Appendix III

Paleotemperature Environment At Yucca Mountain, Nevada (Status Report)

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SECTION I

PALEOTEMPERATURE ENVIRONMENT AT YUCCA MOUNTAIN, NEVADA (STATUS REPORT)

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Paleotemperature Environment at Yucca Mountain, Nevada (Status Report)

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Introduction

Paleothermal environment in the interior of Yucca Mountain during the Timber Mountain Caldera alteration (~11-9 Ma) was reconstructed by Bish and Aronson (1993). Current temperatures in drill holes were extensively studied by Sass and assoc. (Sass et al., 1987). Sometime in-between (~8 Ma to 20 Ka) there was another stage of hydrothermal activity which introduced a large amount of Ca into the essentially Ca-free ignimbrites of Yucca Mountain. This stage was first recognized by Szymanski (1992).

The only paleogeothermal reconstruction pertaining to the time span from the Timber Mountain Caldera event to ~26 Ka BP was performed by Szabo and Kyser (1990), who assumed that calcite and opal in Yucca Mountain were deposited from meteoric water percolating through the vadose zone. This reconstruction will be discussed in more detail in Chapter 2.

Though there are many lines of evidence indicating ascending mode of formation for calcite and elevated temperatures (at least at depth), an alternative hypothesis implying *per descensum* nature of these deposits is also considered. The correct understanding of the thermal history in Yucca Mountain may help to evaluate these competing hypotheses and, though, is of great importance for the assessment of suitability of Yucca Muntain to accommodate a high-level nuclear waste repository. Thus, the scope of the present report is to summarize all available data on paleotemperatures in Yucca Mountain during the post-Timber Mountain time, display status of this research and give recommendations for further studies.

There are four phenomena, potentially usable for paleothermometry at Yucca Mountain: (1) fluid inclusions; (2) depletion of calcite in $\delta^{18}O$ with increase of temperature, (3) fractionation of ^{18}O in co-eval calcite and opal, and (4) thermoluminescence of quartz and other minerals. These four "lines of evidence" are discussed below. The largest amount of information was obtained for calcite collected from cores extracted from deep drill holes (YMP, 1993, Hill and Schluter, 1994). The location map for these holes is given in **Fig. I-1**.

Introduction

Figure...

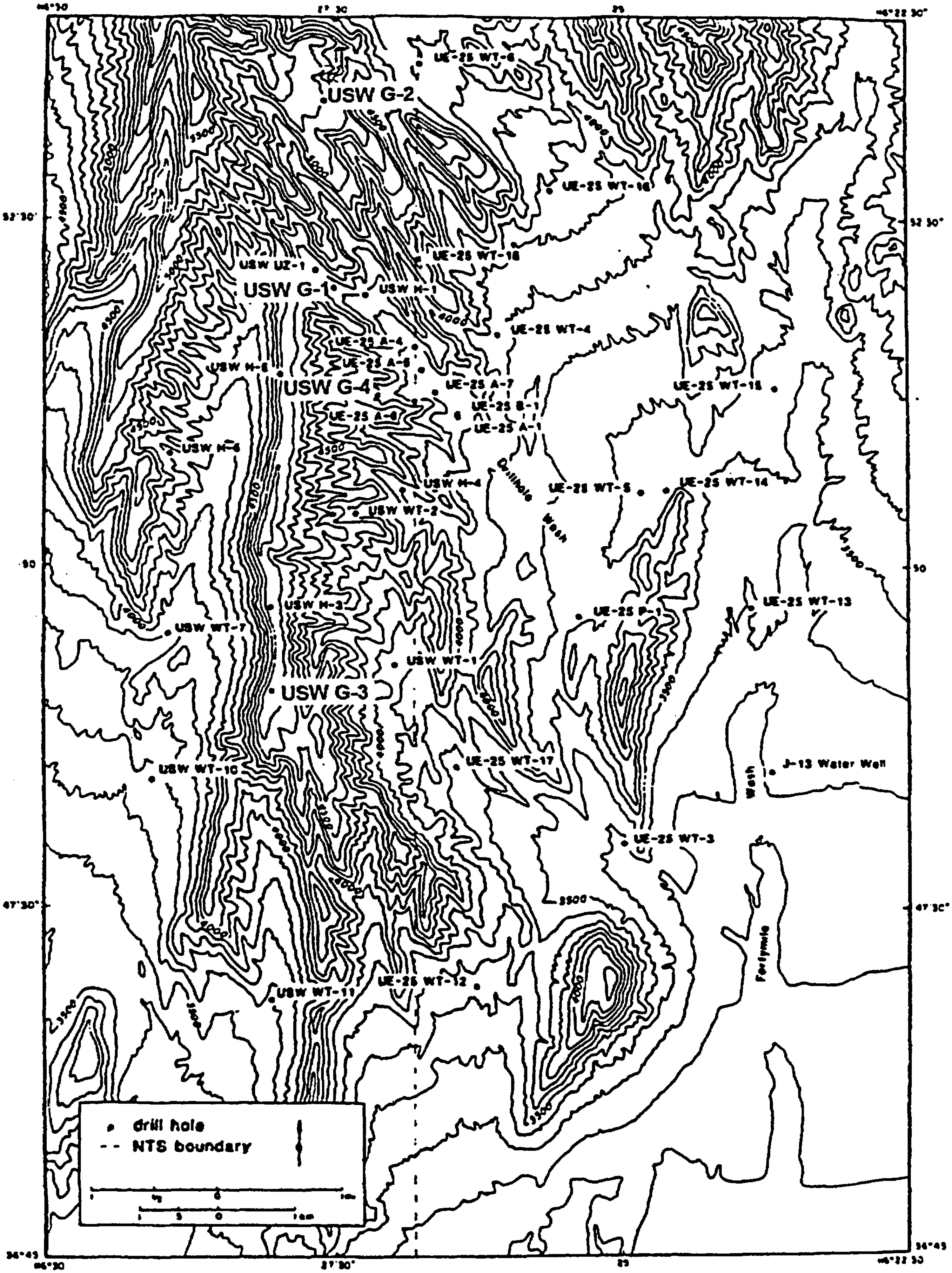


Fig. I-1. Location map: Yucca Mountain and four drill holes discussed in the report (enlarged font)

Chapter 1. Purpose

Szymanski (1992) has identified two chemically- and temporally distinct hydrothermal systems, that caused the alteration of volcanic rocks in Yucca Mountain. First system was alkaline in character. Potassic zeolites were formed at shallower- and sodic zeolites - at deeper depth. The system was localized in northern and western parts of Yucca Mountain and was related to the latter stages of development of the Timber Mountain Caldera volcanism (~11 to 9 Ma). Detailed paleothermal reconstruction for this stage of alteration has been done by Bish & Aronson (1993).

Second system is responsible for alkaline earth zeolitic alteration. It was a fault-based system located to the southeast of Yucca Mountain. The Stagecoach Road Fault has likely served as a major conduit of this system. Significant amount of Ca has been brought into the volcanic rocks and immobilized there in form of calcic zeolites and calcite during this relatively young event (or events). This system post-dates the Timber Mountain Caldera volcanism and its alteration aureole over-prints the aureole of older hydrothermal system. Intermittent expulsions of water may have been operational from ~8 Ma to as recent as ~26 Ka (Szymansky, 1992). Visualization of activity of two systems discussed above is given in **Fig. 1-1**.

Calcite formed during both Timber Mountain Caldera and Stagecoach Road Fault stages of hydrothermal activity. In this report we are going to analyze the thermal features of Yucca Mountain during the younger, second stage of hydrothermal activity (Stagecoach Road Fault hydrothermal system). To do that we must be able to distinguish between calcites formed at different systems. These two genetically and temporally different calcites may be distinguished by several characteristic features. Below we suggest a set of criteria for that. To make description easier, we will use terms "Timber Mountain calcite" or "old calcite" as opposite to "Stagecoach Road calcite" or "young calcite" to denote these two genetic types of calcite in Yucca Mountain.

Spatial occurrence

Old calcite occurs at a depth of -900-1200 m and deeper. Young calcite encountered from the surface down to a depth of -400-500 m. The rocks between -400-500 m and -900-1200 m seem to be essentially "calcite-free". Such a spatial distribution may first be explained by different patterns of two ancient hydrological systems: slow diffuse movement of fluids from Timber Mountain Caldera center and more fast concentrated upwelling of water along Stagecoach Road fault zone with significant lateral spread near surface (**Fig. 1-1**). Also, the modes of calcite deposition must have been different in these two systems. The Timber Mountain calcite was mostly formed as a result of metasomatic replacement. Younger Stagecoach Road calcite was most likely deposited due to escape of CO_2 from the system; it forms veins, veinlets and vugs. (Physical chemistry of systems like the latter one has been studied in detail by S.Malinin (1979); calculations have shown that calcite in such a system can be formed only in the upper 250-1000 m of section, where the solubility of calcite drops drastically; **Fig. 1-2**). Spatially different calcites display different textural features, content of trace elements, as well as distinctive signatures of $\delta^{13}C$, $\delta^{18}O$, and $^{87}Sr/^{86}Sr$ (see discussion below).

Petrography and textures

Old deep-seated Timber Mountain calcite occurs as milky veins and replacement cement in altered fuffs. In contrast, younger and shallower Stagecoach Road sparry calcite occurs as drusy fracture coatings or fillings and, locally, within lithophysal cavity (Whelan et al., 1994).

Trace elements

Old calcites have elevated concentrations of Fe and Mn whereas younger shallow calcites have very low concentrations of Sc, Fe and Mn. Old calcites display a chondrite-normalized REE pattern without any Ce anomaly and little or no negative Eu anomaly, while young calcites reveal patterns with prominent negative Ce and Eu anomalies (Vaniman and Whelan, 1994).

Isotope signatures: carbon, oxygen and strontium

Deep-seated Timber Mountain calcite is enriched in $\delta^{13}C$ (typical values are from +5 to -2 ‰ PDB). Shallow Stagecoach Road calcite is significantly depleted in $\delta^{13}C$ (values from -3 to -10 ‰ PDB are typical). Oxygen displays an opposite behavior: it is "lighter" in old calcite (from -19 to -29 ‰ PDB) and "heavier" for younger shallow calcite (from -9 to -18 ‰ PDB). These two calcites give distinctive fields on $\delta^{13}C/\delta^{18}O$ cross-plot (**Fig. 1-3**). The pattern of ^{13}C and ^{18}O is different for shallow and deep-seated calcite, as it is seen from stable isotope profiles by deep drill holes (**Figs. 1-4 & 1-5**).

These two types of calcite display clear difference in $^{87}Sr/^{86}Sr$ signatures. They vary from 0,7085 to 0,7100 in old Timber Mountain calcite and invariably higher (0,7110 to 0,713) in younger Stagecoach Road calcite (Hill et al., 1994; Hill and Schluter, 1994).

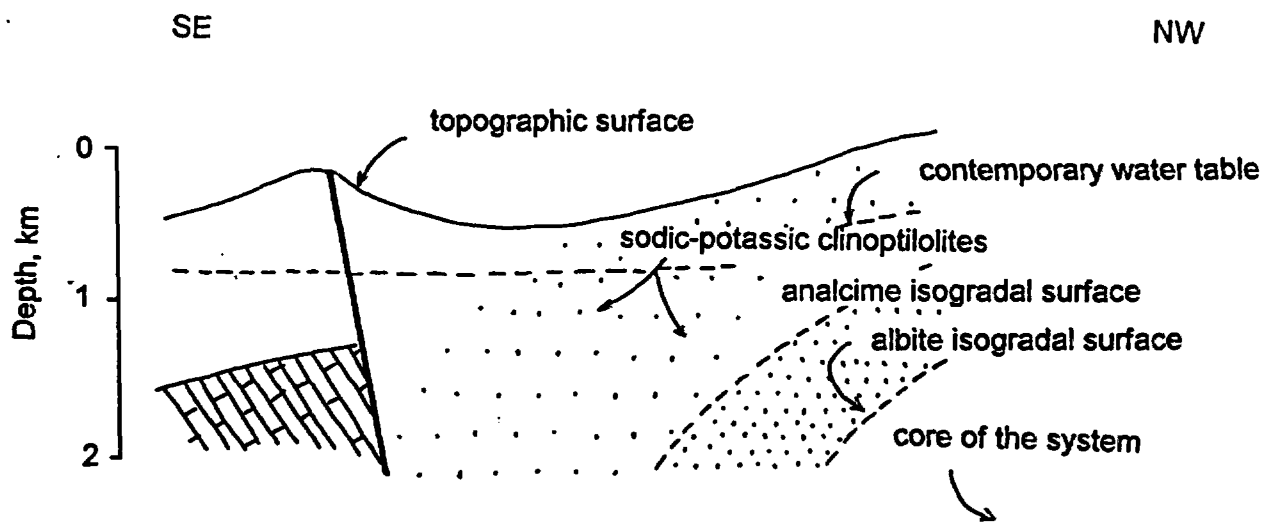
Age

U-series and radiocarbon ages obtained for calcite from shallow zone, as well as ESR-ages obtained by quartz are younger than 7-8 Ma (i.e. younger than Timber Mountain Caldera event that is ~11-9 Ma). In some instances the ages as young as 20,9 Ka (USGS, 1993) and 26 Ka (Szabo and Kyser, 1990) have been reported for shallow calcite.

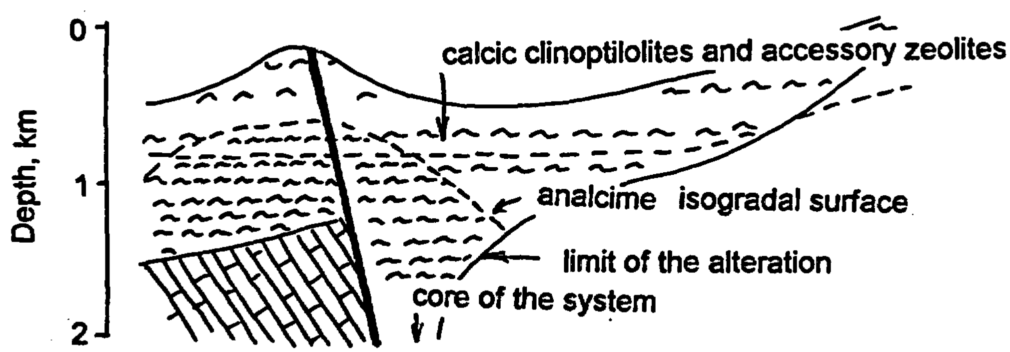
All data used in further paleothermometric evaluations were checked for coherence, using the criteria above. The Data Chart prepared by Hill and Schluter (1994) was used.

Chapter 1. Purpose

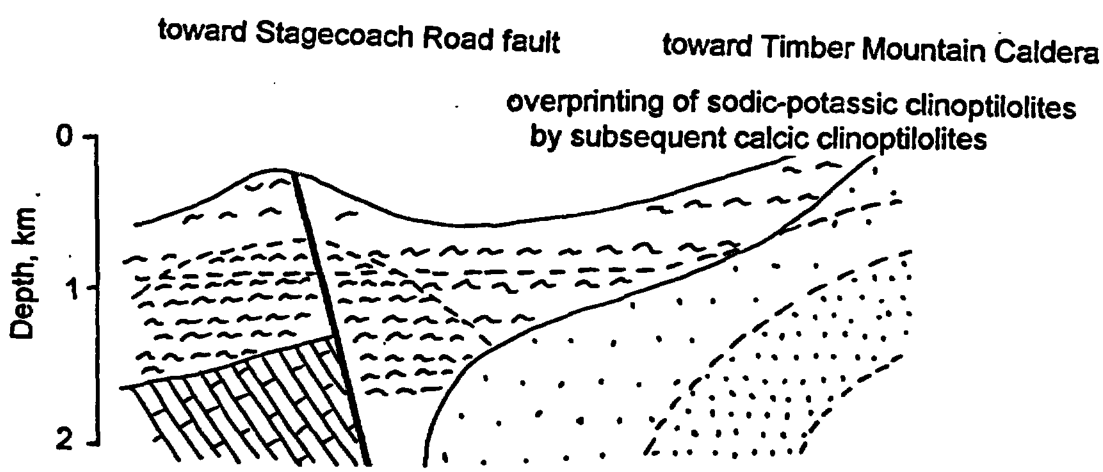
Figures...



