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HYDROTECTONIC ENVIRONMENT AT YUCCA MOUNTAIN & EVIDENCE FOR RECURRENT INVASIONS BY HYDROTHERMAL FLUIDS

SPECIAL REPORT No. 3
CONTRACT No. 92/94.0004

SPECIAL REPORT Submitted to the
Nuclear Waste Project Office
State of Nevada

March, 1993

Documentation of Presentation to:

Assiciation of Engineering Geologists
Southwest Section
on:
November 10, 1992

Presented by:
Dr. Gerald Frazier
Dr. Donald Livingston
Dr. Malcolm Somerville

Hydrotectonic Environment at Yucca Mountain

&

Evidence for Recurrent Invasions by Hydrothermal Fluids

REPORT ORGANIZATION

OVERVIEW

Dr. Gerald Frazier

PART 1

"Evidence for Recurrent Discharges of Deep-Seated Fluids from Field Observations and Radiometeric Determinations of Ages"

Dr. Gerald Frazier

PART 2

"Polygenic Metasomatic Alterations of Volcanic Rocks at Yucca Mountain" *Dr. Donald Livingston*

PART 3

"Evidence for an Intermittently Active Hydrothermal Environment at Yucca Mountain" *Dr. Malcolm Somerville*

PART 4

"Comments on the NAS Report and Conclusions about Hydrothermal Conditions at Yucca Mountain" *Dr. Gerald Frazier*

OVERVIEW

CONTROVERSY ABOUT PALEOHYDROLOGY AT YUCCA MOUNTAIN

UNCONTESTED OBSERVATIONS:

Paleo waters have altered volcanic rocks and deposited vein minerals at Yucca Mountain.

CRITICAL ISSUES:

1. Sources of water?
2. Ages of alterations?

COMPETING HYPOTHESES:

A. Supergene Paragenesis: Young hydrogenic alterations in the vadose zone were produced by infiltrating rainwater, and all hydrothermal alterations occurred more than 10 million years ago.

B. Hypogene Paragenesis: Most hydrogenic alterations resulted from recurrent invasions of Yucca Mountain by deep-seated fluids throughout the past 13 Ma.

CONCLUSIONS REGARDING HYDROTECTONIC CONDITIONS AT YUCCA MOUNTAIN

Conclusion 1. Paleo spring discharges at Yucca Mountain can be deduced from visual observations of field exposures. Many features of hydrogenic alterations seen at the site are consistent with formation by hypogene fluids and are in conflict with formation by supergene fluids.

Conclusion 2. Prolonged invasions of Yucca Mountain by deep-seated fluids are indicated by major changes in chemistry of the volcanic rocks. Compositional changes of a few percent of whole rock samples and zeolitization within the vadose zone cannot be reasonably attributed to infiltrating rainwater.

Conclusion 3. Invasions of Yucca Mountain by hot water are indicated by fluid inclusion temperatures, zircon annealing temperatures, zeolite and clay mineral formation temperatures, and elevated paleo-temperature gradients obtained from $\delta^{18}O$ isotopic contents of vein minerals. These geothermometry data cannot be reasonably attributed to infiltrating rainwater.

CONCLUSIONS REGARDING HYDROTECTONIC CONDITIONS AT YUCCA MOUNTAIN (continued)

Conclusion 4. Radiometric ages indicate that hydrogenic alterations have been occurring throughout the past 10 million years. Origins from infiltrating rainwater are inconsistent with the nature of alterations, and radiometric ages are inconsistent with ancient deuteric origins.

Conclusion 5. The positioning of Yucca Mountain within metamorphic aureoles of recurrent hydrothermal activity is consistent with geodynamic instabilities known to exist in the local crust and upper mantle. Future hydrothermal activity can be expected.

Conclusion 6. The site of the proposed repository at Yucca Mountain is likely to be flooded by upwelling water, posing a serious hazard for waste isolation.

HYDROTECTONIC ENVIRONMENT AT YUCCA MOUNTAIN AND EVIDENCE FOR RECURRENT INVASIONS BY HYDROTHERMAL FLUIDS

Part 1. - "Evidence for Recurrent Discharges of Deep-Seated Fluids from Field Observations and Radiometeric Determinations of Ages" by Dr Gerald Frazier.

Part 2. - "Polygenic Metasomatic Alterations of Volcanic Rocks at Yucca Mountain" by Dr Donald Livingston.

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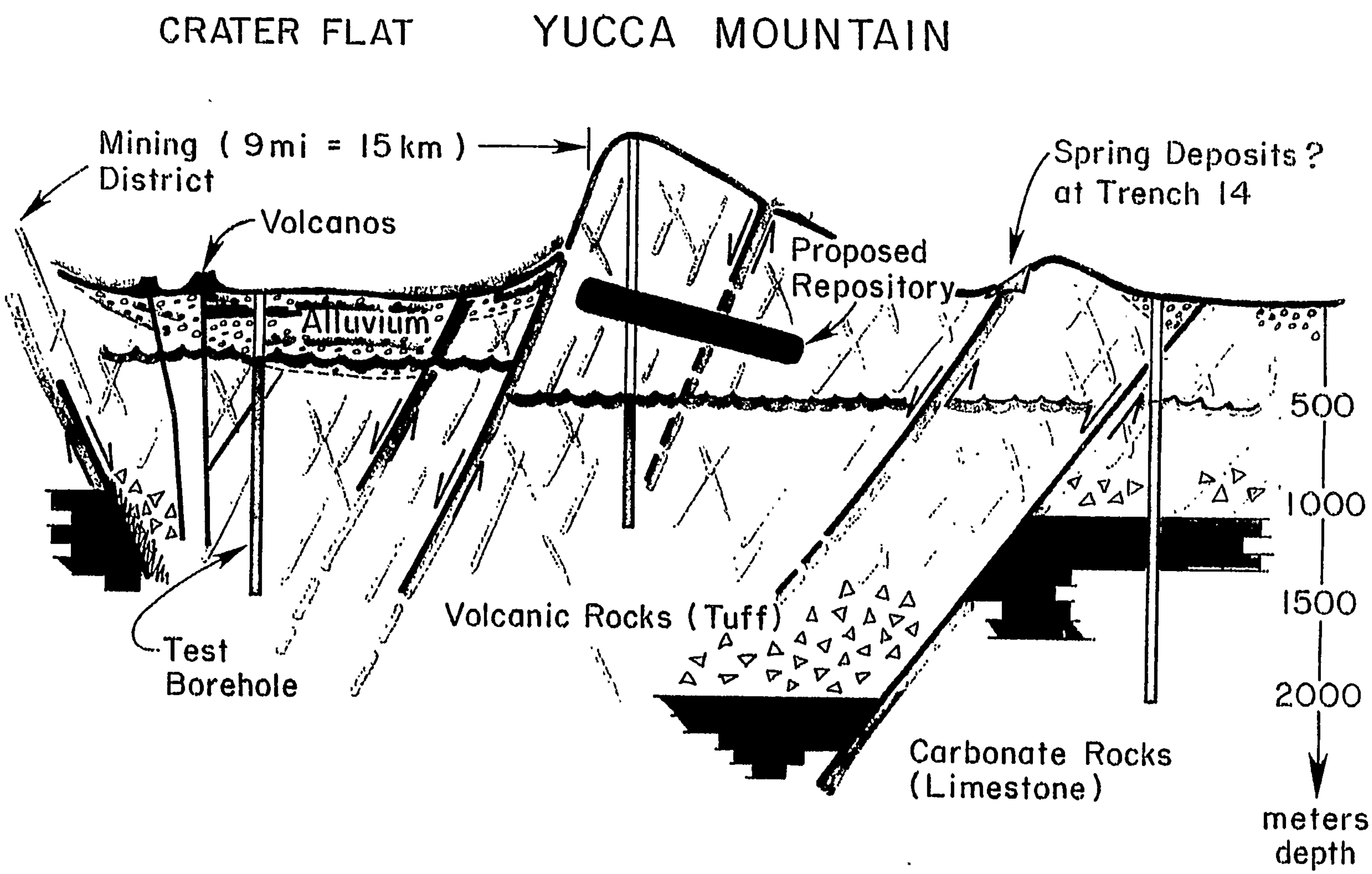
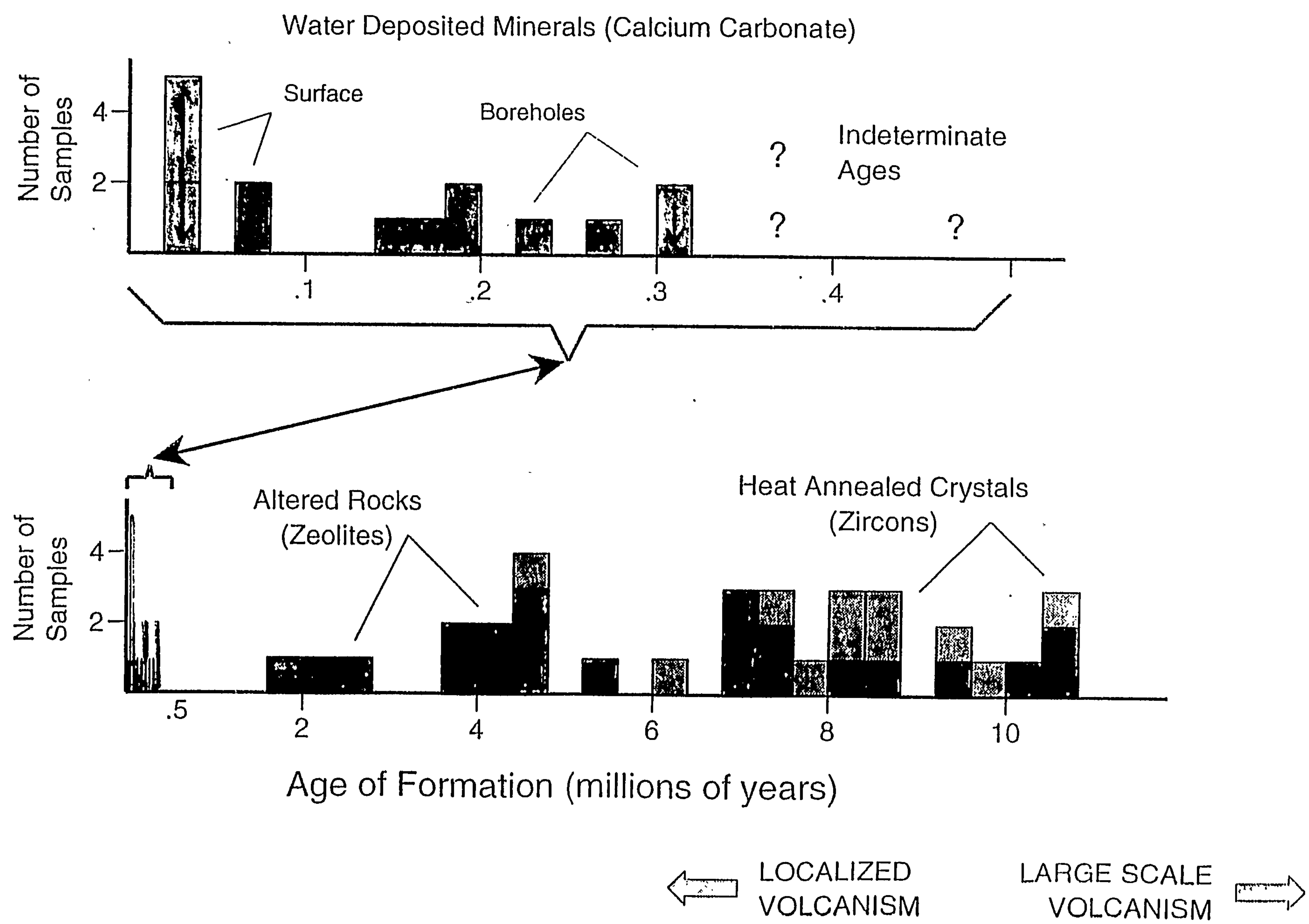
Part 4. - "Comments on the NAS Report and Conclusions about Hydrothermal Conditions at Yucca Mountain" by Dr Gerald Frazier.

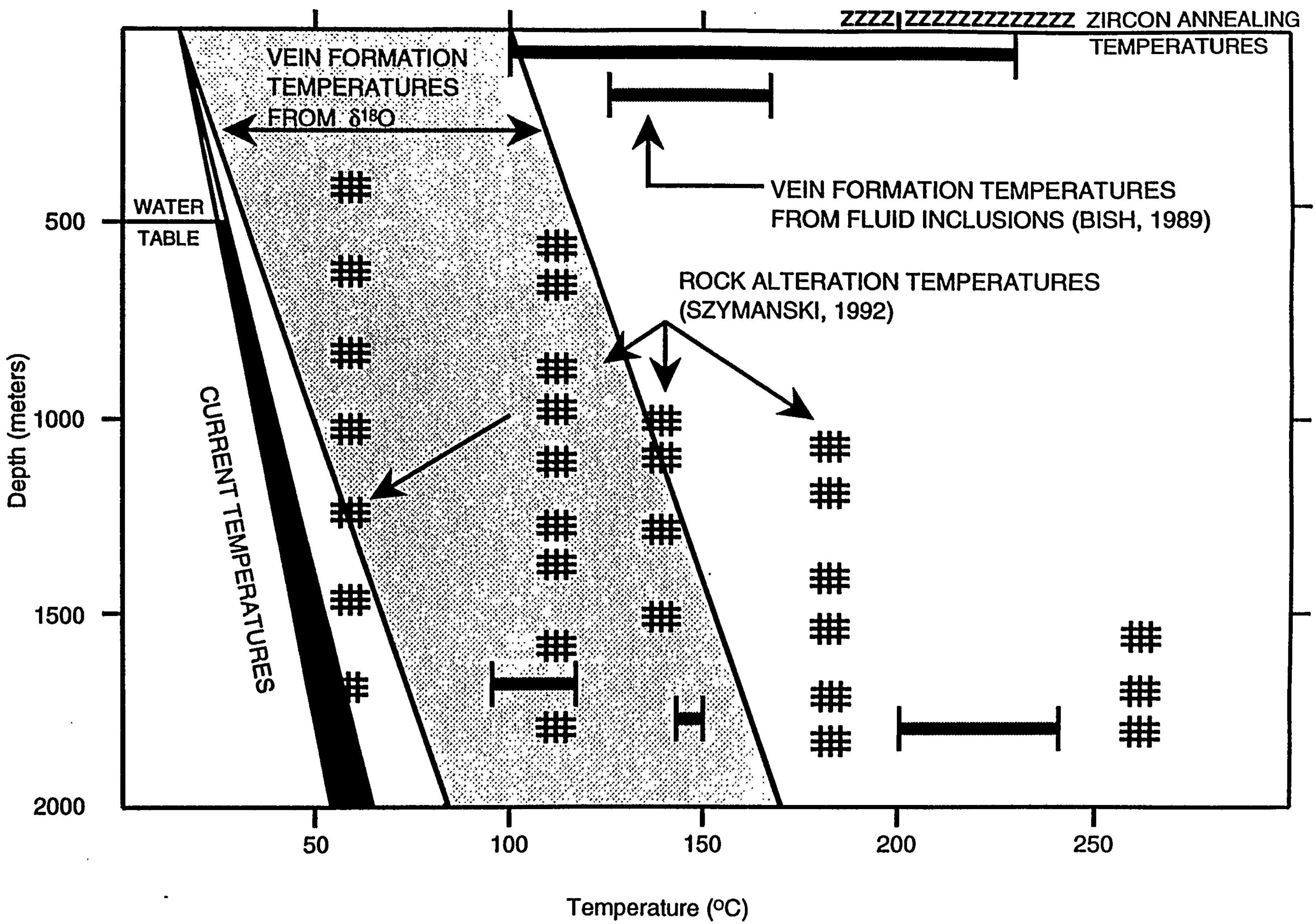
PART 1



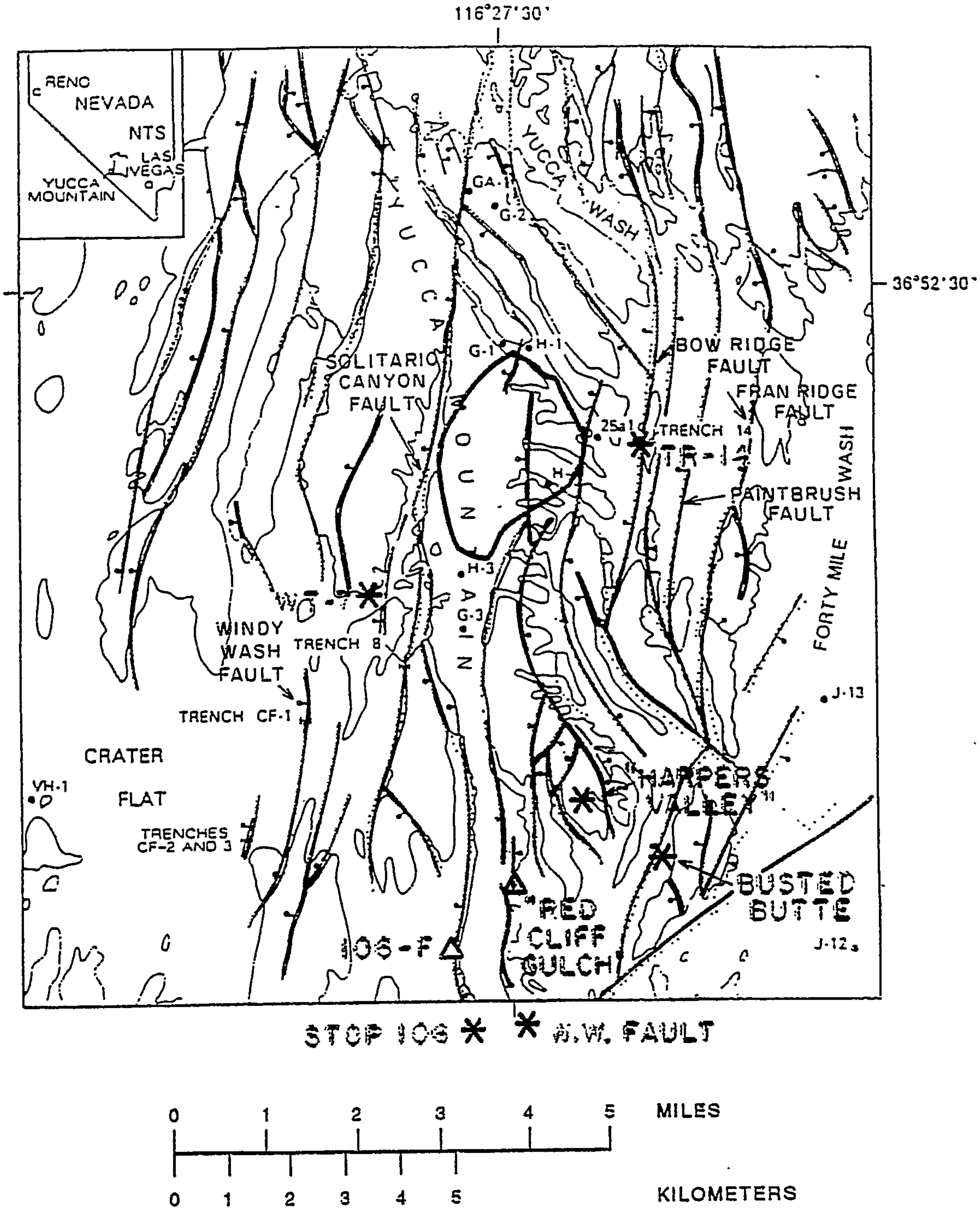
Schematic Depth Section of the Site Looking North
with depictions of faults, veins, water table and repository.

