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THE GALAPAGOS RIFT AT 86°W: 4. STRUCTURE AND MORPHOLOGY OF HYDROTHERMAL FIELDS AND THEIR RELATIONSHIP TO THE VOLCANIC AND TECTONIC PROCESSES OF THE RIFT VALLEY

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Abstract. The *Angus* camera system is used to investigate the detailed structure and morphology of the active hydrothermal vent fields of the Galapagos Rift. Precision navigational data are combined with microtopographic information and detailed geological and biological observations obtained from an analysis of the color bottom pictures to create a series of three-dimensional models for each vent field. The five isolated vents are distributed along the southern boundary of a fissure wedge that cuts along the active axial high. All but one vent occur in pillow terrain. The fifth vent is at the contact between a pillow flow and sheet flow. Vents range in size from 400 m^2 to 1600 m^2 and are spread out along 2.8 km of a lineated fissure system that trends 095°. They are spaced at intervals ranging from 250 m to 1600 m with an average separation of 700 m. Vents are bound by tectonic features such as fissures or small throw faults. The egress of water is localized in small pockets within the fields. These zones of egress are distinctly unfissured. Instead, the water emanates out of rock to rock brecciated contacts. These thermal pockets range from 15 m to 40 m in diameter and are characterized by large concentrations of benthic fauna. On the basis of animal communities the fields may be divided into two different types, the western and the eastern groups. The two western fields are predominantly populated by clams (Vesicomyidae) and mussels (Mytilidae). The eastern three fields are dominated by tube worms (Vestimentifera), mussels, serpulid worms, and the spherical, colonial animal dandelion. The positioning of the vents on the fissure wedge implies a tectonic propagation and age gradation up and down the rift. At any one time, adjacent segments of the rift valley may be in different stages of a volcanic and tectonic cycle. As cooling of a central magma intrusion occurs, fissures propagate toward the remaining heated core, opening up pathways for the egress of heated bottom water. Cooling continues and the outermost vents die out. Precipitates block passages, capping the terrain. As extension continues, the very oldest sector of the valley will fracture. The incipient stress drop generates the eruption of a new magma center down strike from the former center, thus ensuring a volcanic and tectonic periodicity in space and time up and down the rift valley.

Introduction

The Galapagos Rift is a boundary of divergence between the Cocos and Nazca plates, extending for a distance of 2000 km from the triple point junction with the East Pacific Rise at its western limit to the intersection with the Panama fracture zone in the east (Figure 1). In 1972 a detailed investigation of a segment of this rift zone between 90° and 85° was initiated, using both conventional surface ship and deep-towed geophysical techniques [Sclater and Klitgord, 1973; Klitgord and Mudie, 1974; Sclater et al., 1974; Detrick et al., 1974; Williams et al., 1974]. The repeated measurements of positive temperature anomalies in the near bottom waters of the rift valley, as well as high heat flow values measured in the surrounding area, suggested the occurrence of convective cooling of the upper oceanic crust by seawater circulation within the newly fractured rock. This initial effort was followed in 1976 by additional deep-tow work, during which photographs of fresh lava were taken, repeated temperature anomalies were observed, and a water sample was obtained from a temperature anomaly which yielded a high ^3He content [Crane, 1978; Weiss et al., 1977; Lonsdale, 1977]. These new data further supported the earlier suggestion that hydrothermal activity was occurring within this portion of the Galapagos Rift and that it was associated in some way with recent volcanic activity.

In 1977 the DSRV *Alvin* and the deep-towed *Angus* camera system went to the study area. With the help of an acoustic transponder left in the rift valley the previous year during the Deep-Tow program, the area of anomalously high water temperatures was relocated, and a new network of transponders was installed which tracked both *Alvin* and *Angus*. During the course of this expedition these two systems were used to locate and investigate five thermal fields containing several hydrothermally active warm water springs. A series of papers in various degrees of completion discuss the results of this cruise in greater detail [Corliss et al., 1978; Ballard et al., 1979; van Andel and Ballard, 1979; Crane, 1979b; Allmendinger and Riis, 1979; Corliss et al., 1980]. The purpose of this paper is to describe the detailed structure and morphology of these hydrothermal fields and attempt to relate their origin and history to the tectonic

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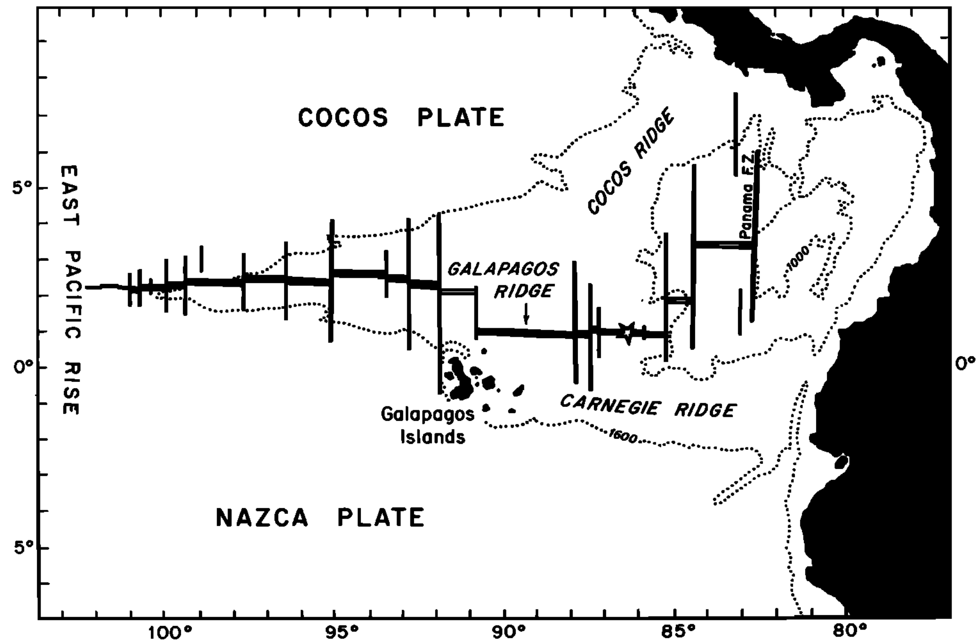


Fig. 1. Locator map showing that portion of the Galapagos Rift in which the active hydrothermal fields discussed in this paper were found.

and volcanic processes known to be occurring within the rift valley.

