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GEOPHYSICAL, GEOCHEMICAL, AND GEOLOGICAL INVESTIGATIONS
OF THE DUNES GEOTHERMAL SYSTEM,
IMPERIAL VALLEY, CALIFORNIA*

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The Dunes anomaly is a water-dominated geothermal system in the alluvium of the Salton Trough, lacking any surface expression. It was discovered by shallow-temperature gradient measurements. A 612-meter-deep test well, drilled by the California Division of Water Resources, encountered several temperature-gradient reversals, with a maximum of 105°C at 114 meters.

Our program involves surface geophysics, including electrical, gravity, and seismic methods, down-hole geophysics and petrophysics of core samples, isotopic and chemical studies of water samples, and petrological and geochemical studies of the cores and cuttings. We aim (a) to determine the source and temperature history of the brines, (b) to understand the interaction between the brines and rocks, and hence (c) to determine the areal extent, nature, origin, and history of the geothermal system.

The source of the fluid is partially evaporated Colorado River water, which equilibrated with the rocks at temperatures ranging from 100 to 170°C. The existence of seven zones of dense, impermeable, grey quartzite in the upper 300 meters indicates that subsurface flow is largely horizontal, that rock-water interactions are essentially self-sealing, and that incursions of hot brine into the system are episodic.

These studies are designed to provide better definition of exploration targets for hidden geothermal anomalies and to contribute to improved techniques of exploration and resource assessment.

The presentation which follows is in three parts. Part A reviews some of the geochemical studies by Coplen and Kolesar; Part B by Elders and Bird is concerned with the geology of the silicified cap rocks. Part C by Combs, dealing with geophysical investigations, was not supplied.

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PART A: GEOCHEMISTRY

T. B. Coplen and P. Kolesar

A geothermal test corehole, DWR Dunes No. 1, was drilled in the Dunes geothermal anomaly by the State of California Department of Water Resources. Water samples from this geothermal system were collected from perforations at 109- and 260-meter depths. These water samples were analyzed for chemical and isotopic composition. A total dissolved solids of 4000 ppm was measured on samples from both depths, and this relatively low value may be a consequence of the low temperatures (100°C) measured in this well. Samples from both depths were nearly identical in chemical and in oxygen and hydrogen isotopic composition, suggesting that the water from the two perforated intervals is derived from the same source.

Oxygen and hydrogen isotope studies of water samples indicate that the source of the geothermal fluid is partially evaporated Colorado River water. The percentage of local rainfall in the geothermal fluid is below detection. The geothermal fluid is probably derived from a source deeper than 400 meters because aquifers shallower than this in this region usually have a significant local rainfall component.

An investigation of chloride/bromide ratios was used to determine the source of the salt in the geothermal fluid from Dunes. The ratio Cl/Br in DWR Dunes No. 1, in the Salton Sea geothermal system, and in Colorado River water is identical at 1600. This result may suggest that the salt in the Salton Sea geothermal system and in the Dunes geothermal anomaly is derived from the Colorado River and that this water has not done any leaching or been mixed with water from other sources.

Several chemical thermometers were applied to the water samples from DWR Dunes No. 1. The silica geothermometer, sodium-potassium-calcium geothermometer, and the calcite-water oxygen isotope geothermometer yielded temperatures of 138, 170, and 117°C, respectively, for DWR Dunes No. 1. These are all greater than the 100°C temperature measured during a pumping test and during geophysical temperature surveys. These results suggest that the geothermal reservoir may be considerably hotter than that measured by this technique.

Clearly, further geophysical studies, such as gravity, seismic refraction, electrical resistivity, and magnetotelluric sounding studies, are needed to locate the reservoir of geothermal fluid in the Dunes system, and these are now in progress. If a reservoir of sufficient size can be located, further drilling at the Dunes geothermal anomaly may be justified.

I. INTRODUCTION

The demand for new energy in the United States has been rising at an annual rate of 7 to 10 percent. If this rate continues, it will approximately double by 1983. The demand has been increasing faster than supply, and reserves are taxed during periods of heavy demand as illustrated by recent power brown-outs in large portions of the United States. This situation has become critical. However, the immediate development of new energy sources should help ensure adequate energy supplies for the future growth of our nation.

One of our resources which is virtually undeveloped and can help alleviate both water and energy shortages is geothermal resources. There are several incentives to develop this resource, for instance, low pollution levels compared to alternative energy sources and the relatively low capital installation costs.

As part of a continuing investigation of geothermal resources, the University of California, Riverside (UCR) is investigating several geothermal anomalies in the Imperial Valley of California. One of the anomalies, the Dunes anomaly (shown in Fig. A-1) was discovered by R. W. Rex, utilizing temperature gradient measurements. Further geophysical investigation of this anomaly indicated a correlation between a positive gravity anomaly and high geothermal gradients in shallow boreholes (Ref. A-1). A temperature of 112°C was observed at a depth of 114 meters in borehole USBR-UCR No. 115. These data and the recovery of silicified sandstone suggested the existence of an intensely silicified nearly impermeable cap which confined the underlying geothermal fluids. It was proposed that hot water from a geothermal environment at depth is precipitating dissolved silica in the upper zone of lower temperature, forming a self-sealing geothermal reservoir. These data and the consequent hypothesis suggested that the Dunes anomaly is a prime target for additional concentrated study. Thus, the California Department of Water Resources (DWR) in cooperation with UCR, drilled a 612-meter-deep test well at the Dunes anomaly, DWR Dunes No. 1. Figure A-2 shows the temperature gradient, electric log, core recovery, and casing perforation program.

In order to maximize the scientific yield of this program, UCR proposed to, and was funded by, the RANN Division of the National Science Foundation a geological, geochemical, and geophysical investigation of the Dunes hot water anomaly. Core studies include the measurement of density, sonic velocity, thermal conductivity, electrical resistivity, permeability, porosity, magnetic susceptibility, mineralogical composition, chemical composition, and isotopic composition. Optical microscope, electron microscope, and scanning electron microscope studies have been conducted to study cementation, metamorphism, and the response of sedimentary minerals and ground waters to a geothermal

environment (Ref. A-2). Various geochemical thermometers are being applied to this system where in situ temperatures can be measured directly. Water sample investigations include various chemical and isotopic studies. Areal geophysical investigations, which include seismic refraction, electrical resistivity, and gravity, are being conducted to delineate the subsurface geometry of the silicified zone and to determine the extent of the geothermal system.

The aims of the proposed work included:

- (1) Improving our understanding of how to explore for and characterize potential geothermal systems in sedimentary environments by integrating a broad geochemical, geophysical, and geological study on a single hot water geothermal anomaly.
- (2) Establishing the existence of a shallow low-salinity hot water field that could be developed for power and water desalination.
- (3) Demonstrating that a circulating geothermal hot water system in alluvium can create its own seal and build up higher shallow temperatures than would otherwise be expected.
- (4) Establishing criteria for recognizing potential geothermal areas from rock and water geochemistry and from geophysical criteria.
- (5) Providing a potential test site for geothermal experimental studies of other investigators.

In order to communicate these results as soon as possible to those who are interested and can make use of them, the results are being issued as a series of technical papers in addition to being submitted to scholarly journals.

A preliminary report incorporating the initial results of the combined geophysical, geochemical, and geological results was issued shortly after the well was completed (Ref. A-3). This new report is one of a series giving more detailed results based on the work of the past two years. It deals with the chemical and isotopic studies of the geothermal fluids from DWR Dunes No. 1. Elders and Bird in Part II (Ref. A-2) have considered the petrological aspects of the Dunes anomaly. In subsequent reports the oxygen and carbon isotope abundances of core samples and site geophysics will be discussed.

II. CHEMICAL STUDIES

The chemistry of water samples from a geothermal system is of importance for a variety of reasons. The abundances of dissolved chemical constituents put constraints on how the system can be developed for power. The chemistry of geothermal fluids enables studies to be conducted on the origin of the salt in the geothermal system. The abundances of various species and the ratio of the abundances of various species can be used to estimate temperatures in geothermal systems and to explore for geothermal anomalies.

