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F. DELLECHAIE, VICE PRESIDENT - EXPLORATION

OCCURRENCE AND HYDROTHERMAL ALTERATION OF DIABASE,
HEBER GEOTHERMAL FIELD, IMPERIAL VALLEY,
CALIFORNIA

by

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June, 1977

*On Leave from New Zealand Geological Survey

Sponsored by USGS/ERDA Grant No. 14-08-0001-G-244
and NSF Grant AER 72-03551 A03

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ABSTRACT

Holtz No. 1, a 1570 m deep well in the Heber geothermal field, penetrated a diabase dike or sill intruded into non-marine sediments of probable Pleistocene age at a depth of 1335 to 1366 m. This is the first known occurrence of igneous rocks in any of the geothermal fields in the Imperial Valley, apart from those associated with the Salton Sea field. Well cuttings show that the diabase has cumulate textures and contains vugs filled with secondary minerals. Primary minerals are augite ($\text{En}_{44.5}\text{Wo}_{44.5}\text{Fs}_{11}$ to $\text{En}_{33.0}\text{Wo}_{38.5}\text{Fs}_{28.5}$), plagioclase (labradorite but zoned An_{15} to An_{76}), olivine and orthopyroxene (both now pseudomorphed by chlorite), and accessory titanomagnetite and ilmenite. Contact metamorphism of sediments by the diabase was not observed but both have reacted with hydrothermal fluids. Chlorite (diabantite) is the most abundant secondary mineral in the diabase and replaces olivine, plagioclase, and early hydrothermal minerals. Prehnite, with up to 5.5 wt. % FeO, typically replaces plagioclase but also occurs in vesicles; calcic plagioclase has locally altered to calcite or sodic albite. Titanomagnetite and ilmenite are partly altered to sphene or minor amounts of pyrite. Iron rich epidote, oligoclase, albite, anhydrite, pectolite(?), wairakite and more rarely quartz occur in veins or vugs but potassium minerals are absent. Small groundmass augite grains and the rims of some larger crystals have altered to ferroaugite (up to Fs_{47}), perhaps due to hydrothermal reaction. The chemical composition of the geothermal brine from Holtz No. 1 is unavailable for proprietary reasons but a nearby well contains 14,200 mg/l TDS, including 693 mg/l Ca and 56 mg/l Fe. A fluid of similar composition may have reacted with the diabase to form the observed hydrothermal Ca-Fe minerals. Tempera-

tures in the well are also confidential at present but paleotemperature measurements of fluid inclusions in calcite record two thermal events; at 1524 m these were, for example, $212 \pm 9^{\circ}\text{C}$ and $235 \pm 5^{\circ}\text{C}$.

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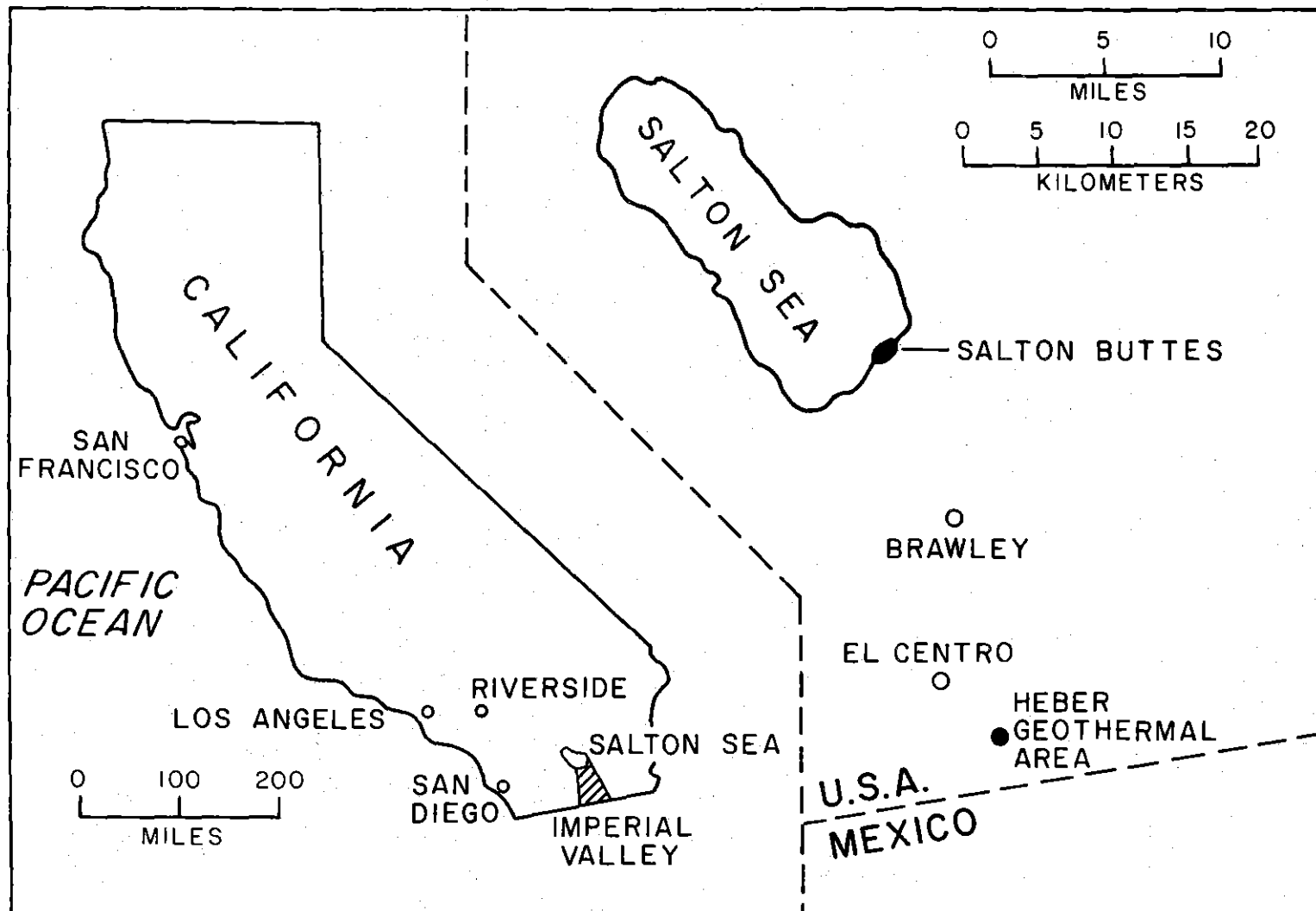
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INTRODUCTION

Current interest in the development of geothermal energy has focused attention on liquid-dominated, hydrothermal systems in the Salton Trough of the Imperial Valley, California (Fig. 1). For several years investigative drilling was mainly concentrated in the well-known Salton Sea field but the geology of other systems has also received attention including the Dunes (Bird, 1975; Elders and Bird, 1976; Bird and Elders, 1976), East Mesa (USDI/BR, 1974; Coplen, 1976; Hoagland, 1976), and Glamis (Elders, 1975). About 75 km south of the international border, the Cerro Prieto geothermal field is now producing 75 megawatts electrical (Reed, 1976). The potential of the Heber field is presently being evaluated by Chevron Oil Co. of California and by Union Oil Co. By 1975, six deep (~2000 m) wells had been drilled in an area outlined mainly by geophysical methods and shallow temperature gradient wells. One of these wells, Holtz No. 1, drilled by San Diego Gas and Electric Co., intersected a thin (30 m) diabase dike or sill between 1335 and 1366 m; although neither the diabase nor the geothermal system have any surface manifestation.

The presence of diabase intruded into what are believed to be Pleistocene non-marine sediments merits attention for three reasons: (1) This is the first reported occurrence of young igneous rocks in the Imperial Valley outside the Salton Sea field (Robinson, Elders and Muffler, 1976) although igneous activity has apparently been important in the formation and development of the Gulf of California and its landward extension, the Salton Trough (Elders et al., 1972). (2) We wish to investigate the relationship, if any, of the diabase to present hydrothermal activity; specifically, did the intrusion of

Figure 1. Map of Salton Trough showing location of the Heber Geothermal Field.



the diabase initiate geothermal activity? (3) Study of hydrothermal minerals formed during fluid/diabase reactions may record changes in fluid compositions and temperatures during the life of the geothermal system. Products of these reactions are more readily distinguished from the primary minerals of igneous rocks than from the more heterogeneous minerals common to the sediments throughout the Salton Trough. An obvious corollary of this is to consider the possibility that the composition of the deep circulating thermal fluid has been affected by contact with the diabase.

GEOLOGIC SETTING

The Salton Trough is a 130 km wide, actively developing, structural depression forming the landward extension of the Gulf of California (Elders et al., 1972). It is partially filled with up to 6 km of lacustrine and deltaic sediments deposited mainly by the Colorado River (Biehler, Kovach and Allen, 1964; Merriam and Bandy, 1965; Muffler and Doe, 1968; Elders, 1975). Ages of the sediments are uncertain but a 4 km deep drillhole south of the Salton Sea penetrated rocks no older than Pleistocene (Muffler and White, 1969). Elders (1975), Elders and Biehler (1975) and Elders et al. (1972) showed that the Salton Trough is undergoing right lateral horizontal displacement by steady creep and associated earthquake activity and that the valley floor is also subsiding relative to the walls. Several thermal anomalies were postulated to be sited on the resultant tension gaps or 'rhombochasms' where crustal spreading, possibly accompanied by introduction of mantle material, is now taking place. It seems probable that the Heber geothermal area is also located within one such 'rhombochasm'. However, its relationship to through-going faults is unclear.

QUATERNARY IGNEOUS ROCKS IN THE SALTON TROUGH

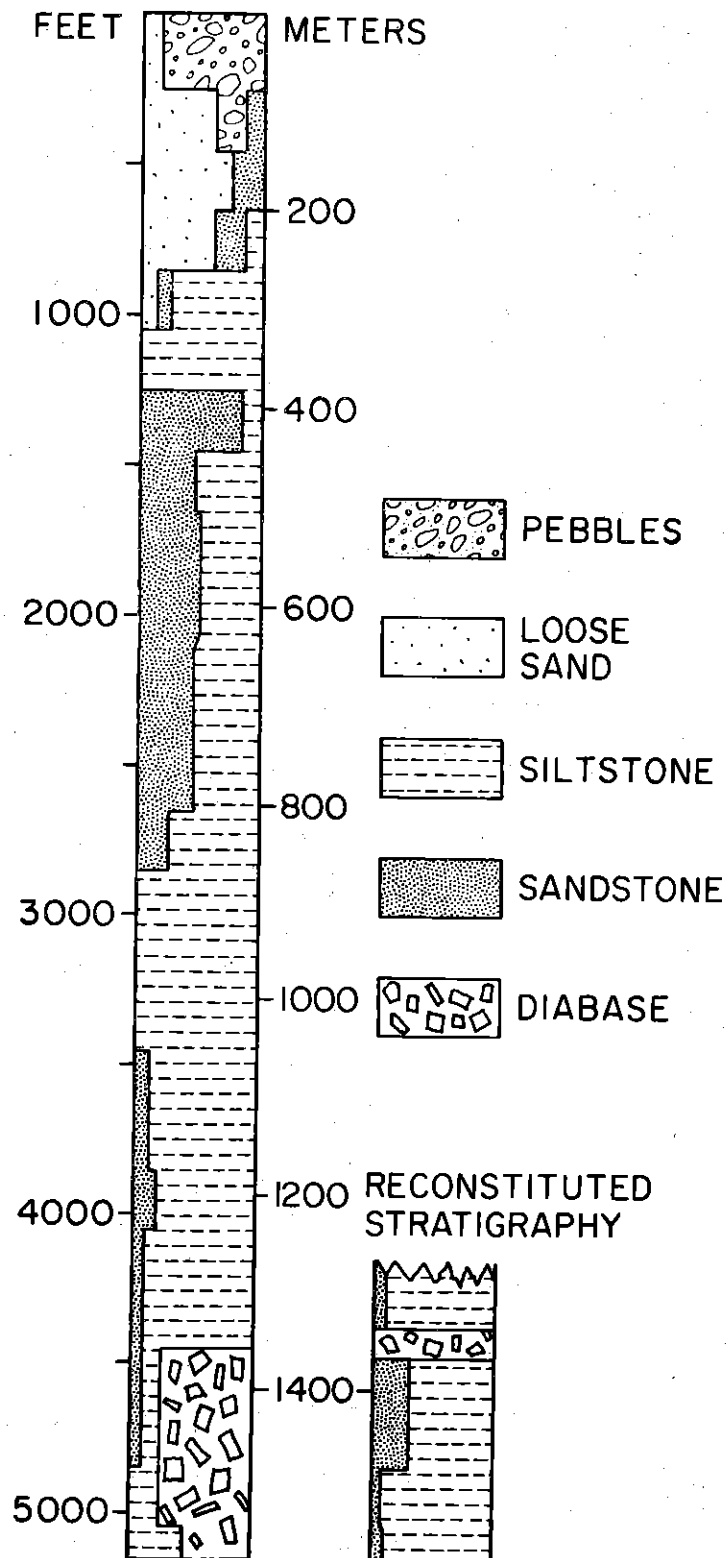
Igneous rocks form a minute but important fraction of the total volume of sedimentary fill in the Trough. The Salton Buttes consist of five aligned Holocene sodic rhyolite domes extruded onto Quaternary sediments near the center of the Salton Sea geothermal field (Robinson, Elders and Muffler, 1976). Potassium-poor tholeiitic basalt occurs as abundant xenoliths in four of the domes and both rhyolite and basalt have also been recorded in at least four geothermal wells, where they form dikes or sills. Interpretation of aeromagnetic data suggests that a stock or dyke swarm with a magnetic susceptibility like that of rhyolite may reach within 300 m of the present ground surface (Griscom and Muffler, 1971). From isotope and chemical evidence, Robinson, Elders and Muffler (1976) concluded that the exposed volcanic rocks formed by successive partial fusion of mantle peridotite.

