette, J. N., Williams, A. E., Barker, C. E., and Collier, P., 1980a, Comprehensive study of samples from geothermal reservoirs: Petrology and geochemistry of surface and subsurface samples in the Cerro Prieto geothermal field, Baja California, Mexico, (in preparation).

Elders, W. A., Hoagland, J. H., Valette, J. N., Williams, A. E., Barker, C. E., and Collier, P., 1980b, Hydrothermal alteration as an indicator of temperture and flow regime in the Cerro Prieto geothermal field of Baja California: Geothermal Resources Council, Transactions, 3, in press.

Ellis, A. J., and Mahon, W. A. J., 1977, Chemistry and Geothermal Systems: Acadmic Press, 392 p.

Flowers, G. C., 1979, Correction of Holloway's (1977) adaptation of the modified Redlich-Kwong equation of state to calculation of the fugacities of molecular species in supercritical fluids of geologic interest: Contr. Mineralogy Petrology, in press.

Fournier, R. O., 1979, A revised equation for the Na/K Geothermometer: Geothermal Resourcs Council, Transactions, v. 3., p. 221-224.

Fournier, R. O. and Potter, R. W., 1979, Magnesium correction to the Na-K-Ca geothermometer: Geochim. et Cosmochim. Acta, v. 43, no. 9, p. 1543-1550.

Fournier, R. O., and Truesdell, A. H., 1973, An empirical Na-K-Ca geothermometer for natural waters: Geochim. et Cosmochim. Acta., v. 10, p. 27-59.

Freckman, J., 1978, A fluid inclusion study of Sinclair #4 and Elmore #1 boreholes, Salton Sea geothermal field, Imperial Valley, California, U.S.A.: M.S. thesis, UCR/IGPP rept. 78-5, 76 p.

Friedman, I., and O'Neil, J. R., 1977, Compilation of stable isotope fractionation factors of geochemical interest: in, Data of Geochemistry, U.S. Geologic. Survey Prof. Paper, 440-KK.

Grover, J. E., and Orville, P. M., 1969, The partitioning of atoms between coexisting single- and multi-site phases with application to the assemblages: orthopyroxene-clinopyroxene and orthopyroxene-olivine: Geochim. et Cosmochim. Acta., v. 33, p. 205-226.

Hayashi, M. and Yamasaki, T., 1974, Hydrothermal alteration of pyroxene andesites in the Otake geothermal area, Japan, in Cadek, J. and Paces, T., eds., Proceedings International Symposium on water-rock interaction: Geological Survey, Prague, p. 158-169.

Helgeson, H. C., 1967, in, Abelson, P. H., ed., Researches in Geochemistry, v. 2: New York, Wiley, p. 362-404.

Helgeson, H. C., 1968, Geologic and thermodynamic characteristics of the Salton Sea geothermal system: Am. Jour. Sci., v. 266, p. 129-166.

Helgeson, H. C., 1969, Thermodynamics of hydrothermal systems at elevated temperatures and pressures: Am. Jour. Sci., v. 267, p. 729-804.

Helgeson, H. C., 1979, A retroactive clock for geochemical processes: GSA Abstracts with Programs v. 7, no. 11, p. 442.

Helgeson, H. C., 1980, Prediction of the thermodynamic properties of electrolytes at high pressures and temperatures, in, Wickman, F., and Rickard, D., eds., Chemistry and Geochemistry of Solutions at High Temperatures and Pressures: Royal Swedish Academy of Sciences, Stockholm, in press.

Helgeson, H. C., and Aagaard, P., 1980, Activity/composition relations among silicates and aqueous solutions. I. Chemical and thermodynamic consequences of preferential site occupancy in montmorillonites, illites, and mixed layer clays: Am. Jour. Sci., v. 279, in press.

Helgeson, H. C., Delany, J. M., Nesbitt, H. W., and Bird, D. K., 1978, Summary and critique of the thermodynamic properties of rock-forming minerals: Am. Jour. Sci., v. 278-A, 229 p.

Helgeson, H. C., and Kirkham, D. H., 1974a, Theoretical prediction of the thermodynamic behavior of aqueous electrolytes at high pressures and temperatures. I. Summary of the thermodynamic/electrostatic properties of the solvent: Am. Jour. Sci., v. 274, p. 1089-1198.

Helgeson, H. C., and Kirkham, D. H., 1974b, Theoretical prediction of the thermodynamic behavior of aqueous electrolytes at high pressures and temperatures. II. Debye-Huckel parameters for activity coefficients and relative partial molal properties: Am. Jour. Sci., v. 274, p. 1199-1261.

Helgeson, H. C., and Kirkham, D. H., 1976, Theoretical prediction of the thermodynamic behavior of aqueous electrolytes at high pressures and temperatures. III. Equation of state for aqueous species at infinite dilution: Am. Jour. Sci., v. 276, p. 97-240.

Helgeson, H. C., Kirkham, D. H., and Flowers, G. C., 1980, Theoretical prediction of the thermodynamic behavior of aqueous electrolytes at high pressures and temperatures. IV. Calculation of activity coefficients, osmotic coefficients, and apparent molal and standard and relative partial molal properties to 5 kb and 600°C: Am. Jour. Sci., in preparation.

Hoagland, J. R., and Elders, W. A., 1977, The evolution of the East Mesa hydrothermal system, California, U.S.A.: Proceedings of the 2nd Inter. Symp. on Water/Rock Interaction, Strasbourg, France, III, p. 127-136.

Hoagland, J. R., and Elders, W. A., 1978, Hydrothermal mineralogy and isotopic geochemistry in the Cerro Prieto geothermal field, Mexico, I. Hydrothermal mineral zonation: Geothermal Resources Council Transactions, 2, p. 283-286.

Hoagland, J. R., and McDowell, D., 1978, Metamorphic zonation in the Cerro Prieto geothermal reservoir, Baja California, Mexico [abs.]: Abs. with Programs, Geol. Soc. America, 10, p. 422.

Kendall, C., 1976, Petrology and stable isotope geochemistry of three wells in the Buttes area of the Salton Sea geothermal field, Imperial Valley, California, U.S.A.: M.S. thesis, UCR/IGPP rept. 76/17, 227 p.

Kerrick, D. M., and Darken, L. S., 1975, Statistical thermodynamic models for ideal oxide and silicate solid solutions, with application to plagioclase: Geochim. et Cosmochim. Acta., v. 39, 1431-1442.

Kristmannsdottir, H., 1976, Hydrothermal alteration of basaltic rocks in Icelandic geothermal areas: Proceedings, Second United Nations symposium on the development and use of geothermal resources, San Francisco, May, 1975, _1_, p. 441-445.

Lagache, M., 1965, Contribution a l'etude de l'alteration des feldspaths, dans l'eau, entre 100 et 200°C, sous diverses pressions de CO_2, et application a la synthese des mineraux argileux: Bull. Soc. Fr. Mineral. Crist. v. 88, p. 223-253.

Lagache, M., 1976, New data on the kinetics of the dissolution of alkali feldspars at 200°C in CO_2 charged water: Geochim. Cosmochim. Acta. v. 40, p. 157-161.

Mahon, W. A. J., 1962, A chemical survey of the steam and water discharged from the drillholes and hotsprings at Kawerau: N.Z. Jour. Sci., v. 5, p. 417-433.

Mahon, W. A. J., 1966, Silica in hot water discharged from drillholes at Wairakei, New Zealand: N.Z. Jour. Sci., v. 9, p. 135-144.

Mahon, W. A. J., and Finlayson, J. B., 1972, The chemistry of the Broadlands geothermal area, New Zealand: Am. Jour. Sci., v. 272, p. 48-68.

Matsui, U., and Banno, S., 1965, Intracrystalline exchange equilibrium in silicate solid solutions: Japanese Acad. Proc., v. 41, p. 461-466.

McDowell, D., and Elders, W. A., 1978, Distribution and chemistry of layer-silicate minerals in the Salton Sea geothermal field, California [abs.]: Geol. Soc. America Abs. with Programs, v. 3, p. 452.

McDowell, D., and Elders, W. A., 1980, Layer silicate minerals in borehole Elmore #1, Salton Sea geothermal field, California, U.S.A.: Contr. Mineralogy Petrology, in press.

McDowell, D., and McCurry, M., 1977, Active metamorphism in the Salton Sea geothermal field, California: mineralogical and mineral changes with depth and temperature in sandstone [abs.]: Geol. Soc. America Abs. with Programs, v. 9, p. 1088.

McDowell, D., and McCurry, M., 1978, Mineralogical variations in borehole Elmore #1, Salton Sea geothermal area: preliminary report: Report no. UCR/IGPP 78/11, 37 p.

Mercado, G. S., 1976, Movement of geothermal fluids and temperature distribution in the Cerro Prieto geothermal field, Baja California, Mexico: 2nd. U.N. Symposium on the Development and Use of Geothermal Resources, 1, 492-494.

Mueller, R. F., 1962, Energetics of certain silicate solid solutions: Geochim. et Cosmochim. Acta., v. 26, p. 581-598.

Muffler, L. J. P., and White, D. E., 1969, Active metamorphism of Upper Cenozoic sediments in the Salton Sea geothermal field and the Salton Trough, southeastern California: Geol. Soc. America Bull., 80, p. 157-182.

Nehring, N. L., and Fausto, J. J., 1978, Gases in steam from Cerro Prieto geothermal wells: Proceedings, First symposium on the Cerro Prieto geothermal field, Baja California, Mexico: Lawrence Berkeley Laboratory rept: LBL-7098, p. 127-129.

Norton, D., 1978, Sourcelines, sourceregions, and pathlines for fluids in hydrothermal systems related to cooling plutons: Econ Geology, v. 72, p. 21-28.

Norton, D., 1979, Transport phenomena in hydrotheermal systems: the redistribution of chemical components around cooling magmas: Bull. Mineral., v. 102, 471-486.

Norton, D., 1980, Transport processes related to copper-bearing porphyritic plutons. Fluid and heat transport in pluton environments typical for the southeastern Arizona porphyry copper province, in Titley, S. R., ed., Geology of the Porphyry Copper Deposits: Tucson, Univ. Ariz. Press, in press.

Norton, D., and Knapp, R., 1977, Transport phenomena in hydrothermal systems. Nature of porosity: Am. Jour. Sci., v. 277, p. 913-936.

Norton, D., and Knight, J. E., 1977, Transport phenomena in hydrothermal systems. Cooling plutons: Am. Jour. Sci., v. 277, p. 937-981.

Norton, D., and Taylor, H. P., 1979, Quantitative simulation of the hydrothermal systems of crystallizing magmas on the basis of transport theory and oxygen isotope data: an analysis of the Skaergaard intrusion: Jour. of Petrology, v. 20, pt. 3, p. 421-486.

Olson, E. R., 1979, Oxygen and carbon isotope studies of calcite from the Cerro Prieto geothermal field, Baja California, Mexico: Proceedings of the First Symposium on the Cerro Prieto geothrmal field, Baja California, Mexico: Lawrence Berkeley Laboratory rept. LBL-7098, p. 119-123.

Paces, T., 1973, Steady-state kinetics and equilibrium between ground water and granitic rock: Geochim. Gosmochim. Acta, v. 37, p. 2641-2663.

Petrovic, R., 1976, Rate control in feldspar dissolution. II. The protective effect of precipitates: Geochim. et Cosmochim. Acta, v. 40, p. 1509-1522.

Petrovic, R., Bernor, R. A., and Goldhaber, M. B., 1976, Rate control in dissolution of alkali feldspars. I. Study of residual feldspar grains by X-ray photoelectron spectroscopy: Geochim. et Cosmochim. Acta, v. 40, p. 537-548.

Powell, R., 1977, Activity-composition relationships for crystalline solutions, in, Fraser, D., ed., Thermodynamics in Geology: Netherlands, Reidel Pub. Co., p. 57-65.

Reed, M. J., 1976, Geology and hydrothermal metamorphism in the Cerro Prieto geothermal field, Mexico: in, Proceedings Second United Nations Symposium on the Development and Use of Geothermal Resources, v. 1, p. 539-547.

