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TO: David Sussman

FM: Daniel L. Carrier DLC by D.S.

RE: HYDROTHERMAL ALTERATION AND WELL LITHOLOGIES FOR GLASS MOUNTAIN WELLS: GMF68-8, GMF31-17 AND GMF 17A-6

SUMMARY

Petrologic, geochemical and temperature data from three exploratory wells indicate a well-developed geothermal system exists in the Glass Mountain area of the Medicine Lake volcano. Wells GMF68-8, GMF31-17 and GMF17A-6 penetrate a sequence of interlayered volcanic, contact metamorphic, and granodioritic intrusive rocks. The interlayered volcanics are the principal reservoir rocks for the Glass Mountain system. Alteration zoning is well-developed in all the wells and generally follows a sequence from zeolite-smectite to argillic and finally to propylitic with increasing depth. Strong argillic alteration and boiling temperatures observed in GMF68-8 and GMF31-17 suggest the upwelling of geothermal fluids, and correlate well with low-resistivity anomalies observed in time-domain electromagnetic and magnetotelluric data. The occurrence of only weak to moderate argillic alteration in GMF17A-6 is consistent with temperature data which indicate the well was not drilled in an area of upwelling and boiling. Strong propylitic alteration occurs in each well, and is primarily found along subvertical fractures and the brecciated tops and bottoms of lava flows. The association of fractures and lithologic boundaries with strong propylitic alteration suggests that these features are the preferred pathways for fluid flow.

Mineralogical data suggest that multiple hydrothermal systems have existed in the Glass Mountain area. Caution is therefore needed in using the first occurrence of epidote to identify the top of the reservoir. In addition to epidote, other significant hydrothermal minerals present include actinolite, wairakite, and clinopyroxene. Smectite and chlorite are the most common hydrothermal clays observed. Smectite occurs in trace amounts at 556°F in GMF68-8, roughly 150°F in excess of its equilibrium temperature stability range, suggesting that low matrix permeability exists in portions of the reservoir.

TABLE OF CONTENTS

INTRODUCTION

The Glass Mountain Federal Unit is formed from Unocal and Freeport-McMoran geothermal leases located at the summit of Medicine Lake volcano. Three deep exploratory wells have been completed in the Glass Mountain Federal Unit since 1984: GMF68-8, GMF31-17 and GMF17A-6 (Figure 1). This report discusses the general lithology and hydrothermal mineralogy of these wells. The objective is to describe the relationships existing at depth among rock-type, alteration, subsurface temperature, and permeability.

Mineralogy of the deep wells will be presented in two reports. This report discusses hydrothermal alteration and lithologic data. A subsequent report will discuss fluid inclusion data obtained on hydrothermal minerals. The ultimate goal of these studies is to develop a three-dimensional model of the Glass Mountain geothermal system. These reports follow an earlier study by Carrier (1987) which dealt with hydrothermal alteration and fluid inclusion data from Glass Mountain temperature boreholes.

GEOLOGIC SETTING

Medicine Lake is a Quaternary shield volcano situated in the southern part of the Cascade Range about 35 miles (56 km) east-northeast of Mount Shasta. Lavas attributed to the volcano are found over a 780 mi^2 (2000 km^2) area, and have an estimated volume of 145 mi^3 (600 km^3) (Donnelly-Nolan, 1988). Although Holocene volcanic rocks are principally bimodal basalt and rhyolite, the upper slopes of the volcano are dominated by andesite lavas of Pleistocene age. Silicic lavas account for 5 to 10% of the surface lavas on the volcano (Figure 1). The silicic lavas occur in four age groups based

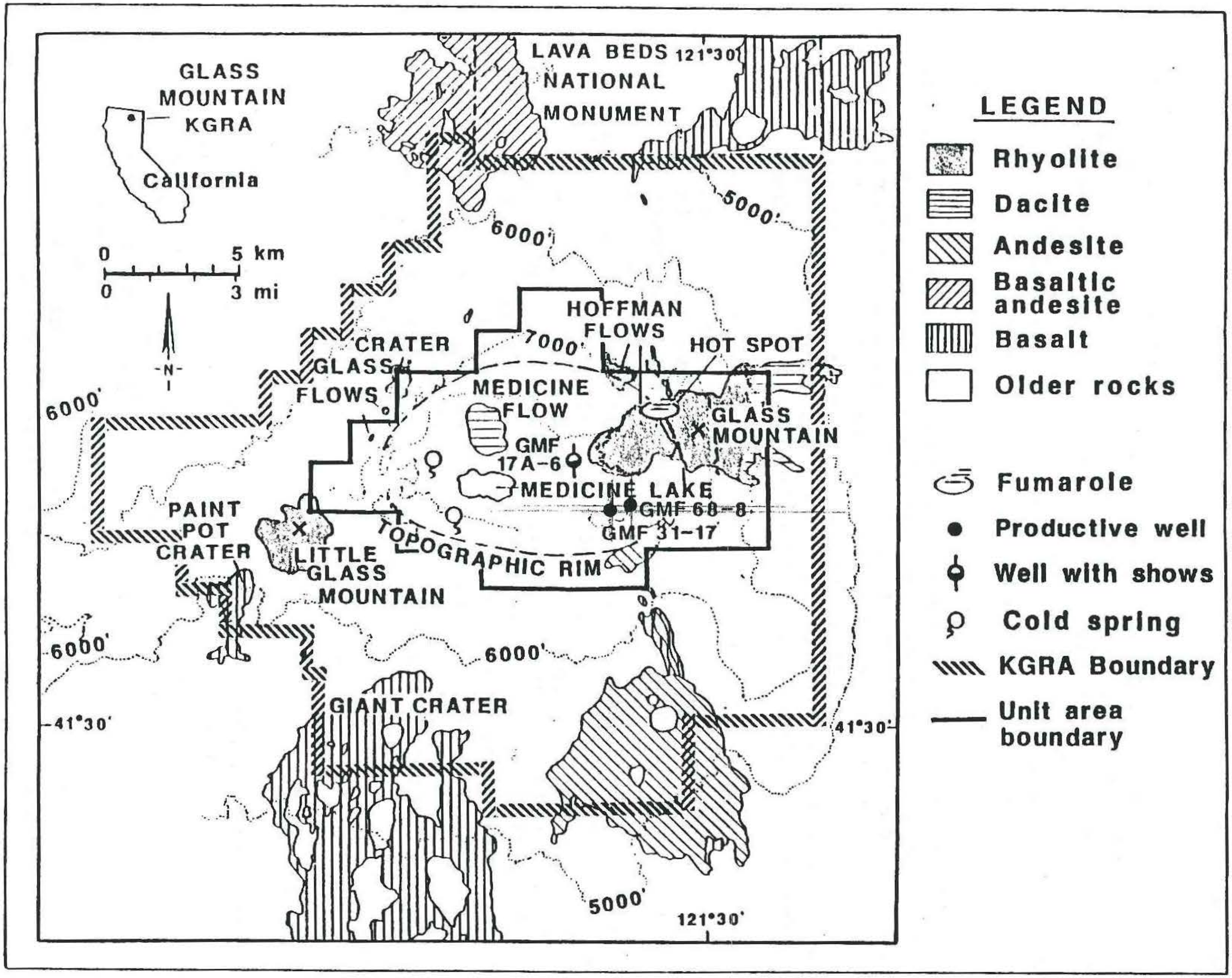

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Figure 1: Geologic map of Medicine Lake volcano showing lavas that are less than 11,000 years old (Donnelly - Nolan, 1988) and the Glass Mountain KGRA.

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on K-Ar age dates: 1.25 to 0.95 m.y., 0.61 to 0.43 m.y., 0.33 to 0.24 m.y., and 0.1 m.y. to about 1,000 years (Mertzman, 1982; Mertzman, 1983).

Several small volcanic centers of basalt, andesite, dacite and rhyolite coalesce to form a constructional rim on the summit of Medicine Lake volcano, enclosing a 4 x 6 mile oval depression. The topographic depression has been called a caldera by several authors (Anderson, 1941; Heiken, 1978; Donnelly-Nolan, 1988). However, there is no evidence on the surface for ring faults or massive tuffs, and no evidence for massive tuffs in the subsurface (Carrier, 1987).

Five silicic eruptive centers, all less than 2,000 years in age (Donnelly-Nolan, personal communication), are located in a 4.5 x 12 mile band across the upper flanks, topographic rim and the summit depression of Medicine Lake volcano (Figure 1). Glass Mountain is the youngest of these silicic centers. The three deep wells were drilled in the topographic depression, and each is located less than 3 miles from the Glass Mountain dome.