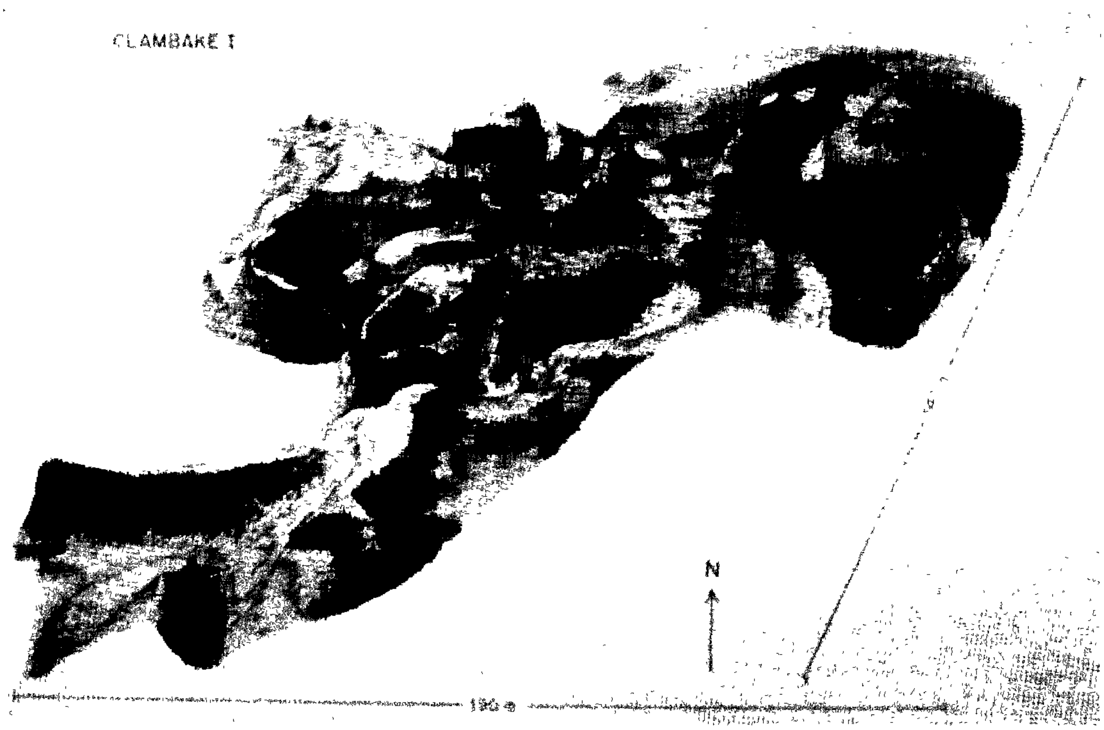
Data Base

The primary data used in this paper are derived from a series of camera lowerings conducted by the Angus system in the five vent areas. Angus consists of a survey camera and lighting system mounted in a heavy duty steel frame which is capable of being towed within a few feet of the ocean floor on a conventional trawl wire. The camera has a 16-mm wide-angle lens and takes 3000 35-mm color photographs per lowering. Upon recovery of the sled this film is immediately processed aboard ship and, within a few hours, can be projected on a screen for subsequent analysis. Each frame contains a digital display of the precise time linked to an acoustic transponder navigation system. With this common time base it is possible to locate each frame within a three-dimensional reference grid. While the Angus sled is being flown within 5 m of the floor (the height necessary to keep the bottom in the field of view), its altitude is acoustically telemetered to the surface and graphically displayed on a recorder. The altitude data (digitized every 30 s) are then merged with the navigational information to produce a series of plots depicting the path of the camera sled both horizontally across the bottom and obliquely through the water column. When the Angus depth information is added to the height off bottom, a record of the microtopography beneath the sled is obtained. In addition to altitude data the ambient temperature of the water which the sled is passing through is telemetered to the surface and graphically displayed.

In all, 22 Angus lowerings were made during the course of the 1977 cruise. The majority of these were conducted along east-west lines within the rift valley and were not only made to locate active hydrothermal fields but were also used to obtain a detailed understanding of the volcanic and tectonic evolutionary history of the rift valley which is presented in a paper by van Andel and Ballard [1979]. Once the five fields were located and confirmed to exist by Angus and Alvin, a separate series of Angus lowerings were made. This paper presents the results of those later lowerings. In each case the grid coordinates of a vent field were loaded into the Angus computer and displayed on a Tektonic scope at a scale of 20 m/cm. The R/V Knorr, using its cyclodial propulsion system, then carefully maneuvered the camera sled back and forth across the vent field, saturating the area with color photographs. Following these lowerings the navigational data were edited to produce a detailed record of the camera's coverage. Initially, an x-y plot was made which was annotated with the microtopographic data. These data were contoured at 1-m intervals to produce a detailed topographic map of the areas studied. Using this map, clay models were made of each vent field at a scale of 4 m/cm with no vertical exaggeration. Each bottom photograph was reviewed, and biological and geological observations were logged according to the precise time the photograph was taken. These observations were then added to the clay models in the form of color coding and surface textures. From these, artistic renderings of the vents were drawn (Plates 1-5).

