UNITED STATES DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

Results From Camera Tows Along the Southern Juan de Fuca Ridge:

A2-84-WF

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Open-File Report 88-371

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ABSTRACT

Nine camera tows carried out along the southern Juan de Fuca Ridge during the summer of 1984 extended photographic and video coverage north of the main USGS study area. These data, together with one camera tow conducted outside of the axial valley, provide ground-truth data for Sea MARC I and II acoustic images of the ridge axial zone. In addition, four new hydrothermal vents were discovered within the axial valley between latitudes 44°43'N and 44°54'N.

INTRODUCTION

The Juan de Fuca Ridge (JdFR) is a medium-rate (full spreading rate of 6 cm/yr) oceanic spreading center located approximately 500 km off the coasts of Oregon and Washington in the northeast Pacific Ocean (Figure 1). The ridge extends for nearly 500 km between the Blanco and Sovanco transform faults and separates the Pacific Plate from the Juan de Fuca Plate.

Discoveries of high temperature hydrothermal venting, associated sulfide deposits, and unusual biota along the neovolcanic zones of medium-rate Pacific spreading centers ,such as the Galapagos Spreading Center (Ballard and others, 1982) and the East Pacific Rise at 21°N (CYAMEX Scientific Team, 1979; RISE Project Group, 1980), prompted scientists from the U.S. Geological Survey (USGS) and the National Oceanic and Atmospheric Administration (NOAA) to look for similar mineral-forming systems along the Juan de Fuca and Gorda Ridges. Part of this ridge system is close to or within the West Coast Exclusive Economic Zone (EEZ). An advantage of studying the southern Juan de Fuca Ridge is its uncomplicated, symmetrical axial rift as well as its proximity to both academic and government oceanographic research facilities in the northeast Pacific region. A continuing effort to study and monitor various aspects of seafloor sulfide deposits, including the chemistry of hydrothermal vent fluids and associated sulfide deposits and the geological setting of the sulfide deposits, has been a priority of these U.S. agencies.

In this report we present the results of nine camera tows carried out along the southern Juan de Fuca Ridge during the summer of 1984. The aim of the camera tows was to characterize acoustic targets of particular interest that were identified on Sea MARC I and Sea MARC II side-looking sonar images. In particular, we were interested in the volcanic morphologies and relative ages (amount of sediment cover) of the seafloor substrate near the spreading axis and the magnitude of variations in these characteristics that could be resolved by the sonar images. A primary goal was to extend the photographic survey north of the area of massive sulfide deposits previously studied by extensive photographic and submersible observations (Normark and others, 1983; USGS Juan de Fuca Study Group, 1986; Normark and others, 1987) to determine if hydrothermal vent fields existed north of the main study area.

PREVIOUS WORK

The base maps for the photographic work in 1984 utilized data collected by the following research groups.

USGS

The University of Washington and the USGS conducted separate reconnaissance surveys of the southern JdFR in 1980. A joint effort in 1981 included comprehensive photographic surveys and sampling that resulted in the discovery of a series of hydrothermal vents along the center of the axial valley between latitudes 44°38'N and 44°42'N. Further sampling of the vent area, together with limited photographic work in 1982, was followed by extensive photographic coverage in 1983 using ANGUS (Phillips and others, 1979) and a new USGS system that employs both 35 mm still photography and color video (Chezar and Lee, 1985). During the same summer, side-looking sonar images of the southern JdFR using the near-surface-towed Sea MARC II system of the Hawaii Institute of Geophysics (Hussong and Fryer, 1983) were obtained as a part of a contracted survey of the Gorda Ridge (Clague and Holmes, 1987).

The wealth of precisely navigated photographic data (~80,000 still photos and more than 50 hours of video) available for the 10 square kilometer segment of the southern JdFR included abundant photographic evidence of sulfide deposits, and provided detailed base maps for the *Alvin* diving expedition to the southern JdFR. The *Alvin* diving program results are are discussed in more detail by the U.S. Geological Survey Juan de Fuca Study Group (1986) and in a special issue of the *Journal of Geophysical Research* (October 1987). The diving program concentrated on the mapping and sampling of hydrothermal vent and sulfide deposits (Normark and others, 1987).

Photographic surveys were conducted during the night-time hours of the 1984 USGS field program aboard the *Atlantis II*. The objectives of the 1984 camera tows were to provide photographic ground truth for acoustic targets picked from the available Sea MARC I and II side-looking sonar images (Figs. 2 and 3), in contrast to the detailed photogeologic mapping of a relatively small section (12 km by 1 km) of the ridge-crest axial valley that characterized work prior to the *Alvin* diving expedition. We also were aware of the location of the ground-truth camera tows completed by scientists from the Lamont-Doherty Geological Observatory (LDGO) and the National Oceanic and Atmospheric Administration (NOAA; Kappel, 1985) and so avoided duplication of already-photographed sonar targets. During our photographic surveys from the *Atlantis II* in 1984, we felt it was particularly critical to tow the camera across the faulted terraces as well as outside the JdFR axial valley in order to document volcanic flow forms and degree of sediment cover as no photographic work had previously been done outside of the axial valley in this area.

NOAA/LDGO Data

During the fall of 1982, scientists from LDGO and NOAA used LDGO's deep-towed Sea MARC I side-looking sonar (Chayes, 1983) to map the spreading axis of a 400 km segment of the JdFR (Kappel and Ryan, 1986). The main objective of the side-looking sonar survey was to map the along-axis variability in tectonic and volcanic terrains of an active midocean ridge. Follow-up ground-truth photographic calibration of the side-looking sonar images along the southernmost 50 km of the JdFR was carried out the following summer by the same groups (Embley and others, 1983; Kappel and others, 1983; Kappel, 1985). A 10-km axial swath along the southernmost 50 km of the JdFR has also been bathymetrically mapped with the Sea Beam multi-beam sonar (A. Malahoff, R. Embley, S. Hammond, unpublished data, 1981). High resolution (5 m contour interval) bathymetric maps along this segment of the southern JdFR were constructed from depth and seafloor morphologic data gathered from the above field expeditions, supplemented by 22 single-narrow-beam crossings perpendicular to the spreading axis gathered during the 1983 field expedition on board the NOAA ship *Discoverer* (Kappel, 1985).

METHODS

Instrumentation

Photographic information was collected with the USGS deep-sea camera sled (Chezar and Lee, 1985). The camera sled contained an instrument package consisting of: 1) a 35 mm Olympus

OM 2N still camera in a deep-sea pressure case; 2) a Sony Beta format DXC 1800 color video camera (industrial quality) in a pressure case ; 3) five Olympus auto-thyristor strobes for illumination for the still camera; 4) two standard 250- watt floodlights for a total of 500 watts of illumination for the video camera; 5) 12 kHz pinger system that transmits a standard acoustic pulse, and two ancillary transmissions from separate sensors that provide an expanded scale altitude profile and a time-delay transmission giving relative water temperature values; and 6) an Aanderaa currentmeter. The Sony video has a recording time of four hours and thirty minutes. The still camera can take photos for about 12 hours if the repetition rate of the camera is set at 14 seconds. The Aanderaa currentmeter records pressure, temperature, speed, heading, and conductivity every 30 seconds throughout the camera lowering. The camera is towed on a non-conducting steel cable at ship speeds rarely exceeding one knot. The altitude of the camera is monitored by the acoustic pinger system and generally maintained within photographic range (3-5 meters above the seafloor) by paying wire in or out.

Navigation

All of the maps presented in this report have been adjusted to the transit satellite coordinate system. First, the USGS transponder system has been tied into the satellite coordinate system by simultaneously acquiring transit satellite fixes and acoustic ranges to the transponders. Sea MARC II is tied directly to the USGS transponder network using a limited number of positions obtained for the ship with the acoustic transponders. Sea MARC I has been translated to the satellite coordinate system from a Loran C coordinate system, thus providing a general registration of Sea MARC I to the transponder network. The Sea MARC I translation was accomplished by averaging the offset between simultaneously recorded Loran C and transit satellite fixes along the ship track. The same method was used to transfer Loran C navigation for the narrow-beam survey to the satellite coordinate system. The satellite coordinate systems computed for both the Sea MARC I and II data have been cross-checked by matching the position of acoustically-distinct targets. Finally, the camera tows from the 1984 *Atlantis II* expedition navigated by Loran C have been translated to the satellite coordinate system; during the transponder-navigated camera tows, Loran C fixes also were recorded, allowing determination of the satellite/Loran C offset and adjustment of the Loran C-navigated camera tows accordingly. Thus, ship-board navigation and, hence, data from 6 cruises (5 different ships) have been directly tied to the U. S. Geological Survey transponder network with varying degrees of certainty.

Transponder Navigation of the Camera Sled : Whenever the USGS camera passed through the main work area of the hydrothermal vents between latitudes 44°38'N and 44°42'N, it was possible to directly position the sled relative to the bottom-anchored transponders. A relay transponder was placed on the mechanical tow cable 100 or 200 meters above the camera sled. The transponder network consists of as many as five transponders that are anchored along the faulted terraces of the ridge's axial valley and are about 2.5-3.0 km apart. Only three bottom transponders could be used at any time for real-time positioning because of limitations of the recording system. Position accuracy is generally on the order of ±5 m. The transponder network has been maintained in this study area since 1981 so that all USGS operations are directly linked.

Loran C +Aanderaa : Where the camera tows left the area of effective positioning using the transponder net, positions were determined by integrating Loran C locations for the ship with the depth, heading and speed information from an Aanderaa currentmeter on the camera sled. First, ship positions were plotted every 10 minutes from Loran C fixes recorded on board the ship. This tentative location of the ship track was checked by comparing the depth at each ship's position estimate with the best available bathymetric data (Kappel, 1985).

The final approximation of camera positions were obtained by fitting seafloor bathymetric profiles from the camera-sled sensors with the high-resolution bathymetric maps using the camera's speed and heading from the Aanderaa current meter for the best fit. The seafloor profiles beneath the camera sled were computed by adding the acoustic measurement of the camera altitude from digitized ship-board records to the pressure depth measurement obtained from the Aanderaa currentmeter. Seafloor depths were adjusted to Sea Beam depths by a linear correction computed by comparing seafloor profile depths (pressure depth) to Sea Beam bathymetric maps in areas where the camera traversed a smooth surface (so that there would be little ambiguity in the Sea Beam depth).

Figure 4 compares the ship's position determined by Loran C for 30-minute intervals during Station 5 with the corresponding position from the acoustic-transponder system. Although individual positions determined by Loran C are between 50 and 425m from the corresponding transponder positions, the tracklines generally agree within 200m; the discrepancies do not show a consistant offset trend. More frequent (10-minute interval) Loran C position determinations outside the area of acoustic-transponder coverage provided more reliable trackline control by allowing us to recognize those positions that are most likely to be bad fixes. Matching the water depth at the camera sled to the detailed bathymetry along the general (smoothed) trackline based on Loran C provides additional constraints on the camera position. Thus, we estimate that our location error for the camera sled using these techniques in the best case is about 100 m.

RESULTS

The along-strike area covered by the 1984 camera tows is more than twice that of the USGS study area of past years (Figures 2 and 3). The main purpose of the camera tows was to provide visual documentation of the seafloor substrate imaged with the side-looking sonars. An additional benefit of the increased photo coverage in the area north of the USGS study (camera runs 7, 8, 9; Figures 3 and 5F-H) was the discovery of numerous regions of active hydrothermal venting. (Table 1).

Appendix of Photographic and Video Data

All of the still photographs and video tapes from the camera tows were examined in detail to produce photographic logs that record the following principal characteristics of the seafloor: 1) volcanic flow morphology; 2) an estimate of the amount of sediment cover; 3) the degree of disruption of the volcanic flow forms by faults, fissures, or collapse pits; 4) the presence of previously unknown hydrothermal vent features; 5) the type (if known) and density of fauna; and 6) orientation and relative offset of faults. The Appendix to this report (in which the main results of this report are tabulated) is an abridged version of the detailed camera logs. This edited summary synthesizes the observations in mappable units to avoid a laborious presentation of individual descriptions of the more than 11,000 photographs and 40 hours of color-video images. The unabridged version of the camera logs is available for inspection from one of the authors (ESK).

Both the still camera and video system were operational during all nine camera stations. However, the 35-mm still camera functioned intermittantly during Camera Station 1 and failed completely for Station 11, so the abridged camera log (Appendix) for these two tows is somewhat less informative than the other camera stations.