Saxena, S. K., 1969, Silicate solid solution geothermometry. I. Use of the regular solution model: Contr. Mineralogy Petrology, v. 21, p. 338-345.

Saxena, S. K., 1973, Thermodynamics of Rock-forming Crystalline Solutions: New York, Springer-Verlag, 190 p.

Taylor, H. P., Jr., 1974, The application of oxygen and hydrogen isotope studies to problems of hydrothermal alteration and ore depositon: Economic Geology, v. 69, p. 843-883.

Taylor, H. P., Jr., 1979, Oxygen and hydrogen isotope relationships in hydrothermal mineral deposits: in, Barnes, H. L., ed., Geochemistry of Hydrothermal Ore Deposits: John Wiley and Sons, New York.

Taylor, H. P., Jr., and Forester, R. W.. 1979, An oxygen and hydrogen isotope study of the Skaergaard intrusion and its country rocks: A description of a 55-m.y. old fossil hydrothermal system: Journal of Petrology, v. 20, p. 355-419.

Thompson, J. B., Jr., 1967, Thermodynamic properties of simple solutions, in, Abelson, P. H., ed., Researches in Geochemistry, v. II: New York, John Wiley & Sons, p. 340-361.

Thompson, J. B., Jr., 1969, Chemical reactions in crystals: Am. Mineralogist, v. 54, p. 341-375.

Truesdell, A. H., 1976, Chemical evidence of subsurface structure and fluid flow in geothermal systems: Proceedings: First International Symposium on Water/Rock Interaction, Prague, p. 250-257.

Truesdell, A. H., Rye, R. O., Rearson, F. J., Jr., Olson, E. R., Nehring, N. L., Huebner, M. A., and Coplen, T. B., 1979, Preliminary isotopic studies of fluids from the Cerro Prieto geothermal field: Proceedings, First symposium on the Cerro Prieto geothermal field, Baja California, Mexico: Lawrence Berkeley Laboratory rept. LBL-7098, p. 95-99.

Vakin, E. A., Polak, B. G., Sugrobov, V. M., Elikh, E. N., Belousov, V. I., and Pilipenko, G. F., 1970, Recent hydrothermal systems of Kamchatka: Proceedings of the United Nations Symposium on the Development and Utilization of Geothermal Resources: Geothermics Special Issue 2, v. 2, pt. 2, p. 1116-1133.

Vonder Haar, S., and Puente, I., 1979, Fault intersections and hybrid transform faults in the southern Salton Trough geothermal area, Baja California, Mexico: Transactions, Geothermal Resources Council, 3, p. 761-764.

Walther, J. V., and Helgeson, H. C., 1977, Calculation of the thermodynamic properties of aqueous silica and the solubility of quartz and its polymorphs at high pressures and temperatures: Am. Jour. Sci., v. 277, p. 1315-1351.

Wilson, S. H., 1963, Chemical investigations at Waiotapu: New Zealand Department of Scientific and Industrial Research, Bulletin 55, p. 87-118.

MANAGEMENT

ORGANIZATION AND MANAGEMENT PLAN

Grantee Organization

The grantee organization is the Regents of the University of California, Institute of Geophysics and Planetary Physics, University of California, Riverside California 92521, U.S.A. (telephone number (714) 787-4500).

Coordination and Management

W. A. Elders is the principal investigator and coordinator of the project. He currently holds an appointment which is 50% as Research Geologist in the Institute and 50% as Professor of Geology in the Department of Earth Sciences. He will coordinate the various laboratory activities and have primary responsiblity for synthesis and interpretation of the results produced. He will contribute approximately 20% of his time to the project during the nine month academic year with salary contributed by the University of California. During the summer months he will contribute 33% of his time to this project with salary paid by the contract. His vita is attached.

D. K. Bird will manage the research operations at the University of Arizona and will devote 38% of his time to this project. Bird is employed by the University of Arizona under funding for extramural grants and contracts. His salary and the research expenses incurred by this project at the University of Arizona will be defrayed by this contract under a subcontract to UA. His vita is attached.

Other staff

The other staff are employed by IGPP under extramural grants and contracts. They include:

1. A. E. Williams, Assistant Research Geologist. Williams will have primary responsibility for procuring the stable isotope data and will devote 33% of his time to the project (vita attached).
2. J. R. Hoagland, Staff Research Associate III. Hoagland will have primary responsiblity for procuring mineral assemblage and phase chemistry data. He will devote approximately 40% of this time to the project (vita attached.)
3. One graduate student Research Assistant (33%), two part-time secretaries (total 17%), and a part-time draftsperson (8%).

Suggested Timetable

Our envisioned timetable for completion of various aspects of this project is depicted in Figure 1. The project essentially involves three phases.

Phase I (January 1981-July 1981): Acquisition of petrologic and stable isotope data.

1. January - compilation of existing data, selection of samples, initiate analyses.
2. February-May - perform analyses.
3. June-July - define water/rock ratios through reservoir and mineral compositional trends, establish boundary conditions for thermochemical and mass transfer calculations.

Phase II (May-October 1981): Thermochemical and mass transfer modeling.

1. May-June - initialize program conditions, perform any necessary software modifications, interface UA and UCR operations and acquire petrologic and geothermal data.

2. July-October - develop thermochemical and mass transfer models using data generated at UCR.

Phase III (October-December 1981): Synthesize and interpret data and models, develop practical applications, write final report.

Suggested Reporting Requirements

We propose to keep DOE fully informed of our activities by short technical quarterly reports and comprehensive annual reports of our research data and findings.

Personnel Vitae

WILFRED A. ELDERS

Research Geologist/Professor of Geology
Institute of Geophysics and Planetary Physics/
Department of Earth Sciences
University of California
Riverside, California 92521
(714) 787-3439

Born: March 25, 1933

Citizenship: British

Education: B.Sc., First class honors in geology, King's College, University of Durham (now called University of Newcastle-upon-Tyne), England, 1957.
Graduate studies, Norwegian State Stipendiat, University of Oslo, Norway, 1957-1959.
Ph.D., Geology, King's College, University of Durham, England, 1961.

Professional Positions:

1973-present	Professor of Geology and Research Geologist, University of California, Riverside, California.
1969-1973	Associate Professor of Geology, University of California, Riverside, California.
1968-1969	Associate Professor of Geology, University of Illinois.
1962-1968	Assistant Professor of Geology, University of Chicago.
1961-1962	Instructor in Geology, University of Chicago.
1959-1961	Demonstrater in Petrology, King's College, Newcastle-upon-Tyne.

Research Interests: Petrology of hydrothermal systems and the integration of geochemical, geophysical and geological components of a geothermal research program. Tectonics of the Salton Trough.

Recent Experience: He returned to UCR in September, 1976, after spending the 1975-1976 academic year on sabbatical leave working with the New Zealand Government's geothermal research program. This involved comparisons of hydrothermal alteration in the Broadlands and Kawerau geothermal fields in New Zealand. Since 1977 he has directed a research program on water-rock reaction in the Cerro Prieto Geothermal Field, Mexico.

Memberships: Geological Society of America, Geological Society of London, Mineralogical Society of America, Mineralogical Society of Great Britain, Norsk Geologisk Föreningen, American Geophysical Union, American Association for the Advancement of Science, National Association of Geology Teachers.

Bibliography

W. A. Elders

Articles Published in Reviewed Professional Journals and Conference Proceedings

Elders, W. A., 1957. "A preliminary note on a xenolith-rich dyke from Lyngen, Arctic Norway." Acta Borealia A. Scientia, No. 12, p. 1-13.

______, 1963. "The form and mode of emplacement of the Herefoss granite." Norges Geol. Undersøk. No. 214, p. 1-58.

______, 1967. "Phase change experiments for introductory courses." Journ. Geol. Education, 15, 5, p. 485-487.

______, 1968. "Mantled feldspars from the granites of Wisconsin." Journ. Geol. 76, p. 37-49.

Elders, W. A. and Rucklidge, J. C., 1969. "Rheomorphism of granite by gabbro intrusions on the coast of South-central Labrador." Journ. Geol., 77, p. 240-244.

Grasty, R. L., Rucklidge, J. C. and Elders, W. A., 1969. "New K-Ar age determinations on rocks from the east coast of Labrador." Canadian Journ. Earth Sci., 6, p. 340-344.

Elders, W. A. and Rucklidge, J. C., 1969. "Layering and net veining in hornblende lamprophyre intrusions from the coast of Labrador." Journ. Geol. 77, p. 721-729.

Elders, W. A., Rex, R. W., Meidav, T., Robinson, P. T., and Biehler, S., 1972. "Crustal spreading in southern California. The Imperial Valley and the Gulf of California formed by rifting apart of a continental plate." Science, 178, no. 4056, p. 15-24.

Elders, W. A., 1972. "Instruct", a geological game. Journ. of Geological Education, XX No. 6, p. 287-291.

Elders, W. A. and Biehler, S., 1975. "Gulf of California rift system and its implications for the tectonics of Western North America." Penrose Conference Report, Geology 3, No. 2, p. 85-87.

Robinson, P. T., Elders, W. A., and Muffler, L. J. P., 1976. "Quaternary volcanism in the Salton Sea geothermal Field, Imperial Valley, California." Geological Society of America Bulletin, 87, p. 347-360.

Elders, W. A. and Bird, D. K., 1976. "Active formation of silicified cap rocks in arenaceous sands in a low-temperature, near-surface geothermal environment in the Salton Trough of California, U.S.A." Proceedings of the International Symposium on Water Rock Interaction of the International Association of Geochemistry and Cosmochemistry, Geol. Survey, Prague, 1974, p. 150-158.

Published Articles (Continued)

Bird, D. K. and Elders, W. A., 1976. "Hydrothermal alteration and mass transfer in the discharge portion of the Dunes Geothermal System, Imperial Valley of California, U.S.A." Proceedings of the Second United Nations Conference on the Development and Use of Geothermal Resources, San Francisco, May 1975. Volume I, p. 285-295.

Hoagland, J. R. and W. A. Elders, 1977. "The evolution of the East Mesa hydrothermal system, California, U.S.A." Proceedings of the Second International Symposium on Water Rock Reaction, Strasbourg, France, International Association of Geochemistry and Cosmochemistry, Univ. Louis Pasteur, H. Paquet and Y. Tardy (editors), Section III, p. 127-136.

Elders, W. A., 1977. "Petrology as a practical tool in geothermal studies", Geothermal Resources Council, Transactions, 1, p. 85-87.

Hoagland, J. R. and W. A. Elders, 1978. "Hydrothermal mineralogy and isotopic geochemistry in the Cerro Prieto geothermal field, Mexico. I. Hydrothermal mineral zonation." Geothermal Resources Council Transactions, 2, p. 283-286.

Olson, E. R. and W. A. Elders, 1978. "Hydrothermal mineralogy and isotopic geochemistry in the Cerro Prieto geothermal field, Mexico. II. Isotopic geochemistry." Geothermal Resources Council Transactions, 2, p. 513-516.

Elders, W. A., J. R. Hoagland and E. R. Olson, 1978. "Hydrothermal mineralogy and isotopic geochemistry in the Cerro Prieto geothermal field, Mexico. III. Practical applications." Geothermal Resources Council Transactions, 2, p. 177-180.

Elders, W. A., J. R. Hoagland, S. D. McDowell and J. M. Cobo, 1979, "Hydrothermal mineral zones in the geothermal reservoir of Cerro Prieto, B.C., Mexico." Geothermics, 8, No. 3, 9 p.

Barker, C. E. and W. A. Elders, 1979. "Vitrinite reflectance geothermometry in the Cerro Prieto geothermal field, Baja California, Mexico." Geothermal Resources Council Transactions, 3, p. 27-31.

McDowell, D., and Elders, W. A., 1979. "Layer silicate minerals in borehole Elmore #1, Salton Sea geothermal field, California, U.S.A." Contr. Mineralogy and Petrology, in press.

Elders, W. A., J. R. Hoagland and A. E. Williams, 1980, Hydrothermal alteration as an indicator of temperature and flow regime in the Cerro Prieto geothermal field of Baja California (in press), Geothermal Resources Council, 3.