AGES OF FLUID ALTERATIONS AT YUCCA MOUNTAIN





THE SITE HAS BEEN INVADED BY HIGH TEMPERATURE FLUIDS



EXPLANATION

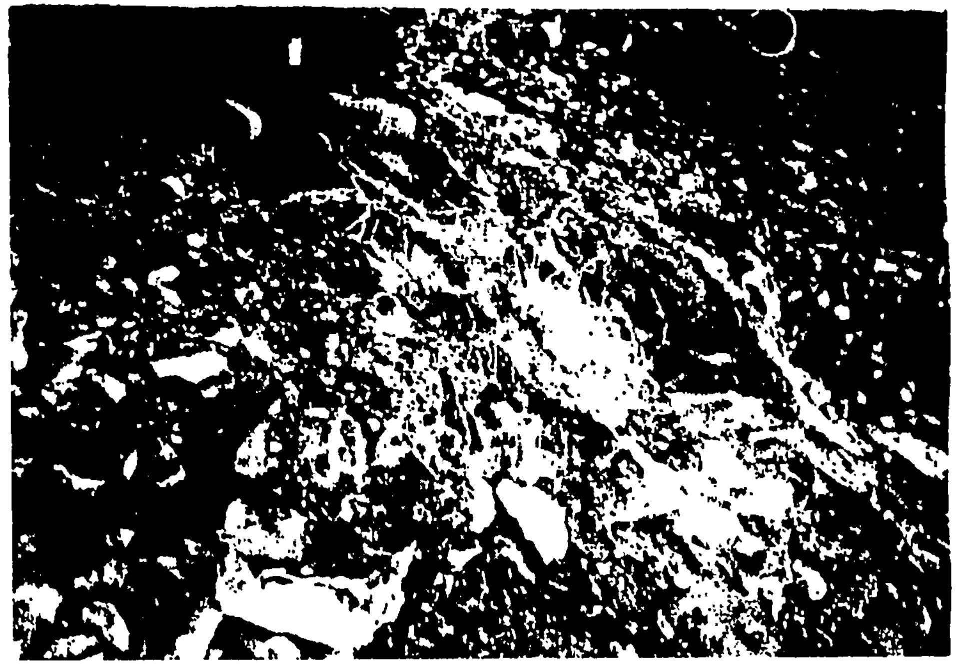
G-2 DRILL HOLE

TRENCH

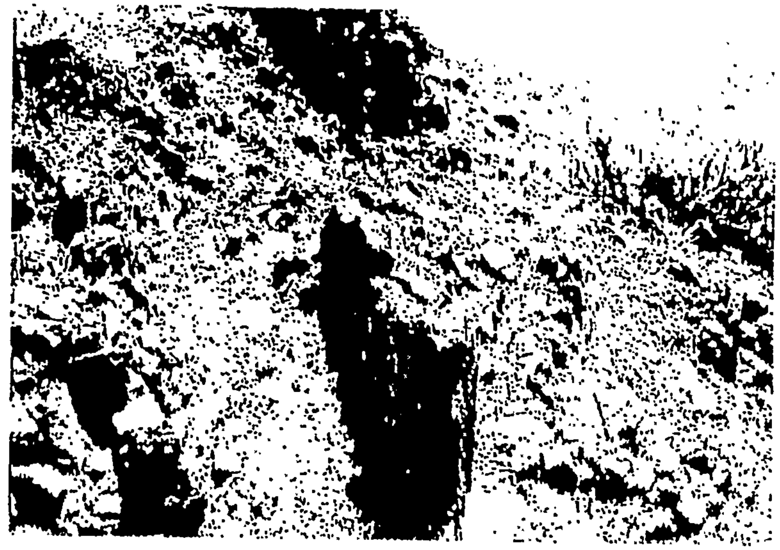
NORMAL FAULT--BAR AND BALL ON DOWNTHROWN SIDE

YUCCA MOUNTAIN AREA AND SELECTED FIELD EXPOSURES

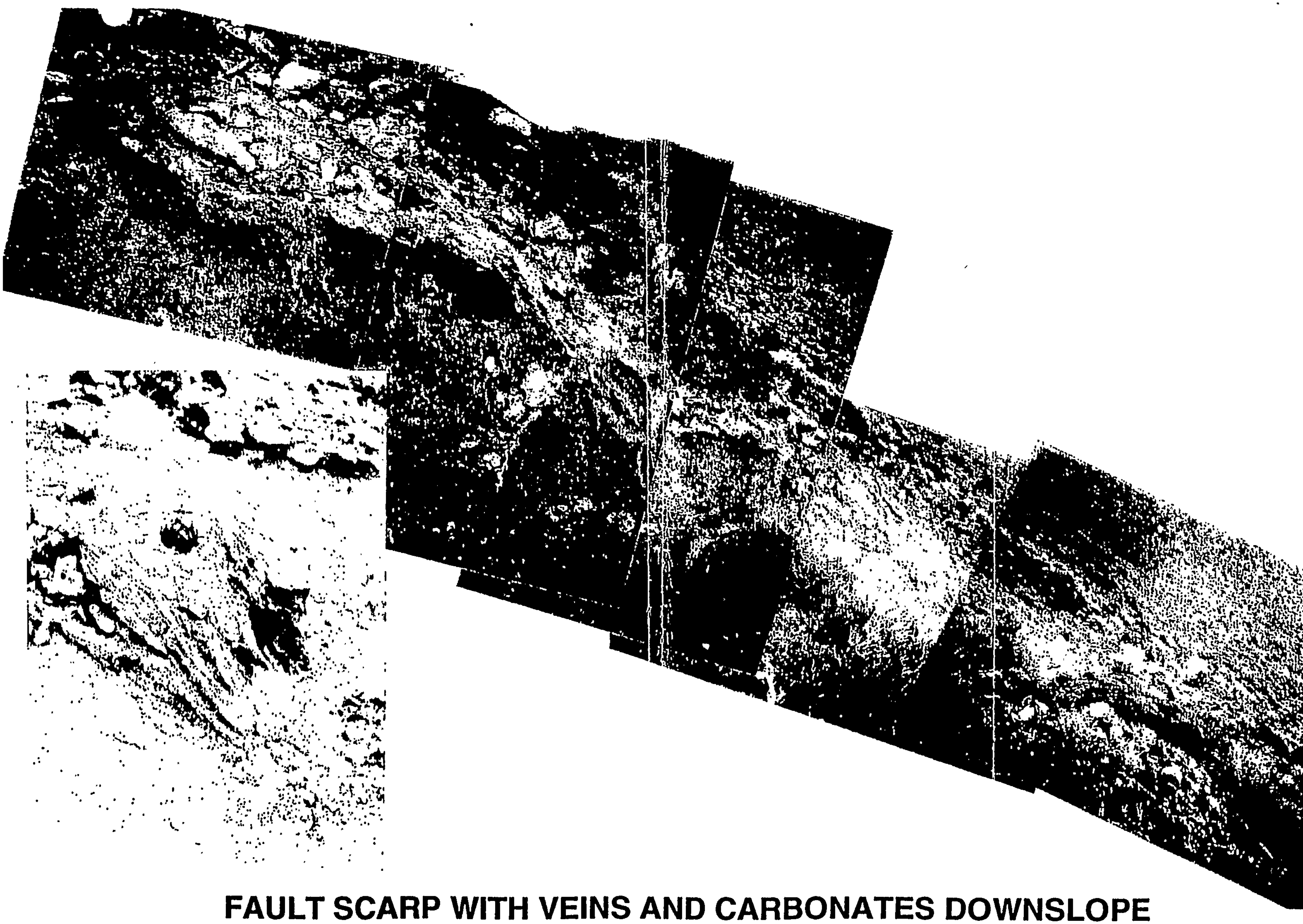
BOW RIDGE FAULT WITH MASSIVE VEINS AND DOWNSLOPE CARBONATES



PROBABLE EXPLOSION BRECCIAS ALONG SOLITARIO CANYON FAULT

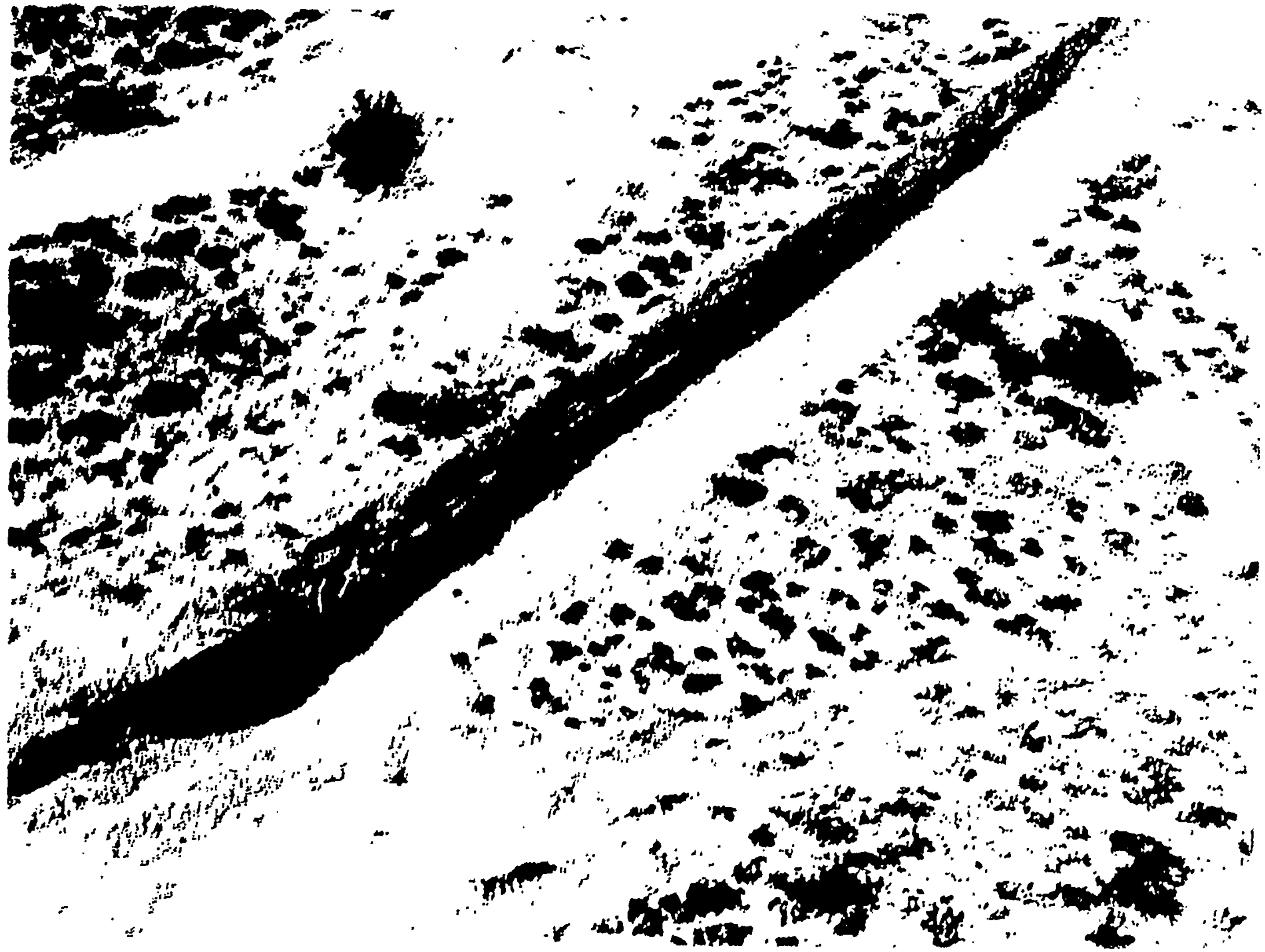


BRECCIA DIKES INDICATE ENERGETIC PROCESSES



FAULT SCARP WITH VEINS AND CARBONATES DOWNSLOPE

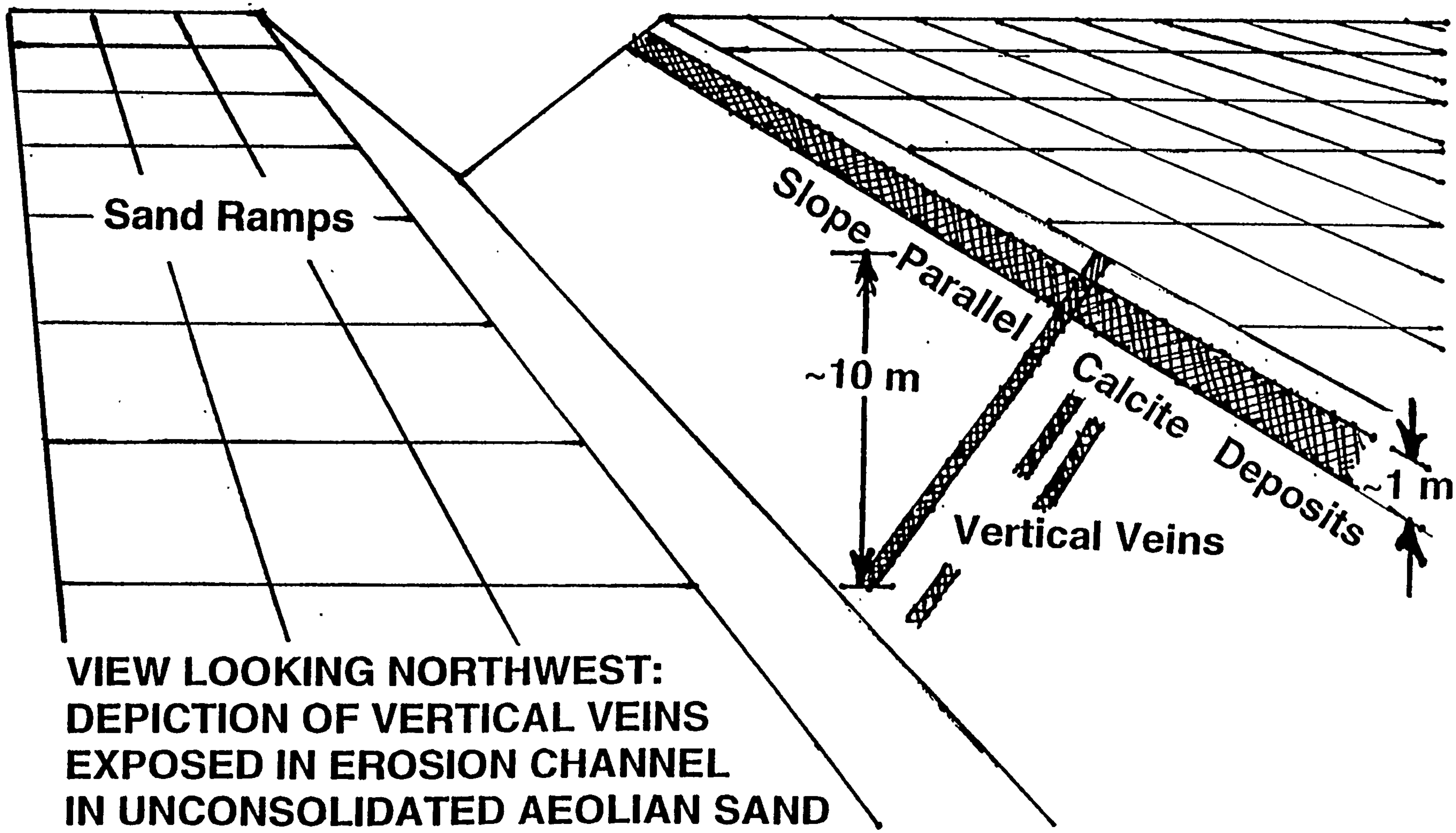
FAULT SCARP WITH VEINS AND CARBONATES DOWNSLOPE



BOW RIDGE FAULT WITH MASSIVE VEINS AND DOWNSLOPE CARBONATES


BOW RIDGE FAULT WITH MASSIVE VEINS AND DOWNSLOPE CARBONATES

East Flank of Busted Butte



VIEW LOOKING NORTHWEST: DEPICTION OF VERTICAL VEINS EXPOSED IN EROSION CHANNEL IN UNCONSOLIDATED AEOLIAN SAND

INTERPRETATIONS OF FLUID-INDUCED ALTERATIONS AT YUCCA MOUNTAIN

A.1. DIRECT OBSERVATIONS	→	FORMATION PROCESS	PARENT WATER
(a) Locations of Water Deposited Minerals			
– VEINS OF CALCITE & SILICA			
• common in faults & fractures	→	fracture flow	probable upwelling
• extend over depths from 0 to 2 km	→	deep source	upwelling
• veins in overlying alluvium & sand	→	springs	upwelling
– SURFACE CALCITES (CALCRETES)			
• occur downslope from faults	→	fault outflows	probable upwelling
• not abundant elsewhere	→	local sources	possible upwelling
(b) Forms of Water Deposited Minerals			
• high purity with isolated rock fragments	→	fast deposition	probable upwelling
• banded, like typical hydrothermal spring deposits (travertine)	→	changing water chemistry	upwelling
• thick bands of silica	→	high temperatures	upwelling
• voluminous calcite	→	imported calcium	probable upwelling
(c) Alterations of Rock Adjacent to Veins			
• altered coloration in adjacent rock	→	reactive fluids	probable upwelling
• fragmented (brecciated) bedrock	→	high pressure	probable upwelling with gas

CONCLUSIONS FROM FIELD OBSERVATIONS AND RADIOMETRIC AGES

Conclusion 1.