Geologic Sections

The new photographic data, even when combined with the existing LDGO/NOAA camera data, do not cover a sufficient area to produce a generalized geologic map of the axial region. All the photographs have been used to help interpret the structural and volcanic textural characteristics mapped with side-looking sonar systems (Kappel and Normark, 1987). We have constructed geologic sections along the camera paths to summarize the volcanic and sedimentary characteristics with respect to topography (Figure 5A-J).

All of the camera tows were primarily within the axial valley with the exception of Camera Station 5, which traversed a section of the western crestal ridge shoulder (Figure 2). Nearly all of the flows within the axial valley were sheet and lobate flows with varying degree of sediment cover. To the north of the USGS study area, we rarely photographed the youngest, glassy flows that have been mapped in the axial valley further south, nor did we encounter many pillow-lava flows. A majority of the sheet and lobate flows were pitted, and the pits were generally shallow (<1m deep).

Along Station 5 where the camera traversed the shoulder of the crestal ridge, the flows was significantly older (they had more sediment covering them, on average, than flows within the axial valley). The relative proportion of pillow-flow forms were also significantly greater on the crestal ridge shoulders, and tectonic fracturing within the flows was rare.

DISCUSSION

The photographic data obtained during the A2-84-WF cruise have been used to provide information for interpretation of both long and intermediate range sonar imagery of the axial region as well as identification of previously unknown hydrothermal vent sites.

Sonar Image Ground Truth

Figures 2 and 3 are interpretations of Sea MARC I and II side-looking sonar images of the southern Juan de Fuca Ridge study area (Kappel and Normark, 1987). The higher proportion of pillow flows on the crestal-ridge shoulders is probably the primary cause for the hummocky texture there (Figures 2 and 3); the smoother axial valley floor is a result of the dominance of lobate and sheet flow lava morphology. Station 5 also confirms our interpretation from the sonar data that the shoulders of the crestal ridge have relatively few faults and fissures, while the camera tows within the axial valley are consistent with previous photogeologic mapping that showed the axial valley floor to be riddled with collapse pits, especially common adjacent to the central cleft.

The camera stations provided the critical ground-truth for the side-looking sonar images and additional detail beyond the resolution of the side-looking sonar systems. Differences in sediment cover within patches of tens of meters or less in diameter are not easily identified on the sonar images. Similarly, flow types cannot generally be distinguished without photographic calibration. We also cannot distinguish very pitted sheet and lobate flows from unpitted ones on the sonar images because either the pitted or unpitted flows generally do not occur in patches large enough to be resolved by the sonar (one pixel width is 125 m).

Relative Age

Average sedimentation rates along the southern JdFR are between 0.6 and 2.0 cm per thousand years (Gary Massoth, written communication, 1986). This rate is based upon cores taken 15 and 43 km, respectively, west of the axis of the southern JdFR. We have also calculated sedimentation rates based upon the thickness of sediment measured on 3.5 kHz wide-beam echo-sounding records for areas extending up to 25 km off axis. Assuming a sound velocity of 1486 m/sec for the sediments, we obtain average sedimentation rates between 0.7 and 1.5 cm per thousand years, which are in general agreement with Massoth's measurements based on the core data.

Extensive areas of sheet and lobate lava flows with low surface relief in the axial valley show little or no sediment cover on fresh glassy basalt surfaces. These flow units are probably only a few hundred years or less in age. On the crestal ridge shoulders where pillow lavas are more common and surface relief is greater, it is harder to estimate the age from the degree of sediment cover. Our photo data show complete sediment cover only locally on the crestal ridge shoulders, and the general degree of sediment cover would suggest an age of ±10,000 years. Based on observations from three cameral tows (Stations 7, 8, and 9), a smaller proportion of the valley floor north of the main USGS study area (Figure 3) is underlain by very young (unsedimented) lava flows.

New Hydrothermal Vents

The A2-84-WF camera stations provided visual evidence for at least four more hydrothermal-vent sites along the ridge axis between 2 and 20 km north of the vent areas studied with the *Alvin* submersible (USGS Juan de Fuca Study Group, 1986; Normark and others, 1987). These new vent areas (Table 1) were not identified by the sonar mapping. The discovery of several new vents with reconnaissance photo coverage suggest that the entire southern segment of the Juan de Fuca Ridge has abundant hydrothermal activity regardless of the distance from fracture zones (or other offsets of the axis) or the relative elevation of the axial zone as has been suggested from studies at other spreading ridges (Francheteau and Ballard, 1983). One of the larger vent areas discovered during the camera work is within the area covered by a large water-column "megaplume" of hydrothermal discharge recently reported (Baker and others, 1987).

ACKNOWLEDGEMENTS

We would like to extend many thanks to the superb "camera team," that includes those who helped carry out the successes at sea as well as those who assisted on the beach. This includes H. Chezar, R. Field and K. O'Toole, whom we acknowledge for the technical workings of the USGS camera system, the night navigation team that included S. L. Ross and R. Zierenberg, and the many people at the USGS who spent endless hours helping to refine the navigation - S. L. Ross, D. Tatman, C. E. Gutmacher, and J. L. Morton. At L-DGO, T. Manley was particularly helpful in deciphering the Aanderaa tapes. We would also like to thank the officers and crew of the *Atlantis II* who, despite the "millions" of course and speed changes per camera tow, the cold, wet and windy nights on the deck running the winch (up one, down two...), and the clambering out of bed before sunrise to recover the camera, were always cooperative and helpful. The authors appreciate the thoughtful review of this manuscript by R. Zierenberg.

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FIGURE CAPTIONS

<u>Figure 1:</u> Schematic diagram of southern Juan de Fuca Ridge (JdFR) and Blanco Fracture Zone, with along-strike extent of the Sea MARC I and Sea MARC II swaths as shown in Figures 2 and 3. See inset for location. The location of Figures 2 and 3 are within the double line that depicts the area of Sea MARC I coverage.

<u>Figure 2:</u> Interpretation of Sea MARC I and II images of the crestal region and eastern flank of the southernmost Juan de Fuca Ridge. Number symbol indicates USGS vent areas visited with the *Alvin* submersible in 1984 (see Normark and others, 1987). The term axial valley is used here instead of elongate summit depression preferred by Kappel and Ryan (1986) in order to be consistent with the historical and current USGS usage of the term.

<u>Figure 3:</u> Interpretation of Sea MARC I image of the crestal region of the southernmost Juan de Fuca Ridge north of segment in Figure 2. Symbols as in Figure 2. The legend for this figure appears in Figure 2. Solid dots indicate hydrothermal vent sites discovered through this study (see Table 1).

<u>Figure 4:</u> Comparison of Loran C positions for the ship with tracklines determined by acoustic-transponder ranges for both the ship and camera system. Location of Station 5 is given in Figure 2.

<u>Figure 5:</u> Annotated depth profiles for the camera lowerings from this study showing the lava-flow morphology and extent of sediment cover. These profiles are not true geologic sections because the horizontal scale is in time of day, not distance, to match the abridged photo log given in the Appendix. A, explanation of symbols in all profiles; B, Station 1; C, Station 3; D, Station 4; E, Station 5; F, Station 7; G, Station 8; H, Station 9; I, Station 10; J, Station 11. See Appendix for examples of lava flow types and degree of sediment cover.

Table 1
Hydrothermal Vent Discoveries[a] North of USGS Study Area

Station	Time	Position[b]	Aanderaa	Pinger	Photos/Video
7	0732-33	44°45.5'N 130°20.1'W	√	√	no convincing photos
7	0949-53	44°43.4'N 130°21.0'W	(√)	√	good; much yellow sediment; chimneys?; abundant filter feeders
8	0934-37[c]	44°49.8'N 130°17.0'W		√	good; yellow sediment; hydrothermal staining
8	0942-44[c]	44°49.9'N 130°16.9'W		√	good (shimmering water?)
9	0605-06[c]	44°50.0'N 130°16.9'W	√	√	good (shimmering water?)
9	0915-18[d]	44°52.9'N 130°16.0'W		?	golden yellow sediment
9	0936-38[d]	44°53.2'N 130°15.8'W	√	√	no convincing photos
9	0942-44[d]	44°53.3'N 130°15.7'W		√	vent fauna; some yellow sediment
9	1037-42	44°53.9'N 130°15.1'W	√	√	golden-yellow sediment

[a] The identification of new vents is based on both temperature (either or both systems) and photographic/video images. One data source alone (photos or temperature) is not considered sufficient evidence for confirmation of a hydrothermal discharge site.

[b] All positions are in Loran C coordinates based on the *R/V Atlantis II* system. The correction is as follows:
Sat (lat) - .11' = Loran (lat)
Sat (long) + .40' = Loran (long)

[c,d] The proximity of these occurrences suggest that they may be from the same vent area within the accuracy of our navigation.

( ) possible erratic record

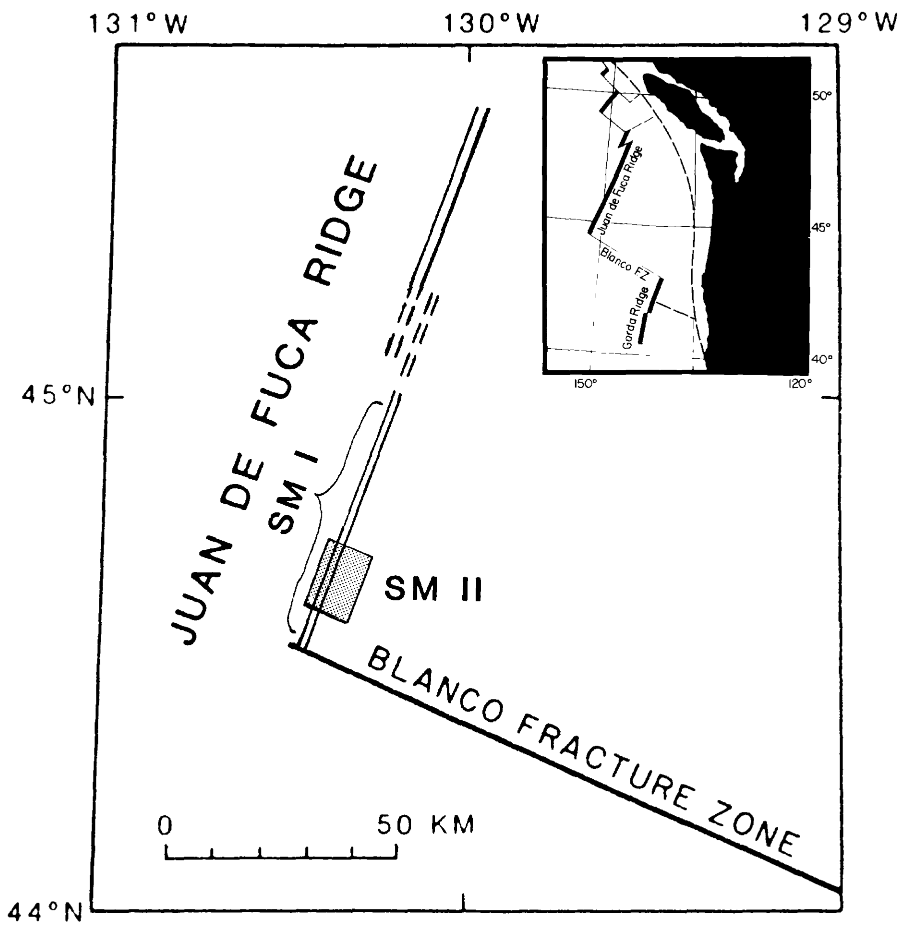

131°W
130°W
129°W
45°N
44°N
JUAN DE FUCA RIDGE
SM I
SM II
BLANCO FRACTURE ZONE
0
50 KM
50°
45°
40°
150°
120°
Juan de Fuca Ridge
Blanco FZ
Gorda Ridge