No basement rocks are exposed in the Glass Mountain area. Granodioritic xenoliths have been found in the young silicic lavas shown in Figure 1. Hausback (1984) suggested the xenoliths were fragments of a Sierran plutonic basement; however textures in the granodiorites indicate they are subvolcanic equivalents of Glass Mountain lavas. The oldest rocks exposed in the vicinity of the volcano are Tertiary basalt and andesitic pyroclastic rocks belonging to the Cedarville Series (Anderson, 1941). These are exposed in several small fault-block mountains north and east of the volcano. Overlying the Cedarville Series are high-alumina olivine basalts of Miocene to Pleistocene age that have been collectively lumped together into a group called the Warner Basalts. Xenoliths of high-alumina basalts have also been observed in the young silicic lavas on the Medicine Lake volcano.

METHODS AND DATA

Data presented in this report have been collected through several methods of study. Drill cutting samples were collected at 10 or 20-foot intervals, and spot cores were taken from depths of 6580 to 6603 feet and 8399 to 8417 feet in GMF68-8 and 8416 to 8436 feet in GMF31-17. The samples were logged using a binocular microscope. Representative samples were then selected for further analysis by thin section, x-ray diffraction (XRD) and whole-rock chemistry. The XRD analyses were done at the University of Utah Research Institute by Jeff Hulen and Susan Lutz. The basic data are reported in Appendix 1. Whole-rock chemical analyses data were done by Chemex Labs, in Sparks, Nevada. The data are presented in Appendix 2. In addition to the sample analyses, each well has been at least partially logged with a gamma ray tool. Dresser Atlas, Schlumberger and Welex logging companies have run logs over different intervals of the wells.

All well depths mentioned in this report are measured depths unless stated otherwise. Elevations, as determined by using true vertical depths, are displayed in the cross-sections. The surface elevation of GMF68-8 is 6991 feet, GMF31-17 is 7000 feet, and GMF17A-6 is 6733 feet. GMF68-8 is drilled as a vertical hole to 6603 feet, and as a directional hole to the measured total depth of 8417 feet and true vertical depth of 8394 feet. GMF31-17 is drilled as a vertical hole to about 2010 feet, and as a directional hole deviated to the measured total depth of 8787 feet and true vertical depth of 8518 feet. GMF17A-6 is drilled as a vertical hole to a measured total depth of 9620 feet and a true vertical depth of 9605 feet.

LITHOLOGY

Rock types and thicknesses have been determined for each well by integrating data obtained from drill cuttings, spot core samples, interpretation of gamma ray logs, and whole-rock chemical analyses. Generalized lithologic logs are presented for the wells in Figure 2. Rocks penetrated by the wells are assigned to one of three groups: interlayered volcanics, contact metamorphics, and granodioritic intrusives. The metamorphic rocks and the granodioritic intrusive rocks are found only in GMF31-17 and GMF17A-6.

The majority of the rocks drilled are interlayered volcanics. The volcanic group generally consists of calc-alkalic to slightly alkalic mafic, intermediate, and silicic lavas. Thinly bedded lithic tuffs, scorias, volcaniclastics, and sandstones occur in minor amounts. Mafic lavas are present in the greatest abundance and are dominated by clinopyroxene-bearing amygdaloidal basalts and basaltic andesites. Although the mafic rocks in general vary from aphyric to porphyritic, they become coarser grained at about 4600 feet measured depth (2500 feet in elevation), and contain microdiabase textures in trace to major amounts. These coarser grained mafic rocks possibly mark the base of the lavas related to the Medicine Lake volcano. That places the base of the volcano in the Glass Mountain area at an elevation which is 1500 feet lower than is evident by the flank exposures of Medicine Lake lavas. Rhyolite to dacite silicic lavas are second to the mafic lavas in abundance. Silicic lavas are more abundant in the wells than on the surface, accounting for 27% of the rocks drilled in the upper 4600 feet of the wells, and 20% of the volcanic rocks drilled below that depth. These rocks are typically microcrystalline to fine-crystalline, and are almost entirely composed of quartz, plagioclase, and potassium feldspar. Granophyric and spherulitic textures are common and well-developed. Micropegmatitic and axiolitic textures are also found in many of the silicic rocks. Dacitic rocks at 1750 to

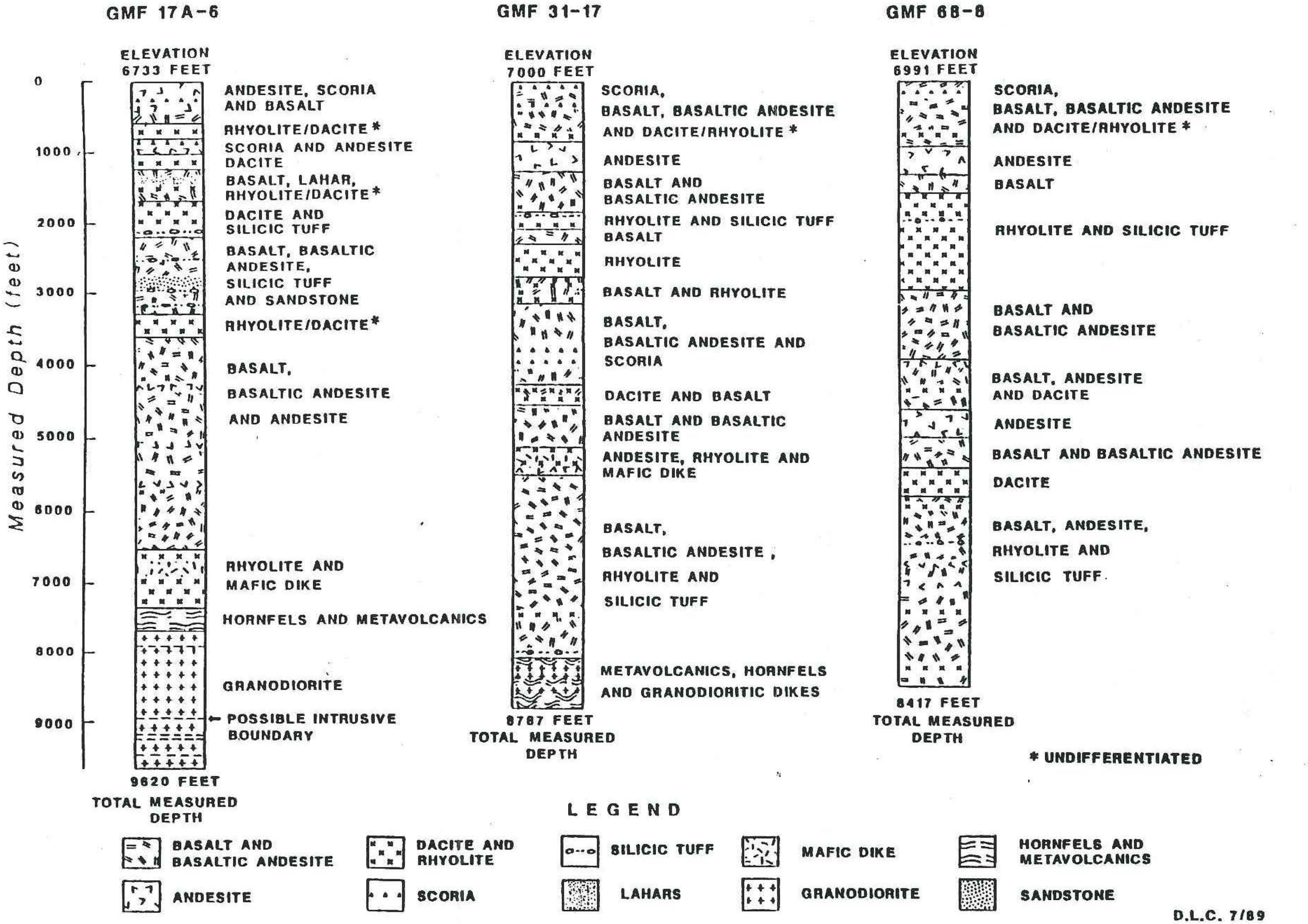

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Figure 2: Generalized lithologic profiles of GMF17A-6, GMF31-17, and GMF68-8.