Multiple lines of evidence indicate that water has repeatedly discharged from Yucca Mountain in the past. Given the overall weight of supporting evidence, this interpretation is near certain.

Conclusion 2.

Local spring discharges appear to have recurred at time intervals of tens of thousands of years and,therefore, are important for repository safety.

PART 2

SOME ASPECTS OF
ALTERATION AND METASOMATISM
AT
YUCCA MOUNTAIN, NEVADA

PRESENTATION TO:

THE ASSOCIATION OF ENGINEERING GEOLOGISTS,
SOUTHWESTERN SECTION,
LAS VEGAS SUBSECTION,

NOVEMBER 10, 1992.

Donald E. Livingston
Technical and Resource Assessment Corp.
Boulder, Colorado.

OUTLINE

I. Chemical Analyses:

A. Microprobe analyses of glass,

Broxton, D. E., R. G. Warren, R. C. Hagan and Gary Luedemann, "Chemistry of Diagenetically Altered tuffs at a Potential Nuclear Waste Repository, Yucca Mountain, Nye County, Nevada", LA-10802-MS, Los Alamos National Laboratory, 1986.

B. Whole rock analyses,

Broxton *et al.*, 1986.

C. Microprobe analyses of zeolites,

Broxton *et al.*, 1986.

D. Mineralogy of bore hole USW G-1,

Bish, D.L. and S. J. Chipera, "Revised Mineralogic Summary of Yucca Mountain, Nevada", LA-11497-MS, Los Alamos National Laboratory, 1989.

E. Potassium-argon ages of clinoptilolite and illite-smectite,

WoldeGabriel, Giday, "Diagenetic Minerals, K/Ar data, and Alteration History in the Yucca Mountain, Nevada; A Candidate High-Level Radioactive Waste Repository", draft report, Los Alamos National Laboratory, 1991.II.

II. Principal types of materials compared:

A. Glass from welded ash flow tuffs (vitropheres) and bedded tuffs,

B. Whole rocks, mostly from zones of zeolitic alteration,

C. Clinoptilolites.

III. Principal alteration types:

A. Smectite-illite,

B. Zeolite, Clinoptilolite-mordenite-analcime.

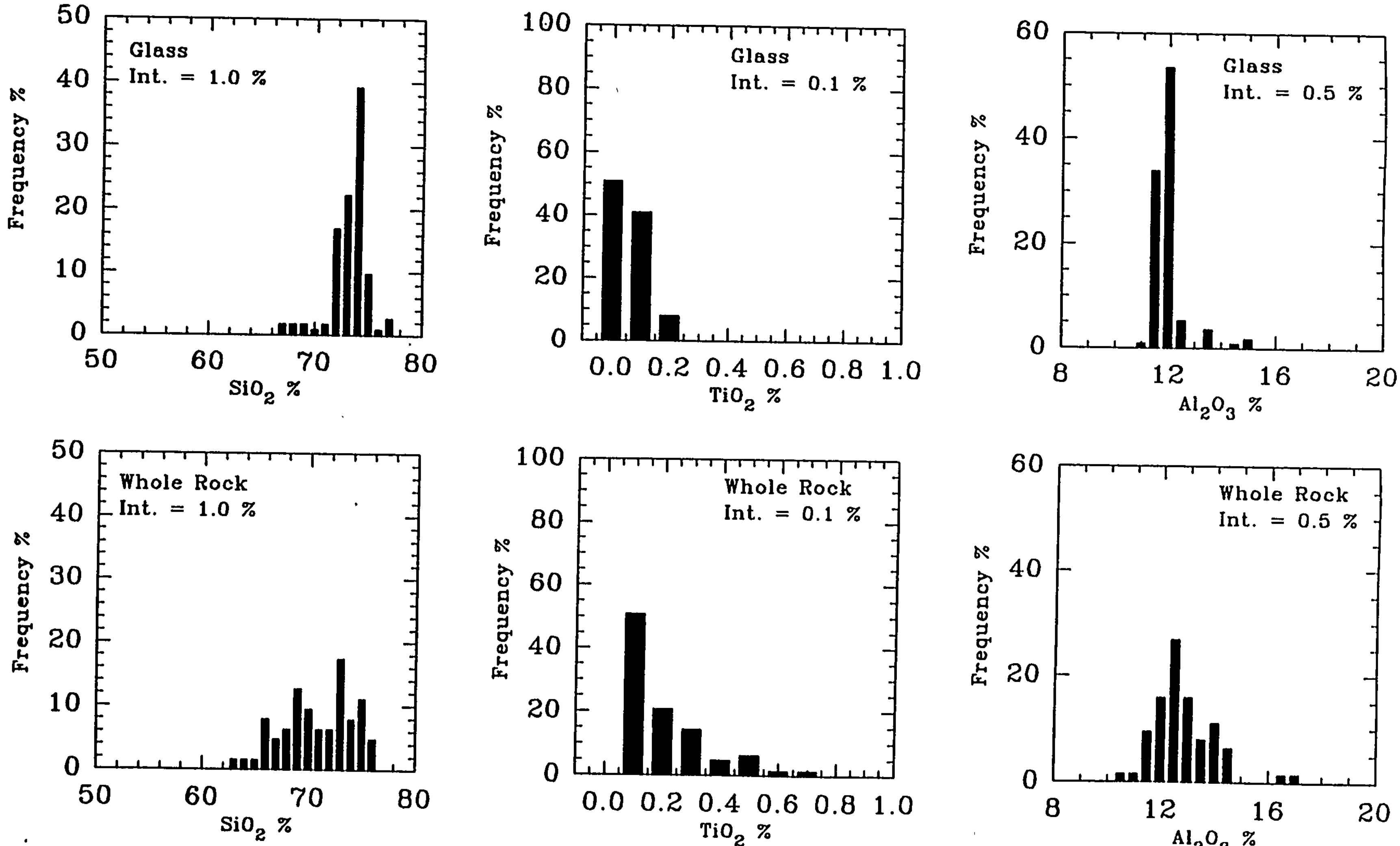
C. Opal,

D. Carbonate, (calcite).

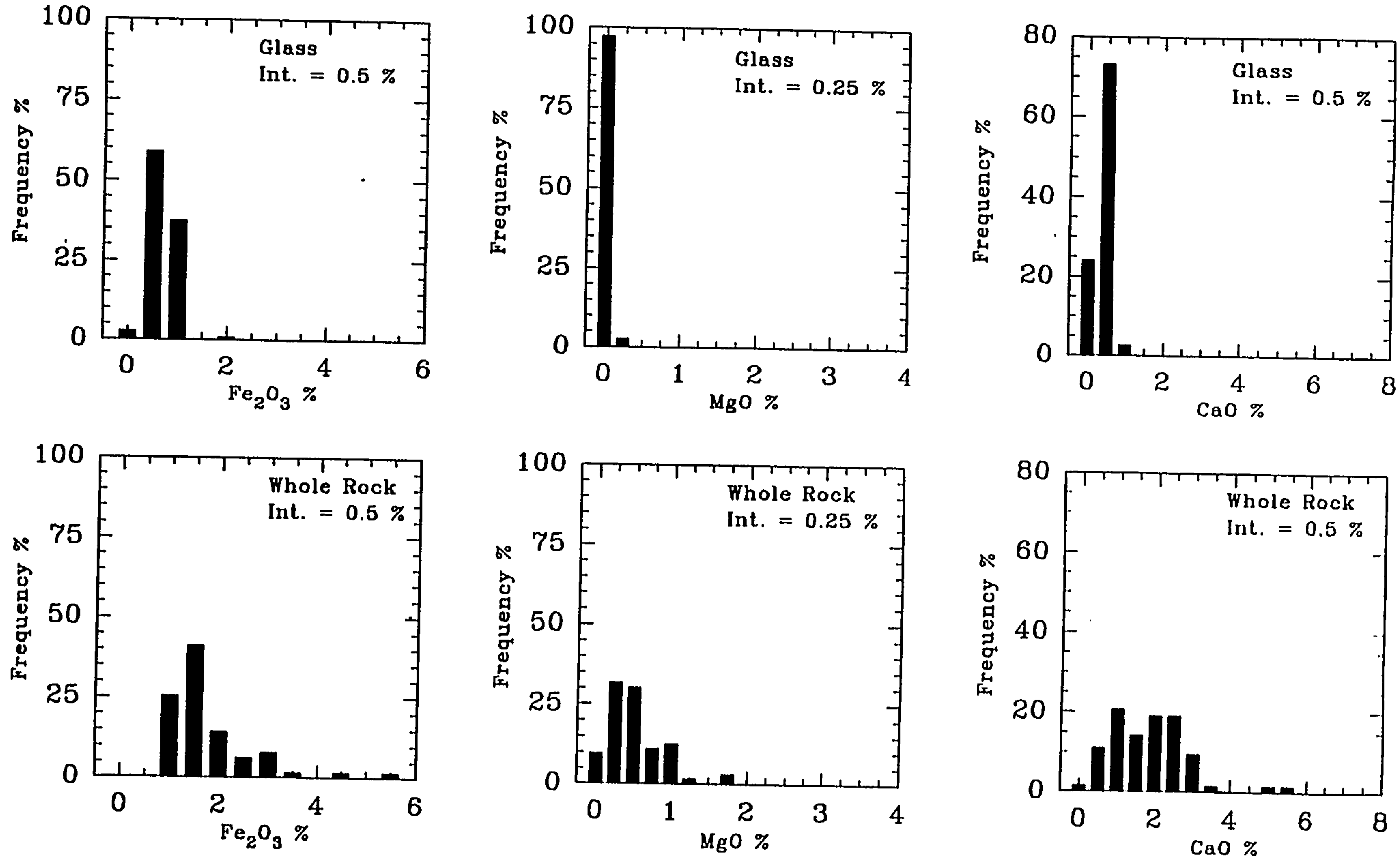
IV. Graphical presentation, first Part:

A. Comparison of glass chemistry with whole rock chemistry,

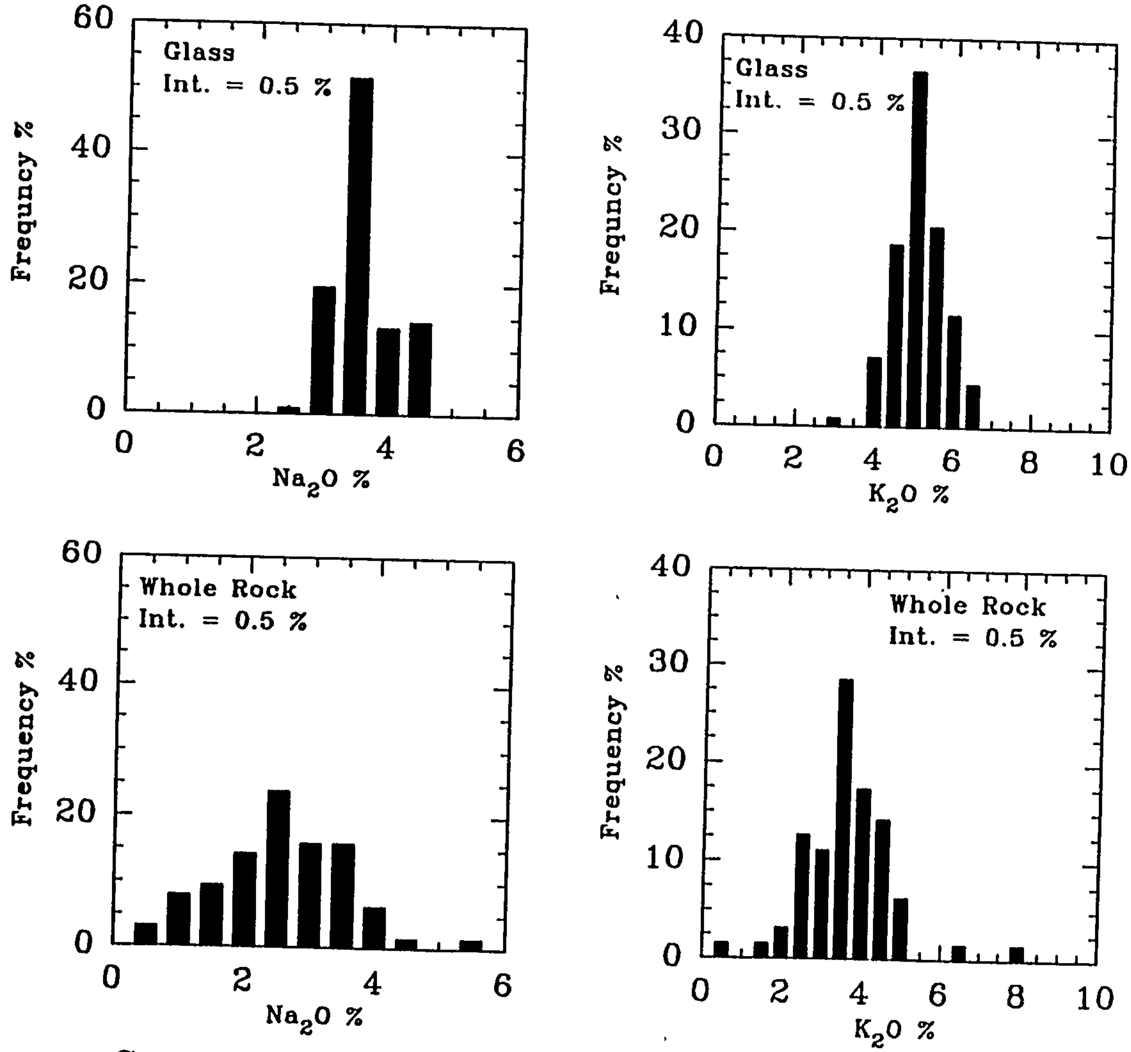
1. Histograms of:
   SiO_2, TiO_2, Al_2O_3, Fe_2O_3, MgO, CaO, Na_2O, K_20.
2. Cross plots of:
   Al_2O_3 vs. SiO_2, Al_2O_3 vs. CaO, MgO vs. CaO, K_2O vs. CaO, Na_2O vs. CaO, Na_2O vs. K_2O, TiO_2 vs. Fe_2O_3



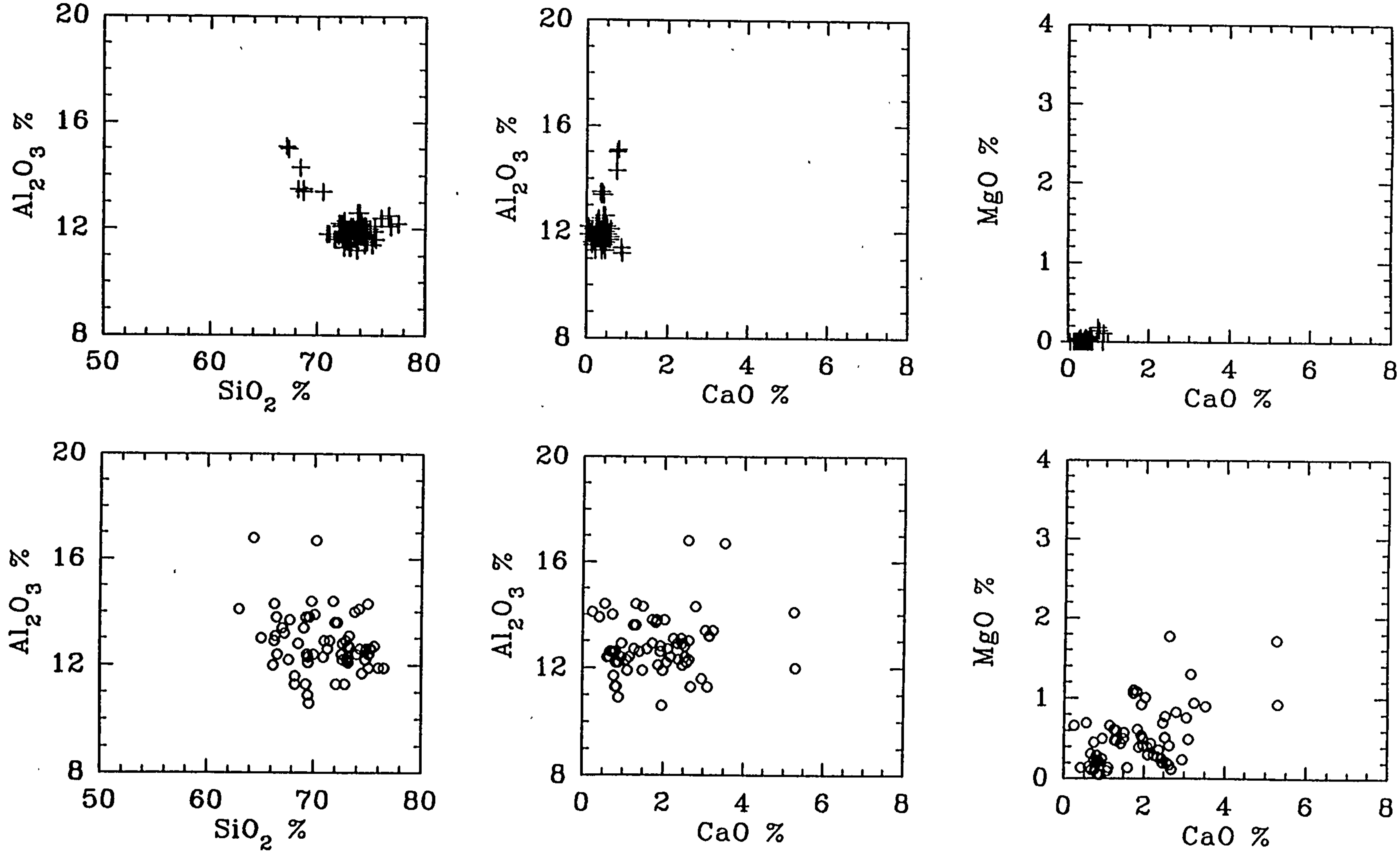
Comparison Between Glass and Whole Rock of SiO_2, TiO_2 and Al_2O_3 for Tuffs of Yucca Mountain, Nevada.