A. the Timber Mountain Caldera alteration areola



B. the alteration areola of the fault-based hydrothermal system



C. the presently observed juxtaposition of the alteration areolas

Fig. 1-1. Schematic diagram illustrating the interpretation of the spatial distribution of the chemical and temporal characteristics of alteration minerals at Yucca Mountain, Nevada (from Szymanski, 1992)

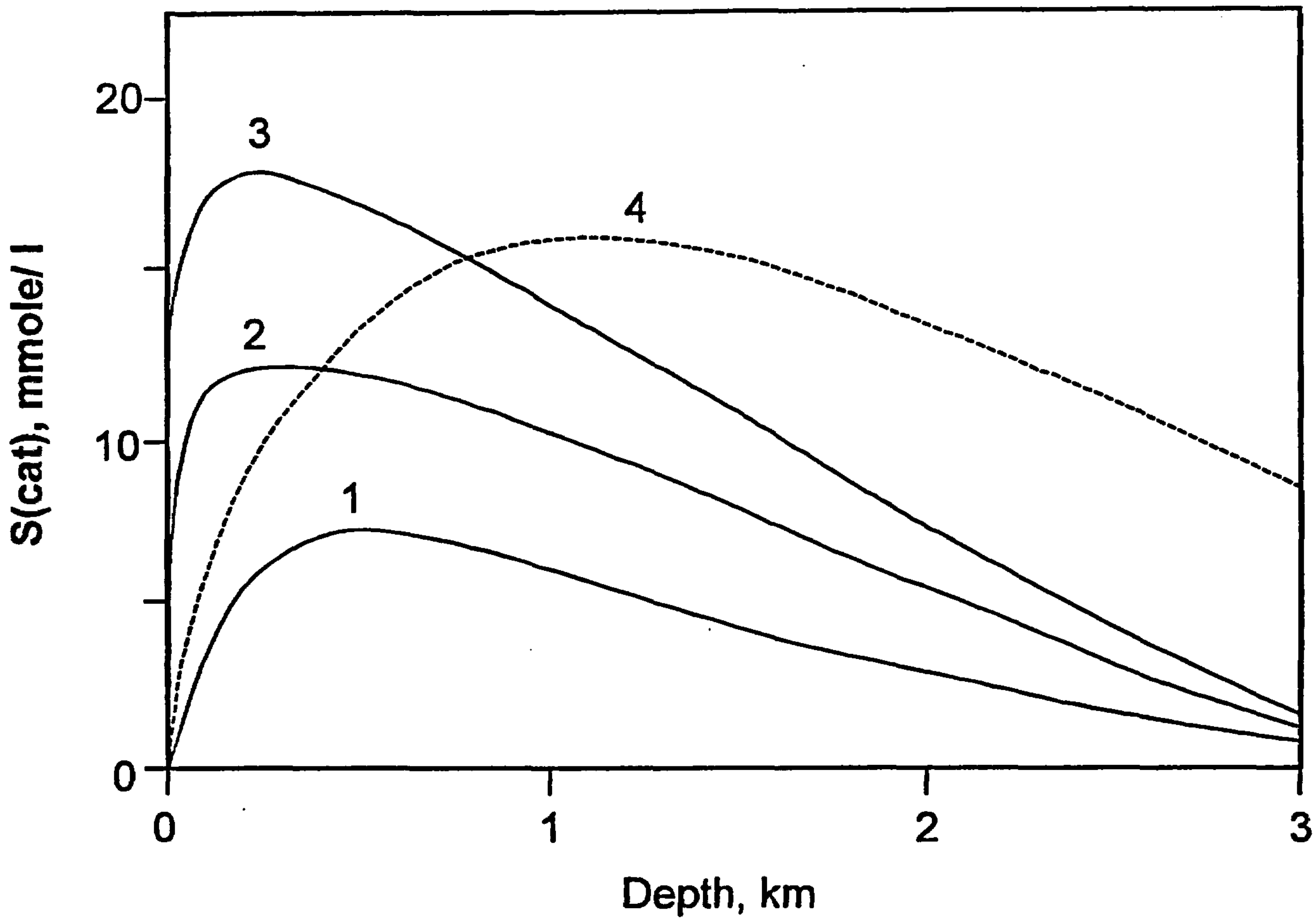


Fig. 1-2. Solubility of $CaCO_3$ in CO_2-saturated hydrothermal system (by Malinin, 1979)

Temperature changes (toward surface) as: **1** - 225 to 100 °C; **2** - 225 to 50 °C; **3** - 225 to 25 °C; **4** - 200 to 100 °C at ionic strength I=1

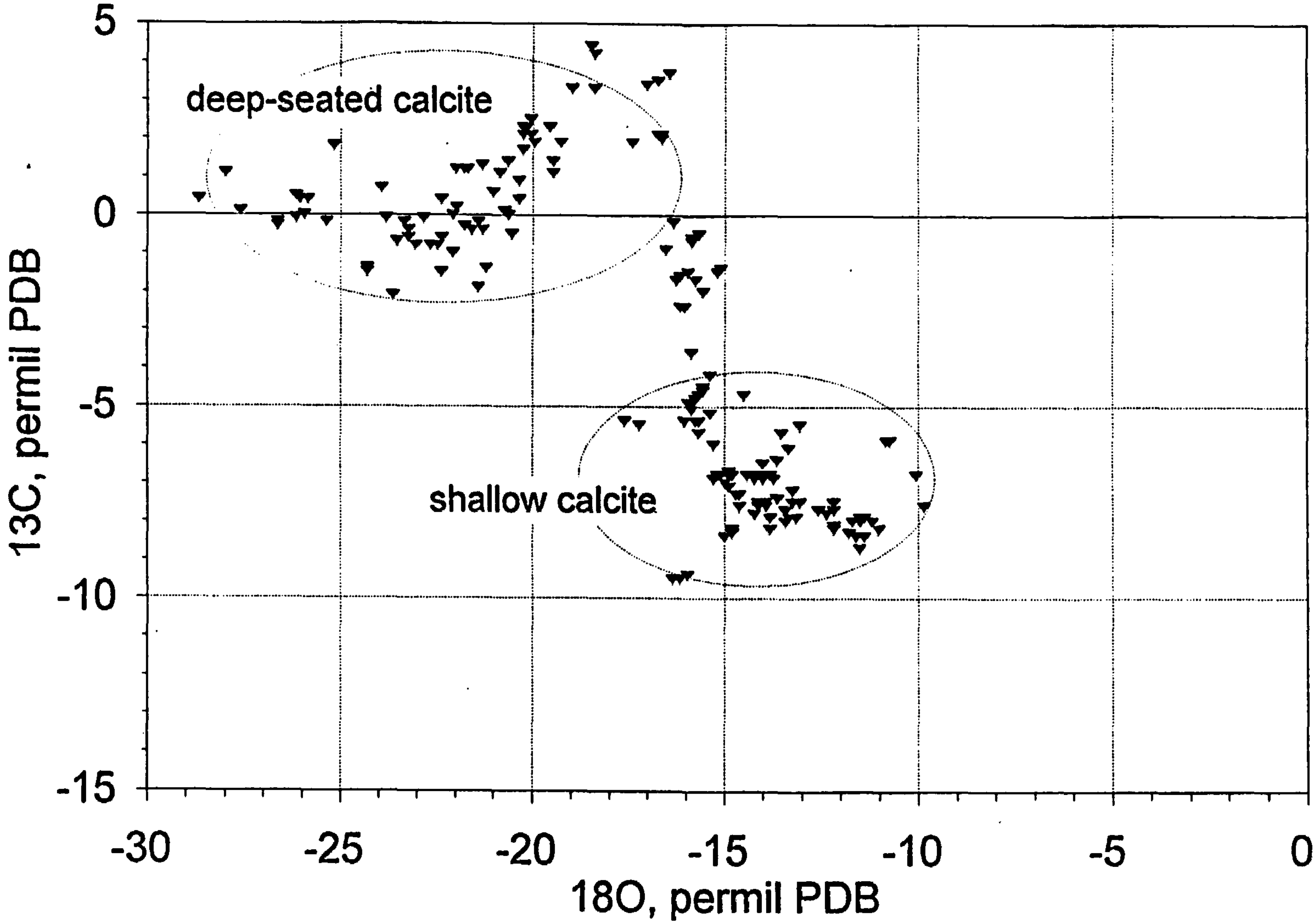


Fig. 1-3. $\delta^{13}C$ vs. $\delta^{18}O$ fields for calcite from drill holes USW G-1 and G-2 (data by YMP, 1993)

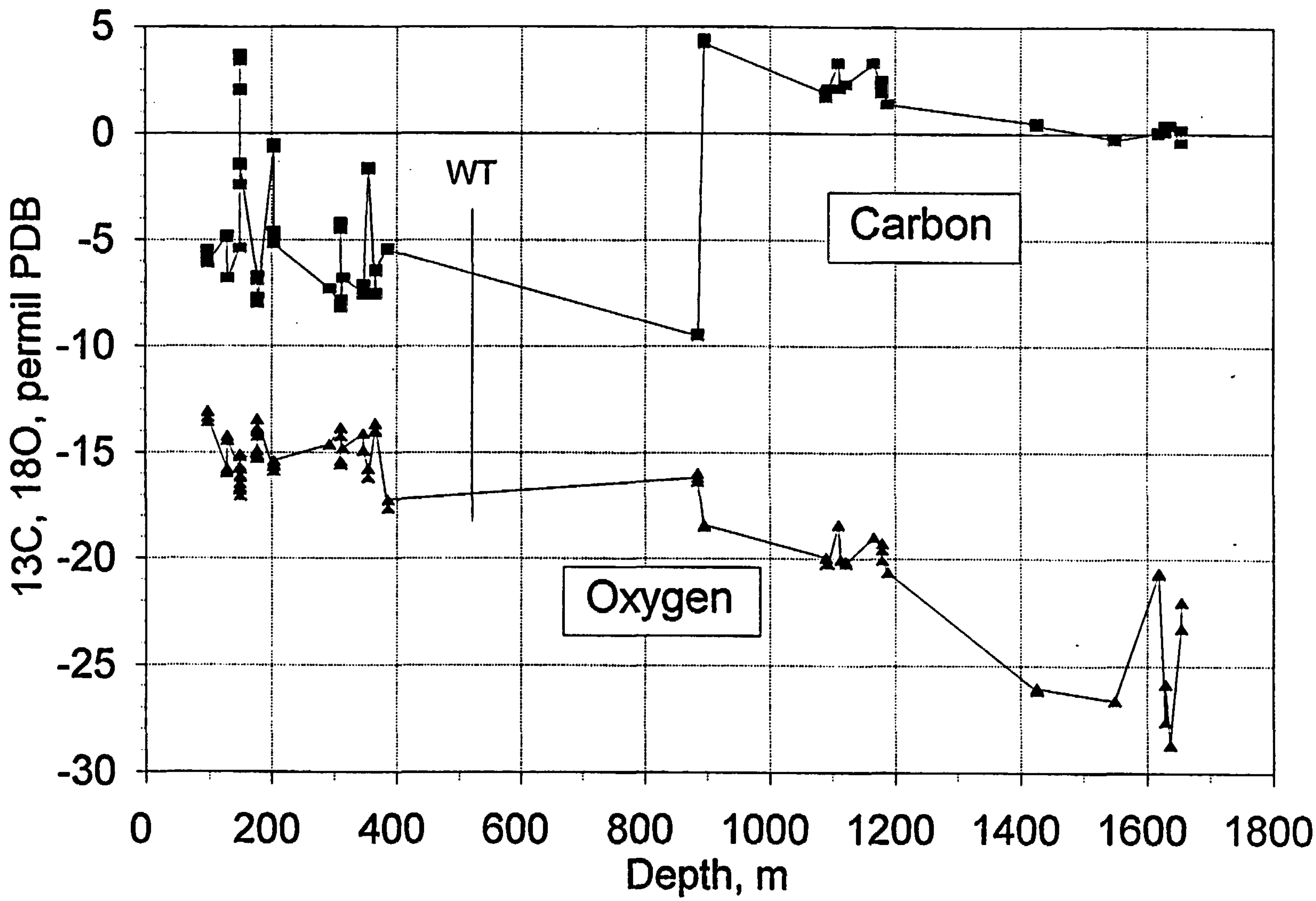


Fig. 1-4. Drill hole USW G-1: change of $\delta^{13}C$ and $\delta^{18}O$ with depth; WT = water table level

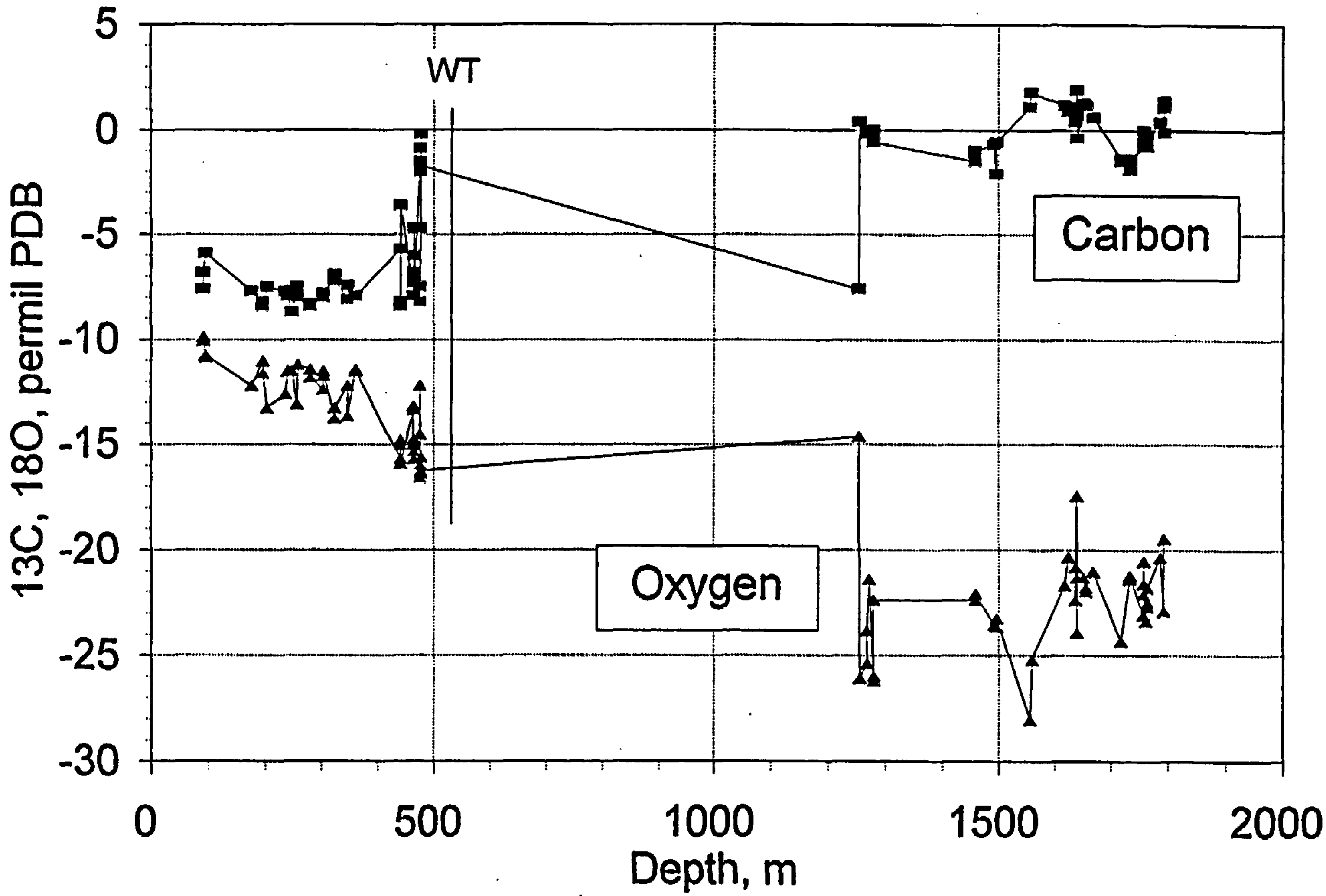


Fig. 1-5. Drill hole USW G-2: change of $\delta^{13}C$ and $\delta^{18}O$ with depth: WT = water table level

Chapter 2. Previous Paleo-Geothermal Reconstructions

Secondary calcite and opal from Yucca Mountain were studied by Szabo and Kyser (1990). They obtained a number of U-series ages for these minerals removed from three drill holes (UE-25a; USW G-2 and USW G-3/GU-3), as well as ^{18}O and ^{13}C signatures. Eight out of eighteen samples gave ages >400 Ka, that is a conventional limit for U-series dating. Eight data points cluster between ~140 and 310 Ka; two more samples gave an age of ~26 and 30 Ka.

The paleothermometric evaluation by the authors is based on the assumption that both minerals were deposited from meteoric water. As a main indication of this the authors use a statement that both calcite and opal in Yucca Mountain were formed at low temperature:

> *There are several factors which suggest that the fracture-filling calcite and opal of this study formed at low temperature. These include (1) the lack of any visible fluid inclusions that often form in calcites at high temperatures; (2) the absence of minerals in the tuffaceous wall rock that would indicate the fluids were hydrothermal; (3) the presence of opal-CT as the silica polymorph, which is characteristic of low temperatures; and (4) the high $\delta^{18}O$ values of both the calcite and opal and the large difference in their values, although their ages ... and petrographic relations indicate they did not form from the same fluid.*

Being analyzed one by one, the arguments given above either appear to be equivocal, or are simply contradicted by the currently available data:

(1). *Lack of fluid inclusions.* Fluid inclusions have been found in calcite from the same drill holes as discussed by Szabo and Kyser (Bish, 1989; Bish and

Aronson, 1993; YMP, 1993), as well as in calcite and quartz from some other occurrences in the area (Harmon, 1993; Roedder et al., 1994). Temperatures obtained by fluid inclusions are discussed in Chapter 3 of this Report.

(2). *The absence of hydrothermal minerals.* Sulfides have been found in samples from Wailing Wall fault, WT-7 and Pull Apart fault forming individual grains (pyrite) scattered throughout the crystals of quartz and calcite; micro veinlets (chalcopyrite); as well as microcrystals trapped into fluid inclusions (Harmon, 1993). Fluorite was found at depth of ~300 m in drill hole UE 25p#1 (Weiss et al., 1991).

(3). *Opal-CT as a low-temperature silica polymorph.* Opal is indeed believed to be a low-temperature phase, though the "low-temperature" does not necessarily mean the "ambient temperature". For instance, opal is known to form in deposits of thermal springs (Glossary of Geology, 1980), that is "low-temperature environment" from the standpoint of an ore geologist, but still is a hydrothermal environment.

(4). *High $\delta^{18}O$ values of the calcite and opal; and the large difference in their values.* Because:

> *The isotopic composition of a mineral precipitated from a fluid is determined by both the temperature of precipitation and the isotopic composition of the fluid.*

(Szabo and Kyser, 1990, p.1715) the "high $\delta^{18}O$ values" by themselves <u>may not</u> unequivocally indicate low depositional temperatures, <u>unless the isotopic composition of the fluid is known</u>. "Large difference" in $\delta^{18}O$ values for calcite and opal from depth -347 m (Δ=6,5 ‰) implies temperature ranging from 31 to 48 °C, depending on what fractionation equation is used for the calculation. Even conservative estimate gives temperature some 20 % higher than one caused by current geothermal gradient (temperature at -350 m in drill hole USW G-2, from which these calcite and opal were collected is 26 °C; Sass et al., 1987). More data on calcite-opal thermometry now become available (YMP, 1993; Harmon, 1993). These data suggest historic geothermal gradients much steeper than current ones (see Chapter 5 in this Report).

The final "geotherm" produced by Szabo and Kyser (**Fig. 2-1**) is based on several rather problematic assumptions that: (1) calcite is formed from infiltrating rainwater (that is not necessarily true); (2) the later has a $\delta^{18}O$ value of -10,5 ‰ (that is arbitrary); (3) the average temperature gradient in Yucca Mountain is 34 °C (that is not true; see Chapter 7 of this Report); and (4) the surface temperature was 14 °C (that is, again, arbitrary). So, the conclusion that :

> *stable isotope data ... suggest that meteoric water moved downward from the surface along fractures and precipitated calcite in near equilibrium with the geotherm*

(p. 1719) is based on circular logic and unceratin at best (Szabo and Kyser first have assumed that calcite and opal in Yucca Mountain were deposited from meteoric water, and then they come to the conclusion, that meteoric water precipitated calcite). Moreover, the numerical data given in this paper suggest much higher gradients in the system (**Fig. 2-2**). Using fractionation parameters for calcite and water determined by O'Neil et. al., (1969), the average gradient may be estimated to be as high as ~60 °C/km.

Chapter 2. Previous Reconstructions

Figures...