A Quaternary lithoidal rhyodacite forms a prominent topographic feature near the Cerro Prieto geothermal field but has yet to be described in detail; it does appear, however, to be similar to young volcanic rocks at the Barcena volcano on the Revillagigedo Islands of the East Pacific Rise and Consag Rock at the head of the Gulf of California (Elders, 1975). Drillholes at Cerro Prieto have not been reported to have intersected intrusive igneous rocks. However, a positive gravity anomaly associated with the volcano may indicate that they also occur at depth (Reed, 1976).

STRATIGRAPHY OF HEBER GEOTHERMAL FIELD

Sediments penetrated by the six wells consist of interbedded fluvial and deltaic siltstones and less abundant sandstones of probable Pleistocene age. They contain a variety of detrital minerals and clasts and are similar to other geothermal areas of the Salton Trough (Muffler and Doe, 1968;

Figure 2. Summary stratigraphic log based on cuttings of Holtz #1 well, Heber. Reconstituted stratigraphy subcolumn assumes diabase from below 1366 m has sloughed off the side of the well.



Elders and Bird, 1976; Hoagland, 1976) which were also deposited as detritus from the ancestral Colorado River. Geophysical evidence (Biehler, 1971) indicates that the basement at Heber is at least 6500 m below ground surface.

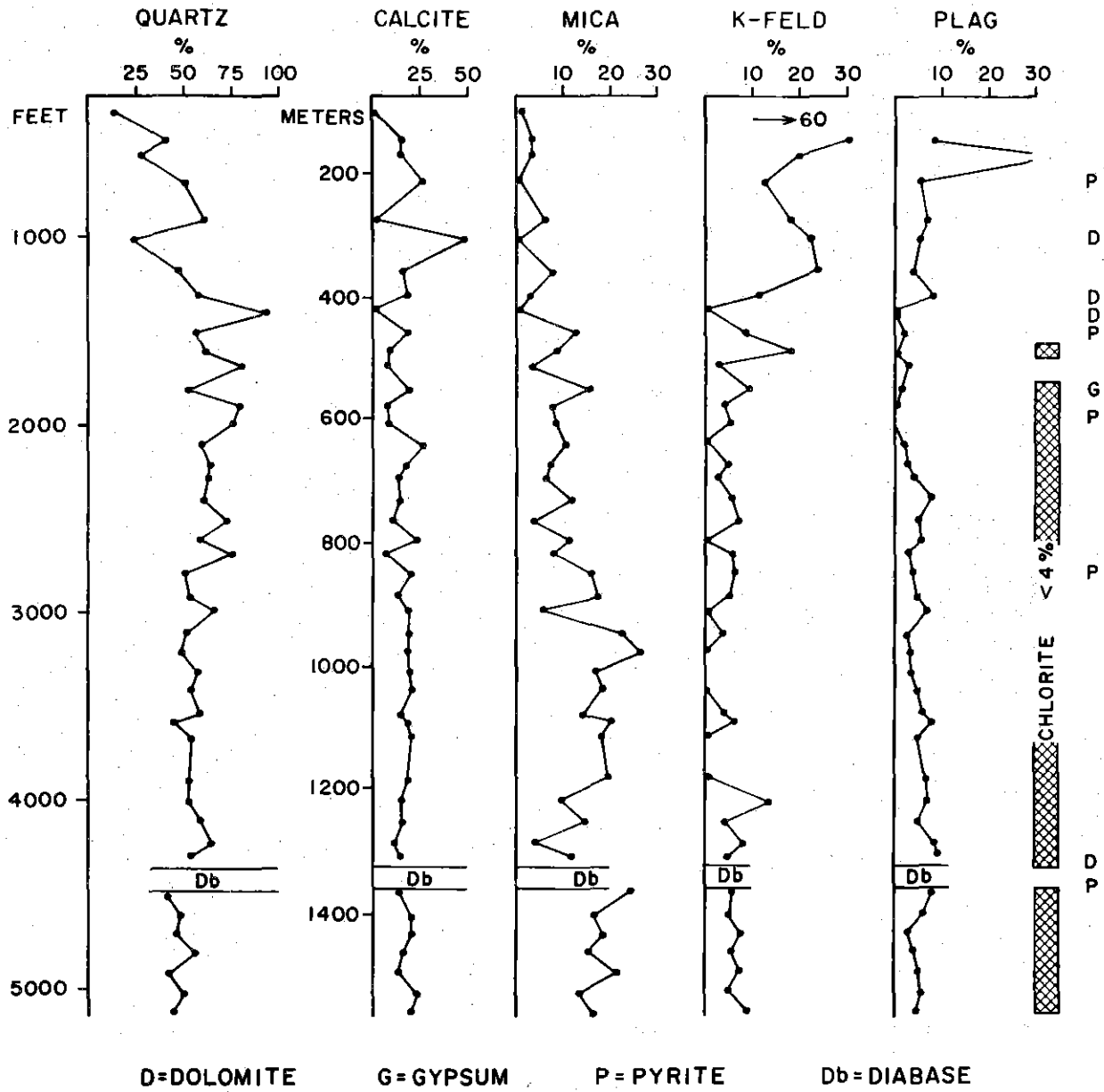
SEQUENCE IN HOLTZ WELL NO. 1

Cutting samples mainly taken at 10 m intervals throughout the 1570 m drilled depth were examined by binocular microscope and approximate mineral abundances determined using an automated X-ray diffractometer. No cores were recovered.

A summary lithologic log is shown in Fig. 2. Rounded to subrounded pebbles of quartzite, granite and chert occur down to 150 m and unconsolidated, medium to coarse-grained, angular to rounded sand is common above about 300 m. Sand grains include chert, feldspar, rock fragments and more rarely heavy minerals. The deeper quartz grains have frosted surfaces. Between 400 and 880 m, fine to coarse, well-sorted sandstone is a major component but is apparently interbedded with siltstone. The sandstone contains subangular to subrounded quartz grains, accessory feldspar and lithic grains cemented by sparry calcite and locally, fresh to tarnished pyrite; some quartz grains have syntaxial overgrowths.

Siltstones of several colors are present below 200 m and are abundant between 450 m and well bottom. Light to dark grey-colored, locally thin-bedded types predominate below 900 m depth and red-colored siltstones, suggestive of a high hematite content, occur between 460 and 975 m. White and tan siltstones are less common (<10%) and are generally coarser grained than red or grey types; the former occur between 365 and 385 m and the latter at two intervals: 105 to 180 m and 520 to 620 m. Siltstones and shales of different colors also occur at the Salton Sea and East Mesa geothermal

Figure 3. Summary of downhole mineralogy based on X-ray modal analysis by automated Picker X-ray diffractometer at UCR.



fields (Kendall, 1976; Hoagland, 1976) and these color differences have been attributed to variations in post-depositional alteration conditions. X-ray diffraction results (Fig. 3) show that the sediments now consist of varying proportions of quartz, K-feldspar, plagioclase, mica, calcite, dolomite, pyrite and gypsum. Although these phases occur as detrital minerals, all can also be deposited (or dissolved) by hydrothermal fluids so that to determine their origin in cutting samples usually requires more detailed studies involving at least use of a petrographic microscope.

DIABASE

PRIMARY FEATURES

Occurrence

All cuttings reportedly collected from below 1344 m contain appreciable quantities of diabase chips. However, several types of geophysical well logs show that the diabase was penetrated between 1335 and 1366 m so that it is, at most, only 30 m thick (D. R. Butler, Chevron Oil Co., pers. comm.). This means that diabase chips collected from below 1366 m have sloughed off the side of the well. The attitude of the intrusion is not known nor has diabase been identified in other wells, some less than 1.5 km distant. The small residual Bouguer anomaly associated with the geothermal field precludes the possibility that the diabase forms part of a very large, or shallow mafic body (S. Biehler, U.C.R., pers. comm.) but it could well form one of a series of thin, irregular dikes and sills similar to that suggested earlier for the Salton Sea (Griscom and Muffler, 1971). The age of the diabase is unknown but the intruded sediments are thought to be Pleistocene or, at most, Pliocene. A youthful age for the intrusion is suggested by its coarsely

crystalline nature which necessitated slow cooling and consequently an appreciably thick insulating rock cover. Deposition and subsidence still continue in the Salton Trough so that the diabase presumably now has its maximum overburden.

Nature of the Intrusion

Primary minerals present in the diabase are clinopyroxene, plagioclase (Fig. 4), titanomagnetite and ilmenite; olivine and orthopyroxene have been entirely replaced by chlorite.

The diabase is too altered to give meaningful values of the original whole-rock chemical composition. However, sufficient fresh clinopyroxene is present so that electron microprobe analyses of this phase have been used to help characterize the nature of the original intrusion.

On an En - Wo - Fs diagram (Fig. 5) the clinopyroxene compositions plot below, or close to the boundary separating alkaline from nonalkaline magma types (Le Bas, 1962). The ratios of $\text{SiO}_2/\text{Al}_2\text{O}_3$ and $\text{Al}_2\text{O}_3/\text{TiO}_2$ and of Al_2O_3 and TiO_2 versus Fs ratios (Figs. 6, 7) and to a lesser extent, of $\text{Na}_2\text{O}/\text{Fs}$ (Fig. 8) confirm the nonalkaline character of the intrusion. The clino-pyroxene compositions, particularly the variation in iron, and the existence of abundant chlorite pseudomorphs suggest that orthopyroxene was formerly present. Such a primary mineralogy suggests that the magma had a tholeiitic affinity (Kuno, 1968). An alternate interpretation, however, is simply that calcic plagioclase started to crystallize before pyroxene (Barberi, Bizard and Varet, 1971).

Although intruded into a thick sequence of water-saturated sediments, the absence of primary biotite or hornblende indicates that H_2O activity in magma was low. Most titano magnetite and ilmenite has partly altered to

TABLE 1. SELECTED ELECTRON MICROPROBE ANALYSES OF
TITANOMAGNETITE (0002) AND ILMENITE (0014).

Sample Chip	0002	0002	0014
Indicated Depth(m)	1341-1555	1341-1555	1401-1410
Analysis No.	28	29	141
MgO	0.00	0.00	0.07
Al ₂ O ₃	0.57	0.60	0.00
SiO ₂	0.32	0.45	0.81
TiO ₂	15.87	16.46	48.84
CaO	-	-	-
Cr ₂ O ₃	0.00	0.00	0.05
MnO	0.97	0.94	4.33
FeO(a)	78.10	76.90	46.24
ZrO ₂	0.00	0.00	-
ZnO	0.32	-	0.00
F	-	-	-
Ce ₂ O ₃	-	-	-
Sum	96.13	95.35	100.34

(a) Total Fe as FeO.

sphene, leucoxene or pyrite but calculations (Buddington and Lindsley, 1964) using analyses (Table 1) of fresh crystals in different chips give a temperature for last ilmenite-magnetite equilibration of 840-855°C and an oxygen fugacity of about 10^{-14} atmospheres. If 850°C was in fact the temperature of crystallization, then an order of magnitude calculation (Jaegger, 1957) shows that magma in the dike or sill would take only 10-15 years to cool by conduction alone from 1100°C to this temperature. A sill only 30 m thick would then cool very rapidly to ambient temperatures by convection; consideration of Norton and Knights' (in press) model suggests this convective cooling would occur in less than 1000 years. Although intrusion of even a semisolid igneous body would alter fluid flow in an already active geothermal system (or could perhaps initiate one), a body of such small dimensions is clearly unlikely to be a significant heat source for presently observed activity within the Heber geothermal reservoir.

Textures

Crystals of primary minerals in the diabase are commonly up to 3 mm long and textures vary from ophitic and subophitic to poikilitic. Mineral relations indicate that plagioclase and olivine formed first but continued to crystallize after augite precipitation began. It is difficult to determine relative mineral abundances in the diabase from cuttings as the ratios of pyroxene to plagioclase vary greatly. Oblate or spherical vesicles of 2-3 mm diameter occur in several diabase chips but it is impossible to estimate their volume in the intrusion. Moore and Schilling's work (1973) shows that vesicles can form in alkali-rich basalt (with 0.9% H₂O) intruded on to the ocean floor where the water depth is 5-6 km. By analogy, vesicles could be expected in the diabase at Heber, since even present day lithostatic pressure is less than that exerted by 6 km of sea water.

TABLE 2. SELECTED ELECTRON MICROPROBE ANALYSES OF PRIMARY PLAGIOCLASE.