During September of 1972 the casing of DWR Dunes No. 1 was perforated in three zones, two where the temperature versus depth curve (Fig. A-1) indicated the highest temperatures, and the third near the bottom of the hole. The interval 572-585 meters was perforated September 14, 1972. The well flowed at about 4 liters per second. Samples for chemical and isotope analysis were taken both from the surface flow and by bailing. A bridge plug was installed and the interval 259-271 meters was perforated. This zone did not flow. The water level was about 9 meters below the surface. Samples were obtained by bailing. The interval 104-116 meters was perforated and samples were obtained by bailing because again the flow was not artesian. Depth to the water level was 9 meters. No bridge plug was installed between the upper two perforations so that additional perforating could be accomplished without need of a drill rig to drill out the bridge plug.

The chemical analysis of the samples from these three zones suggested that the reliability of these samples was in question due to contamination by drilling mud. Therefore, a second attempt at sampling water from DWR Dunes No. 1 was tried in May, 1974. Because a bridge plug had been installed at 556 meters, only the upper two aquifers could be sampled. An evacuated stainless steel cylinder with a glass breakoff was lowered to 109 meters. A metal sender was employed to actuate the filling of the cylinder. A second sample was obtained from 260 meters in an identical manner. A downhole lift pump was then installed at a depth of 42 meters, and the well was pumped for several hours until the leather gaskets on the downhole pump assembly failed. After replacement, several thousand liters were pumped from the formation at a rate of 10 liters per minute. Water temperatures up to 100°C were recorded. After approximately one day of pumping, two water samples were taken one hour apart. The pump was then shut down.

The two samples collected by evacuated cylinders and the two pumped samples were split into unfiltered, filtered, and filtered acidified aliquots. Aliquots for isotopic analysis were also taken. Chemical analyses were performed by the California Department of Water Resources and by UCR. A summary of the results are listed in Table A-1 in parts per million by weight. The stable isotope analyses are discussed in the next section.

The analyses of the two pumped samples and the two samples collected by evacuated cylinder are nearly identical. Column 2 in Table A-1 is an analysis of the last pumped sample and the third column is an analysis of the 260-meter-deep sample collected with the evacuated cylinder. The agreement among all four water samples suggests that these analyses are good. The observation that the samples collected opposite each perforation with the evacuated cylinder are identical in chemical and isotopic composition suggests that there certainly is a single source for the water entering both perforations unless mixing in the borehole is complete. If we discount mixing in the well, one explanation for this observation is vertical flow of geothermal fluid in formations penetrated by DWR Dunes No. 1.

The total dissolved solids in these samples is relatively low, about 4000 ppm, compared to other geothermal systems in the Imperial Valley (15,000 - 250,000 ppm). In the hot water geothermal systems in the Imperial

and Mexicali Valley, an increase in temperature is usually accompanied by an increase in salinity. Thus, the low salinity measured at Dunes may be a consequence of low temperatures in this system.

Silica, ammonia, and zinc were not measured on the sample obtained with the evacuated cylinder from the 259-271-meter perforation. The error in the chemical analyses is unknown. However, it is probably not great because the sum of the cations and anions in both analyses is within 5 percent of the measured TDS.

The abundances and the ratio of the abundances of several chemical constituents of geothermal brine have been shown to be useful indicators of subsurface temperature (Ref. A-4). In order to apply this geothermometer, one must make the following assumptions: (1) that chemical equilibrium exists in the geothermal system, (2) that transport of the geothermal fluid to the surface is sufficiently quick to prevent precipitation or retrograde exchange at lower temperatures, and (3) that there is negligible contamination by other sources of water. The simplest of the geochemical thermometers is the silica geothermometer. The quantity of silica in a solution in a sample of geothermal fluid increases as a function of temperature. The calibration curve is reported by Fournier and Truesdell (Ref. A-5). The silica content measured in various samples from DWR Dunes No. 1 corresponds to a temperature of $138 \pm 10^\circ\text{C}$. The measured temperature is 100°C .

Another geothermometer which has proved useful is the sodium-potassium-calcium geothermometer. The use of this geothermometer is discussed by Fournier and Truesdell (Ref. A-6). The equilibration temperature is a function of

$$\log \frac{\text{Na}}{\text{K}} + \beta \log \frac{\sqrt{\text{Ca}}}{\text{Na}}$$

where β is 1.333 unless equilibrated temperatures are above 100°C , in which case it is 0.333. The Na-K-Ca temperature of DWR Dunes No. 1 geothermal fluid is 170°C , a value much higher than actually measured (Fig. A-2). The explanation of this may be:

- (1) Chemical equilibration does not exist in the region of DWR Dunes No. 1.
- (2) The Na-K-Ca geothermometer cannot be applied at the Dunes geothermal anomaly because the mineralogy at Dunes is different than at the systems used to calibrate this geothermometer. This possibility appears to be the least likely.
- (3) The temperature at depth at the source of the geothermal fluid is greater than the 100°C temperatures measured during our water sampling or geophysical logging.

Explanation (3) appears to be most likely if one also considers the temperature of 138°C determined from the silica geothermometer.

The calcite-water oxygen isotope geothermometer has been applied to DWR Dunes No. 1. Coplen (Ref. A-7) reported temperatures of 97 and 117°C for two samples of calcite from the core, assuming oxygen isotope equilibrium between calcite and water.

These results suggest that a geothermal reservoir may exist at the Dunes anomaly with a temperature of 97, 117, 138, or 170°C. In order to examine this possibility of a hot geothermal reservoir at the Dunes anomaly, additional site geophysics is required. This is presently being undertaken by Shawn Biehler at UCR and Jim Combs now at the University of Texas, Dallas. If it is possible to identify a geothermal reservoir of sufficient magnitude, further drilling at the Dunes anomaly is probably justified.

The ratio of chloride to bromide in water has been used to investigate the origin of salt in geothermal systems (Refs. A-4 and A-8). Cl/Br ratios of the ocean and Cerro Prieto geothermal field in Baha California are 300 and 400, respectively. The ratio in the Salton Sea geothermal system and the Colorado River is 1600. This ratio in all of the samples from DWR Dunes No. 1 is 1600, identical to that of the Salton Sea system and the Colorado River. White (Ref. A-9) has suggested that the very saline brine in the Salton Sea geothermal system is derived from the solution of evaporites, which were formed from Colorado River water. Because the Cl/Br ratio of water from the Salton Sea geothermal field and from DWR Dunes No. 1 is identical with that from the Colorado River, it is possible that the source of the salts in both these geothermal anomalies is Colorado River water. However, the situation is probably not so simple as pointed out by Rex (Ref. A-8), because Cl/Br ratios in evaporites are usually highly variable and the Cl/Br ratio of salt from local precipitation is much lower than 1600. Future measurements on other geothermal systems in the Imperial Valley should shed light on the problem of the origin of the salts. Note that the origin of the salts and water in a geothermal system may be different. This possibility is discussed by Rex (Ref. A-8) for Cerro Prieto. For the Dunes geothermal system we demonstrate in the section on stable isotopes that the water in this system is most likely derived from partially evaporated Colorado River water.

III. STABLE ISOTOPE STUDIES

The primary stable isotopic species of water are H_2O^{16} , H_2O^{18} , and HDO. These stable isotopes can be employed for a variety of hydrological investigations (Ref. A-10). Water samples from DWR Dunes No. 1 were employed in a stable isotope investigation directed towards identification of the source of the water in the Dunes geothermal anomaly.

Hydrogen isotope abundances in this study were determined on a 5-cm radius, 180-degree sector, isotope ratio, mass spectrometer (Ref. A-11) from hydrogen quantitatively extracted from an aliquot of the water sample by reaction with hot uranium metal. Corrections have been made for H_3^+ contribution to the mass-3 ion beam and for mixing of the sample and standard

gases due to glass valve leakage (Ref. A-12). The hydrogen isotopic composition of water samples is reported in parts per thousand difference ($^{\circ}/\text{oo}$) from Standard Mean Ocean Water (SMOW) (Ref. A-13). Thus,

$$\delta D(^{\circ}/\text{oo}) = \left[\frac{\left(\frac{D}{H}\right)_{\text{Sample}}}{\left(\frac{D}{H}\right)_{\text{SMOW}}} - 1 \right] 1000$$

The precision of the hydrogen isotopic analyses is $\pm 1^{\circ}/\text{oo}$.