Figure 1

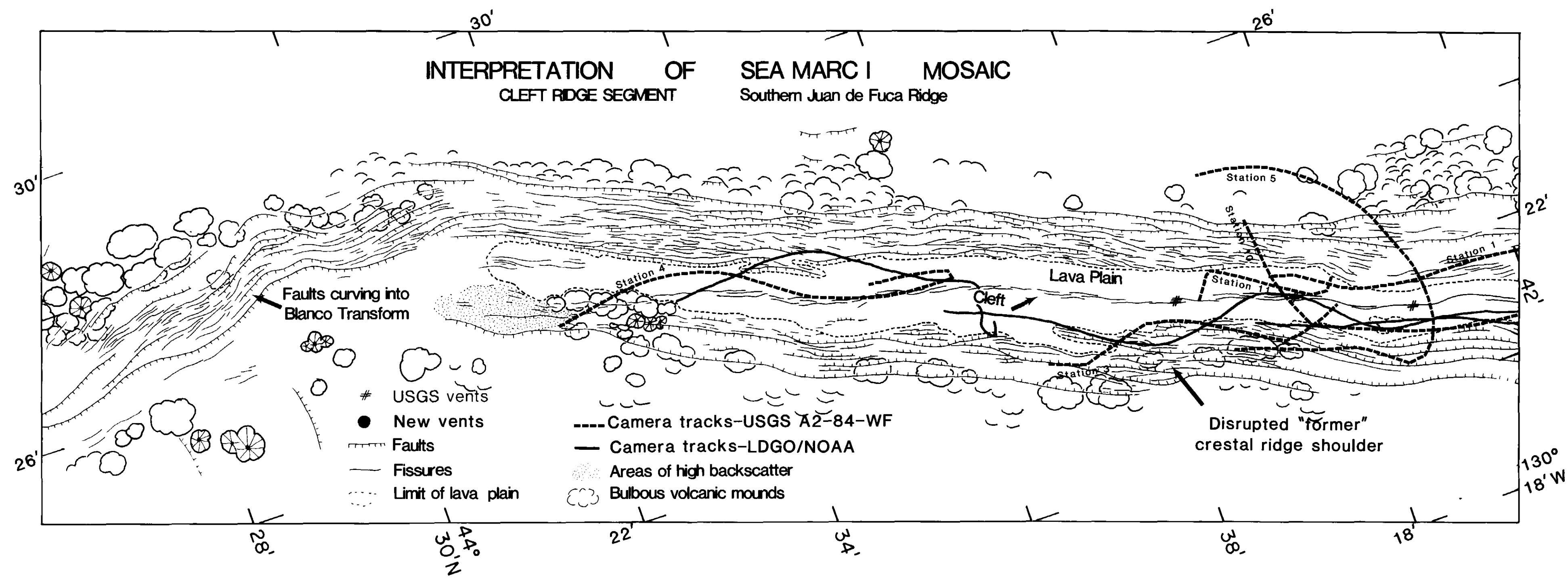
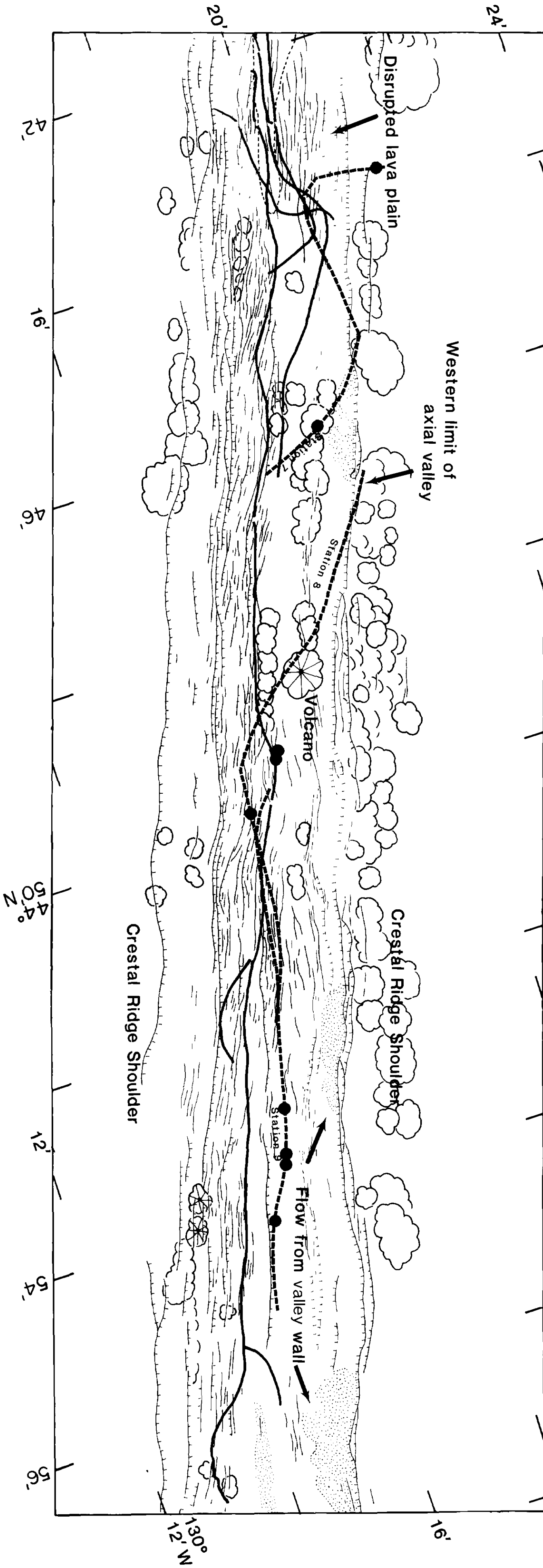
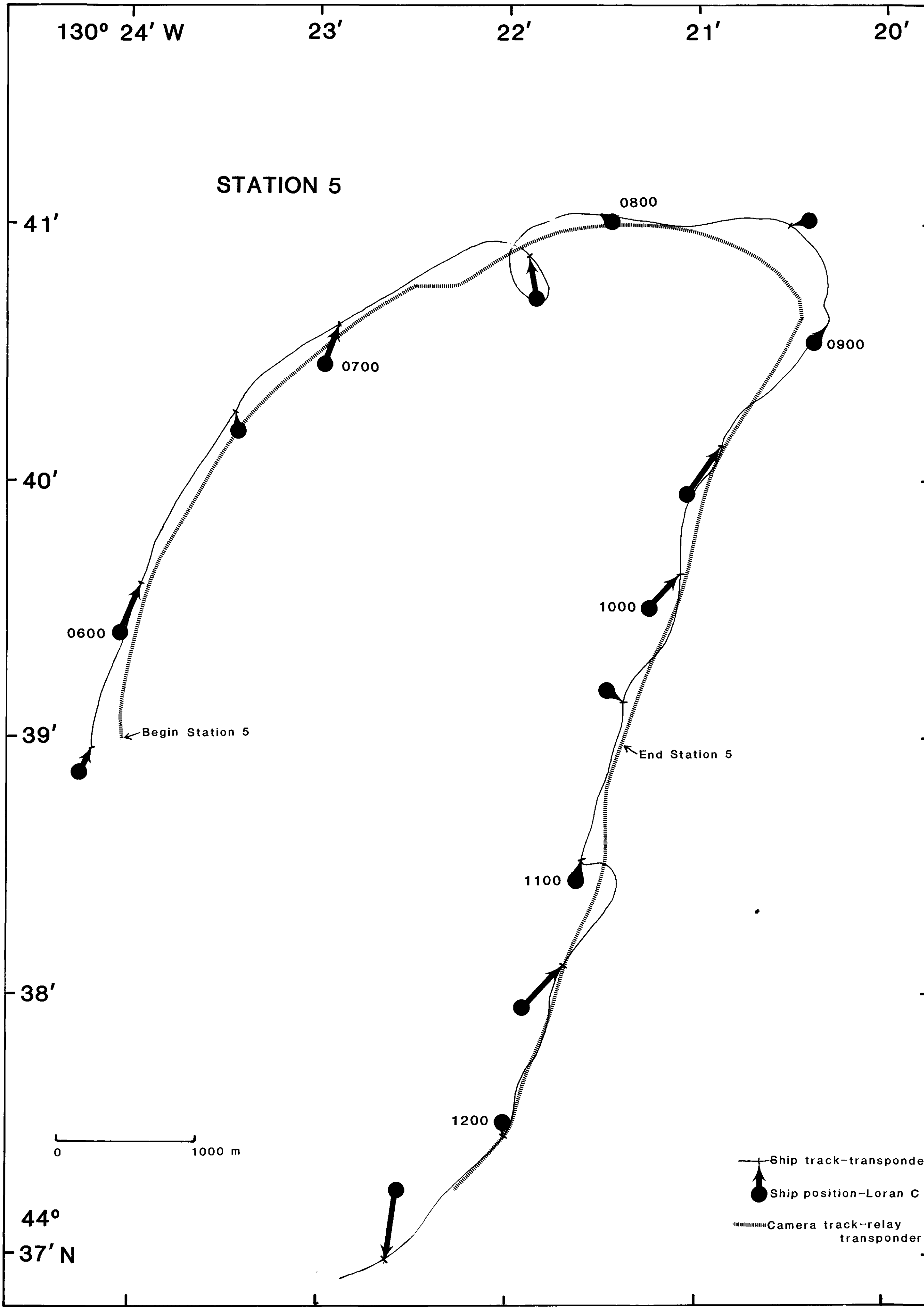

INTERPRETATION OF SEA MARC I MOSAIC
CLEFT RIDGE SEGMENT
Southern Juan de Fuca Ridge
30'
26'
22'
42'
28'
44° 30'N
34'
38'
18'
130° 18'W
Faults curving into Blanco Transform
Station 4
Station 5
Station 1
Station 3
Cleft
Lava Plain
Disrupted "former" crestal ridge shoulder
USGS vents
New vents
Faults
Fissures
Limit of lava plain
Camera tracks-USGS A2-84-WF
Camera tracks-LDGO/NOAA
Areas of high backscatter
Bulbous volcanic mounds

Figure 2



20'
24'
24'
42'
16'
46'
44°50'N
12'
54'
56'
130° 12'W
16'
20'
Disrupted lava plain
Western limit of axial valley
Station 8
Volcano
Crestal Ridge Shoulder
Crestal Ridge Shoulder
Flow from valley wall

Figure 3



130° 24′ W
23′
22′
21′
20′
STATION 5
41′
40′
39′
38′
44°
37′ N
0800
0900
0700
0600
1000
1100
1200
Begin Station 5
End Station 5
0
1000 m
Ship track-transponder
Ship position-Loran C
Camera track-relay transponder

Figure 4

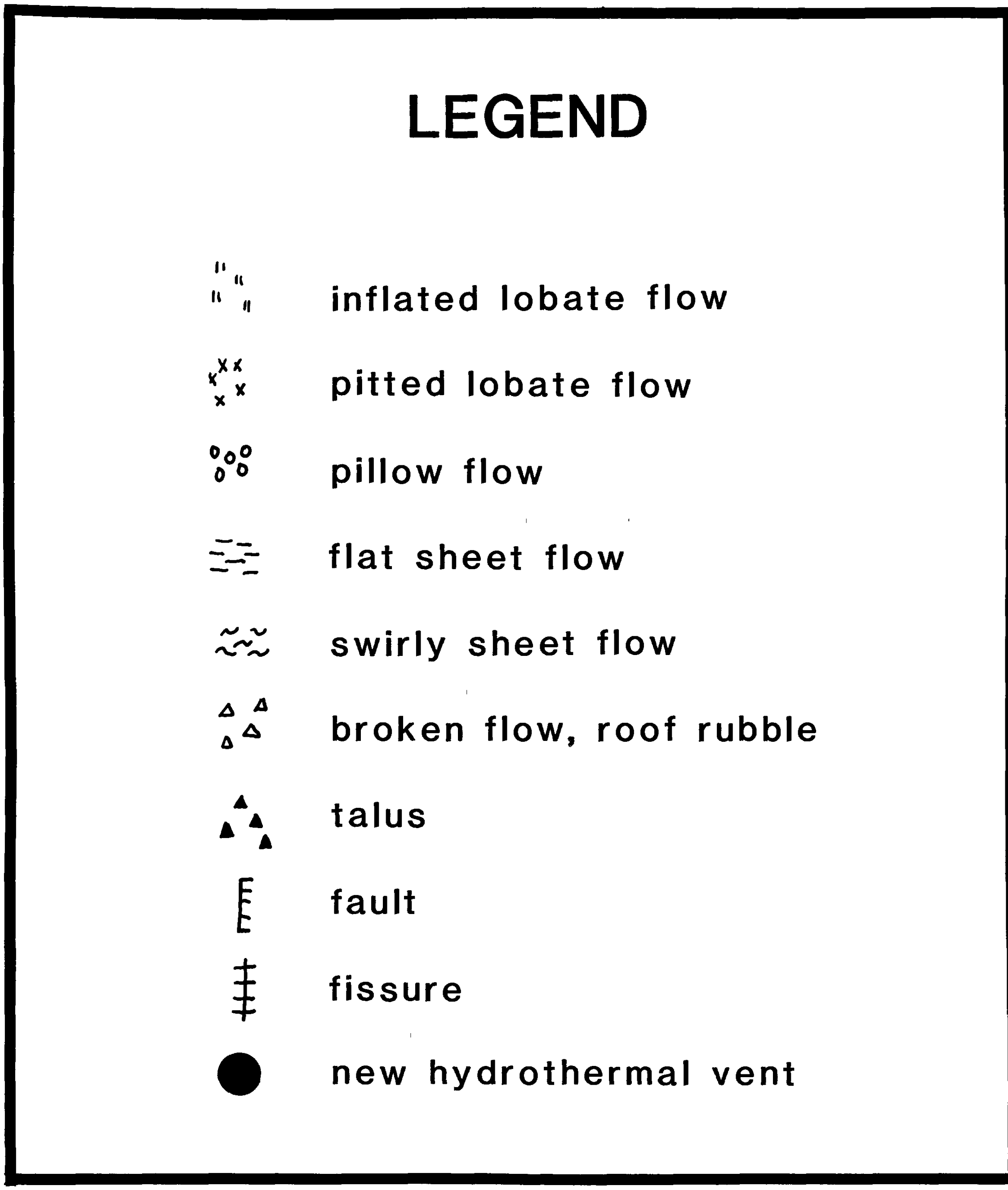

LEGEND
inflated lobate flow
pitted lobate flow
pillow flow
flat sheet flow
swirly sheet flow
broken flow, roof rubble
talus
fault
fissure
new hydrothermal vent