2160 feet in GMF17A-6 contain fine-crystalline granodioritic xenoliths. Although andesite and trachyandesite lavas are the most common lavas exposed on the volcano (Hausback, 1984), they are the rarest of the lavas observed in the deep wells. The andesites drilled are orthopyroxene or clinopyroxene bearing, are commonly flow banded, and contain aphyric to porphyritic textures.

Contact metamorphic rocks are found at 7345 to 7690 feet in GMF17A-6, and at 8060 to 8787 feet in GMF31-17. The metamorphic rocks are in general meta-volcanics and hornfels. The hornfels, as sampled in GMF17A-6, is essentially fine-crystalline quartz-plagioclase-biotite rock containing minor hornblende and clinopyroxene. Near the base of the GMF17A-6 sequence at 7680 feet, the metamorphic rocks are moderate-to well-foliated, and appear to be intermediate between a hornfels and a phyllite or a fine-crystalline schist. Contact metamorphic rocks in GMF31-17 consist of meta-andesites, meta-dacites, and hornfels, all of which are intercalated with granodioritic dikes or sills. The meta-andesite and meta-dacite rocks have poorly defined textures, and the hornfels rocks contain well-developed granoblastic textures.

Granodiorites occur as shallow plutonic rocks at 7690 to 9620 feet in GMF17A-6 and as multiple thin dikes or sills at 8110 to 8787 feet in GMF31-17. The granodioritic rocks are fine-crystalline and contain biotite and hornblende. Exsolution textures are common in the potassium-rich portions of the granodiorites. The granodiorites are similar in composition and texture to the xenoliths of plutonic rocks contained in surface exposures of the young silicic rocks. Abrupt variations are observed in the percentages of potassium feldspar and mafic minerals in the granodiorite in GMF17A-6, and are possibly due to the drilling of multiple intrusive bodies. The more mafic zones have compositions that approach quartz diorite. The rapid change from volcanics to meta-volcanics to fine-crystalline granodiorite without intervening erosional events indicates that the granitic rocks have been intruded into the older Tertiary volcanics. Thus the granodiorite rocks probably represent intrusive phases related to late Tertiary or Quaternary silicic lavas and not Sierran plutonic rocks. The thickest granodioritic dike in GMF31-17 has an apparent measured thickness of 280 feet.

ALTERATION MINERALOGY

Alteration minerals present in the well samples are generally the same as those observed in other well-documented geothermal areas. The types and distribution of the minerals are shown as a function of depth in Figures 3, 4, and 5. Temperature, rock type, and permeability are the three main factors controlling the style and intensity of alteration in the Glass Mountain wells. A diagram summarizing the distribution of selected

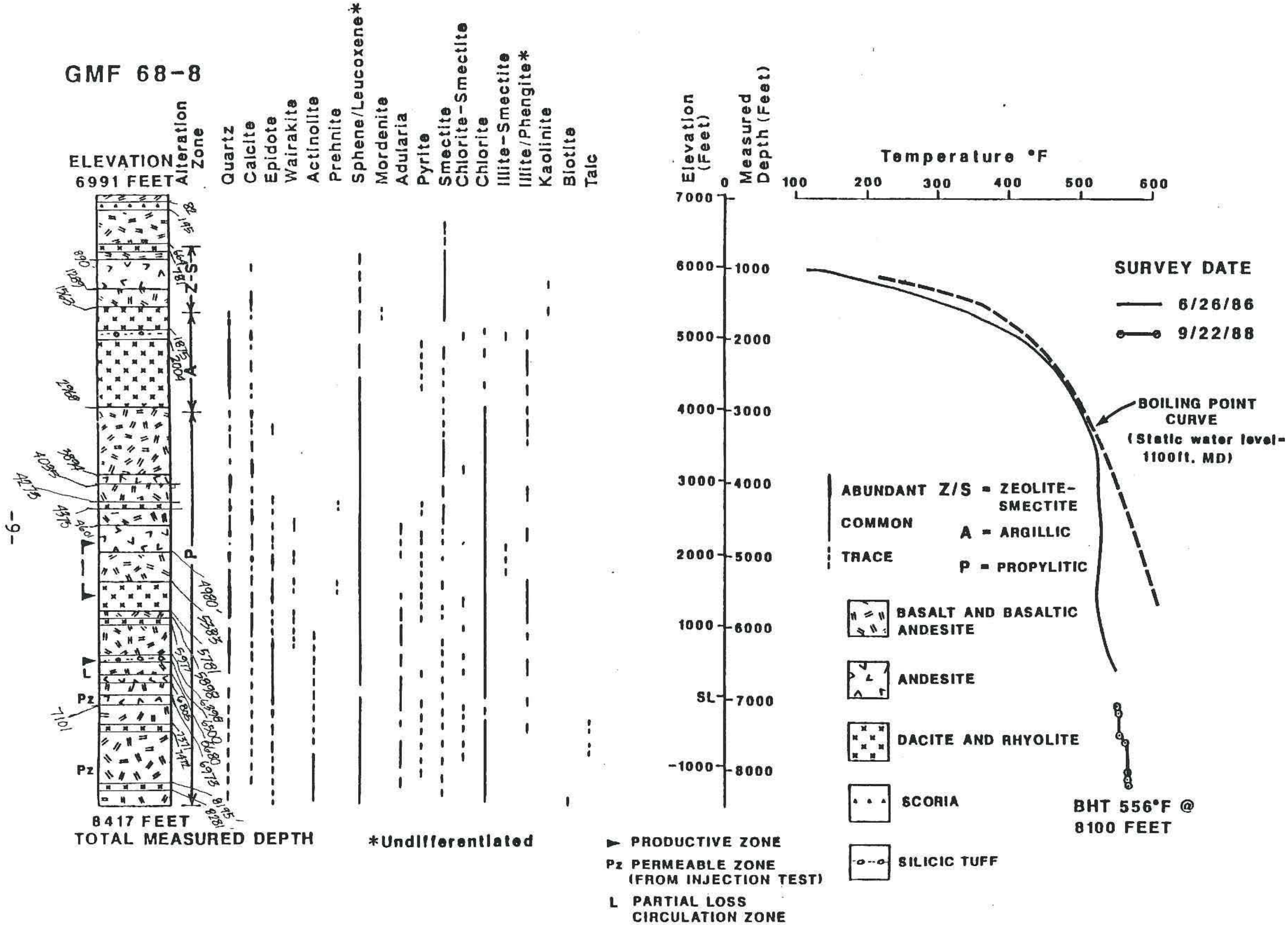

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Figure 3: Lithology, alteration zones, mineralogy, and downhole temperatures for GMF68-8. The 6/26/86 temperature survey was taken after the well was static for 311 days. The 9/22/88 temperature survey was taken af[illegible]r the well was deepened and four days after a 32-hour flow[illegible]st.

