FRESH-WATER SPRINGS OF HAWAII FROM INFRARED IMAGES

INTRODUCTION

The discharge of water from the island of Hawaii into the sea consists of ground-water flow at sea level from rock along the shore, flow in perennial streams, and occasional flow in ephemeral streams. From Hilo (pl. 1) clockwise around the island to the vicinity of Kawaihae, virtually all the discharge is ground-water flow at sea level. Around the rest of the island, the discharge is partly ground-water flow and partly streamflow. Perennial streams enter the sea from Kohala Mountains along the stretch of shore between Pololu Stream and Waipio Bay and from the northeastern slope of Mauna Kea between Laupahoehoe and Hilo.

Most of the discharge of ground water at sea level is diffused along rocky shores exposed to the waves; consequently, the flow can be measured at only a few places and many springs have gone unrecognized. Measurements indicated that the ocean waters surrounding the island are commonly warmer than the ground water discharging into them, thus suggesting that spring discharges might be located by observation of thermal patterns in the nearshore waters.

In an effort to gain further information on the location and flow of these springs, infrared images showing the distribution of apparent temperatures in the waters surrounding the island were obtained in January and February 1963 (Fischer, et al, 1964). These images, in the form of positive prints from negatives produced with electro-optional scanning radiometers (Harris, D. E., and Woodbridge, C. L., 1964), show differences in apparent temperatures as distinctions in shades of gray; relatively warm objects are recorded with lighter shades of gray than relatively cool objects. Figure 26B is a representative example of one of the images.

The infrared images, obtained in the course of these investigations, do show numerous features that contrast in apparent temperature with the surrounding ocean (fig. 26B). The pattern of these features and their thermal contrast with adjacent ocean waters suggest that they result from the spring discharge of fresh, relatively cool or relatively warm ground water into the ocean.

DATA GATHERED

Airborne data.—Aerial infrared imagery (recording energy in the part of the electromagnetic spectrum) between 4.5 and 5.5 microns and conventional aerial photographs were taken of nearly all coastline of the island. Areas imaged are shown on pl. 1. More than half the coastline was imaged more than once. Most flights were made during daylight hours.

Surface temperature measurements.—Measurements of the temperature of sea water were made throughout the period of investigation, principally in the vicinity of Hilo, Kalapana, and Punaluu. The maximum ocean temperature recorded was 28.5°C, the minimum 21°C, and the mean 23.1°C. The temperature of water pumped from wells near Kona ranged from 18° to 22°C. Temperature measurements made in caverns on the east flank of Kilauea suggest that these caverns, and the water that percolates through them, have a relatively constant temperature of approximately 16°C.

Ground-water discharge and its relation to thermal anomalies.—The average rainfall on the island of Hawaii amounts to more than 10 billion gallons of water per day, of which a substantial part discharges as perennial ground-water flow at the shore. The ground-water flow would be expected to be greatest along the shore of island sectors where rainfall is heavy. This pattern is illustrated to some degree by the number, size, and density contrast of the anomalies outlined on figures 1-26A and 27-29. These figures are ordinary aerial photographs rather than infrared images. Loss in clarity that occurs in halftone printing made it impractical to reproduce most of the infrared images, though figure 26B, in which the tonal contrasts are most distinct, is included as an example.

The most striking sector of apparently large discharge is the Hilo area (figs. 26A, 26B, and 27), where the mean annual rainfall is 100 to 200 inches. Large ground-water flows have been observed and measured along the Hilo coast. These measurements confirm the large discharges suggested by the anomalies on the infrared images. The greatest ground-water discharge in the Hilo area is at the outlet of Waiakea Pond into Hilo Bay (spring 165, figs. 26A and 26B). Waiakea Pond is estuarine, and the flow fluctuates with the tide and includes varying amounts of sea water. A series of measurements made during a 27-hour period in June 1930 showed an average discharge from the pond of 146 mgd (million gallons per day). In a series of 16 measurements made between November 1959 and May 1960, the flow varied between 120 and 238 mgd and averaged about 160 mgd. The flow is estimated to be at least two-thirds fresh ground water that issues from lava flows at the bottom and around the shore of Waiakea Pond.

A large ground-water discharge is visible at the head of Reeds Bay just east of Hilo Bay (spring 170, figs. 26A and 26B). The flow is difficult to measure by conventional methods but has been estimated to be 10 to 20 mgd.

In the Kau area, measurements of a part of the discharge have been made at Ninole and Kawaa Springs. The measurable flow at Ninole Springs (spring 61, fig. 7) was about 27 mgd in July 1961 and about 29 mgd in September 1963. The flow at Kawaa Springs (spring 64, fig. 7), a mile southwest of Ninole Springs, was about 13 mgd in October 1963. Unknown amounts flowed into the sea outside the measureable sections at both springs.

A contrasting sector of low discharge is the western shore of the island, covered by figures 20, 21, and 22, where the annual rainfall in the tributary area is generally less than 50 inches. Density anomalies in the infrared images here are few and scattered, are small in area, and have a relatively low contrast.

Areas of thermal anomaly suggesting discharge of water warmer than the ambient sea are numerous along the southeastern shore of the island (figs.. 1, 2, 4, 5, and 6). These anomalies can be attributed to the heating of ground water by volcanic activity. The cause of warm spots along the Kona coast (figs. 15 and 16), however, cannot be explained by information now available.