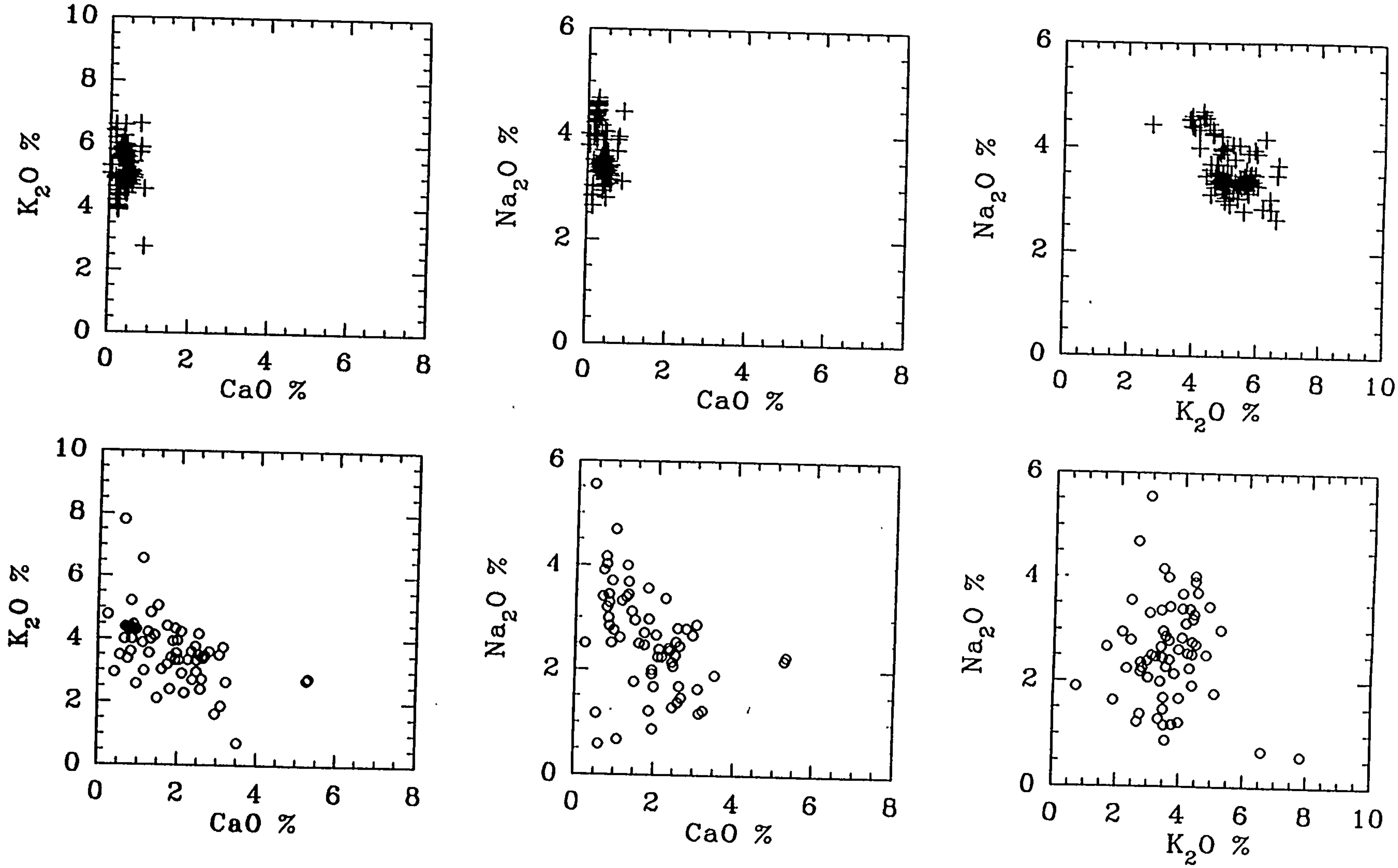
Comparison Between Glass and Whole Rock of Fe_2O_3, MgO and CaO for Tuffs of Yucca Mountain, Nevada.



Comparison Between Glass and Whole Rock of Na_2O and K_2O for Tuffs of Yucca Mountain, Nevada.



Comparison Between Glass (+) and Whole Rock (∘) of Al_2O_3 vs. SiO_2, Al_2O_3 vs. CaO and MgO vs. CaO for Yucca Mountain, Nevada.

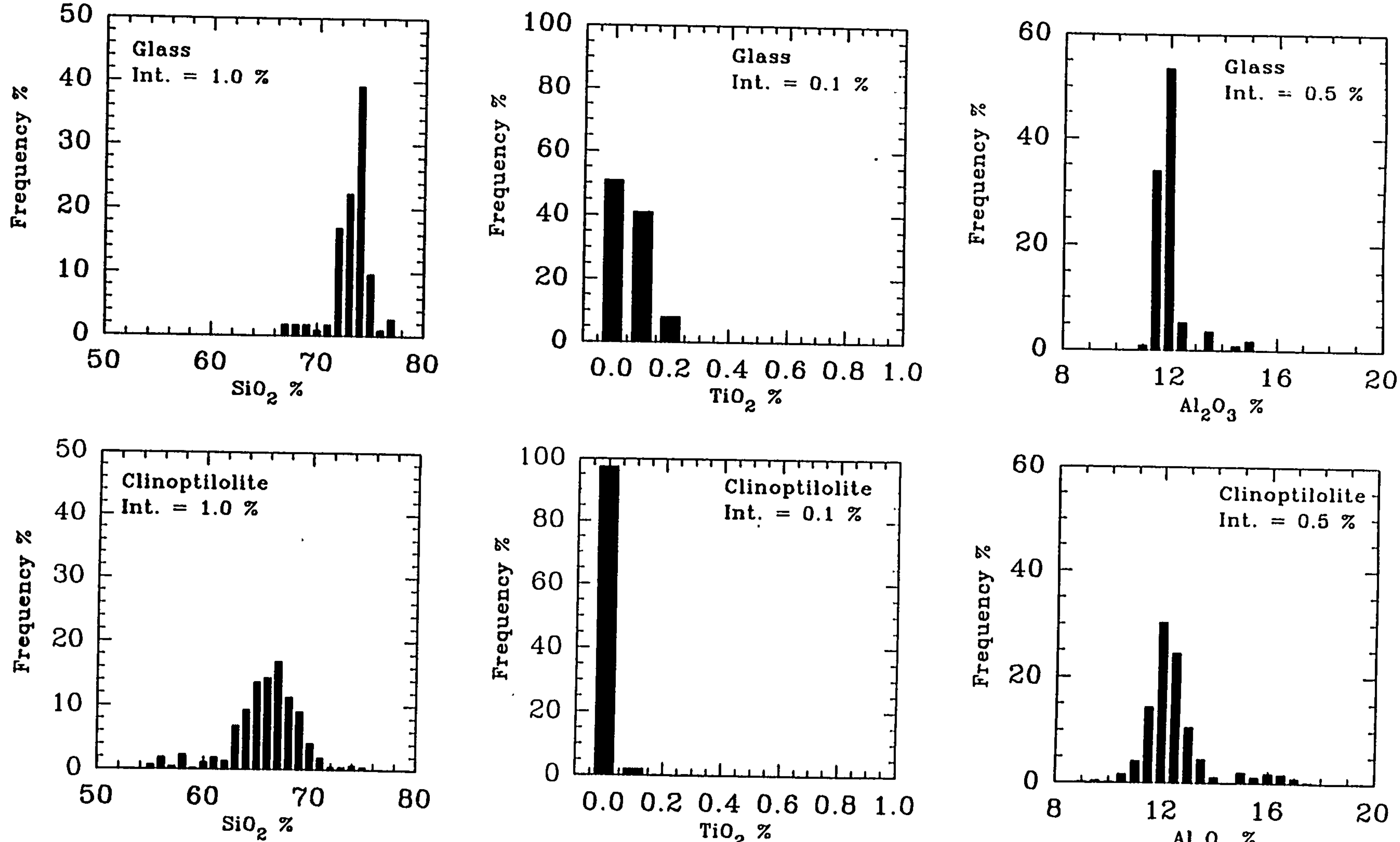


Comparison Between Glass (+) and Whole Rock (∘) of K_2O vs. CaO, Na_2O vs. CaO and Na_2O vs. K_2O for Yucca Mountain, Nevada.

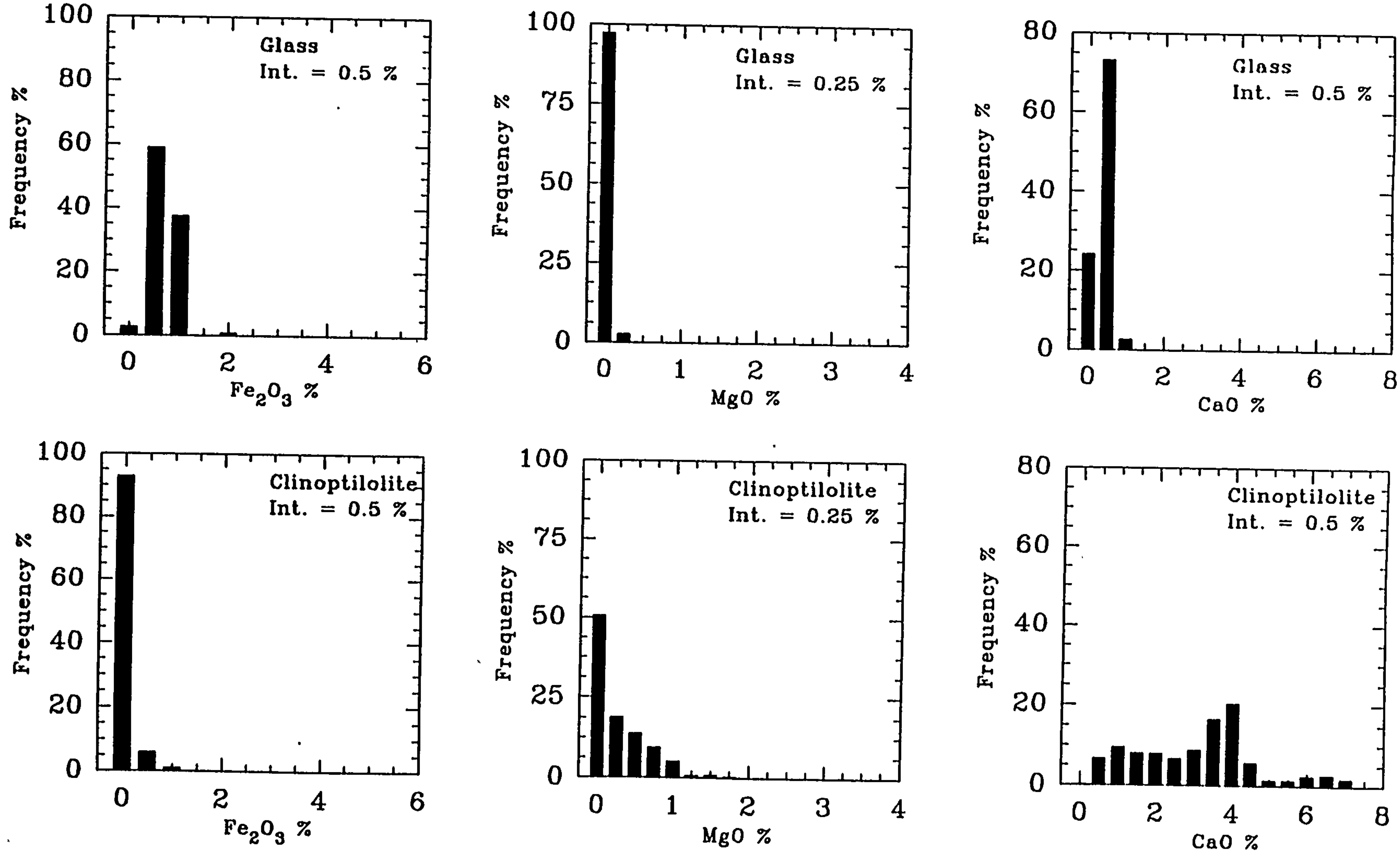
IV. Graphical presentation, first Part:

B. Comparison of glass chemistry with clinoptilolite chemistry.

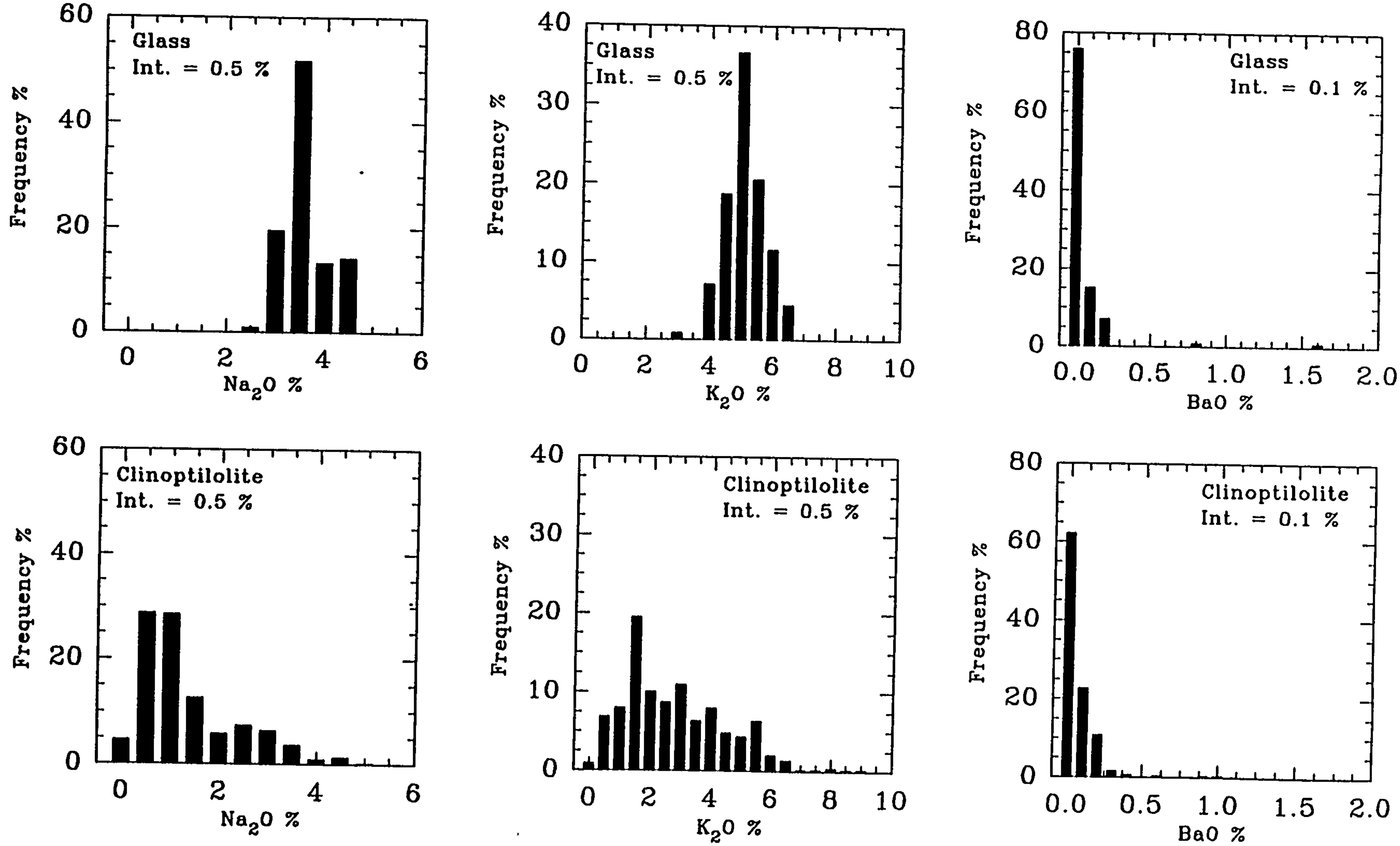
1. **Histograms of:**
   SiO_2, TiO_2, Al_2O_3, Fe_2O_3, MgO, CaO, Na_2O, K_2O, BaO.
2. **Cross plots of:**
   Al_2O_3 vs. SiO_2, Al_2O_3 vs. CaO, MgO vs. CaO, K_2O vs. CaO, Na_2O vs. CaO, Na_2O vs. K_2O.