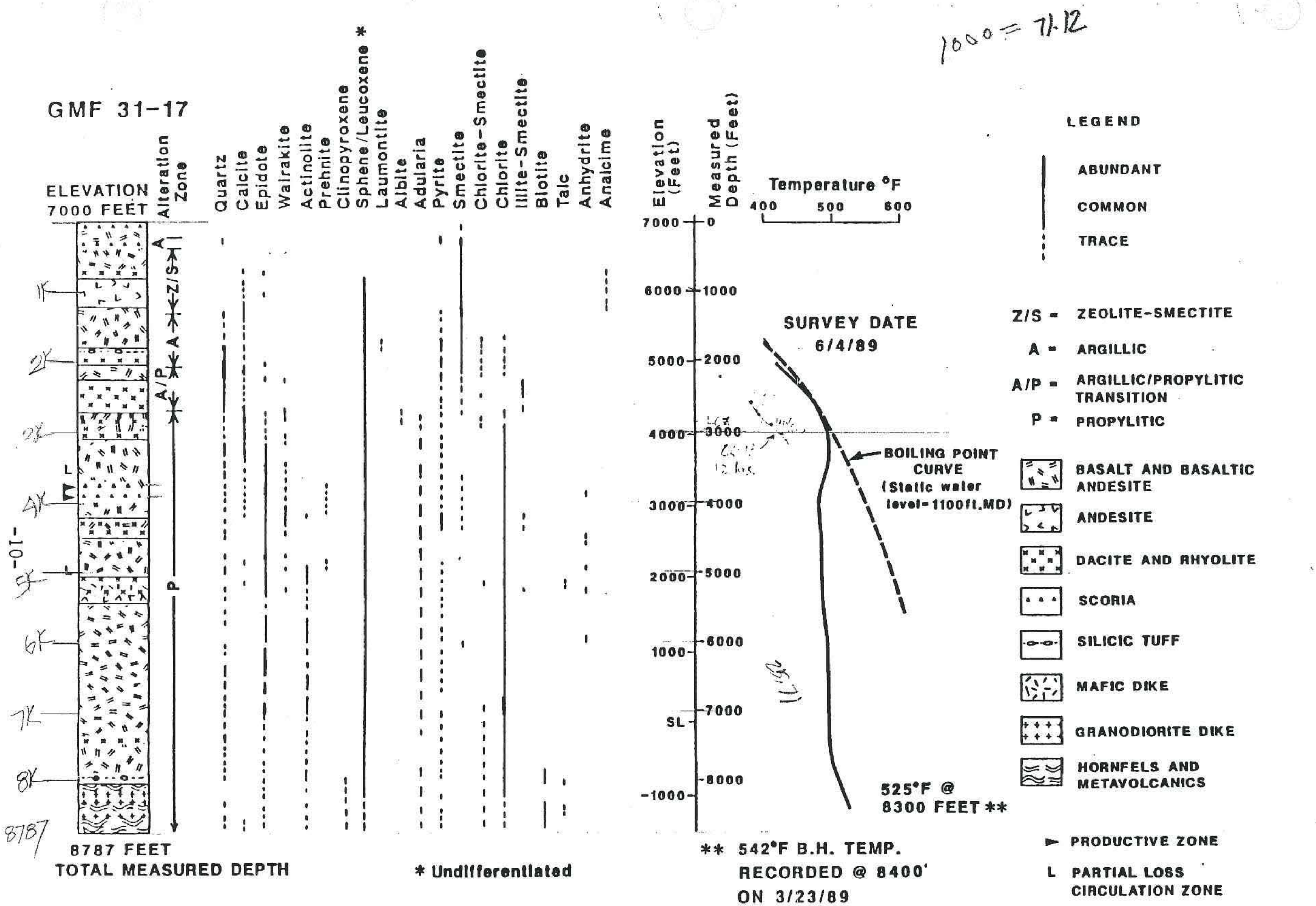

Figure 4: Lithology, alteration zones and mineralogy, and downhole temperatures for GMF31-17. The 6/4/89 survey of GMF31-17 was taken after the well had been static for 247 days.

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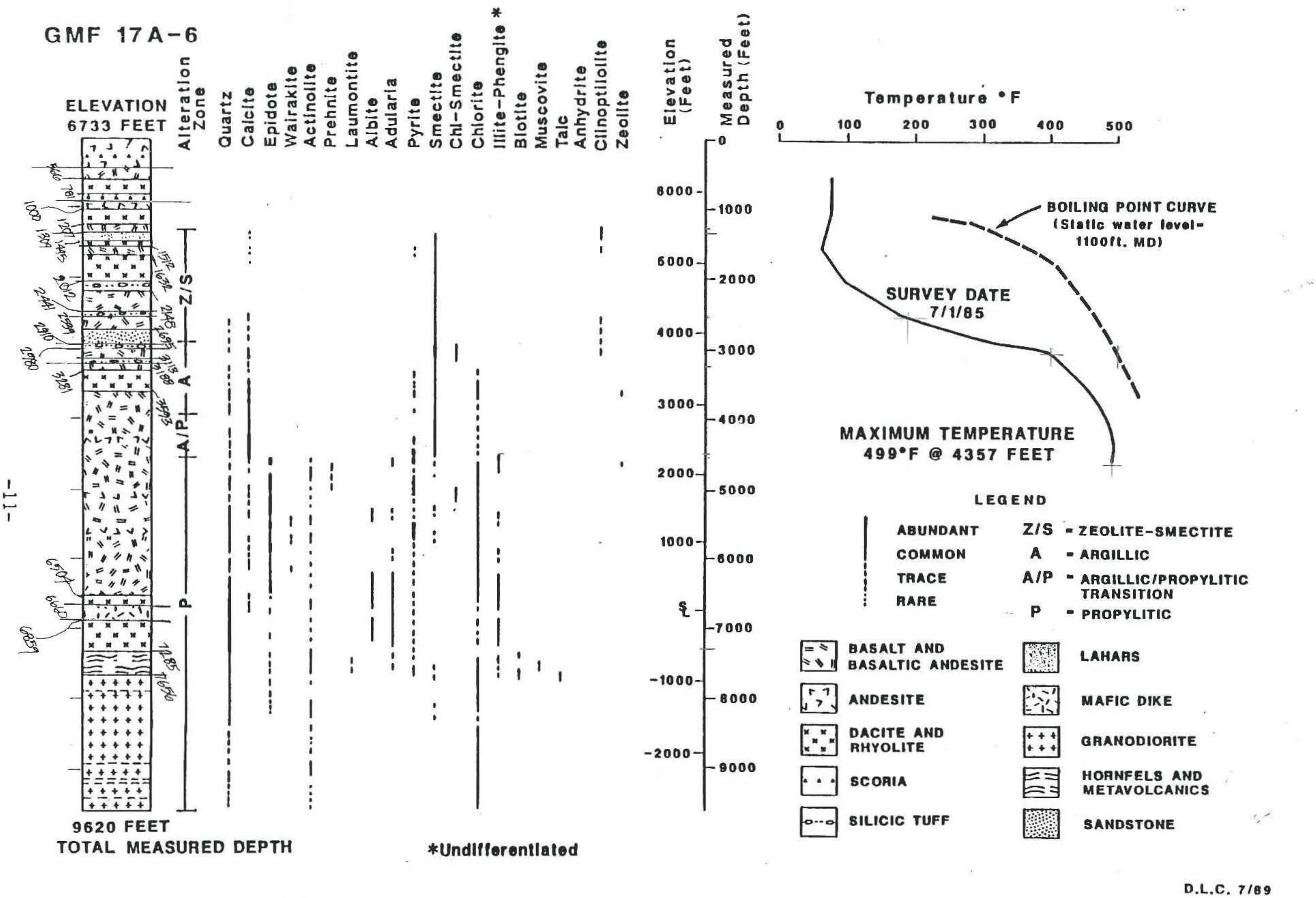

Figure 5: Lithology, alteration zones and mineralogy, and downhole temperatures for GMF17A-6. No stabilized temperature data are available for depths greater than 4550 feet.

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hydrothermal minerals with temperature is shown in Figure 6. Although the influence of rock type on an alteration assemblage is greatest at lower temperatures, it becomes an almost insignificant factor when formation temperatures exceed 500°F as in GMF68-8 (Figures 3 and 6). Permeability controls the intensity of the alteration, and determines the degree to which equilibrium between rocks and reservoir fluids is approached.

Most secondary minerals in the Glass Mountain samples are readily assigned to one of seven hydrothermal mineral groups: silica, carbonate, calcium silicate, phyllosilicate, non-calcium silicate zeolite, feldspar, and oxide-sulfate-sulfide. Members of each group and their mode of occurrence are shown in Table 1. Two of the most diagnostic hydrothermal mineral groups are calcium silicates and phyllosilicates, and they are discussed in further detail below.

Calcium Silicates

The calcium silicate minerals observed include epidote, actinolite, prehnite, clinopyroxene, sphene, and the zeolites wairakite, laumontite, and mordenite. Epidote and actinolite are the most common calcium silicate minerals, and wairakite is the most common zeolite. A cross-section depicting the distribution of epidote, actinolite and wairakite in the three wells is shown in Figure 7. Prehnite and hydrothermal clinopyroxene are found in the wells, but are rare. Sphene is problematic since the mineral can occur as both a primary and an alteration mineral. In addition, the XRD patterns of sphene and leucoxene, which is an iron-titanium-oxide alteration product of ilmenite, are difficult to distinguish.

Epidote is the most important calcium silicate for two reasons: its occurrence in active geothermal fields is frequently associated with the top of the reservoir, and it is easily distinguishable with a binocular microscope. Epidote is first observed in GMF68-8 and GMF17A-6 at temperatures exceeding 495°F, which is higher than the 460°F onset for epidote in several other fields (Brown, 1978). However, hydrothermal epidote is also observed to exist in an equilibrium assemblage with other alteration minerals at temperatures as low as 430°F in GMF31-17. Epidote occurs as open space fillings in fractures and vugs and as a replacement of primary plagioclase. Epidote becomes the dominant hydrothermal calcium silicate at 2740 feet in GMF31-17, 4120 feet in GMF68-8, and 4520 feet in GMF17A-6. The mineral is most abundant in GMF31-17, where XRD data show concentrations as great as 26 weight percent of the rock at 3760 to 3900 feet and 5230 to 5240 feet, and 23 weight percent of the rock at 5780 to 5840 feet. Anomalous traces of hydrothermal epidote were identified in lavas of GMF31-17 at 800 and 1100 feet in a lower-temperature assemblage consisting of zeolites and smectite clay. The epidote is not in equilibrium with the zeolite-smectite assemblage.