METHODS OF STUDY

Measurements of image tone (apparent temperature).—Positive transparencies of the infrared images were scanned to locate all nearshore areas having apparent thermal contrast with the image tone of the open sea. Images including thermal anomalies were compared with correlated conventional aerial photographs to identify and eliminate from further consideration those anomalies which clearly correspond to partially submerged rocks or surf. The contrast in film density between ambient ocean water and apparent nearshore thermal contrasts was measured with a MacBeth-Ansco densitometer. Density contrast is expressed, on figures 1-26A and 27-29 and in table 1, by a number which represents the maximum relative difference in film density between the anomaly and the ambient ocean water. The thermal contrast of warm anomalies is shown as a negative number. Where the area was imaged more than once, the image showing the maximum thermal contrast was used for this measurement.

Measurement of size of anomalies.—Contrast in film density between thermal anomalies and the ambient ocean seemingly relates to the temperature contrast between them. The areal extent of some anomalies on the imagery, however, is smaller than the minimum area that can be measured with the densitometer; thus, this measurement may not provide a reliable estimate of the thermal contrast of the smaller anomalies. Nevertheless, if one assumes that the temperatures of the smaller springs are relatively uniform, this measurement may serve to assist in estimating the relative flow of the springs causing the smaller anomalies.

The size of each of the thermal anomalies, as shown on figures 1-26A and 27-29 and in table 1, is considered to relate, in part at least, to the rate of flow of the springs. This size was determined by a combination of densitometer measurement and visual inspection. The outlines of the anomalies, shown on figures 1-26A and 27-29, represent the edges of detectable tone contrasts. Where multiple images were available, the image showing the maximum areal extent of the anomaly was used to derive the outline.

Differences between massive images of the same area may relate to changes in sea condition or tidal stage, but they may be due also to differences in gain settings of the infrared equipment (gain settings must be adjusted in flight to accommodate varying levels of energy emitted from the earth).

REFERENCES

Fischer, W. A., Moxham, R. M., Polcyn, F., and Landis, G. H., 1964, Infrared surveys of Hawaiian volcanoes: Science, vol. 146, no. 3645, p. 733-742.
Harris, D. E., and Woodbridge, C. L., 1964, Terrain mapping by use of infrared radiation: Photogramm. Eng., 30, no. 1, p. 134-139.