Geologic Setting

van Andel and Ballard [1979] present a detailed discussion of the morphology and structure of the rift valley at 86°W. In summary, the Galapagos Rift is analogous to the inner rift valley of the Mid-Atlantic Ridge in the French-American Mid-Ocean Undersea Study (Famous) area [Ballard and van Andel, 1977]. It consists of three major morphologic provinces: the inward facing walls,



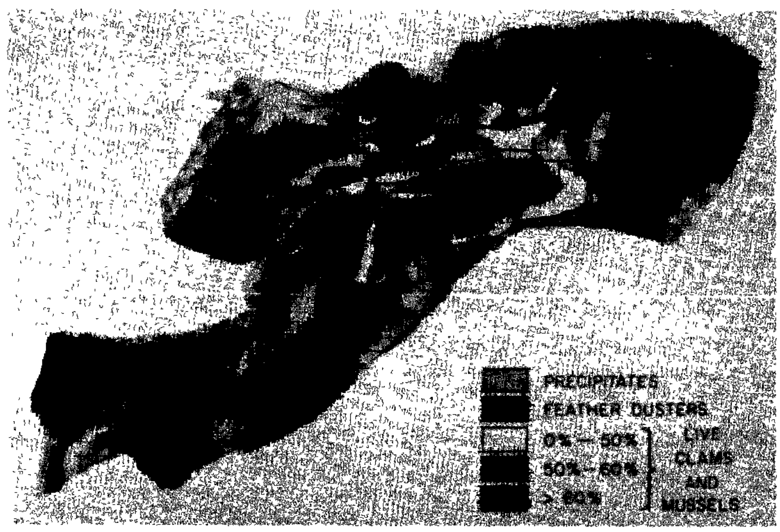


Plate 1. Artistic renderings, animal distributions, and representative photographs obtained from Angus lowerings in Clambake I.

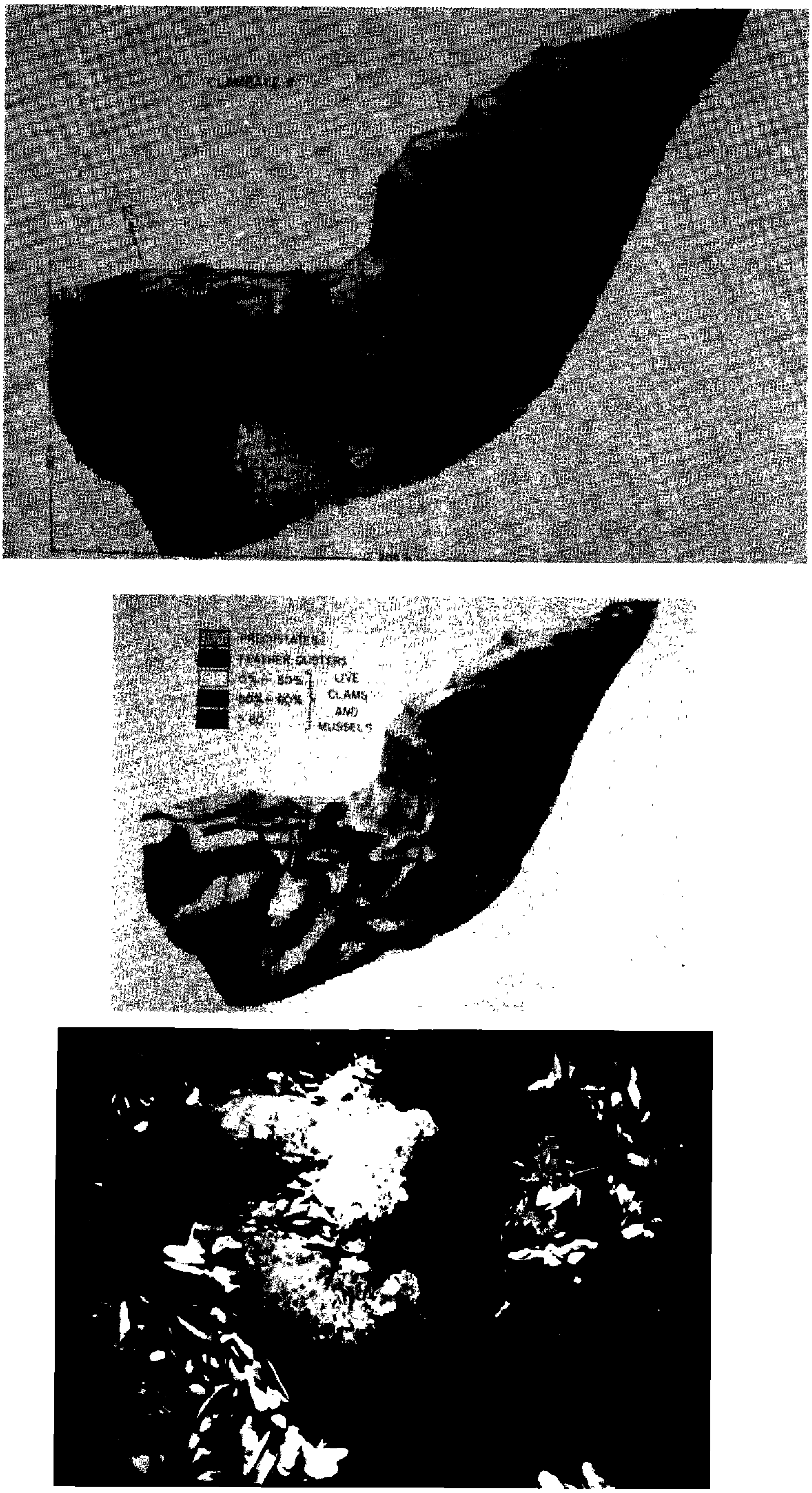


Plate 2. Same as Plate 1 for Clambake II.