TABLE 1 Hydrothermal mineral groups and their mode of occurrence as observed in Glass Mountain Wells GMF68-8, GMF31-17 and GMF17A-6

Mineral Group	Mode of Occurrence: veins & vugs	Mode of Occurrence: replacement	Associated Veinlet Minerals	Primary Minerals Replaced	Comments
1. SILICA					
Quartz (QTZ)	X		CAL, EP, ACT, WAIR, PREH, SPH, CHL, ILL, PHG, BTE, KF, OLIG, PY, MAG, HEM, ANH		most common hydrothermal mineral
Cristobalite (CRIS)		X		(glass)	devitrification product
Chalcedony (CHAL)	X		CHL, PHG		rare in occurrence
2. CARBONATE					
Calcite (CAL)	X	X	QTZ, EP, WAIR, CHL PHG, PLAG, HEM		replace vein EP & WAIR at 2840/60 ft. in GMF31-17
Aragonite (ARAG)	X	X			replaces secondary cristobalite, usually in vugs
3. CALCIUM SILICATE					
Epidote (EP)	X	X	QTZ, CAL, ACT, WAIR, PREH, CHL, PGH, BTE, AB, KF, ANH, HEM	plagioclase	includes clinozoisite
Actinolite (ACT)	X	X	QTZ, EP, PREH, SPH, CHL, BTE, TLC, KF, MAG	pyroxene, hornblende	Fe content increases with depth
Wairakite (WAIR)	X	X	QTZ, EP, CAL, CHL, AB, KF	plagioclase	zeolite
Prehnite (PREH)	X		QTZ, EP, ACT, CHL, PGH, KF, ANH, HEM		relatively rare in G.M. rocks
Clinopyroxene (CPX)	X		QTZ, OLIG		also occurs as a contact metamorphic mineral
Sphene (SPH)	X		QTZ, EP, ACT, KF, MAG		also occurs as a primary mineral
Laumontite (LAU)	X				zeolite
Mordenite (MOR)	X				zeolite

TABLE 1 Continued

Mineral Group	Mode of Occurrence: veins & vugs	Mode of Occurrence: replacement	Associated Veinlet Minerals	Primary Minerals Replaced	Comments
4. PHYLLOSILICATE					
Smectite (SM)	X	X	ANAL, PY		most common low-temperature clay
Kaolinite (KAO)	X				
Chlorite (CHL)	X	X	QTZ, CHAL, CAL, EP, WAIR, PREH, ILL, PHG, HEM, LEU	pyroxene, amphibole, biotite	most common high-temperature clay
Illite/Phengite (ILL/PHG)	X	X	QTZ, CHAL, CAL, EP, WAIR, CHL, PY, HEM		differentiated in thin section but not in XRD
Chlorite-Smectite (mixed-layer) (C-S)	X	X			chlorite content increases with temperature
Illite-Smectite (I-S)	X	X			illite content increases with temperature
Biotite (BTE)	X	X	QTZ, ACT, TLC	amphibole	
Muscovite (MUS)	X	X		feldspars	
Talc (TLC)	X		ACT, BTE		
5. NON-CALCIUM SILICATE ZEOLITE					
Analcime (ANAL)	X		SM		low-temperature zeolite
Clinoptilolite (CLIN)	X				low-temperature zeolite
6. FELDSPAR					
Albite (AB)	X	X	QTZ, WAIR, KF	plagioclase	
Oligioclase (OLIG)	X		QTZ, CPX		gives way to anorthoclase
Adularia (KF)	X	X	QTZ, EP, ACT, WAIR, PREH, SPH, CHL, AB, MAG, LEU	plagioclase	

TABLE 1 Continued

Mineral Group	Mode of Occurrence: veins & vugs	Mode of Occurrence: replacement	Associated Veinlet Minerals	Primary Minerals Replaced	Comments
7. OXIDE-SULFATE-SULFIDE					
Pyrite (PY)	X		QTZ, EP, CHL, SM, ILL, KF, LEU		
Anhydrite (ANH)	X		QTZ, EP, PREH		
Magnetite (MAG)	X		QTZ, EP, ACT, SPH, KF		also a common primary mineral
Hematite (HEM)	X		QTZ, CAL, CHL		also a weathering product
Geothite (GEO)	X	X	HEM	primary magnetite	
Leucoxene (LEU)	X		QTZ, EP, WAIR, CHL, KF, PY		indistinguishable from sphene in XRD

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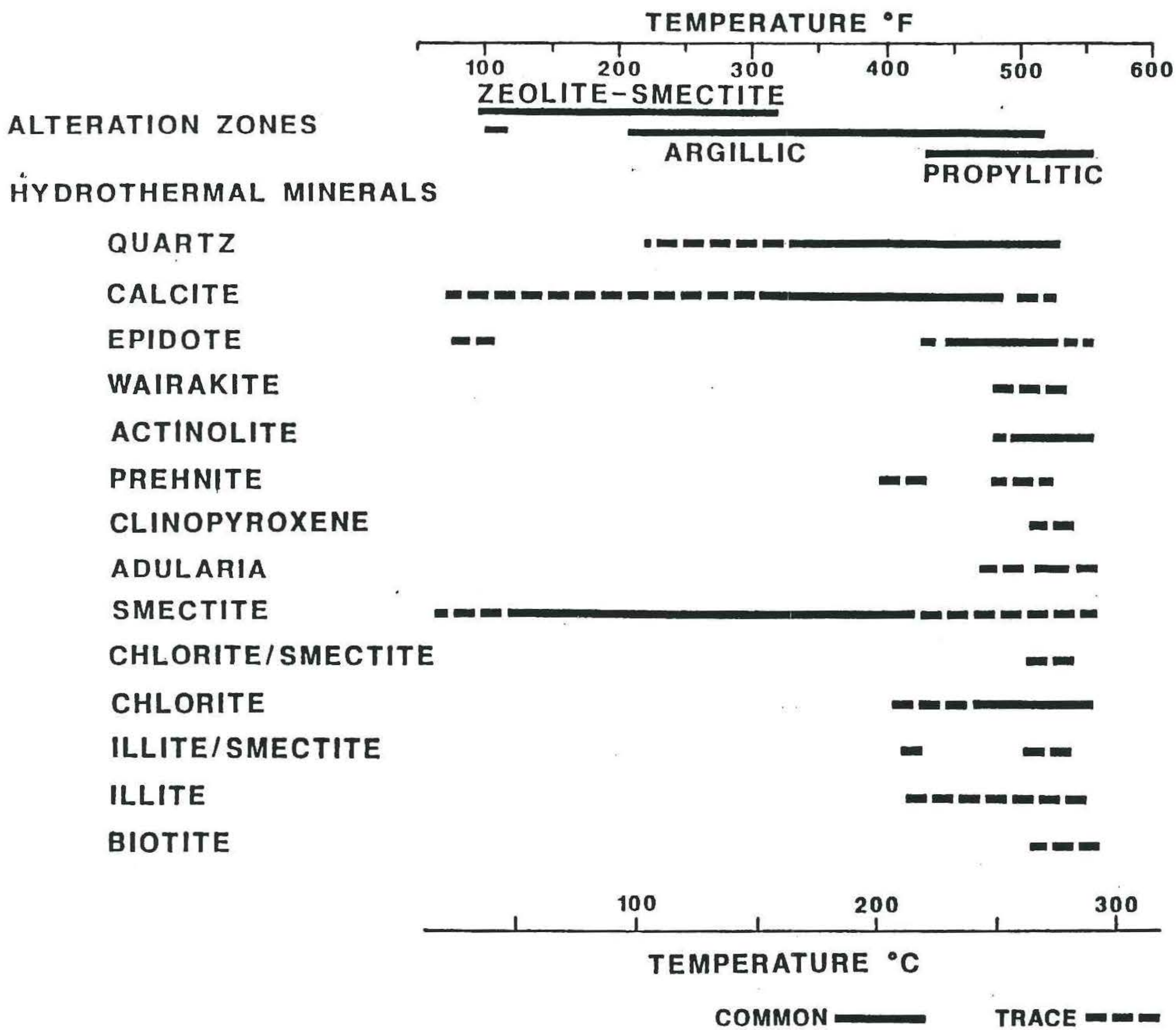

Figure 6: Temperature ranges for the occurrence of hydrothermal minerals and alteration zones in Glass Mountain deep wells. No temperature data are available for depths greater than 4550 feet in GMF17A-6.