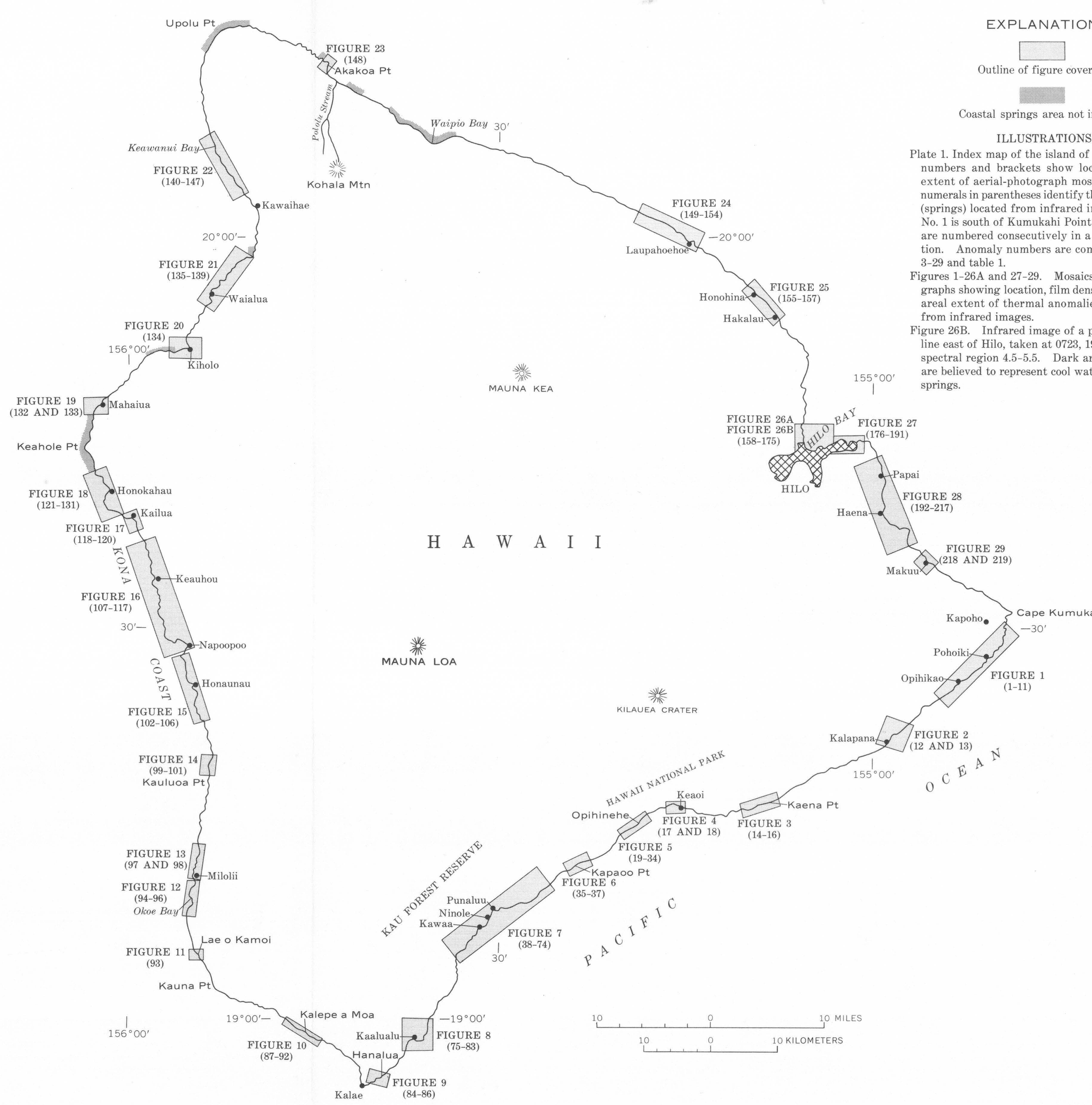

PLATE 1.— *Location map of spring areas*

EXPLANATION

Outline of figure coverage

Coastal springs area not imaged

ILLUSTRATIONS

Plate 1. Index map of the island of Hawaii. Figure numbers and brackets show location and areal extent of aerial-photograph mosaics (figs. 3-29); numerals in parentheses identify thermal anomalies (springs) located from infrared images; anomaly No. 1 is south of Kumukahi Point; other anomalies are numbered consecutively in a clockwise direction. Anomaly numbers are common to figures 3-29 and table 1.

Figures 1-26A and 27-29. Mosaics of aerial photographs showing location, film density contrast, and areal extent of thermal anomalies as interpreted from infrared images.

Figure 26B. Infrared image of a part of the coastline east of Hilo, taken at 0723, 19 February 1963; spectral region 4.5-5.5. Dark areas in the ocean are believed to represent cool water discharged by springs.

TABLE 1.—*Table showing spring number, area of thermal disturbance, and descriptive information*

[Under "Reliability", a question mark indicates doubt whether the anomaly represents a discharge of ground water. Under "Density contrast", a minus sign indicates ground water warmer than the ambient sea]