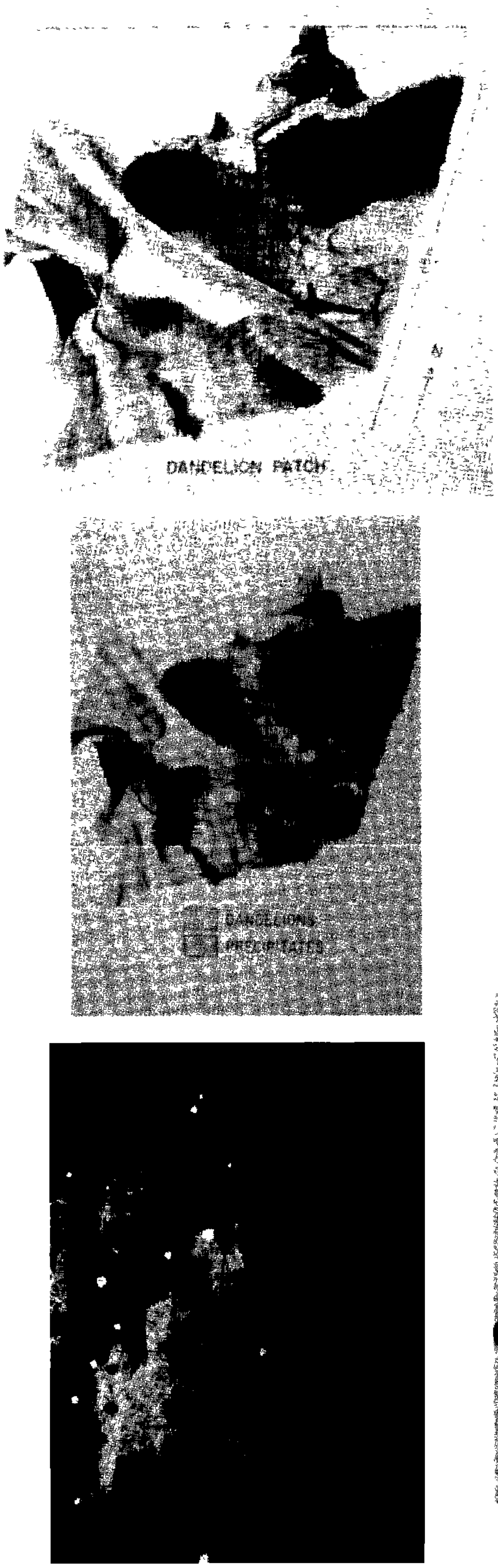


Plate 3. Same as Plate 1 for Dandelion Patch.

Plate 4. Same as Plate 1 for Oyster Beds.

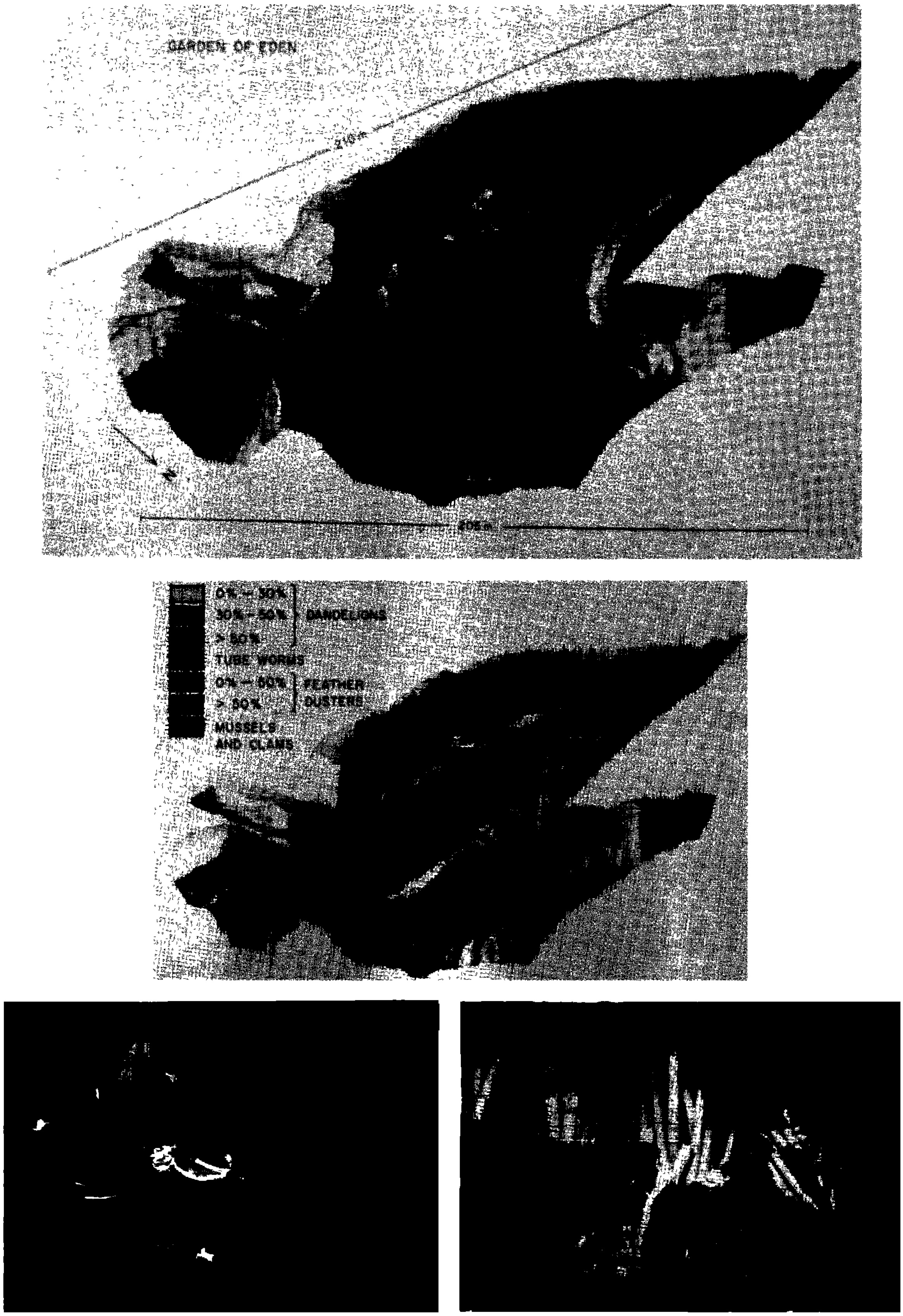


Plate 5. Same as Plate 1 for Garden of Eden.

marginal highs, and central zone (Figure 2). The central zone, 0.5 to 1.0 km wide, is characterized by the youngest lava flows, and contains (1) a ridge of small volcanic hills 20-60 m high, formed by interlocking lobated pillow flows, (2) a broad, flat southern zone covered by sheet flows, and (3) a narrow northern zone of both small sheet flow-filled depressions and pillowed highs.

This central volcanic zone varies along its length in several important ways. The percentage of the surface area covered by pillowed flows increases from west to east, as does the amount of fissuring, with the surprising absence of any fissuring in a 1.5-km^2 region in the west. The apparent age of the various flow units (based on presence or absence of glass and sediment cover) also increases from west to east [Ballard and van Andel, 1977].