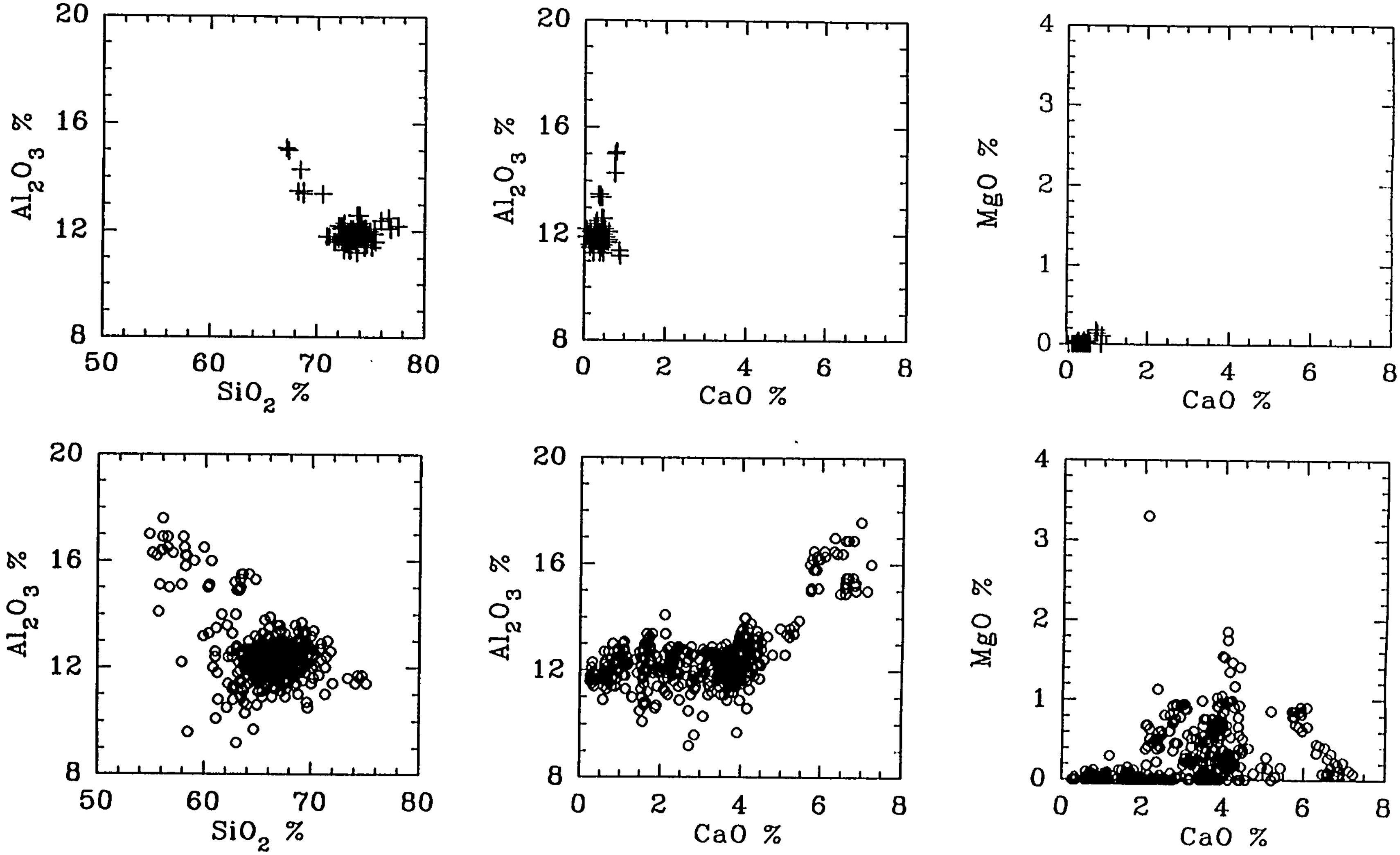
Comparison Between Glass and Clinoptilolite of SiO_2, TiO_2 and Al_2O_3 for Tuffs of Yucca Mountain, Nevada.



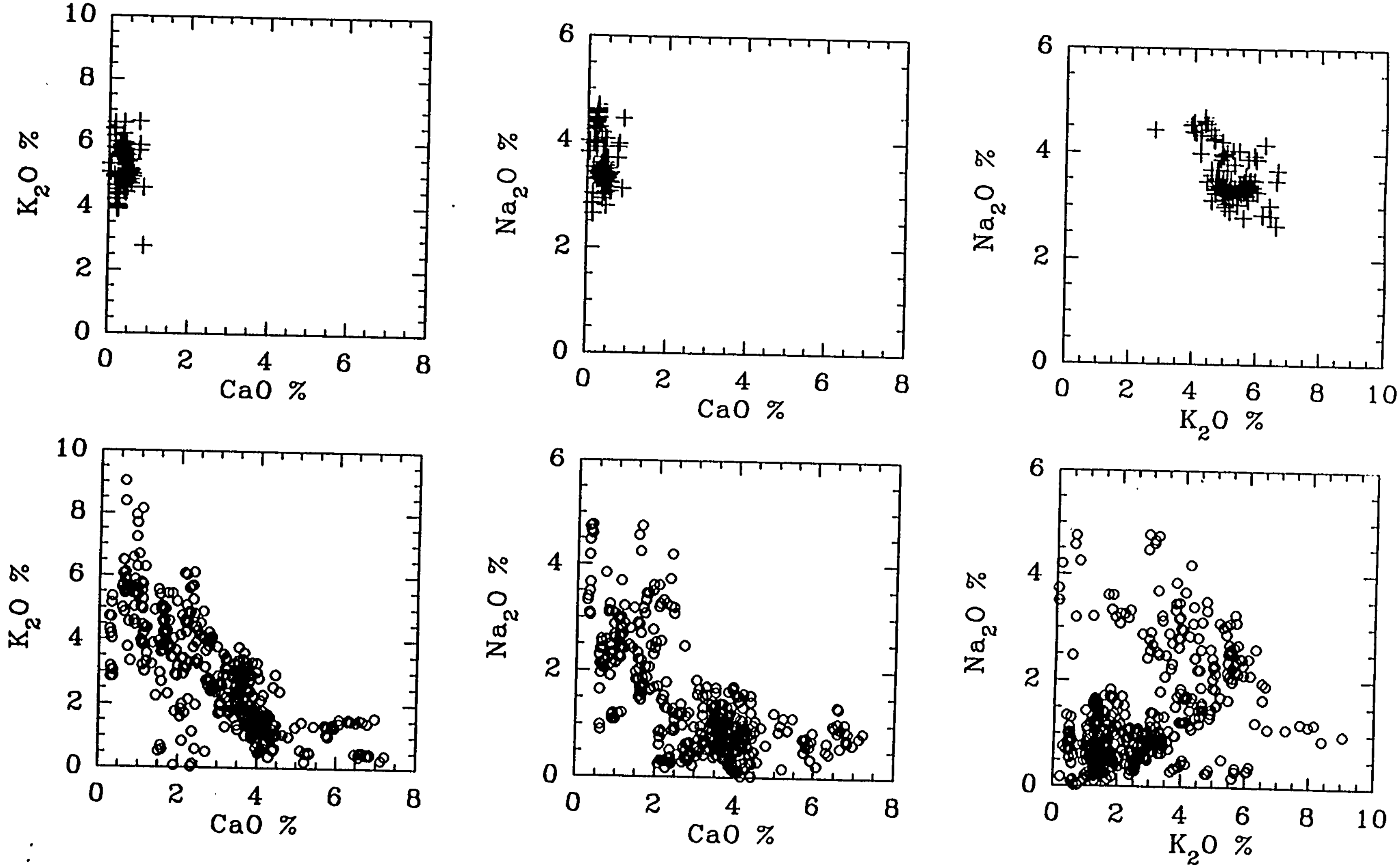
Comparison Between Glass and Clinoptilolite of Fe_2O_3, MgO and CaO for Tuffs of Yucca Mountain, Nevada.



Comparison Between Glass and Clinoptilolite of Na_2O, K_2O and BaO for Tuffs of Yucca Mountain, Nevada.



Comparison Between Glass (+) and Clinoptilolite (∘) of Al_2O_3 vs. SiO_2, Al_2O_3 vs. CaO and MgO vs. CaO, for Yucca Mountain, Nevada.



Comparison Between Glass (+) and Clinoptilolite (○) of K_2O vs. CaO, Na_2O vs. CaO and Na_2O vs. K_2O for Yucca Mountain, Nevada.

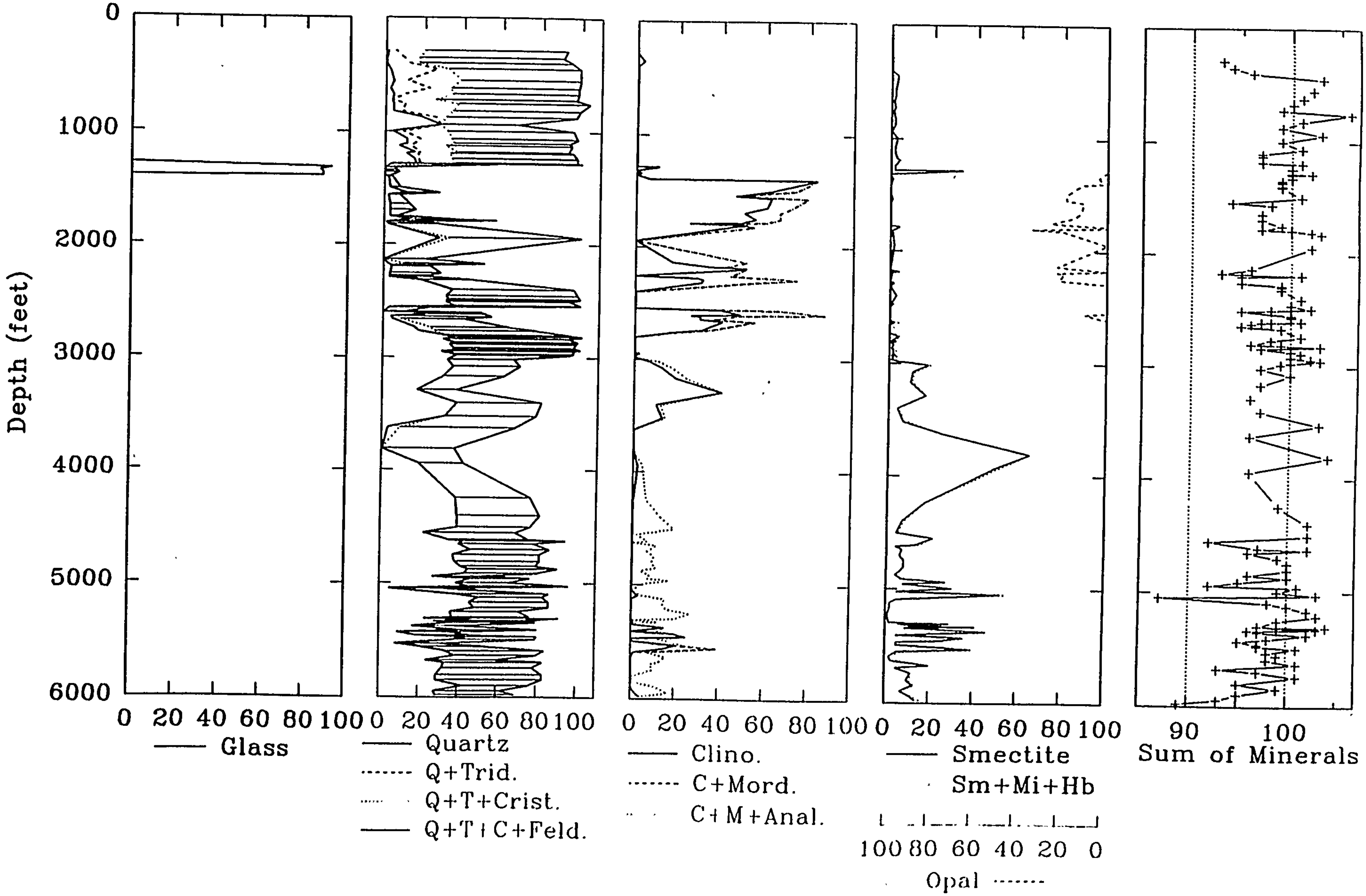
V. Graphical presentation, Second Part:

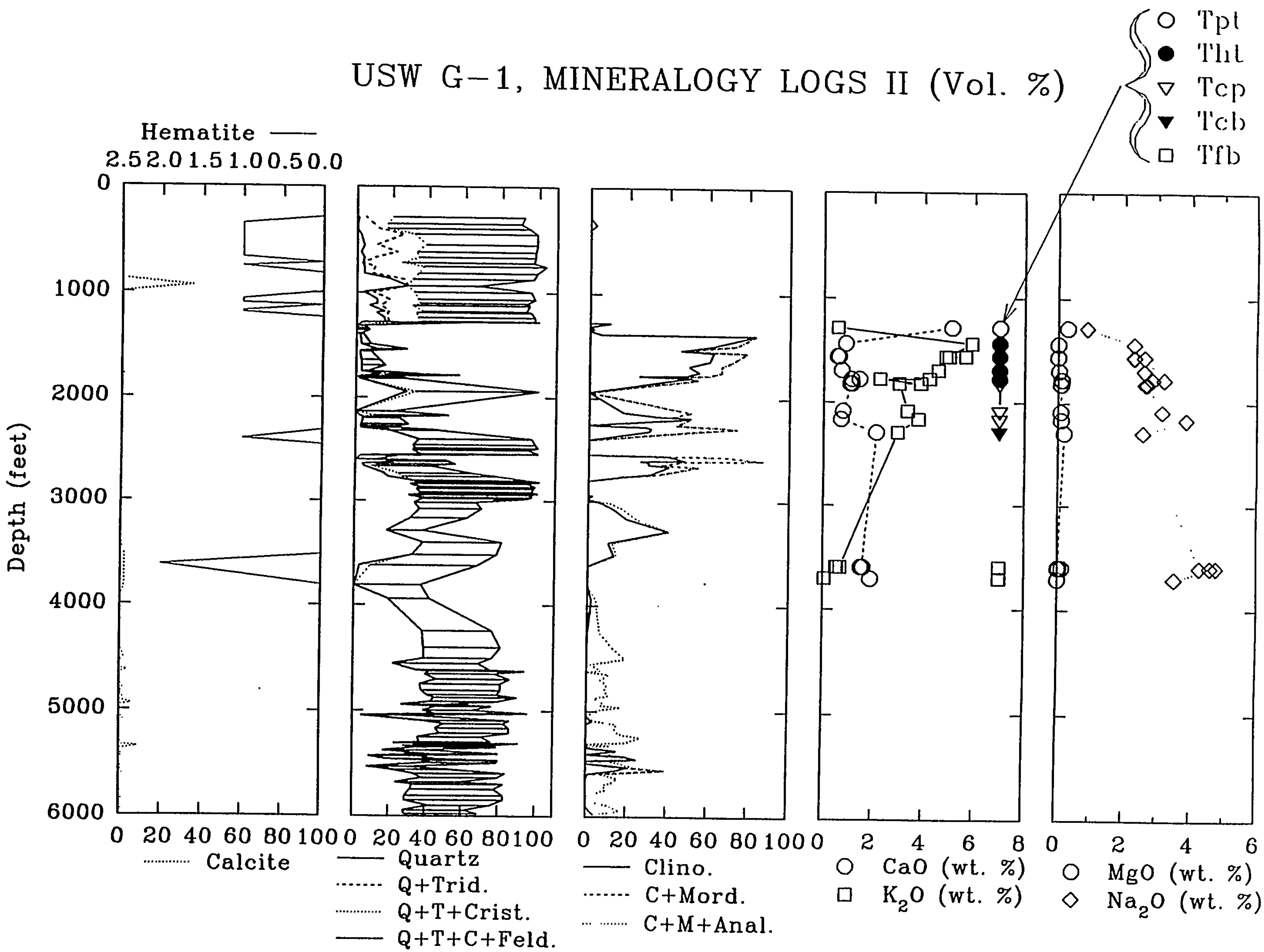
A. Comparison of mineralogy with clinoptilolite chemistry in bore hole USW G-1.

1. Mineralogy Log of bore hole USW G-1.

2. Comparison of zeolite chemistry with mineralogy of bore hole USW G-1.

USW G-1, MINERALOGY LOGS I (Vol. %)

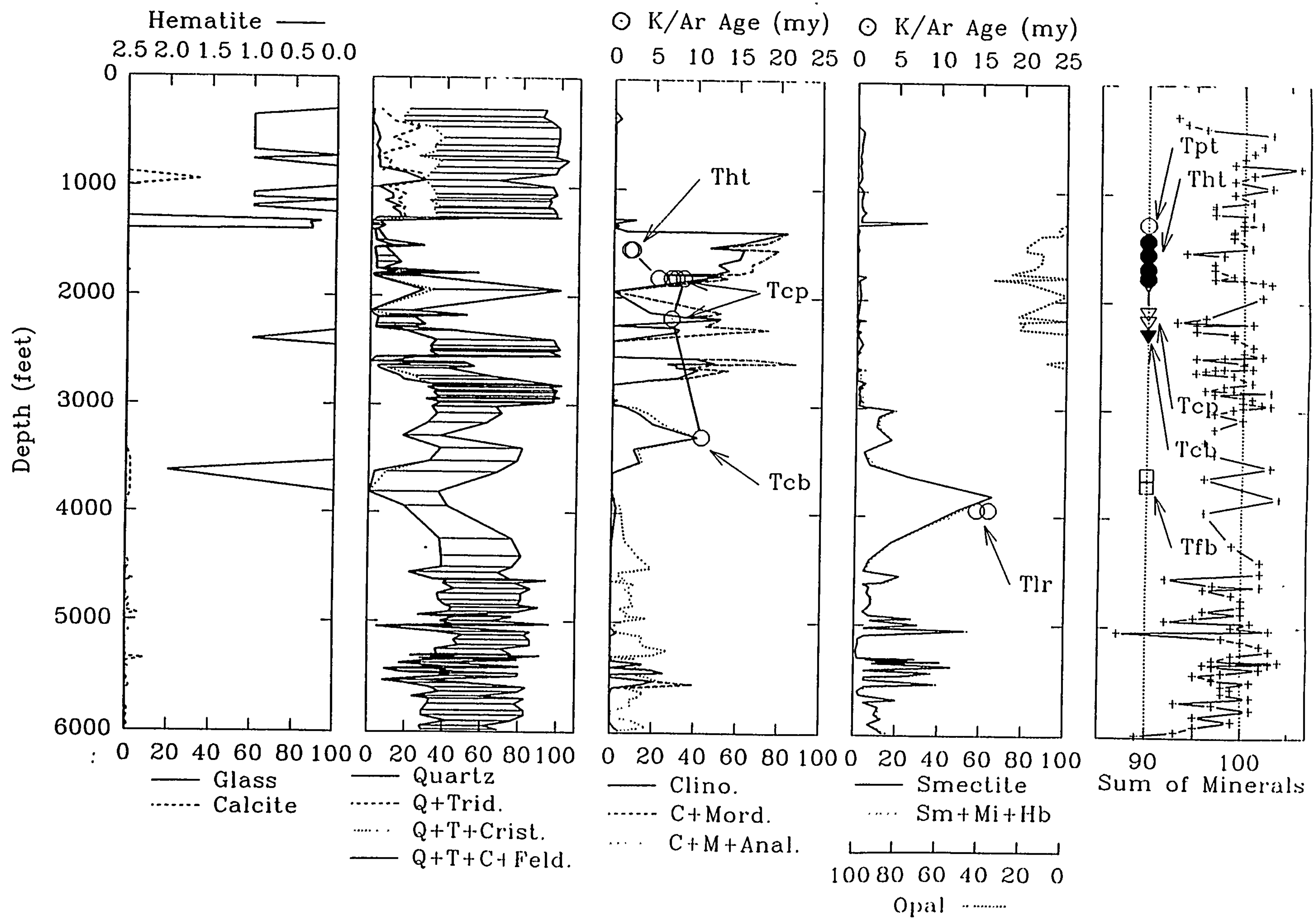



USW G-1, MINERALOGY LOGS II (Vol. %)
Tpt
Tht
Tcp
Tcb
Tfb
Hematite
2.5 2.0 1.5 1.0 0.5 0.0
Depth (feet)
0
1000
2000
3000
4000
5000
6000
0 20 40 60 80 100
Calcite
0 20 40 60 80 100
Quartz
Q+Trid.
Q+T+Crist.
Q+T+C+Feld.
0 20 40 60 80 100
Clino.
C+Mord.
C+M+Anal.
0 2 4 6 8
CaO (wt. %)
K_2O (wt. %)
0 2 4 6
MgO (wt. %)
Na_2O (wt. %)

V. Graphical presentation, Second Part:

B. Comparison of K/AR Ages with mineralogy of bore hole USW G-1.

USW G-1, MINERALOGY LOGS III (Vol. %)



VI. Summary and conclusions:

A. Summary:

1. Zeolites are diversely distributed in space at Yucca Mountain, from the surface at Prow Pass to more than 6,000 feet deep.