Spring No.	Reliability	Approximate area (sq. ft.)	Density contrast	Remarks	Figure
1	[illegible]	[illegible]	[illegible]		1
2	[illegible]	[illegible]	[illegible]		
3	[illegible]	[illegible]	[illegible]		
4	[illegible]	[illegible]	[illegible]		
5	[illegible]	[illegible]	[illegible]		
6	[illegible]	[illegible]	[illegible]	Hot	
7	[illegible]	[illegible]	[illegible]		
8	[illegible]	[illegible]	[illegible]		
9	[illegible]	[illegible]	[illegible]		
10	[illegible]	[illegible]	[illegible]		
11	[illegible]	[illegible]	[illegible]		
12	[illegible]	[illegible]	[illegible]	do	2
13	[illegible]	[illegible]	[illegible]		
14	[illegible]	[illegible]	[illegible]	do	3
15	[illegible]	[illegible]	[illegible]		
16	[illegible]	[illegible]	[illegible]		
17	[illegible]	[illegible]	[illegible]	do	4
18	[illegible]	[illegible]	[illegible]		
19	[illegible]	[illegible]	[illegible]		5
20	[illegible]	[illegible]	[illegible]		
21	[illegible]	[illegible]	[illegible]		
22	[illegible]	[illegible]	[illegible]		
23	[illegible]	[illegible]	[illegible]		
24	[illegible]	[illegible]	[illegible]		
25	[illegible]	[illegible]	[illegible]		
26	[illegible]	[illegible]	[illegible]	do	
27	[illegible]	[illegible]	[illegible]		
28	[illegible]	[illegible]	[illegible]		
29	[illegible]	[illegible]	[illegible]		
30	[illegible]	[illegible]	[illegible]		
31	[illegible]	[illegible]	[illegible]		
32	[illegible]	[illegible]	[illegible]		
33	[illegible]	[illegible]	[illegible]		
34	[illegible]	[illegible]	[illegible]		
35	[illegible]	[illegible]	[illegible]		6
36	[illegible]	[illegible]	[illegible]	do	
37	[illegible]	[illegible]	[illegible]		
38	[illegible]	[illegible]	[illegible]		7
39	[illegible]	[illegible]	[illegible]		
40	[illegible]	[illegible]	[illegible]		
41	[illegible]	[illegible]	[illegible]		
42	[illegible]	[illegible]	[illegible]		
43	[illegible]	[illegible]	[illegible]		
44	[illegible]	[illegible]	[illegible]		
45	[illegible]	[illegible]	[illegible]		
46	[illegible]	[illegible]	[illegible]		
47	[illegible]	[illegible]	[illegible]		
48	[illegible]	[illegible]	[illegible]		
49	[illegible]	[illegible]	[illegible]		
50	[illegible]	[illegible]	[illegible]		
51	[illegible]	[illegible]	[illegible]		
52	[illegible]	[illegible]	[illegible]		
53	[illegible]	[illegible]	[illegible]		
54	[illegible]	[illegible]	[illegible]		
55	[illegible]	[illegible]	[illegible]		
56	[illegible]	[illegible]	[illegible]		
57	[illegible]	[illegible]	[illegible]		
58	[illegible]	[illegible]	[illegible]		
59	[illegible]	[illegible]	[illegible]		
60	[illegible]	[illegible]	[illegible]		
61	[illegible]	[illegible]	[illegible]		
62	[illegible]	[illegible]	[illegible]		
63	[illegible]	[illegible]	[illegible]		
64	[illegible]	[illegible]	[illegible]		
65	[illegible]	[illegible]	[illegible]		
66	[illegible]	[illegible]	[illegible]		
67	[illegible]	[illegible]	[illegible]		
68	[illegible]	[illegible]	[illegible]		
69	[illegible]	[illegible]	[illegible]		
70	[illegible]	[illegible]	[illegible]		
71	[illegible]	[illegible]	[illegible]		
72	[illegible]	[illegible]	[illegible]		
73	[illegible]	[illegible]	[illegible]		
74	[illegible]	[illegible]	[illegible]		
75	[illegible]	[illegible]	[illegible]		8
76	[illegible]	[illegible]	[illegible]		
77	[illegible]	[illegible]	[illegible]		
78	[illegible]	[illegible]	[illegible]		
79	[illegible]	[illegible]	[illegible]		
80	[illegible]	[illegible]	[illegible]		
81	[illegible]	[illegible]	[illegible]		
82	[illegible]	[illegible]	[illegible]		
83	[illegible]	[illegible]	[illegible]		
84	[illegible]	[illegible]	[illegible]		9
85	[illegible]	[illegible]	[illegible]		
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94	[illegible]	[illegible]	[illegible]		12
95	[illegible]	[illegible]	[illegible]		
96	[illegible]	[illegible]	[illegible]		
97	[illegible]	[illegible]	[illegible]		13
98	[illegible]	[illegible]	[illegible]		
99	[illegible]	[illegible]	[illegible]		14
100	[illegible]	[illegible]	[illegible]		
101	[illegible]	[illegible]	[illegible]		
102	[illegible]	[illegible]	[illegible]	Hot	15
103	[illegible]	[illegible]	[illegible]		
104	[illegible]	[illegible]	[illegible]		
105	[illegible]	[illegible]	[illegible]	do	
106	[illegible]	[illegible]	[illegible]		
107	[illegible]	[illegible]	[illegible]		16
108	[illegible]	[illegible]	[illegible]	do	
109	[illegible]	[illegible]	[illegible]	do	
110	[illegible]	[illegible]	[illegible]		
111	?	35,000	−0.10	Hot	16
112	?	70,000	−.05	do	
113	?	140,000	.20		
114	?	110,000	−.10	do	
115	?	110,000	−.05	do	
116	?	45,000	−.05	do	
117	?	215,000	−.05	do	
118	?	10,000	.10		17
119	?	10,000	.10		
120		665,000	.21		
121	?	25,000	.05		18
122	?	10,000	.20		
123		10,000	.38		
124		15,000	.44		
125		10,000	.44		
126		10,000	.24		
127		40,000	.24		
128		15,000	.18		
129		65,000	.10		
130		100,000	.14		
131	?	10,000	.20		
132	?	115,000	.10		19
133	?	55,000	.10		
134	?	55,000	.10		20
135	?	505,000	.20		21
136	?	200,000	.16		
137	?	305,000	.15		
138	?	2,025,000	.20		
139	?	150,000	.10		
140	?	10,000	.06		22
141	?	15,000	.06		
142	?	10,000	.06		
143	?	15,000	.06		
144	?	10,000	.06		
145	?	10,000	.06		
146	?	20,000	.06		
147	?	25,000	.06		
148		110,000	.10		23
149	?	1,010,000	.10		24
150	?	405,000	.12		
151	?	150,000	.12		
152	?	100,000	.12		
153	?	1,420,000	.30		
154	?	1,010,000	.30		
155		200,000	.10		25
156	?	200,000	.14		
157		1,420,000	.20		
158	?	2,455,000	.24		26
159	?	1,155,000	.20		
160	?	2,020,000	.30		
161		1,590,000	.38		
162	?	2,310,000	.44	Diffuse flow; difficult to determine boundaries	
163	?	5,200,000	.50		
164	?	4,765,000	.60		
165		127,940,000	.62		
166		6,790,000	.34		
167		10,540,000	.42		
168		6,790,000	.44	do	
169	?	360,000	.44		
170		30,610,000	.70	do	
171		13,000,000	.64		
172		1,820,000	.62		
173		4,455,000	.60		
174		3,180,000	.60		
175		720,000	.34		
176		11,500,000	.66	do	27
177		8,665,000	.68		
178		1,445,000	.54		
179	?	110,000	.10		
180		375,000	.54		
181		300,000	.68		
182		360,000	.68		
183		2,890,000	.40		
184		2,310,000	.60	do	
185		1,010,000	.50		
186		435,000	.38		
187		290,000	.15		
188		145,000	.15		
189		80,000	.15		
190		865,000	.40		
191		360,000	.36		
192	?	75,000	.10		28
193	?	150,000	.04		
194		100,000	.70		
195		405,000	.70		
196		365,000	.20		
197	?	150,000	.20		
198	?	150,000	.30		
199		1,115,000	.30		
200	?	75,000	.10		
201	?	80,000	.10		
202	?	202,000	.04		
203	?	405,000	.10		
204	?	810,000	.20		
205	?	250,000	.46		
206		150,000	.10		
207		100,000	.10		
208	?	50,000	.10		
209	?	100,000	.10		
210	?	210,000	.10		
211	?	500,000	.10		
212	?	200,000	.10		
213	?	150,000	.10		
214	?	150,000	.10		
215	?	160,000	.10		
216	?	405,000	.10		
217	?	100,000	.10		
218	?	72,000	.20		29
219	?	470,000	.10		