The oxygen isotopic composition of water samples was determined on a double-focusing double-collecting isotope ratio mass spectrometer (Ref. A-14) by analyzing an aliquot of carbon dioxide which had been isotopically equilibrated with the water sample in a 25.0°C temperature bath (Ref. A-15). Corrections were made after Mook (Ref. A-12). The oxygen isotopic composition of water samples is reported relative to SMOW in the per mil notation:

$$\delta O^{18}(^{\circ}/\text{oo}) = \left[\frac{\left(\frac{O^{18}}{O^{16}}\right)_{\text{Sample}}}{\left(\frac{O^{18}}{O^{16}}\right)_{\text{SMOW}}} - 1 \right] 1000$$

The precision of the oxygen isotope analyses is $\pm 0.1^{\circ}/\text{oo}$.

As discussed by Craig (Ref. A-16) and Coplen (Ref. A-17), the stable isotope technique is useful in determining the origin of water in geothermal systems because:

- (1) The oxygen and hydrogen isotopic compositions of precipitation differ in general from one locality to another due primarily to differences in the temperature of precipitation. Craig (Ref. A-18) found a linear correlation between δD and δO^{18} for meteoric water samples from all over the earth such that

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

Samples from colder locations are more negative in δD and δO^{18} while precipitation from equatorial zones is closer to SMOW.

- (2) A geothermal system has negligible effect upon the hydrogen isotopic composition of the water flowing through the system because the quantity of hydrogen in rocks is so low. The hydrogen isotopic composition of precipitation which enters a ground water

system and flows through that system is in general unchanged. Thus, hydrogen isotopic composition can serve to "tag" water from different sources.

- (3) The oxygen isotopic composition of precipitation samples which enters a geothermal system can be modified if the system is sufficiently hot (150°C or greater) due to exchange of oxygen in water with oxygen in the rock. The net effect is to increase the O¹⁸ content of the water and decrease the O¹⁸ abundance in the rock. This "O¹⁸-shift" is discussed by Craig (Ref. A-16).

Figure A-3 is a plot of δD versus δO^{18} for water samples from DWR Dunes No. 1, the Mesa geothermal system, central Imperial Valley wells, and other Imperial Valley wells. Figure A-3 demonstrates that most of the water samples from the Imperial Valley plot along a line which is the path followed by evaporating water from the lower Colorado River (Lake Mead). Note that the isotopic composition of local precipitation lies far to the left of this evaporation path. This strongly suggests that most of the subsurface water in the Imperial Valley was derived from the Colorado River. Only near the margins and in a few shallow aquifers is there significant water derived from local precipitation as shown by the open well in Fig. A-3.

The geothermal fluid from both (upper) perforations of DWR Dunes No. 1 plot in Fig. A-3 with central Imperial Valley wells, suggesting that the source of the water in the Dunes system is not local precipitation, but is deeper partially evaporated Colorado River water. The samples from both the 110- and 260-meter aquifers are identical in isotopic composition (see Table A-1) and plot at the same point on Fig. A-3. This suggests that both are derived from the same source.

The samples from DWR Dunes No. 1 do not show the oxygen isotope shift shown by the sample of geothermal brine from Cerro Prieto (Fig. A-3). This may be due to the fact that

- (1) The higher temperatures at Cerro Prieto promote oxygen exchange between water and silicates, but temperatures at the Dunes are not sufficiently high to promote exchange of oxygen between water and silicates.
- (2) So much water has passed through the Dunes system that the oxygen isotopic composition of the rock has been lowered such that it is in equilibrium with water entering the system. Thus, there would be no chemical potential to increase the O¹⁸ content of water entering the system.

In order to investigate which of these hypotheses may be correct, we are in the process of analyzing the carbonates and silicates from this well for oxygen and carbon isotopic composition. The results of this study will be issued shortly as a technical report in this series.

The Mesa geothermal system, whose location is shown in Fig. A-1, is being developed by the U.S.D.I. Bureau of Reclamation to provide desalted

water to augment the flow of the Colorado River. Because the anomaly is geographically near the Dunes anomaly and because the geology of the system is very similar to that of the Dunes anomaly, it is informative to examine the isotopic composition of water samples obtained from the Mesa anomaly. Figure 3 shows 6 samples from the Mesa system. Samples 1 and 2 are from two shallow aquifers about 50 and 80 meters deep. They are distinctly different in both oxygen and hydrogen isotopic composition than deeper sample numbers 3, 4, and 5. This suggests that near surface ground water was not derived from the geothermal brine at depth. The isotopic composition of these shallow samples suggests that a large proportion of the near-surface water was derived from local precipitation. Samples 3, 4, and 5 were obtained during drill stem tests of Mesa 6-1 from depths of 780, 1350, and 1650 meters, respectively. They plot near the Colorado River water evaporation line in Fig. A-3. In addition, two of these samples plot near the central Imperial Valley well waters. These results strongly suggest that the water in the Mesa geothermal system was, like that of the Dunes anomaly, derived from Colorado River water (Lake Mead). Sample 6 is a brine from which steam was flashed. It lies to the right of the evaporation line, demonstrating that steam depleted in O^{18} flashed from this brine, thus enriching the brine in O^{18} . This result shows the importance of obtaining a quantitative sample of the fluid in order to ensure accurate stable isotope analyses.

In conclusion, the oxygen and hydrogen stable isotope studies of water samples from DWR Dunes No. 1 indicate that the water samples from the perforations at 109 and 260 meters are identical in oxygen and hydrogen isotopic composition within experimental error. These results strongly support the conclusion that geothermal fluid obtained from both of these aquifers flows from the same source. The source of the geothermal fluids from DWR Dunes No. 1 is moderately deep ground water (probably greater than 400 meters), containing a negligible amount of local precipitation. The geothermal brine was derived from partially evaporated Colorado River water.

IV. OTHER GEOCHEMICAL STUDIES BY UCR

C^{14} R. E. Taylor at the University of California, Riverside is measuring the C^{14} abundance of dissolved carbonate species in order to obtain information on the "age" of the water in the Dunes geothermal system. The age of the water in geothermal systems is of particular importance in estimating the lifetime of a geothermal system developed for its energy potential. Should this technique be successively refined here, it can be used on other hot water geothermal systems. C^{14} studies have not proved fruitful at the Salton Sea geothermal system because very large quantities of "dead" CO_2 are released from decarbonation reactions of ancient carbonates, which occur in the range of $300^\circ C$. Thus, the ages obtained are infinite. We are hopeful that the C^{14} technique may be of use in the Dunes geothermal system because the temperatures are much less than those at the Salton Sea geothermal field.

V. GEOCHEMICAL STUDIES BY OTHER ORGANIZATIONS

Work is presently being carried out by the geothermal resources group at Stanford University under the direction of Professor Paul Kruger to investigate environmental aspects and reservoir properties of the Dunes anomaly utilizing radon abundances.

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Table A-1. Chemical and isotopic composition of water samples from DWR Dunes No. 1

Chemical/isotope	From 104-116-meter perforation, ppm	From 259-271-meter perforation, ppm
Lithium	1.85	1.85
Sodium	1262	980
Potassium	103	107
Magnesium	1.7	1.4
Calcium	136	101
Strontium	0.6	0.5
Manganese	0.07	0.07
Iron	0.36	0.03
Copper	0.00	0.09
Zinc	1.14	
Cadmium	0.10	0.05
Arsenic	0.06	0.02
Lead	0.00	0.00
Fluoride	4.6	1.9
Chloride	2021	2040
Bromide	1.26	1.28
Iodide	0.094	0.13
Sulfate	178	140
Nitrate	0.0	0.0
Bicarbonate ^a	76	67
Carbonate ^a	0.04	0.03
Ammonia	0.84	
pH ^a	6.58	6.43
Boron	2.2	1.9
Silica	118	
TDS	3940	3950
δD	-94 ‰	-94 ‰
δO ¹⁸	-10.77 ‰	-10.80 ‰
δC ¹³ of bicarbonate	- 8.6 ‰	

^aField analysis; all other analyses are laboratory analyses.