Figure 5A

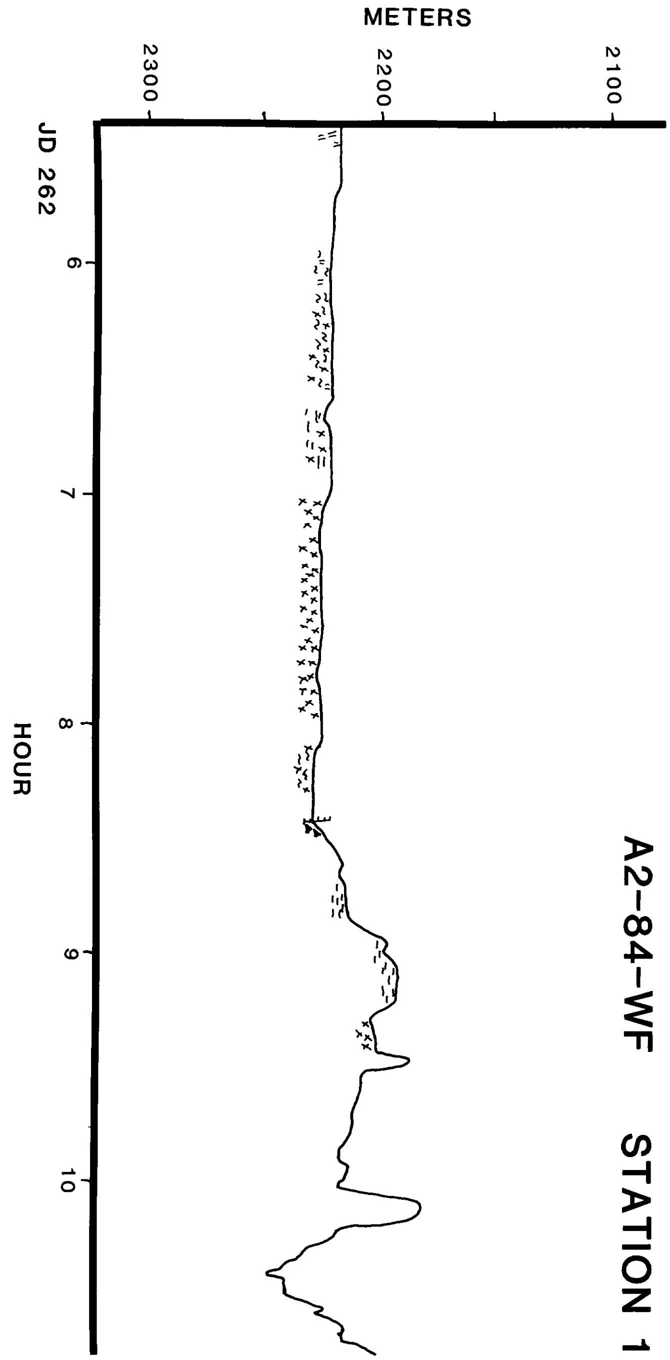


Figure 5B

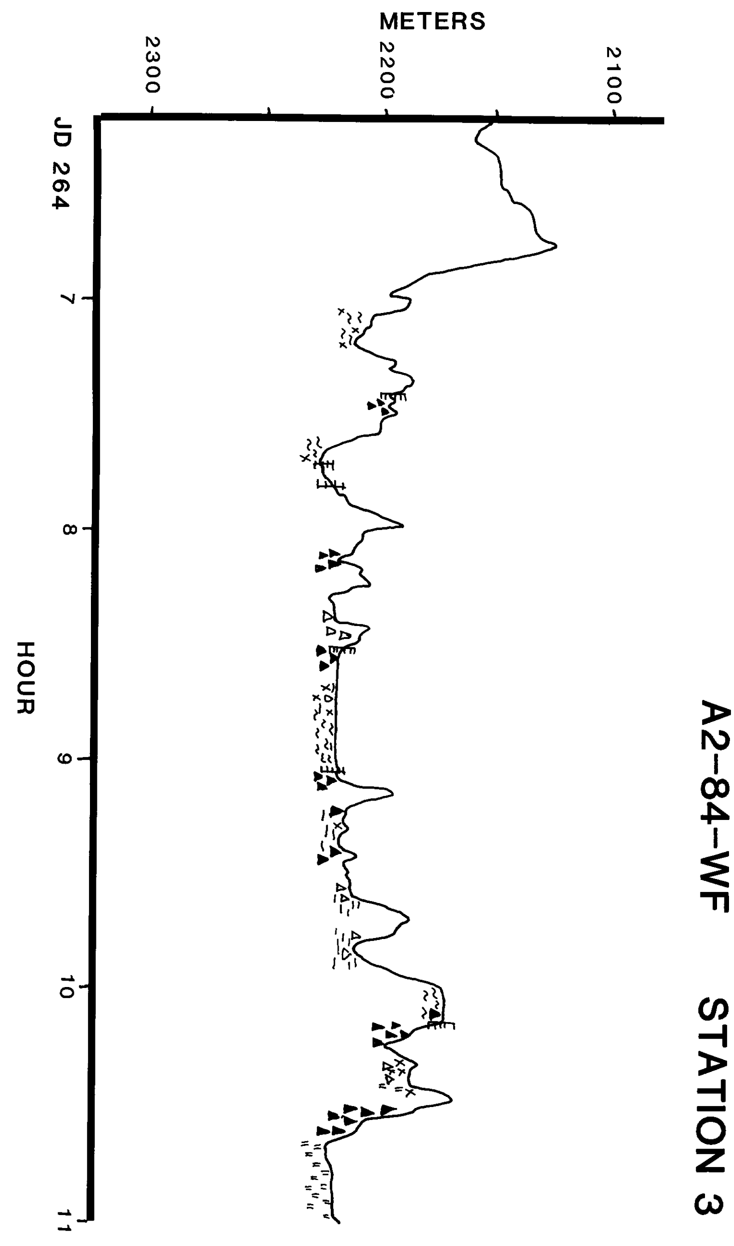
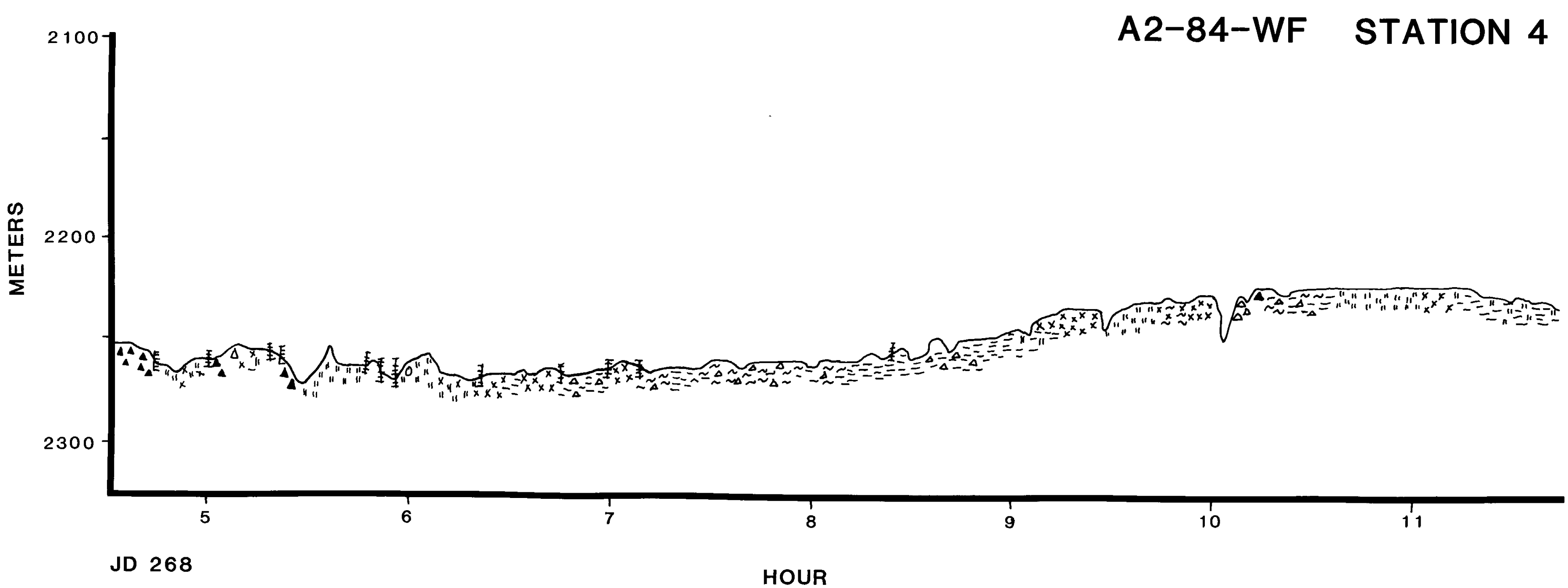
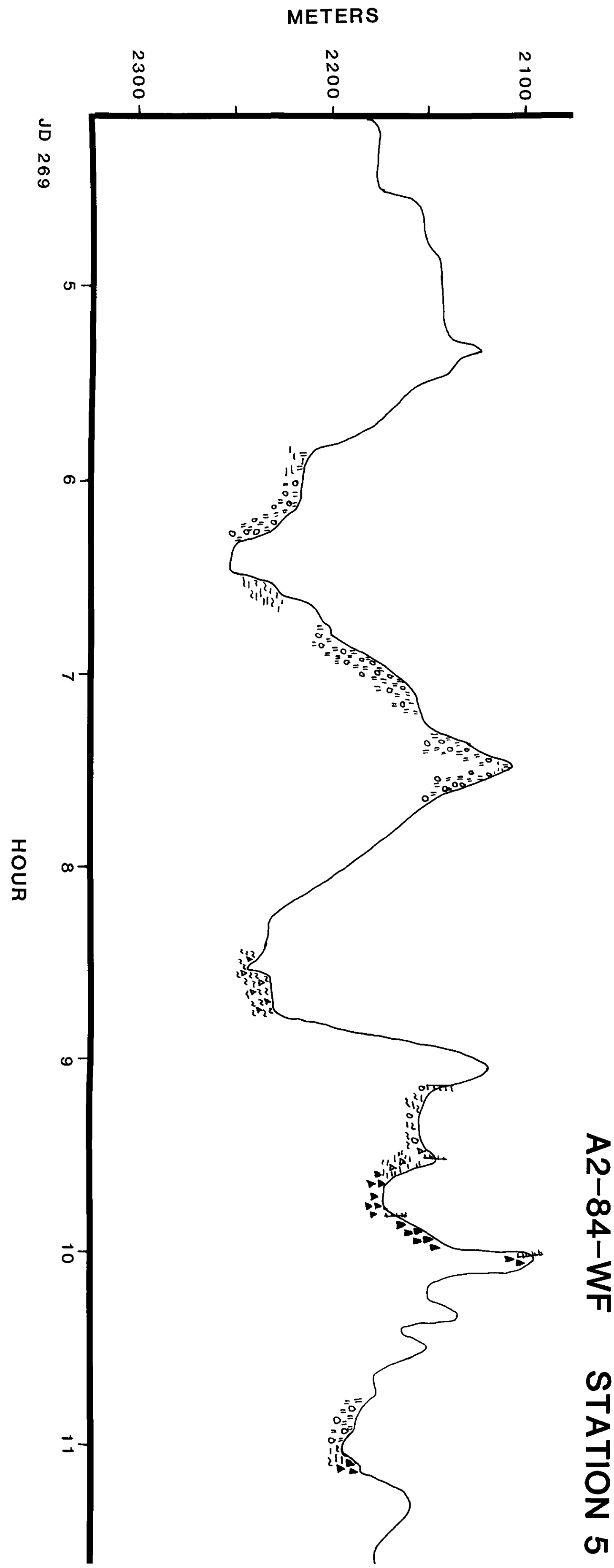