Barker, C. E. and W. A. Elders, 1980, Vitrinite reflectance in the Cerro Prieto Geothermal Field: an interim report (in press), Proceedings of the Second Symposium on the Cerro Prieto Field, Baja California, Mexico, 11 p.

Published Technical Articles

Elders, W. A., 1958. "Geology of Lyngen Peninsula, Northern Norway." Expedition reports published by Durham University, Exploration Society Newcastle-upon-Tyne, p. 1-58.

______, 1960. "Banded gneisses at Rognstrand." Appendix (p. 23-26) to Pre-Cambrian genisses and granites of the Skaggerakk coastal area, South Norway. Guide to Excursion A8 of Internat. Geol. Cong. 1960.

______, 1966. "Earth", Britannica Junior Encyclopedia, *5*, p. 206-212B.

______, 1966. "Earthquake", *ibid*, *5*, p. 212B-212F.

______, 1966. "Basalt", *ibid*, *3*, p. 80.

______, 1966. "Glacial Period", *ibid*, *6*, p. 351-355.

______, 1966. "Lava", *ibid*, *9*, p. 83-85.

______, 1966. "Volcano", *ibid*, *14*, p. 362-362B.

______, 1966. "Rock", *ibid*, *13*, p. 119-120A.

Elders, W. A. and Nitecki, M., 1966. "Fossil", *ibid*, *6*, p. 167-171.

Elders, W. A. and DeMar, R., 1966. "Geology", *ibid*, *6*, p. 289-303.

Elders, W. A., 1968. "Recent advances in Geology, Geochemistry and Geophysics". 1969 Britannica Yearbook of Science and the Future, Encyclopedia Britannica Inc., Chicago, p. 321-333.

Elders, W. A. (editor), 1971. "Geological Excursions in Southern California". Riverside Campus Museum Contributions No. 1, pp. iv + 181.

Rex, R. W., Babcock, E. A., Biehler, S., Combs, J., Coplen, T. B., Elders, W. A., Furgerson, R. B., Garfunkel, Z., Meidav, T., and Robinson, P. T., 1971. "Cooperative Geological-Geophysical-Geochemical Investigations of Geothermal Resources in the Imperial Valley area of California." Report to the U.S. Bureau of Reclamation, p. 1-153.

Elders, W. A., 1972. "Geology", Encyclopedia Britannica Yearbook 1971, p. 327-328.

Elders, W. A., 1972. "Earth Sciences", The 1972 Compton Yearbook, p. 218-221.

Elders, W. A., 1973. "Geology", Encyclopedia Britannica, 1973 Book of the Year, p. 324-326.

Elders, W. A., 1973. "Petrology of the Cores", *in* Coplen, *et al*., 1973, Preliminary Findings of an Investigation of the Dunes Thermal Anomaly, Imperial Valley, California. A joint study by the State of California, Department of Water Resources and the Institute of Geophysics and Planetary Physics, UCR. IGPP-UCR 73-7, p. 21-30.

Published Technical Articles (continued)

Elders, W. A. (editor) 1973. "Geological Investigations of the San Jacinto Fault Zone, and Aspects of the Socio-Economic Impact of Earthquakes in the Riverside-San Bernardino Area, California". University of California, Riverside, Campus Museum Contributions, No. 3, 120 p.

Elders, W. A., 1974. "Seismic Safety and Public Policy". Cry California, p. 20-25, 9, No. 2.

Elders, W. A., Combs, J., Coplen, T. B., Kolesar, P., and Bird, D. K., 1974. "Geophysical, Geochemical and Geological Investigations of the Dunes Geothermal System, Imperial Valley, California", in Proceedings of the Conference on Research for the Development of Geothermal Energy Resources, Jet Propulsion Laboratory/California Institute of Technology, September 1974, NSF-RANN 74-159, p. 45-72.

Elders, W. A., 1975. "Regional Geology of the Salton Trough" in T. D. Palmer, J. H. Howard and D. P. Lande (editors) Geothermal development of the Salton Trough, California and Mexico Guidebook for the 2nd U.N. Symposium on Geothermal Resources, May 1975. Lawrence Livermore Laboratory Publication UCRL 4-17-75, p. 1-12 and 41-43.

Johnson, P. D., Elders, W. A., Strubble, L., and Collier, P., 1977. "A Quantitative Automated X-ray Diffraction Mineral Characterization System for Use in the Study of Natural Hydrothermal Systems". University of California, Riverside, UCR/IGPP rept. 77/25, 34 p.

Elders, W. A., Olson, E. R., Hoagland, J. R., Barker, C. E., Johnson, P. D., and Collier, P., 1977. "A Comprehensive Study of Samples from Geothermal Reservoirs: Petrology and Light Stable Isotope Geochemistry of Wells M48, M84, M90, M91, M92 and Prian No. 1". IGPP Report UCR 77-37, 153 p.

Elders, W. A., 1977. "Petrological Studies of Geothermal Systems". Proceedings of La Primera Reunión de Intercambio Téchnico sobre Geotermia, San Felipe, B.C. México, Nov. 1977.

Elders, W. A., Hoagland, J. R., Olson, E. R., McDowell, S. D., and Collier, P., 1978. "A Comprehensive Study of Samples from Geothermal Reservoirs: Petrology and Light Stable Isotope Geochemistry of twenth-three wells in the Cerro Prieto Geothermal Field, Baja California, Mexico". IGPP Report UCR 78-26, Final Report to the DOE to Lawrence Berkeley Laboratory.

Elders, W. A. (editor), 1979. "Guidebook: Geology and Geothermics of the Salton Trough". UCR Campus Museum Contribution No. 5, 109 p., Prepared for the Geological Society of America 92nd Annual Meeting, San Diego, California, November 1979.

Elders, W. A., 1979. "The Geological Background of the Geothermal Fields of the Salton Trough" in Elders, W. A. (editor) Guidebook: Geology and Geothermics of the Salton Trough. Prepared for the Geological Society of America 92nd Annual Meeting, San Diego, California, November 1979.

Published Technical Articles (continued)

McDowell, D. and Elders, W. A., 1979. "Geothermal Metamorphism of Sandstone in the Salton Sea Geothermal System" in Elders, W. A. (editor) Guidebook: Geology and Geothermics of the Salton Trough. Prepared for the Geological Society of America 92nd Annual Meeting, San Diego, California, November 1979.

Elders, W. A., Hoagland, J. R., Valette, J. N., Williams, A. E., Barker, C. E., and Collier, P., 1979. "A Comprehensive Study of Samples from Geothermal Reservoirs; Petrology and Geochemistry of Subsurface and Surface Samples from the Cerro Prieto Geothermal Field, Baja California, Mexico." IGPP Report 79/27, Final Report to the DOE to Lawrence Berkeley Laboratory.

Miller, K. R., and Elders, W. A., 1980. "Geology, Hydrothermal Petrology, Stable Isotope Geochemistry and Fluid Inclusion Geothermometry of LASL Geothermal Test Well C/T-1 (Mesa 31-1), East Mesa, Imperial Valley, California, U.S.A." Final Report to Los Alamos Scientific Laboratory.

Published Book Reviews

Elders, W. A., 1965. Review of "Principles of Physical Geology", by A. Holmes, Journ. Geol., 73, No. 6, p. 908-910.

______, 1968. Review of "Selected Works: Granites and Migmatites", by J. J. Sederholm, Journ. Geol., 76, p. 612.

______, 1974. Review of "Experimental Petrology", by A. D. Edgar, American Mineralogist, 59, No. 7, p. 878.

Published Abstracts of Papers Presented at Scientific Meetings

Elders, W. A., 1963. "High-level faulting in the PreCambrian basement rocks of Southern Norway", Geol. Soc. of America, 74, p. 172.

______, 1964. "Tectonically induced features resembling sedimentary structures in banded genisses of Southern Norway", Geol. Soc. of America, 75, p. 195.

______, 1966. "Mantled feldspars and xenoliths in some Maine granites", Geol. Soc. of America, Program 79th Annual Meeting, p. 61.

Elders, W. A. and T. I. Poe, 1966. "Mantled feldspars from the granites of Wisconsin", Geol. Soc. Australia, Specialists Meeting, August 1966.

Elders, W. A., 1967. "Experimental hybridization and rapakivi texture", Geol. Soc. America, Special Paper, 115, p. 56.

Elders, W. A. and J. C. Rucklidge, 1968. "Layered lamprophyres from Labrador", Geol. Soc. America, Program 81st Annual Meeting, p. 88.

Elders, W. A., 1969. "Zoned alkali feldspars from the Lincoln Sill syenite, Maine", (Discussion paper) Geol. Soc. America, Abstracts with Programs for 1969, Part 7, p. 271-273.

Elders, W. A., T. Meidav, R. W. Rex, P. T. Robinson, 1970. "The Imperial Valley of California: The product of oceanic spreading centers acting on a continent", Geol. Soc. America, 2, No. 7, p. 545.

Robinson, P. T. and W. A. Elders, 1970. "Possible sea-floor spreading in the Imperial Valley of California III: Xenoliths in Rhyolite Volcanoes as Samples of the Basement", American Geophysical Union Annual Meeting, EOS, p. 421.

Robinson, P. T. and Elders, W. A., 1970. "Possible sea-floor spreading in the Imperial Valley of California IV: A model for magma generation", American Geophysical Union Annual Meeting, EOS, p. 422.

Elders, W. A., R. W. Rex, T. Meidav, P. T. Robinson, and S. Biehler, 1971. "A Plate Tectonic Model for the Salton Trough", Geol. Soc. America, Abstracts with Programs, 3, No. 2, p. 116.

Robinson, P. T. and W. A. Elders, 1971. "Late Cenozoic Volcanism in the Imperial Valley, California", Geol. Soc. America, Abstracts with Programs, 3, No. 2, p. 185.

Elders, W. A., 1972. "Instruct" A New Geological Game, Geol. Soc. of America, Abstracts with Programs, 4, No. 3, p. 154.

______, 1972. "Mantled Feldspars in Hybrid Rocks", NATO Advanced Study Institute of Feldspars, Manchester, England, Programme and Abstracts, p. 22.

Published Abstracts of Papers Presented at Scientific Meetings (continued)

Elders, W. A., 1972. "Oscillatory zoning in alkali feldspars from the Lincoln Sill, Maine, USA", ibid, p. 27.

Elders, W. A. and D. Bird, 1973. "Active Low-Temperature Alteration of Arenaceous Sands in a Near-Surface Geothermal Environment in the Imperial Valley of California". Geol. Soc. America Abstracts with Programs, 5, No. 7, p. 610.

Bird, D. and W. A. Elders, 1973. "Petrology of Silicified Cap Rocks in the Dunes Geothermal Anomaly, Imperial Valley of California". Transactions of American Geophysical Union, II, No. 11, p. 1215.

Sydnor, R. and W. A. Elders, 1974. "Intermingling of Acid-Basid Magmas in Minor Intrusives of the San Jacinto Pluton, in the Southern California Batholith". Geol. Soc. Amer. Abstracts with Programs, 6, No. 3, p. 265, Cordilleran Section, Las Vegas, Nevada.

Bird, D. and W. A. Elders, 1975. "Hydrothermal Alteration and Mass Transfer in the Discharge Portion of the Dunes Geothermal System Imperial Valley, California". Second United Nations Symposium on the Development and Use of Geothermal Resources, San Francisco, May 1975, Abstract 11-2.

Elders, W. A., 1976. "Application of Petrology to the Investigation of Geothermal Reservoirs in California and New Zealand". International Conference on the Geothermal Reservoir, Rotorua, New Zealand, August, 1976.

Browne, P. R. L. and W. A. Elders, 1976. "Hydrothermal Alteration of Diabase, Heber Geothermal Field, Imperial Valley, California". Geol. Soc. Amer. Abstracts with Programs, 8, No. 6, p. 793.

Elders, W. A., 1977. "The Geological Setting of the Geothermal Resources of the Salton Trough of California and Mexico". Heliosciences Institute, Palm Springs (invited paper).

______, 1977. "Physical Effects of Water/Rock Reactions in Evolving Geothermal Systems". Joint Symposium of the International Association of Seismology and Physics of the Earth's Interior and the International Association of Volcanology and Chemistry of the Earth's Interios, Assembly, Durham, England.