Fissuring is also observed to occur almost exclusively in pillowed flows. Sheet flows apparently respond to tensional stresses by forming collapse structures instead of fissures [Ballard et al., 1979].

Hydrothermal Fields

Five active hydrothermal vent fields were found during the 1977 R/V Lulu, DSRV Alvin, and R/V Knorr cruise (Figure 2). From west to east these were named Clambake I, Clambake II, Dandelion Patch, Oyster Beds, and the Garden of Eden. These names evolved out of the preliminary impressions developed during each dive and bear no true relationship to the unique animal communities. Corliss et al. [1978] reported that only four of the five vent sites were active, with the fifth being inactive and characterized by dead organisms. Since the Angus lowerings were conducted at the end of the cruise, it was not until after the preliminary results had been submitted for publication [Corliss et al., 1978] that the fifth vent area was also found to be active.

Clambake I (Plate 1). Clambake I, the westernmost hydrothermal field, occurs at the apex of the fissure wedge on the crest of a narrow ridge consisting of young pillowed flows. This narrow ridge connects the larger eastern and western volcanic highs. The ridge is immediately flanked to the north and south by young, flat-lying sheet flows in which no fissuring was observed. The vent field is situated within a small grabenlike structure approximately 50 m across. Clambake I covers a total surface area of about 4000 m^2, which includes both active and inactive vents and occurs within a depth range of 24 m (2468-2492 m). It is shaped like two ovals joined together along their lengths. Two large east-west fissures a few meters in width cut across the field. The southernmost of the two occurs along the contact where the ovals join, while the other marks the northern boundary of the field. The southern boundary is marked by a 3- to 10-m high fault scarp. As the fissures enter the vent field, they subdivide into numerous interwoven microfissures. The major temperature anomalies measured by Angus while traversing this area were associated with these microfissures. The active vent sites themselves are characterized by dense concentrations of marine organisms with the most dominant forms being large white clams (Vesicomyidae), smaller-sized brown mussels (Mytilidae), and small serpulid worms [Corliss et al., 1978]. Their location and approximate concentrations are shown in Figure 3, accompanied by individual Angus pictures showing them in greater detail. At least four different sites of dense living white clams and brown mussels can be seen in the Angus photographs. At each of these sites (5- to 10 m in diameter) the animal life covers up to 50% of the bottom, and, where measured by Alvin [Corliss et al., 1978], the temperature increases to as much as 10°C above ambient. These active vents are interconnected by near-concentric rings denoting smaller populations of living organisms. The entire vent field is surrounded by a ring of dead white clams with their shells lying opened and scattered amongst the individual lava pillows. This dead outer ring represents about 36% of the total surface area in the field. Separated from the larger field by approximately 20 m is another small area of dead clam shells at the southeastern limit of the Angus coverage. Whether this is the border of another vent site containing living organisms and active hydrothermal activity or just a small, inactive vent is unknown. While the clams and mussels are directly associated with the most active portions of the vents, the serpulid worm concentrations are always located 5-10 m away. Whether they are being displaced by the larger forms or whether they prefer these sites is unknown.

Throughout Clambake I the young pillow forms are lightly coated with a brown manganese precipitate that smooths and dulls their otherwise glassy surfaces. Also within the field and particularly around its outer perimeter and extending along several of the fissures outside, a white hydrothermal stain can be seen on the pillows. This staining is most commonly seen around the rims of freshly fractured pillow fragments.

Clambake II (Plate 2). This vent field lies 1600 m to the east of Clambake I (Figure 2). It is situated in the center of the hydrothermally active zone in a region of moderate fissuring. Like Clambake I this vent field occurs in relatively young pillow terrain near a contact with sheet flows which lie in a depression to the north. When this field was initially located by Angus, the camera sled crossed a portion of the field containing only what appeared to be dead clams and having no measurable temperature anomalies. When Alvin subsequently visited this site, it also went to the area of dead clams and found no living organisms or warm water vents [Corliss et al., 1978]. Unfortunately, the submersible then traveled east, reporting that the area was inactive. The Angus lowering on which this discussion is based occurred at the end of the cruise, and the associated data were not reviewed until after the cruise had ended. It was at that time that this site was found to be active, having both warm water anomalies and dense concentrations of animal life. Since this final Angus lowering centered itself on the eastern portion of the field, the coverage was not extensive enough to fully survey the field's total limits (Plate 2).