Figure 5C



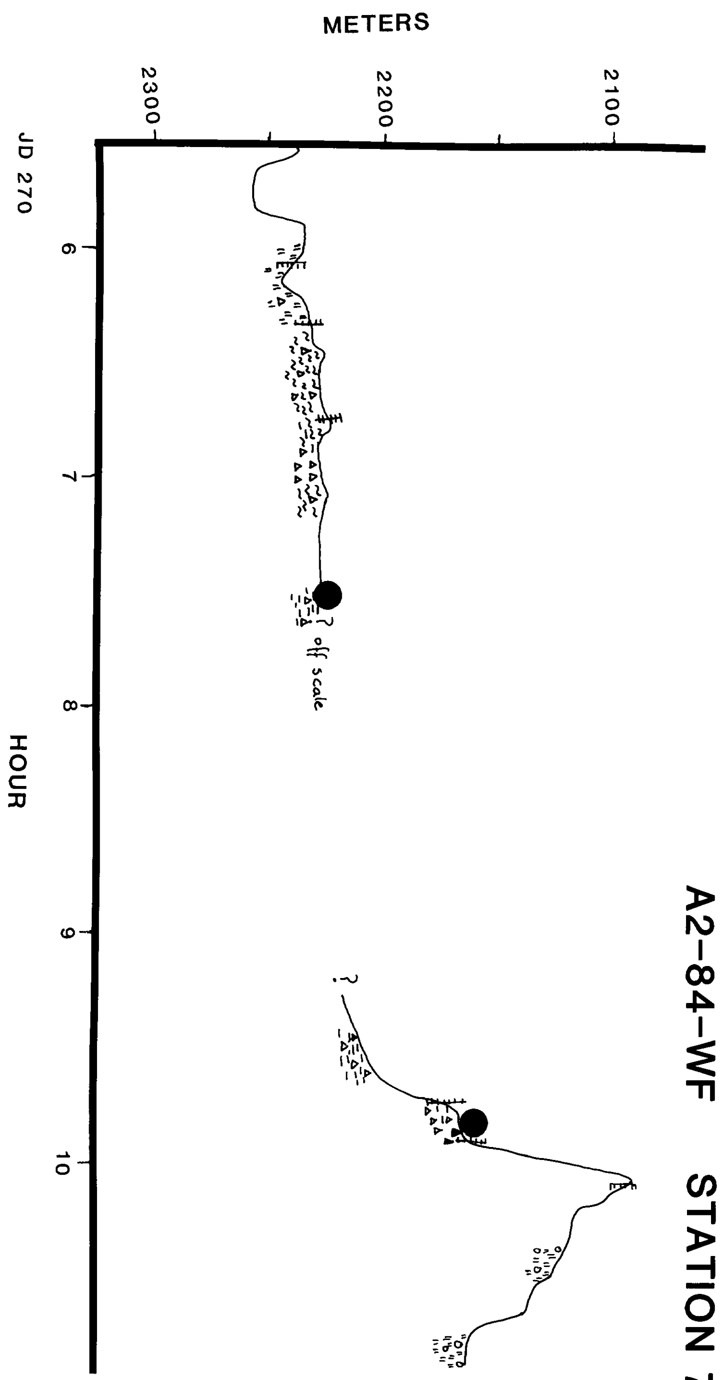
A2-84-WF STATION 4
METERS
2100
2200
2300
5
6
7
8
9
10
11
JD 268
HOUR