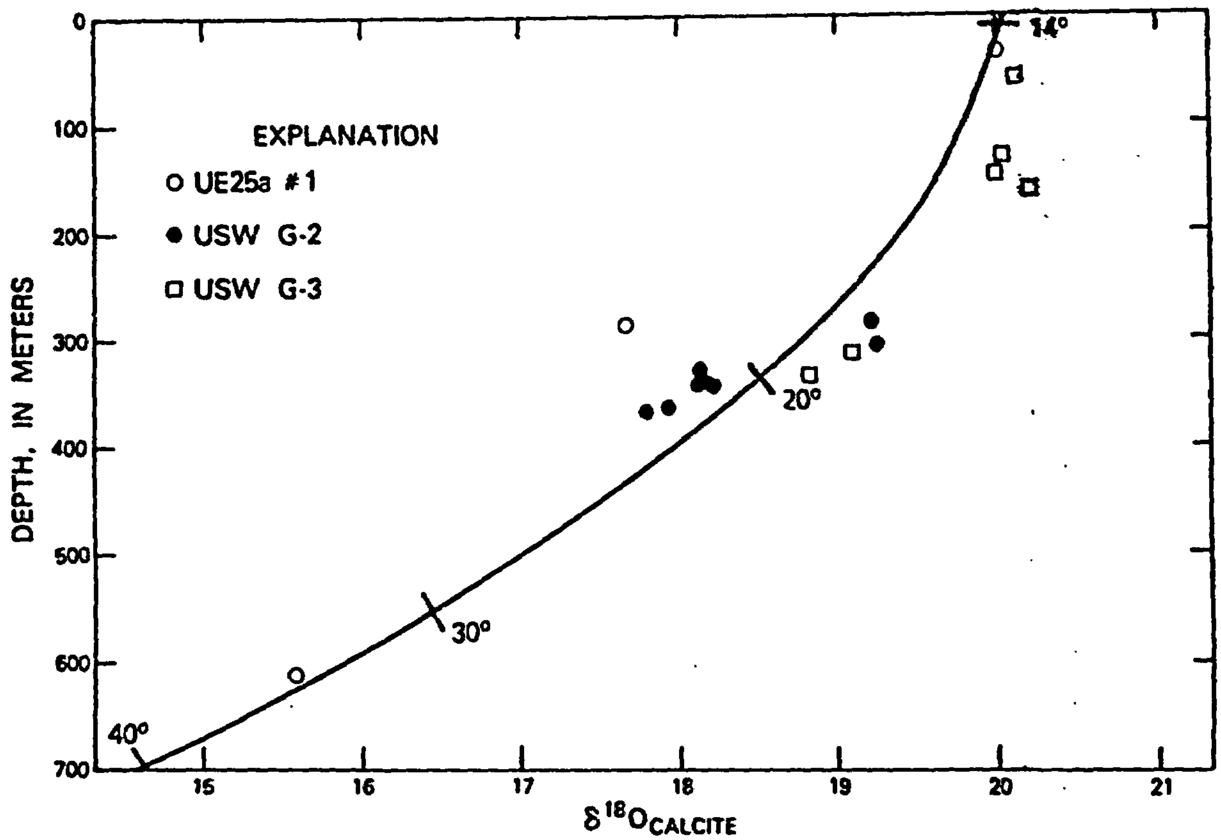


Fig. 2-1. Relationship between $\delta^{18}O$ values of calcite from drill holes and depth. Line depicts the $\delta^{18}O$ values of calcite calculated to be in equilibrium with ground water having a $\delta^{18}O$ value of -10,5 at temperatures along a geotherm of 34 °/km, assuming a surface temperature of 14 °C (by Szabo and Kyser, 1990)

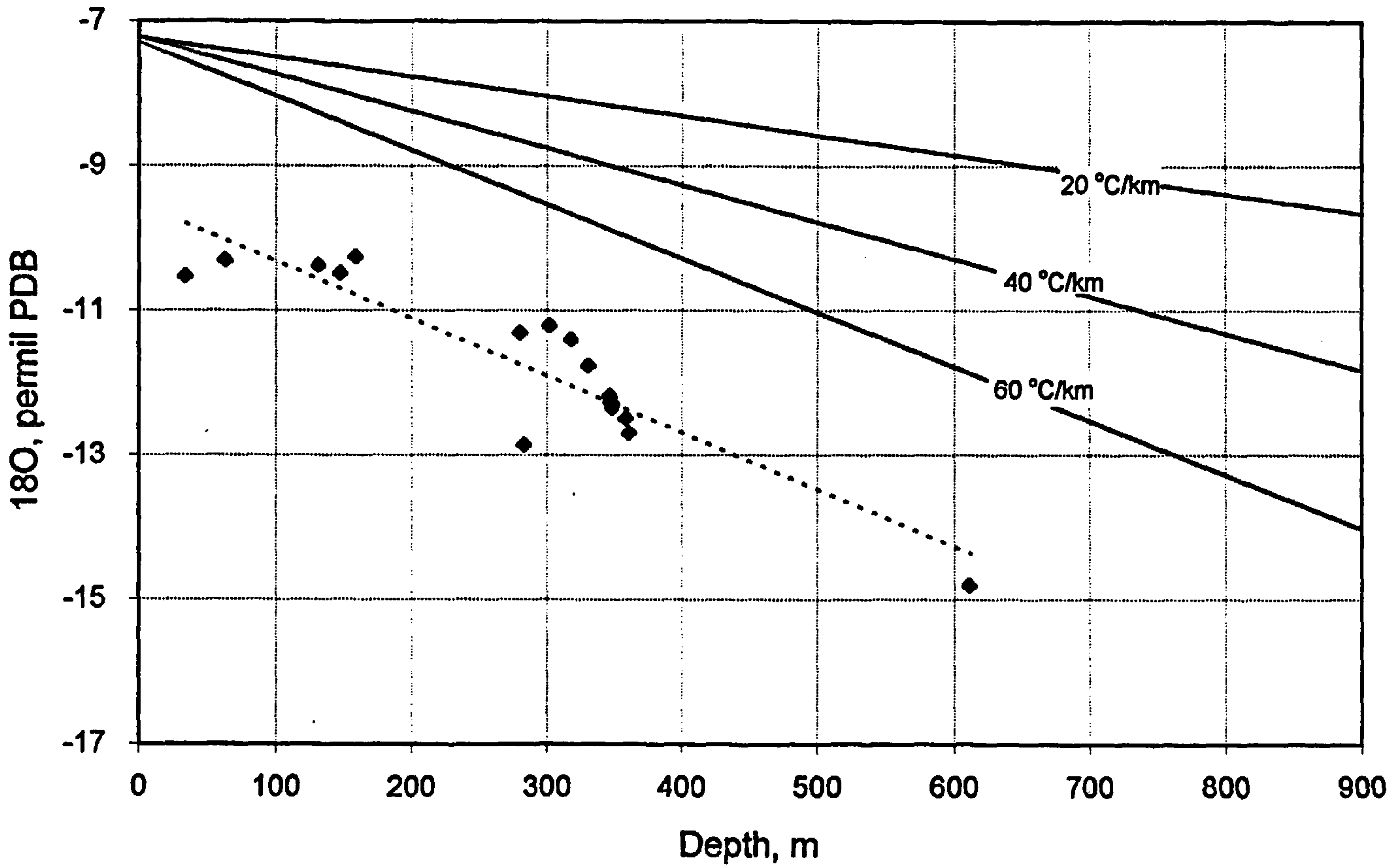


Fig. 2-2. A linear-fit approximation for $\delta^{18}O$ values in calcites from three drill holes in Yucca Mountain (data from Szabo and Kyser, 1990). Solid lines represent the calculated change in $\delta^{18}O$ with depth at three thermal gradients chosen.

Chapter 3. Paleothermometry by Fluid Inclusions in Calcite

3.1. Fluid Inclusion Method: Basic Principles and Limitations

Fluid inclusions (i.e., microscopic portions of a mineral-forming fluid, residing in cavities in a host mineral) trapped at an elevated temperature will split when cooling on two phases: liquid and gas. This splitting occurs due to difference in compressibility between the solid (mineral) and liquid (fluid inclusion) phases. The *rationale* of thermometry by fluid inclusions is to run this process in an opposite direction, i.e., to heat an inclusion until the gas (steam) bubble is eliminated, and the inclusion becomes homogene. The homogenization temperature (T_{hom}) is always represent the **minimal** possible temperature of a mineral-forming fluid.

Several important assumptions are made when using the fluid inclusion method (Roedder, 1984):

- The fluid was trapped as a single homogene phase (i.e., neither boiling nor effervescence have taken place);
- The volume of the fluid inclusion does not change after sealing;
- Nothing is added or lost from the inclusion after sealing;
- The origin of inclusion is known; and
- The determination of homogenization temperatures are not only precise, but accurate (e.g.: the measurement of T_{hom} by stretched inclusions may be very precise but it **is not** accurate).

Unfortunately, all these assumptions are questionable when dealing with soft and cleavable minerals like calcite. The proof of all of the above assumptions require detailed petrographical observations and some laboratory tests. Besides these inevitable "natural" reliability problems, other major source of error may be induced during sample preparation. The routine procedure of producing doubly polished sections consist of cutting, grinding and polishing. All these techniques involve plastic resin or thermoplastic cement to bind a sample to a glass slide. Both bonds either produce high temperatures during polymerization (>100 °C) or require heating to at least 70 °C. Usually these temperatures are not monitored. Cutting with a normal speed rock-saw can also produce both heating and mechanical (vibrational) stress. Significant heating (up to 60-70 °C) may be generated during grinding and polishing. It is important that all these procedures are performed before the petrographic study of a sample.

Each of the factors mentioned above may lead to complete or partial decrepitation, or stretching of inclusions, that in turn will produce apparently **too high** T_{hom}. The most "dangerous" situation is represented by stretched inclusions (decrepitated and/or leaked inclusions can be identified petrographically). These inclusions are the major source of erroneously high homogenization temperatures published in literature or produced by the laboratories.

Summary. Two aspects should be kept in mind when analyzing the data on fluid inclusions: (1) T_{hom} reflects **minimal** possible formation temperature, and (2) **erroneously high** T_{hom} are easily measured in calcite. Thus, it is an appropriate approach to consider fluid inclusion temperatures as lower estimates of paleotemperatures, keeping suspect the highest-temperature datapoints.

3.2. Analysis of Data Published

Detailed analysis of data published has been done by Dublyansky (1994a & b). The following text is a condensed version of these publications. The analysis is based on the following data: (1) Bish, 1989; (2) Bish and Aronson, 1993; (3) Data released by Yucca Mountain Site Characterization Project Office on December 20, 1993 (further referred as YMP, 1993); and (4) Roedder at al., 1994.

Bish D.L., (1989)

The samples of calcite were collected from cores extracted from two drill holes: USW G-2 and USW G-3/GU-3. Altogether 10 homogenization temperatures were measured (**Table 3-1**). In fact, 8 datapoints are given as the boundaries of temperature intervals, so, the real number of measurements made is not clear.

Table 3-1

Homogenization temperatures (T_{hom}) measured by fluid inclusions in calcite from drill holes USW G-2 & G-3/GU-3 (by Bish, 1989)

Drill Hole USW G-2	
Depth, m	**T_{hom}, °C**
-1640	94-115
-1756	147
-1774	202-139
Drill Hole USW G-3/GU-3	
Depth, m	**T_{hom}, °C**
-31	101-227
-131	125-170
-1464	97

Note. Data, potentially usable for paleogeothermal reconstruction of the Stagecoach Road Fault hydrothermal system are shaded.

These sparse data remained the only information available on fluid inclusions for about five years, and were widely quoted in many reports. The author (Bish) seemed, however, to not be very sure of the interpretation of some of his data, particularly the high homogenization temperatures measured in the shallow calcite from the USW G-3/GU-3 core:

> *Lack of mineralogical data to support elevated alteration temperatures suggest that the higher temperature inclusions in the upper part of USW G-3 probably formed during the initial deposition or cooling of the tuffs. Alternatively, the relatively high homogenization temperatures in the shallow G-3 calcites may be a result of re-equilibration of variable initial vapor-to-liquid ratios (Goldstein, 1986).*

Most unfortunately, neither fluid inclusions observed, nor the procedures of sample preparation and laboratory techniques and equipment used are described in the report. Thus, the reliability of data (especially, of high temperatures measured in shallow calcite) is questionable.

Bish D.L. and Aronson J.L., (1993)

This publication is heavily based on the report reviewed above. All numeric data and inferences are essentially the same as ones given in (Bish, 1989). Some data are given on samples studied and techniques used:

> *Fluid inclusions in thin-sections from USW G-2 and GU-3/G-3 were examined using techniques described by Roedder (1984). In general, only calcite contained secondary inclusions that might provide information on secondary alteration conditions, and inclusion large enough for study were very rare.*

Two alerting statements are present in the above quotation: (a) thin sections prepared using standard methods <u>are not suitable</u> for fluid inclusion studies in calcite; and (b) secondary inclusions are rarely used in fluid inclusion studies unless they are clearly distinguishable from primary ones, that is particularly difficult for calcite.

Summary on (1) and (2). The fluid inclusion temperatures given in these two publications characterize mostly "deep seated" calcite and, respectively, the environment of old (~11 to 9 Ma) stage of alteration induced, most probably, by

Timber Mountain moat volcanism. Calcites from -31 and -131 m in USW G-3/GU-3 may represent younger calcite we are interested in. There is no possibility to check this (as there are no data on stable isotope- or trace element pattern for these samples). On the other hand, the fluid inclusion temperatures measured by these samples are quite doubtful *per se*. The inference is that the data given in (1) and (2) may not be used for paleothermometry reconstruction of younger hydrothermal system.

YMP, (1993)

The data were obtained for two drill holes: USW G-1 and USW G-2. Altogether 27 measurements are given (**Table 3-2**). No data on sample preparation as well as procedures and techniques used were available.

Seven out of twenty-seven datapoints represent young "shallow" calcite, we are interested in (**Fig. 3-1**). Even being quite restricted in number, these data imply the paleothermal gradient much steeper than current geothermal gradients in the area (about 170 °C/km), and underground temperatures some 40-50 °C higher than current ones.

Roedder, Whelan and Vaniman, (1994)

The authors describe two-phase liquid+vapor inclusions in calcite from four depths: -130, -204, -292 and -314 m in core USW G-1. No numerical data on homogenization temperatures are given. The authors only mention that:

> *...inclusions occurred in groups, with an apparently uniform and small V/L ratio, which visually indicated that the inclusions had formed at low temperatures, probably ≤~100 °C (p.1858)*

Table 3-2

Fluid inclusion temperatures, stable isotope signatures and radiocarbon ages for calcite from drill holes USW G-1 & G-2 (YMP, 1993)

Drill Hole USW G-1					
HD#	**Depth, m**	**$\delta^{13}C$, ‰ PDB**	**$\delta^{18}O$, ‰ PDB**	**Age by ^{14}C, Ka**	**T_{hom}, °C**
322	-204	-0,6 & -4,8	-15,8	20,9±0,9	81
338	-1094	2,1	-20,2		99, 102, 114
343	-1178	2,2	-19,6		74, 86
348	-1630	0,3	-26,7		87, 91, 91, 96
Drill Hole USW G-2					
HD#	**Depth, m**	**$\delta^{13}C$, ‰ PDB**	**$\delta^{18}O$, ‰ PDB**	**Age by ^{14}C, Ka**	**T_{hom}, °C**
359	-178	-7,7	-12,2	45,26±1,85	57, 59
368	-347	-7,8	-12,9		81> 72
369	-386	-	-		103, 104
579	-1269	-0,2	-24,6		78, 79, 80, 80, 82
582	-1497	-1,4	-23,4		240-260
583	-1557	1,1	-28,0		215, 216, 242, 245

Note. Data, potentially usable for paleogeothermal reconstruction of Stagecoach Road Fault hydrothermal system are shaded. Calcite from -204 m in USW G-1 revealed presence of two varieties with mean $\delta^{13}C$ = -0,6 ‰ (HG#322A; n=4) and $\delta^{13}C$ = -4,8 ‰ (HG#322B&C; n=4); the $\delta^{18}O$ for both calcites vary within 0,5 ‰.

and latter conclude that:

> *...these calcites have formed at low temperatures, <100 °C, possibly comparable to modem ambient temperatures (p.1859).*

From the author's description one may infer that the temperature of paleofluid was higher than ~40 °C; otherwise the shrinkage vapor bubbles in inclusions just would not have nucleated (see Dublyansky, 1994-b for discussion). Thus, paleotemperatures must have been higher than the "modern ambient temperatures".

Stable isotope signatures of calcites studied are not given in the paper. Comparison with data presented in YMP, 1993 shows that, most probably, the samples studied were: HD#318 (-129,7 m), HD#322 (-204,0 m), HD#325 (-292,5 m) and HD#326 (-313,6 m). The stable isotope signatures for these samples are given in **Table 3-3**.

Table 3-3

Stable isoptope signatures and approximate formation temperatures for calcite samples discussed in Roedder at al., 1994

Drill Hole USW G-1					
HD#	**Depth, m**	**n**	**$\delta^{13}C$, ‰ PDB**	**$\delta^{18}O$, ‰ PDB**	**~T, °C**
318	-129,7	5	-6,2	-14,6	40 to 100
322	-204,0	4 & 4	-0,6 & -4,8	-15,8	40 to 100 (81*)
325	-292,5	2	-7,3	-14,6	40 to 100
326	-313,6	2	-6,8	-14,8	40 to 100

Note: Temperature of 81 °C for sample HD#322 is by YMP, 1993. Calcite HD#322 revealed presence of two varieties with mean $\delta^{13}C$ = -0,6 ‰ (HG#322A; n=4) and $\delta^{13}C$ = -4,8 ‰ (HG#322B&C; n=4); the $\delta^{18}O$ for both calcites vary within 0,5 ‰.

3.3. Conclusion and Recommendations

All the data available on fluid inclusion temperatures are compiled in **Fig. 3-2**. Solid line represents paleothermal gradient inferred by homogenization temperatures measured in calcite from USW G-1 & G-2 (YMP, 1993). The data, derived from analysis of text by Roedder et al. (1994) are given as a shaded area (depth from -130 to -314 m; temperatures from 40 to 100 °C). Being semi-quantitative, these data are still consistent with temperatures by YMP, 1993. Temperatures published by Bish and Aronson (1993; thick vertical lines) seem to be too high. They probably were obtained either from another genetic type of calcite (we have no possibility to check it out) or from inappropriate inclusions (stretched or leaked). These data may not be used in paleothermal reconstruction.

We may conclude that fluid inclusion data obtained from young shallow calcite deposited, we believe, by Stagecoach Road Fault hydrothermal system, imply paleothermal gradient of ~170 °C/km. It is much higher than current geothermal gradients varying from ~20 to 24 °C/km at Yucca Mountain (Sass et al., 1987). One must keep in mind, however, that this conclusion is based only on <u>seven</u> datapoints. Thus, an extensive and detailed fluid inclusion studiy is highly recommended.

Chapter 3. Paleothermometry by Fluid Inclusions

Figures...