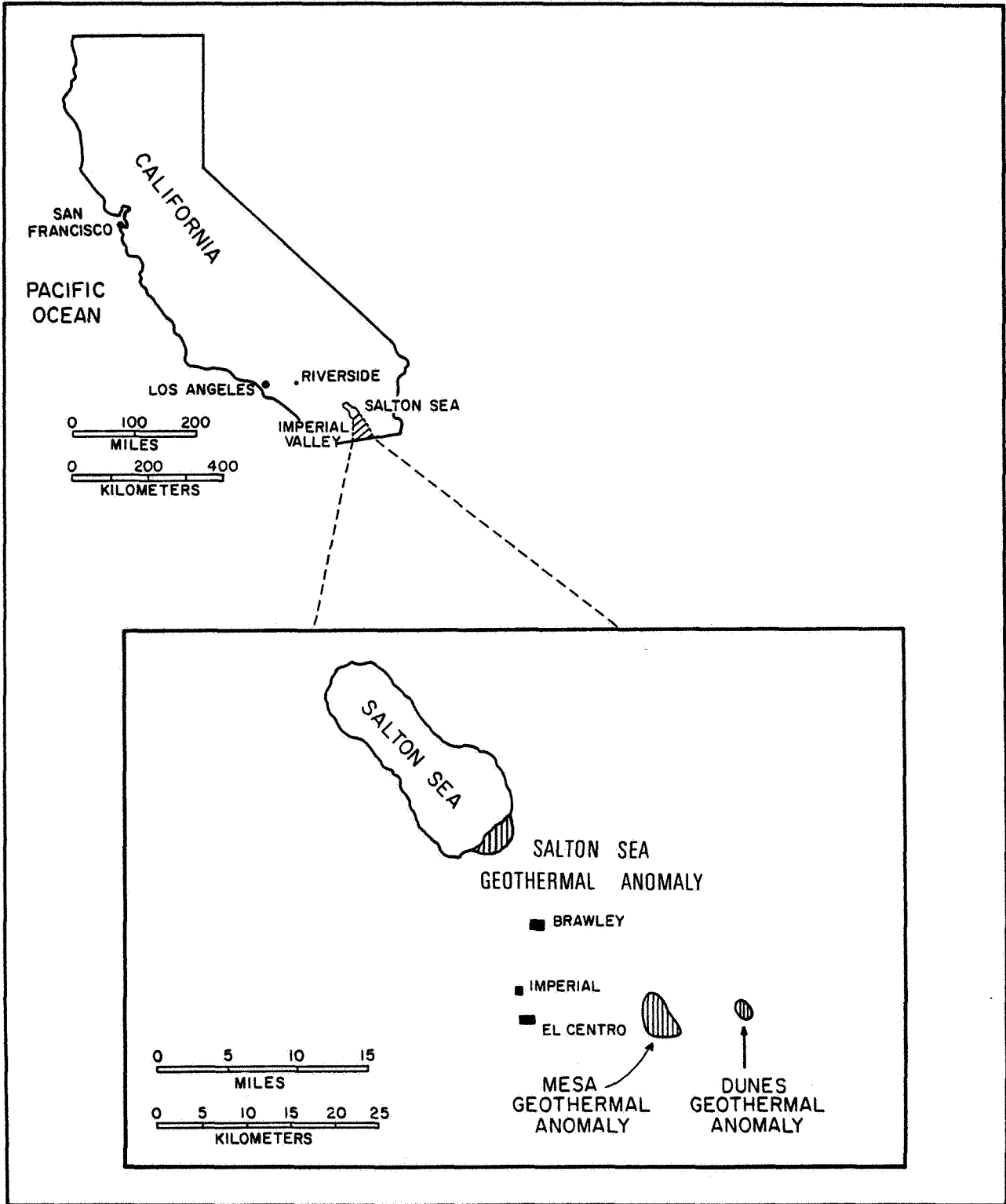


Fig. A-1. Imperial Valley geothermal anomalies

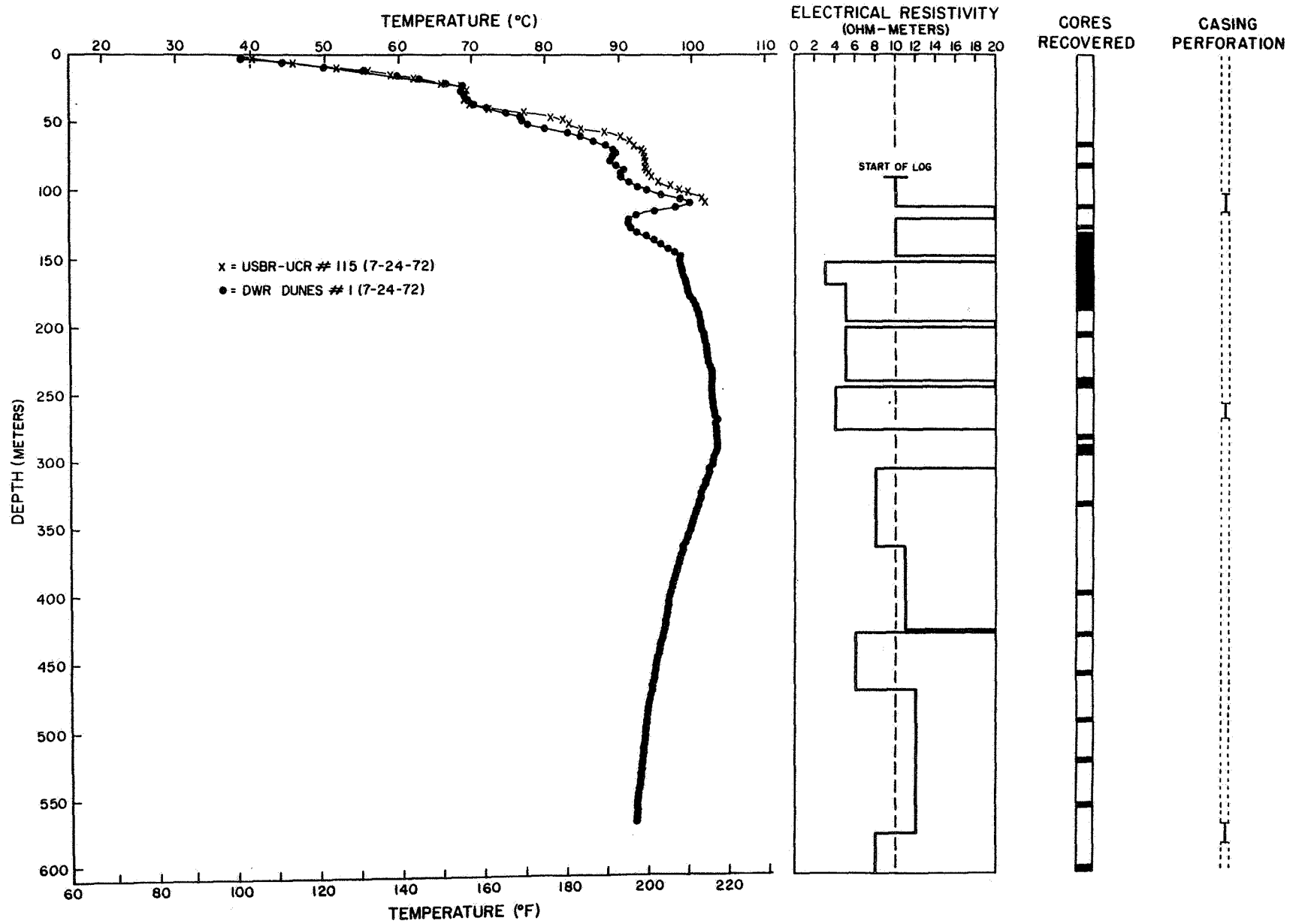


Fig. A-2. Temperature gradient, electric log, core recovery, and casing perforation program