Figure 5D



A2-84-WF STATION 5
METERS
2300
2200
2100
JD 269
5
6
7
8
9
10
11
HOUR

Figure 5E



A2-84-WF STATION 7
METERS
2300
2200
2100
JD 270
6
7
8
9
10
HOUR
off scale

Figure 5F

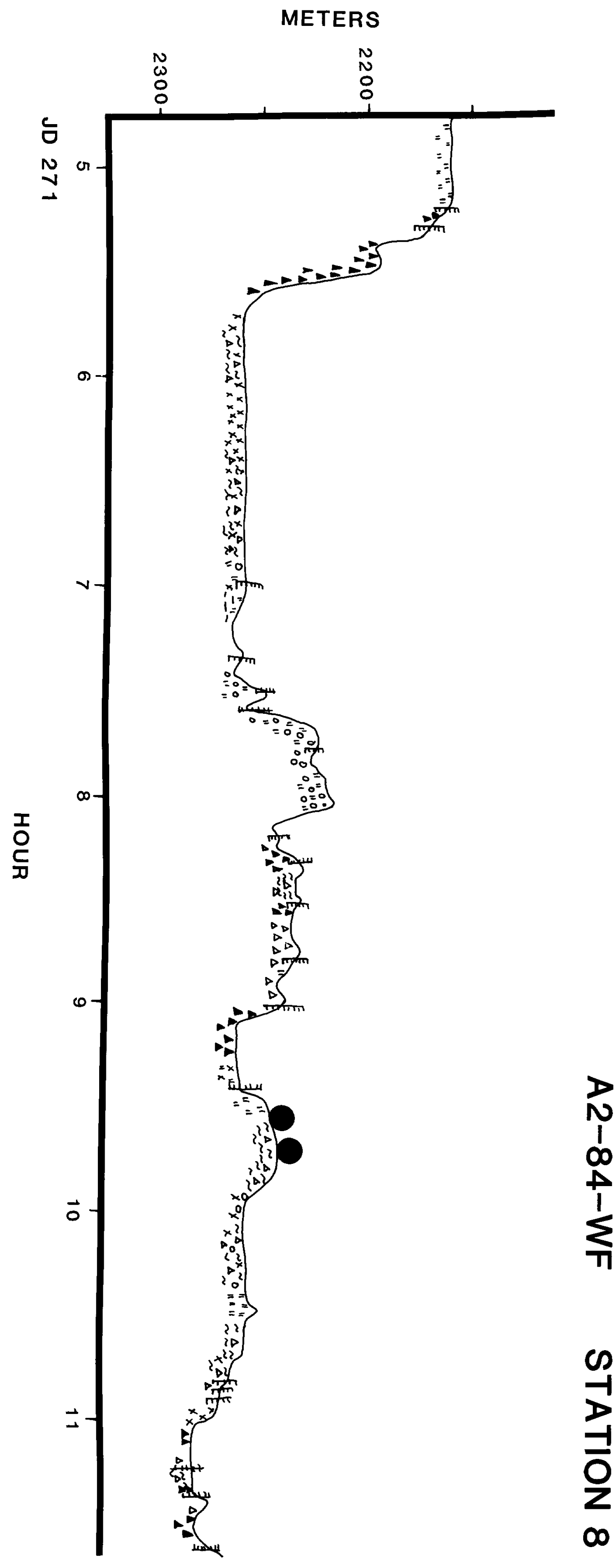


Figure 5G

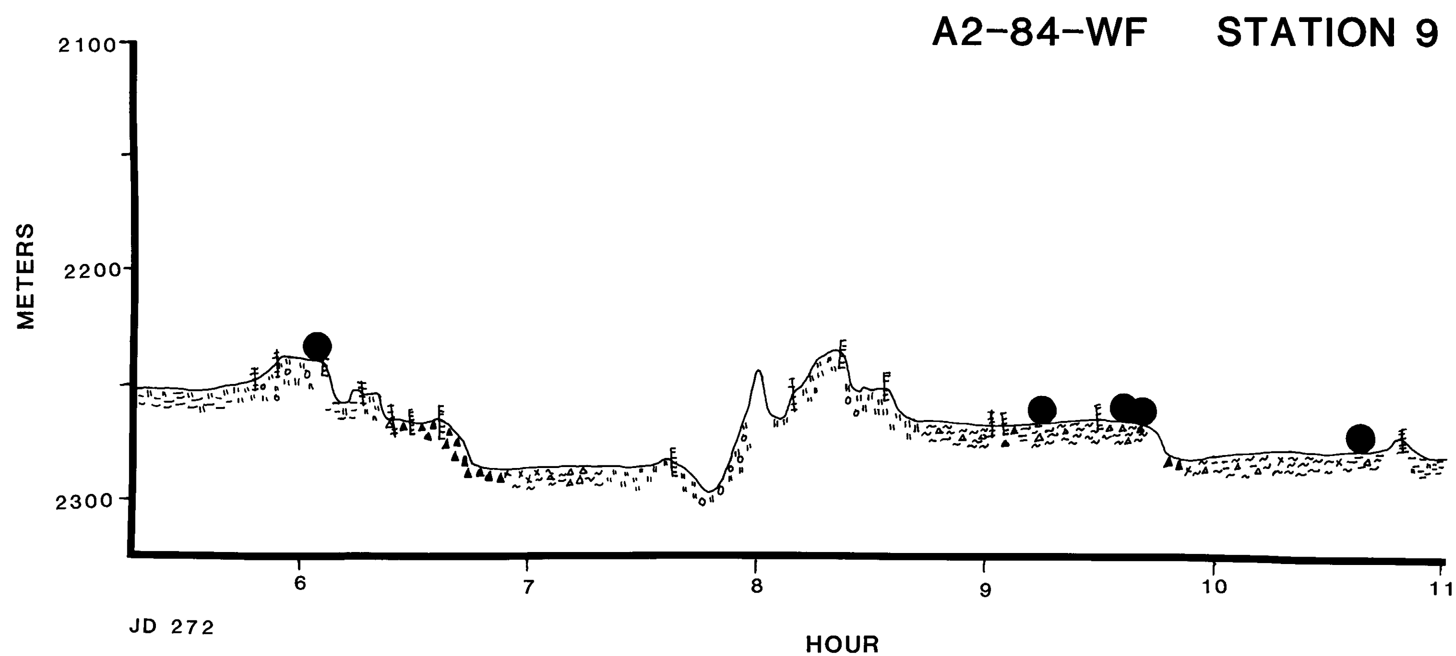


Figure 5H

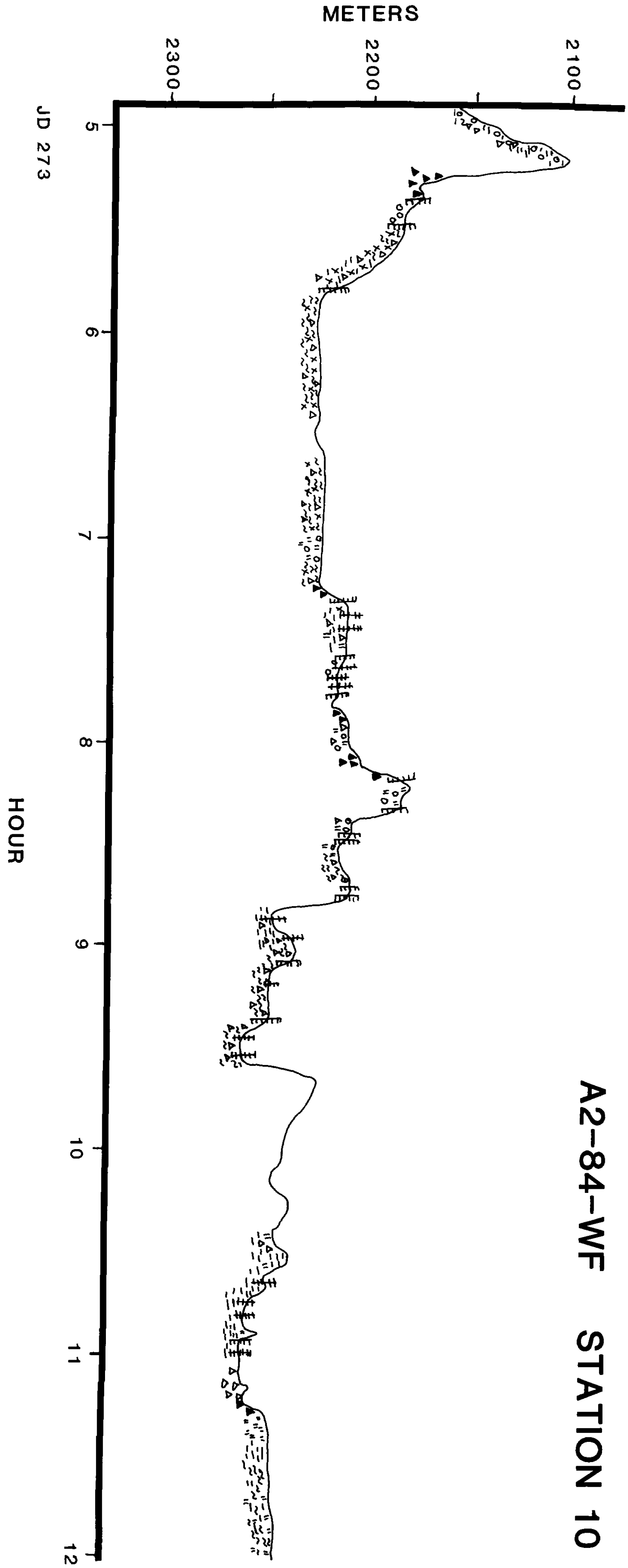

A2-84-WF STATION 10
METERS
2100
2200
2300
HOUR
JD 273
5
6
7
8
9
10
11
12

Figure 5I

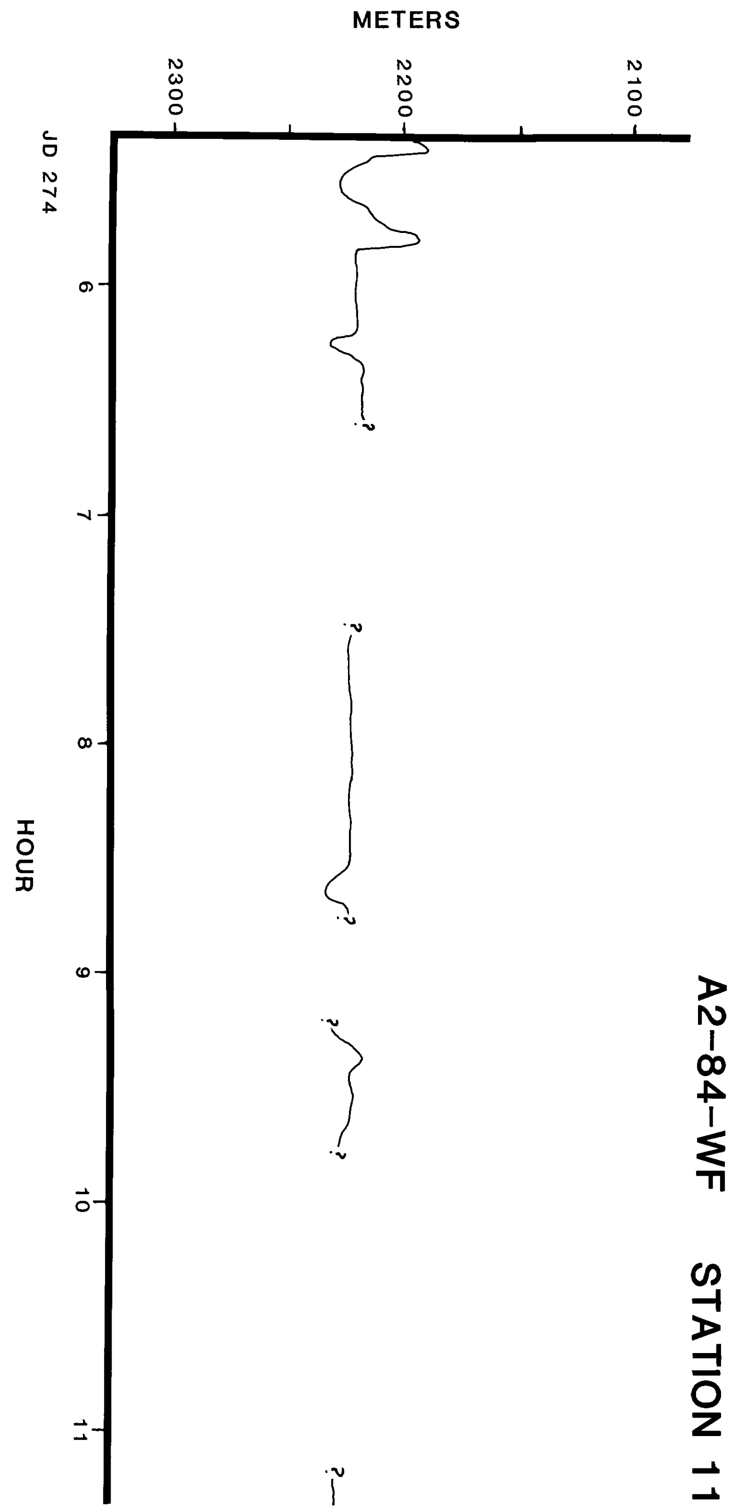

A2-84-WF STATION 11
METERS
2100
2200
2300
JD 274
6
7
8
9
10
11
HOUR
?

Figure 5J

APPENDIX A

ABRIDGED CAMERA LOG FOR A2-84-WF

EXPLANATORY NOTE

The terminology used to describe lava-flow morphology and extent of sediment cover is still evolving and is not standardized among users. Therefore, we include photographic examples of some of the types of flows from the Juan de Fuca Ridge to aid the reader in using the descriptions presented in this Appendix (Figures A-1 and A-2).

The descriptions of the degree of sediment cover are more subjective because the magnitude of local relief, which is a function of the lava-flow morphology and structural modification including fissuring and local collapse, will affect the perception of the amount of sediment present. The abbreviations used in the Appendix are as follows: SC, sediment cover, refers to a complete, or nearly complete, layer of sediment such that it can be impossible to distinguish the lava-flow morphology underneath; SP, sediment ponding, refers to sediment smoothing within the low areas of the lava flow, such as between adjacent pillow structures or in the low spots within a lava drape; SV, sediment veneer, reflects a thin layer of sediment that covers most of the rock surface but does not prevent identification of the type of lava flow; and SD, sediment dusted, means a very sparse accumulation of sediment particles that does not obsure the surface of the lava flows to any extent. As used in the Appendix, the percentage values of the type of sediment cover refer to the dominant type for each interval of time along the track.

We use the non-standard terminology, "lemon drops," which refers to accumulations, generally in the shape of equant to elliptical balls, of bacterial and fine sediment particles typically observed adjacent to hydrothermal vents. The colors of the balls range from off-white to light orange, varying with the amount of oxidized pariculate matter derived from the hydrothermal discharge, with yellow colors the most common.

Figure A-1: Photographs A and B show sheet flows with a form referred to as lava drapes, folds, or ribbons; the flow in B is populated by numerous benthic siphonophores from near the central cleft; both show a very small amount of sediment ponded in the low areas between the higher-standing folds in the lava surface. Photograph C shows pillow lava (upper left) that has flowed over an irregular lineated sheet flow surface (lower right); a thin veneer of sediment is easy to recognize on the pillow forms. Photograph D is over a lava lake collapse with a small segment of the original lobate flow surface preserved (upper right). A free-standing lava pillar, left after the drainback of the lake, is at the left side of the photograph; the glassy, reflective surface of the lobate flow segment has only a light dusting of sediment.

Figure A-2: Photographs A and B illustrate sediment ponding between the talus blocks in areas of extensive lava lake collapse; the tops of the pillars have a thin veneer of sediment. Photograph C shows sediment ponding in the low areas of a sheet flow with a drape or ribbon form. Photograph D shows a collapse pit in an area of lobate flow (upper and left hand margins of the photo) with a veneer of sediment on both the lobate surface and the floor of the collapse pit.

STATION 1: A2-84-WF

Station Time: 0430-1156Z/ JD 262
Bottom Time: 0521-1045Z

During this camera station the 35mm system operated erratically providing about one picture per minute until 0936, when the system failed completely. Much of this photo log is based on color video.

0601-0614	Sheet and lobate flows. SP 30-70%.
0616-0622	Young, glassy lobate flows. SP 5-10%. Sponges clinging to hacklier surfaces (ribbony sheets and hackly flows, not smoother lobate surfaces).
0623-0706	Collapse pits in lobate and sheet flows. SP still 5-10%.
0713-0754	Clinkery lava, lineated sheet flows and pitted lobate flows. SC is variable, but generally 20-30%.
0755-1017	SP 70-100%. Pitted flows. At 1000 there are lots of sponges, though the floor is still heavily sedimented.
1018	Darkness. Essentially nothing on Tape 3.

STATION 3: A2-84-WF

Station time: 0507-1230Z/ JD264
Bottom time: 0615-1100Z

0714.5- 0718.4	Pitted lobate and sheet flows. Very high SC (to 100% locally), nearly totally covering up flows. SP 70-80%, locally thick (few cm). All flows are sediment dusted.
0718.5	Slabby sheet (sediment dusted). 60% of the frame shows light yellow/brown sediment. A few ophiuroids.
0719.1- 0719.2	Unbroken lobate flows. 80% SP.
0720.1- 0720.2	Lobate flows and massive sheet flows, which become lobate flows with lava inflation cracks. SV =100%. SP=60-70%.
0720.3	Broken lobate flows. Collapse pit. SP 20%. Worms in sediment ponds.
0720.4	Crash!
0721.1	Crash recovery. Sediment in water column. Unbroken lobate flows.
0721.3- 0722.3	Sediment-dusted, pitted lobate flows. SP generally 20-30%.
0722.4	Crash!
0722.5	Lobate flows, collapsed lava tube. SP 20%, but all dusted with sediment.
0723.1	Close-up. Nearly crashed. Sediment pond with ophiuroids.
0723.2	Lobate flow. Inflated?
0723.3	Unbroken lobate flow. Old. SP 50% (thick enough for worm burrows). SV 100% (all dusted).
0723.4- 0725.3	Unbroken lobate flows, SP on lobates 20-30%, but all sediment dusted. Some fissuring.
0725.4- 0743.5	Small-offset faults in the lobate flows, lots of rubble. SV 100% in most places.

0744- 0809.2	Water shots
0809.3- 0825.5	Blocky rubble (fault talus?). All sediment dusted.
0826.1- 0838.4	Broken sheet and lobate flows. SV=100%. From 32.3-34.1, detected what appears to be hydrothermal staining on the talus chunks.
0839.1- 0844.1	Sheet flows, SV=100%. Camera flying high off bottom.
0844.2- 0856.1	Pitted lobate and sheet flows. Sediment color is more brownish than before (varying shades of chocolate brown). SV still 100%.
0856.2- 0916.3	Broken sheet and lobate flows. The flows are broken because of faults and fissures rather than collapse pits. Talus blocks are sometimes present. SV still 100%.
0916.4- 0932.3	Lots of sled crashing, strobes not firing consistently. Fault scarp appears, followed by talus with variable rock fragment size.
0932.4- 1005.4	Both broken (pitted?) and unbroken lobate flows and ribbony sheet flows. SV=100%.
1006.1- 1058.2	Talus slopes, fault scarps, lots of water shots. Sheet and lobate flows at other times. SV=100% (at 42.3 there is a "big" scarp).
1058.3	Water Shots.

STATION 4: A2-84-WF

Note: No navigation until 0511z ship time. Still photograph descriptions are supplemented with video descriptions.