Sample Chip	0001 ^b	0001	0001	0001	0001	0004	0004	0012	0013	0022
Indicated Depth(m)	1341-1555	1341-1555	1341-1555	1341-1555	1341-1555	1341-1555	1341-1555	1526-1535	1526-1535	1547-1562
Analysis No.	7	6	9	5	8	48	49	121	125	211
Na ₂ O	4.34	4.84	4.99	6.02	9.16	7.15	9.36	3.07	4.41	2.58
MgO	0.15	0.13	0.09	0.07	0.03	0.05	0.00	0.15	0.08	0.11
Al ₂ O ₃	30.10	29.16	28.85	27.57	24.22	25.98	20.68	30.70	29.05	32.00
SiO ₂	52.34	52.73	53.11	55.09	60.86	57.76	64.86	51.31	53.01	48.17
K ₂ O	0.04	0.05	0.05	0.08	0.25	0.10	0.56	0.04	0.09	0.01
CaO	13.33	12.27	12.14	10.40	5.87	8.42	2.94	14.03	12.54	16.07
TiO ₂	0.05	0.03	0.03	0.15	0.16	0.10	0.07	0.01	0.16	0.07
FeO ^a	0.54	0.60	0.61	0.67	0.51	0.53	0.47	0.58	0.76	0.39
BaO	0.06	0.00	0.24	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sum	100.94	99.81	100.10	100.05	101.06	100.08	98.92	99.89	100.10	99.39
An	62.8	58.2	57.2	48.6	25.8	39.2	14.3	71.4	60.7	77.5
Ab	37.0	41.5	42.5	50.9	72.9	60.2	82.5	28.3	38.7	22.4
Or	0.2	0.3	0.3	0.4	1.3	0.5	3.2	0.3	0.5	0.1

(a) Total Fe as FeO.

(b) Analyses of chip 0001 are of same crystal.

Figure 4. Plot of plagioclase composition in diabase.

About 3% of the igneous cuttings are nonporphyritic basalt, perhaps derived from the chilled margins of the intrusion. If this basalt is part of the diabase intrusion, the absence of phenocrysts can be interpreted in a number of different ways. It could mean for instance, that the magma was close to its liquidus when it was intruded. However, the strong normal zoning of primary plagioclase in the diabase (An_{77} to An_{14}) testifies to fluctuating conditions during their crystallization. Although it is possible that these zoned crystals formed in situ, it seems more likely that they nucleated and grew at greater depth so that the magma was emplaced in a semisolid condition. If this was the case the basalt could represent the chilled, crystal-poor margin of the flowing magma, which flow-differentiated during intrusion.

Mineralogy

Cutting chips were examined by petrographic microscope and polished thin sections analyzed using an automated MAC 5-A electron microprobe of the California Institute of Technology.

Plagioclase is the most abundant primary mineral and forms clear, euhedral to subhedral crystals. Strong normal zoning is common, testifying to changing conditions possibly prior to final emplacement of the magma; crystal centers are typically of labradorite or sodic bytownite (Fig. 4, Table 2), but rims are of andesine or rarely sodic oligoclase. For example, a single crystal in chip 0015 contains irregular shaped domains of An_{70} but rims are as sodic as An_{30} . MgO , TiO_2 and BaO contents are low and for 36 analyses do not exceed 0.25 wt%; K_2O is exceptionally low and is seldom above 0.1 wt%. However, iron is present in solid solution in significant quantities (average 0.6 ± 0.1 wt% FeO) although the amount is unrelated to the alkali content. Because of the uncertainty of the depths of origin of

TABLE 3. SELECTED ELECTRON MICROPROBE ANALYSES OF AUGITE.

Sample Chip	0013	0010	0005	0008	0022	0022	0022	0002	0002
Indicated Depth(m)	1526-1535	1526-1535	1341-1555	1489-1498	1547-1562	1547-1562	1547-1562	1341-1555	1341-1555
Analysis Nos.	126-129	96-102	51,52,55, 56,58,59	84,85	204 ^b	203 ^b	205 ^b	19 ^c	20 ^c
Na ₂ O	0.32 [±] .04	0.30 [±] .03	0.36 [±] .03	0.54 [±] .01	0.40	0.42	0.46	0.35	0.45
MgO	15.08 [±] .20	15.47 [±] .18	15.40 [±] .44	13.84 [±] .12	14.74	14.61	12.21	13.37	12.16
Al ₂ O ₃	3.14 [±] .82	3.37 [±] .29	3.08 [±] .61	1.68 [±] .43	3.64	2.06	1.44	1.15	1.92
SiO ₂	51.50 [±] .59	51.16 [±] .57	50.36 [±] .83	51.33 [±] .27	50.16	50.96	50.63	51.96	50.55
CaO	21.17 [±] .76	21.86 [±] .06	21.08 [±] .27	19.69 [±] .05	21.56	21.23	20.04	18.45	19.46
TiO ₂	0.95 [±] .22	0.96 [±] .07	0.96 [±] .14	1.24 [±] .13	1.03	1.05	1.01	0.91	1.29
Cr ₂ O ₃	-	-	0.34 [±] .10	0.00	0.52	0.04	0.00	0.00	0.03
MnO	0.17 [±] .01	0.16 [±] .02	0.20 [±] .03	0.35 [±] .01	0.19	0.23	0.48	0.41	0.32
FeO ^(a)	7.51 [±] .09	6.92 [±] .19	7.33 [±] .19	11.76 [±] .14	7.29	8.85	13.02	14.37	13.48
Sum	99.84	100.20	99.11	100.44	99.51	99.44	99.34	100.97	99.67
En	43.6 [±] .7	44.0 [±] .4	44.1 [±] .9	39.8 [±] .4	42.8	41.8	35.8	38.3	35.9
Wo	43.9 [±] .8	44.7 [±] .2	43.6 [±] .8	40.7 [±] .1	45.0	43.6	42.0	38.0	41.3
Fs	12.5 [±] .3	11.3 [±] .3	12.1 [±] .4	19.5 [±] .3	12.2	14.6	22.1	23.7	22.8

(a) All Fe as FeO.

(b) Different crystals.

(c) Same crystals.

Figure 5. Plot of pyroxene compositions.

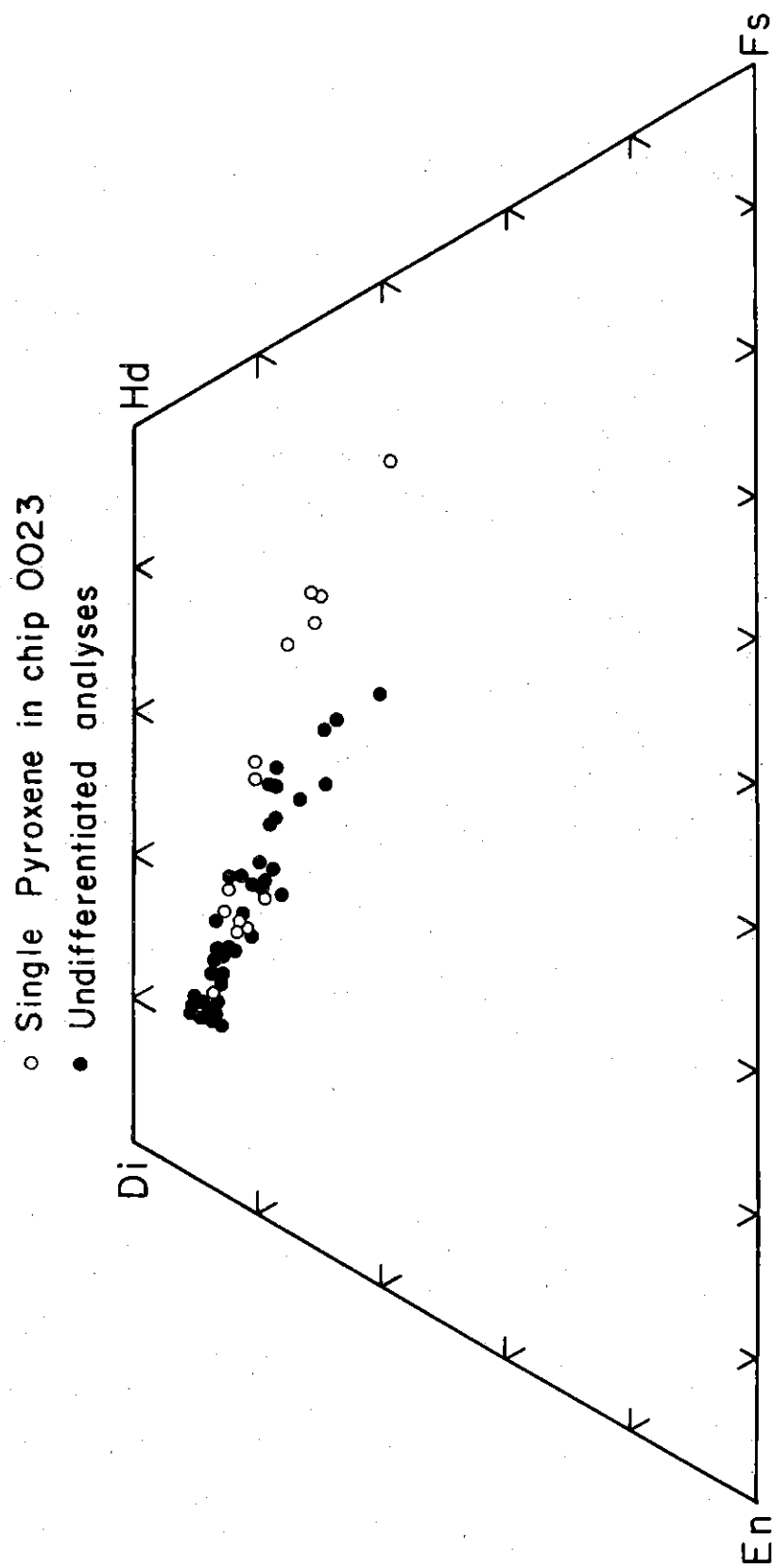


Figure 6. Plot of Al_2O_3 versus ferrosilite content of pyroxenes;
same symbols as in Figure 5.

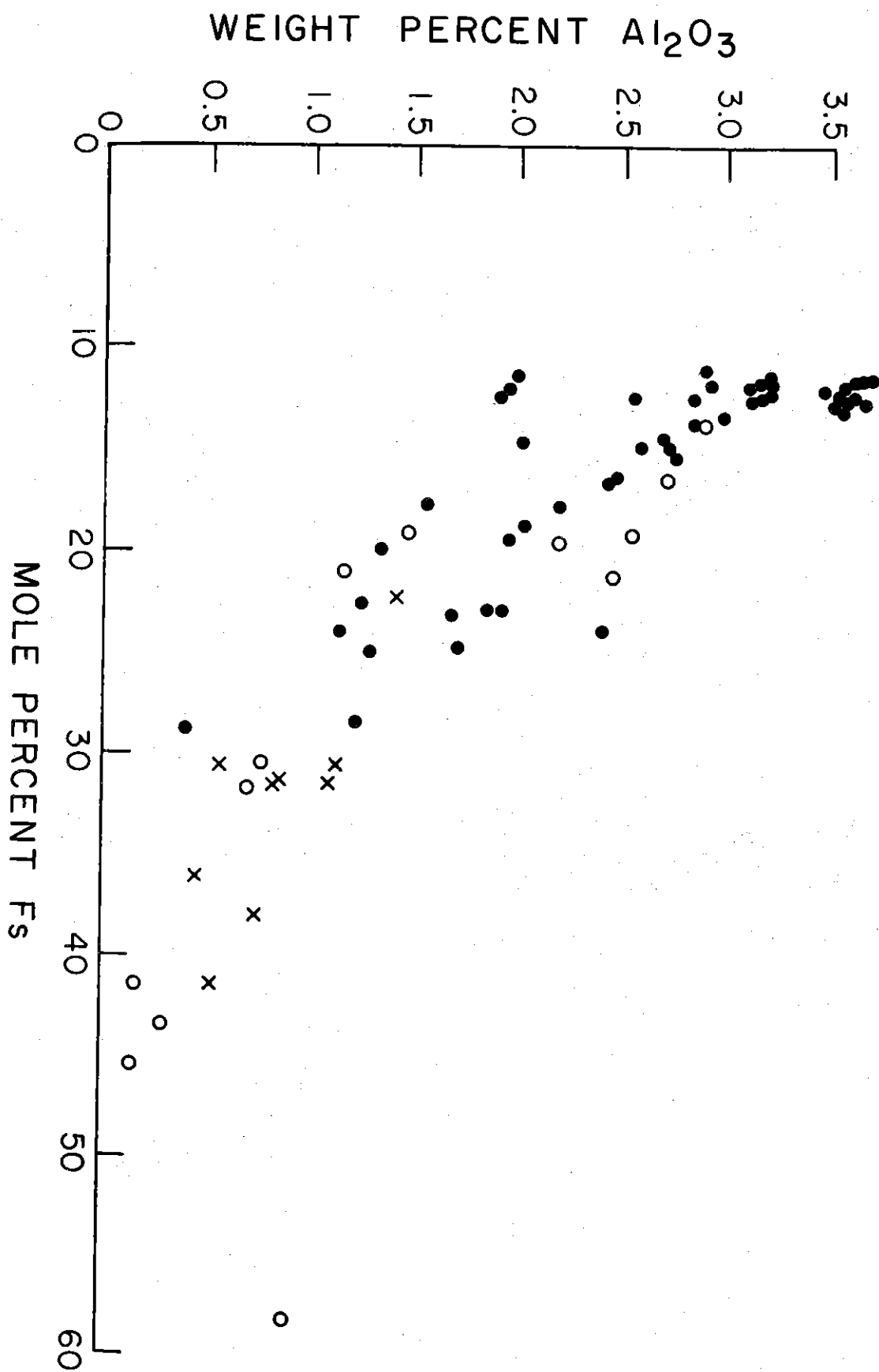


Figure 7. Plot of TiO_2 versus ferrosilite content of pyroxenes;
same symbols as in Figure 5.