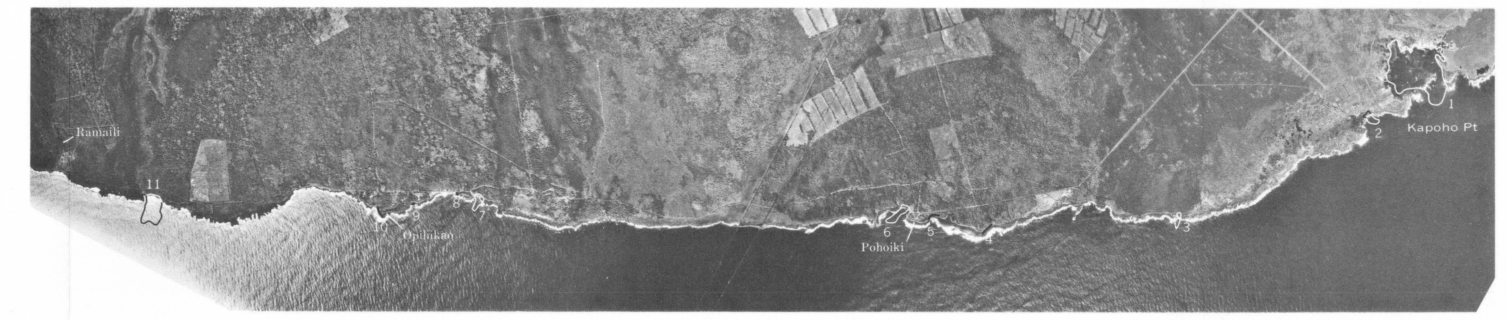

FIGURE 1
(1-11)

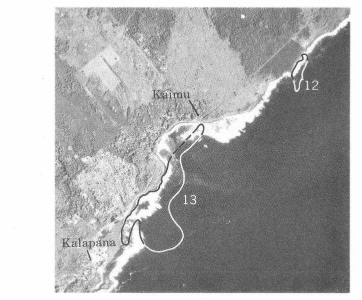

FIGURE 2
(12 AND 13)

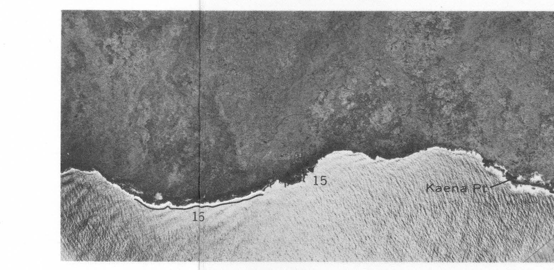

FIGURE 3
(14-16)

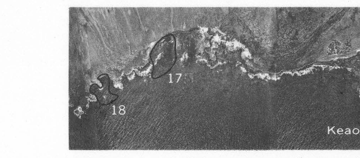

FIGURE 4
(17 AND 18)

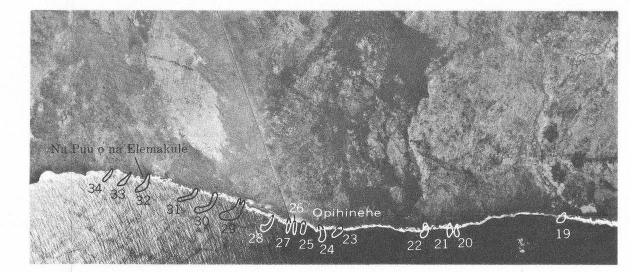

FIGURE 5
(19-34)

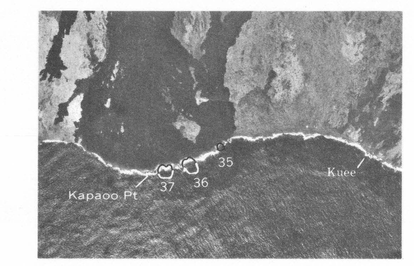

FIGURE 6
(35-37)

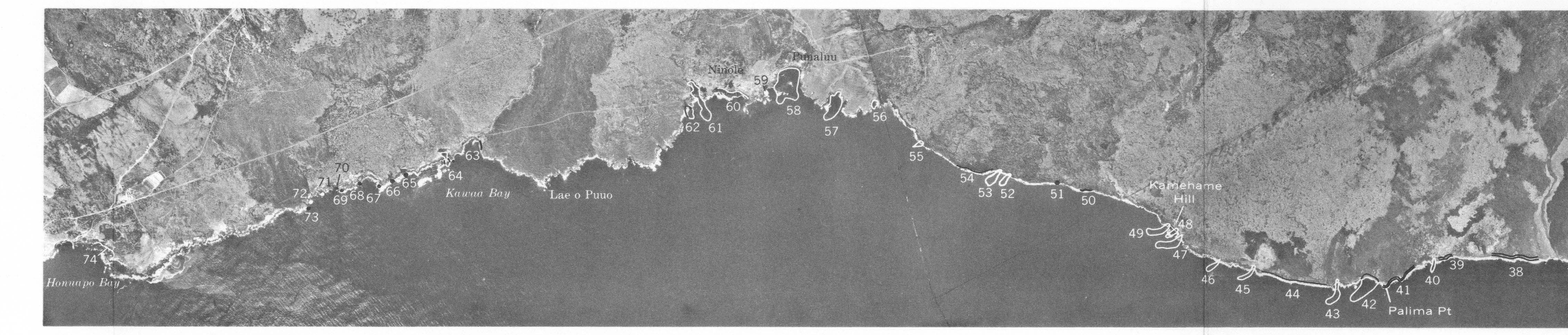

FIGURE 7
(38-74)