______, 1977. "Rock-Water Interaction and Temperature Distribution in the Salton Sea Geothermal Field, Imperial Valley, California, U.S.A." Geol. Soc. Amer. Abstracts with Programs, 9, No. 7, p. 965.

McDowell, C. and W. A. Elders, 1978. "Distribution and Chemistry of Layer-Silicate Minerals in the Salton Sea Geothermal Field, California". Geol. Soc. Amer. Abstracts with Programs, 10, No. 7, p. 452.

Elders, W. A. and J. R. Hoagland, 1979. "Studies of Water-Rock Interaction in the Cerro Prieto Geothermal Field, Baja California, Mexico". Program and abstracts: Second Symposium on the Cerro Prieto Geothermal Field, Baja California, Mexico, p. 18.

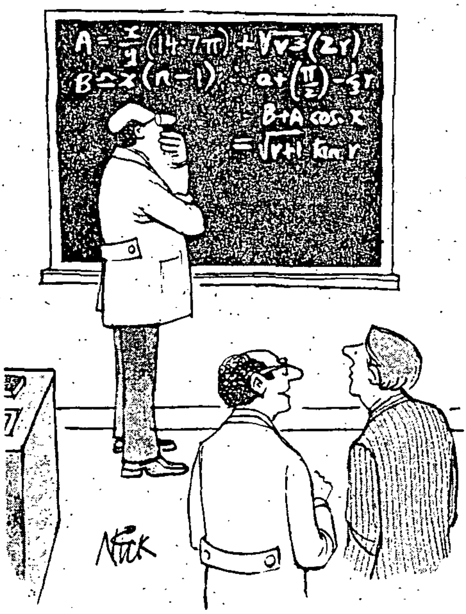
Published Abstracts of Papers Presented at Scientific Meetings (continued)

Valette, J. N., W. A. Elders and J. R. Hoagland, 1979. "Surface Emanations and Low Temperature Hydrothermal Alteration in the Cerro Prieto Geothermal Field, Baja California, Mexico. EOS, 60, p. 973.

Elders, W. A., 1980. "Hydrothermal Minerals, Temperature and Flow Regime in the Cerro Prieto Geothermal Field: A Model for Greenschist Metamorphism". EOS, 61, no. 17, p. 389-390.

Elders, W. A., 1980. "Applications of Petrology and Geochemistry to the Study of Active Geothermal Systems in the Salton Trough of California and Baja California." 109th AIME Annual Meeting, Las Vegas, The Metallurgical Society, Technical Program in Process Mineralogy, p. 291. (The Journal of Metals, January, 1980), (invited paper).

Elders, W. A., 1980. "Petrologic Indicators of Fluid Flow in High Temperature Geothermal Systems." Proceedings, National Conference on Renewable Energy Technologies (invited paper).



"Professor Elders *working on a way to get our research grant renewed."*

DENNIS K. BIRD

Research Associate
Department of Geosciences
University of Arizona
Tucson, Arizona 85721
(602) 626-5609

Date of Birth: July 24, 1949

Education: B.S., Geology, University of California, Riverside, 1971;
M.S., Geology, University of California, Riverside, 1975;
Ph.D., Geology, University of California, Berkeley, 1978.

Positions Held: 1968-1971: Surveyor, U.S. Forest Service, Stanislaus National Forest, California; 1972: Field Geologist, U.S. Geological Survey, Denver, Colorado; 1972-1974: Graduate student, research associate, teaching assistant, Institute of Geophysics and Planetary Physics, University of California, Riverside; 1975-1978: Graduate student, research assistant, University of California, Berkeley; 1978-present: Research assistant, Department of Geosciences, University of Arizona, Tucson.

Affiliations: Geological Society of America; Geology Club, University of California, Berkeley; National Rifle Association of America.

Awards:

1974, The American Association of Petroleum Geologists, Grants in Aid.

1974, Arthur L. Coggins Research Fellowship: field investigation of geothermal systems in the North Island of New Zealand.

Abstracts:

1973, (with W. A. Elders), Active low-temperature alteration of arenaceous sands in the Imperial Valley of California: Geological Society of America, Abstracts with Programs, v. 5, p. 610.

1973, (with W. A. Elders), Petrology of silicified cap rocks in the Dunes geothermal anomaly, Imperial Valley of California: American Geophysical Union Transactions, v. 54, p. 1214.

1977, (with H. C. Helgeson), Prediction of the chemical characteristics of geothermal reservoir fluids from authigenic mineral assemblages: Geological Society of America, v. 9, p. 898-899.

1979, (with D. Norton), Correlation of the spatial variations in the composition of geothermal reservoir fluids from petrochemical observations and thermodynamic calculations in the Salton Sea geothermal system: Geological Society of America, Abstracts with Programs, v. 11, p. 388.

Papers:

1974, (with W. A. Elders, J. Combs, T.B. Coplen, P. Kolesar), Geophysical, geochemical and geological investigations of the Dunes geothermal system, Imperial Valley, California: Proceedings, Conference on research for the development of geothermal energy resources, Pasadena, California, National Science Foundation report no. NSF-RA-N-74-159, p. 45-72.

1976, (with W. A. Elders), Active formation of silicified cap rocks in arenaceous sands in a low-temperature, near-surface geothermal environment in the Salton Trough of California, U.S.A.: Proceedings, International Association of Geochemistry and Cosmochemistry on Water-Rock Interaction, Prague, Czechoslovakia, September, 1974, p. 150-157.

1976, (with W. A. Elders), Hydrothermal alteration and mass transfer in the discharge portion of the Dunes geothermal system, Imperial Valley of California, U.S.A.: Proceedings, Second United Nations Symposium on the Development and Use of Geothermal Resources; San Francisco, May, 1975, v. 1, p. 285-296.

1978, (with H. C. Helgeson, J. M. Delany, and H. W. Nesbitt), Summary and critique of the thermodynamic properties of rock-forming minerals: American Journal of Science, v. 278-A.

1980, (with D. Norton), Chemical mass transfer between circulating fluids and rocks in geothermal systems: I. Phase relations among aqueous solutions and minerals in the system Na_2O-K_2O-CaO-Al_2O_3-SiO_2-H_2O: Contributed to Mineralogy and Petrology, in review.

1980, (with H. C. Helgeson), Chemical interaction of aqueous solutions with epidote-feldspar mineral assemblages in geologic systems. I. Thermodynamic analysis of phase relations in the system CaO-FeO-Fe_2O_3-Al_2O_3-SiO_2-H_2O, American Journal of Science, accepted for publication.

Invited Lectures:

1975, Petrology, hydrothermal alteration and mass transfer in geothermal systems: Geothermal Energy Conference, New Mexico State University, Las Cruces, New Mexico.

1977, Effects of reactions in intracontinental geothermal systems on the ore forming potential of hydrothermal solutions: Gordon Research Conference on the Inorganic Geochemistry of Ore Deposits, Andover, New Hampshire.

ALAN E. WILLIAMS

Assistant Research Geochemist I
Institute of Geophysics and Planetary Physics
University of California
Riverside, California 92521

Born: October 4, 1952

Citizenship: United States

Education: B.S., Juniata College, Huntingdon, Pennsylvania, 1974
M.S., Brown University, Providence, Rhode Island, 1976
Ph.D., Brown University, Providence, Rhode Island, 1980

Recent Experience:

9/77 - 9/79	NSF National Needs Graduate Traineeship in Geothermal Energy, Brown University, Providence, Rhode Island
9/74 - 9/77	Research Assistant, Brown University, Providence, Rhode Island
1/74 - 5/74	Teaching Assistant, Juniata College, Huntingdon, Pennsylvania
5/72 - 9/72	Geological Field Assistant, Juniata College, Huntingdon, Pennsylvania

Research Interests:	Stable isotope geochemistry Study of interactions between water and rock; geothermal energy, migration of fluids, ore formation Use of natural tracers in geologic processes; stable isotopes, radioactive isotopic decay systems, trace elements
Memberships:	American Geophysical Union; Geological Society of America

Publications:

Erikson, E. H., Williams, A. E., 1976, Implications of apatite fission track ages in the Mount Stuart Batholyth, Cascade Mountains, Washington, (abs): G.S.A. Abstracts with Programs, 8, No. 3, p. 372.

Williams, A. E., and Giletti, B. J., 1976, Natural variations of the stable calcium isotopes (abs.): G.S.A. Abstracts with Programs, 8, No. 6, p. 1170.

Williams, A. E., and Sommer, M. A., 1977, ^{18}O study of the Alamosa River stock, a fossil geothermal area (abs.): Trans. Amer. Geophys. Union, 58, No. 6, p. 540.

Williams, A. E., 1978, Circulation in a fossil geothermal area; ^{18}O study (abs.): Proceedings on the 4th International Conference on Geochronology, Cosmochronology and Isotope Geology.

Williams, A. E., 1978, ^{18}O depletion and hydrothermal flow patterns: Alamosa River Stock, Colorado (abs.): G.S.A. Abstracts with Programs, 10, No. 7, p. 516.

Williams, A. E., 1979, Unravelling multiple water-rock interactions in the Alamosa River Stock, Colorado (abs.): Trans. Amer. Geophys. Union, 60, No. 18, p. 417.

Williams, A. E., 1980, Investigation of Oxygen - 18 depletion of igneous rocks and ancient meteoric - hydrothermal circulation in the Alamosa River Stock Region, Colorado: Ph.D. thesis, Brown University, Providence, Rhode Island (271 p)

Elders, W. A., Hoagland, J. R., and Williams, A. E., 1980, Hydrothermal alteration as an indicator of temperature and flow regime in the Cerro Prieto geothermal field of Baja California (in press, Geothermal Resources Council).

JAMES ROBERT HOAGLAND

Staff Research Assistant III
Institute of Geophysics and Planetary Physics
University of California
Riverside, CA 92521

Born: November 24, 1951

Citizenship: U.S.

Education: B.S., geological sciences, University of California, Riverside, California, 1973
M.S., geological sciences, University of California, Riverside, California, 1976

Positions:

2/77-9/78	Assistant Specialist, Institute of Geophysics and Planetary Physics, University of California, Riverside, California.
4/74-9/75 & 3/76-2/77	Staff Research Associate/Research Assistant, Institute of Geophysics and Planetary Physics, University of California, Riverside, California.
8/76-10/76	Chemist P-4, Energy and Environment Division, Lawrence Berkeley Laboratory, Berkeley, California.
10/73-4/74	Teaching Assistant, Department of Earth Sciences, University of California, Riverside, California.

Research Interests:

Hydrothermal petrology and geochemistry.

Affiliations:

Geological Society of America

Publications:

1976 Hoagland, J. R., Petrology and geochemistry of hydrothermal alteration in borehole Mesa 6-2, East Mesa geothermal area, Imperial Valley, California: M.S. thesis, Dept. Earth Sciences and Institute of Geophysics and Planetary Physics publ. 76-12, University of California, Riverside, 90 p.

Hoagland, J. R., Petrology and geochemistry of hydrothermal alteration in borehole Mesa 6-2, East Mesa geothermal area, Imperial Valley, California (abs.): Geol. Soc. Amer. Abstracts with Programs, v. 8, no. 4, p. 919; also published in Econ. Geology (1977), v. 72, no. 4, p. 730.

1977 Hoagland, J. R., Applications of solute equilibrium models to the study of geothermal reservoirs: Geothermal Resources Council, Transactions, v. 1, p. 143-145.

Hoagland, J. R., and Elders, W. A., The evolution of the East Mesa hydrothermal system, California, U.S.A.: Proceedings, 2nd International Symposium on Water/Rock Interaction, Strasbourg, France; v. III, p. 127-136.

Hoagland, J. R., Chemical change in thermal fluids produced from the East Mesa geothermal system (abs.): Geol. Soc. Amer. Abstracts with Programs, v. 9, no. 7, p. 1016.

1978 Hoagland, J. R. and W. A. Elders, Hydrothermal mineralogy and isotopic geochemistry in the Cerro Prieto geothermal field, Mexico. I. Hydrothermal mineral zonation: Geothermal Resources Council Transactions, 2, 283-286.