2. Zeolites and zeolitic alteration are exceedingly abundent at Yucca Mountain.

3. The chemistry of clinoptilolites is diverse for silica and alumina and exceedingly diverse for soda, potash, magnesia and lime.

4. The K/Ar ages of clinoptilolites range from 10 to 2 million years.

VI. Summary and conclusions:

B. Conclusions:

1. The zeolites at Yucca Mountain are ***polygenetic***, having been formed from a variety of waters of diverse chemistry, from various sources at more than one, if not many, times.

2. Because of its great abundance and chemical and spatial diversity, the origin of the zeolitic alteration is best understood as ***hypogene***, that is to say, formed by the upwelling of water from deep seated sources.

3. These waters from deep seated sources have reached upward to the present day surface of Yucca Mountain and the possibility of this happening again must be seriously considered.

4. These conclusions are the same as conclusions that can be drawn from data and observations of vein deposits and other indications of hydrothermal alteration .

PART 3

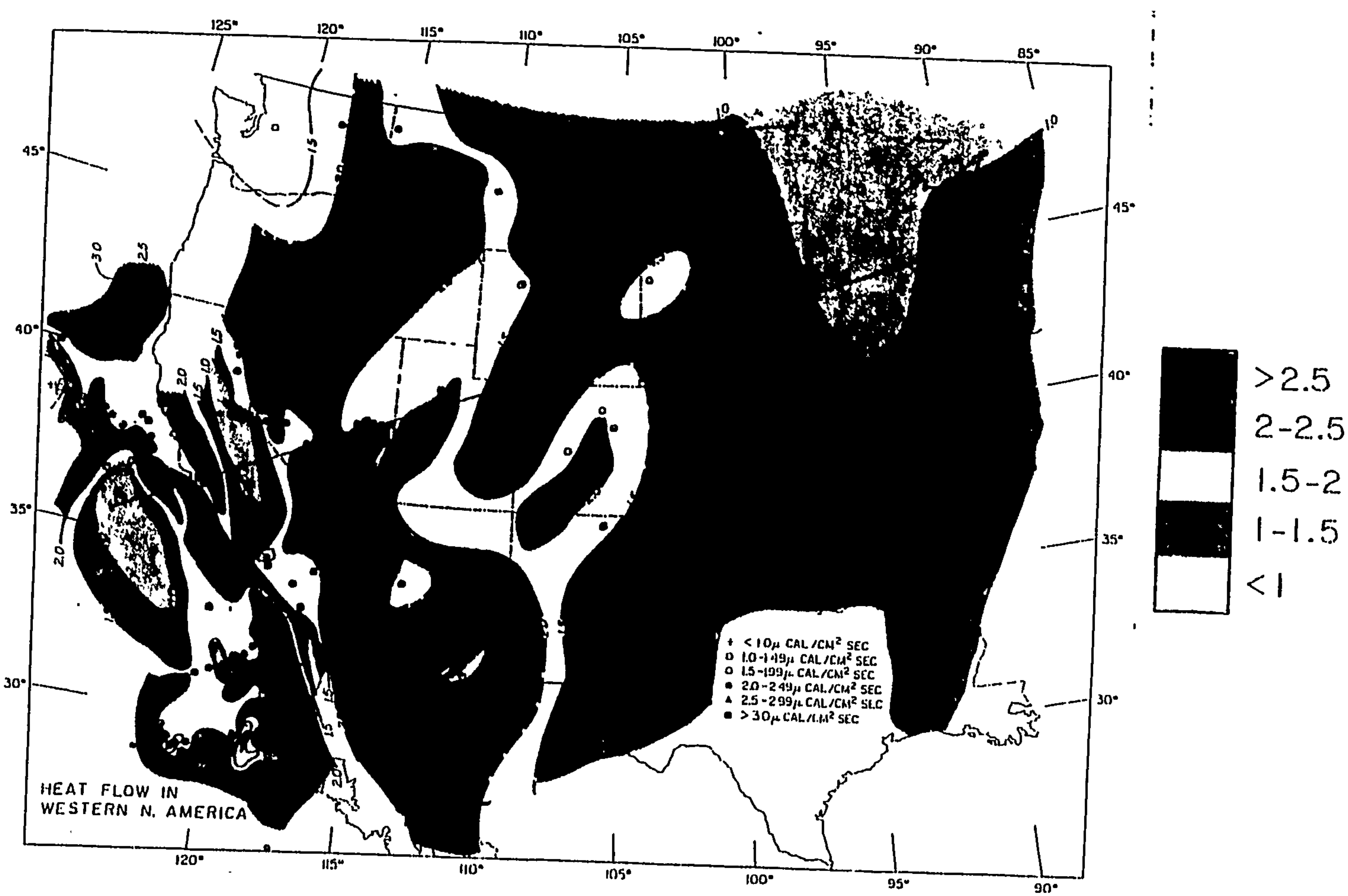
GEODYNAMICS

Heat flow and crust/mantle structure of the western United States.

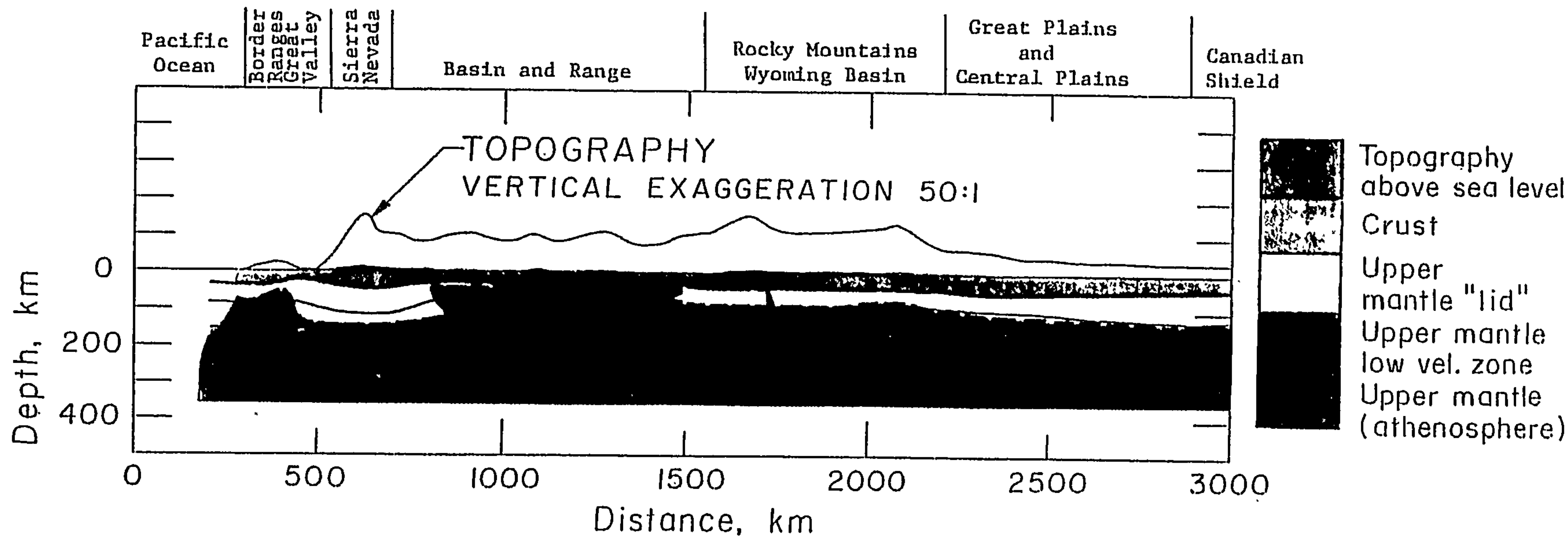
Crust/mantle structure in the vicinity of Yucca Mountain.

Heat flow in the Yucca Mountain vicinity.

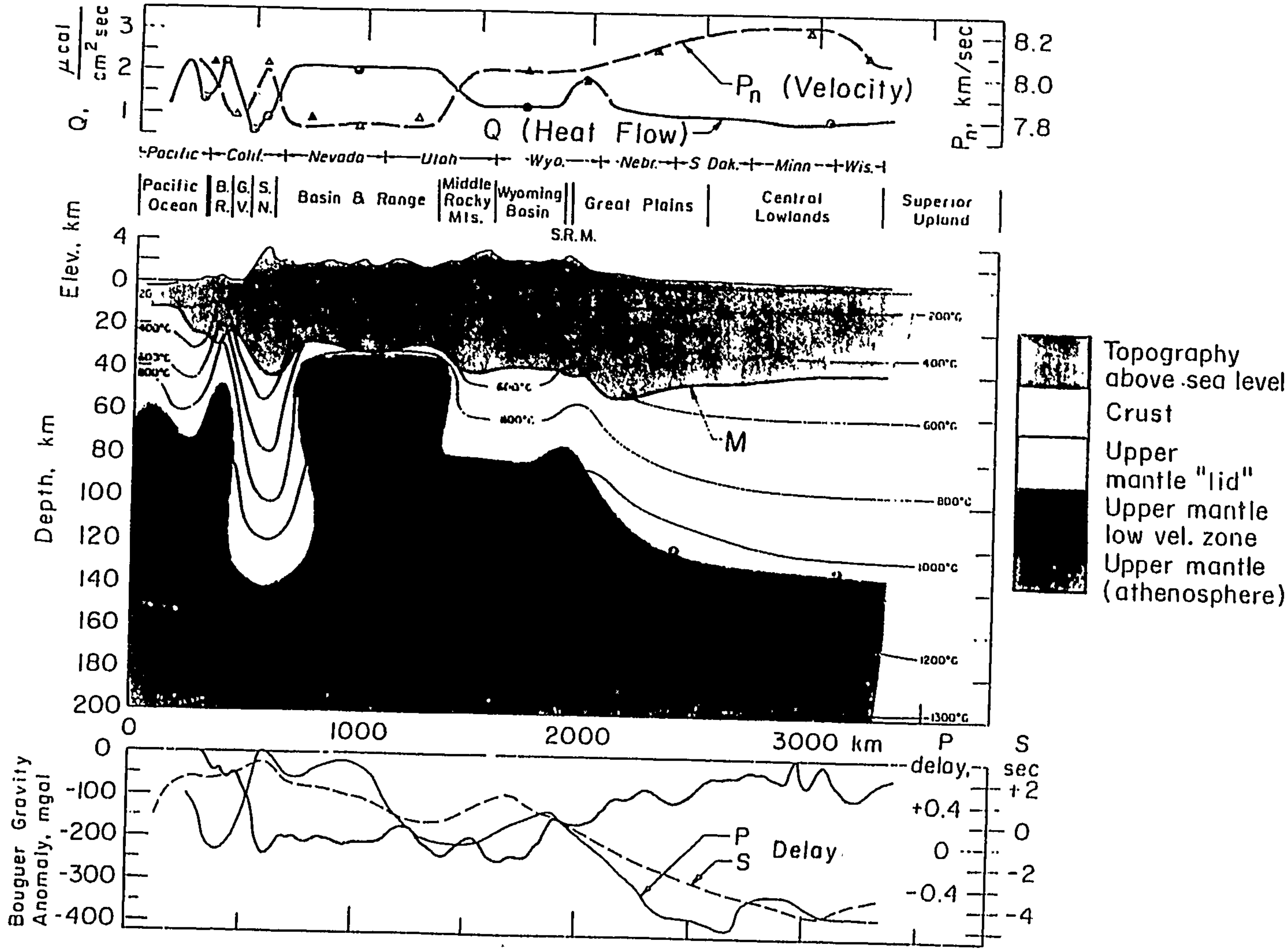
Paleogeothermal conditions at Yucca Mountain.



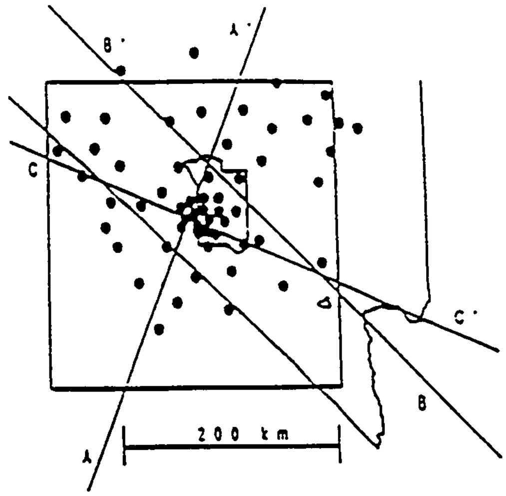
TERRESTRIAL HEAT FLOW, WESTERN U.S.



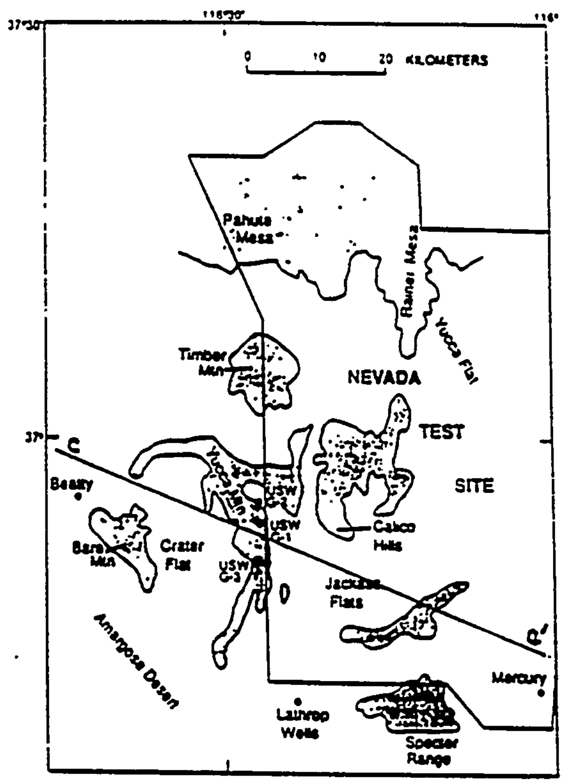
CRUST AND UPPER MANTLE STRUCTURE



Continental structure section showing the crust and upper mantle along the profile AA' in Figure 13. Major chemical- physical divisions of the upper mantle (eg. "Lid zone" and "Low Velocity zone") are also shown. The (partially molten) upper mantle "Low Velocity Zone" gives rise to high heat flow values at the surface, low gravity observations and low compression wave velocities within the Basin and Range.