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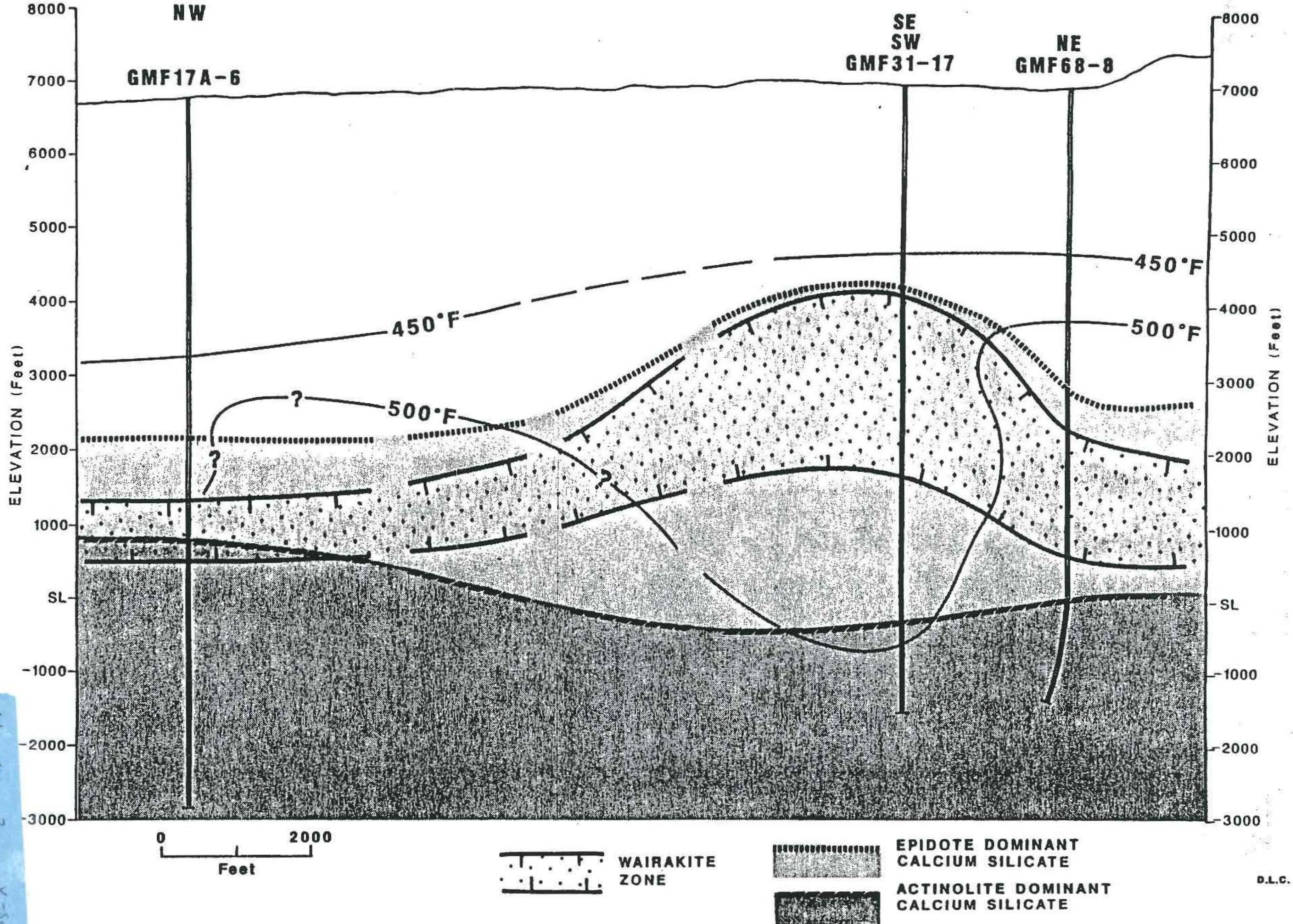

Figure 7: Cross-section showing the distribution of calcium silicate minerals epidote, actinolite and wairakite and subsurface temperatures as observ- in Glass Mountain deep wells.

Alteration Zones X-Section

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Actinolite is the second most common hydrothermal calcium silicate mineral observed in the wells, and is observed at temperatures greater than 480°F. The mineral first occurs at depths of 4220 feet in GMF31-17, 6400 feet in GMF68-8, and 4620 feet in GMF17A-6. It occurs as an alteration product of pyroxene and hornblende, and in veins commonly containing quartz, adularia and epidote. Actinolite replaces epidote as the dominant calcium silicate at depths below 7460 in GMF31-17, 6940 feet in GMF68-8, and 5950 feet in GMF17A-6. Below 8030 feet in GMF31-17, actinolite is also observed in veins containing talc and biotite (Table 1).

The calcium silicate zeolite, wairakite, is observed only at depths between 2800 and 6400 feet and at temperatures between 479 and 535°F. The mineral occurs in veins with quartz, epidote, adularia, and chlorite, and as an alteration product of plagioclase. As much as seven weight-percent of wairakite is observed at 2840 to 2860 feet in GMF31-17; however calcite is replacing both wairakite and epidote at this depth. The zeolite is least common in GMF17A-6, where it has only a spotty occurrence at 5400 to 6200 feet.

Most of the secondary clinopyroxene observed in GMF31-17 and GMF17A-6 formed as contact metamorphic minerals. Hydrothermal clinopyroxene does occur as a vein mineral in association with quartz and oligoclase at 8090 feet and 8421 feet in GMF31-17. It is uncertain whether the veins formed as part of a hydrothermal event closely following the metamorphic event, or as part of the present hydrothermal system. The veins of clinopyroxene in GMF31-17 are found at present-day temperatures as low as 515°F. Reported occurrences of clinopyroxene in other active geothermal systems are at temperatures in excess of 572°F (Bird, and others, 1984).

Phyllosilicates

The phyllosilicate group of alteration minerals consists of micas, clays, and talc. Hydrothermal micas observed in the wells include both biotite and rare muscovite. The clay minerals include smectite, chlorite, illite, phengite, kaolinite and mixed-layer chlorite-smectite and illite-smectite. Illite and phengite are both potassium-bearing clays that have similar x-ray diffraction patterns and have not been differentiated in this study. Illite and biotite also have similar x-ray diffraction patterns, and have been distinguished by using thin section analysis.

The hydrothermal clays are hydrous minerals and their formation is temperature-dependent. Temperature stability ranges for clays and other phyllosilicates are shown in Table 2. Clay minerals in the wells (Figure 6) occur at temperatures generally consistent with their stability ranges. The exception is smectite, which is observed at temperatures as

TABLE 2 Temperatures of occurrence, reported formation temperatures, and temperature stability ranges for selected hydrothermal phyllosilicate minerals

HYDROTHERMAL PHYLLOSILICATE MINERALS	TEMPERATURES OF OCCURRENCE AT GLASS MTN. (°F)	REPORTED FORMATION TEMPERATURES AND TEMPERATURE STABILITY RANGES (°F)	REFERENCE
Smectite	70 to 556*	86 to 284**	Browne (1984)
Kaolinite	190 to 300	122 to 302	Browne (1978)
Chlorite	483 to 556	>446	Browne (1978)
Illite/Phengite	450 to 535	>428	Browne (1984)
Chlorite-Smectite	375 to 542	392 to 518	Browne (1978)
Illite-Smectite	375 to 494	284 to 428	Browne (1984)
Biotite	511 to 556	>428***	Hulen and Nielson (1986)
Talc	485 to 546	no data	

* maximum temperature recorded in any of the wells
** does not include saponite (see Eberl, and others, 1978)
*** more commonly above 572°F (Elders, and others, 1981; Hulen and Nielson, 1986).

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high as 556°F in GMF68-8. Only the magnesium rich smectite saponite is stable at these temperatures. If the smectite identified in GMF68-8 is not saponite, then the existence of the smectite at such high temperatures suggests the rocks have low matrix permeability, and there is insufficient water for the smectite to react and form higher-ordered clays.