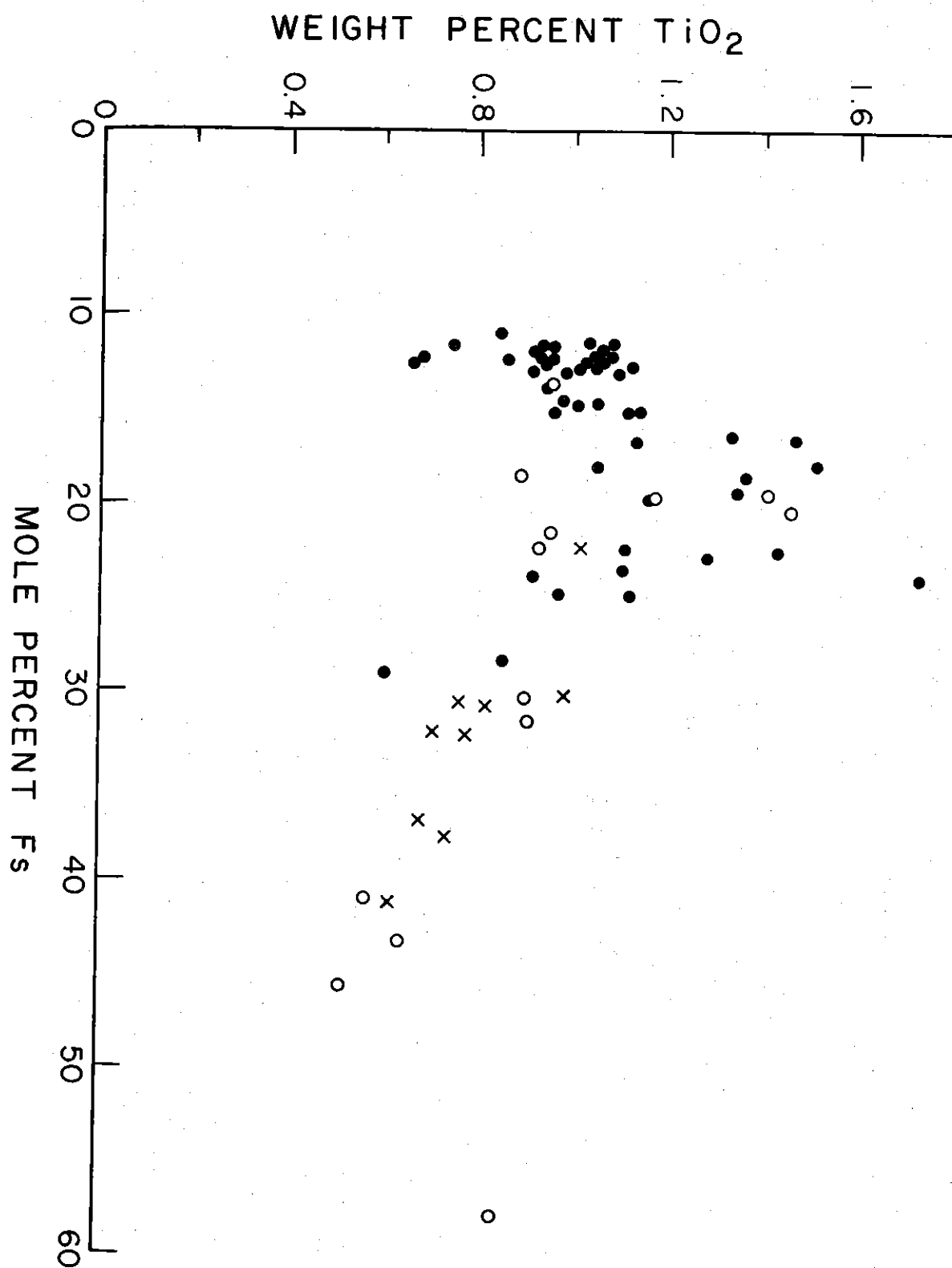
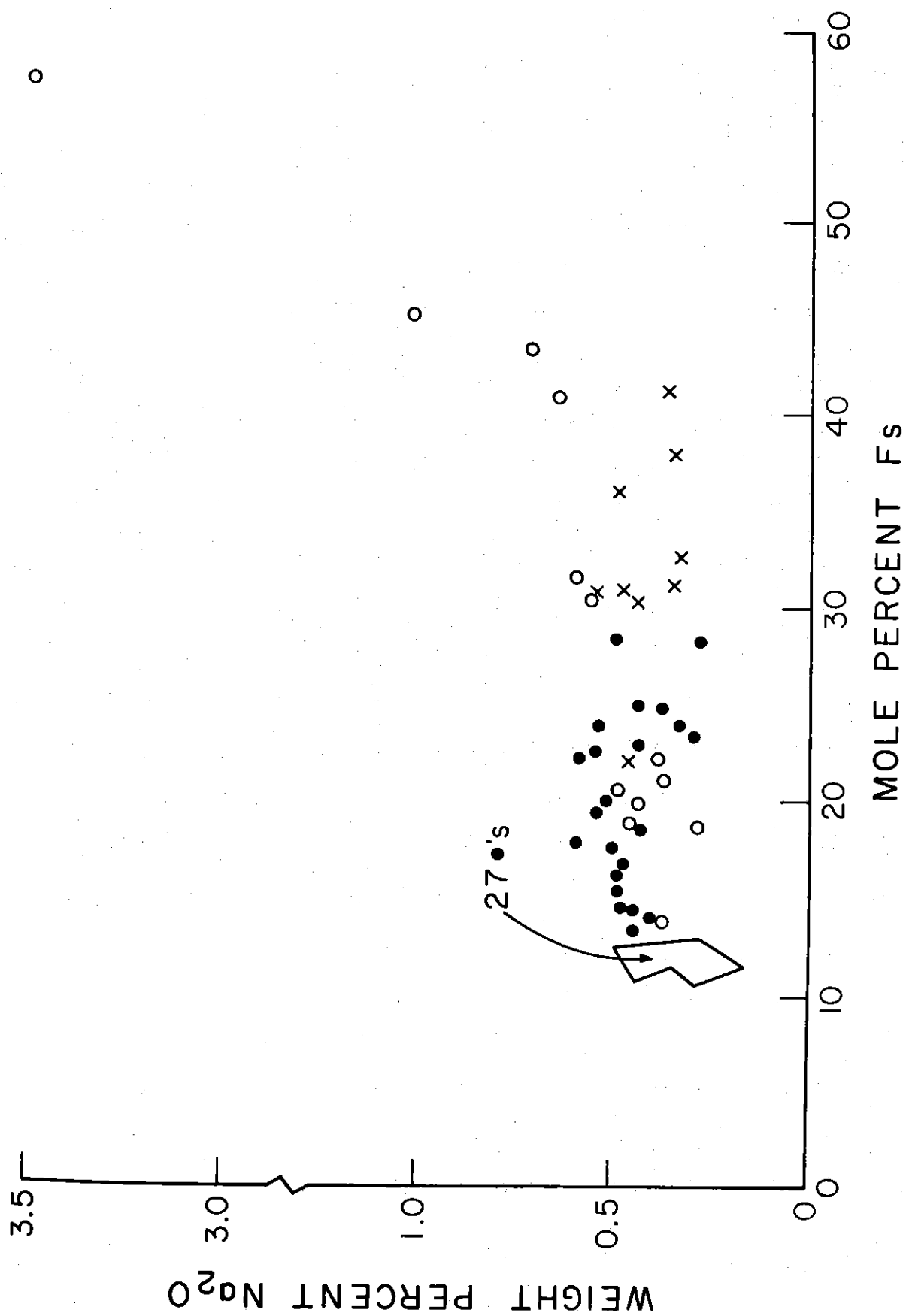


Figure 8. Plot of Na_2O versus ferrosilite content of pyroxenes.
Same symbols as in Figure 5.



the cuttings and the pronounced zoning, systematic changes in composition of plagioclase with depth in the diabase cannot be recognized.

Pyroxenes. Augite is the most abundant and stable ferromagnesian mineral in the diabase but there is evidence that orthopyroxene was also formerly present. This is suggested by chlorite pseudomorphs and by clinopyroxene compositions (Fig. 5) which are typical of a 2-pyroxene diabase.

Augite occurs as subhedral and euhedral crystals in places poikilitically enclosing euhedral plagioclase, but relationships are more commonly subophitic or ophitic; no exsolution textures were seen. Typical crystals are clear to pale green but those with more iron (Fs 20 to 30) are usually pale brown. Optical and chemical zoning is common although several large crystals are homogeneous (e.g. chip 0010, Table 3). Electron microprobe analyses (Figs. 5-8, Table 3) of crystals which have not obviously been affected by secondary reactions, show a wide composition range, strongly suggesting that some igneous differentiation of the magma occurred. For example, the ferrosilite contents are between 11 and 29 mole %, Al_2O_3 varies from 0.4 to 3.6 wt% (in approximately inverse relation to FeO) and TiO_2 from 0.6 to 1.7 wt%. Na_2O is uniformly present between 0.3 and 0.5 wt% but Cr_2O_3 is rarely above 0.5 wt%; manganese is also low but some iron rich crystals contain as much as 0.8 wt% MnO.

Titanomagnetite and Ilmenite. These form near equant, but often skeletal, crystals up to 1.5 mm long; they comprise 10% of some chips but elsewhere are present only in traces. Analyses show varying amounts of SiO_2 and CaO indicating their partial alteration to sphene, although some may also occur in the ilmenite structure. Several ilmenite crystals also contain appreciable concentrations of manganese (up to 4% MnO) substituting for iron (Table 1).

However, both MgO and ZnO in partly altered and unaltered grains do not exceed 0.3 wt%.

SECONDARY FEATURES

Although all the diabase chips observed have been altered by hydrothermal fluids, the intensity and type of alteration varies. Since the temperature and composition of the hydrothermal fluid are unlikely to have been different over a distance of only 30 m, local differences in alteration can be more readily attributed to permeability variations and temporal changes within the reservoir. For example, the persistence of some primary minerals clearly shows that equilibrium between fluid and the diabase has not yet been reached, and textural and fluid inclusion evidence shows that the temperatures and the composition of the circulating fluid have changed since the onset of hydrothermal activity.

Stability of Primary Minerals in the Diabase

Augite is the most stable primary mineral followed by plagioclase; ilmenite alters slightly more readily than titanomagnetite but unaltered crystals of both are rare. Olivine and orthopyroxene have been completely replaced by chlorite. This stability sequence contrasts with that observed in other geothermal systems. For example, at Wairakei, in New Zealand, the order of increasing mineral stability is magnetite/ilmenite - pyroxene/hornblende - plagioclase-biotite-quartz (Steiner, 1968). The same sequence holds at Broadlands, New Zealand except that plagioclase is more stable than biotite (Browne and Ellis, 1970). There are, therefore, clear differences in the alteration environment for fluid/rock reactions at Heber and the two New Zealand fields, the most obvious being the compositions of the thermal fluids.

TABLE 4. OCCURRENCE OF SECONDARY MINERALS IN DIABASE

<u>Primary Minerals</u>	<u>First Alteration Product</u>	<u>Second Alteration Product</u>
Orthopyroxene) Olivine)	Chlorite	
Titanomagnetite) Ilmenite)	Sphene, leucoxene Pyrite	
Calcium plagioclase	Chlorite, albite + iron oxides, prehnite, ?pectolite	Calcite
Augite	Ferroaugite	
<u>Deposited from Solution</u>	Albite, oligoclase epidote, quartz wairakite anhydrite prehnite	Calcite Chlorite Chlorite

Occurrence and Character

Alteration of the diabase is characterized by formation of calcium and iron bearing minerals (Table 4); no potassium phase was observed and hydrothermal quartz was identified only in one chip. Secondary minerals replace both primary igneous phases and, in places, earlier hydrothermal minerals, but many secondary minerals also deposited from solution into veins or vugs.

Secondary Plagioclase. In a few cuttings, untwinned, dusty, highly sodic albite full of inclusions completely replaces primary plagioclase (Fig. 4); epidote is also usually present. The albitized plagioclase contains little MgO or TiO₂ and FeO is also very low, exceeding 0.2 wt% only where measurable calcium is present (Table 5). This contrasts with primary calcic plagioclase with 0.6±0.1 wt% FeO (Table 2). The material composing the inclusions is far too small for quantitative electron microprobe analysis but an inclusion-

TABLE 5. SELECTED ELECTRON MICROPROBE ANALYSES OF SECONDARY PLAGIOCLASE.