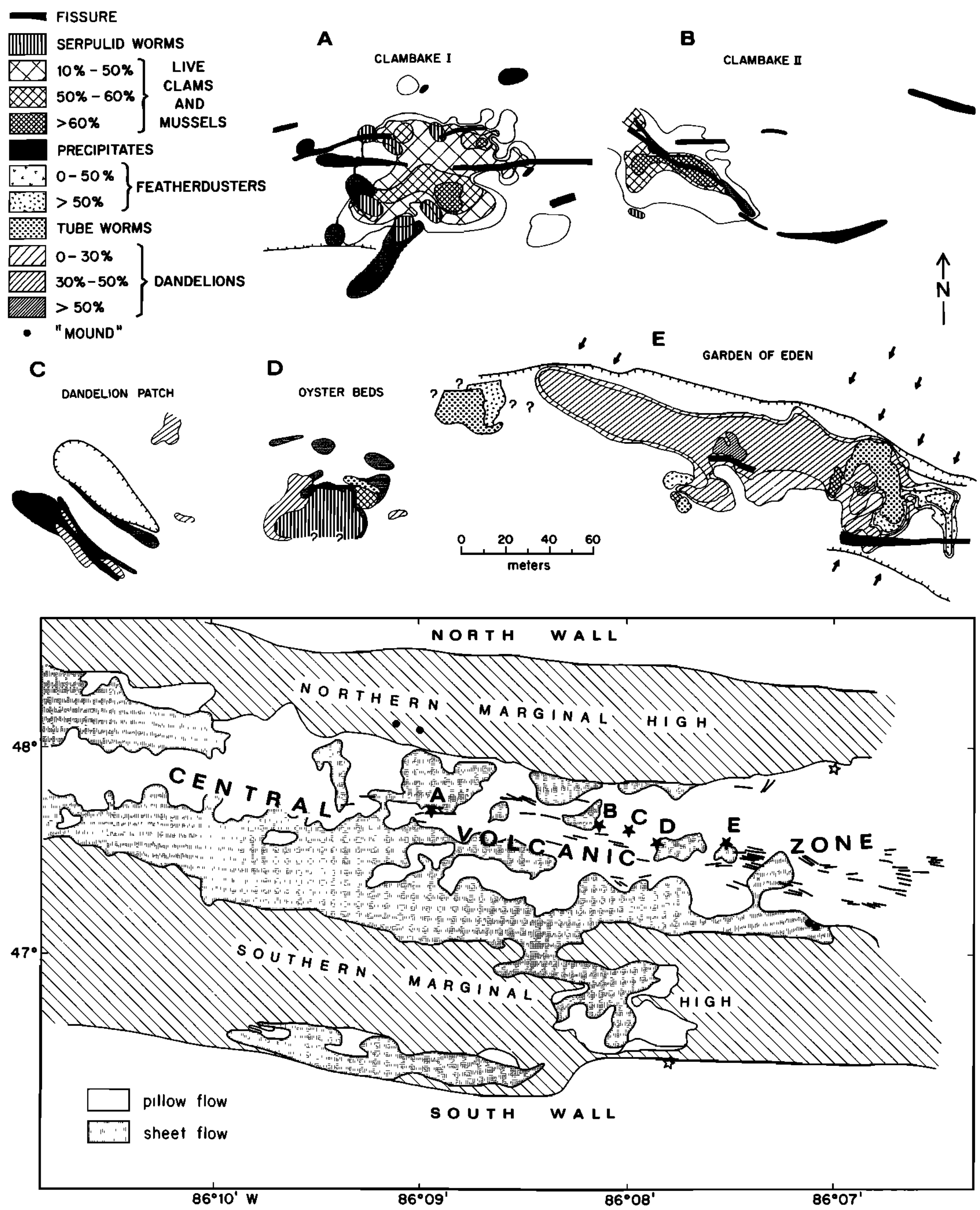


Fig. 2. Geologic map (simplified from van Andel and Ballard [1979]) showing (1) the major morphologic provinces of the rift valley, (2) the regional distribution of pillow flows and sheet flows in the central zone, (3) the location and names of the five vent fields, and (4) the distribution of fissures in the central zone of recent volcanic activity. Biological zonation maps on the periphery indicate the relative sizes of the vent fields.

For that reason the numbers given pertain only to the area surveyed and should be taken as the lower limit. The vent area studied is roughly oval-shaped, trends 115°, and covers a surface area of 1850 m^2. Two fissures enter the field: one trending east-west and running along the northern boundary of the field and the other trending 115° and running down its center.

The dominant organisms found here are the same as those identified in Clambake I: large white clams (Vesicomyidae), smaller brown mussels (Mytilidae), and small serpulid worms. The field occurs within an 8-m depth range (2468-2476 m). Of the total area surveyed, 27%, or 450 m^2, has a living population density of greater than 50%, while the total living population covers 800 m^2 (60 m x 15 m). As in Clambake I, decreasing percentages of living versus dead organisms occur in roughly concentric oval-shaped rings about three apparent vent sites. Unlike Clambake I, however, this field does not have an outer ring of totally dead organisms; instead, they occur in three distinct areas around the outer perimeter. Here also the serpulid worms occur off to the side of the active vents.

Although this field also contains a dull coating of manganese on the pillow forms within it, it lacks the major areas of hydrothermal staining seen in Clambake I. The pillow flows just outside the field area commonly have fresh glassy surfaces. On the steeper southern slopes of Mount Swift, the pillow forms become more elongate and frequently have fresh glassy buds indicative of a high degree of freshness. North of Clambake II the flank of Mount Swift is predominantly composed of less fresh pillows.

Dandelion Patch (Plate 3). Although this vent field is located only 250 m to the east of Clambake II (Figure 2), the two biological communities are quite different. The Dandelion Patch is situated near the center of the hydrothermally active zone and is the only field located in pillowed lava flows some distance (250 m) from any contact with flatter-lying flows. The thermal field covers a total area of 400 m^2 and is divided into four separate patches which surround a teardrop-shaped depression (Plate 3). This 55-m-deep graben is bounded to the north and south by two scarps trending 125°. The graben is 65 m long and 20 m wide. A third scarp, parallel and southwest of the graben, has a large fissure at its base, along which the major thermal field is located. To the north of the field, the lava terrain consists of pillows, none of which are particularly fresh. A lobe of elongate pillows cascades down the higher slope toward the teardrop-shaped depression. The perimeter of this depression is surrounded by fresh glassy pillows, with the highest concentration of glass occurring on the northwest and southeast sides. A long strip of glassy lava 50 m long and 5 m wide lies just south of and parallel to the graben. Hydrothermal precipitates stain and coat the pillow surfaces on either side of this glassy zone.

This thermal field is characterized by the presence of numerous small spherical-shaped organisms approximately 2-3 cm in diameter. These organisms are a form of siphonophore. They are found near the base of pillows and have many fine filaments which radiate out 6-8 cm from their spherical bodies, attaching them to the rocks. The surface texture of the animal is bumpy, resembling a dandelion gone to seed, thus accounting for the name applied to the field. These organisms are found in the four different patches which vary in area from 10 m^2 to 280 m^2. The patch which is 15 m north of the graben has an average density of 3 dandelions/m^2 and ranges in depth from 2472 to 2482 m. The two central patches range over a depth of 2474-2482 m. The major portion of the field situated along the base of the southernmost scarp has a density of up to 11 dandelions/m^2 and extends over a depth range from 2486 to 2494 m.

Oyster Beds (Plate 4). The Oyster Beds thermal field lies on the southeastern flank of Mount Swift in pillow lava terrain near a contact with a small depression containing sheet flows (Figure 2). The slope on which it is located consists of flow lobes stacked on top of one another, creating a terraced surface broken by a series of small scarps trending roughly east-west (Plate 4). The active portion of the vent field occurs halfway down one of the pillow lava flow lobes, although the total field covers an area of 1050 m^2, with its associated animal community covering a portion of the flow front and the small terraced area above it. This flatter terrace is characterized by the presence of bulbous pillows, while the slopes contain more elongated pillows. At the base of the flow lobe is a talus apron. Only one small fissure is found near the field, and it divides into two smaller fractures, each 10 m long and 2 m wide, lying just northwest and northeast of the field.