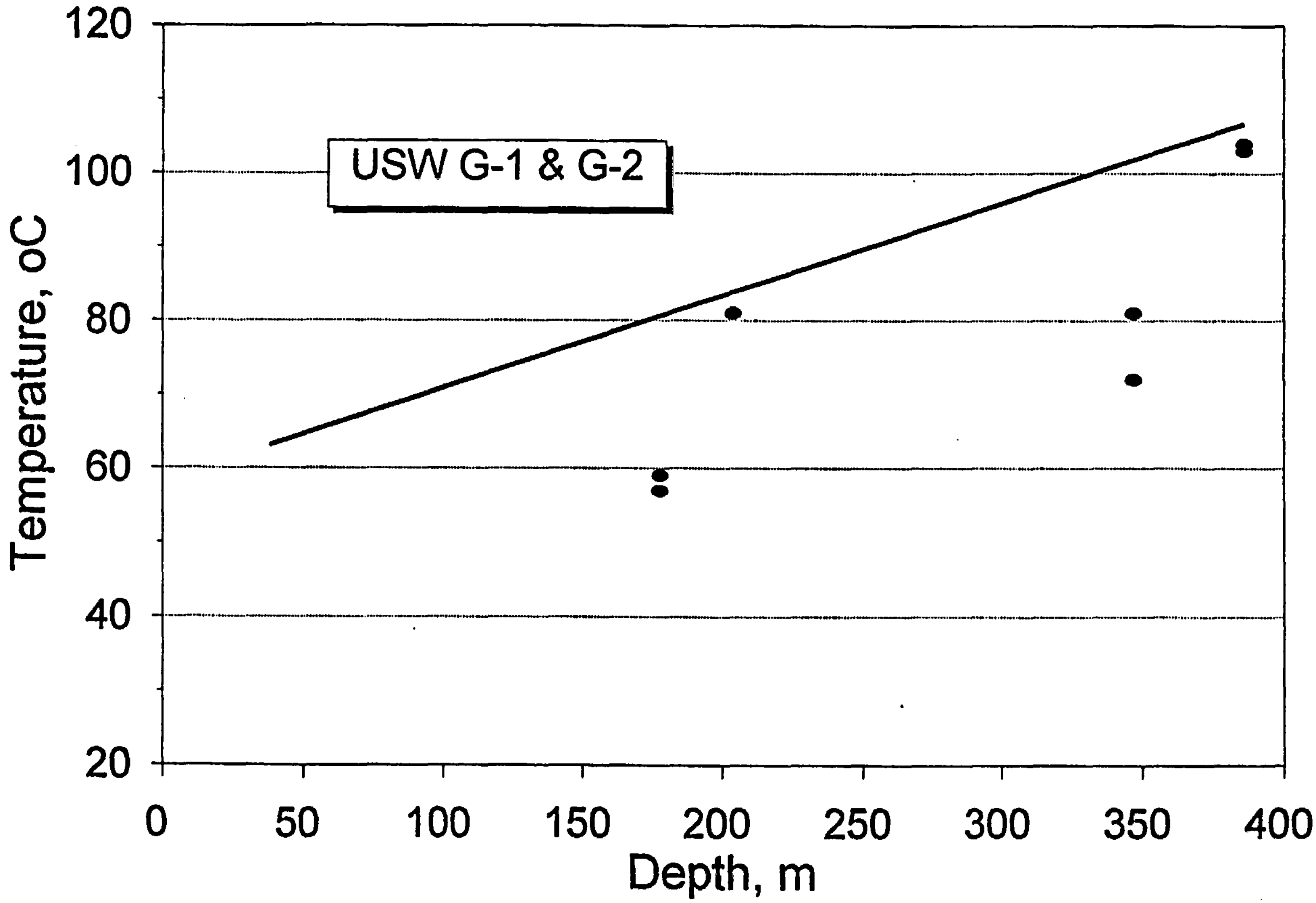


Fig. 3-1. Fluid inclusion temperatures measured in calcite from drill holes USW G-1 and USW G-2 (by YMP, 1993)
Solid line represents an inferred paleothermal gradient at time of calcite deposition

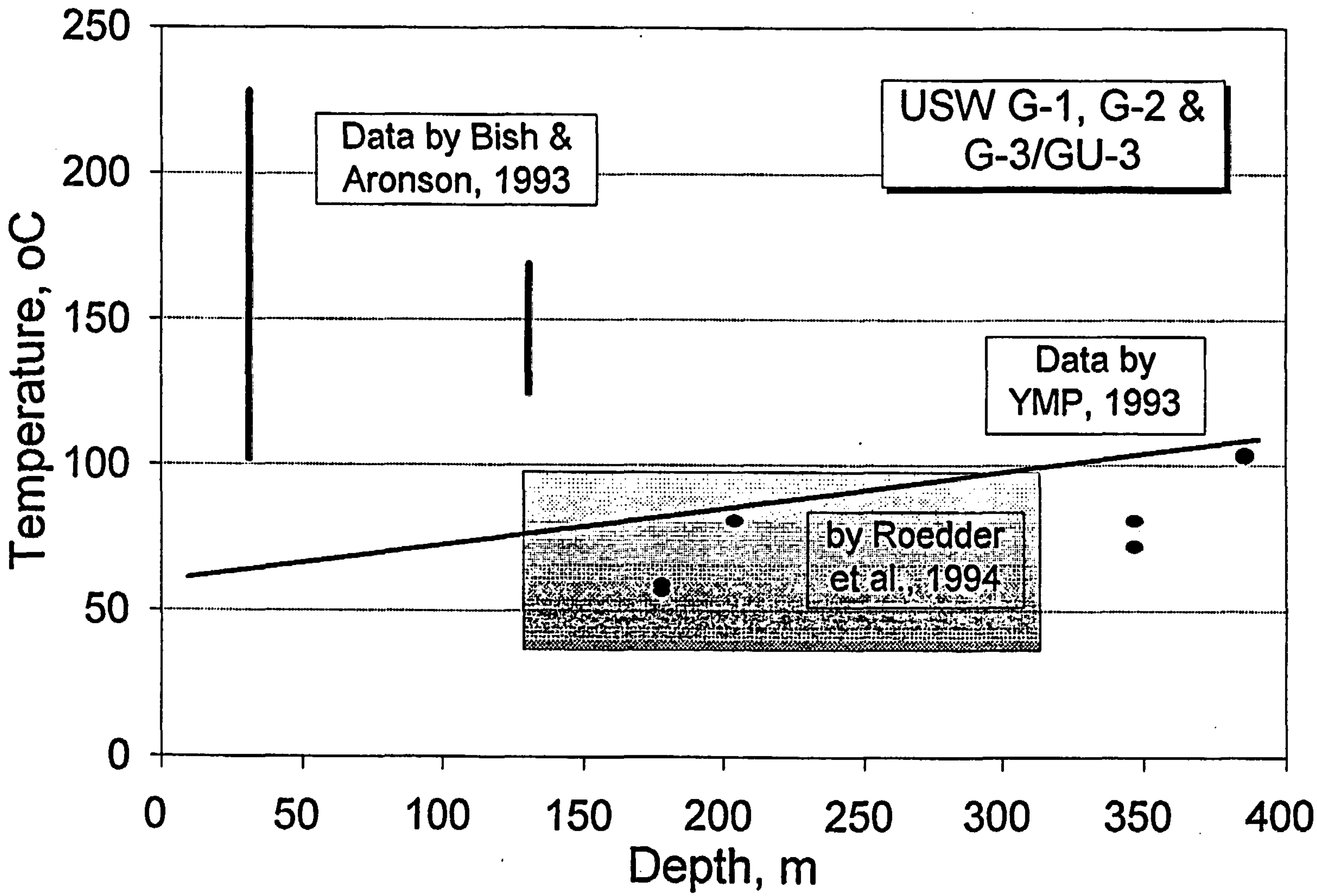


Fig. 3-2. Summary of fluid inclusion temperatures obtained for calcite from drill holes USW G-1, G-2 and G-3/GU-3 (by Bish & Aronson, 1993; YMP, 1993; and Roedder et al., 1994)
Solid line is inferred paleothermal gradient

Chapter 4. Paleothermometry by $\delta^{18}O$ in Calcite

The fractionation of $\delta^{18}O$ in calcite is a temperature-dependent process. Thus, the change of $\delta^{18}O$ in subsurface calcite with depth may reflect change in depositional temperatures, i.e.:

$$d\delta^{18}O/dz \rightarrow dT/dz \qquad (4\text{-}1)$$

First estimates of paleothermal gradients in Yucca Mountain by this method were performed by Szymanski (1993), who also discussed the reliability of the approach. The reconstruction has been done on the basis of restricted data available by that time (~60 datapoints; only 19 out of them represented subsurface calcite). Now, when more data have been released (YMP, 1993; Hill and Schluter, 1994) there is an opportunity to perform similar reconstruction on the basis of much larger, statistically representative data set separately by different drill holes.

Equilibrium fractionation of ^{18}O between water (mineral forming solution) and calcite deposited from this water may be described by equation:

$$\Delta_{c-w} = 2{,}70\left(\frac{10^6}{T^2}\right) - 3{,}39 \quad \text{(O'Neil at al., 1969),} \qquad (4\text{-}2)$$

where w = water, c = calcite, T = absolute temperature, and $\Delta_{c-w} = (\delta^{18}O_c - \delta^{18}O_w)$. Assuming $\delta^{18}O_w$ = const., the relation between temperature (in °C) and $\delta^{18}O_c$ may be expressed as:

$$T = \sqrt{\frac{A}{\delta^{18}O_c - B}} - C, \qquad (4\text{-}3)$$

where A = 2,7·10^6; B = ($\delta^{18}O_w$+3,39); and C = 273. Equation (3) was used to plot the change of $\delta^{18}O_c$ *vs*. depth for three chosen geothermal gradients (**Fig. 4-1**). Then values of $\delta^{18}O$ measured in shallow calcites from four drill holes were plotted and approximated by linear-fit lines. It is seen, that for three out of four drill holes the apparent paleothermal gradients are much higher than the current gradients measured in these drill holes (that is, ~24 °C/km in USW G-1 and G-2; ~22 °C/km in G-3; ~20 °C/km in G-4; Sass et al., 1987). For drill hole USW G-1 the linear fit for $\delta^{18}O$ values displays an apparent paleothermal gradient as low as ~20 °C/km.

The data given in **Fig. 4-1** also imply that temperatures at the surface were higher in G-1 and G-4 and lower in G-2 and G-3.

Discussion and Recommendations

To judge the reliability of the above paleothermal gradient estimates one must be aware about all the assumptions made. Specifically, it was assumed that:

- Fractionation of ^{18}O between parent fluid and calcite attained equilibrium; non-equilibrium effects were either negligible or depth-invariant.
- Fractionation due to difference in temperature was the only leading process, i.e., fractionation due to depositional kinetics and the effects like effervescence, boiling, evaporation, etc., may be neglected.
- Isotopic characteristics of parent fluid did not change within the time span of calcite deposition (up to 7-8 Ma in our case) and in space (several km distance between drill holes USW G-1 to G-4, and up to 0,8 km depth).
- The calcite analyzed for $\delta^{18}O$ is homogene, i.e., it represents one geological system and one depositional episode.

Since all of the above assumptions are hard to prove, the reliability of this method of paleothermometry is not high. It must also be emphasized, that the approach discussed above is relativistic: it may be used for estimation of paleotemperature gradients (dT/dz), but may not be used as an absolute paleothermometer (see, e.g., Szabo and Kyser, 1990).

As for as the obtained data is concerned, three more factors must be considered:

- Lack of consistency between four boreholes analyzed;
- Lack of consistency with results obtained by fluid inclusions (see **Chapter 3**) and calcite/opal pairs (see **Chapter 5**); and
- Variability of ^{18}O signatures in calcites from drill holes (**Figs. 4-2** to **4-5**).

The obvious way to improve further results is to couple isotopic studies with detailed petrographic examinations. It may help to discriminate calcites belonging to different depositional stages, yielding in turn, different $\delta^{18}O$ signatures. Most of the assumptions discussed above, however, remain unavoidable, and thus, the method is of questionable value for numeric paleothermometry. As a relativistic method, however, it gives a strong evidence of historic temperature gradients which were significantly (hundreds percent) higher than those observed at Yucca Mountain today.

Chapter 4. Paleothermometry by $\delta^{18}O$ in Calcite

Figures...

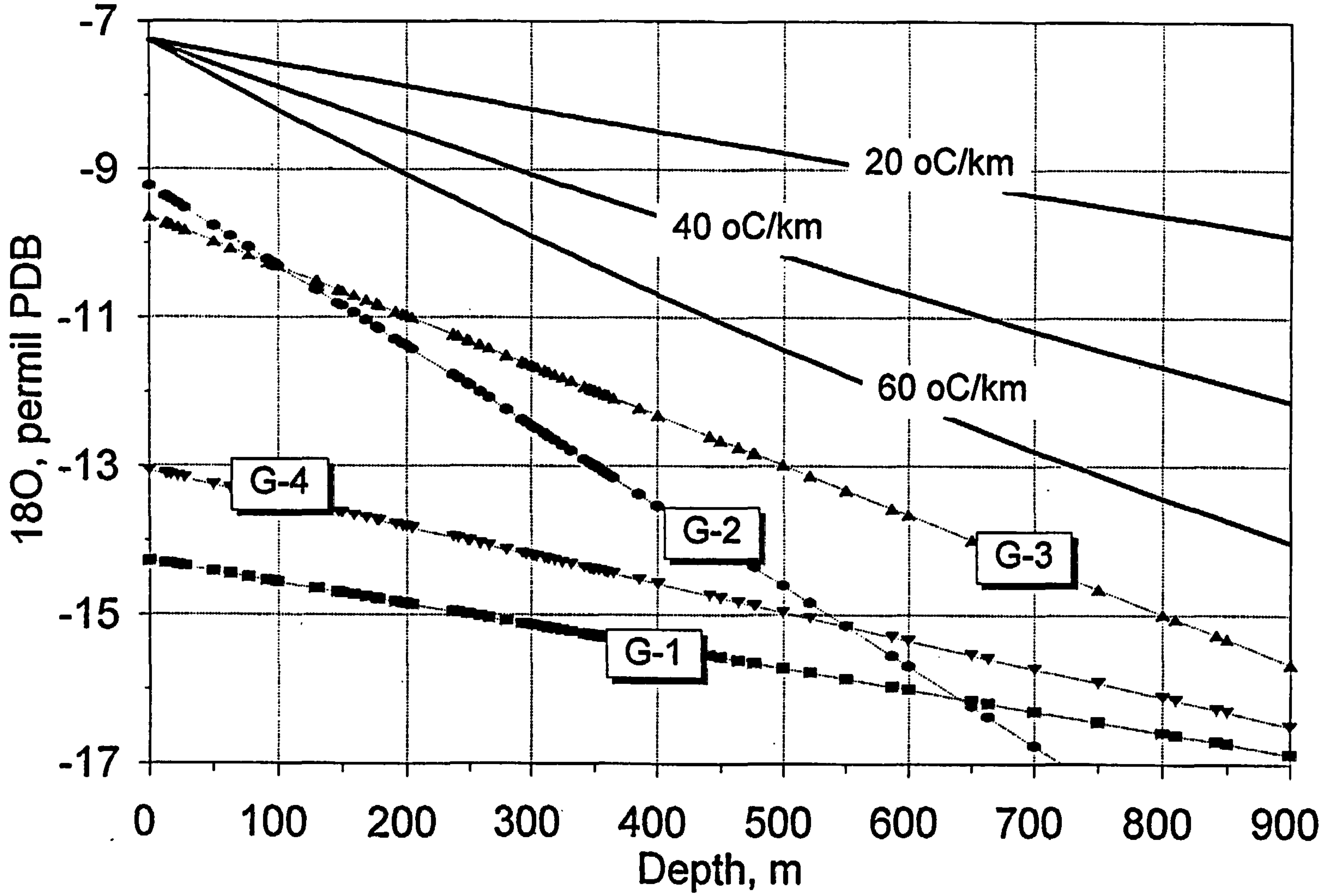


Fig. 4.1. Linear-fit approximation for $\delta^{18}O$ of calcites from four drill holes in Yucca Mountain in comparison with $d\delta^{18}O/dz$ calculated for three chosen geothermal gradients

Numeric data for $\delta^{18}O$ were taken from YMP, 1993; Szabo and Kyser, 1990; and Hill and Schluter, 1994. Theoretical temperature-dependent gradients $d\delta^{18}O/dz$ were calculated by O'Neil et al., 1969 (equation 4-3).