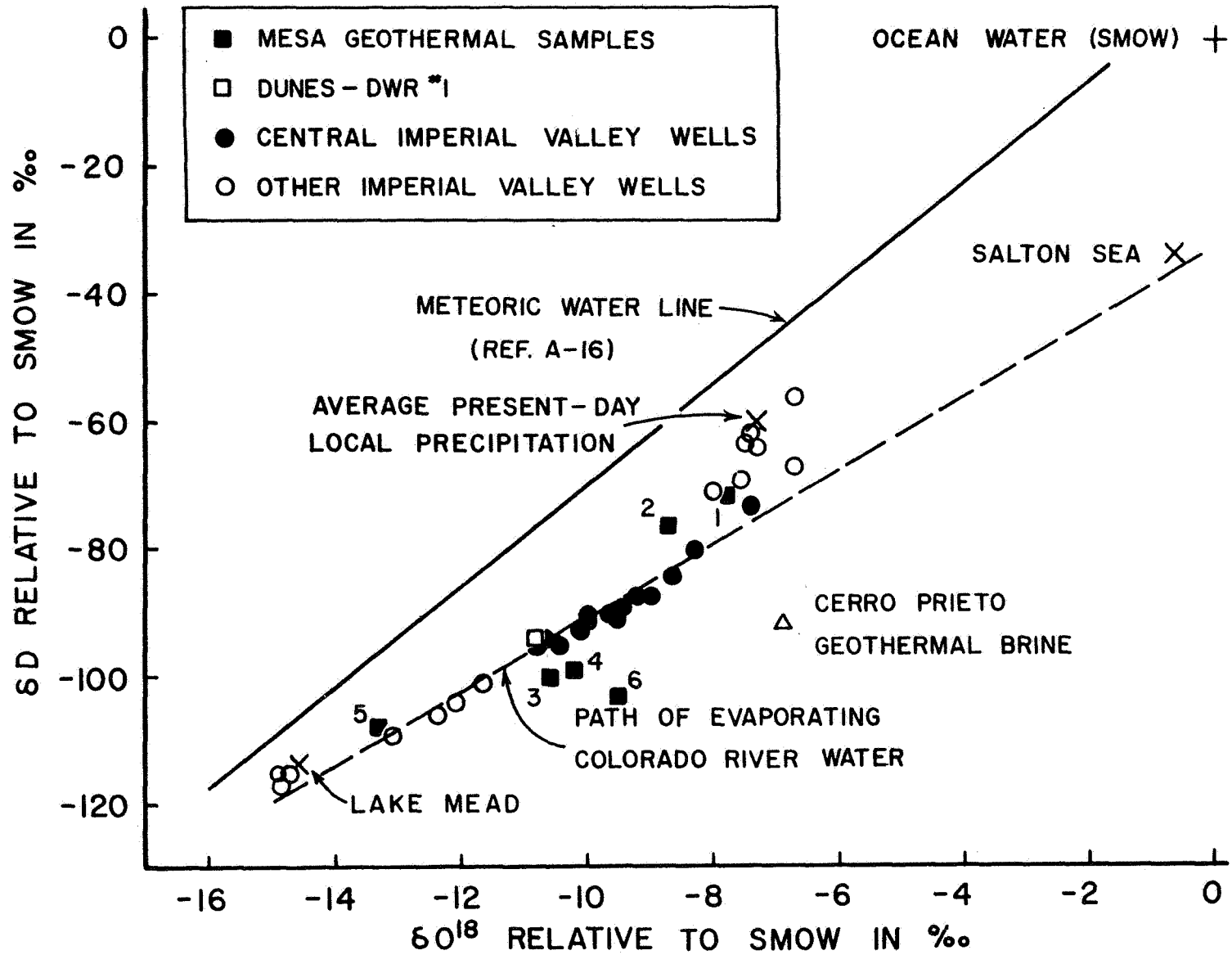


Fig. A-3. δD versus δO^{18} for water samples from DWR Dunes No. 1

PART B: GEOLOGY

W. A. Elders and D. K. Bird

Extensive alteration of sedimentary rocks by geothermal brines is common in a zone of high heat flow within the Salton Trough, the landward extension of the Gulf of California rift system. Several localized areas of very high temperature gradients at shallow depth, accompanied by positive gravity anomalies, occur within this zone.

A 612-meter deep test well encountered a maximum of 104°C at the 285-meter depth in the Dunes anomaly, at the southeast margin of the Trough. The rocks penetrated were deltaic sediments deposited by the Colorado River. Water samples recovered are alkaline sodium chloride brines with up to 3000 ppm of total dissolved solids. In the upper 300 meters of the hole, there are seven zones of dense gray quartzite formed by the reaction of the brines with the permeable sandstones. Precipitation of quartz, adularia, and pyrite has made the sediments impermeable and increased their density from 2.2 to 2.6 g-cm⁻³. The amount of silica precipitated is greatest below impermeable shale beds. However, extensive hydrothermal alteration is absent in the lower 300 meters of the hole, where only diagenetic processes seem to have occurred. This shows that the hydrothermal brines migrated laterally between impermeable barriers rather than vertically through the formations. Based upon studies of the textures it is evident that there have been various stages of hydrothermal and diagenetic alteration in each of these silicified zones. The presence of temperature gradient reversals and the existence of both diagenetic and hydrothermal alteration in fractures in silicified rocks suggests that the silicification was episodic. Brines of different oxidation state and presumably different temperatures have entered the system at various times.

It appears that when moderately hot brines encountered colder rocks, precipitation of quartz and feldspar made the rocks impermeable. Any further flow of water through the heavily silicified rocks was through later fractures.

Thus, water-dominated geothermal systems which operate in porous sandstones are essentially self-sealing. Convective overturn of the geothermal brine is very strongly influenced by the original and subsequent permeability of the system. A sealed

geothermal system, like this one, may therefore have no surface expression. However, the silica cap rock is a good exploration target for geophysical surveys and can give rise to high temperature gradients near the surface.

I. INTRODUCTION

An unusually clear-cut example of silicification of sedimentary rocks, by hydrothermal reactions at shallow depth, was discovered in test wells drilled into a geothermal anomaly in the southeastern part of the Imperial Valley of California, U.S.A. The Imperial Valley forms the northern end of a physiographic province known as the Salton Trough, which is a structural extension of the Gulf of California into the continent of North America (Fig. B-1a). The Salton Trough is a complex rift valley, partly filled to a depth of 6-7 km with sediments of late Tertiary and Quaternary age (Ref. B-1).

Several geothermal anomalies occur in the Imperial Valley north of the international border (Fig. B-1b). The best known of them is the Salton Sea geothermal field at the south end of the lake known by that name (Ref. B-2).

The only geothermal anomaly in the region that is currently being exploited occurs at Cerro Prieto, 20 km south of Mexicali, Mexico, where a 75-MW generating plant produces electricity from steam flashed from a water-dominated system (Ref. B-3).

The Dunes geothermal anomaly lies 15 km north of the international border on the east side of the Imperial Valley (Fig. B-1b). The anomaly, which is about 2.5 km² in extent, was discovered during geophysical surveys (Ref. B-4).

At this location a shallow temperature gradient anomaly occurs together with a 2-milligal positive, residual gravity anomaly (Ref. B-5) and a shallow, electrical resistivity anomaly of 2 ohm-m (Ref. B-6). The alignment of these anomalies parallel to the structural trend of the San Andreas Fault suggests that they are at least partly fault-controlled (Fig. B-1b).

A 612-m-deep test-well (Dunes DWR No. 1) was drilled into the anomaly by the California Department of Water Resources (Ref. B-7). The thermal gradient is complex with a maximum of 100°C at 110 m followed by a temperature inversion and another maximum of 104°C at 285 m (Fig. B-2).

A dense cap rock is developed in which seven distinct zones of intensive silicification of sandstones were observed. The highest temperatures recorded are all within shales and intensively silicified sands of low permeability. The well casing was perforated at three intervals: 572-585 m, 259-271 m, and 104-116m. The lower perforation in the well flowed at about 4 liters/second; the upper two perforations did not flow and water samples were obtained by bailing immediately after completing the well and by pumping a year and a half later. The waters recovered are primarily sodium chloride brines with about 3000 ppm of total dissolved solids (Table B-1).