Elders, W. A., J. R. Hoagland and E. R. Olson, Hydrothermal mineralogy and isotopic geochemistry in the Cerro Prieto geothermal field, Mexico. III. Practical applications: Geothermal Resources Council Transactions, 2, 177-180.

Elders, W. A., J. R. Hoagland, S. D. McDowell and J. M. Cobo, Hydrothermal mineral zones in the geothermal reservoir of Cerro Prieto, B.C., Mexico: Proceedings of the First Symposium on the Cerro Prieto Geothermal Field, Baja California, Mexico, San Diego, California.

Hoagland, J. R. and D. McDowell, Metamorphic zonation in the Cerro Prieto Geothermal Reservoir, Baja California, Mexico (abstr.): *Geological Society of America*, Abstracts with Programs, 10, no. 7, 422.

Elders, W. A., Hoagland, J. R., Olson, E. R., McDowell, S. D., and Collier, P., A comprehensive study of samples from geothermal reservoirs: Petrology and light stable isotope geochemistry of twenty-three wells in the Cerro Prieto geothermal field, Baja California, Mexico: UCR/IGPP report 78/26, 264 p.

1979 Valette, J. N., Elders, W. A., and Hoagland, J. R., 1979, Surface emanations and low temperature hydrothermal alteration in the Cerro Prieto geothermal field, Baja California, Mexico (abs.), EOS, 60 p. 973.

1979 Elders, W. A., and Hoagland, J. R., 1979, Studies of water/rock interaction in the Cerro Prieto geothermal field, Baja California, Mexico (abs.), Program and abstracts: Second Symposium on the Cerro Prieto geothermal field, Baja California, Mexico, p. 18.

1980 Elders, W. A., Hoagland, J. R., and Williams, A. E., Hydrothermal alteration as an indicator of temperature and flow regime in the Cerro Prieto geothermal field of Baja California (in press, Geothermal Resources Council).

Invited Lectures:

1980 Mineralogy, hydrothermal alteration, and geochemistry: Exploration and reservoir assessment and development; tools, techniques, and case histories. Geothermal Resources Council technical training course no. 5: Basic Geology for the Exploration of Geothermal Resources, Klameth Falls, Oregon, July 21 - 23.

CONTRACT PRICING PROPOSAL
(RESEARCH AND DEVELOPMENT)

Office of Management and Budget
Approval No. 29-RO184

This form is for use when (i) submission of cost or pricing data (see FPR 1-3.807-3) is required and (ii) substitution for the Optional Form 59 is authorized by the contracting officer.

PAGE NO.

NO. OF PAGES

NAME OF OFFEROR The Regents of the University of California

SUPPLIES AND/OR SERVICES TO BE FURNISHED

HOME OFFICE ADDRESS
University of California, Riverside
Riverside, CA 92521

DIVISION(S) AND LOCATION(S) WHERE WORK IS TO BE PERFORMED Institute of Geophysics & Planetary Physics

TOTAL AMOUNT OF PROPOSAL $ 99,991

GOV'T SOLICITATION NO. DE-SC07-80ID12145

DETAIL DESCRIPTION OF COST ELEMENTS

1. DIRECT MATERIAL (Itemize on Exhibit A) See exhibit (I) for breakdown			EST COST ($)	TOTAL EST COST[1]	REFERENCE[2]
a. PURCHASED PARTS					
b. SUBCONTRACTED ITEMS (see attached Univ. of Arizona budget)			39,781		
c. OTHER—(1) RAW MATERIAL					
(2) YOUR STANDARD COMMERCIAL ITEMS			1,000		
(3) INTERDIVISIONAL TRANSFERS (At other than cost)					
TOTAL DIRECT MATERIAL				40,781	
2. MATERIAL OVERHEAD[3] (Rate %X$ base =)					
3. DIRECT LABOR (Specify)	ESTIMATED HOURS	RATE/HOUR	EST COST ($)		
W. A. Elders, Research Geologist II	174	24.04	4,183		
A. Williams, Asst. Res. Geochemist	348/348	10.35/	7,506		
		11.22			
Staff Research Assoc. III	348/522	10.69/	10,077		
		12.18			
Secretary II	174	7.24	1,260		
TOTAL DIRECT LABOR				23,026	
4. LABOR OVERHEAD (Specify Department or Cost Center)[4]	O.H. RATE	X BASE =	EST COST ($)		
Faculty Summer Salaries	8.06%	4,183	337		
Academic year salaries	26.00%	7,506	1,952		
Staff salaries	25.00%	11,337	2,834		
TOTAL LABOR OVERHEAD				5,123	
5. SPECIAL TESTING (Including field work at Government installations)			EST COST ($)		
TOTAL SPECIAL TESTING				0	
6. SPECIAL EQUIPMENT (If direct charge) (Itemize on Exhibit A)				0	
7. TRAVEL (If direct charge) (Give details on attached Schedule) See exhibit (I)			EST COST ($)		
a. TRANSPORTATION			1,722		
b. PER DIEM OR SUBSISTENCE			1,800		
TOTAL TRAVEL				3,522	
8. CONSULTANTS (Identify—purpose—rate)			EST COST ($)		
TOTAL CONSULTANTS					
9 OTHER DIRECT COSTS (Itemize on Exhibit A) See exhibit (I)				7,375	
10. TOTAL DIRECT COST AND OVERHEAD				79,827	
11. GENERAL AND ADMINISTRATIVE EXPENSE (Rate 31 % of cost element Nos. 65,046)[5]				20,164	
12. ROYALTIES[6]					
13. TOTAL ESTIMATED COST				99,991	
14. FEE OR PROFIT					
15. TOTAL ESTIMATED COST AND FEE OR PROFIT					

OPTIONAL FORM 60
October 1971
General Services Administration
FPR 1-16.806

This proposal is submitted for use in connection with and in response to *(Describe RFP, etc.)*

DE-SC07-80ID12145

and reflects our best estimates as of this date, in accordance with the Instructions to Offerors and the Footnotes which follow.

TYPED NAME AND TITLE
M. Jeanne Thornburg, Manager
Contracts and Grants

SIGNATURE
Jeanne Thornburg

NAME OF FIRM
The Regents of the University of California

DATE OF SUBMISSION
8/04/80

EXHIBIT A—SUPPORTING SCHEDULE *(Specify. If more space is needed, use reverse)*

COST EL NO.	ITEM DESCRIPTION *(See footnote 5)*	EST COST ($)
	See exhibit (I)	

I. HAS ANY EXECUTIVE AGENCY OF THE UNITED STATES GOVERNMENT PERFORMED ANY REVIEW OF YOUR ACCOUNTS OR RECORDS IN CONNECTION WITH ANY OTHER GOVERNMENT PRIME CONTRACT OR SUBCONTRACT WITHIN THE PAST TWELVE MONTHS?

☒ YES ☐ NO *(If yes, identify below.)*

NAME AND ADDRESS OF REVIEWING OFFICE AND INDIVIDUAL: DHEW Audit Agency, University of California, 2000 Center St., Rm. 302, Berkeley, CA 94704

TELEPHONE NUMBER/EXTENSION: (415) 643-4163

II. WILL YOU REQUIRE THE USE OF ANY GOVERNMENT PROPERTY IN THE PERFORMANCE OF THIS PROPOSED CONTRACT?

☐ YES ☒ NO *(If yes, identify on reverse or separate page)*

III. DO YOU REQUIRE GOVERNMENT CONTRACT FINANCING TO PERFORM THIS PROPOSED CONTRACT?

☒ YES ☐ NO *(If yes, identify.)*: ☒ ADVANCE PAYMENTS ☐ PROGRESS PAYMENTS OR ☐ GUARANTEED LOANS

IV. DO YOU NOW HOLD ANY CONTRACT *(Or, do you have any independently financed (IR&D) projects)* FOR THE SAME OR SIMILAR WORK CALLED FOR BY THIS PROPOSED CONTRACT?

☐ YES ☐ NO *(If yes, identify.)*: We certify that, to the best of our knowledge, the principal investigator for this project does not currently hold a contract for the same or similar work called for by this SCAP.

V. DOES THIS COST SUMMARY CONFORM WITH THE COST PRINCIPLES SET FORTH IN AGENCY REGULATIONS?

☒ YES ☐ NO *(If no, explain on reverse or separate page)*

See Reverse for Instructions and Footnotes

OPTIONAL FORM 60 (10-71)

DOE PROPOSAL BUDGET
12 months
January 1, 1981 - December 31, 1981

Budget Category	DOE Funded Man-Months			Grantee Man-Months			Proposed		
	Cal	Acad	Sum	Cal	Acad	Sum	DOE	G'ee	Total
A. SALARIES AND WAGES*									
1. Senior Personnel									
a. W. A. Elders, Principal Investigator Research Geologist, Step 2 Base $31,400/yr., 9 mo appointment (Res Geol, Step 3, Base $34,700 effect. 7/1/81)			1.0		2.0		$4,183	$7,672	$11,855
b. A. Williams, Co-Investigator Asst. Res Geochemist, Step 1 Base $21,600, fiscal appt.	4.0						7,506		7,506
2. Other Staff									
a. Staff Research Associate III Step 3 1/2, Base $22,320 (Step 4 1/2, Base $23,436 effect. 7/1/81)	5.0						10,077		10,077
b. Secretary II, Step 5 Base $1260/mo	1.0						1,260		1,260
TOTAL SALARIES AND WAGES							23,026	7,672	30,698
B. BENEFITS									
1. Faculty summer salaries w/Social Security 8.06% x $4,183							337		337
2. Academic year salaries 26% x ($7,506) ($7,672)							1,952	1,995	3,947
3. Other Staff 25% x $11,337							2,834		2,834
TOTAL BENEFITS							5,123	1,995	7,118
C. SUPPLIES AND EXPENSES									
1. Miscellaneous laboratory and office supplies (telephone, mail, etc.)							1,000		1,000
TOTAL SUPPLIES AND EXPENSES							1,000		1,000
D. TRAVEL									
1. Round trip air fare Ontario/Tucson $168 x 4 trips = $672 Per diem, 30 days x $35/day = $1,050							1,722		1,722
2. 3 trips to scientific meetings (TBA)							1,500		1,500
3. 15 Round trip Riverside/Cal Tech @ $20/trip							300		300
TOTAL TRAVEL							3,522		3,522
E. PUBLICATION CHARGES									
1. Page charges, drafting, photography, duplicating, Xeroxing, etc.							1,500		1,500
TOTAL PUBLICATION CHARGES							1,500		1,500
F. OTHER COSTS									
1. University of Arizona, Tucson, sub-contract (Appendix A)							39,781		39,781
2. Electron microprobe 100 hrs. @ $16/hr.							1,600		1,600
3. IGPP Laboratory Services									
a. 65 Isotope silicate analyses @ $50/ea	3,250								
b. 15 Isotope carbonate analyses @ $35/ea	525								
c. 50 Polished thin section probe mounts @ $10/ea	500								
Total Lab services							4,275		4,275
TOTAL OTHER COSTS							45,656		45,656
G. TOTAL DIRECT COST							79,827	9,667	89,494
H. INDIRECT COST 31% MTDC** (65,046) (9,667)							20,164	2,997	23,161
I. TOTAL COST							99,991	12,664	112,655

---

*An anticipated 8.5% range adjustment has been included on all salaries effective 7/1/81.

**The indirect cost rate is predetermined for the period 7/1/78 through 6/30/82 and provisional thereafter. DHEW agreement dated 10/1/79.

CONTRACT PRICING PROPOSAL
(RESEARCH AND DEVELOPMENT)

Office of Management and Budget
Approval No. 29-RO184

This form is for use when *(i)* submission of cost or pricing data (see FPR 1-3.807-3) is required and *(ii)* substitution for the Optional Form 59 is authorized by the contracting officer.

PAGE NO.
NO. OF PAGES

NAME OF OFFEROR
Dennis K. Bird

HOME OFFICE ADDRESS
Dept. of Geosciences
University of Arizona
Tucson, AZ 85721

SUPPLIES AND/OR SERVICES TO BE FURNISHED
Quantitative analysis and interpretation of thermodynamic constraints of solution-mineral reactions in geothermal systems.