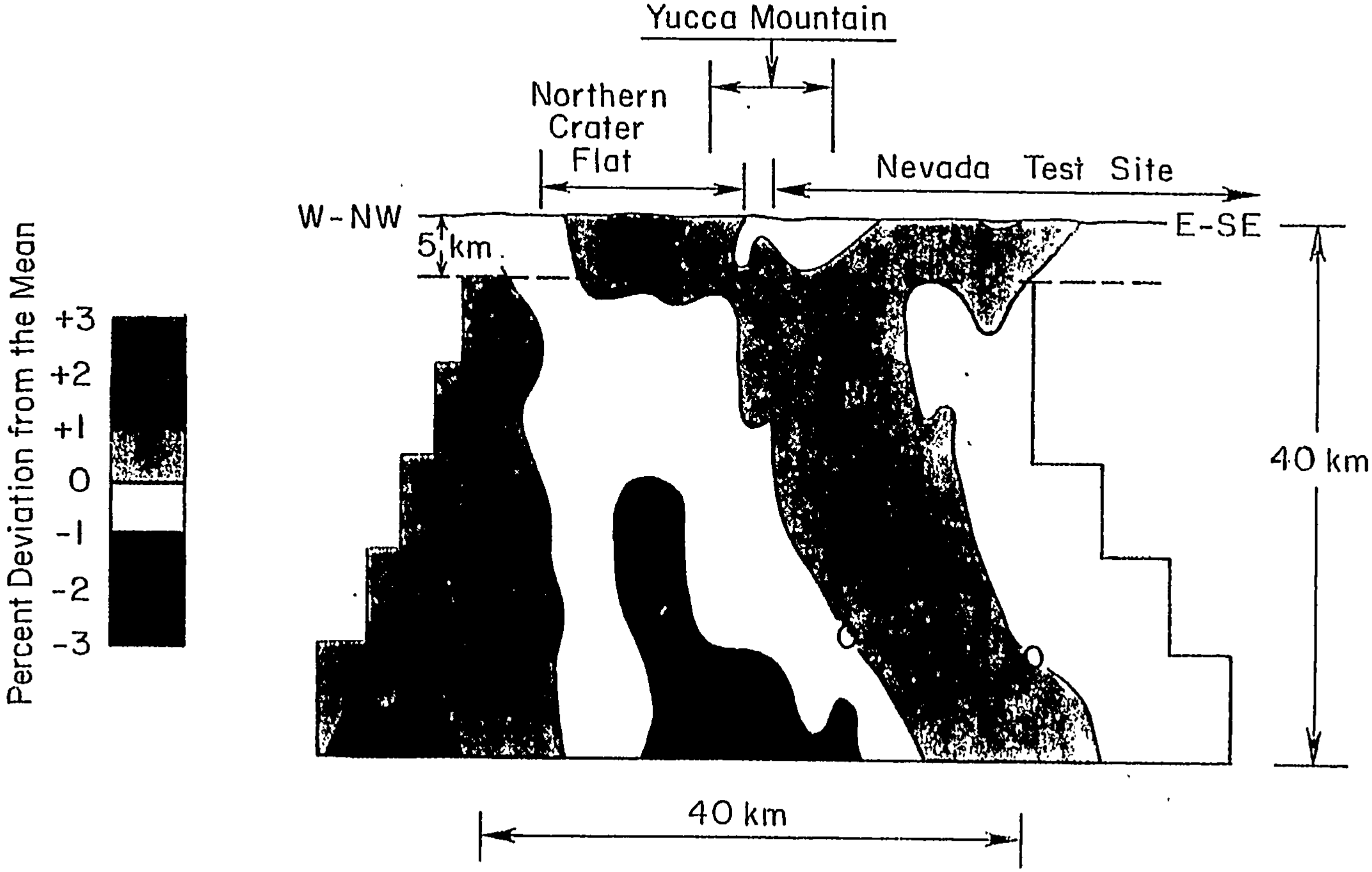


TOMOGRAPHIC SECTIONS



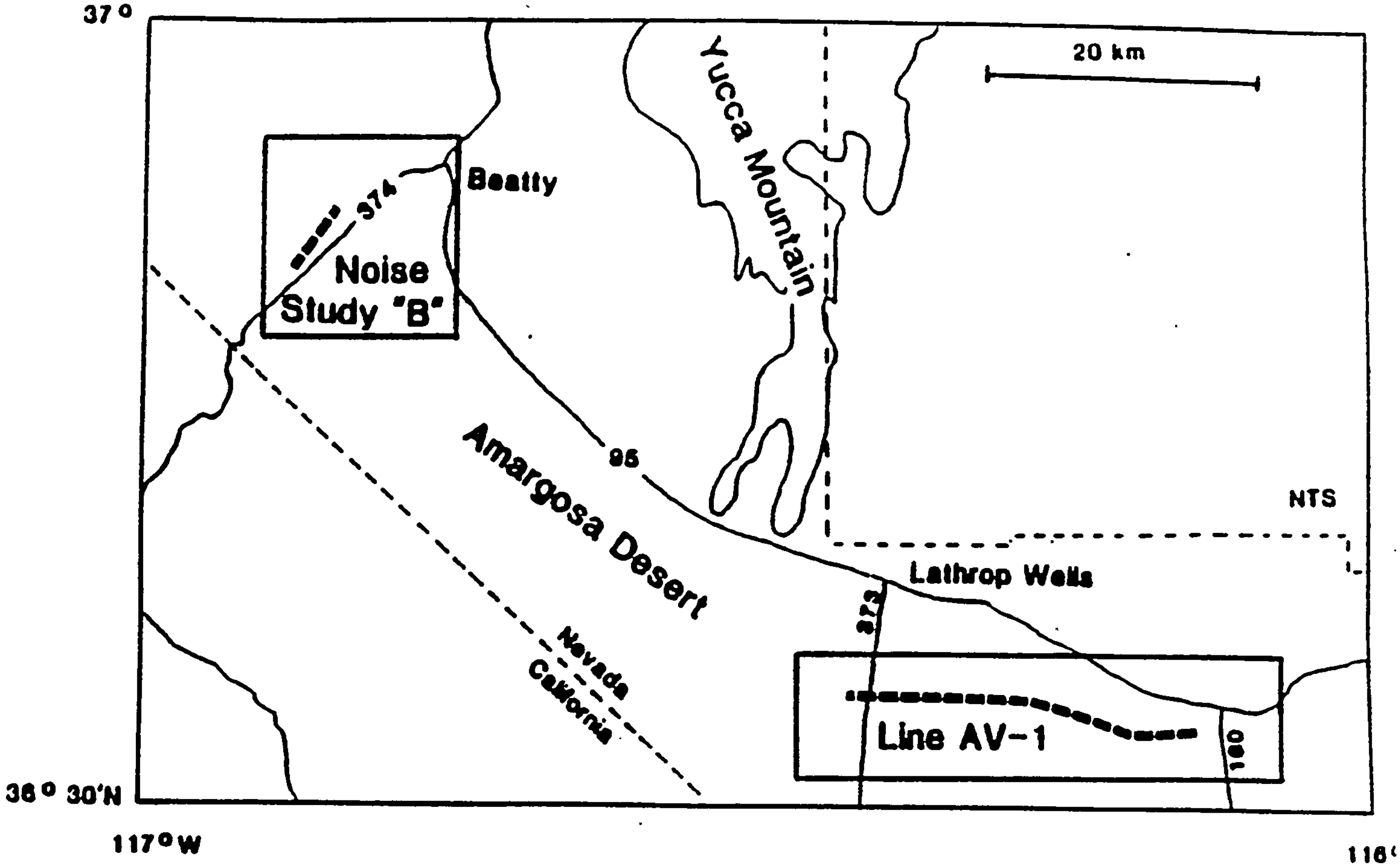
Maps of the seismic station distribution and principal topographic features in the Yucca Mountain and Nevada Test Site areas. Tomographic sections showing the structure at depth along the profiles AA', BB' and CC' were obtained by Evans and Smith, 1992.

Crustal Compressional Velocity Variations at Yucca Mountain

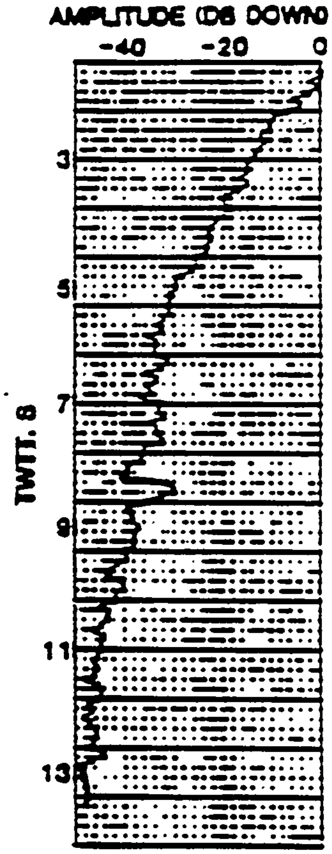


Tomographic depth section (profile CC') showing seismic velocity variations (in percent of deviation from the horizontally averaged mean) in the crust beneath and near Yucca Mountain. Velocity variations in the top 5 km are more uncertain than those at larger depths. The low velocity zone beneath Crater Flat and Yucca Mountain may represent crustal heating and a source of new volcanism. *(From: Evans and Smith, USGS, 1992)*