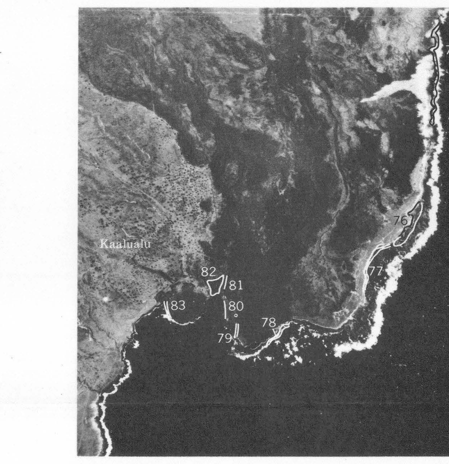

FIGURE 8
(75-83)

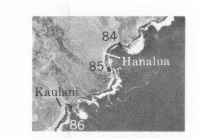

FIGURE 9
(84-86)

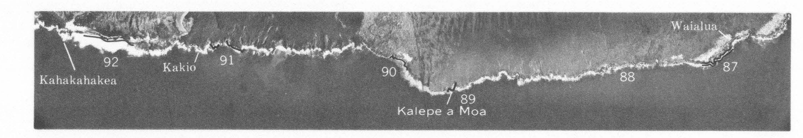

FIGURE 10
(87-92)

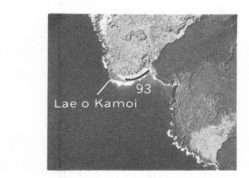

FIGURE 11
(93)

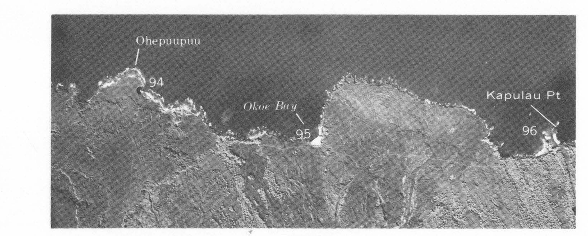

FIGURE 12
(94-96)

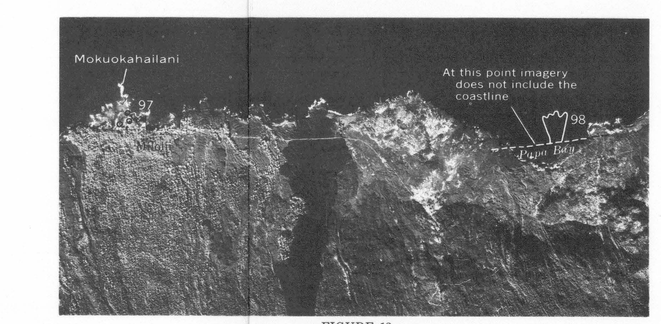

FIGURE 13
(97 AND 98)

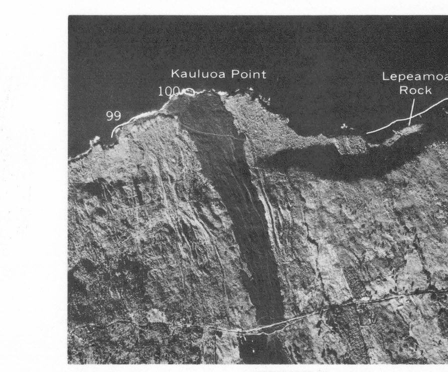

FIGURE 14
(99-101)

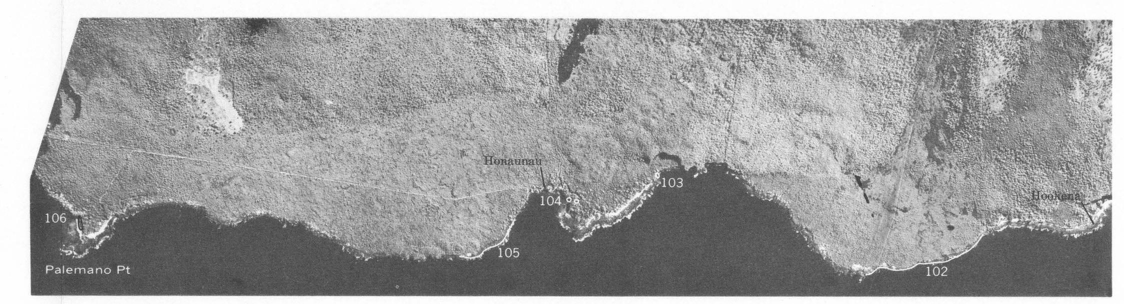

FIGURE 15
(102-106)