Smectite and chlorite are the most common clays observed in the wells (Figures 3, 4, and 5). Hydrothermal smectite forms primarily as a low-temperature alteration product of rocks high in magnesium and calcium and low in potassium (Deer, and others, 1975). Mafic lavas containing minerals high in magnesium and calcium alter readily to smectite at low temperatures and under saturated conditions. The alteration of high-potassium silicic rocks, however, tends to yield kaolinite and illite clays rather than smectite. The occurrence of smectite in the wells therefore generally follows the distribution of mafic rocks. Smectite is the most common clay observed at lower temperatures and in the upper 3000 feet of GMF68-8 and GMF31-17 and in the upper 4000 feet of GMF17A-6. At greater depths and temperatures, hydrothermal chlorite becomes the dominant clay. Chlorite formed at Glass Mountain as an alteration product of primary ferromagnesian minerals such as pyroxene, amphibole and biotite. Mixed-layer chlorite-smectite formed as an intermediate mineral between chlorite and smectite. The percentage of chlorite in the mixed-layered clays is observed to increase with temperature.

Hydrothermal biotite first occurs at 8409 feet in GMF68-8, 7900 feet in GMF31-17, and 7400 feet in GMF17A-6. The biotite occurs in GMF31-17 as a vein mineral together with actinolite and talc. In GMF17A-6 the biotite occurs as a ragged replacement of metamorphic mafic minerals in the hornfels, and in well-defined cross-cutting veinlets.

ALTERATION ZONES

Alteration zoning is well-developed in the Glass Mountain wells. Diagnostic assemblages of hydrothermal minerals are classified into three distinctive types or zones: zeolite-smectite, argillic, and propylitic. The classification is a modification of those presented by Rose and Burt (1979), Kristmannsdottir (1982), Guilbert and Park (1985), and Carrier (1987), and is based on observed mineralogy. Zeolite-smectite alteration is defined here by the presence of either low-temperature zeolites or hydrothermal smectite clay in concentrations greater than three percent of the whole-rock. Argillic alteration is defined by the presence of hydrothermal quartz and either hydrothermal smectite or kaolinite. Propylitic alteration begins when any two of the following four secondary minerals are present: albite, epidote, calcite (replacing plagioclase), and chlorite (greater than smectite). A cross-section showing the distribution of alteration zones in the wells is presented in Figure 8. The boundaries between the alteration zones are not always sharp. A transition zone is observed in GMF31-17 and GMF17A-6 between the argillic and propylitic alteration zones. Rocks in the transition zone have diagnostic minerals of both alteration assemblages.

The zeolite-smectite zone is found at 380 feet in GMF31-17, 700 feet in GMF68-8, and 1280 feet in GMF17A-6. The top of the zone is probably determined by lithology and the pre-existing water table in the area. At 1280 feet in GMF17A-6, the zeolite-smectite zone is anomalously deep relative to the present static water level in the well of about 1100 feet.

The argillic alteration zone occurs beneath the zeolite-smectite zone at 1320 feet in GMF31-17, 1640 feet in GMF68-8, and 2680 feet in GMF17A-6. Well-developed argillic alteration zones are found in GMF68-8 and GMF31-17, and coincide with observed boiling-point formation temperatures (Figures 3 and 4). Only weak to moderately developed argillic alteration is found in GMF17A-6, a well in which formation temperatures are considerably less than boiling (Figure 5). Argillic alteration in GMF68-8 becomes moderate to strong in intensity at 2080 to 2780 feet, and persists to 3000 feet. Argillic alteration in GMF31-17 occurs at 1320 feet, becomes moderate to strong in intensity at 1780 feet, and persists to at least 2100 feet. A zone of weak argillic alteration occurs in GMF31-17 at the anomalously shallow depth of 260 to 380 feet, and is possibly related to ancient hot spring activity. Argillic alteration in GMF17A-6 begins at 2680 feet, does not progress beyond weak to moderate in intensity, and persists to 3900 feet.

The propylitic alteration zone is first observed at 2740 feet in GMF31-17, 3000 feet in GMF68-8, and 4500 feet in GMF17A-6, and extends to the total depth of each well. Propylitic alteration is well-developed from its first occurrence in GMF31-17 and GMF17A-6, and becomes well-developed at 4120 feet in GMF68-8. Strong propylitic alteration is often observed in cutting samples to be associated with the brecciated zones at the tops and bottoms of lava flows, and in intervals of known production. In the spot cores, strong propylitic alteration is observed to line subvertical fractures and open spaces.

Transition zones are observed in GMF31-17 and GMF17A-6 between argillic and propylitic alteration. The transition zone in GMF31-17 occurs at 2100 to 2740 feet in silicic rocks, and is characterized by mixed-layered clays and the spotty occurrence of poorly crystallized epidote and chlorite. The occurrence of the transition zone is probably due to lithology. Silicic rocks as a whole are not as conducive as mafic rocks to the formation of epidote or chlorite. The transition zone in GMF17A-6 occurs at 3900 to 4500 feet. Although temperatures in the zone exceed 450°F (Figure 5) and chlorite is present, the chlorite remains subordinate to smectite. The transition zone in GMF17A-6 probably results from low matrix permeability which allows the smectite to exist at higher temperatures.

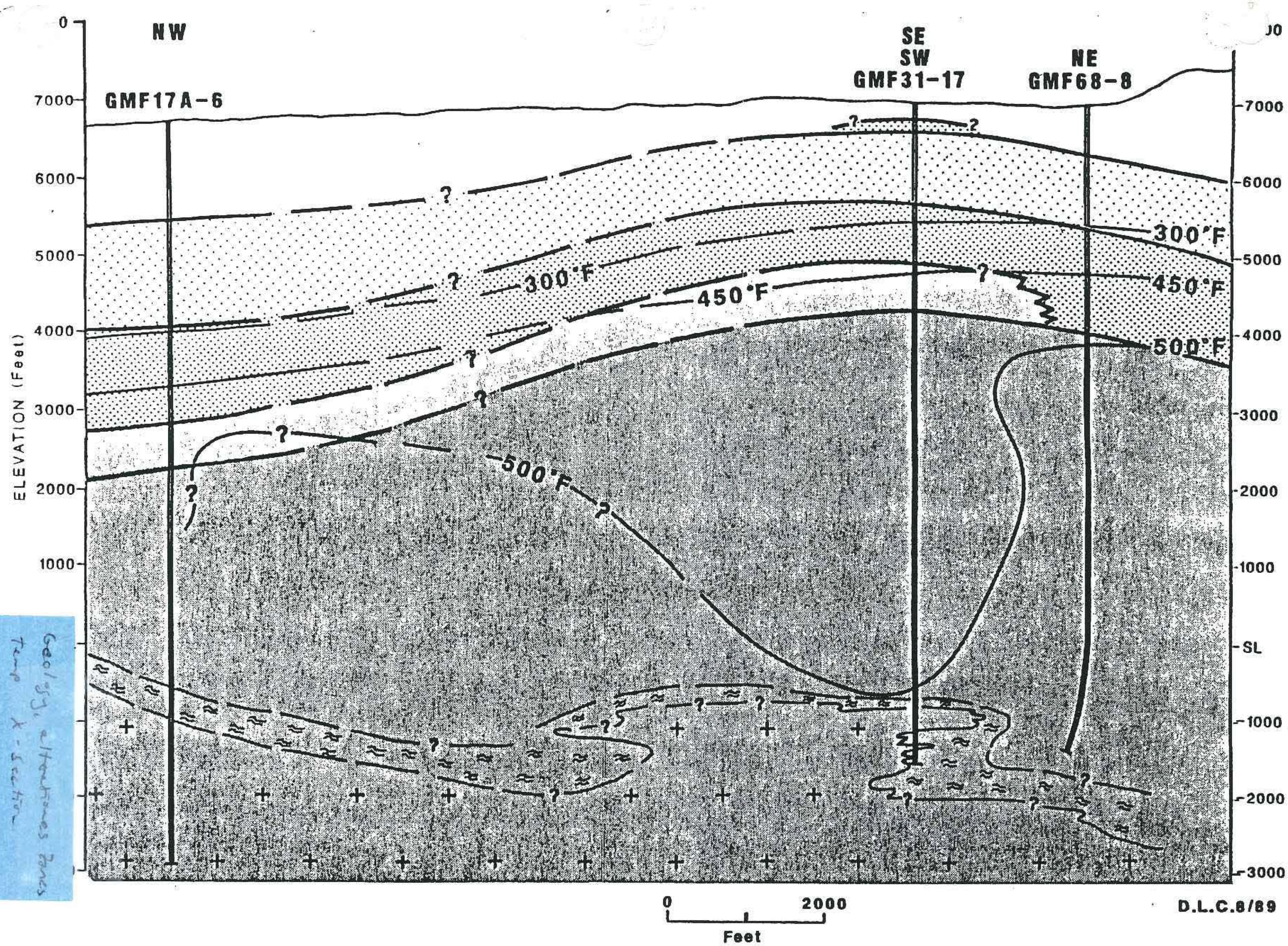

Figure 8: Cross-section showing generalized geology, alteration zones, and subsurface temperatures as observed in the Glass Mountain deep wells.