Within the hydrothermally active zone, clusters of animals occur in distinct bands according to their species. This thermal field is inhabited by four different animals which are recognizable in the *Angus* photographs. The most active vent site is populated by tall white-body and red-top tube worms. These worms are approximately 45 cm in length (Class Vestimentifera), occupy 5%, or 50 m^2, of the total area, and were found to be associated with the warmest vent sites [Corliss et al., 1978]. Next to these animals is a concentration of small brown mussels (Mytilidae) originally mistaken for oysterlike organisms (for which the vent was named). These animals occur in tightly packed clumps covering 100 m^2, or 10% of the total field. Farther away from the active vent and covering about 29% of the total area (300 m^2) are serpulid worms. On the outer perimeter of the field are dandelions with an average density of 2 animals/m^2. The total depth range of this field is 23 m (extending from 2478 to 2490 m).

Garden of Eden (Plate 5). The fifth thermal field occurs at the eastern limit of the hydrothermally active zone, 650 m east of the Oyster Beds (Figure 2). It is similar to the majority of the other fields in that it is located near the contact of pillow flows and sheet flows, but unlike the others it lies predominantly in the sheet flow terrain. The model made of the field using the *Angus* data (Plate 5) reveals that it is flanked to the north, south, and east by inward facing pillowed flow lobes with a small embayment containing sheet flows occurring to the west. A fissure 2-4 m in width runs along the sheet flow-pillow flow contact and marks the southern boundary of this vent site. A small fissure is also seen along the central axis of the field. The vent area itself covers 5300 m^2, 1.3 times greater in area than the next largest field, Clambake I. It is elongate in shape, striking 105° with a length of 190 m and width of 30 m. Three major loci of concentrated animal life occur at this site. The largest by far is in the eastern portion of the field and is characterized by large tube worms (Vestimentifera) similar to those seen at the Oyster Beds. These worms cover a 475 m^2 area. Adjacent to them are the smaller serpulid worms, which decrease in abundance away from the vent site and cover 400 m^2 of area in the eastern portion. Also adjacent to the tube worms are mussels (Mytilidae) located in a smaller area of 100 m^2 over a depth range of 2496-2502 m.

The second concentration of life in the field occurs 110 m to the west of the first. Here also, tube worms, mussels, and serpulid worms can be found covering 25 m^2, 15 m^2, and 100 m^2, respectively. The third locus of life occurs

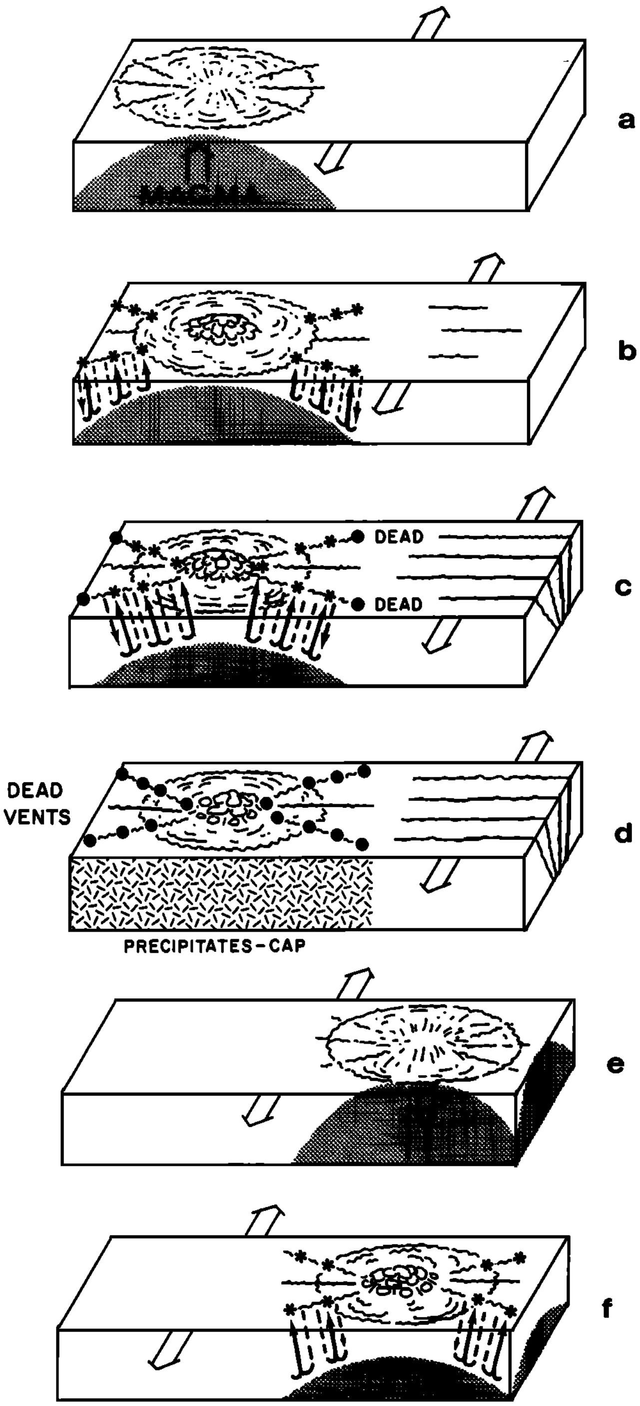


Fig. 3. Schematic diagram that describes the cyclic evolution of hydrothermal vents. (a) The crust upbows and fractures. Sheet flows are extruded, covering up the fissures, yet the planes of weakness remain. (b) Pillow flows channelize. With cooling and extension, further fissuring takes place along previous planes of weakness. Hydrothermal vents start to operate with rapid exchange of heat. (c) With further cooling, the outermost fields die down. (d) The intrusion has now cooled, and the vents cease. Precipitates from these vents have clogged the fractures in this part of the rift valley. (e) With continued tension, lava upwells in the adjacent section of the rift valley, starting the cycle over again.

along the small fissure in the center of the field and is characterized by a dense population of dandelions. Dandelions in dense concentration are also found near the eastern vent site, while less dense populations can be found throughout the entire field.