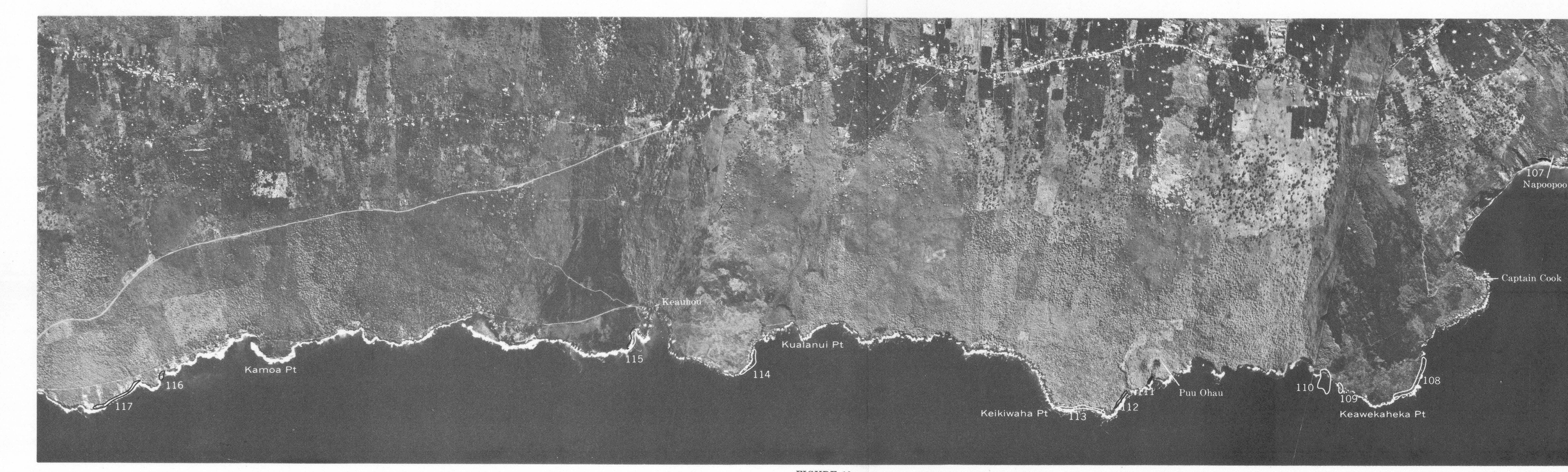

FIGURE 16
(107-117)

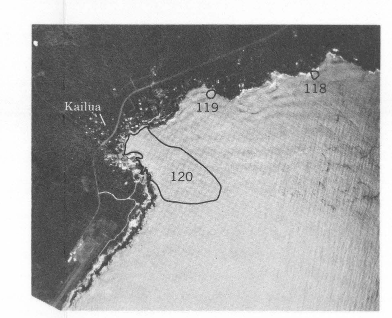

FIGURE 17
(118-120)

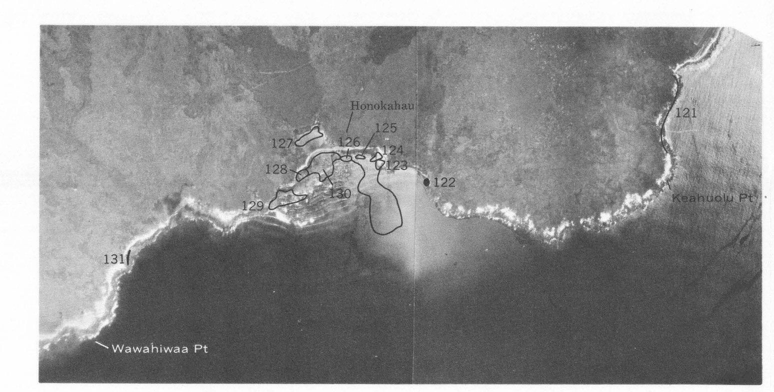

FIGURE 18
(121-131)

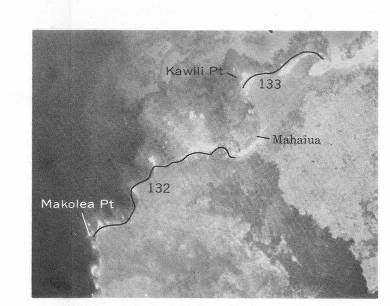

FIGURE 19
(132 AND 133)

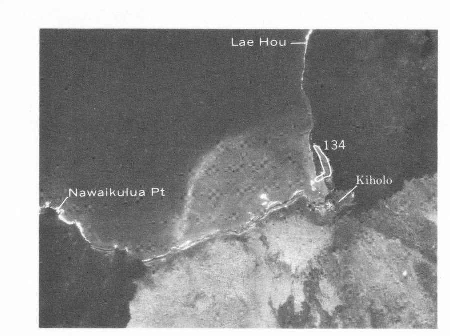

FIGURE 20
(134)

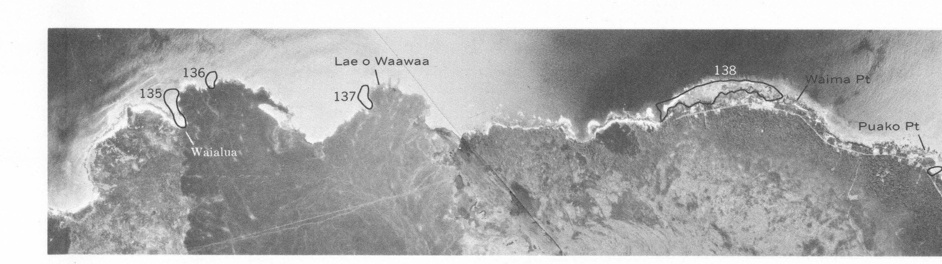

FIGURE 21
(135-139)

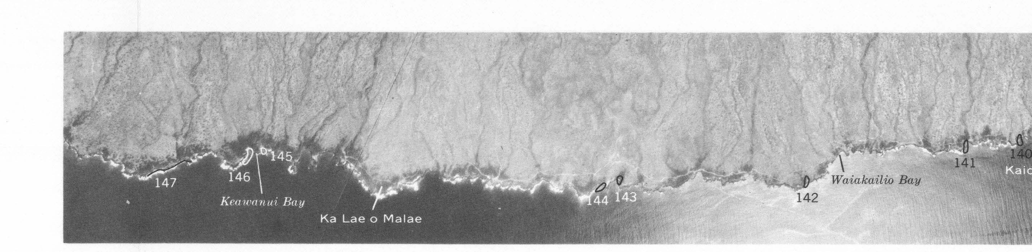

FIGURE 22
(140-147)