DIVISION(S) AND LOCATION(S) WHERE WORK IS TO BE PERFORMED
Dept. of Geosciences, UofA, Tucson, AZ

TOTAL AMOUNT OF PROPOSAL
$ 39,781

GOV'T SOLICITATION NO.

DETAIL DESCRIPTION OF COST ELEMENTS

			EST COST ($)	TOTAL EST COST[1]	REFERENCE[2]
1. DIRECT MATERIAL *(Itemize on Exhibit A)*					
a. PURCHASED PARTS					
b. SUBCONTRACTED ITEMS					
c. OTHER—(1) RAW MATERIAL					
(2) YOUR STANDARD COMMERCIAL ITEMS					
(3) INTERDIVISIONAL TRANSFERS *(At other than cost)*					
TOTAL DIRECT MATERIAL					
2. MATERIAL OVERHEAD[3] *(Rate %X$ base =)*					
3. DIRECT LABOR *(Specify)*	ESTIMATED HOURS(*)	RATE/ HOUR(*)	EST COST ($)		
Co-Principal Investigator	400/400	9.48/10.43	7,964		
Research Assoc.-Graduate Student	400/400	8.63/9.49	7,248		
Secretary III	87/87	5.85/6.44	1,069		
Drafts person	87/87	7.92/8.71	1,447		
(*)The two sets of figures represent					
the 10% cost of living salary increase					
effective 7/1/81 *TOTAL DIRECT LABOR*				17,728	
4. LABOR OVERHEAD *(Specify Department or Cost Center)*[3]	O.H. RATE	X BASE =	EST COST ($)		
Faculty	16.5%	7,964	1,314		
Staff	19%	2,516	478		
Graduate Associate-Ph.D. Candidate	1.5%	7,248	109		
TOTAL LABOR OVERHEAD				1,901	
5. SPECIAL TESTING *(Including field work at Government installations)*			EST COST ($)		
TOTAL SPECIAL TESTING					
6. SPECIAL EQUIPMENT *(If direct charge) (Itemize on Exhibit A)*					
7. TRAVEL *(If direct charge) (Give details on attached Schedule)* @$250/trip/person			EST COST ($)		
a. TRANSPORTATION To national meetings for technology transfer			500		
b. PER DIEM OR SUBSISTENCE 6 days @$40 / day-person			240		
TOTAL TRAVEL					
8. CONSULTANTS *(Identify—purpose—rate)*			EST COST ($)	740	
TOTAL CONSULTANTS					
9. OTHER DIRECT COSTS *(Itemize on Exhibit A)*				7,450	
10. *TOTAL DIRECT COST AND OVERHEAD*				27,819	
11. GENERAL AND ADMINISTRATIVE EXPENSE *(Rate* 43 *% of cost element Nos.* 10 Overhead				11,962	
12. ROYALTIES[4]					
13. *TOTAL ESTIMATED COST*				39,781	
14. FEE OR PROFIT					
15. *TOTAL ESTIMATED COST AND FEE OR PROFIT*					

OPTIONAL FORM 60
October 1971
General Services Administration
FPR 1-16.806

This proposal is submitted for use in connection with and in response to *(Describe RFP, etc.)*

Dept. of Energy Idaho Operations Office, Methods for Improving Geothermal Exploration and Assessment Technology, Solicitation for Cooperative Agreement Proposals

and reflects our best estimates as of this date, in accordance with the Instructions to Offerors and the Footnotes which follow. DE-SC-07-80 1D1245

TYPED NAME AND TITLE **A. RICHARD KASSANDER, JR.**
VICE PRESIDENT FOR RESEARCH

SIGNATURE Charles H Peyton
acting for A. Richard Kassander Jr

NAME OF FIRM
University of Arizona

DATE OF SUBMISSION

EXHIBIT A—SUPPORTING SCHEDULE *(Specify. If more space is needed, use reverse)*

COST EL NO.	ITEM DESCRIPTION *(See footnote 5)*	EST COST ($)
	I) Computer Service	
	a) CDC CYPER 175	
	6 hours @$800/system hour	$4,800
	b) DEC system - 10	
	6 hours @$350/system hour	$2,100
	Total computer services	$6,900
	II) Miscellaneous small computer-related	
	supplies, graphis hardware system supplies,	$ 400
	and research supplies (i.e. pens,pencils,paper,xeroxing,	$ 150
	etc.)	
	III) Communications and Postage	$ 150
	TOTAL of I, II, and III	$7,450

I. HAS ANY EXECUTIVE AGENCY OF THE UNITED STATES GOVERNMENT PERFORMED ANY REVIEW OF YOUR ACCOUNTS OR RECORDS IN CONNECTION WITH ANY OTHER GOVERNMENT PRIME CONTRACT OR SUBCONTRACT WITHIN THE PAST TWELVE MONTHS?

☒ YES ☐ NO *(If yes, identify below.)*

NAME AND ADDRESS OF REVIEWING OFFICE AND INDIVIDUAL
DHEW AUDIT AGENCY 1326 N. First St. Phoenix, AZ

TELEPHONE NUMBER/EXTENSION
602-261-4171

II. WILL YOU REQUIRE THE USE OF ANY GOVERNMENT PROPERTY IN THE PERFORMANCE OF THIS PROPOSED CONTRACT?

☐ YES ☒ NO *(If yes, identify on reverse or separate page)*

III. DO YOU REQUIRE GOVERNMENT CONTRACT FINANCING TO PERFORM THIS PROPOSED CONTRACT?

☐ YES ☒ NO *(If yes, identify.)*: ☐ ADVANCE PAYMENTS ☐ PROGRESS PAYMENTS OR ☐ GUARANTEED LOANS

IV. DO YOU NOW HOLD ANY CONTRACT *(Or, do you have any independently financed (IR&D) projects)* FOR THE SAME OR SIMILAR WORK CALLED FOR BY THIS PROPOSED CONTRACT?

☐ YES ☒ NO *(If yes, identify.)*:

V. DOES THIS COST SUMMARY CONFORM WITH THE COST PRINCIPLES SET FORTH IN AGENCY REGULATIONS?

☒ YES ☐ NO *(If no, explain on reverse or separate page)*

See Reverse for Instructions and Footnotes

OPTIONAL FORM 60 (10-71)

SUPPORTING DATA

Current Support and Pending Applications

Currently Elders is funded by the Department of Energy through the Lawrence Berkeley Laboratory to investigate subsurface samples from the Cerro Prieto geothermal field. This $183,000 subcontract for the last year of a three-year program terminates on September 30, 1980.

A two-year proposal to complete this basic petrologic and geothermal work at Cerro Prieto and extend it to other geothermal systems is currently under consideration by the Division of Geothermal Energy of DOE. The funding and work statement proposed in the two-year proposal will not allow the detailed petrologic, geochemical and computational work at Cerro Prieto described in this proposal.

A proposal to the Earth Sciences Division of the National Science Foundation is currently under consideration. This would involve extensive dating of the thermal events in the Salton Trough area using fission track methodology.

Past Contracts and Grants in Related Fields--W. A. Elders

(1) DOE/Lawrence Berkeley Laboratory Contract No. 7100410 "A comprehensive study of samples from geothermal reservoirs: Conclusion of work at Cerro Prieto, B.C., Mexico". 10/1/79 - 9/30/80 Amount $180,908.

(2) DOE/Los Alamos Scientific Laboratory Contract No. N294953H-1 "Applications of a comprehensive study of samples from well 31-1 in East Mesa geothermal test site to geothermal well logging". 11/15/78 - 1/31/80 Amount $18,759.

(3) National Science Foundation Grant No. EAR78-01969 "A study of active hydrothermal ore formation in the Salton Sea geothermal field, California". 7/15/78 - 12/21/79 Amount $27,900.

(4) DOE/Lawrence Berkeley Laboratory Contract No. 7100410 "A comprehensive study of samples from geothermal reservoirs, work at Cerro Prieto". 10/1/78 - 9/30/79 Amount $158,501.

(5) DOE/Lawrence Berkeley Laboratory Contract No. 7100410 "Reservoir engineering techniques". 7/1/77 - 12/30/77 Amount $55,370.

(6) DOE/Lawrence Berkeley Laboratory Contract No. 7111410 "Reservoir engineering techniques". 7/1/77 - 12/30/77 Amount $55,370.

(7) USDI/Geological Survey Grant No. 14-08-0001-G-430 "Refinement of a model of water/rock reaction in the Salton Sea geothermal field, California". 5/1/77 - 10/31/77 Amount $31,036

(8) National Science Foundation Grant No. AER72-03551-A04/A05 "Geological-geochemical-geophysical investigations of a recognized geothermal area in the Imperial Valley of Southern California". 6/1/76 - 11/30/77 Amount $197,900.

(9) National Science Foundation Grant No. AER72-03551-A03 "Geological-geochemical-geophysical investigations of a recognized geothermal area in the Imperial Valley of Southern California". 3/1/75 - 2/29/76 Amount $341,600.

(10) USDI/Geological Survey Grant No. 14-08-0001-G-244 "A comprehensive study of samples from geothermal reservoirs". 6/26/75 - 2/28/77 Amount $163,931.

(11) National Science Foundation Grant No. OIP75-21905 "Application of petrological and geochemical methods to the discovery and assessment of geothermal resources". 9/1/75 - 8/31/76 Amount $18,100.

(12) National Science Foundation Grant No. AER72-03551-A02 "Geological-geochemical-geophysical investigations of a recognized geothermal area in the Imperial Valley of Southern California". 3/1/74 - 2/28/75 Amount $241,500.

(13) National Science Foundation Grant No. GA-42938 "Grant to support Penrose Conference on the Gulf of California rift system and its implications for the tectonics of western North America". 4/15/74 - 9/30/74 Amount $2,000.

(14) National Science Foundation Grant No. GI-36250 "Geological-geochemical-geophysical investigations of a recognized geothermal area in the Imperial Valley of Southern California". 10/1/72 - 3/31/74 Amount $143,400.

GEOTHERMAL, GEOLOGICAL, GEOPHYSICAL, AND GEOCHEMICAL REPORTS

Published by

Institute of Geophysics and Planetary Physics
University of California
Riverside, California 92521, U.S.A.

REPORT NUMBER	TITLE	AUTHORS
69/1	Application of electrical resistivity and gravimetry in deep geothermal exploration (22 p.)	Meidav, T.
69/2	Structural geology and geophysics of the Durmid Area, Imperial Valley, California (Dissertation) (157 p.)	Babcock, E. A.
70/1	Investigation of geothermal resources in the Imperial Valley and their potential value for desalination of water and electricity production, 1970 (16 p.)	Rex, R. W.
70/2	Investigation of geothermal resources in the Imperial Valley and their potential value for desalination of water and electricity production (58 p.)	Meidav, T.; Rex, R. W.
71/1	Cooperative geological-geophysical-geochemical investigations of geothermal resources in the Imperial Valley (3 p.)	Rex, R. W.
71/2	Cooperative geological-geophysical-geochemical investigations of geothermal resources in the Imperial Valley area of California: Final report to U.S. Bureau of Reclamation (155 p.)	Rex, R. W.; Babcock, E. A.; Combs, J.; Coplen, T.; Elders, W. A.; Furgerson, R.; Garfunkel, Z; Meidav, T.; Robinson, P. T.
72/1A	Geothermal resources development in California: Imperial Valley Potential. Vols. I and II. (262 p.)	Prepared for the Joint Committee on Public Domain, Calif. State Legislature, 1972
72/9	Geothermal energy in the United States (4 p.)	Rex, R. W.
72/10	Geothermal energy--it's potential role in the national energy picture (9 p.)	Rex, R. W.
72/19	A double-focusing double-collecting mass spectrometer for light stable isotope ratio analyses: Int. Jour. of Mass Spectrometry and Ion Physics, 1973, 11, 37-40	Coplen, T.
72/21	Geothermal energy (98 p.)	Combs, J.
72/22	Environmental problems of hot water: paper presented at NSF (RANN) Geothermal Conference, Seattle, WA, 1972, (4 p.)	Coplen T.
72/26	Crustal spreading in southern California. The Imperial Valley and the Gulf of California formed by the rifting apart of a continental plate: Science, 1972, 178, no. 4056, 15-24	Elders, W. A.; Rex, R. W.; Meidav, T.; Robinson, P. T.; Biehler, S.
72/27	Terrestrial heat flow determinations in the north central United States: J. Geophs. Res., 78, no. 2, 441-461	Combs, J.; Simmons, G.
72/28	Exploration for geothermal energy: in Geothermal Energy: Resources, Production, Stimulation, edited by Paul Kruger and Carel Otte, Stanford University Press, Stanford, CA, 95-128	Combs, J.; Muffler, L. P. J.