Station time: 0339-1223Z/ JD268
Bottom time: 0432-1145Z

0431.4-0442.3	Pitted lobate flows. SV=100%, SP 5-10% locally.
0442.4-0502.3	Looking down a fault scarp or talus ramp? Some filter-feeders are clinging to the rocks. The rocks do not look like broken-up pillow flows; cross-section of flows indicates that they are probably fractured massive sheet flows or lobate flows. The video indicates that there are fields of rubble all around the talus ramp. We never see remnant pillars, which suggests that this rubble is not part of a large collapsed lava lake.
0502.4-0504.5	Talus, broken flows, camera crashing. Looks as if the camera is going up a fault scarp. SP= 70-80%.
0505.1-0518.1	Lobate flows and some hackly lava. The video shows glimpses of occasionally breached hollow tunnels beneath the flow surface. From 0506-0510 the camera was being towed sideways.
0518.2-0519.4	Rubble-filled fissures. Sometimes both sides of a fissure can be seen in one photo. The talus in the fissures has a SV=100%.
0519.5-0522.1	Sheet and lobate flows. Sediment cover sometimes so heavy that you cannot tell what type of flow is beneath; burrows in the sediment. Flows are still pitted.
0522.2-0557.3	Unbroken lobate flows, with some inflation cracks. (0532.3 Crash) Old. SV=100%. Occassional pillow flow. 0544, 0547, 0550, 0554, 0556 there was some fissuring.
0557.4	CRASH! Going up a constructional mound (?).
0558.1	Not all of the strobes are firing.
0558.2-0558.4	Water shots. Going up a scarp. Catch a glimpse of flows dripping over the edge of the scarp with the video.
0559.1-	Lobate flows, old, sometimes pitted. SV=100%.

0615.2	
0615.3- 0617.4	Broken sheet flows, roof rubble, collapse pits.
0618.1- 0718.2	Lineated and swirly sheet flows, and lobate flows. Pitted. SV=100%. Fissures or large collapse pits at 0619, 0630, 0644, 0658, 0701, 0703, 0709, 0711-12.
0718.3- 0722.3	Still in sheet flows. (18.3- Crab).
0722.4	Heavily sedimented, mostly hydrothermal sediments, some bright yellow.
0722.5 0759.4	Sheet flows, some broken (collapse pits). All sediment-dusted.
0800.1- 0904.3	Still angular flows, but yellow hydrothermal sediments (0800, 0811, 0842), sponges.
0904.4- 0948.1	Sheet and lobated flows, pitted. Variable amounts of sediment cover.
0948.2- 1015.4	Sponges becoming abundant. Mostly broken sheet flows. Flows are at least sediment-dusted. (All of this corresponds to temperature anomalies on the Aanderaa records.) At 1010 there are lots of sponges. At 1013-15 there is lots of white material, mainly in the cracks in the flows.
1015.5- 1046.1	Lobate and sheet flows, pitted. SP 30-50%. (1024: Number of sponges increasing. 1035: Dense population of sponges).

STATION 5: A2-84-WF

Station time: 0256-1243Z/ JD 269
Bottom time: 0407-1137Z

0552.1	100% SC. Can't see flow type underneath, though I expect it's a sheet flow. Sediment color is grayish and yellow-brown.
0552.3-0629.2	Pitted lobate and flattened pillow flows. SP 70%. Sediment cover very heavy- at least 1cm to a few cm. Sheet flows locally. There appears to be a pattern of sorts- alternating flat, sediment-covered floor, then a flat floor with some pillows on it. All of the flows have been tectonically unbroken as far as I could tell. 70% or more of the photos contained no pillow flows- only flat sediment cover or lobate flows peeking through the sediment.
0629.3-0713.5	Lots of crashing of the camera. Some sheet flows that appear significantly younger than those described above (i.e. they have less sediment cover on them). Otherwise, the sediment cover is fairly heavy (as above). By 0742, we are back into alternating lobate and pillow flows, high sediment cover.
0714.1-0820.2	Fault scarps, crashing, lots of water shots.
0820.3-0832.3	Sheet flows, SV 100%, but not like the heavy sediment cover described above. In fact, there is an abrupt transition in amount of sediment cover and flow type between 0713 and 0820.
0832.4-0850.1	Young flows! Flattened lobate and sheet flows with a hint of a glassy surface.
0850.2-0904.1	Fault, then water shots mostly.
0904.2-0905.4	Pillow and lobate flows. SV 100%
0906.1-0907.5	Water shots.
0910.1 0910.2	Interesting photo. Hackly lava. Lots of white critters on surface of flow. At 0910.2 there is an isolated column of hackly flow. Strange stuff!!
0910.3-0911.2	Water shots.
0911.3-	Sheet flows mixed with some lobate and pillow flows. SP up to 80%. Terrain

0922.4	similar to description at 0552.3. Between 12.3 and 22.4 the number of pillows greatly increases.
0922.5-0928.4	Mostly broken flows, possibly large areas of collapse within sheet flows.
0929.1-0931	Sheet flows, mostly unbroken though. SP high, up to 90%, but variable.
0932.4-0935.4	Water shots.
0936.1-1000.3	Talus, faulting, some water shots and crashing. SV 100%.
1000.4-1038.2	No strobes until 1028. Last crash did camera in for a while. Then intermittent strobing--of water column.
1038.3-1102.2	Old pillows and lobate flows, alternating as described earlier in 0552. SP 70% or more.
1102.3	Crash!
1105.5	Strobes finally go out for good.

STATION 7: A2-84-WF

Station time: 0434-1200Z/ JD 270
Bottom time: 0528-1100Z

This camera tow description is supplemented by video observations.

0559.1- 0601.1	Crash landing.
0601.2- 0655.1	Extremely pitted lobate and sheet flows. SC very high--SP 50-80%. This appears to be an old, collapsed lava lake. At 0553.1 the camera crashed into a wall and was being towed sideways until about 0655.
0655.2- 0655.3	Hydrothermal sediment. A lot of filter feeders. Hackly flow type.
0655.4- 0657.2	Water shots.
0657.3- 0708.1	Pitted lobate and sheet flows, nearly totally sediment-covered. SP 50-80%.
0708.2- 0731.4	Water shots.
0732.1- 0744.1	Pitted lobate and sheet flows. Sediment cover still high.
0744.2- 0922.5	Water shots.
0923.1	Broken sheet flow. Patch of bright yellow sediment.
0923.2- 0950.1	Pitted lobate and sheet flows. SC still very high. SP 70-90%. Yellow sediment is common after 0949.
0950.2	Unbroken, flat sheet flow. SC 90%. Only a hint of pavement beneath. Yellow, lemon drop-looking things on it.
0950.3- 0951.2	Sheet and broken lobate flows. Patches of almost black sediment and yellow sediment.
0952.2	Lots of sponges (?) hanging off of a scarp.
0952.3-	Water shots, crash, then a long sequence of yellow sediment.

1003.1	
1003.2- 1004.4	Sheet and lobate flows. SV 100%.
1006.1- 1008.3	Fissured terrain in lobate flows. SV 100%. SP up to 80 or 90%.
1008.4- 1020.2	Crash, then water shots.
1021.2- 1029.1	Getting pillows along with lobate flows that are unbroken and old. SP more than 90% at times. Sediment totally covers the floor in some frames. The terrain is similar to that described in Camera Tow 5 at 0552.
1029.2- 1036.4	Crash, or dragging camera. Then water shots.
1042.1	Sediment cover a little lighter than before. In this frame there is a patch of black (Mn staining?) and a patch of dull yellow sediment adjacent to it.
1042.2- 1047.1	Still in lobate and pillow flows as before, just less sediment cover. All is sediment-dusted, but much less ponding. Mostly pillow flows.
1047.2- 1100.4	Sediment cover seems to have picked up again. SP>50%. Still mostly pillow flows.
1100.5	Water shots.

STATION 8: A2-84-WF

Station time: 0352-1240Z/JD 271
Bottom time: 0445-1139Z

0445.2-0509.3	Lobate and sheet flows. Very high sediment cover--80-90% (up to 100%) of the flow surface is buried in sediment, which is at least a few cm thick in some places. Some pillows in most frames, but generally surrounded by flat sediment. All flows are unbroken.
0509.4-0512.1	It seems as if we passed into some slightly younger flows. They are still relatively old- all sediment-dusted, but SP only 20-30%. Terrain is faulted and fissured.
0512.2-0514.1	Talus. Many of the fracture surfaces seem to be relatively fresh.
0514.2-0516.4	Pitted lobate flows. SV 100%.
0516.5-0522.4	Fault. Cannot see the bottom of it. Then descending the wall and water shots.
0523.1-0527.5	Lots of little angular pieces of same size-talus. None of the broken pieces have fresh faces.
0528.1-0535.4	Lobate flows, some pillow flows and broken sheet flows. Faults, then water shots and rubble.
0536.1-0651.4	Pitted lobate flows with very high sediment cover. Some fissuring. SP up to 80-90%. At 0628.3 and for the next 10 minutes, there are abundant collapse pits that are sediment-filled. You cannot even identify the roof pieces under the sediment.
0652.1-0701.4	Getting into more bulbous lobate terrain with some pillows. SP still generally 50-80%. Some of the pillows are hollow inside.
0701.5-0703.1	Faulting, but only tens of cm of offset.
0703.2-0715.2	Mostly pitted sheet and lobate flows. SP still up to 80%, but varies from frame to frame.
0715.3-0730.1	Lobate and pillow flows. SP 10-30%. Occassional small fault scarp.

0730.4- 0808.3	Sediment cover very variable now. Alternating older and younger flows. Sediment ponding varies from 10% to 60 or 70% in these frames. Some fissuring.
0809.1- 0907.3	SC has dramatically increased to 80+% on sheet flow. Most of the flow is buried under sediment, but can still see patches of the flow. Lots of fissuring and small faults (~1m relief). By 0814, there are many frames of ill-defined fault scarps, rubble, talus, broken sheet and lobate flows. At 0818 there is lots of fissuring again and more talus.
0908.1- 0917.2	Unbroken lobate flows. SP 70+%.
0917.3- 0925.2	Collapse pits in lobate flows are sediment-filled (cannot see roof rubble beneath the sediment). By 22.1, the broken flows are fault talus and not roof rubble. Some faulting at 0925 where cannot see bottom.
0925.3- 0938.1	Lobate and sheet flows that are not pitted. SP 50-80%. Some yellow sediment and hydrothermal staining of rock surfaces from 0934-0937.
0938.2- 0942.3	Sheet flows as above, but now riddled with collapse pits, faulted, and fissured. It differs from frame to frame as to which of the three disruptions occur in the flows.
0942.4- 0943.3	Sheet flows, SP 70-80% (but up to 90%). 0943.2 is a strange photo. It appears to be a hydrothermal deposit on the sediment. Black (Mn-coated?) patches and smaller yellow patches. Could shimmering water have done this (i.e., the photo is somewhat out of focus)?
0943.4- 1036.2	Fractured sheet flows. Fissures are small, generally less than .5 m wide and 10-30 cm deep. SP >70%. By 1001 to 1012, pillows begin appearing occassionally.
1036.3- 1052.3	Fissured and faulted sheet flows, some several meters deep. SP 70-100%.
1053.1- 1107.3	Pitted sheet and lobate flows. SP>70%. 0959.3-1101 looks like a hyaloclastite, then again at 1102.2.
1108.2- 1136.3	Faults and camera crashing. SC locally up to 80%. 1114.4-1115.1 there are Mn-coated rocks, golden yellow patches, and some lemon drops. 1123.1- Mn-stained rocks. 1123.4 there is some dull yellow and black hydrothermal staining.
1139.1	Crashing, then water.

STATION 9: A2-84-WF

Station time: 0427-1215Z/JD 272
Bottom time: 0517-1100Z

0517.1-0544.1	Sheet and lobate flows primarily, with a few scattered pillows. SP 50-70%. 0535 small fissures.
0544.1-0639.2	Some younger flows, mostly lobate, but pillows and hackly sheet flows present too. Fissures and small faults. SP on average 50%. 0605-0606 there is a slight blurring of photos that suggests shimmering (hot) water discharge.
0639.3-0701	Broken flows, talus. 0651.4: some golden yellow sediment lies between broken and pitted flows. All the flows are dusted with sediment, but SP is generally no more than 5-10%.
0701-0715.1	Mostly broken, ribbony sheet flows (not glassy). SP~10% or less. Some hackly lava at times.
0715.2	Golden yellow sediment. Some lemon drops.
0715.3	Lots of patches of golden yellow sediment. Octopus.
0715.4	Fairly young, but not glassy hackly flow and hyaloclastite(?).
0716.3-0733.4	Sheet and lobate flows, with an occassional pillow flow. SP 30-50%.
0734.3	Lots of patches of golden yellow sediment. Bundles of lemon drops.
0734.4-0738.1	Unbroken bulbous lobate flows.
0738.2-0752.1	Water shots.
0752.2-0821.3	Lobate flows. SP 30-50%. Some fissuring at 0811 and 0818.
0822.4-0833.5	Lobate flows and some inflated pillow flows. SP 30-50%. From ~0830-32 there are some fractures in the flows.
0834.2-0846.3	Water shots, crashing. Not able to give much description of the bottom.