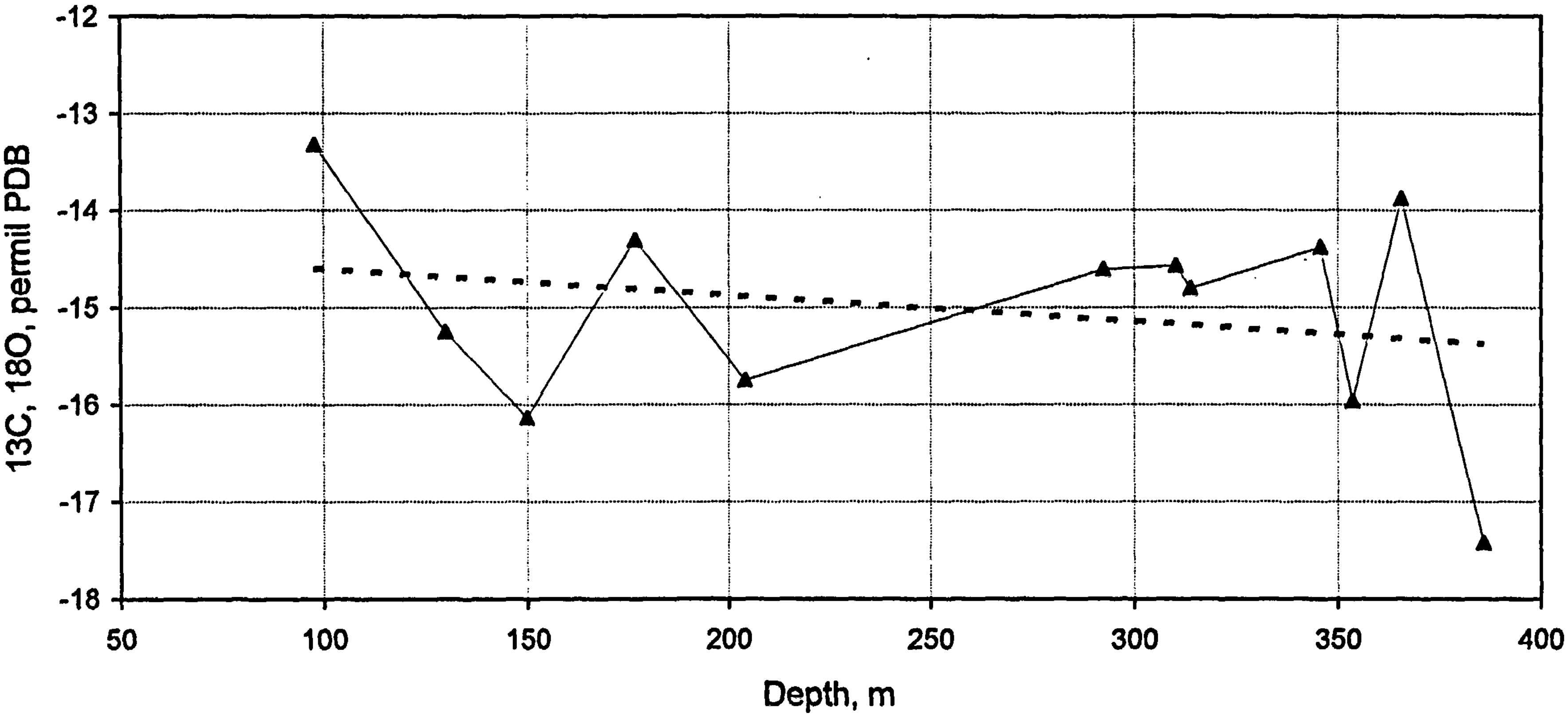


Fig. 4-2. Data and linear trend for $\delta^{18}O$ in calcites from drill hole USW G-1

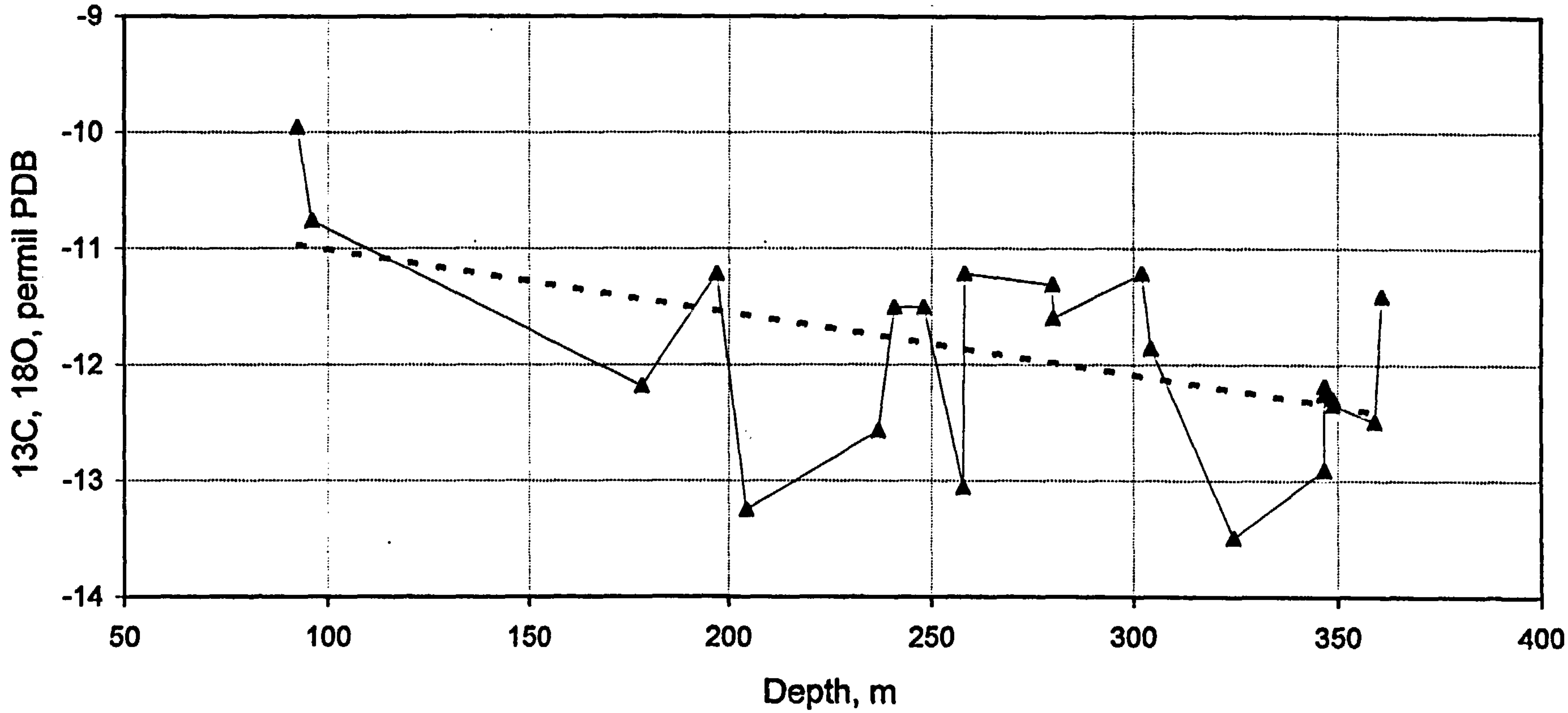


Fig. 4-3. Data and linear trend for $\delta^{18}O$ in calcites from drill hole USW G-2

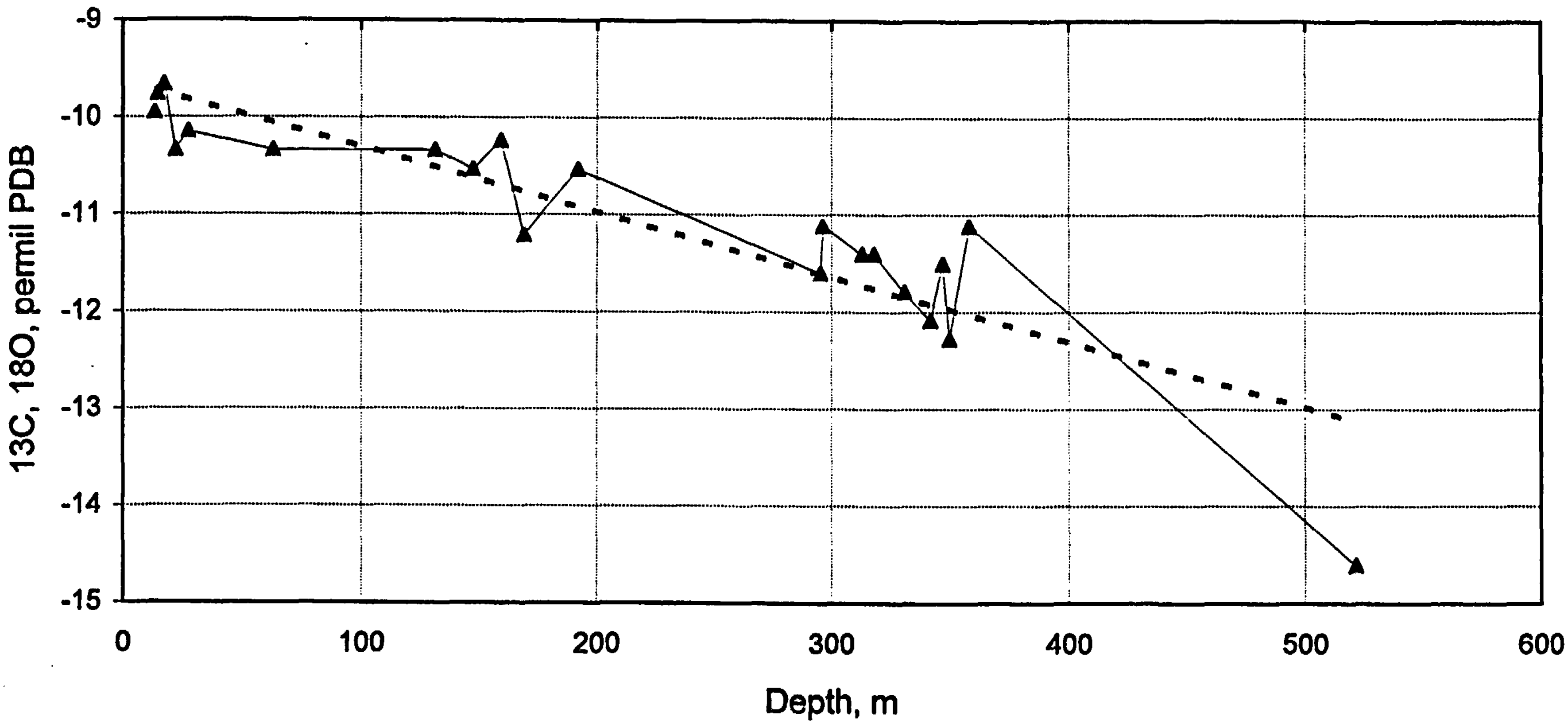


Fig. 4-4. Data and linear trend for $\delta^{18}O$ in calcites from drill hole USW G-3

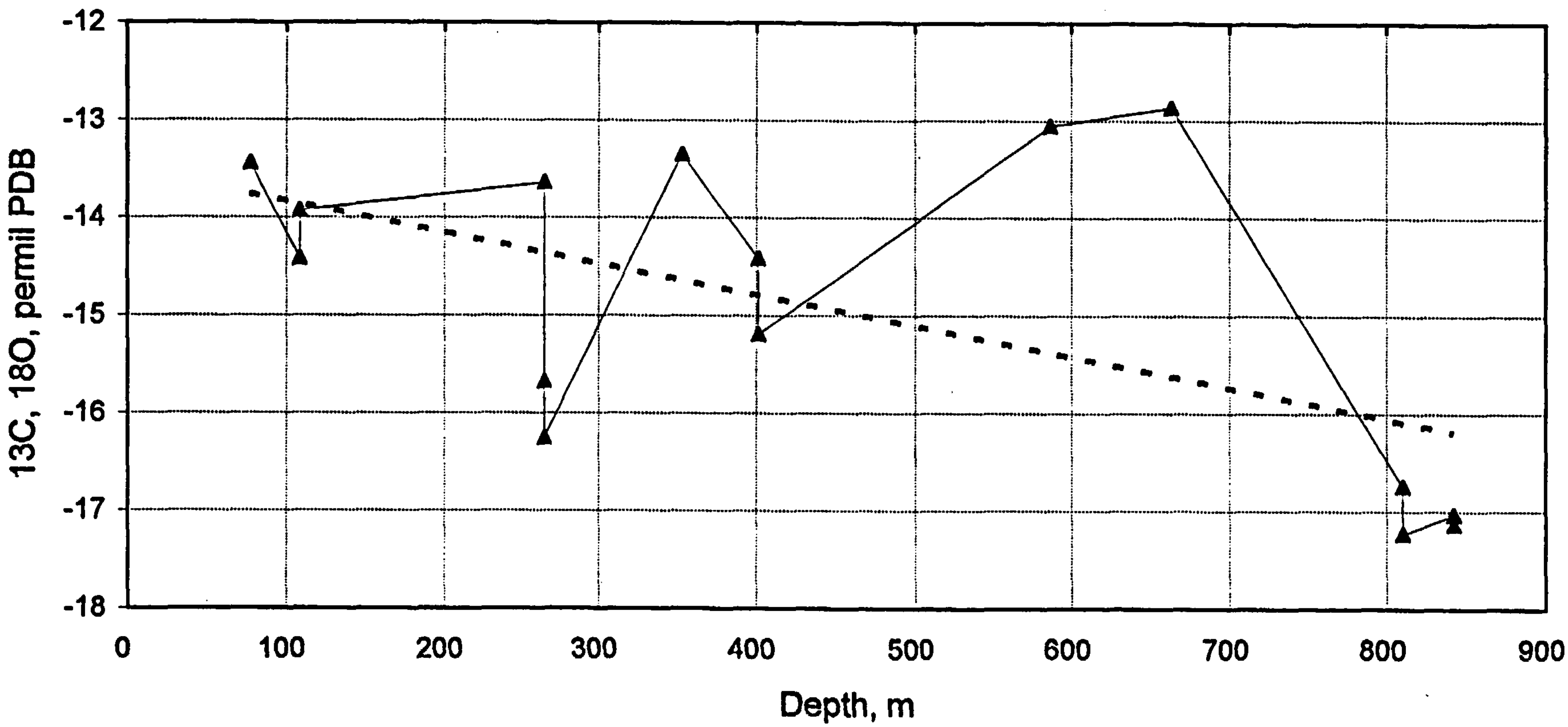


Fig. 4-5. Data and linear trend for $\delta^{18}O$ in calcites from drill hole USW G-4

Chapter 5. Paleothermometry by $\delta^{18}O$ in Calcite/Opal Pairs

The controversial deposits in Yucca Mountain are often composed of two mineral phases: calcite and opal. Thus, theoretically, the method of thermometry by $\delta^{18}O$ in calcite/silica pairs may be applied.

Some of Yucca Mountain calcite/opal deposits (especially containing opal A) may have been formed at comparatively low temperatures. Others, found at depth of up to 280 m in association with calcite yielding elevated fluid inclusion temperatures (50-80 °C) or containing relatively high-temperature quartz (e.g., Pull Apart fault, 125-190 °C, Harmon, 1993) may be denoted as "high-temperature" occurrences. Fractionation of ^{18}O in these two "end-member" pairs may be described by two different equations. To get them, three base equations should be used:

$$\Delta_{C-W} = 2{,}70\left(\frac{10^6}{T^2}\right) - 3{,}39 \quad \text{(O'Neil at al., 1969)} \qquad (5\text{-}1)$$

$$\Delta_{Q-W} = 3{,}38\left(\frac{10^6}{T^2}\right) - 3{,}4 \quad \text{(Clayton at al., 1972)} \qquad (5\text{-}2)$$

and

$$\Delta_{S-W} = 0{,}60\left(\frac{10^6}{T^2}\right) - 3{,}39 \quad \text{(Kita at al., 1985)} \qquad (5\text{-}3)$$

where W = water, C = calcite, Q = quartz, S = amorphous silica, and T = absolute temperature. By combination of equations (5-1) to (5-3), two equations for silica-calcite and quartz-calcite fractionation may be derived:

$$\Delta_{S-C} = 0{,}74\left(\frac{10^6}{T^2}\right) - 0{,}69 \qquad (5\text{-}4)$$

and

$$\Delta_{Q-C} = 0{,}60\left(\frac{10^6}{T^2}\right) \qquad (5\text{-}5)$$

Equation (5-4) is applicable within temperature interval from 34 to 93 °C. Conventionally, equation (5-5) is in use for 0 to 500 °C, though one of the "parent" equations (5-2) is applicable only within 200-500 °C interval (Clayton at al., 1972). Isotherms described by equation (5-4) are the better approximation for low-temperature calcite/opal deposits, while ones described by (5-5) are applicable to high-temperature deposits with higher degree of crystallinity.

Two equations for calculation the temperature (in °C) derived from (5-4) and (5-5) are:

$$T = \sqrt{\frac{0{,}74 \cdot 10^6}{\Delta_{S-C} + 0{,}69}} - 273 \qquad (5\text{-}6)$$

and

$$T = \sqrt{\frac{0{,}6 \cdot 10^6}{\Delta_{Q-C}}} - 273 \qquad (5\text{-}7)$$

The $\delta^{18}O$ signatures have been measured for 11 calcite/opal pairs in the Yucca Mountain area (Hill and Schluter, 1994; **Table 5-1**). Three superficial calcite/opal deposits (Busted Butte, Wailing Wall and Bare Mountain) give more or less reasonable temperature estimates being compared with isotherms for amorphous silica/calcite (**Fig. 5-1**). All other datapoints lie beyond the "working interval" of this thermometer. The data on opal-calcite from drill holes as well as from the Pull Apart fault should rather be compared with isotherms for quartz/calcite pair (**Fig. 5-2**). The Pull Apart fault sample reveals temperatures lower than those determined by fluid inclusions (approx. 80 °C by ^{18}O *vs.* 125-190 °C by fluid inclusions; Harmon, 1993).

Fluid inclusion data have provided an estimate of paleothermal gradient in the drill hole USW G-2 (see **Chapter 3, Fig. 3-1**). According to this estimate, the temperatures at -90 to -350 m were as high as 70 to 110 °C. One may see from **Fig. 5-2** and **Table 5-1** that some ^{18}O-temperatures are in reasonable agreement with fluid inclusion data (-85 and -92 m), while other imply either too high (~200 °C at -237-240 m, 238 °C at -280 m) or too low temperatures (~26 °C at -258 m and ~31 °C at -347 m).

We have plotted temperatures calculated by equation (5-7) *vs.* depth and have calculated a linear-fit line for them (**Fig. 5-3**; three datapoints yielding geologically irrelevant temperatures were omitted). This line may be considered as an estimate of paleothermal gradient.

Conclusion and Recommendations

The reliability of paleothermometric reconstruction by ^{18}O in calcite/opal pairs still remains questionable due to several reasons:

- Quartz-calcite thermometer does not work perfectly being applied to low-temperature formations, as the data on fractionation at temperatures below 400 °C are uncertain (Kyser, 1987).
- Opal and calcite in Yucca Mountain were not necessarily formed at isotopic equilibrium.

Table 4-1

Locality	HG#	Depth, m	$\delta^{18}O$ in Opal, ‰ SMOW	$\delta^{18}O$ in Calcite, ‰ SMOW	Δ, ‰	Calculated T calcite/silica (eqn. 5-6), °C	Calculated T calcite/quartz (eqn. 5-7), °C	Source
Pull Apart fault	-	0	28,17	23,36	4,81	93,8	80,2	Harmon, 1993
Bare Mountain	-	0	28,19	20,27	7,92	20,2	2,2	do
Wailing Wall	-	0	28,17	19,84	8,33	13,4	-4,6	do
Busted Butte	-	0	29,91	20,23	9,68	-5,6	-24,0	do
USW G-2	351B	92,2	26,6	20,6	6,00	59,6	43,2	YMP, 1993
do	355A	236,7	20,6	17,9	2,70	194,2	198,4	do
do	356A	240,7	21,7	19,0	2,70	194,2	198,4	do
do	358A	257,8	24,1	17,4	6,70	43,4	26,3	do
do	362A	280,2	21,2	18,9	2,30	224,5	237,8	do
do	-	346,8	24,8	18,3	6,50	47,8(*)	30,8(*)	Szabo &Kyser,1994
UE25 A5	926A	85,2	21,9	17,8	4,10	120,1	109,5	YMP, 1993
do	929A	92,2	23,3	17,9	5,40	75,6	60,3	do

Notes: Light shading = geologically unreasonable calculated temperatures; **dark shading** = the result of calculations falls outside the "working interval" for equation (5-6), that is 34 to 93 °C. (*) = U-series age and petrographic relationship indicate that these calcite and opal were not formed from the same fluid.

- Significant change in $\delta^{18}O$ signatures may have been caused by re-crystallization of opal A to opal CT, that occurs in presence of water.
- Porous calcite in superficial occurrences may also be a subject to isotopic exchange with meteoric water.

The paleothermal gradient of ~180 °C/km shown in **Fig. 5-3** is based on nine datapoints, displaying significant scatter. Obviously, it may not be considered as a sufficient set of data. It is noteworthy, however, that this gradient is consistent with one, obtained by an independent method - fluid inclusion study (~170 °C/km; see **Fig. 3.1** in **Chapter 3**).