REPORT NUMBER	TITLE	AUTHORS
72/33	Cooperative investigation of geothermal resources in the Imperial Valley area and their potential value for desalting of water and other purposes: Final Report to the U.S.D.I. Bureau of Reclamation, No. 14-06-300-2258 (268 p.)	Rex, R. W., Biehler, S.; Combs, J.; Coplen, T.; Furgerson, R.; Garfunkel, Z.; Getts, R.; Maas, J.; Reed, M.
72/39	Assessment of U.S. geothermal resources: in Geothermal Energy: Resources, Production, Stimulation, edited by Paul Kruger and Carel Otte. Stanford Univ. Press, Stanford, CA, 1973, 59-67	Rex, R. W.; Howell, D.
72/41	The economics of hot dry rock geothermal energy development: Final Report to Los Alamos Scientific Laboratory, Pt. I, No. XP3-00736-1 (83 p.)	Howell, D.; Rex, R. W.
72/42	East Mesa Imperial Valley as a site for a geothermal engineering test facility: Final Report to Los Alamos Scientific Laboratory, Pt. II, No. XP3-00736-1 (28 p.)	Rex, R. W.
72/43	Melt drill-rock interactions: Final Report to Los Alamos Scientific Laboratory, Pt. III, No. XP3-00736-1 (16 p.)	Rex, R. W.
72/46	Review and discussion of geothermal exploration and techniques: in Geothermal Resources Council, Special Report No. 2, 49-68	Combs, J.
73/5	Ultrafiltration by a compacted clay membrane-I. Oxygen and hydrogen isotopic fractionation: Geochimica et Cosmochimica Acta, 1973, 37, 2295-2310	Coplen, T.; Hanshaw, B.
73/6	Ultrafiltration by a compacted clay membrane-II. Sodium ion exclusion at various ionic strengths: Geochimica et Cosmochimica Acta, 1973, 37, 2311-2327	Hanshaw, B.; Coplen, T.
73/7	Preliminary findings of an investigation of the Dunes thermal anomaly, Imperial Valley, California: A joint study by the State of Calif., Dept. of Water Resources and IGPP (54 p.)	Coplen, T.; Combs, J.; Elders, W. A.; Rex, R. W.; Burckhalter, G.; Laird, R.
73/9	A high resolution cycloidal double-collecting mass spectrometer for hydrogen isotope ratio measurement (15 p.)	Coplen, T.; Clayton R.
73/10	Hydrogen isotopic composition of NBS and IAEA stable isotope water reference samples: Geochimica et Cosmochimica, Acta, 1973, 37, 2347-2349	Coplen, T.; Clayton, R.
73/18	Feasibility study for development of hot water geothermal systems: Final Report to AFOSR, No. 72-2393 (124 p.)	Combs, J.
73/20	Microearthquake study of the Elsinore fault zone, southern California: Bull. Seis. Soc. Am., 1974, 63, No. 1, 187-203	Langenkamp, D.; Combs, J.
73/21	The solubility of hydrocarbons and petroleum in water as applied to the primary migration of petroleum: Ph.D. Dissertation and submitted to AAPG Bull., 1976, 60, 213-244	Price, L.
73/33	A geothermal resources reconnaissance of the Imperial Valley and surrounding area, California, utilizing the sodium-potassium-calcium geochemical exploration technique: U.S.D.I. Report (4 p.)	Coplen, T.
73/34	Microearthquake study of the San Jacinto Valley, Riverside, California: Conference on Tectonic problems of the San Andreas Fault system (10 p.)	Combs, J.; Cheatum, C.
73/36	Proceedings National Conference on Geothermal Energy, Vols. I and II (309 p.)	Veysey, V. (Chairman)
73/40	Microearthquake distribution and mechanism of faulting in the Fontana - San Bernardino area of southern California (Thesis) (91 p.)	Hadley, D. M.

REPORT NUMBER	TITLE	AUTHORS
73/40A	Microearthquake distribution and mechanism of faulting in the Fontana - San Bernardino area of southern California: Bull. Seis. Soc. Am., 1974, 64, No. 5, 1477-1499	Hadley, D.; Combs, J.
73/45	Quaternary volcanism in the Salton Sea geothermal field, Imperial Valley: Bull. Geol. Soc. Am., 1976, 87, 347-360	Robinson, P. T.; Elders, W. A.; Muffler, L. P. J.
73/48	Cooperative geochemical investigation of geothermal resources in the Imperial Valley and Yuma areas: Final Report to the U.S.D.I., Bureau of Reclamation, 1973, (26 p.)	Coplen, T.
74/2	Utilization of the sodium-potassium-calcium geothermal exploration technique in the Imperial Valley area, California: Report to the Bureau of Reclamation (8 p.)	Coplen, T.
74/9	Geophysical investigations in southeastern Mojave Desert, California (Dissertation) (187 p.)	Rotstein, Y.
74/13	Investigations of the Dunes geothermal anomaly, Imperial Valley, California: Part II. Petrological studies: Active formation of silicified cap rocks in arenaceous sands in a low-temperature, near-surface geothermal environment, in the Salton Trough of California, U.S.A.: in Cadek, J. and T. Paces (eds.), Proceedings of the International Symposium on Water-Rock Interaction, Geological Survey, 1976, Prague, Czechoslovakia (1974), 150-157	Elders, W. A.; Bird, D. K.
74/14	A microearthquake study of the San Jacinto Valley, Riverside County, California (Thesis) (100 p.)	Cheatum, C.
74/16	Heat flow on Mesa geothermal anomaly, Imperial Valley, California (6 p.)	Combs, J.
74/18	Investigations of the Dunes geothermal anomaly, Imperial Valley, California: Part I. Geochemistry of geothermal fluids (23 p.)	Coplen, T.; Kolesar, P.
74/24	Penrose Conference Report: The Gulf of California rift system and its implications for the tectonics of western North America: Geology, 1975, 3, No. 1, 85-87	Elders, W. A.; Biehler, S.
74/25	Microearthquake investigation of the Mesa geothermal anomaly--Imperial Valley, California (38 p.)	Combs, J.
74/29	Empirical relationships between thermal conductivity and other physical parameters in rocks (Dissertation) (233 p.)	Goss, R.
75/2	Geology and geochemistry of the Dunes hydrothermal system, Imperial Valley of California (Thesis) (134 p.)	Bird, D. K.
75/4	Focusing and defocusing of heat flow by a buried sphere: Geophys. Journ. of the Royal Astr. Soc., 1975, 43, 635-641	Lee, T. C.
75/6	Regional geology of the Salton Trough, in Palmer, T. D.; J. H. Howard; and D. P. Lande (eds.), Geothermal Development of the Salton Trough, California and Mexico: Lawrence Livermore Laboratory Publication UCRL-51775, 1975, 1-12 and 41-43	Elders, W. A.
75/9	Heat flow near the South Atlantic triple junction, 55°S, 0°E: Geophysical Research Letters, 1975, 2, No. 6, 201-204	Lee, T. C.
75/10	Telluric mapping over the Mesa geothermal anomaly, Imperial Valley, California (11 p.)	Maas, J. P.
75/11	Heat flow through the southern California borderland: Journ. of Geophysical Research, 1975, 80, No. 26, 3733-3743	Lee, T. C.; Henyey, T. L.

REPORT NUMBER	TITLE	AUTHORS
75/14	Hydrothermal alteration and mass transfer in the discharge portion of the Dunes geothermal system, Imperial Valley of California, U.S.A.: Proceedings of the Second United Nations Geothermal Symposium, 1976, San Francisco, May, 1975, 1, 285-295	Bird, D. K.; Elders, W. A.
75/18	Telluric anomaly caused by shallow structure: an ellipsoidal approximation: Geophysics, 1977, 42, No. 1, 97-102	Lee, T. C.
75/20	Investigations of the Dunes geothermal anomaly, Imperial Valley, California: Part IV. Geochemical studies of water, calcite, and silicates (43 p.)	Coplen, T. B.; Kolesar, P.; Taylor, R. E.; Kendall, C.; Mooser, C.
75/24	An electrical survey of the Dunes geothermal anomaly and surrounding region, Imperial Valley, California (Thesis) (137 p.)	Wilt, M. J.
76/1	Cooperative geochemical resource assessment of the Mesa geothermal system: Final Report to the U.S.D.I., Bureau of Reclamation (105 p.)	Coplen, T.
76/5	A composite Trans-Atlantic heat flow profile between 20°S and 35°S: Earth and Planetary Science Letters, 1977, 35, 123-133	Lee, T. C.; Von Herzen, R. P.
76/6	On shallow-hole temperature measurements--a test study in the Salton Sea geothermal field: Geophysics, 1977, 42, No. 3, 572-583	Lee, T. C.
76/8	Final report on a resource assessment of the Imperial Valley: Final Report to the County of the Imperial Valley (69 p.)	Biehler, S.; Lee, T. C.
*76/9	Earthquake potential and geothermal energy extraction (19 p.)	Lee, T. C.
76/12	Petrology and geochemistry of hydrothermal alteration in borehole Mesa 6-2, East Mesa geothermal area, Imperial Valley, California (Thesis) (99 p.)	Hoagland, J. R.
76/14	Telluric mapping over the Mesa geothermal anomaly, Imperial Valley, California (Dissertation) (152 p.)	Maas, J.
76/16	Seismic refraction investigation of the Dunes thermal anomaly, Imperial Valley, California (Thesis) (89 p.)	Van De Verg, P.
76/17	Petrology and stable isotope geochemistry of three wells in the Buttes area of the Salton Sea geothermal field, Imperial Valley, California, U.S.A. (Thesis) (227 p.)	Kendall, C.
76/18	Solution to Laplace's equation in the bispherical coordinates (18 p.)	Lee, T. C.;
76/20	Oxygen isotope studies of the Salton Sea geothermal field: New insights: in Robinson, B. W. (comp. and ed.), 1978: Stable Isotopes in the Earth Sciences. DSIR Bulletin 220: 121-126; New Zealand Department of Scientific and Industrial Research	Olson, E. R.
76/23	AX-DANS-An interactive data analyses system: Proceedings of the Digital Equip. Users Soc., 1976, Las Vegas, NV, 527-531	Johnson, P. D.
76/24	Isotopic dating, geomorphology, and paleoclimatic study of speleothems from the Yorkshire Dales, England (2 p.)	Harmon, R. S.; Waltham, A. C.; Olson, E. R.
77/2	The evolution of the East Mesa hydrothermal system, California, U.S.A.: Proceedings of the 2nd Inter. Symp. on water/rock reaction, Strasbourg, France, III, 127-136	Hoagland, J.; Elders, W. A.
77/7	Applications of solute equilibrium models to the study of geothermal reservoirs: Geothermal Resources Council, 1977, Transactions, 1, 143-145	Hoagland, J.
77/8	Petrology as a practical tool in geothermal studies: Geothermal Resources Council, 1977, Transactions, 1, 85-87	Elders, W. A.