Approximately 96 m of core were recovered, along with drill cuttings sampled every 3 m. This paper is primarily based upon petrological investigations of the cores and cuttings recovered together with interpretation of the subsurface geophysical logs. The emphasis is primarily placed upon the post-depositional changes in the sandstones.

II. STRATIGRAPHY AND SEDIMENTATION

The sedimentary rocks recovered are all terrigenous detritus of the Colorado River Delta, rich in quartz and feldspar. We have recognized four sedimentary facies: (a) deltaic sands; (b) interbedded sands, silts, and shales; (c) dune-graded sand sequence; and (d) channel fill conglomerates. The deltaic sand facies, which represents about 80% of the section, consists of medium to fine arenaceous sands and silty sands. The interbedded sands, silts, and shales, which locally contain calcite concretions and gypsum, are believed to be a lake deposit. The dune-graded sand sequence contains cyclical graded sand sequences which appear to be a braided stream delta deposit. It is interbedded with well-sorted sands believed to be reworked dune sands. The lower 300 m of the well records fairly continuous deltaic deposition with intercalated lake deposits. The upper 300 m records the history of active distributaries of the river, with channel fill conglomerates and deltaic sands.

III. POST-DEPOSITIONAL ALTERATION

We have distinguished between two different degrees of post-depositional alteration in these rocks: hydrothermal and diagenetic. Hydrothermal alteration, which is found only in the upper 300 m of the well, in the silicified zones, is of a much more intense kind than the diagenetic alteration, which is found above and below the silicified zones. The effects of both types of alteration are to reduce permeability and porosity and increase the density by cementation of sands to sandstones. For example, in the diagenetically altered sandstones, the porosity averages 30-35% and the bulk density 2.1 g-cm^{-3} , whereas the hydrothermally altered sandstones have porosities as low as 3-4% and average bulk densities of 2.6 g-cm^{-3} (R. Goss, unpublished data, 1974).

Two further groupings of the post-depositional alteration can conveniently be made. We can distinguish between interstitial mineralization and fracture mineralization on the basis of whether water-rock interaction occurred within the primary and secondary pores of the rock, or within natural fractures within the silicified zones.

A. Interstitial Mineralization

Below 300 m diagenesis has produced grayish sandstones with localized calcite cement and concretions. Other diagenetic effects are incipient overgrowths of quartz and chalcedony on detrital quartz sand grains and of adularia on detrital microcline, together with minor amounts of gypsum. In

spite of this cementation, the sandstones are poorly indurated and friable. Similar diagenetic effects occur in the upper 75 m of the well; however, these rocks are variable in color, from pink to brick red, due to varying amounts of disseminated hematite (Fig. B-3a).

Between 75 and 300 m, seven zones of hydrothermal alteration occur in which intensive interstitial mineralization of arenaceous sands has formed well-indurated gray quartzites. In the initial stages of this hydrothermal alteration, hematite is reduced to pyrite and syntaxial growth of quartz is common. In more intensive stages epitaxial pyramidal quartz overgrowths develop on lithic clasts and adularia overgrowths on altered plagioclase and orthoclase detrital grains. Optically continuous overgrowths are common, and the void space is almost entirely filled with quartz or chert (Fig. B-3b and c). This interstitial precipitation restricts the permeability, sealing off further penetration by brine.

The distribution of interstitial authigenic mineral facies is strongly stratified. At least four distinct zones or facies of mineralization with depth can be noted, each associated with accessory authigenic minerals. These are (a) hematite + calcite (0-75 m), (b) hematite + quartz + adularia (75-100 m), (c) quartz + adularia + pyrite (100-160 m and 200-300 m), and (d) calcite ± gypsum ± chloritized biotite facies (300-610 m). The zonation of these mineral assemblages with depth is illustrated in Fig. B-2 under the heading of interstitial mineralization.

The development of these zones is clearly stratigraphically controlled as the flow of the brine seems to have been initially controlled by impermeable shalt or silt beds which overlies six of the seven silicified zones (Fig. B-2). Presumably, the hot, silica-saturated brines moved laterally through the formation, controlled by impermeable beds, and, as they cooled, precipitated silica. This made the rocks even less permeable so that the process was essentially self-sealing.

B. Fracture Mineralization

Within the intensely silicified zones, any further flow of brine could only occur where later fractures developed. These are especially numerous in four of the highly silicified zones (Fig. B-2). Six zones or facies of fracture mineralization can be recognized in which the following minerals are dominant: (a) quartz, (b) adularia (Fig. B-3d), (c) pyrite (Fig. B-3e), (d) pyrite oxidized to hematite (Fig. B-3f), (e) and calcite. The zonation of these minerals with depth is also shown in Fig. B-2. Most of these changes can be described as prograde metamorphism in response to higher than normal geothermal gradient. However, the texture of hematite in the hematite facies shows that it formed as pseudomorphs after authigenic pyrite, both in the fractures and also disseminated through the host rock adjacent to the mineralized fractures.

All of the post-depositional alteration in this well seems to record rock-water reaction in a near-surface geochemical environment, in which there was strong stratigraphic control over lateral flow of brine through the system and in which there developed episodic prograde and retrograde reactions

in younger fractures. Thus, the depth interval containing the seven silica cap rocks appears to be part of a laterally extensive hydrothermal aquifer. The idea that lateral transfer and episodic incursions of different brines occurred is also supported by the presence of the temperature gradient reversals (Fig. B-2). It is noteworthy that the highest temperatures are measured in what are now the least permeable rocks, suggesting that brines colder than those formerly present have now entered the system. As indicated in Fig. B-2 between 70 and 300 m, there appears to be a hydrothermal aquifer in which flow is horizontal. One explanation offered for the retrograde development of hematite after pyrite is that this aquifer is encroached upon, above, and below by more oxidizing meteoric waters (Fig. B-2).

IV. SELF-SEALING

Figure B-4 is a very schematic "cartoon" for the flow of water envisaged. The core hole, DWR Dunes No. 1, is shown at the top left; the rest is largely conjectural. At some as yet unexplored depth, a heat source or geothermal reservoir heats meteoric water, permitting solution of silica, together with lesser amounts of K_2O , and Na_2O . Impermeable shale beds restrict flow of the brines in the system so that upward flow is along fractures. The hot water encounters impermeable clay barriers and moves laterally, cooling and precipitating quartz, chalcedony, adularia or pyrite, thus forming a self-sealing cap rock which further restricts the upward flow. The system is shown recharging by cold, dilute, meteoric water descending another system of fractures, precipitating carbonate and sulfate as it heats up.

Although convection is initially controlled by the original stratigraphy, the system is progressively modified through time until self-sealing becomes a dominant factor. The importance of cap rocks and self-sealing in certain geothermal fields has already been pointed out (Ref. B-8).

In the Dunes anomaly discussed here, the self-sealing has sealed off the geothermal fluids so that there is no surface expression of geothermal activity. The low thermal conductivity of these impermeable rocks permits a high temperature gradient near the surface. However, such cap rocks are an excellent target for geophysical exploration in searching for new geothermal areas. In particular, the Dunes geothermal anomaly is a readily accessible natural laboratory for studying the self-sealing mechanism and rock-water interaction in a geothermal area near the surface.

ACKNOWLEDGMENT

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Table B-1. Partial chemical analyses of water pumped from
 104-116-m level in the Dunes DWR No. 1 borehole
 (Analyst P. Kolesar)

Sample	Field pH	Na, ppm	K, ppm	Ca, ppm	Si, ppm
1	6.65 at 79° C	1310	100	103	55
2	6.65 at 79° C	1330	100	104	55
3	6.58 at 87° C	1330	100	104	56
4	6.58 at 87° C	1340	100	103	55

Note: These partial analyses are preliminary values determined on water collected by pumping in June 1974. Earlier analyses of water collected by bailing are believed to be contaminated by drilling water (Ref. B-7). Analyses of total dissolved solids determined on earlier samples ranged from 1260-3040 ppm, whereas the new samples contain 3940 ppm.