More analyses on calcite/opal pairs should be performed. Two aspects of the problem may be addressed separately:

- Study of calcite/opal pairs from drill cores may provide more reliable data than those obtained from superficial deposits.
- Study of change in $\delta^{18}O$ signatures for calcite/opal pairs in controversial deposits laterally from suspected "feeders" (faults-conductors) may reveal trends, depicting relative cooling of fluids.

All stable isotope analyses by calcite/opal pairs must be coupled with detailed petrographic and fluid inclusion studies.

Chapter 5. Paleothermometry by $\delta^{18}O$ in Calcite/Opal

Figures...

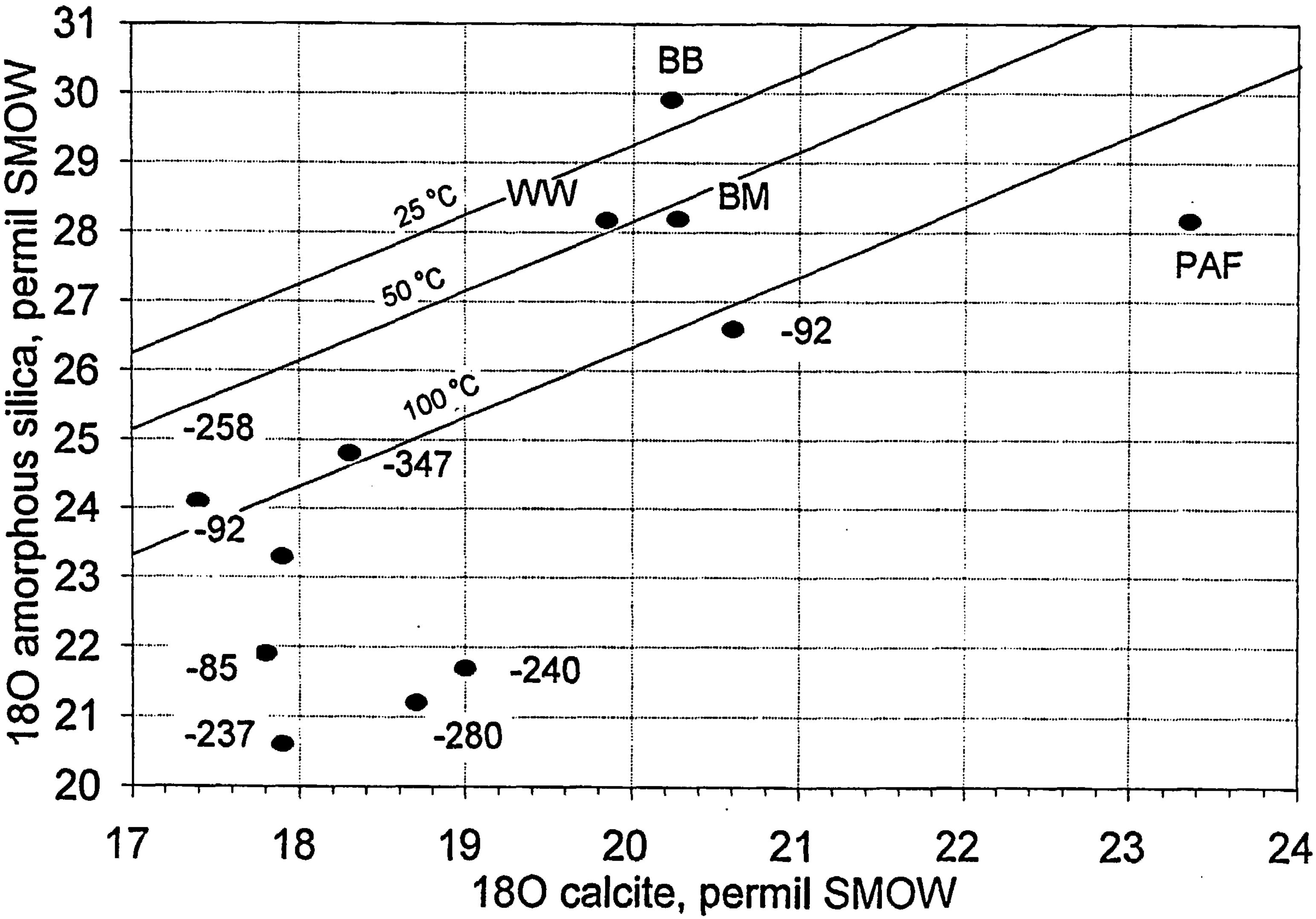


Fig. 5-1. Calcite/opal pairs and isotherms for calcite/amorphous silica. Equation $\Delta_{s\text{-}c} = 0{,}74(10^6/T^2)-0{,}69$ was used to plot the isotherms. As this equation is applicable from 34 to 93 °C, the high-temperature isotherms are not shown.

BB = Busted Butte, WW = Wailing Wall, BM = Bare Mountain, PAF = Pull Apart fault (by Harmon, 1993); numbers indicate the depth of sampling in drill holes (by YMP, 1993)

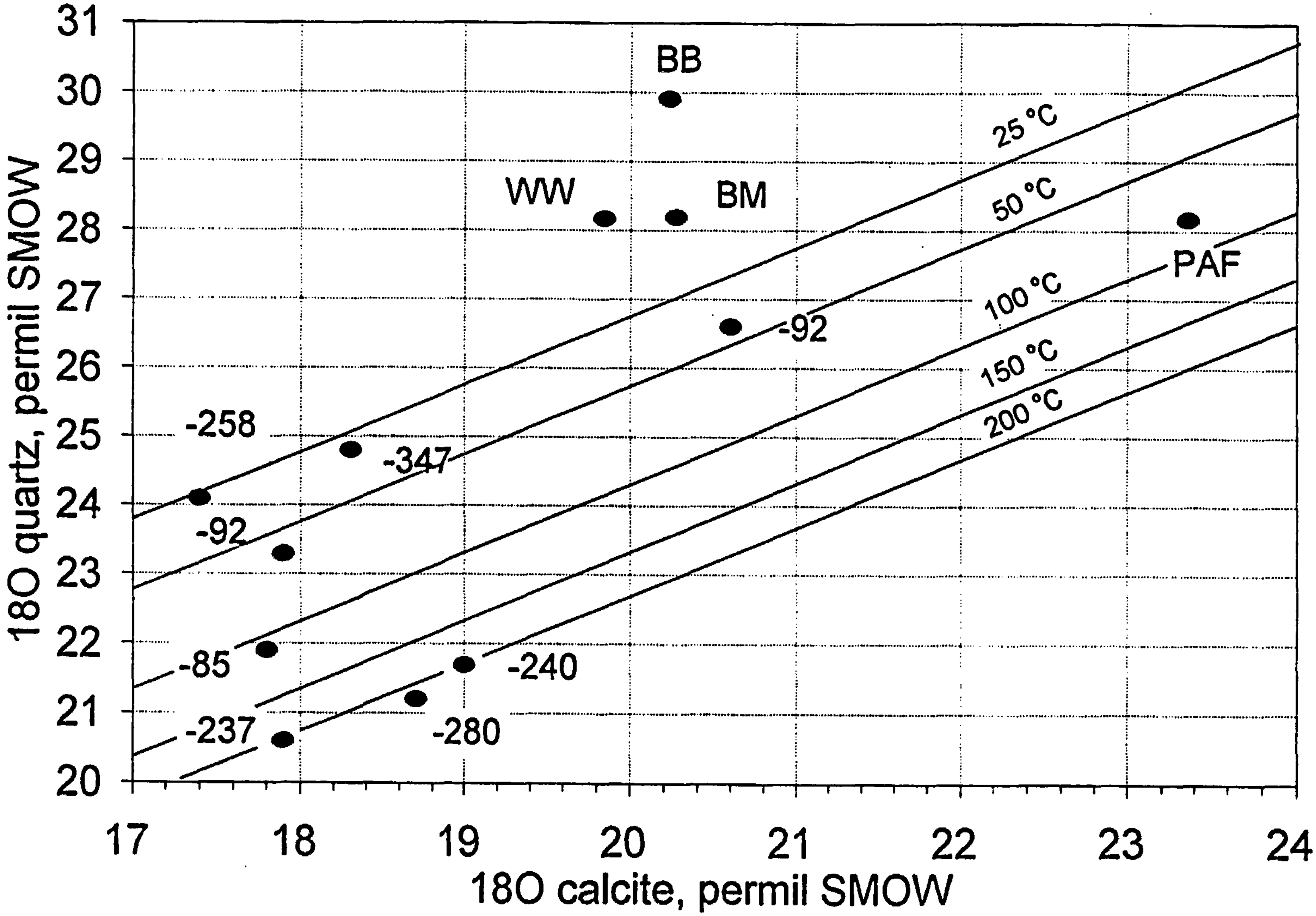


Fig. 5-2. Calcite/opal pairs and isotherms for calcite/quartz. Equation $\Delta_{q\text{-}c} = 0,6(10^6/T^2)$ was used to plot the isotherms.
Superficial occurrences (except Pull Apart fault) plot in irrelevantly low-temperature area. BB = Busted Butte, WW = Wailing Wall, BM = Bare Mountain, PAF = Pull Apart fault (by Harmon, 1993); numbers indicate the depth of sampling in drill holes (by YMP, 1993)

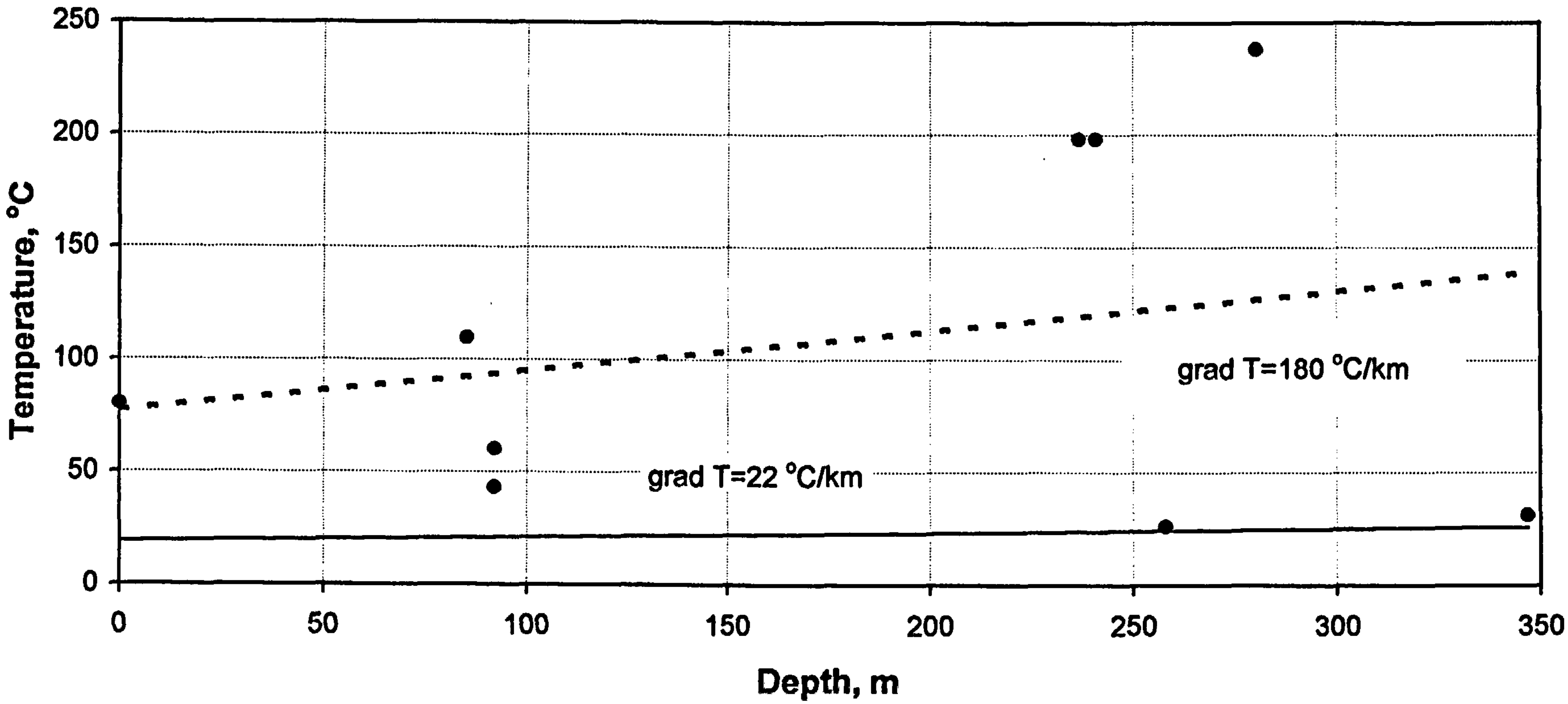


Fig. 5-3. Change in temperature with depth calculated by calcite/opal pairs of Yucca Mountain

Circles = calculated temperatures; **dashed line** = linear-fit approximation; **solid line** = current temperatures measured in drill holes. Data from **Table 5-1** were used. Geologically unreasonable temperatures (values in shaded cells in Table) were omitted.

Chapter 6. Paleothermometry by Thermoluminescence

Kinetic thermoluminescence techniques have been successfully applied to determine paleotemperatures by two samples of quartz and other minerals removed from cores taken at various locations at Yucca Mountain (Haskell and McKeever, 1994). Similarly to fluid inclusions, ^{18}O in calcite and calcite-opal pairs, thermoluminescence implies elevated temperatures in the past:

> *Preliminary thermal analyses on polymineral grains as well as quartz extracts from two core samples suggest historical temperatures (<50 Ka) were in excess of current ambient temperatures by 12 °C to 52 °C. These preliminary results will be expanded once trapping parameters are determined for other minerals present in the cores.*

(Haskell and McKeever,1994). Temperatures determined by thermoluminescence were: 34, 58, 67 and 83 °C for the sample from -283 m in drill hole USW GU-3a (the ambient temperature at that location is 22 °C); and 38 and 62 °C for the sample from -436 m in drill hole USW GU-2b (the ambient temperature is 26 °C). The relationship between TL- and ambient temperatures is given in **Fig. 6-1.**

Recommendations. Thermoluminescence analysis of Yucca Mountain samples is still on the stage of feasibility study. The results are promising, as they give possibility to discriminate a "time series" in thermal history, i.e., to evaluate trends of heating/cooling. In order to enhance the confidence of the results, this study must be coupled with fluid inclusion study performed by the same specimens that latter will became a subject of TL analysis. Also, the nature of luminescent minerals other than quartz that remain in the sample after 10 to 60-minute etching in HF, must be clarified.

Chapter 6. Paleothermometry by Thermoluminescence

Figure...

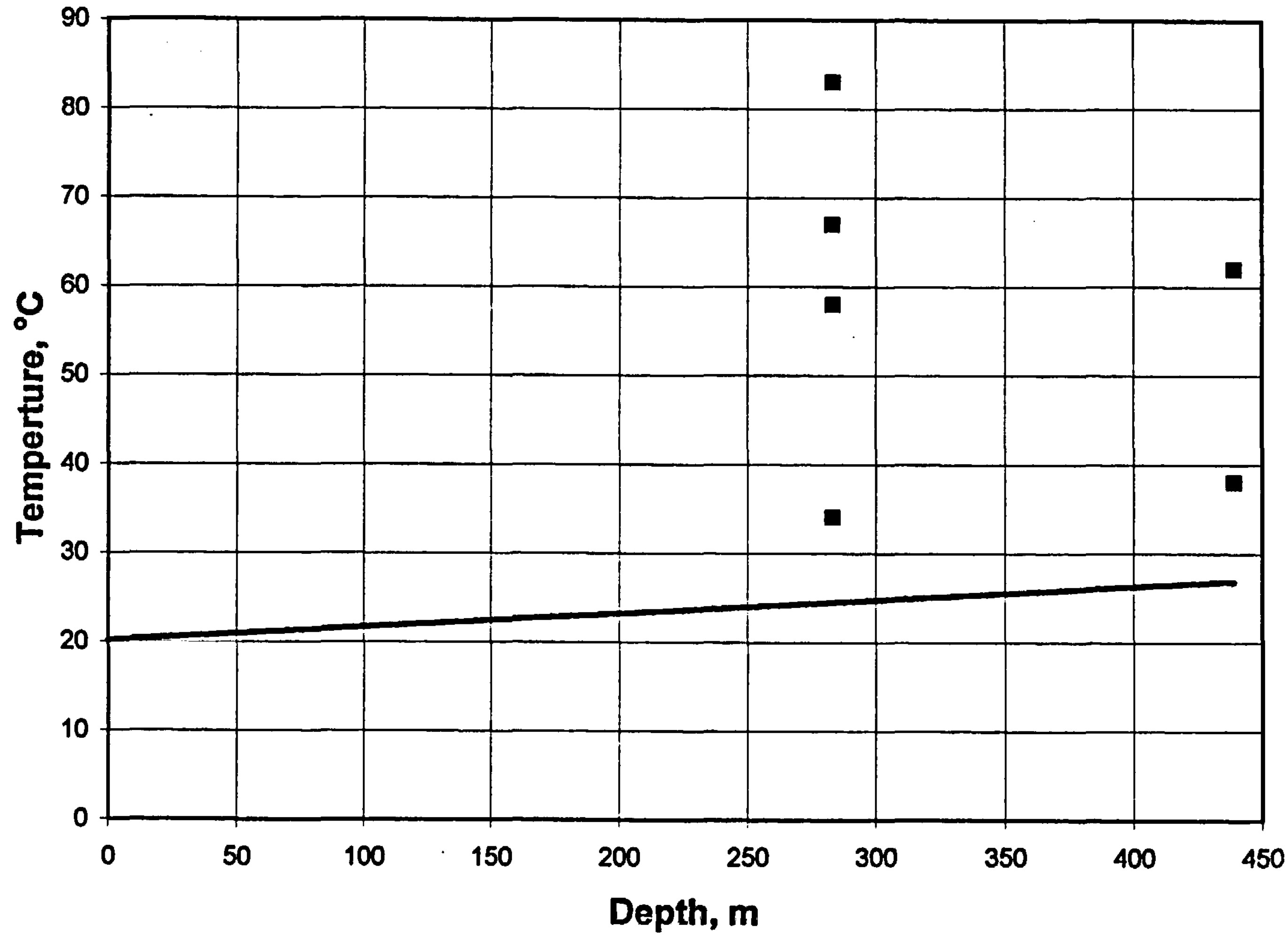


Fig. 6-1. Thermoluminescence temperatures (squares) and ambient temperatures (line)

Chapter 7. Current Thermal Flux: Deep Borehole Logs

It is interesting to compare temperatures inferred by paleothermometry (see previous chapters) with current temperatures in Yucca Mountain. Data on thermometry by drill holes have been published by Sass and Lachenbruch (1982) and Sass at al. (1987). Temperatures measured in more than 40 drill holes are summarized in these reports.