0847.1- 0859.1	Broken sheet flows, mostly ribbony in texture. SP~50%, often much higher.
0900.2- 0907.2	Lobate and sheet flows. The flows appear to be covering a formerly intensely fissured terrain. The flows drip into fissures, and the edges of the fissures are not ragged. Often the fissures are almost totally covered by the younger flows.
0907.3- 0913.1	Faults, talus, ledges.
0913.3- 0932.3	Pitted lobate and sheet flows. SP 30%, up to 80%. At 0918.1 there was some golden yellow sediment along cracks in a lobate flow.
0932.4- 0959.3	Lobate and sheet flows. SP still up to 80%. Collapse pits rare.
1000.1- 1043.4	Pitted lobate and sheet flows. Occassionally some hackly flows. SP generally 20-50%. At 1037.3 there is some golden yellow sediment in a collapse pit.
1044.1- 1056.2	Unpitted lobate flows and some pillows. SP 30-50%. At 1037-1042, there are some patches of golden-yellow sediment. At 1049, you get the distinct impression that these lobate flows are filling fissures. At 1050.4, there is some golden-yellow sediment.
1056.3- 1100.3	Pitted flows once again. SP 10-20%.

STATION 10: A2-84-WF

Station time: 0319-1255Z/JD 273
Bottom time: 0454-1200Z

0453.3-0456.3	Inflated pillow and sheet flows. SP generally >50%.
0456.4-0500	Collapse pits and hollow tubes.
0501.1-0502.3	Hackly sheet flow with lots of sponges hanging on to flow at 0501.3. SP very variable- from as little as 5% to more than 50%.
0502.4-0515.3	Mainly lobate and sheet flows, with some pillow flow. SP>50% up to 100% (where all sheet flow). At 0515.2 there are lots of sponges.
0516.1-0519.2	Fault then water shots.
0519.3-0521.2	Talus- large blocks. SP up to 30-40%. Sponges hanging off some of them.
0521.3-0532.5	Faults and fissures, water shots, some crashes.
0533.1-0626.1	Pitted lobate and sheet flows. SP 30-50% or more.
0628.3-0635.5	Pitted sheet and lobate flows, but younger. Virtually no sediment ponding. The youngest flows appear glassy.
0637.3-0718.1	Pitted sheet and lobate flows. SP 30% or more. Highly sediment-dusted.
0718.2-0830.1	Lobate flows and pillow flows, some broken pieces. All well-sediment dusted. SP 30-50% on average, though in places there is a lot less sediment, but sometimes more. By 0820.4 there is a lot of fissuring. Some of the cracking may be large collapse pits.
0830.2-0930.2	Collapsed lava lake-old. SP>30%. Mostly see a jumble of broken sheet flow pieces. By 0859.2, the sheet flows are heavily sediment-dusted, though SP is about 30-50%.
0938.1-	Water shots.

1015.3	
1015.4- 1027	Heavily sediment-dusted, fissured terrain. Lobate and sheet flows. SP>50%.
1028.1- 1032.2	Collapse pits, roof rubble, sheet flows. SP 20-60%.
1032.3- 1100.2	Mostly unbroken, flattened lobate flows. SP averages 30-50%. It appears that most of the flows have erased a very fissured terrain. Still see some small fissures.
1100.4- 1200.4	Pitted sheet and lobate flows. SP 10-30%.
12001.1	Water shots.

STATION 11: A2-84-WF

Station time: 0425-1230Z/JD 274
Bottom time: 0520-1119Z

There were no still photos for this camera tow, so the camera log is based solely on the lower-resolution video images.

Film blank until 0520.

0520-0540	Fault scarp. Crashing. Blackness.
0541-0601	Camera sled still high off the floor most of the time. There appears to be a lot of sediment ponding. Perhaps a lot of the reason for the blackness (i.e., flying the camera too high most of the time) is that this terrain is so faulted, fissured, and pitted that it is difficult to get a close-up.
0604-0729	Flows are glassy, but extremely pitted. SP 20-30% when there are ribbony sheet flows. Collapse pits are often pretty deep.
0730-0807	Very sedimented, pitted lobate and ribbony sheet flows. SP averages about 70%, but can be up to 100% locally.
0808	**THE END.**

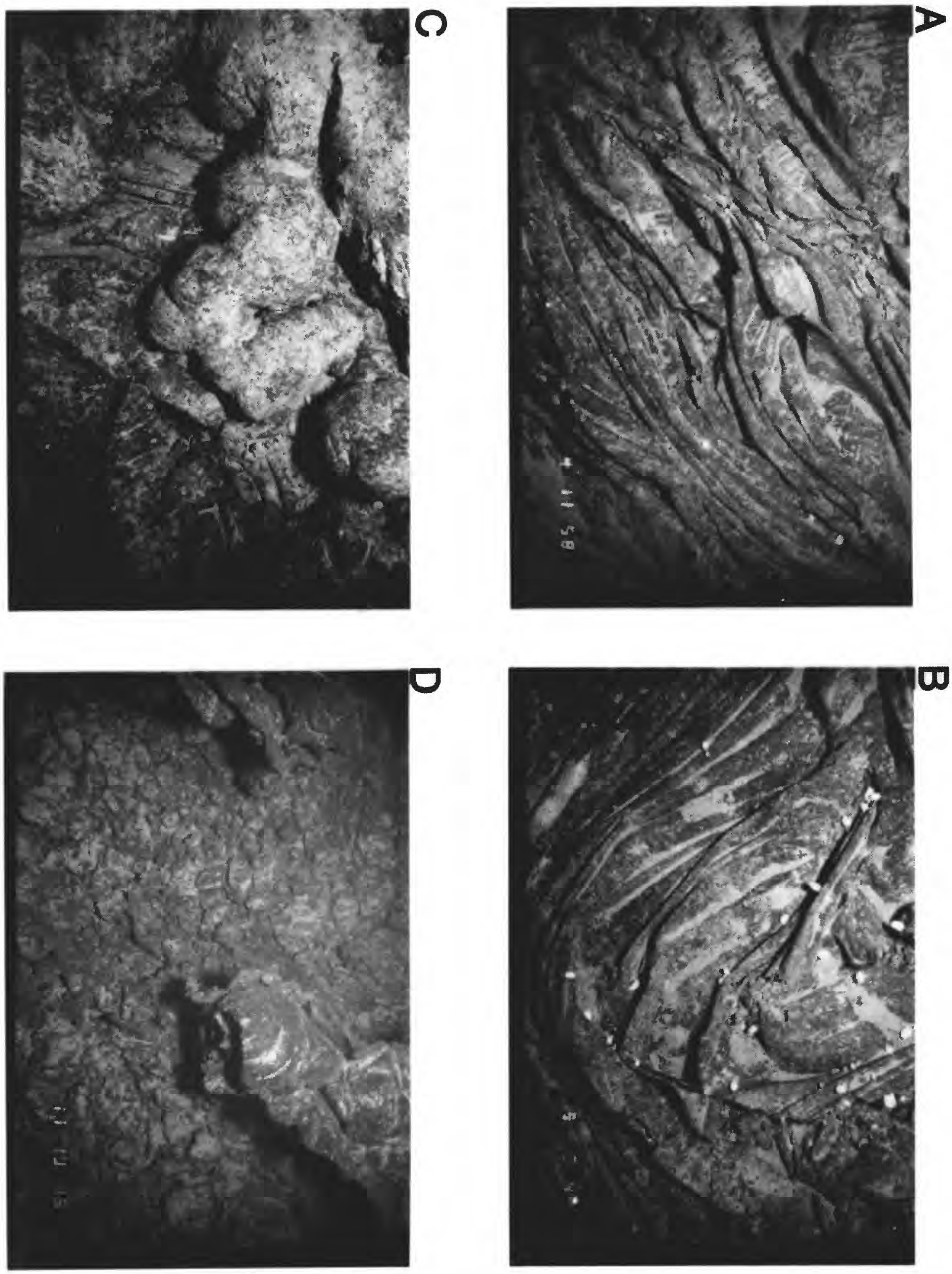


Figure A-1

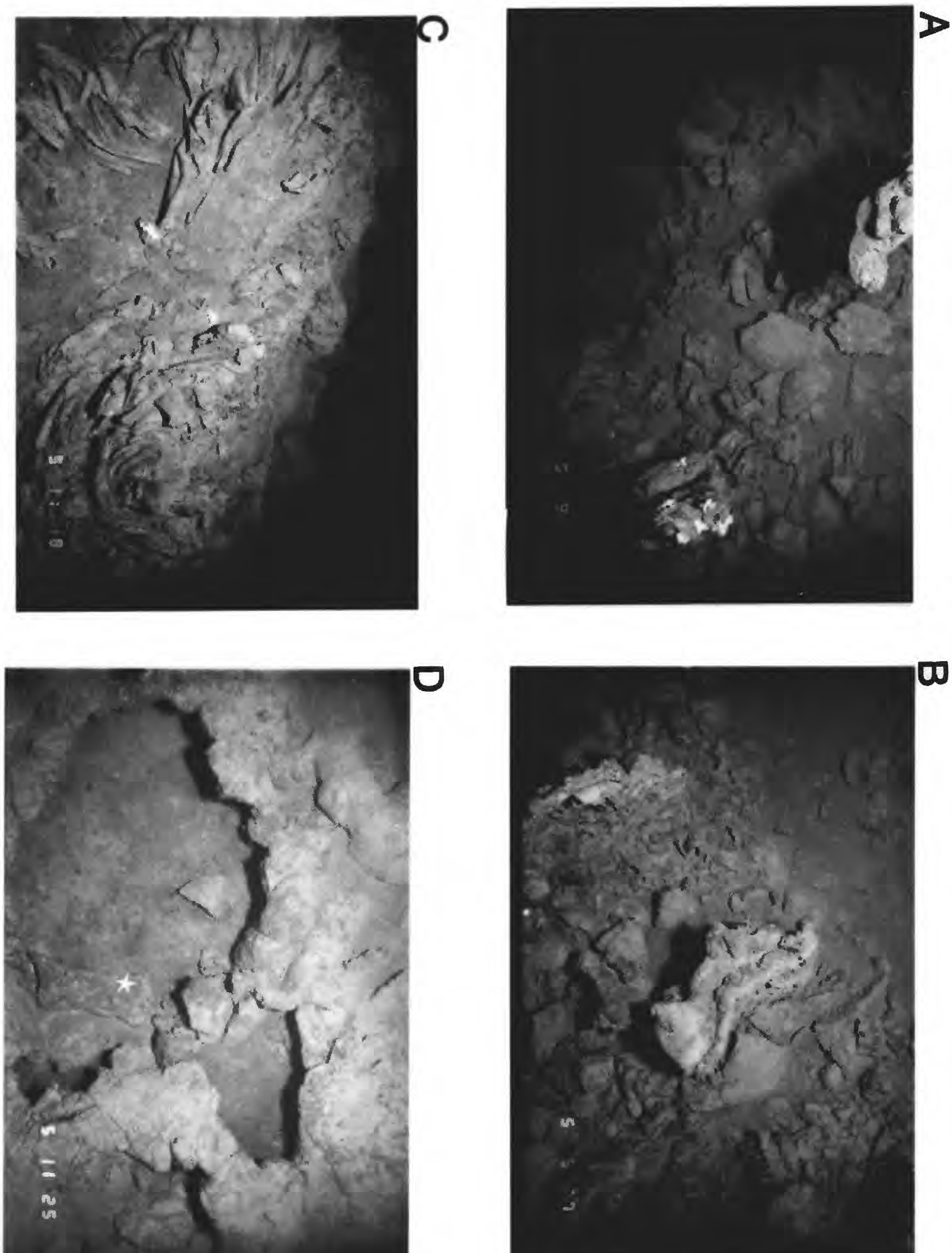


Figure A-2