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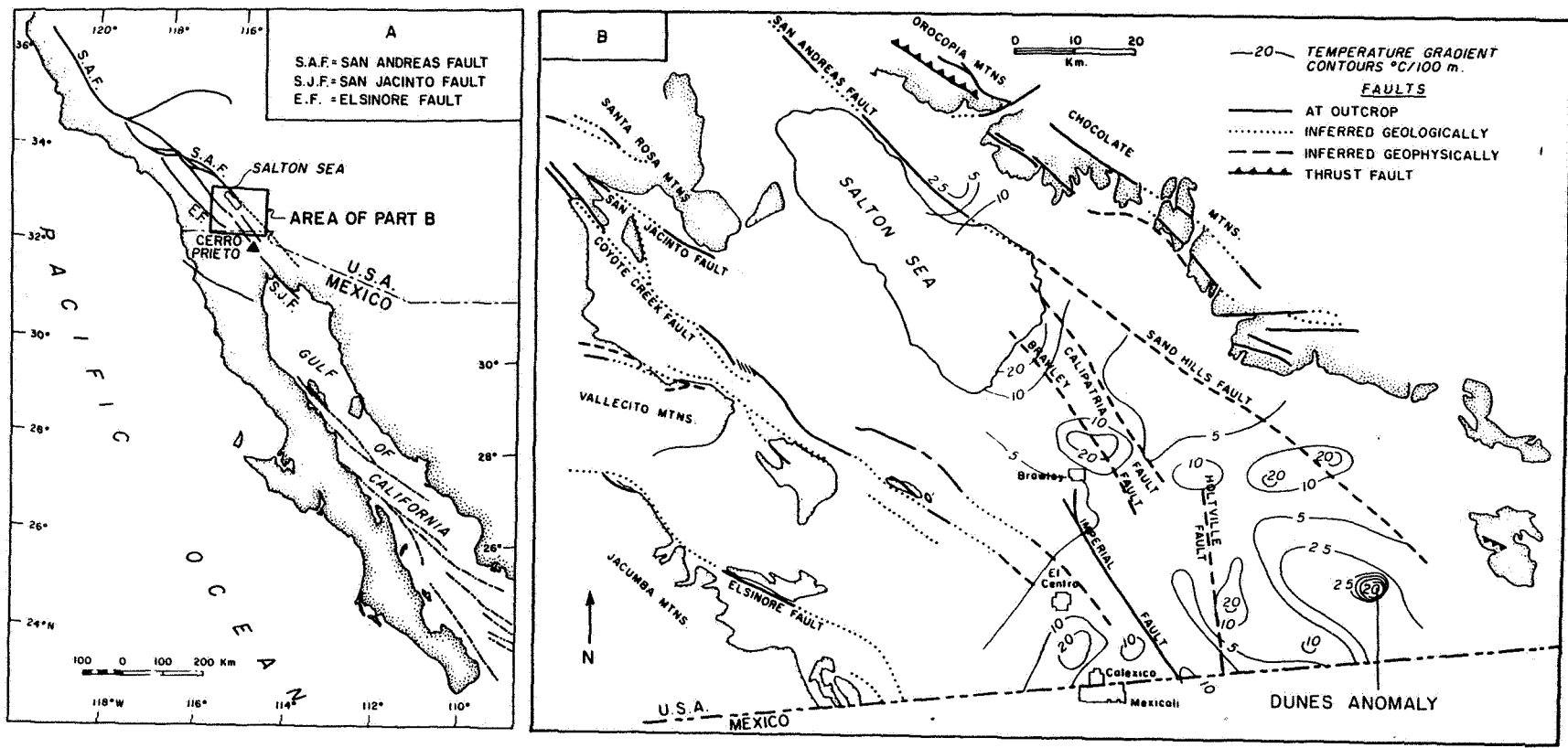


Fig. B-1. (a) Location of the Salton Trough; (b) faults and isotherms in the Imperial Valley showing the location of the Dunes geothermal anomaly

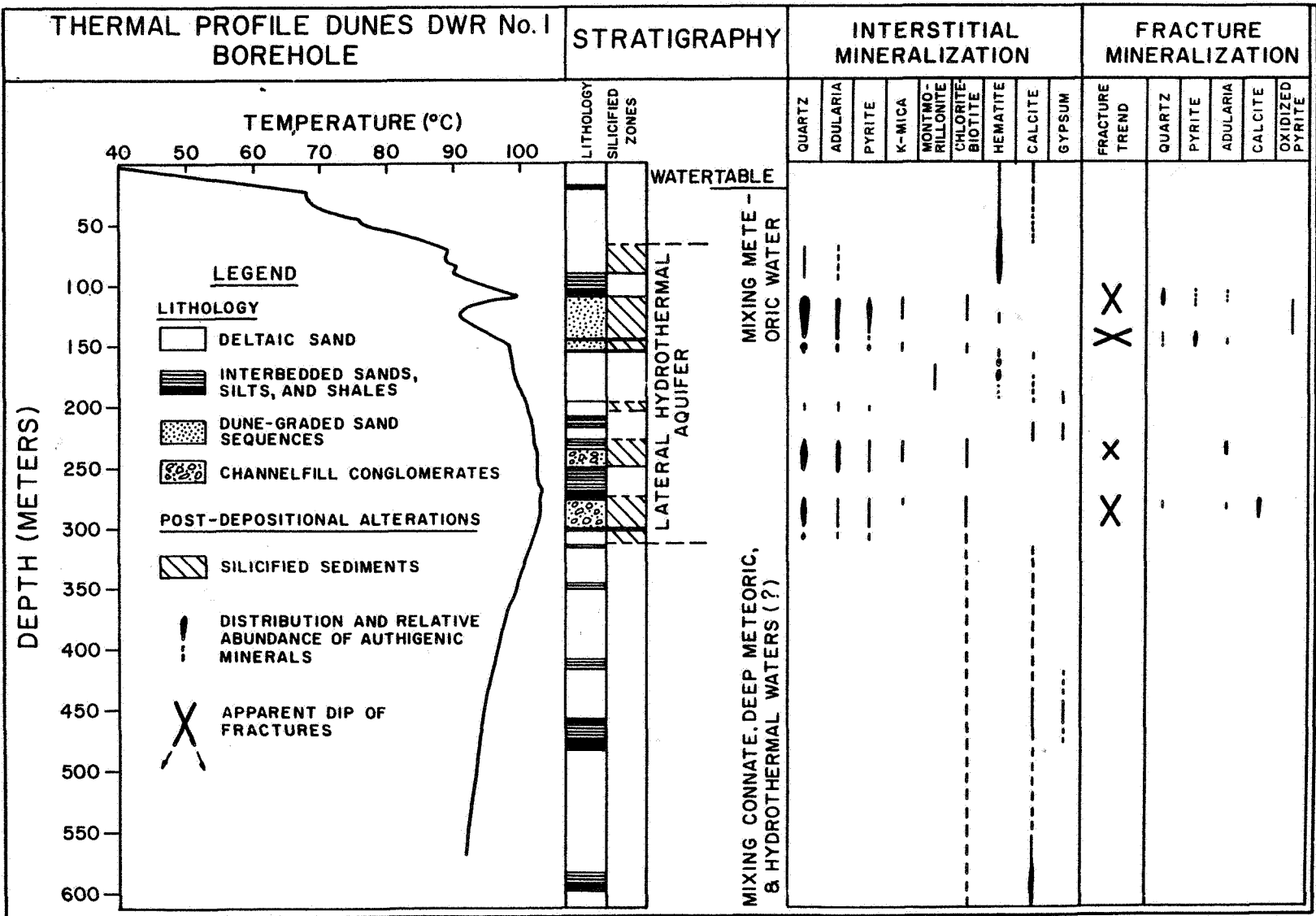


Fig. B-2. Summary of the thermal profile, physical stratigraphy, and post-depositional mineralization in pore spaces and fractures in the borehole of DWR Dunes No. 1