---

*Not available for distribution at this time

REPORT NUMBER	TITLE	AUTHORS
77/9	Occurrence and hydrothermal alteration of diabase, Heber geothermal field, Imperial Valley, California (70 p.)	Browne, P. R. L.
77/10	A microearthquake study of the Salton Sea geothermal area, Imperial Valley, California (Thesis) (192 p.)	Gilpin, B.
77/11	Stratigraphy, structure and a seismic refraction survey of a portion of the San Felipe Hills, Imperial Valley, California (Thesis) (155 p.)	Oronyk, M. P.
77/12	Use of automated X-ray diffraction analysis in studies of natural hydrothermal systems: Advances in X-ray analysis, 1978, 21, 267-274	Johnson, P. D.
77/13	The geological setting of the geothermal resources of the Salton Trough of California and Mexico: Heliosciences Institute, Palm Springs, 1977, (2 p.)	Elders, W. A.
77/15	Application of finite element analysis to terrestrial heat flow: Indiana Geological Survey Occasional Paper--Geophysical Computer Program (72 p.)	Lee, T. C.
77/16	Correspondence betwen heat flow and telluric electric field anomalies in the Imperial Valley, California (10 p.)	Maas, J. P.; Humphreys, E.
77/17	A microearthquake study in the Salton Sea geothermal area: Bull. Seis. Soc. of America, 1978, 68, 441-450	Gilpin, B.; Lee, T. C.
77/22	Onshore and offshore temperature measurements in the Salton Sea geothermal area: Geophysics, 44, No. 2, 206-215	Cohen, L.; Lee, T. C.
77/23	Erosion, uplift, exponential heat source distribution and transient heat flux: Journ. of Geophys. Research, 84, No. B2, 585-590	Lee, T. C.
77/24	Stratigraphy and sedimentation of the Pleistocene Brawley and Borrego Formations in the San Felipe Hills area, Imperial Valley, California, U.S.A. (Thesis) (140 p.)	Wagoner, J. L.
77/25	A quantitative automated X-ray diffraction mineral characterization system for use in the study of natural hydrothermal systems (34 p.)	Johnson, P. D.; Elders, W. A.; Strubble, L.; Collier, P.
77/26	Microseismic activity in the vicinity of the Salton Sea geothermal anomaly during early 1977 (14 p.)	Maas, J. P.
77/37	A comprehensive study of samples from geothermal reservoirs: Petrology and light stable isotope geochemistry of wells M48, M84, M90, M91 and Prian No. 1: Final Report to the Dept. of Energy/Lawrence Berkeley Laboratory, No. 7100410 (153 p.)	Elders, W. A.; Olson, E.; Hoagland, J. R.; Barker, C.; Johnson, P.; Collier, P.
78/4	Petrological studies of geothermal systems (submitted to the Proceedings of La Primera Reunión de Intercambio Téchnico sobre Geotermia, San Felipe, B. C. México, Nov. 1977) (41 p.)	Elders, W. A.
78/5	A fluid inclusion study of Sinclair #4 and Elmore #1 boreholes, Salton Sea geothermal field, Imperial Valley, California, U.S.A. (Thesis) (76 p.)	Freckman, J.
*78/7	A lateral flow-through model for the Westmoreland geothermal system, California (13 p.)	Olson, E.; Matlick, S.
78/8	Hydrothermal mineralogy and isotopic geochemistry in the Cerro Prieto geothermal field, Mexico I. Hydrothermal mineral zonation: Geothermal Resources Council, Transactions, 1978, 2 283-386	Hoagland, J. R.; Elders, W. A.

---

*Not available for distribution at this time

REPORT NUMBER	TITLE	AUTHORS
78/9	Hydrothermal mineralogy and isotopic geochemistry in the Cerro Prieto geothermal field, Mexico. II. Isotopic geochemistry; Geothermal Resources Council, 1978, Transactions, 2, 513-516	Olson, E.; Elders, W. A.
78/10	Hydrothermal mineralogy and isotopic geochemistry in the Cerro Prieto geothermal field, Mexico. III. Practical applications: Geothermal Resources Council, 1978, Transactions, 2, 177-180	Elders, W. A.; Hoagland, J. R.; Olson, E.
78/11	Mineralogical variations in borehole Elmore #1, Salton Sea geothermal area: Preliminary report (30 p.)	McDowell, D.; McCurry, M.
78/13	Geophysical investigation of the northern Palo Verde Valley, Blythe, California (Thesis) (64 p.)	Mees, R. L.
78/15	Layer silicate minerals in borehole Elmore #1, Salton Sea geothermal field, California (75 p.)	McDowell, D.
78/17	Telluric sounding and mapping in the vicinity of the Salton Sea geothermal area, Imperial Valley, California (Thesis) (159 p.)	Humphreys, G.
78/19	A seismic refraction investigation of the Salton Sea geothermal area, Imperial Valley, California (Thesis) (104 p.)	Frith, R.
78/26	A comprehensive study of samples from geothermal reservoirs: Petrology and light stable isotope geochemistry of twenty-three wells in the Cerro Prieto geothermal field, Baja California, Mexico (264 p.)	Elders, W. A.; Hoagland, J. R.; Olson, E. R.; McDowell, S. D.; Collier, P.
79/2	Hydrothermal mineral zones in the geothermal reservoir of Cerro Prieto, B. C., Mexico: Proceedings of the First Symposium on the Cerro Prieto geothermal field, Baja California, Mexico (8 p.)	Elders, W. A.; Hoagland, J. R.; McDowell, D.; Cobo, J. M.
79/10	Vitrinite reflectance geothermometry in the Cerro Prieto geothermal field, Baja California, Mexico (Thesis) (135 p.)	Barker, C. E.
79/11	Vitrinite reflectance geothermometry in the Cerro Prieto geothermal field, Baja California, Mexico. Geothermal Resources Council, Transactions. (4 p.)	Barker, C. E.; Elders, W. A.
79/12	The Homestead Valley earthquakes of March 15, 1979: A progress report on some aftershocks and field observations; California Geology	Stierman, D. J.; Lee, T-C.; Zappe, S. D.; Seamount, D.
79/13	Oxygen and carbon isotope studies of calcite from the Cerro Prieto geothermal field, Baja California, Mexico: Proceedings of the First Symposium on the Cerro Prieto geothermal field, Baja California, Mexico (7 p.)	Olson, E. R.
79/17	Ore minerals in the Salton Sea geothermal system, Imperial Valley, California, U.S.A. (Thesis) 99 p.)	McKibben, M. A.
79/18	Whole rock chemical analysis using NAA and geochemistry of wells M-19A, M-53 and M-84, Cerro Prieto geothermal field, Baja California, Mexico (Thesis)	Garner, C. K.
79/21	Earthquake sounds and animal cues: Some field observations; Bull. Seis. Soc. (12 p.)	Stierman, D. J.
79/23	Guidebook: Geology and Geothermics of the Salton Trough. Prepared for the Geological Society of America 92nd Annual Meeting, San Diego, November 1979. UCR Campus Museum Contribution Number 5 (109 p.)	Elders, W. A. (Editor)

REPORT NUMBER	TITLE	AUTHOR
79/24	The geological background of the geothermal fields of the Salton Trough. Guidebook: Geology and Geothermics of the Salton Trough. Prepared for the GSA 92nd Annual Meeting, November 1979. (19 p.)	Elders, W. A.
79/25	Geothermal metamorphism of sandstone in the Salton Sea geothermal system. Guidebook: Geology and Geothermics of the Salton Trough. Prepared for the GSA 92nd Annual Meeting, November 1979. (7 p.)	McDowell, S. D.; Elders, W. A.

Facilities and Equipment

Equipment at UCR which is available for these investigations includes:

(1) An automated, computer-controlled, Picker X-ray diffractometer, interfaced with a versatile graphic display and capable of producing rapid mineral modal analyses of drillhole cuttings and cores, with associated preparation facilities.

(2) Research-model optical polarizing microscopes with reflected light and photomicroscopy accessories.

(3) A wet chemical laboratory with atomic absorption spectrometer.

(4) Norelco X-ray fluorescence analyzer.

(5) A hydrothermal synthesis laboratory with internally and externally heated bombs.

(6) One freezing and two heating stages for fluid inclusion studies.

(7) A double-focusing, double-collecting mass spectrometer for oxygen and carbon isotope ratio measurements, with extraction lines for water, carbonates, and silicates.

(8) Cold-cathode electron-excited luminoscope.

(9) A mineral separation laboratory including magnetic separators, centrifuges, and heavy liquids.

(10) A JEOLCO-JSM-UZA scanning electron microscope.

(11) A pycnometer for measuring rock densities.

(12) Approximately 300 square meters of laboratory, preparation, and storage space is available to do the project and is under control of the principal investigator.

The electron microprobe laboratory at California Institute of Technology in Pasadena, California, will be utilized for microprobe work. All three investigators are experienced in the use of this facility. The facility includes a fully automated MAC 3-channel electron microprobe with an Energy Dispersive System option and computerized data handling capabilities.

The laboratory facilities at the University of Arizona include numerical tools for analysis of the thermal, mechanical, and chemical processes in magma-hydrothermal systems. These facilities provide the basis for analyzing data on natural systems and reconstruction of their geologic history. The programs have been developed or modified from the published work of colleagues. The program library includes:

*Written in laboratory.

°Modified for local use.

FLOW* - Computes conductive and convective heat transfer away from thermal anomaly in two dimensions. Solves conservation of mass, energy, and momentum equations using ADI methods.

LAGRAN* - Computes pathlines for individual fluid packets and sourcelines or streaklines for fixed positions in domain. Stores dependent parameters, e.g., temperature and pressure, along flow paths.

POIS* - General Poisson equation solver for equations of form $\frac{\partial \zeta}{\partial t} + \frac{1}{k} \nabla \cdot k \nabla \zeta = 0$ by ADI method or by SOR method.

GEAR° - Integrates sets of n-ordering differential equations, stiff or nonstiff systems, using multistep and variable order method, Gear, 1971.

KEENAN° - Equation of state for phases in H_2O system to 100°C and 1 kb (also from 1 kb to 10 kb), Helgeson and Kirkham, 1977.

ETCH* - User-oriented interactive program for plotting results of FLOW and LAGRAN computations. Generates steady state as well as Eulerian plots of dependent variables.

RESIST* - Computes intrinsic resistivity of pore fluids from temperature, pressure, and equation of state for $NaCl$-H_2O systems and bulk rock resistivity from Archie's function.

POREF* - Computes stresses caused by differential expansion of pore fluids and confining matrix, and effective pressures in domain for which temperature is known, using finite element method.

PATH3° - Version of Helgeson (1970) program. Solves grand matrix for multicomponent, multiphase system over range of conditions from surface weathering to subsurface environments.

DIST* - Computes equilibrium distribution of components between aqueous complexes and ions for specified temperature, pressure, and bulk composition.

GRAFIT* - Interactive program which fits data to polynomial whose order is selected in interactive mode.

DIAGRAM° - Interactive version of Brown (1970) program. Computes mineral stability diagrams in activity-activity coordinates.

PATPLT* - Interactive program for analyzing output from PATH3.

TRENDS° - Interactive version of multivariable regression program.

QMIN* - Mineral mass abundance, chemical gains and losses are computed from analytical data on major component distribution in rocks.

EXCHGE* - Computes irreversible and equilibrium mass transfer of stable light isotopes between circulating fluid phase and rock, for system where T, P, and $\overline{U}$ have been specified independently.

MASADV* - Computes irreversible and equilibrium mass transfer for multiphase, multicomponent system in time, temperature, and pressure coordinates.

REETCH* - Retrieves and plots diagrams, saved on disc or tape, in interactive mode. Permits simultaneous analysis of thermal and chemical output from FLOW, EXCHGE, and MASADV.

RUPTUR* - Computes in-situ stresses and strains for domain in which temperature in known, using finite element method.

SUPCRT° - Retrieves thermodynamic data for mineral-solution equilibrium reaction from standard state data of minerals and aqueous species and equations of state for ions and H_2O. Programs provided by H. C. Helgeson.

PAAD° - Modification of DIAGRAM that permits interactive generation of equilibrium diagrams from SUPCRT.

Hardware support includes an Execuport hard copy terminal, a Regent CRT terminal, a Tektronix 4014 graphics terminal, hard copy device and dual floppy disc, acoustical couplers, and one direct line to the DEC-10 system. This equipment provides access to the coupled DEC-10 and CYBER 175 systems at the University Computer Center.

Laboratory facilities also include a comprehensive library of numerical models of idealized systems for which temperature, pressure, and fluid velocity data have been stored on magnetic tapes. These data are accessible by interactive programs that facilitate making additional computations and analyses.