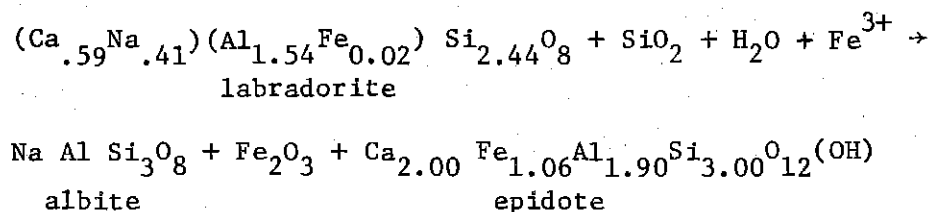
Sample Chip	0002	0002	0003	0023	0004	0005
Indicated Depth(m)	1341-1555	1341-1555	1341-1555	1341-1555	1341-1555	1341-1555
Analysis No.	17 ^r	25 ^r	36 ^r	226 ^v	43 ^e	54 ^v
Na ₂ O	11.51	10.87	11.33	10.28	9.56	10.32
MgO	0.00	0.01	0.00	0.01	0.00	0.00
Al ₂ O ₃	19.75	19.68	19.37	19.27	22.21	21.92
SiO ₂	68.95	68.62	68.54	68.45	63.65	64.70
K ₂ O	0.03	0.05	0.04	1.03	0.08	0.06
CaO	0.08	0.10	0.19	0.70	3.41	2.74
TiO ₂	0.11	0.00	0.00	0.02	0.06	0.04
FeO	0.01	0.08	0.19	0.57	0.13	0.01
BaO	0.00	0.20	0.01	0.01	0.08	0.00
Sum	100.44	99.61	99.66	100.34	99.17	99.81
An	0.4	0.5	0.9	3.4	16.4	12.8
Ab	99.5	99.2	98.9	90.6	83.2	86.9
Or	0.2	0.3	0.2	6.0	0.4	0.3

(r) replacement of calcic plagioclase.

(v) vein.

(e) vesicle.

rich patch contains 2.2% FeO; this and their red-brown color strongly suggests that they are composed of iron oxide. This probably formed when Fe^{3+} , substituting for Al^{3+} , exsolved during albitization. The close spatial association of iron-rich epidote with albite suggests that calcite released may have precipitated in this form, although extra iron must also have been added from solution. A possible representation using as compositions analyzed phases is:



Where CO_2 is high, calcite would form instead of epidote.

Albitization is a common process in geothermal fields, although it has not previously been demonstrated in the Imperial Valley, most probably because of the difficulty of distinguishing between detrital and hydrothermal albite in sedimentary rocks.

Secondary albite also occurs as a 0.1 mm wide vein in chip 0023 where it cuts augite and chlorite (after calcic plagioclase, Table 5). This albite contains more potassium, calcium and iron than albite formed by replacement. Oligoclase was recognized in two samples; in chip 0004 it occurs as well terminated tabular crystals about 1 mm long and 0.1 mm wide filling a vesicle together with anhydrite, prehnite and chlorite. It is untwinned, has undulose extinction and, except near crystal faces, contains abundant small opaque inclusions of unknown composition. Electron microprobe analysis shows that both clear and inclusion rich parts of the crystals contain very little MgO , FeO or TiO_2 . Oligoclase also forms a 0.3 mm wide vein in an augite crystal (0005); it varies in composition from $\text{An}_{11.7}$ to $\text{An}_{15.0}$ (Fig. 4) but there is

TABLE 6. SELECTED ELECTRON MICROPROBE ANALYSES OF IRON AUGITE AND FERROAUGITE.

Sample	Chip 0004	0002	0002	0002	0002	0002	0002	0023	0023	0023	0023
Indicated Depth(m)	1341-1555	1341-1555	1341-1555	1341-1555	1341-1555	1341-1555	1341-1555	1341-1555	1341-1555	1341-1555	1341-1555
Analysis No.	45 ^b	22 ^c	23 ^c	221 ^c	254 ^d	253 ^d	255 ^d	229 ^e	234 ^e	232 ^e	231 ^e
Na ₂ O	0.52	0.44	0.50	0.48	0.35	0.35	0.37	0.61	0.72	1.03	3.51
MgO	9.71	12.11	11.14	11.06	9.93	9.69	9.57	9.62	7.03	6.11	3.86
Al ₂ O ₃	0.49	1.73	1.22	1.13	0.83	0.76	0.54	0.70	0.31	0.18	0.94
SiO ₂	50.15	51.27	51.46	51.08	50.82	50.80	50.96	51.26	49.34	49.26	49.85
CaO	16.45	18.12	18.01	17.04	17.72	16.03	13.85	18.82	16.11	16.24	11.45
TiO ₂	0.68	1.12	0.85	0.82	0.71	0.73	0.61	0.90	0.64	0.53	0.82
Cr ₂ O ₃	0.00	0.00	0.00	0.06	0.00	0.02	0.00	0.00	0.00	0.00	0.02
MnO	0.82	0.38	0.50	0.68	0.44	0.68	0.78	0.51	0.78	0.86	0.84
FeO ^a	21.47	14.49	16.49	17.81	18.60	22.31	23.64	18.51	24.49	25.66	28.60
Sum	100.29	99.67	100.18	100.16	99.39	101.36	100.33	100.93	99.42	99.86	99.88
En	28.5	36.2	33.1	32.8	29.8	28.4	28.8	28.4	21.4	18.69	13.5
Wo	34.7	38.9	38.5	36.4	38.2	33.8	29.9	40.0	35.3	35.73	28.8
Fs	36.8	24.9	28.4	30.8	32.0	37.8	41.3	31.6	43.3	45.58	57.7

(a) All Fe as FeO.

(b) Crystal coexists with Augite, Fs of 13.5.

(c) Same crystal; coexists with augite in Table 3.

(d) Same crystal.

(e) Same crystal.

no evidence, on a microscopic scale, that it is peristeritic. Hydrothermal oligoclase is rare in active geothermal fields. Possibly, as in chip 0005, it represents incomplete replacement of a more calcic primary plagioclase vein, but the low iron content suggests a hydrothermal origin. Textural relations in chip 0004 shows that oligoclase deposited early, possibly by an unusual autometasomatic process involving residual solutions left during late cooling; it is presently not possible to distinguish such an event from alteration produced by reaction with later geothermal fluids.

Iron augite and ferroaugite. Pale green clinopyroxene occurs in about 15% of the chips examined either as (a) small, irregular shaped crystals coexisting with augite (Table 6), or (b) chemically gradational rims mantling large augite crystals. The latter type is well shown by a pyroxene crystal in grain 0023 where from center to rim the composition changes from 13.6 to 57.8 mole % Fs (Fig. 5) and from 2.8 to 22.5 mole % acmite (Fig. 8). Of other oxides, TiO_2 shows an overall decrease and MnO an increase with increasing iron.

Although primary clinopyroxenes are known to vary widely in iron contents in several sills (e.g., Shiant Island, Gibb, 1973), it is suggested that some crystals of the Heber diabase have changed composition since its intrusion. Evidence for this is the coexistence of separate crystals of augite and ferroaugite in the same small chip and the marked iron and, to a lesser extent, sodium zoning of some crystals, in contrast with the homogeneity of others. Possibly the magma intruded with augite as a suspended solid phase and iron augite and ferroaugite when formed in situ perhaps in response to reaction with sediments similar to that suggested by Nakamura and Coombs (1973) for clinopyroxenes of the Tawhiroko sill at Moeraki, New Zealand. Alternatively, iron augite and ferroaugite may represent uncompleted exchange reactions

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TABLE 7. SELECTED ELECTRON MICROPROBE ANALYSES OF CHLORITE.

Sample Chip	0001	0001	0004	0006	0006	0014	0014	0016
Indicated Depth(m)	1341-1555	1341-1555	1341-1555	1341-1555	1341-1555	1401-1410	1401-1410	1364-1373
Analysis No.	12 ^{bc}	13 ^{bc}	38 ^c	64 ^{bcd}	66 ^{bce}	139 ^{bf}	142 ^{bc}	152 ^g
Na ₂ O	0.40	0.34	0.34	0.69	0.00	1.26	0.71	0.26
MgO	14.36	14.04	16.56	18.58	14.99	20.57	20.61	21.74
Al ₂ O ₃	15.19	13.71	12.61	10.34	13.00	10.64	12.64	11.75
SiO ₂	28.58	29.33	33.05	36.72	31.22	35.12	31.39	35.03
TiO ₂	0.01	0.00	0.02	0.00	0.04	0.05	0.02	0.01
CaO	0.42	0.58	0.89	1.03	1.41	0.61	0.69	1.36
Cr ₂ O ₃	0.01	0.01	0.06	0.00	0.01	0.01	0.02	0.00
MnO	0.17	0.18	0.17	0.00	0.29	0.16	0.14	0.01
FeO ^a	25.93	23.94	21.74	19.21	27.52	13.55	17.37	14.13
ZnO	0.09	0.00	0.21	0.00	0.00	0.12	0.00	0.00
F	0.15	0.03	0.00	0.15	0.00	0.00	0.08	0.02
Cl	0.07	0.12	0.10	0.01	0.00	0.05	0.01	0.04
Sum	85.30	82.24	85.71	86.34	88.38	82.08	83.63	84.43

(a) All Fe as FeO.

(b) Same crystal.

(c) Replaces olivine or orthopyroxene.

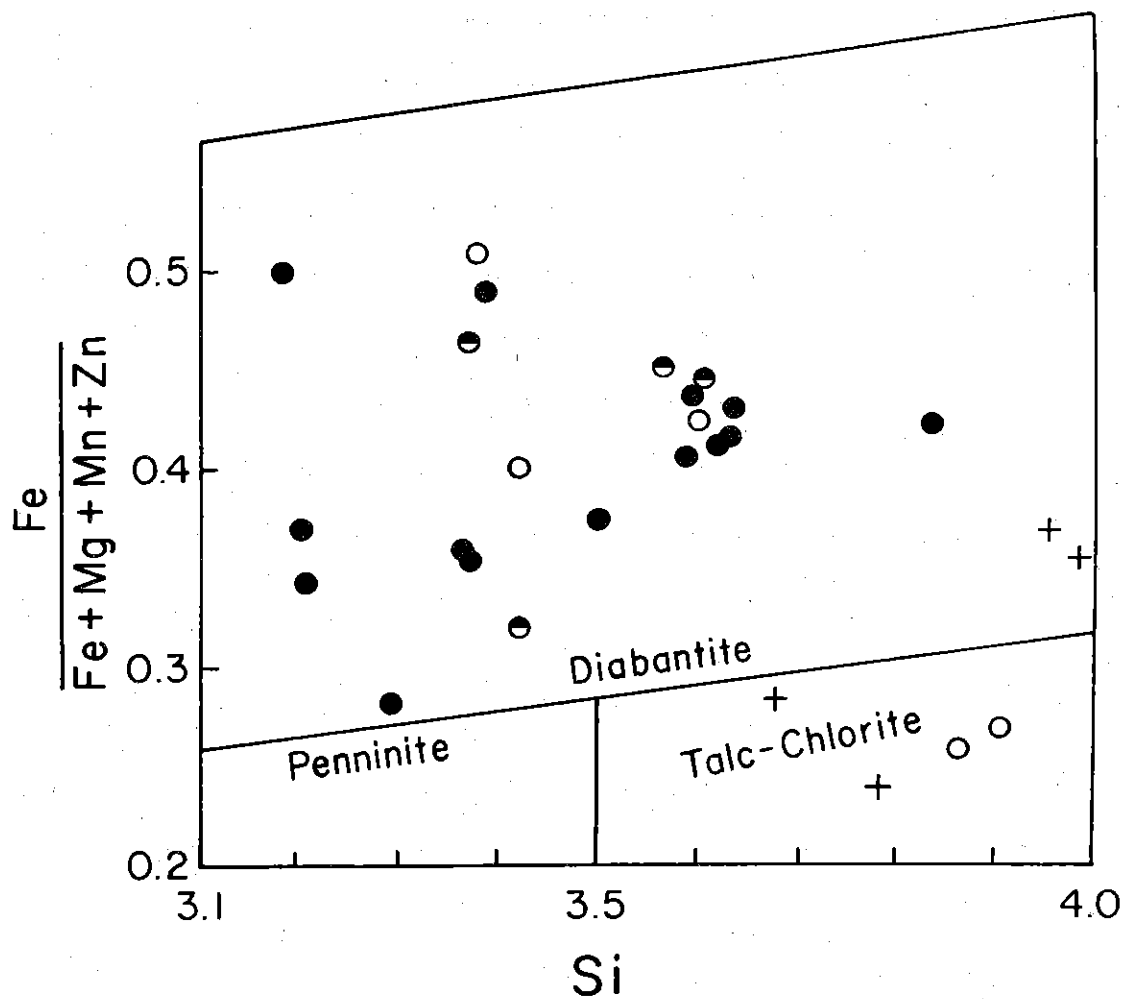
(d) Rim.

(e) Center.

(f) Replaces plagioclase.

(g) Booklet.

Figure 9. Plot of chlorite compositions.



- Replaces Plagioclase
- Replaces Pyroxene or Olivine
- + Replaces Prehnite
- Parent mineral uncertain

between primary augite and iron rich fluids (fluid discharged from a nearby well contained 56 mg/liter Fe) whereby iron and sodium were introduced into the pyroxene structure at the expense of magnesium and minor calcium.