Figures 7-1 to 7-4 show change of temperature with depth in four boreholes that provided information about the Stagecoach Road Fault paleohydrothermal system: USW G-1 to G-4. It is seen that current temperature gradients are not as steep as paleothermal ones (20-25 °C/km *vs.* 170-180 °C/km, respectively). Though current geothermal environment is quite "mild", temperature field under Yucca Mountain is not monotone. Isotherms, plotted by temperatures measured at fixed depth show rather complicated pattern. Temperatures increase along fault zones (**Fig. 7-5**). The shape of isotherms indicates roughly south-north trend of thermal (rather, lukewarm) water movement. Undulation of isotherms is clearly seen in **Fig. 7-6**.

Conclusion

As the current system displays non-linear spatial and temporal behavior, we may presume that the paleohydrothermal Stagecoach Road Fault system was "non-linear". Oscillations of discharge and, respectively, temperature may have been occurring in this paleosystem. Detailed fluid-inclusion, thermoluminescence and calcite/opal pair studies, coupled with detailed U-series (calcite) and ESR (opal) dating may provide information on temporal behaviour of the Stagecoach Road Fault hydrothermal system.

Chapter 7. Current Thermal Flux: Deep Borehole Logs

Figures...

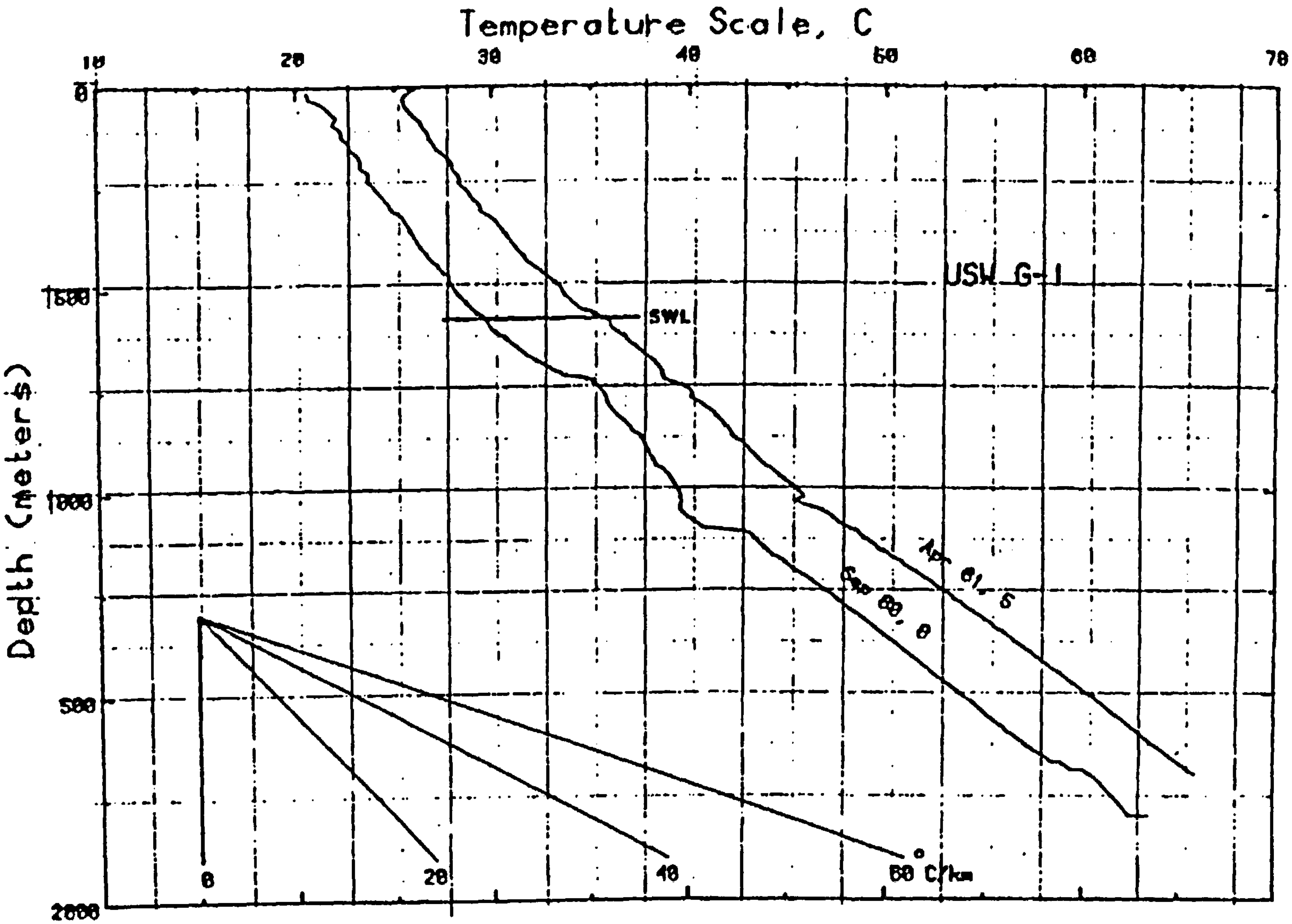


Fig. 7-1. Well USW G-1. Temperature profile. From Sass at al., 1987

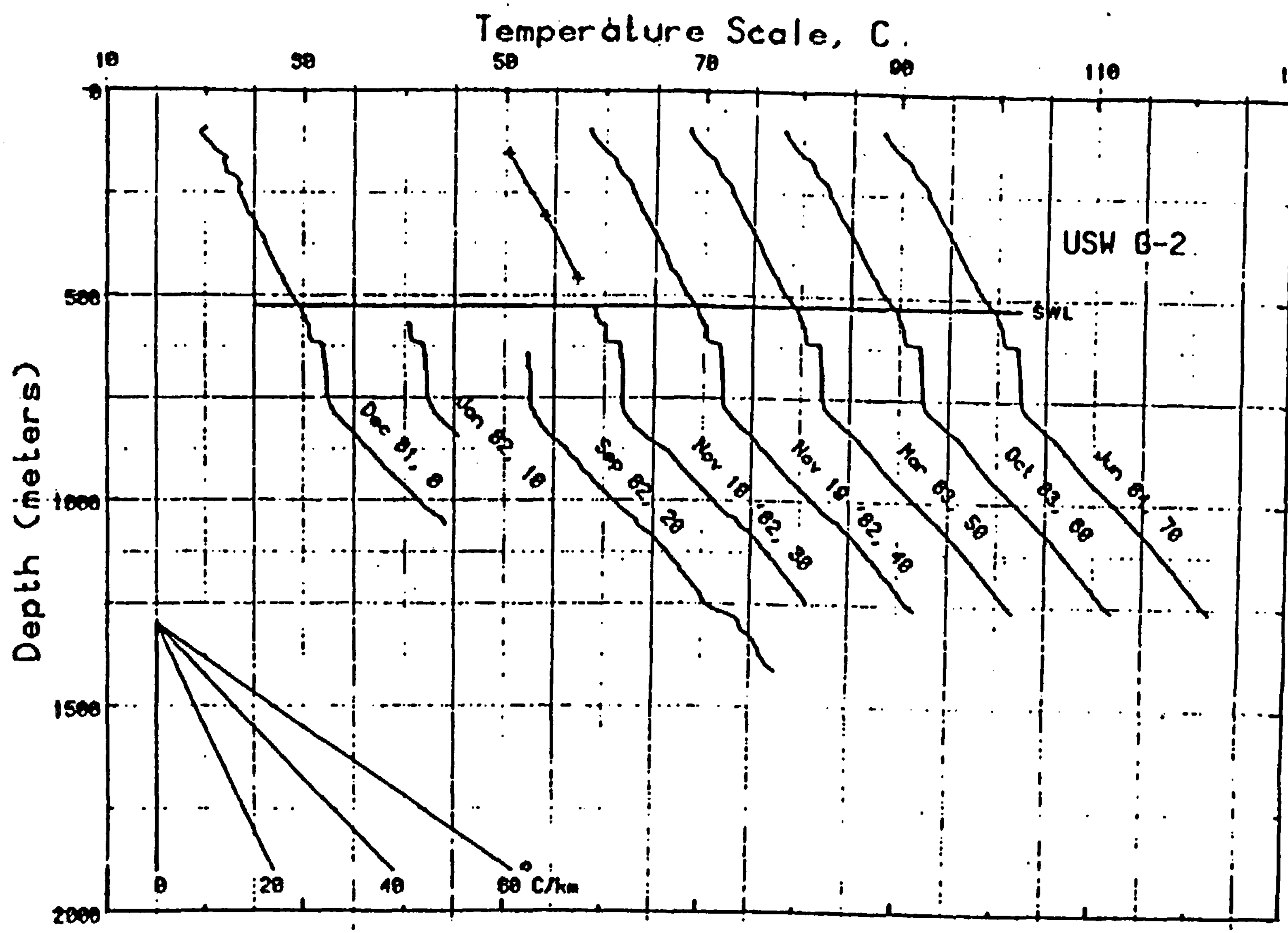


Fig. 7-2. Well USW G-2. Temperature profile. From Sass at al., 1987

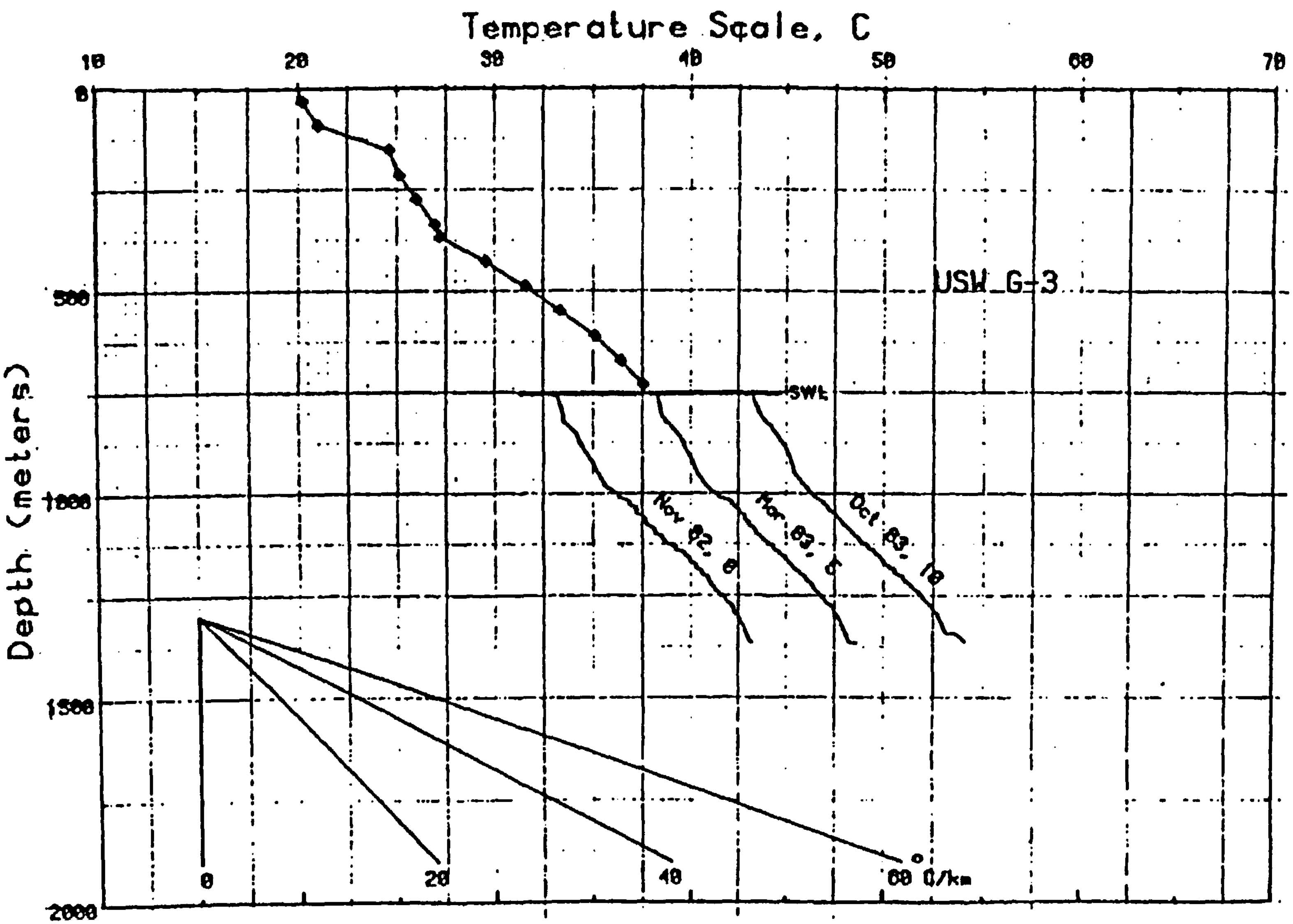


Fig. 7-3. Well USW G-3. Temperature profile. From Sass at al., 1987

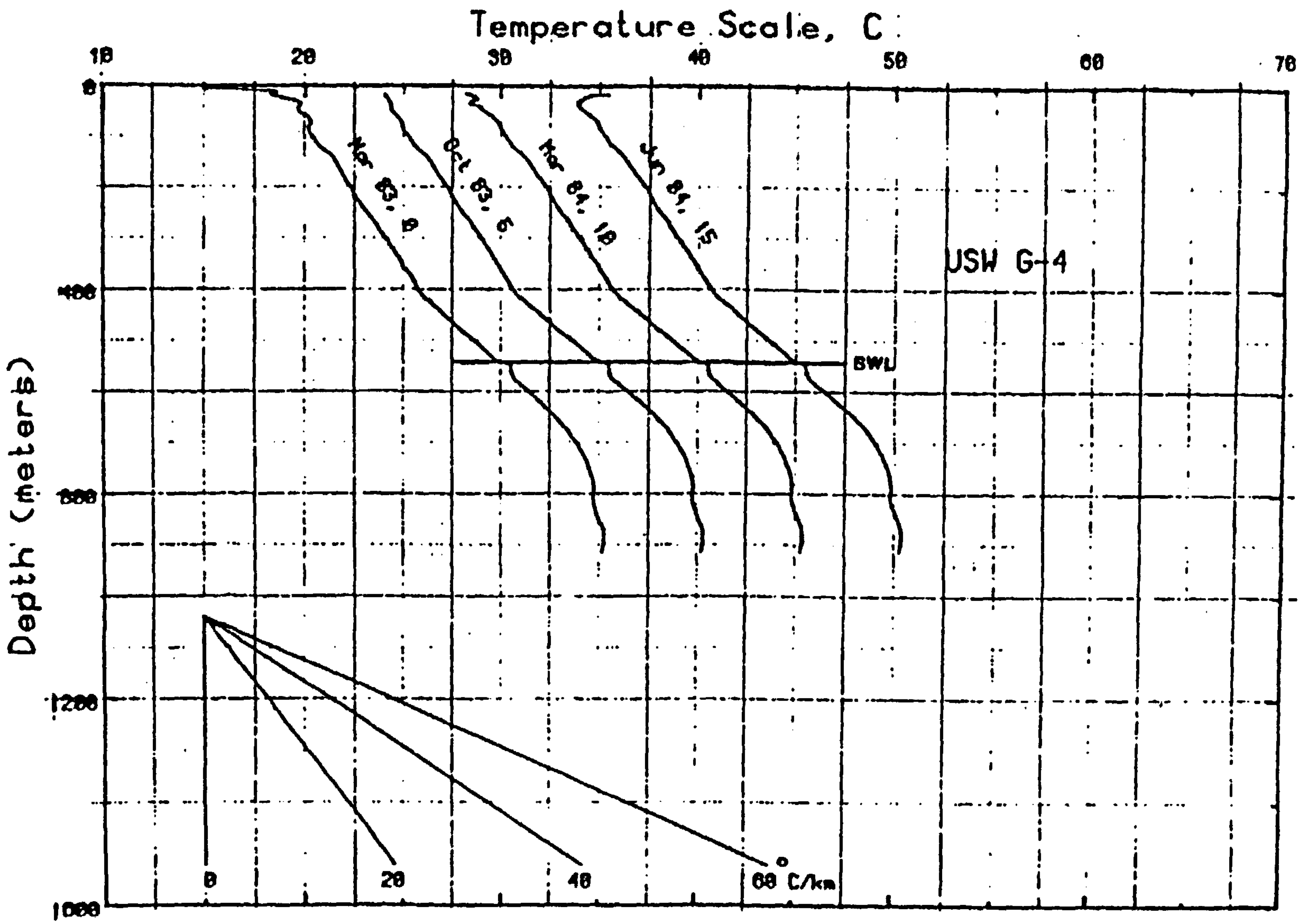


Fig. 7-4. Well USW G-4. Temperature profile. From Sass at al., 1987

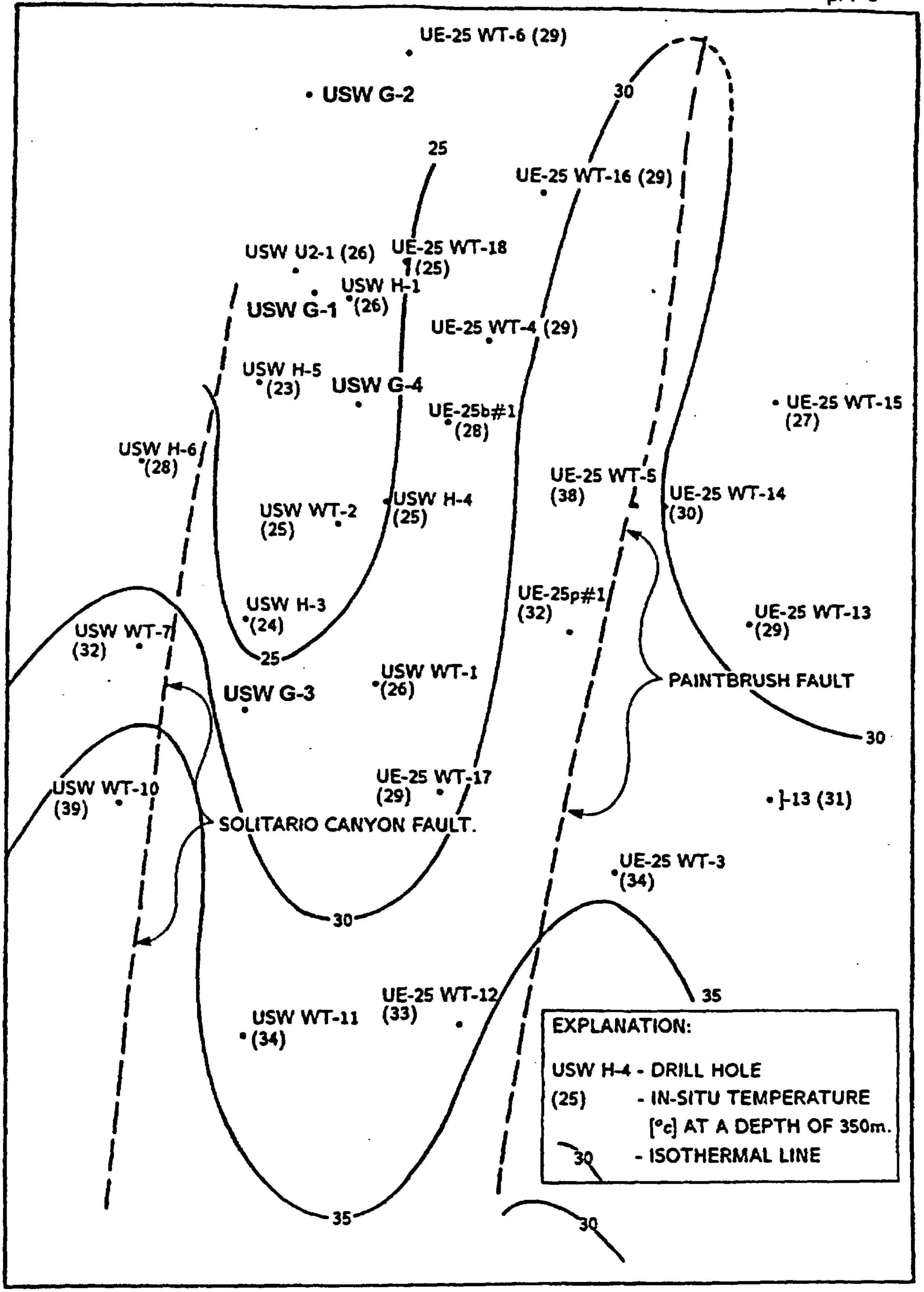


Fig. 7-5. *In-situ* temperatures at depth of 350 m in Yucca Mountain vadose zone. From Szymanski, 1993