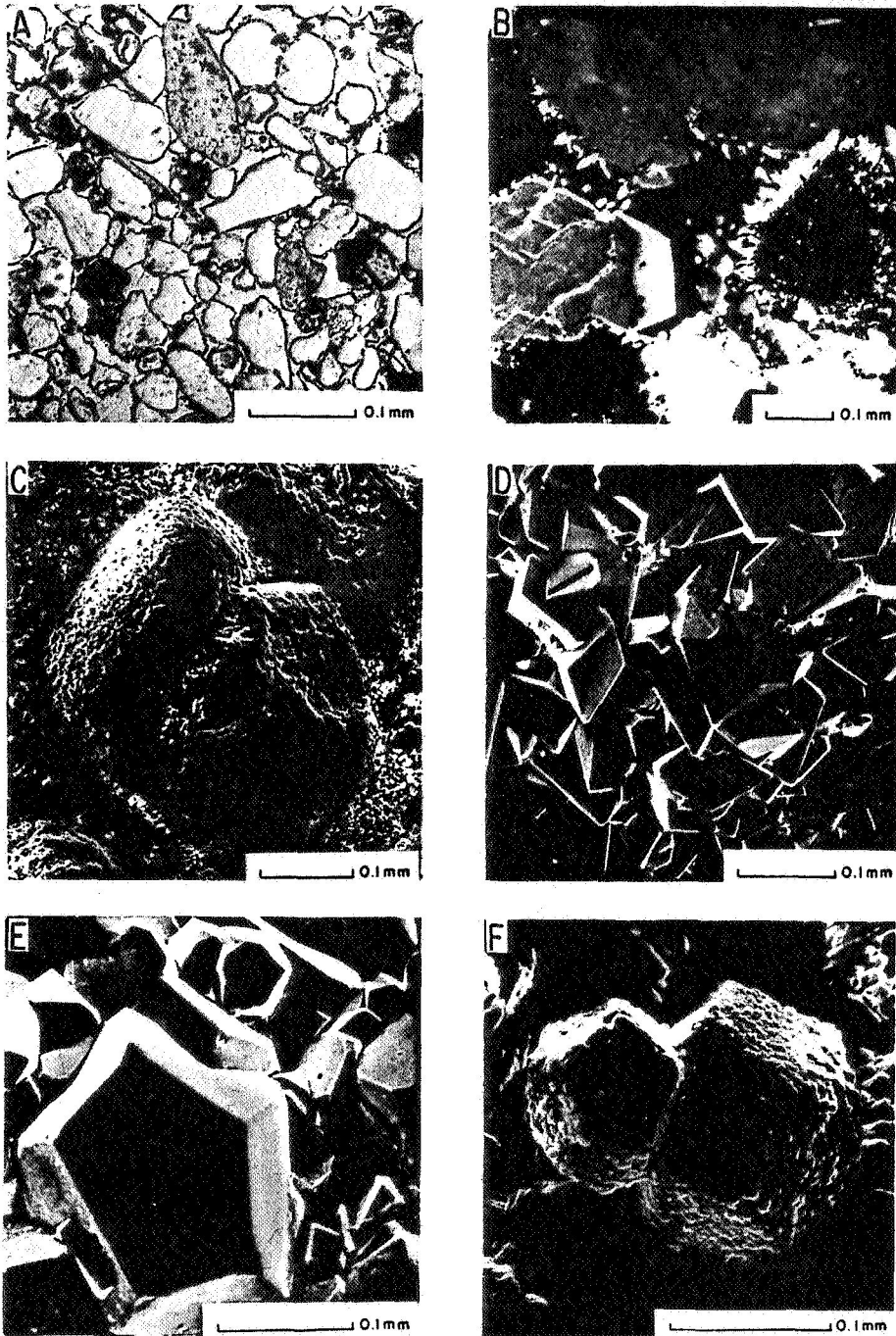
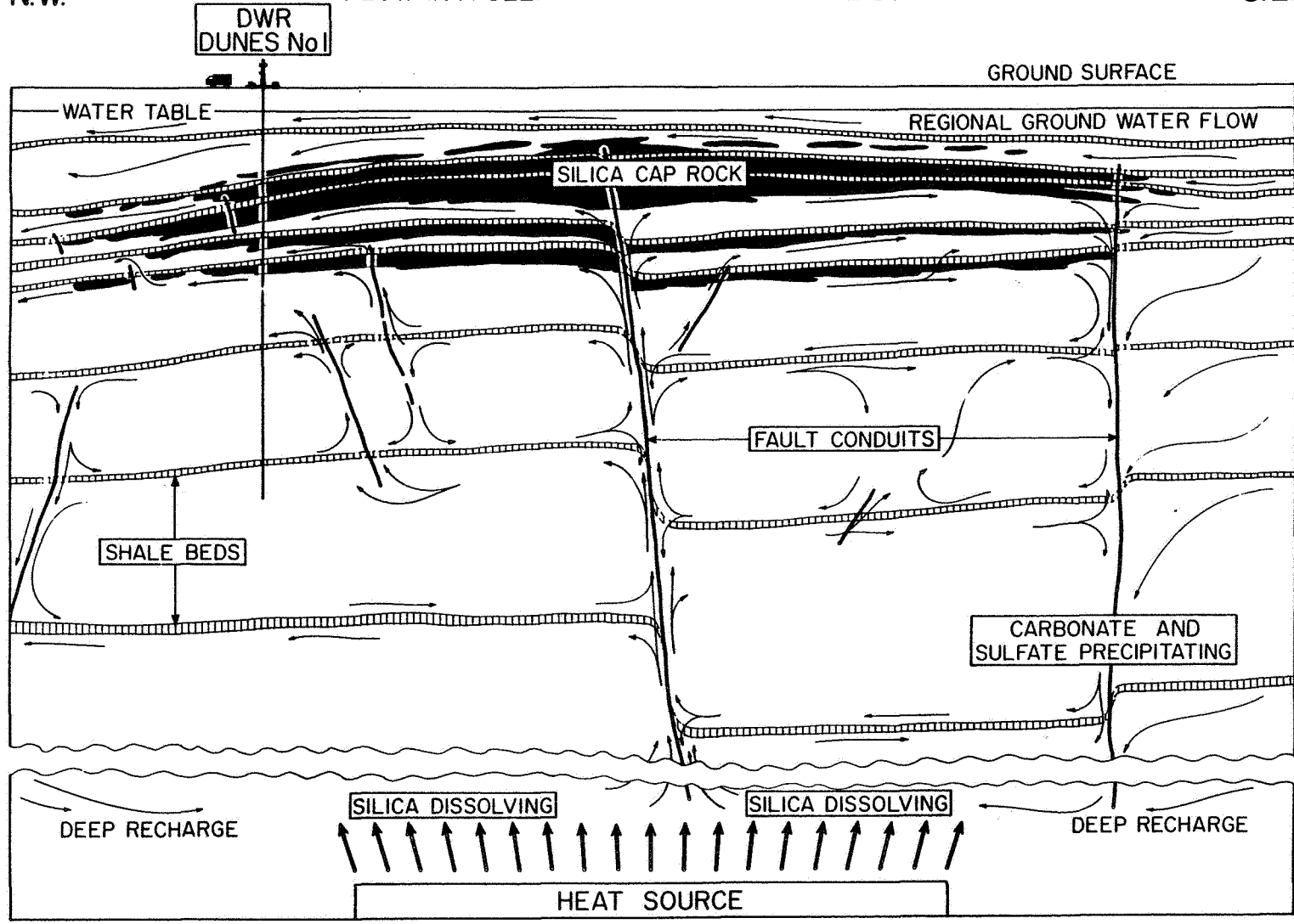


Fig. B-3. (a) Thin section of the core at 69.5-m depth in ordinary light--pale red arkosic sandstone with incipient quartz and hematite cement; (b) thin section of the core at 115.1-m depth with crossed polars--dense gray quartzite with overgrowths of quartz and adularia filling pore space; (c) core at 115.1 m showing quartz and feldspar overgrowths; (d) adularia coating a fracture surface at 246.6 m; (e) pyrite coating a fracture surface at 148.7 m; (f) hematite pyrite at 133.5-m depth

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FLOW IN A SELF-SEALING GEOTHERMAL SYSTEM

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Fig. B-4. Schematic representation of the self-sealing mechanism

PART C: GEOPHYSICS

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(Paper not supplied)