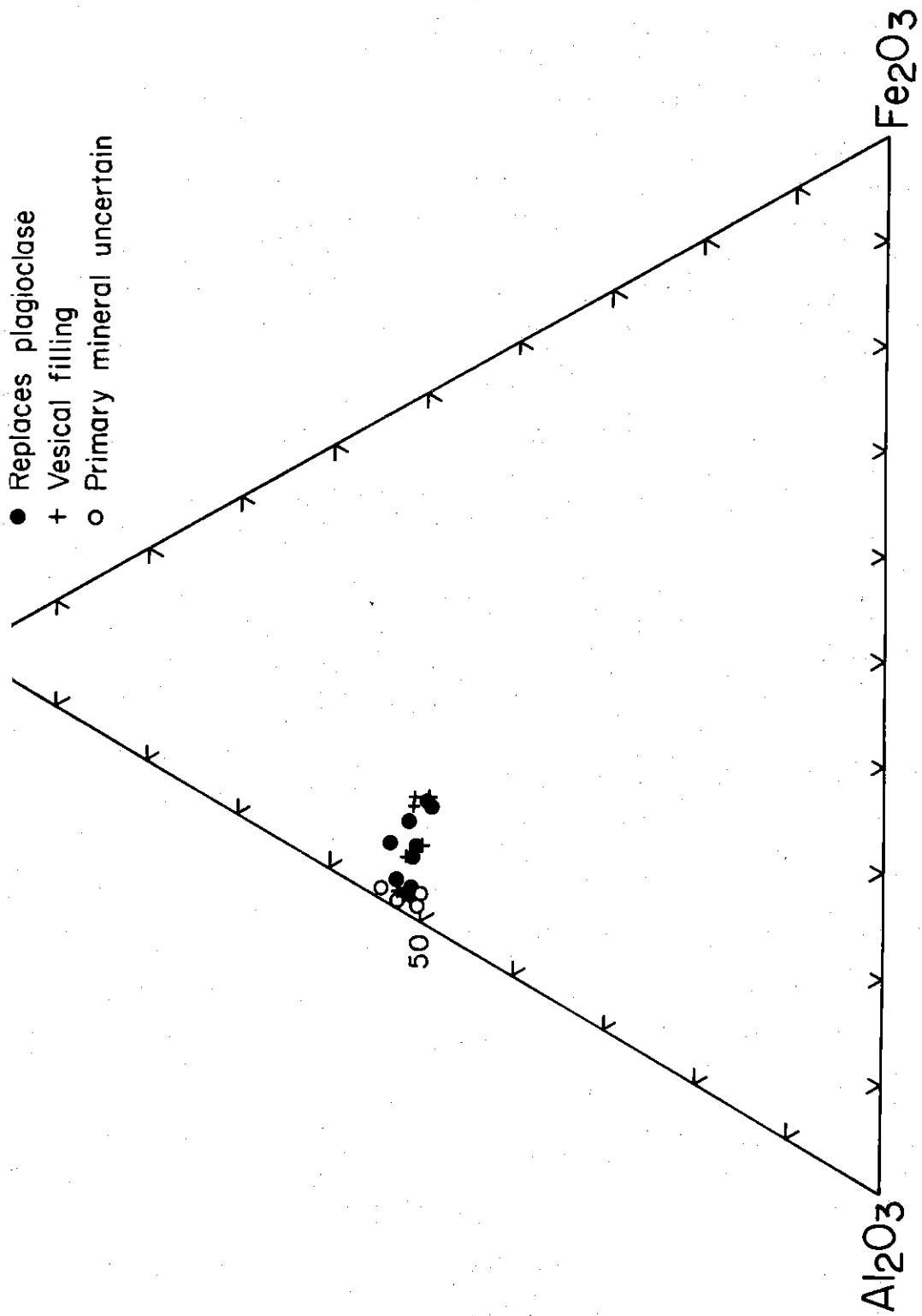
This type of alteration has not been previously reported from active geothermal fields although aegirine deposited from geothermal fluids was observed in cores from Y-1 well, Yellowstone (Honda and Muffler, 1970).

Chlorite. This is the most abundant and widespread hydrothermal mineral and the only phyllosilicate in the diabase; it is also common in the surrounding sediments (Fig. 3). Birefringent, well crystallized, green chlorite pseudomorphs orthopyroxene and olivine and, in many places, also forms small mosaic flakes partly or completely replacing labradorite; chlorite booklets have also been deposited directly from solution, often filling cavities together with prehnite. Replacement of primary plagioclase by chlorite occurs initially along crystal fractures but where alteration has progressed further, replacement is from the center outward. This reaction involves a drastic chemical change with loss of some SiO_2 , Al_2O_3 , most Na_2O and CaO and introduction of MgO , FeO and H_2O .

Most of the chlorites analyzed classify as diabantite (Deer, Howie and Zussman, 1962) but a few plot in the talc-chlorite field (Fig. 9). Their compositions (Table 7) cannot be closely related to the parent mineral, although chlorite pseudomorphing orthopyroxene/olivine contains more iron (17.4%), less sodium (0.7%) and has a lower $\text{SiO}_2/\text{Al}_2\text{O}_3$ ratio (2.5) than that replacing plagioclase in the same chip ($\text{FeO} = 13.1\%$; $\text{Na}_2\text{O} = 1.2\%$; $\text{SiO}_2/\text{Al}_2\text{O}_3 = 3.3$) (Table 7). Textures indicate that chlorite deposited over a long period compared with other hydrothermal minerals but again it is not possible to recognize any systematic composition changes with time. However, in

Figure 10. Triangular diagram plot of prehnite compositions.

compositions.



several chips, chlorite shows some chemical and optical zoning: for example, in grain 006 the margin of a composite grain contains 37% SiO_2 , and 19% FeO whereas the center has 32% SiO_2 and up to 27.5% FeO. Cause for such variation is uncertain but it may be due to fluctuations in the composition of the altering fluid (e.g., oxygen fugacity).

Prehnite. Prehnite is a common hydrothermal mineral in the diabase where it occurs as platy crystals (0.01 to 0.1 mm diameter) replacing primary plagioclase or partly filling vesicles sometimes as composite crystals with a fibrous appearance. Uncorroded crystal faces suggest it is a stable phase except in sample 0004 where it is partly replaced by chlorite. All non-essential elements except iron are of low abundance (Table 8, Fig. 10). Iron, which substitutes for alumina, varies in concentration from less than 0.1% to as much as 5.5 wt% FeO and there seems to be solid solution between $\text{Ca}_2 \text{Al}_2 \text{Si}_3 \text{O}_{10} (\text{OH})_2$ and about $\text{Ca}_2 (\text{Fe}_{0.3} \text{Al}_{1.7}) \text{Si}_3 \text{O}_{10} (\text{OH})_2$. Iron contents are not apparently related to the parent mineral (Fig. 10) and may reflect fluctuations in oxygen fugacity.

Prehnite is a common secondary mineral in altered diabbases and low grade metamorphic rocks but, although known at Wairakei (Coombs et al., 1959) and Pauzetstk (Rusinov, 1965), is not very common in active geothermal fields. Iron-rich prehnite replaces plagioclase and occurs as amygdaloidal minerals with wairakite in low grade metavolcanic rocks of the Karmatsen Group from Vancouver Island (Surdam, 1969). Experimental work (e.g., Liou, 1971a) indicates that prehnite should not be stable at the low pressures measured in geothermal fields but, as Liou suggests elsewhere (1971b), Fe^{3+} may stabilize its structure, thus extending its stability field. It seems probable that in the Heber reservoir, prehnite deposition was favored by the occurrence of fluids with high calcium and low CO_2 contents.

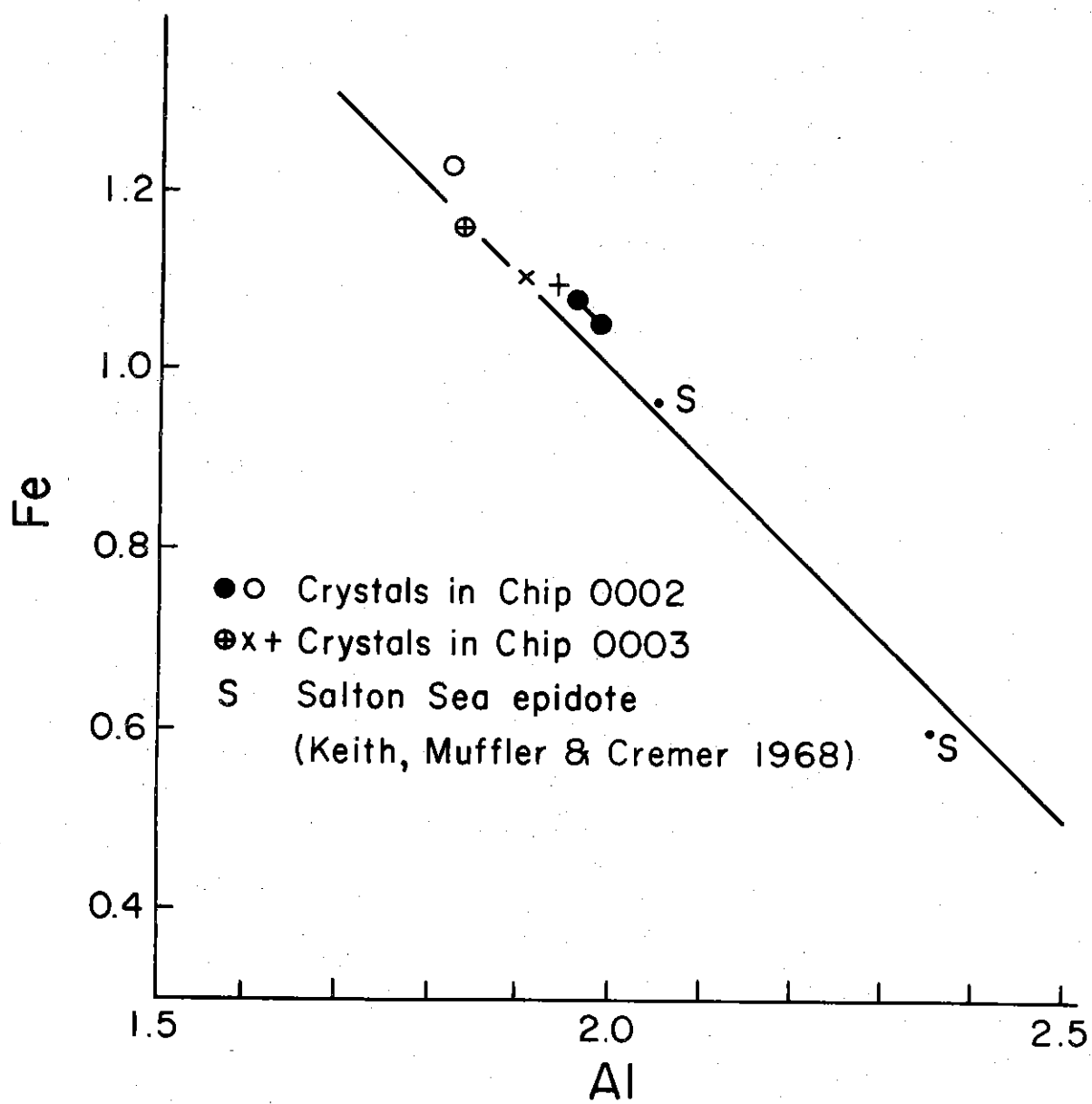
TABLE 8. SELECTED ELECTRON MICROPROBE ANALYSES OF WAIRAKITE (WK), PREHNITE (PR) AND EPIDOTE (EP).

Sample Chip	0001	0016	0017	0007	0024	0002	0002	0003
Indicated Depth(m)	1341-1555	1364-1373	1364-1373	1341-1555	1341-1555	1341-1555	1341-1555	1341-1555
Analysis No.	11, WK	148, PR	167, PR	78, PR	247, PR	16, EP ^b	24, EP ^b	34
Na ₂ O	0.18	0.07	-	-	-	-	-	-
MgO	0.00	0.00	0.01	0.02	0.01	0.01	0.01	0.03
Al ₂ O ₃	23.33	23.87	21.43	21.05	20.01	20.41	19.10	19.00
SiO ₂	55.12	43.37	43.03	42.86	43.44	37.09	37.55	36.56
K ₂ O	0.03	0.03	-	-	-	-	-	-
CaO	11.72	28.67	28.17	27.19	25.71	22.44	22.51	22.58
TiO ₂	0.00	0.01	0.04	0.12	0.04	0.02	0.19	0.19
MnO	0.00	0.03	0.02	0.03	0.07	0.06	0.05	0.10
FeO ^(a)	0.02	0.25	2.54	3.94	5.33	15.86	18.10	16.86
Ce ₂ O ₃	-	0.11	0.00	0.12	0.00	0.03	0.00	0.04
F	0.04	0.03	0.03	0.01	0.00	0.01	0.02	0.15
Cl	0.00	0.01	-	-	-	-	-	-
Sum	90.40	96.44	95.24	95.32	94.73	95.92	97.52	95.45

(a) All Fe as FeO.

(b) Different crystals.

Figure 11. Plot of Total Fe as Fe^{3+} against Al in epidote.



Wairakite. Wairakite has been recognized in one chip where it forms several irregular weakly anisotropic, optically continuous grains of up to 0.2 mm diameter; diagnostic cross hatch twinning is poorly developed. It is near the calcium end member in composition, with all nonessential element oxides totaling only about 0.25% (Table 8).