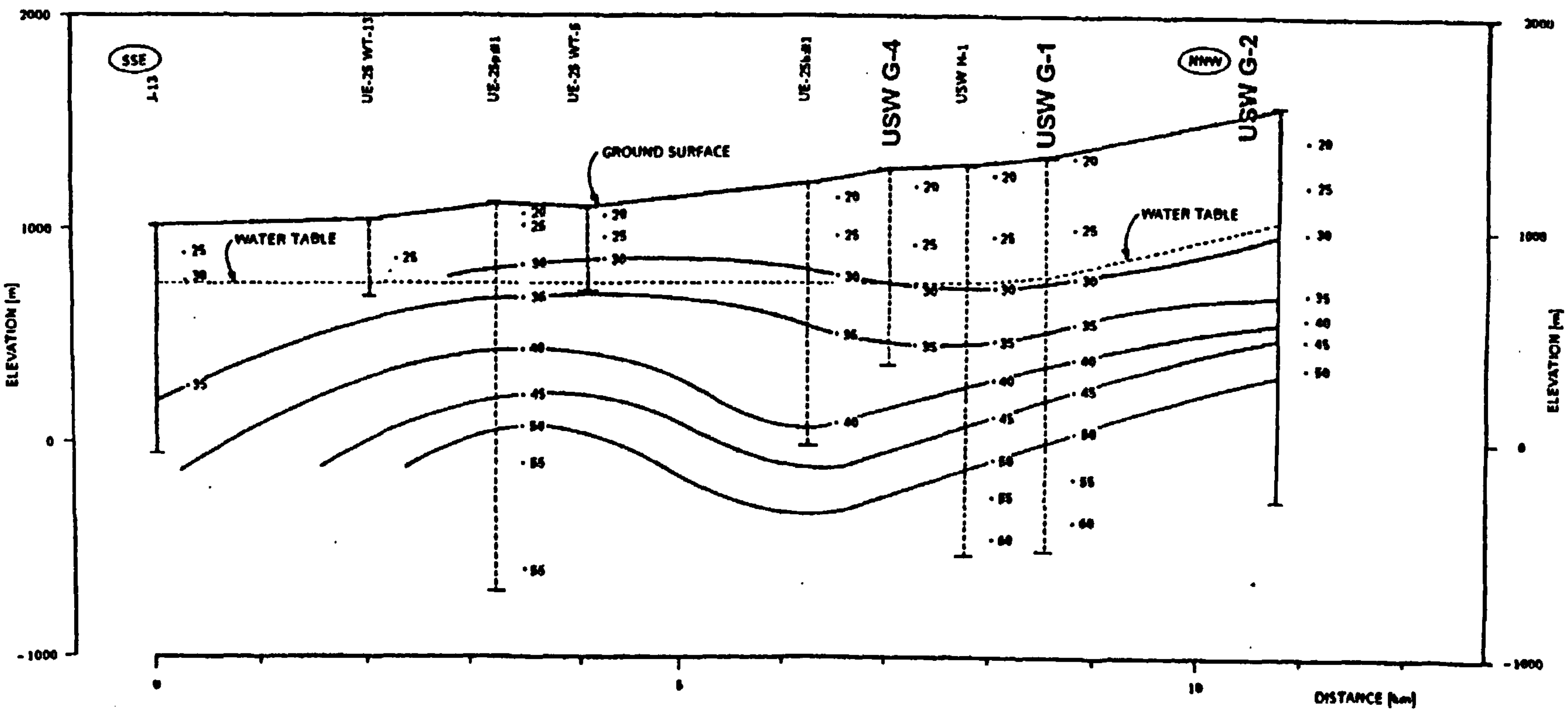


Fig. 7-6. NNW-SSE thermal cross-section through Yucca Mountain. From Szymanski, 1993

Chapter 8. Discussion and Recommendations

8.1. Discussion

We have analyzed the data on: (1) fluid inclusions, (2) $\delta^{18}O$ in calcite, (3) fractionation of ^{18}O in calcite/opal pairs, (4) thermoluminescence, and (5) current geothermal pattern in Yucca Mountain. Some inferences will be summarized below.

Two independent methods: fluid inclusions and calcite/opal thermometry gave consistent estimates of paleothermal gradient during the deposition of young calcite-opal veins of ~170-180 °C/km (**Fig. 8-1**). This value is much greater than those of current geothermal gradient in Yucca Mountain (20 to 24 °C; Sass et al., 1987). Fluid inclusion method gives somewhat lower absolute temperatures, that is understandable, as homogenization temperatures reflect the minimal possible temperatures of paleofluids (see **Chapter 3**).

It must be emphasized, that the number of reliable data by fluid inclusions and opal/calcite pairs is quite small: 7 measurements of homogenization temperatures and 9 measurements of $\Delta_{(calcite-opal)}$ (the later display significant scatter). 16 data points for several km of drill cores are not regarded as a sufficient set of data. So, the results must be interpreted with caution. The results of thermoluminescence study display a reasonable agreement with fluid inclusion and calcite/opal thermometry (**Fig. 8.2**). These data are also restricted in number (6 measurements).

The method of temperature estimation by degree of depletion of calcite in ^{18}O (that is temperature-dependent process) did not yield consistent results. Many assumptions must be introduced to apply this method for thermometry, and the result still will remain relativistic (temperature gradients instead of absolute temperatures). Paleogradients, obtained by calcite from four drill holes display significant discrepancy (from ~20 to >65 °C), being generally lower than gradients obtained by fluid inclusions and calcite/opal pairs. This method may be used in addition to fluid inclusion studies, as well as in situations, where fluid inclusion method may not be applied (e.g., near-surface deposits with micritic texture).

Despite of the low amount of data available and, as a consequence, a considerable uncertainity in numerical estimates, all the data obtained by young shallow calcite imply depositional temperatures much higher that those that may be explained by "normal" geothermal gradient (**Table 8-1**).

Temperature gradients as large as 60 and 170-180 °C/km, obtained by different independent methods may not be attributed to calcite deposition in the vadose zone, where the heat transfer is conductive by its nature. Instead, such high gradients imply convective heat transfer, which means that Yucca Mountain has been inundated with thermal water in the past. This conclusion is regarded as fairly certain. It provides strong basis for questioning the *per descensum* origin of the Yucca Mountain calcite-silica deposit, as proposed by the Yucca Mountain Project scientists.

Table 8.1

Summary on paleotemperatures obtained by different techniques

Depth, m	Ambient tempertaures, °C	TL temperatures, °C	Fluid inclusion temperatures, °C	Calcite/opal temperatures, °C
0				82
85				110
92	20			43, 60
178	22		57; 59	
204	26		81	
236.7	24			198
240.7	24			198
257.8	24,5			26
280.2	25			238
283	22	34; 58; 67; 83		
347	26		72; 81	31
386	26.5		103; 104	
439	26	38; 62		

8.2. Recommendations

(1). The list of priority for paleothermomertic methods may be given as follows:

- Fluid inclusions;
- Thrmoluminescence;
- Calcite/Opal thermometry; and
- Oxygen-18 in calcite.

(2). If possible, these methods must be applied jointly. They must also be coupled with (a) detailed petrographic studies, and (b) absolute dating of deposits (U-series for carbonates and ESR for opal).

(3). The set of data on $\delta^{18}O$ in calcite is quite extensive. Now we need to obtain statistically valid arrays of data by fluid inclusions, thermoluminescence and calcite/opal pairs. The tunnel constructed in Yucca Mountain offers a perfect opportunity to study the paleothermal environment.

(4). Phosphorescence of calcite under excitation by normal photographic flash may be recommended as a simple and efficient field method for estimation of formation temperatures. Hydrothermal calcite yields normally short (~0,3 s) but still distinguishable glow that may be followed by longer (few seconds) blue afterglow. Low-temperature hydrothermal calcite displays phosphorescence in blue color. The temperature of transition between red and blue phosphorescence is ~60 °C (data by fluid inclusions). Low temperature calcite, especially formed from water enriched by soil organic acids reveals, normally, phosphorescence in yellowish colors.

Chapter 8. Discussion and Recommendations

Figures...

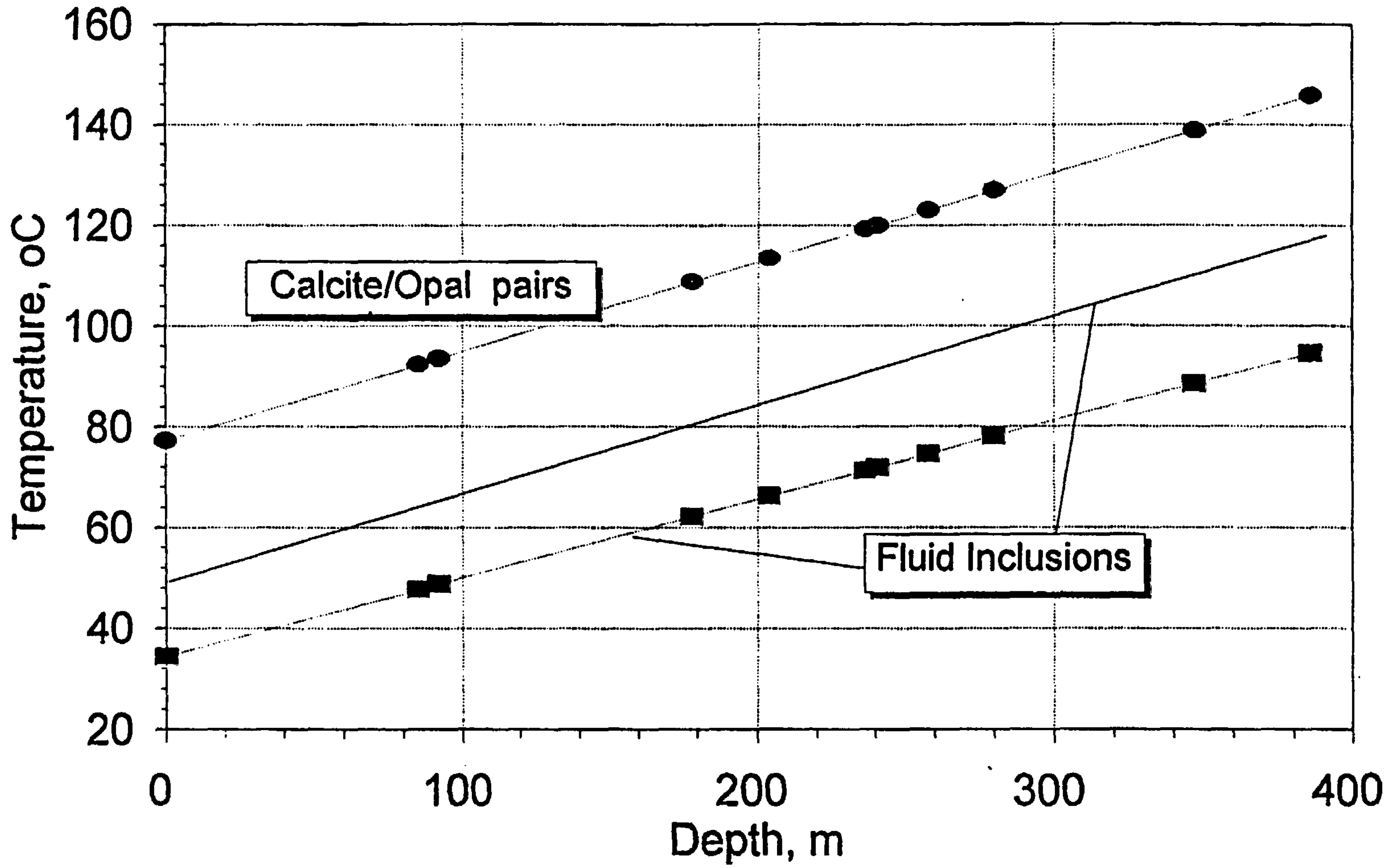


Fig. 8-1. Two paleotemperature lines obtained by linear-fit approximation of data by Calcite/Opal pairs and fluid inclusions. Both lines give almost identical paleothermal gradient about 170-180 °C/km. It sould be taken into account that the actual temperature line by fluid inclusions must be plotted through the <u>highest</u> temperatures measured (solid line)

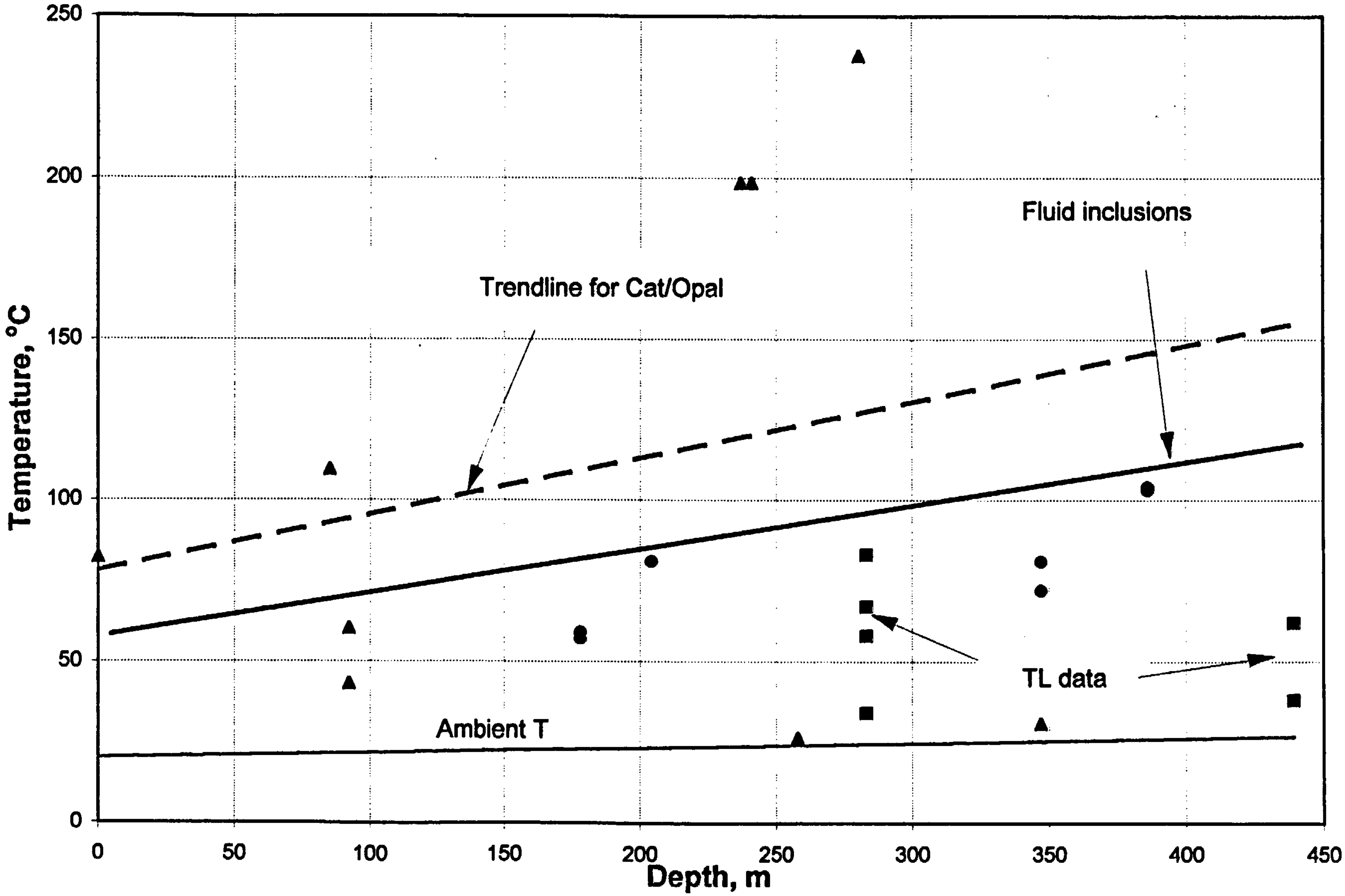


Fig. 8-2. Summary on paleothermomertic data obtained by different methods. **Circles** = fluid inclusion data; **triangles** = calcite-opal pair temperatures; **squares** = thermoluminescence temperatures

Conclusions

The overall conclusions on the status of paleotemperature research at Yucca Mountain may be summarized as following:

- Four independent methods suggest that, during the Plio-Quaternary time span, depositional temperatures were much higher than could have been attributed to the "normal" geothermal gradient.
- Whatever the absolute temperatures were, they exceeded temperatures that may be expected within the vadose zone (i.e., in the environment of essentially conductive heat transfer). The gradients as large as 60-180 °C/km strongly suggest a saturated zone environment (i.e., setting where the heat transfer is convective).
- The existing set of data does not allow for the solid reconstruction of numeric parameters of this young paleohydrothermal system. Extensive further instrumental studies are needed. However, the data set currently available is sufficient to question the "meteoric water", "pedogenic" or "*per descensum*" origin of calcite/opal formations in Yucca Mountain, as advocated by many scientists affiliated with DOE and Yucca Mountain Site Characterization Project.

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