Rock Groups (by pattern)
- interlayered volcanics
- contact metamorphics
- granodiorites

Alteration Zones (by shading)
- zeolite-smectite
- argillic
- argillic/propylitic transition
- propylitic

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Geology, alterations zones
Temp X-section

[redacted]

A good correlation is observed to exist between alteration zones and modelled low-resistivity anomalies (Figure 9). The resistivity data are compiled from one-dimensional inversions of time-domain electromagnetic (TDEM) and magnetotelluric (MT) data. Modelled low-resistivities in general coincide with the zones of argillic alteration and are believed to be associated with smectite clay (Nordquist, 1986). The lowest resistivities are modelled for the GMF31-17 and GMF68-8 areas, at which moderate to strong argillic alteration and boiling-point formation temperatures exist. Modelled resistivities in the GMF17A-6 area are not as low as at GMF31-17 and GMF68-8. In GMF17A-6, only weak to moderate argillic alteration and less than boiling-point formation temperatures are observed.

CONCLUSIONS

The deep well data show that reservoir rocks at Glass Mountain are dominantly layered volcanics. Primary permeability therefore probably has a much higher horizontal component than a vertical component. The thick sequence of volcanic rocks indicates that the area has had a long volcanic history. Further work is needed to substantiate the preliminary conclusion that the coarser grained volcanics observed at depths of 4600 feet mark the base of Medicine Lake volcano. The apparent depression of the pre-Medicine Lake lavas can be attributed to some combination of three factors: paleotopography, volcanic subsidence, or isostatic compensation. The absence of massive tuffs underlying the caldera floor indicates no catastrophic eruption of pumice and ash has occurred. Any subsidence is therefore probably the result of isostatic compensation.

The mineralogical data suggest that either multiple hydrothermal systems have existed in the Glass Mountain area, or that temperatures in the present geothermal system have declined. This is evident by the occurrence of epidote at an anomalously low temperature of 430°F at 2840 to 2860 feet in GMF31-17. Caution is therefore needed in using the first occurrence of epidote to identify the top of the reservoir. In addition, the replacement of epidote and wairakite by calcite at 2840 to 2860 feet in GMF31-17 is indicative of boiling and CO_2 exsolution. These processes are consistent with the boiling-point temperatures currently observed at those depths (Figure 4). In addition to epidote, hydrothermal clinopyroxene also appears at lower-than-expected temperatures in GMF31-17. The clinopyroxene-quartz-oligoclase and biotite-actinolite-talc veins in the contact metamorphic rocks in GMF31-17 and GMF17A-6 possibly record high-temperature hydrothermal alteration that closely followed the metamorphism. Fluid inclusion data will be useful in resolving these relationships further.

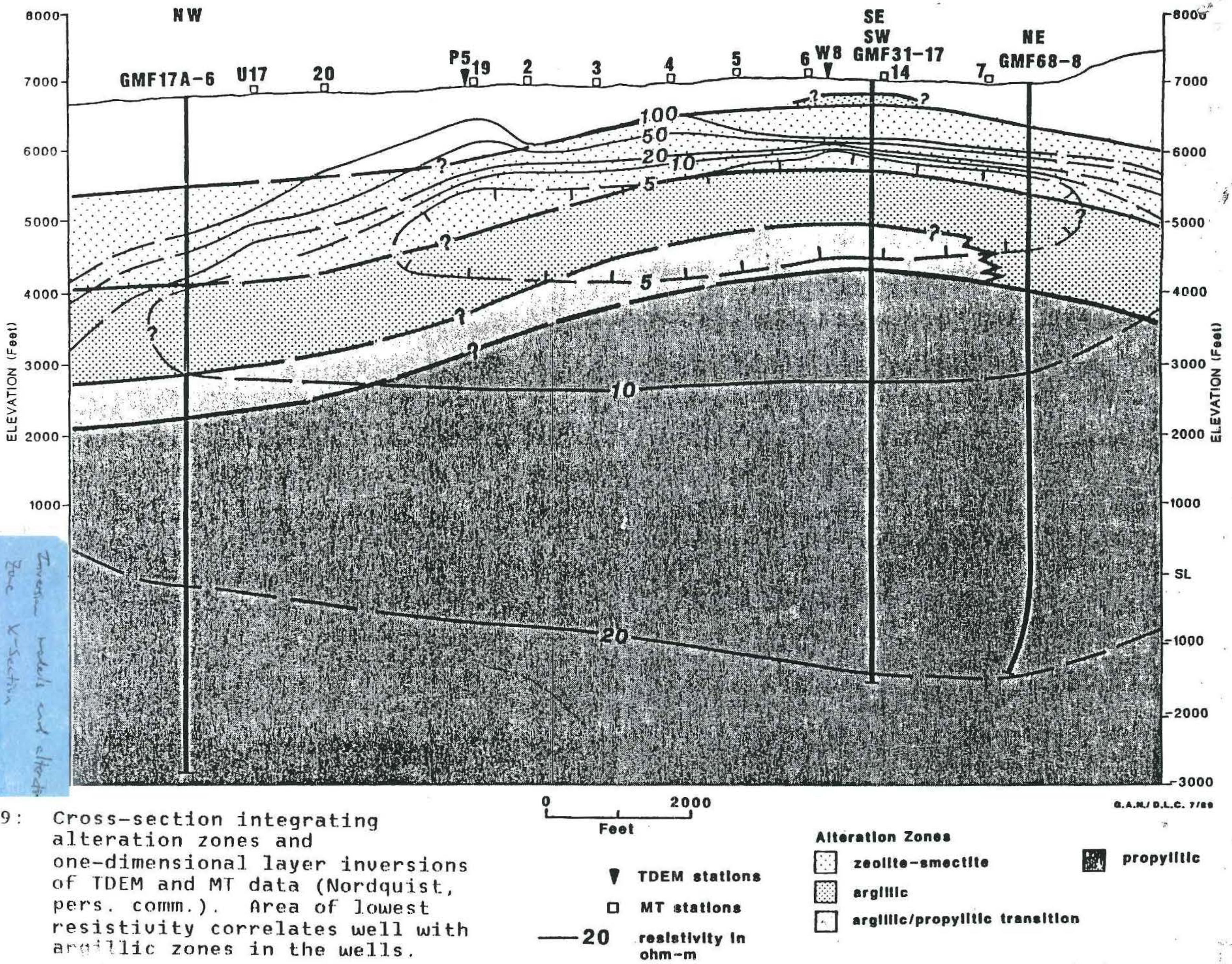

Figure 9: Cross-section integrating alteration zones and one-dimensional layer inversions of TDEM and MT data (Nordquist, pers. comm.). Area of lowest resistivity correlates well with argillic zones in the wells.

Inversion models and alteration zone X-section

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The systematic pattern of alteration zoning in the wells indicates a well-developed geothermal system has existed in the Glass Mountain area. Strong argillic alteration in GMF31-17 and GMF68-8 is due to the upwelling of thermal fluids in the area to levels where boiling occurs (Figures 3, and 4,). Similar upwelling or boiling of thermal fluids do not appear to have occurred in the GMF17A-6 area (Figure 5). TDEM and MT have been shown to be useful in the Glass Mountain area for predicting the occurrence of strong argillic alteration. The anomalously shallow weak argillic alteration at 260 feet in GMF31-17, together with the occurrence of epidote and wairakite at 2840 to 2860 feet, suggests that past hydrostatic water levels in the area have been shallower than the current 1100 feet. The occurrence of strong propylitic alteration along fractures and the brecciated tops and bottoms of lava flows suggests that these areas are a preferred pathway for geothermal fluids.

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