Wairakite is a common zeolite mineral in geothermal fields of New Zealand, Indonesia and Japan and has also been ejected from a well at the Geysers (Steiner, 1958). It has not been previously identified in geothermal systems of the Imperial Valley but occurs in altered sediments from Cerro Prieto, Mexico (Reed, 1976). Extrapolation of Liou's (1970) experimental work and observations in thermal areas suggests that wairakite is stable between about 200 and 300°C but only where CO₂ concentrations are low (Browne and Ellis, 1970).

Epidote. Epidote comprises about 2 vol % of 2 chips where it occurs as small (150 µm long), euhedral crystals deposited into vesicles. Crystals are extremely iron rich (Fig. 11; Table 8); chemical but not optical zoning is typical. Epidote occurs in several geothermal fields (White and Sigvaldason, 1963; Sekt, 1972) including the Salton Sea (Keith et al., 1968; Kendall, 1976) where it is iron rich, but occasionally shows both optical and pronounced chemical zoning (McCurry and McDowell, pers. comm.). Fluctuations in oxygen fugacity of the thermal fluid are thought to be reflected in the iron-content of depositing epidotes (Keith et al., 1968); this could also occur in the diabase at Heber as magnetite is unstable, pyrite is rare and it is unlikely that phases such as chlorite or pyroxene could form an effective solid solution mineral buffer to maintain a constant oxygen fugacity.

Calcite. This is the only carbonate mineral recognized in the diabase. It forms up to 10% of individual cutting chips where it occurs as a late stage replacement and vein mineral. Crystals are clear to white and platy or anhedral; fluid inclusions are abundant in samples from below 500 m. Calcite is near pure CaCO_3 in composition as MgCO_3 , FeCO_3 and BaCO_3 contents are all less than 0.5%; however, MnCO_3 reaches 0.5 and 0.9 wt % in two of the five samples analyzed.

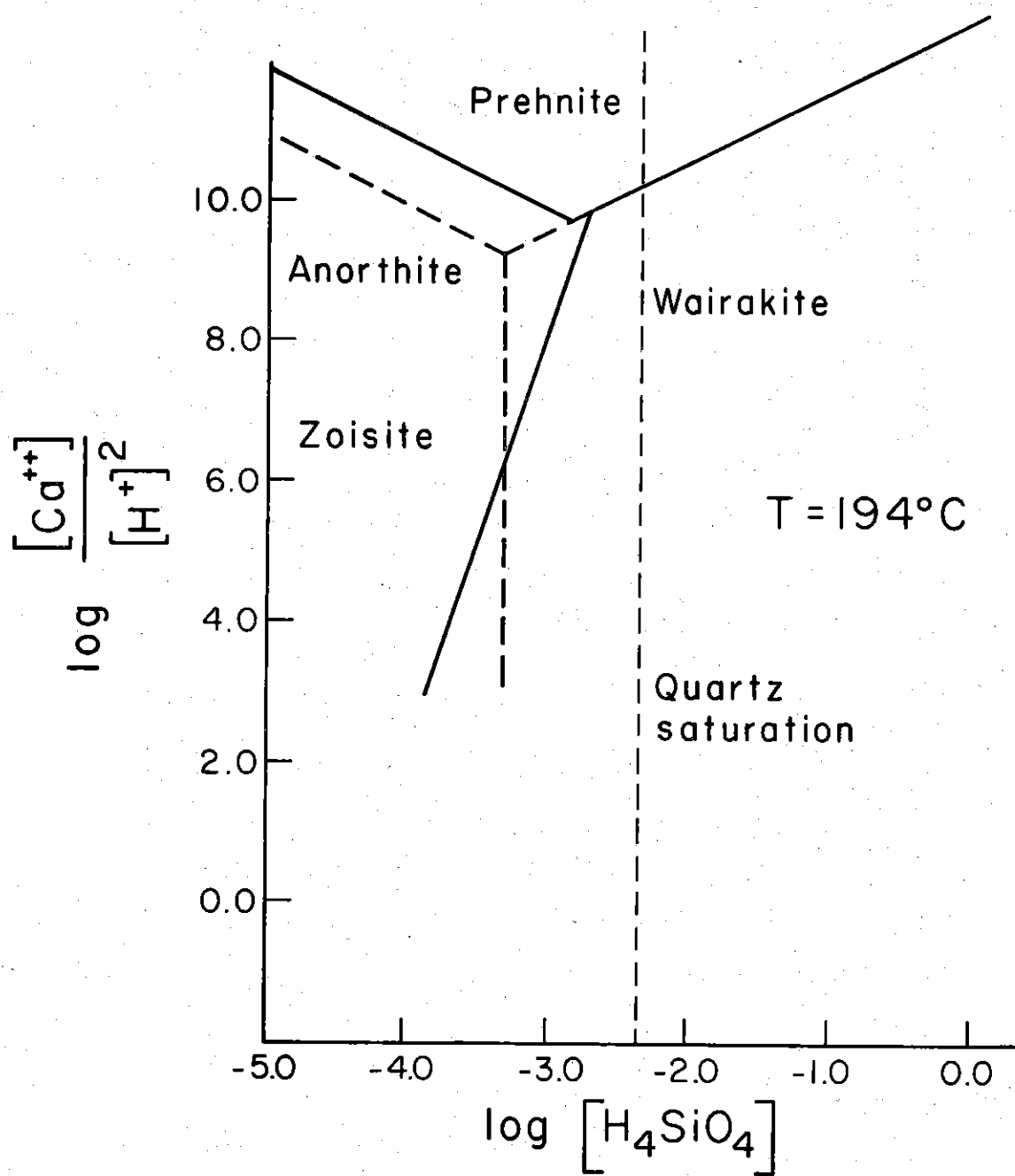
Calcite is a common and widespread hydrothermal mineral in geothermal fields. It often deposits in response to boiling or heating of a thermal fluid but at Heber the high calcium content of the thermal fluid means that slight increases in dissolved CO_2 will cause CaCO_3 to precipitate.

Other Minerals. Sphene occurs as small (20 μm), anhedral grains formed as an alteration product of titanomagnetite and ilmenite; minor leucosene may also be a product of this reaction but pyrite is rare. Occasional needles of a fibrous mineral, which is too small to analyze or identify optically, occurs in three cutting samples with prehnite and calcite--an association which suggests it may be pectolite, $\text{Na Ca}_2\text{Si}_3\text{O}_8(\text{OH})$. Anhydrite occurs in a vesicle in one sample (0004) where it is partly replaced by chlorite.

Relationship between Alteration and Fluid Composition

Alteration of the diabase is characterized by abundant calcium and iron-bearing hydrothermal minerals. The composition of the Holtz Well No. 1 fluid is proprietary information but an analysis (of unknown quality and unspecified sampling conditions) of fluid discharged from a nearby (1.5 km) well, Nowlin No. 1, was made available to us (Chevron Oil Co., unpublished information). This contains 14,000 to 14,500 mg/liter total dissolved solids with much iron (38-68 mg/liter). James Hoagland (pers. comm.) has calculated,

Figure 12. Mineral stability diagram showing calculated relationships of anorthite, zoisite, wairakite and prehnite at 194°C; thermodynamic data from Naimov et al. (1974), Helgeson (1969), Zen (1972) and Latimer (1952).



using the ENTHALP computer program (Truesdell and Singers, 1974), that before flashing the deep water contained 56 mg/kg iron and 693 mg/kg of calcium. However, this assumes that the fluid enthalpy is that of a vapor saturated with pure H_2O at the aquifer temperature, and that the fluid was sampled after flashing at atmospheric pressure. It seems a reasonable assumption that the hydrothermal fluid which reacted with the diabase contained high concentrations of calcium and iron and was not greatly different from that now discharged from the Nowlin No. 1 well. A mineral stability diagram (Fig. 12) kindly calculated by James Hoagland shows the relationships between prehnite, wairakite, epidote (zoisite) and calcic plagioclase (anorthite) for $194^\circ C$ (the temperature indicated by the SiO_2 content of fluid from Nowlin No. 1). The mineralogy of the cutting samples suggest that the fluid which produced the alteration plots within the prehnite field but close to the wairakite-prehnite boundary. Assuming the deep fluid contained 693 mg/liter Ca, this means that at $194^\circ C$ the deep fluid has a pH of about 6.4.

Because calcium concentrations are so high it follows that dissolved CO_2 in the deep fluid must be extremely low for calcite not to dominate alteration of the diabase at the expense of wairakite, prehnite and epidote: using the ENTHALP program James Hoagland calculated that the CO_2 concentration must be less than 0.01 millimoles/100 moles H_2O .

Changes in the Reservoir

Neither the age of the diabase nor the duration of thermal activity are known; it is also unclear whether the diabase intruded an already active geothermal field. However, alteration of both sediments and diabase indicate changes in temperature, permeability and fluid composition have occurred during the life of the system.

OLIGOCLASE

PREHNITE

ANHYDRITE

WAIKAKITE

? _____ ?

?PECTOLITE

CALCITE

CHLORITE

TIME

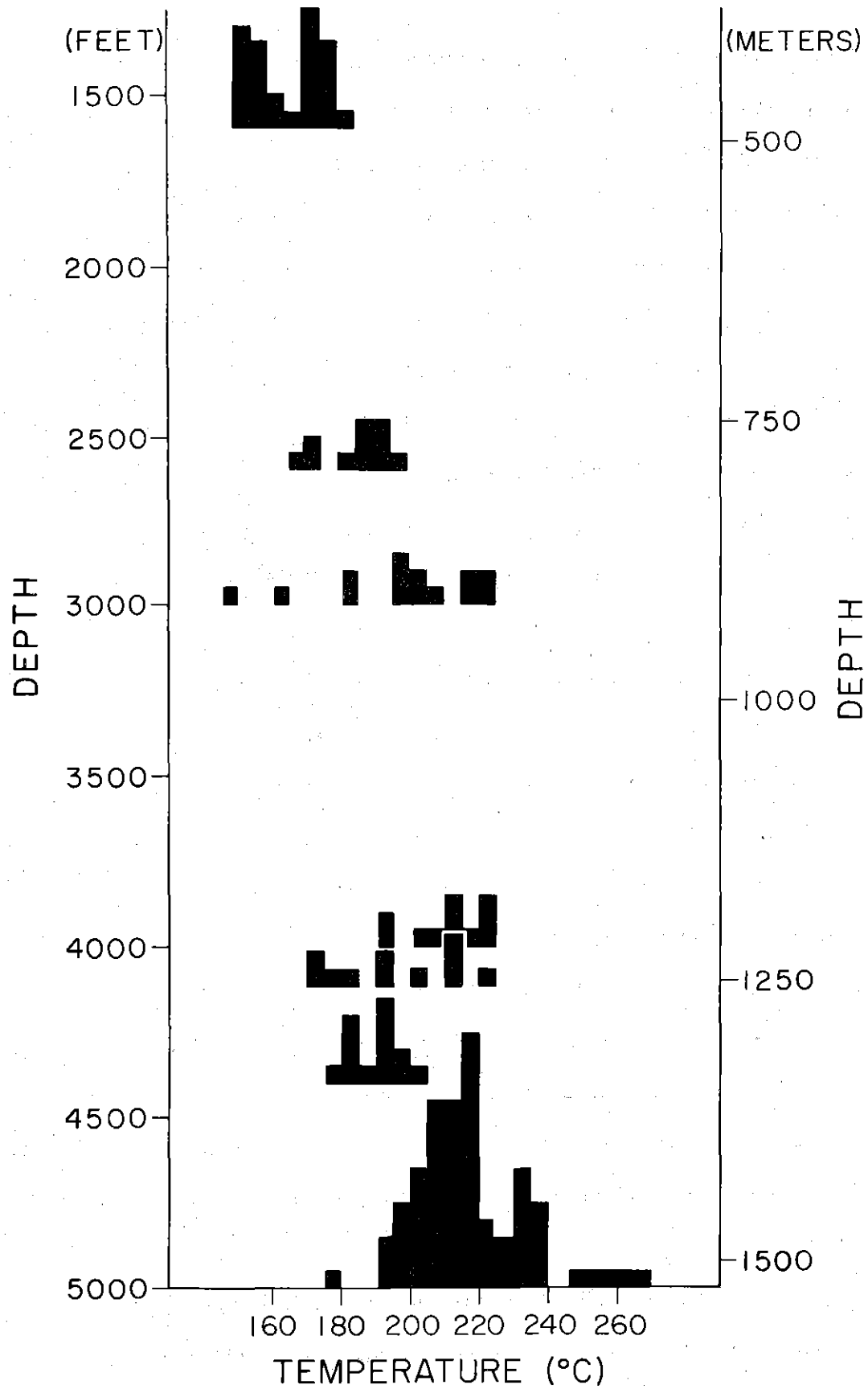
Figure 13. Possible paragenetic sequence of hydrothermal minerals based on mineral textures. The position of epidote, albite, sphene and pyrite is not known.