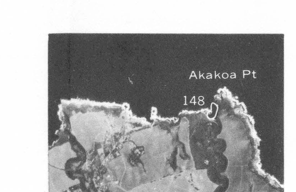

FIGURE 23
(148)

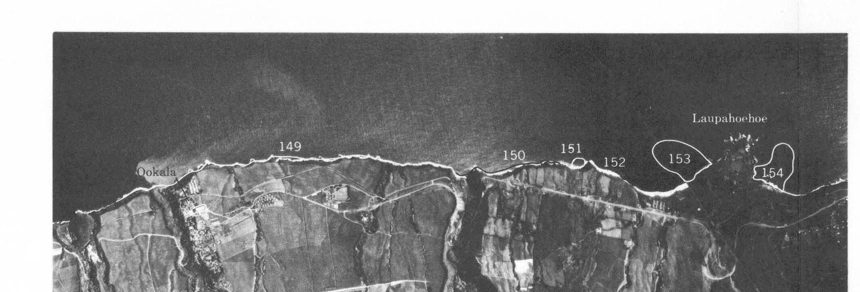

FIGURE 24
(149-154)

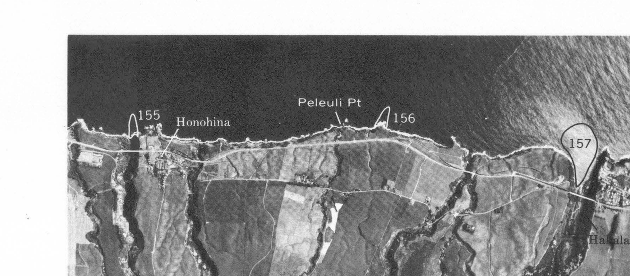

FIGURE 25
(155-157)

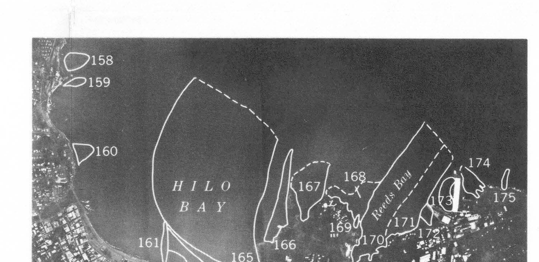

FIGURE 26A
(158-175)

FIGURE 26B

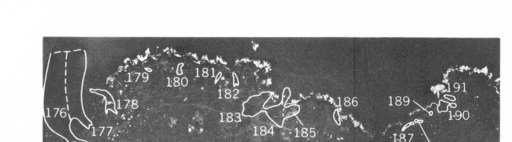

FIGURE 27
(176-191)

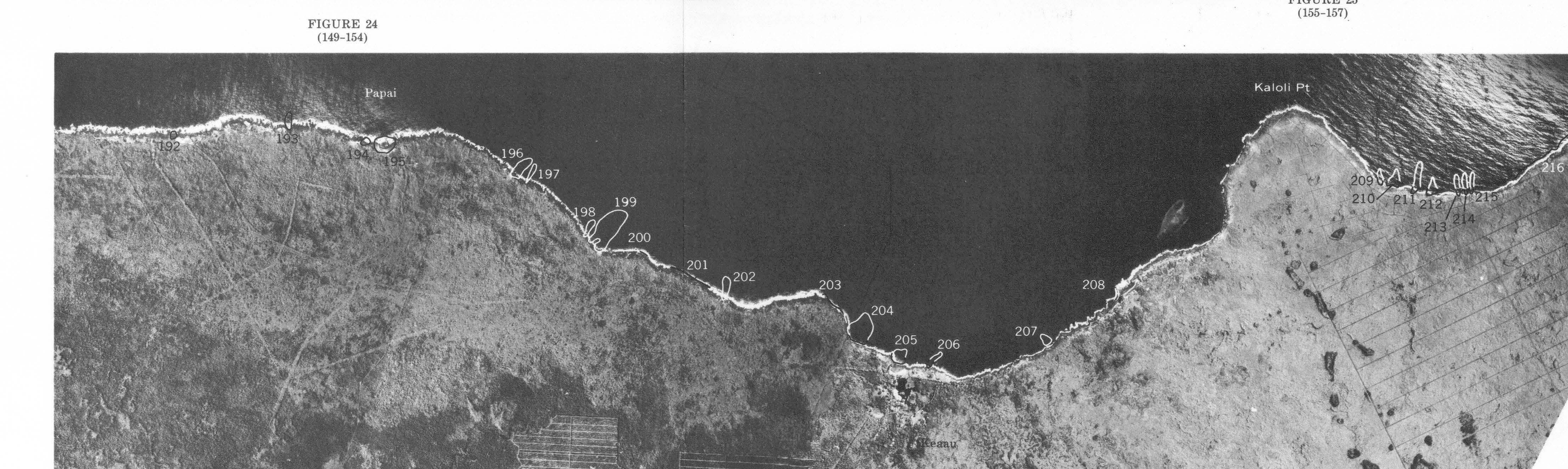

FIGURE 28
(192-217)

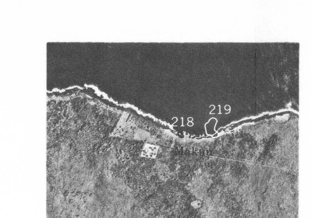

FIGURE 29
(218 AND 219)

FRESH-WATER SPRINGS OF HAWAII FROM INFRARED IMAGES

By
William A. Fischer, Dan A. Davis, and Theresa M. Sousa

1966

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