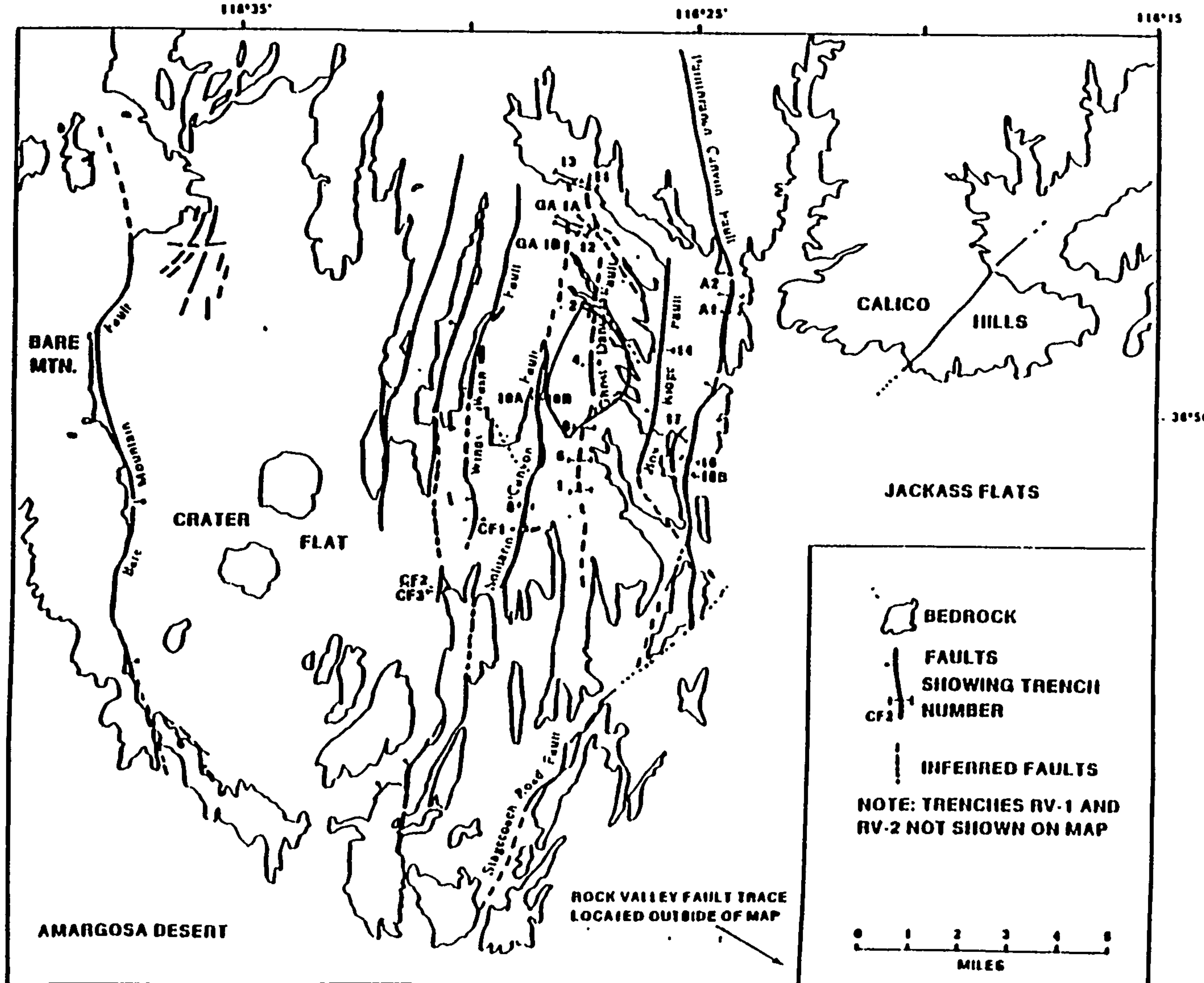
SEISMIC REFLECTION LINE



SEISMIC REFLECTION RECORD
AMARGOSA DESERT

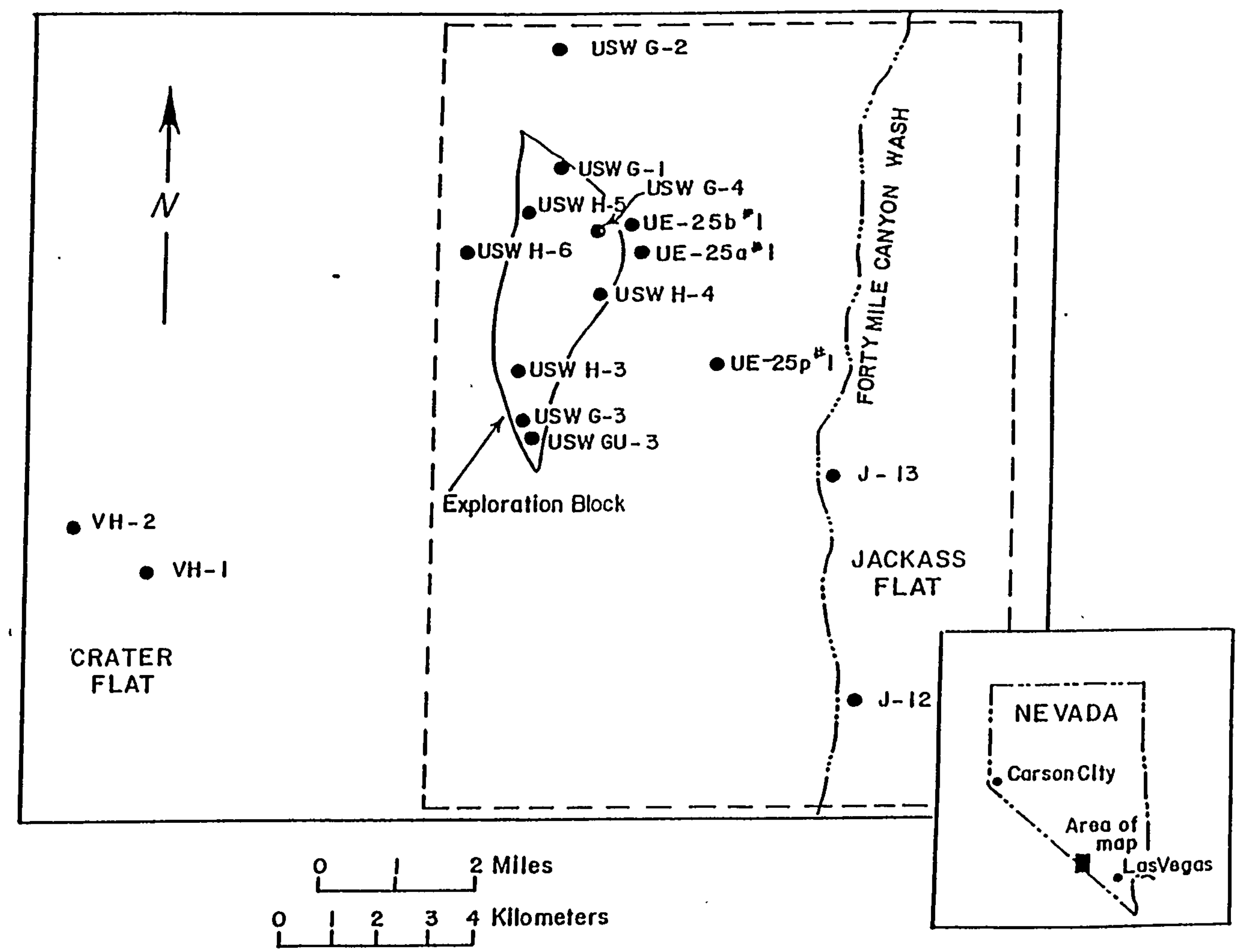


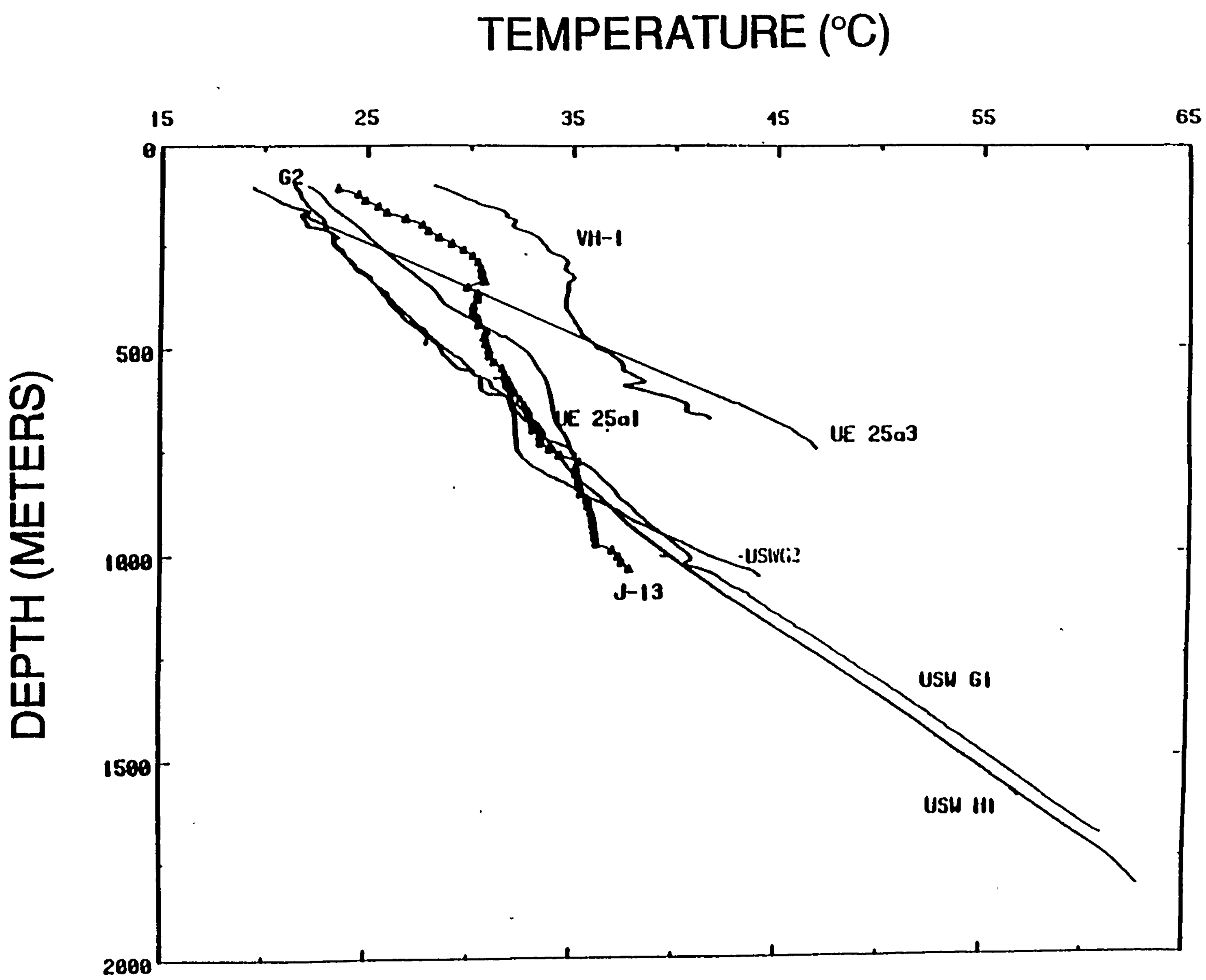
FAULTS IN THE REPOSITORY AREA



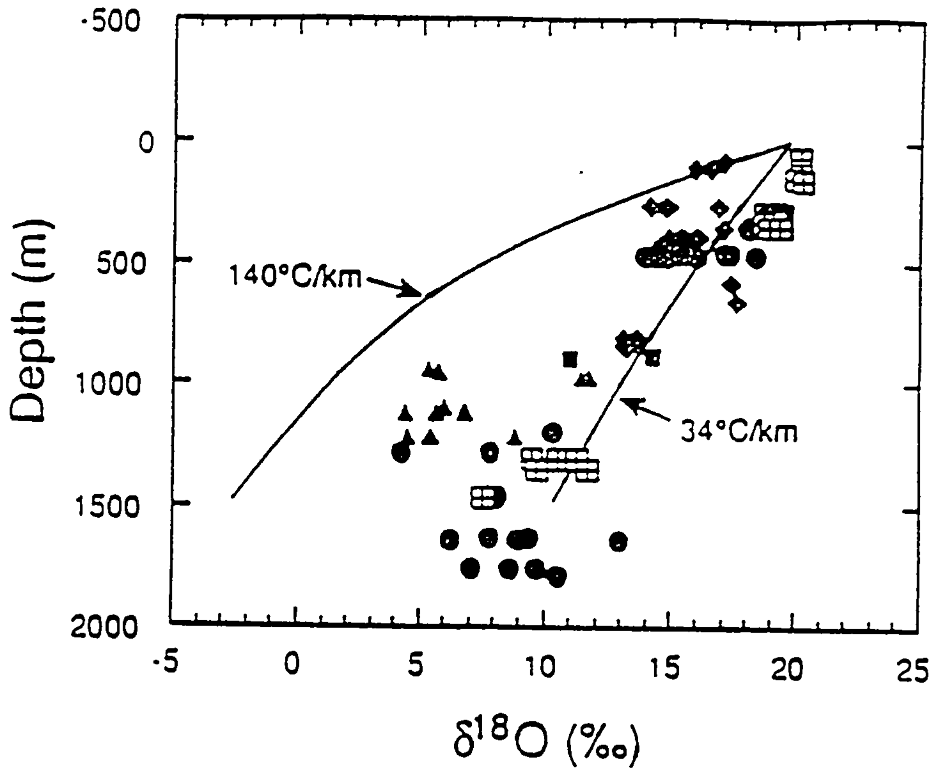
Information provided by K. Fox and W. Swadley, USGS.

DRILL HOLE LOCATIONS

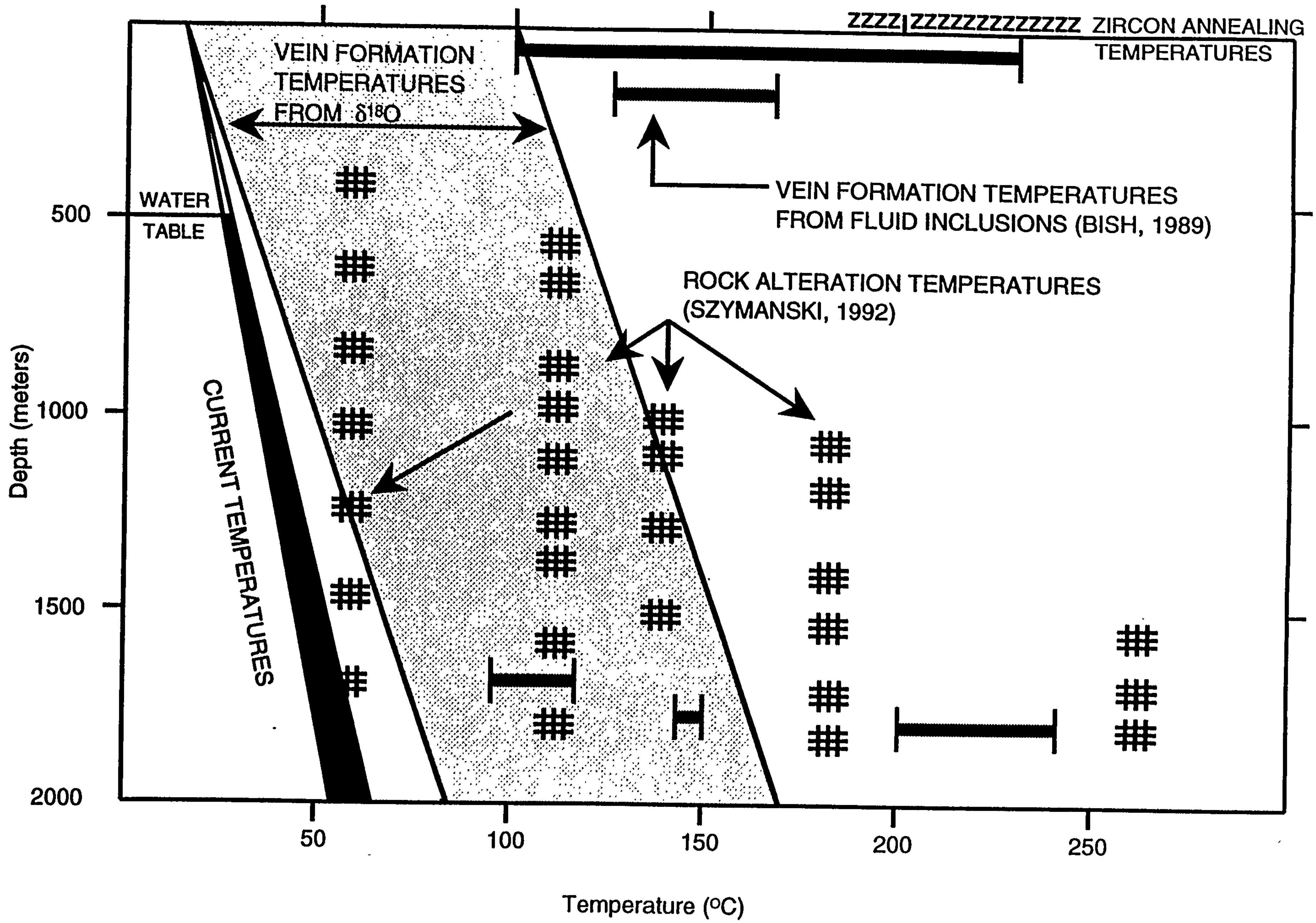



TEMPERATURE (°C)
15
25
35
45
55
65
DEPTH (METERS)
0
500
1000
1500
2000
G2
VH-1
UE 25a1
UE 25a3
USWG2
J-13
USW G1
USW H1

PALEOGEOTHERMS DETERMINED FROM OXYGEN ISOTOPIC RATIOS OF CALCITES

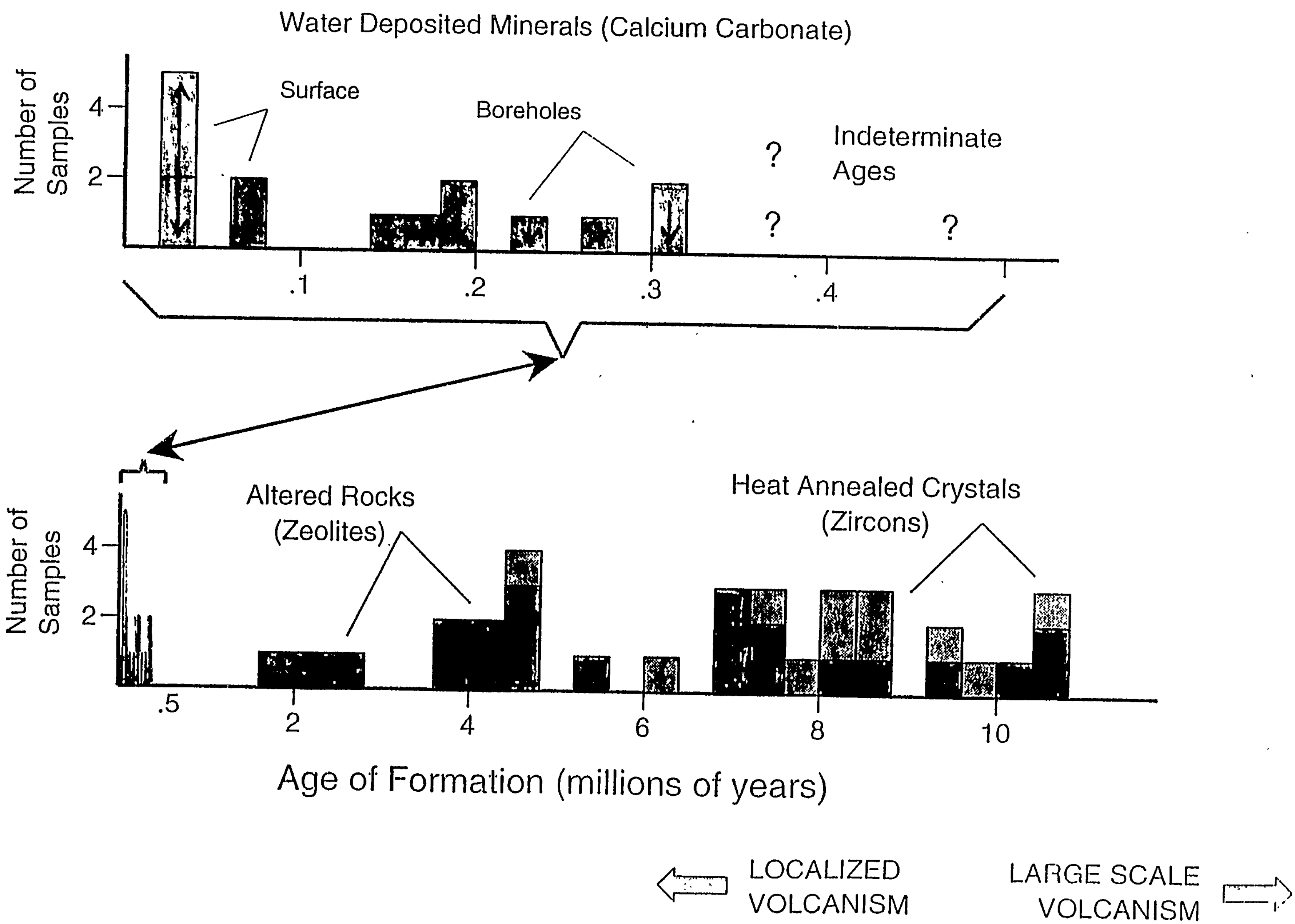


Paleo-geothermal gradients determined by Whelan and Stuckless (1992) from the depth-distribution of isotopic ratios of oxygen-18 and -16 in boreholes USW G-1, G-2, G-3, G-4 and UE-25b#1. Contemporary geothermal gradients measured in these boreholes are 18, 24, 22, 24, and 20° C/km respectively (Sass et al., 1987). Paleo-gradients during crystallization of the calcitic veins were at least 50% greater than the contemporary gradient.



THE SITE HAS BEEN INVADED BY HIGH TEMPERATURE FLUIDS

AGES OF FLUID ALTERATIONS AT YUCCA MOUNTAIN



CONCLUSIONS

1. Heat flow at Yucca Mountain is atypical of continental heat flow, but is typical of the planet as a whole in that roughly equal quantities of heat are transported by thermal conduction and by fluid flow.

2. Results of seismic tomography and seismic reflection are consistent with incipient/partial melting of the lower crust and upper mantle directly below Yucca Mountain.

3. The present thermal state of Yucca Mountain, with the geotherm depressed by aqueous convection in the shallow crust, is not a steady state. There is a 10 million year history of episodic changes to a different state with much higher temperatures in the shallow crust. There is no way of knowing when the next change of state will occur.

PART 4

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Comments on NAS/NRC Report on Hydrotectonic Conditions at Yucca Mountain

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Southwestern Section

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COMMENTS ON NAS/NRC REPORT ON HYDRO-TECTONIC CONDITIONS AT YUCCA MOUNTAIN

1. The basic approach was not valid. In conflict with geodynamic conditions at Yucca Mountain,

> *"... the panel discounted hydrothermal systems as a potential mechanism for raising the water table level in the Yucca Mountain area."* (pg. 130)

Consequently, the Panel did not inquire about indications of hydrothermal activity or consider the possibility of hydrothermal origins for data that were cited, such as the isotope content of vein minerals.

2. Relevant data were ignored. Examples:
- field evidence for paleo spring discharges at Yucca Mountain, e.g.: soil veins, thick bands of hydrogenic silica in soils, floating textures of detritus in hydrogenic minerals, calcite coatings over exposed bedrock downslope from apparent vein sources, visible alterations of adjacent rock.
- isotope similarities between local veins and known hydrothermal waters and deposits in the region.
- metasomatic alterations of tuffaceous rock above contemporary water table.
- radiometric ages of zeolites in shallow rock.
- evidence for high temperature fluids, e.g.: $\delta^{18}O$ gradients with depth, fluid inclusion temperatures, and mineral alteration temperatures.

COMMENTS ON NAS/NRC REPORT ON HYDROTECTONIC CONDITIONS AT YUCCA MOUNTAIN (continued)

3. Facts were misrepresented.

First example: The argument given for prolonged stability of the paleo water table in its presently deep configuration is based on an alleged boundary between altered and unaltered tuffs at Yucca Mountain:

> *"The boundary between altered and vitric tuffs indicated that water reached its highest levels and receded downward from 12.8-11.6 Ma, and that since that time the water level at central Yucca Mountain has probably not risen more than 60 m above its present position."* (pg. 48)

Related facts: The alleged boundary does not exist. Glass appears hundreds of meters below the water table and zeolites extend to the topographic surface with ages nearly uniformly distributed over past 10 million years. The Panel misrepresents distributions of alteration minerals and ignores radiometric ages.

3. Facts were misrepresented. (continued)

Second example: The only analytic data used by the Panel to support the claim that the last hydrothermal event occurred over 10 million years ago are fission track ages of zircons embedded in breccia cements. The Panel mischaracterized these results as follows:

> *"...within the analytical uncertainty, most of the ages are about 10-12 Ma, or about the same as those of the dominant volcanic rocks in the region."*

Related facts: The referenced work stated:

> *"... there are zircons from multiple sources present. In both samples there are crystals significantly younger and significantly older than the age of the tuff."* (Levy and Naeser, 1992)

The fission track ages display a multiply peaked distribution. Most of the annealing ages for zircons are younger than host tuff, which is given by K/Ar dating as 13 Ma. The youngest is 4.8 ± 2.5 Ma for the ninety percent confidence interval.

COMMENTS ON NAS/NRC REPORT ON HYDRO-TECTONIC CONDITIONS AT YUCCA MOUNTAIN (continued)

4. Faulty logic was used.

First example: Without checking for isotope compatibilities of vein calcites with infiltrating rainwater or with known hydrothermal waters or deposits in the region, the Panel concluded on the basis of isotopes that:

> *"Trench 14 and Busted Butte vein carbonates have isotopic contents within the range characteristic of soil carbonates in the region, showing the veins formed from rainwater and soil-forming processes."* (pg. 5)

The Panel's deduction is equivalent to assuming the answer. The logical deduction from isotopic affiliations is that vein and soil calcites were precipitated from a common source of water, a deduction that is conspicuously apparent from field observations.

4. Faulty logic was used. (continued)

Second example: Without regard for dissimilarities in hydrologic conditions at Yucca Mountain and Devils Hole, the Panel argued that:

> *"Considering that Devils Hole is located in the same active tectonic region, and is extending at two to three times the rate of the Yucca Mountain area, the fact that earthquakes have not resulted in even a 15 m rise in the Devils Hole water table inspires serious doubt that the seismic pumping mechanism can cause a greater than 100 m rise in the water table in the Yucca Mountain area."* (pg. 55)

The analogue is conspicuously faulty. Whereas, the water table at Yucca Mountain is hundreds of meters deep, at Devils Hole, water is currently discharging along the immediate perimeter of the limestone outcrop containing Devils Hole. Additional upwelling water at Devils Hole would simply increase current volumes of surface runoff with little effect on water table elevations. Hence, it is not logical to attribute limited rises in water levels at Devils Hole to benign hydrotectonic processes in either location, Devils Hole or Yucca Mountain.

COMMENTS ON NAS/NRC REPORT ON HYDRO-TECTONIC CONDITIONS AT YUCCA MOUNTAIN (continued)

5. Major conclusions were unsupported by facts and in conflict with data. Example:

> *"The panel's overall conclusion was that none of the evidence cited as proof of ground-water upwelling in and around Yucca Mountain could be reasonably attributed to that process."* (pg. 3)

Conspicuous indications of upwelling water were either scarcely addressed or ignored. Accordingly, the Panel's overall conclusion is unsupported. Furthermore, the conclusion is directly contradicted by multiple lines of independent evidence, such as:

- data on zeolitization in the vadose zone;
- young radiometric ages for alteration minerals and veins;
- geothermometry data indicating hot paleo fluids;
- presence of vertical veins in soils that resemble spring orifices and not supergene pedogenisis;
- presence of thick bands of calcite and silica in soils indicating rapid precipitation of minerals, alternating water chemistry, and origins from hot fluids;
- affiliations of chemical and isotopic compositions of vein minerals with known hydrothermal deposits;
- chemical composition of remnant water found in pore spaces of unsaturated rock in the vadose zone.