Textures provide evidence of qualitative changes and these are summarized in Figure 13. For example, within the diabase, calcite replacing wairakite or deposited after (?) pectolite and prehnite probably means there was an increase in the amount of CO_2 dissolved in the thermal fluid of a change in temperature. Elsewhere, chlorite replacement of prehnite implies a marked change in the concentrations of at least Ca, Mg and Fe in the fluid. Alteration of the sediments whereby quartz overgrowths on detrital quartz as well as the host have been partly replaced by chlorite and calcite implies a change in fluid composition, possibly in conjunction with a local temperature increase; in a sample from 1400-1410 m, hydrothermal calcite replaces hydrothermal chlorite. Hoagland (1976) also concludes that there has been a change in fluid composition during the life of the East Mesa geothermal system.

More quantitative information about past temperatures and fluid salinities can often be deduced from the study of fluid inclusions formed in hydrothermal minerals (e.g., Browne, Roedder and Wodzicki, 1976). Homogenization temperatures (Fig. 14) were measured on fluid inclusions in calcite chips from between 500 and 1524 m depth in Holtz No. 1 well, using a combined heating-freezing stage. Vertical temperature gradients within the stage were kept below 2°C during heating and the instrument was calibrated by measuring the melting point of metal standards. No pressure corrections were necessary (Browne, Roedder and Wodzicki, 1976) and the temperatures are believed accurate to 2 or 3°C ; duplicate measurements showed good agreement.

The fluid inclusions are of two phases and daughter minerals are absent; no vapor rich types were seen, indicating that boiling did not occur during crystal formation. Oxygen isotope δ values measured for prehnite (-2.0), chlorite (-2.4) and calcite (-0.6) with respect to SMOW indicated isotopic

Figure 14. Fluid inclusion homogenization temperatures for calcite against depth; each square represents one measurement.



equilibrium occurred at temperatures close to the fluid inclusion filling temperatures (Olson, 1976). Inclusions in crystals from the same depth homogenize over a range of temperatures (Fig. 14), indicating fluctuations in deposition temperatures of 20 to 30°C. For most depths, filling temperatures have at least a bimodal distribution, making it tempting to join their modes and plot the resultant curves as 'fossil geothermal profiles'.

Unfortunately, the irregular shape of most calcite chips makes it difficult to determine the directions of crystal growth. It is thus unclear if there is a relationship between the temperature of homogenization and the relative age of the inclusion, i.e., it is not possible to decide if the reservoir is heating up or cooling down based on fluid inclusion evidence alone. It is clear, however, that temperatures have changed. Present downhole temperatures are still confidential at the time of writing but if the silica geothermometer temperature for Nowlin No. 1 well of 194°C is characteristic of the reservoir, then it seems likely that the field is cooling. Six inclusions from 1524 m have homogenization temperatures (245-270°C) well above others at this depth, possibly because some leakage has occurred. However, calcite from an indicated depth of 1335 m (i.e., near the diabase, 1335-1366 m) has fluid inclusions with filling temperatures 20 to 30°C below the mean temperatures measured in samples from above (1260 m) and below (1524 m). Reasons for this apparent temperature reversal may be: (1) temperatures were lower at this depth due to inflow of colder water, possibly channeled via the diabase; (2) crystals have sloughed off the side of the well and come from a shallower depth.

In summary, the fluid inclusion temperature measurements indicate that, at least locally, the Heber reservoir has been cooling at an undetermined

rate, from a maximum of about 240°C , but that there were at least two significantly larger pulses of thermal fluid; at 1524 m, for example, these occurred at 212 ± 9 and $235\pm 5^{\circ}\text{C}$.

REFERENCES

- Barberi, F., H. Bizourd and J. Varet (1971): Nature of clinopyroxene and iron enrichment in alkali and transitional basaltic magmas. *Contributions to Mineralogy and Petrology*, 33, 93-107.
- Biehler, S. (1971): Gravity studies in the Imperial Valley, in Cooperative geological-geophysical-geochemical investigations of geothermal resources in the Imperial Valley area of California: Final Report (FY 1971), Contribution No. 14-06-300-2194, United States Bureau of Reclamation, 21-42.
- Biehler, S., R. L. Kovach and C. R. Allen (1964): Geophysical framework of northern end of Gulf of California structural province, in van Andel, T. H. and G. C. Shor, Jr., eds. Marine geology of the Gulf of California (a symposium). *American Association Petroleum Geologists Memoir* 3, 126-143.
- Bird, D. K. (1975): Geology and geochemistry of the Dunes hydrothermal system, Imperial Valley of California. M.S. Thesis, University of California at Riverside, Institute of Geophysics and Planetary Physics report no. 75-2, 123 p.
- Bird, D. K. and W. A. Elders (1976): Hydrothermal alteration and mass transfer in the discharge portion of the Dunes Geothermal System, Imperial Valley of California, U.S.A. *Proceedings, Second United Nations Symposium on the Development and Use of Geothermal Resources*, San Francisco, May 1975, Vol. 1, 285-295.
- Browne, P. R. L. and A. J. Ellis (1970): The Ohaki-Broadlands hydrothermal area, New Zealand: mineralogy and related geochemistry. *American Journal of Science*, 264, 97-131.

- Browne, P. R. L., E. Roedder and A. Wodzicki (1976): Comparison of past and present geothermal waters from a study of fluid inclusions, Broadlands Field, New Zealand. Proceedings International Symposium on Water-Rock Interaction, Prague 1974, Geological Survey, Czechoslovakia, 140-149.
- Buddington, A. F. and D. H. Lindsley (1964): Iron-Titanium oxide minerals and synthetic equivalents, *Journal of Petrology*, 5, 310-357.
- Coombs, D. S., A. J. Ellis, W. S. Fyfe and A. M. Taylor (1959): The zeolite facies with comments on the interpretation of hydrothermal synthesis. *Geochimica Cosmochimica Acta*, 17, 53-107.
- Coplen, T. B. (1976): Cooperative geochemical resource assessment of the Mesa geothermal system. Final report to the USDI, Bureau of Reclamation Contract No. 14-06-300-2479. Institute of Geophysics and Planetary Physics Report No. 76-1, University of California, Riverside, 97 p.
- Deer, W. A., R. A. Howie and J. Zussman (1964): Rock-forming minerals, Longmans, London, Vol. 3.
- Elders, W. A. (1975): Regional geology of the Salton Trough in T. D. Palmer, J. H. Howard and D. P. Lande (eds.): Geothermal Development of the Salton Trough, California and Mexico. Lawrence Livermore Laboratory report UCRL-51775, 1-12 and 41-43.
- Elders, W. A. and S. Biehler (1975): Gulf of California Rift System and its implications for the tectonics of western North America. *Geology*, 3, no. 2, 85-87.
- Elders, W. A. and D. K. Bird (1976): Active formation of silicified cap rocks in arenaceous sands in a low-temperature, near-surface geothermal environment, in the Salton Trough of California, U.S.A. Proceedings International Symposium on Water-rock Interaction, Prague 1974, Geological Survey, Czechoslovakia, 150-157.

- Elders, W. A., Robert Rex, Tsvi Meidav, P. T. Robinson and Shawn Biehler
(1972): Crustal spreading in southern California. *Science* 178, 15-24.
- Gibb, F. G. (1973): The zoned clinopyroxenes of the Shiant Isles Sill,
Scotland, *Journal of Petrology*, 14, 203-230.
- Griscom, A. and L. J. P. Muffler (1971): Aeromagnetic map and interpretation
of the Salton Sea geothermal area, California. United States Survey
Geophys. Inv. Map GP-754.
- Helgeson, H. C. (1969): Thermodynamics of hydrothermal systems at elevated
temperatures and pressures. *American Journal of Science*, 267, 729-804.
- Hoagland, J. R. (1976): Petrology and geochemistry of hydrothermal alteration
in borehole Mesa 6-2, East Mesa geothermal area, Imperial Valley,
California. University of California, Riverside, Institute of Geophysics
and Planetary Physics Report No. 76-12, 90 p.
- Honda, S. and L. J. P. Muffler (1970): Hydrothermal alteration in core from
research drill hole Y-1, Upper Geyser Basin, Yellowstone National Park,
Wyoming. *American Mineralogist*, 55, 1714-1737.
- Jaeger, J. C. (1957): The temperature in the neighborhood of an intrusive
sheet. *American Journal of Science*, 255, 306-318.
- Keith, T. E. C., L. J. Patrick Muffler and Marcelyn Cremer (1963): Hydro-
thermal epidote formed in the Salton Sea geothermal system, California.
American Mineralogist, 53, 1635-1644.
- Kendall, Carol (1976): Petrology and Stable Isotope Geochemistry of three
wells in the Buttes area of the Salton Sea geothermal field, Imperial
Valley, California, U.S.A. University of California, Institute of
Geophysics and Planetary Physics, Report No. 76-17, 211 p.

- Kuno, H. (1968): Origin of andesite and its bearing on the island arc structure. *Bulletin Volcanologique*, 32, 141-176.
- Latimer, W. M. (1952): The oxidation states of elements and their potentials in aqueous solutions. Prentice-Hall Inc., Englewood Cliffs, N. J., 392 p.
- LeBas, M. J. (1962): The role of aluminum in clinopyroxene with relation to their parentage. *American Journal of Science*, 260, 267-288.
- Liou, J. G. (1970): Synthesis and stability relations of wairakite, $\text{CaAl}_2\text{Si}_4\text{O}_{12} \cdot 2\text{H}_2\text{O}$. *Contributions to Mineralogy and Petrology*, 27, 259-282.
- Liou, J. G. (1971a): P-T stabilities of laumontite, wairakite, lawsonite, and related minerals in the system $\text{CaAl}_2\text{Si}_2\text{O}_8\text{-SiO}_2\text{-H}_2\text{O}$. *Journal of Petrology*, 12, 379-411.
- Liou, J. G. (1971b): Synthesis and stability relations of prehnite, $\text{Ca}_2\text{Al}_2\text{Si}_3\text{O}_{10}(\text{OH})_2$. *American Mineralogist*, 56, 507-531.
- Merriam, R. and O. L. Bandy (1965): Source of Upper Cenozoic sediments in the Colorado River Delta region. *Journal of Sedimentary Petrology*, 35, 911-916.
- Moore, J. G. and J. G. Schilling (1973): Vesicles, water and sulfur in Reyhjanas Ridge basalts. *Contributions to Mineralogy and Petrology*, 41, 105-118.
- Muffler, L. J. P. and B. R. Doe (1968): Composition and mean age of detritus of the Colorado River Delta in the Salton Trough, Southeastern California. *Geological Society of America Bulletin*, 80, 157-182.
- Muffler, L. J. P. and D. E. White (1969): Active metamorphism of Upper Cenozoic Sediments in the Salton Sea Geothermal Field and the Salton Trough, Southeastern California. *Bulletin Geological Society of America*, 80, 157-182.

- Naimov, G. B., B. N. Ryzhenko and L. L. Khodakovsky (1974): Handbook of thermodynamic data. NTIS Report PB 226 722, 328 p.
- Nakamura, Y. and D. S. Coombs (1973): Clinopyroxenes in the Tawhiroko tholeiitic dolerite at Moeraki, North-eastern Otago, New Zealand. Contributions to Mineralogy and Petrology, 42, 213-228.
- Norton, D. and J. Knight (in press): Transport phenomenon in hydrothermal systems of cooling plutons. American Journal of Science.
- Olson, E. R. (1976): Oxygen isotope study of diabase, Heber geothermal field, Imperial Valley, California. Geological Society of America Abstracts with Programs, 8, No. 6, 1036.
- Reed, M. (1976): Geology and hydrothermal metamorphism in the Cerro Prieto geothermal field, Mexico. 2nd United Nations Symposium on the Development and Use of Geothermal Resources, San Francisco, 539-548.
- Robinson, P. T., W. A. Elders and L. J. P. Muffler (1976): Quaternary volcanism in the Salton Sea geothermal field, Imperial Valley, California. Geological Society of America Bulletin, 87, 347-360.
- Rusinov, V. L. (1965): On prehnite fields and the clastic nature of epidote in rocks of some areas of contemporary hydrothermal metamorphism. Izvestia Akademy Naub, U.S.S.R., Geological Series, 2, 33-43.
- Seki, Y. (1972): Lower grade stability limit of epidote in the light of national occurrences. Journal of the Geological Society of Japan, 78, 405-413.
- Steiner, A. (1958): Occurrence of wairakite at the Geysers, California. American Mineralogist, 43, 781.
- Steiner, A. (1968): Clay minerals in hydrothermally altered rocks at Wairakei, New Zealand. Clays and Clay Minerals, 16, 193-213.

- Surdam, R. C. (1969): Electron microprobe study of prehnite and pumpellyite from the Karmutsen Group, Vancouver Island, British Columbia. *American Mineralogist*, 54, 256-266.
- Truesdell, A. H. and W. Singers (1974): The calculation of aquifer chemistry in hot water geothermal systems. *Journal Research of United States Geological Survey*, 2, 271-278.
- U.S.D.I., Bureau of Reclamation (1974): Geothermal resource investigations, East Mesa Test Site, Imperial Valley, California. Status Report, 64 p.
- White, D. E. and G. E. Sigvaldason (1963): Epidote in hot spring systems, and depth of formation of propylitic epidote in epithermal ore deposits. *United States Geological Survey Professional Paper* 450-E, 80-84.
- Zen, E. (1972): Gibbs free energy, enthalpy, and entropy of ten rock forming minerals: calculations, discrepancies, implications. *American Mineralogist*, 57, 524-533.