Discussion and Conclusions

On the basis of the previous sections, several points can be made:

1. All of the active vent fields occur in the central zone of most recent volcanic activity, a zone which averages 0.5-1.0 km in width and is nearest to the magma source.
2. The lava flows in this central zone are the youngest encountered thus far and are estimated to range in age from less than a decade to a few thousand years [van Andel and Ballard, 1979].
3. Further evidence of the recency of volcanism is given by the lack of fissuring in much of the western central zone. Such large areas of no fissuring have not been encountered in any other rift valley except the EPR at 21°N.
4. A wedge of fissuring appears to be extending from the east into this unfissured area, and the dense fracturing in the eastern portion of the central zone is equal to that observed in the older volcanic terrain of the marginal high provinces to the north and south. This suggests that the eastern area has already reached a mature state of fracturing.
5. This wedge of fissuring implies some sort of age gradient along the strike of the central zone, decreasing in age from east to west.
6. Fissuring is almost exclusively restricted to pillow flow terrain, rarely occurring in the young sheet flows.
7. All but one vent field occur in pillow terrain, and that exception occurs at the contact between a pillow flow and sheet flow.
8. All but one vent field occur near the contact between sheet flows and pillow flows.
9. The distance along the strike from the zone of no fissuring in the west to the zone of mature fissuring in the east is 2.8 km, and it is within this region that all the hydrothermal fields are found.
10. The five vent fields can be grouped into two types based upon their unique animal communities: Clambakes I and II in one group and the other three in another group.
11. The uniform sizes of the various animals found in the vent fields suggest a single 'year-class,' further suggesting that the vents are young in age. Initial settlement and subsequent space competition, with adults being superior competitors, could also be another explanation.
12. The presence of large dead clam shells on the outer perimeter of Clambake I suggests that this vent is decreasing in its activity.
13. The active vents within any particular field are not associated with the larger fissures in the area but with small microfissures.

Ballard and van Andel [1977] proposed a kinematic model for the growth of the central volcanic zone, its subsequent fracturing, and its eventual lateral displacement outside the zone of magma extrusion. This model is based upon their observations using similar techniques in the rift valley of the Mid-Atlantic Ridge. It postulates a discontinuous eruptive and deformational history with the formation of the upper oceanic crust in discrete volcanic blocks formed during different eruptive periods. These volcanic ridges, made up of individual volcanoes, are later faulted along their boundaries and transported laterally as intact units.

More recently, van Andel and Ballard [1979] have applied this model to the Galapagos Rift and postulated a similar kinematic history [van Andel and Ballard, 1979, Figure 7]. Although the Galapagos Rift has a faster opening rate than the Famous area (7.0 cm/yr, compared to 2.4 cm/yr), the period separating major volcanic cycles in any one area is about 10,000 years. A volcanic cycle begins with the outpouring of massive sheet flows which fill the topographic lows. As the eruptive cycle continues, channelization develops within these ponded lava lakes, leading to the formation of more localized pillowed flows [Ballard et al., 1979]. These latter flows begin to build small volcanic hills along the central axis. The cycle ends with pillowed flows slowly covering the earlier sheet flows. The duration of the volcanic cycle is unknown, but van Andel and Ballard [1979] estimate that the flows within the central zone of the Galapagos Rift span a period ranging in age from less than a decade to a few thousand years (approximately 10-20% of the total cycle).

With the cessation of surficial volcanism, the newly formed crust undergoes renewed rifting beginning with unfissured volcanic terrain and ending with a maturely fractured crust. This total spectrum of fissuring is present within the central zone studied, occurring along the strike over a distance of 2.8 km, with the mature stage having been reached in volcanic terrain estimated to be of the order of a few thousand years in age [van Andel and Ballard, 1979].

We propose a slight modification of van Andel and Ballard's model in order to accommodate the distinct wedge-shaped fissuring observed in the older parts of the inner rift. Crane [1978, 1979a], using Ramberg's buoyance-tectonic models, stated that just prior to the period of localized magma extrusion the crust must undergo an upbowing resulting from subjacent pressure buildup. Crust which has cooled and become impermeable due to hydrothermal precipitates clogging the fractures acts as a sufficient cap to the upwelling magma. As tension across the base of the crust continues, magma continues to rise toward the surface where it is blocked by the 'throttling' effect of the impermeable cap. As the pressures exceed the strength of the crust, the cap fractures in radiating patterns away from the extruding magma (Figure 3). These fractures may soon be covered by sheet flows, but the planes of weakness are still pervasive. As the extrusion dies down, concentric cooling ensues around the fresh volcanic hill. Fissures form both from continued tension due to rifting and contraction in the cooling crust. While the central intrusion is still quite hot, these newly formed radiating fissures serve as localized channels for the egress of heated seawater [Lister, 1977, 1978]. Actually, it is the intensely disturbed zones of microfissures bounded by larger fissures and small faults that are the point source loci for the emanating water [Corliss et al., 1978, Figures 3-7]. Work by Corliss et al. [1980] suggests that on the basis of their analysis of the water samples obtained in the Galapagos vent fields, the depth of water penetration in the central zone is 1-2 km. They also support Lister's [1977, 1978] estimates that the seawater descends at a rate of about 10 m/yr, attains a temperature of 200°-350°C, and rapidly rises back to the surface in a matter of hours.

The fact that all of the thermal vents are located in the zone of transitional fissuring extending for a distance of 2.8 km in volcanic terrain only a few thousand years in age (at the most) suggests that the active hydrothermal stage is short-lived. This is supported by the recent studies of C. Turekian (personal communication, 1977) on the 210Pb content of the large white clams, showing them to be tens of years or less in age.

Presumably, seawater circulation at these sites will continue, resulting in a slow drop in the temperature of the water flowing out of the vents. Once that temperature drops below 10°C (J. Edmond, personal communication, 1977), hydrogen sulfide is no longer present in the water. Because this compound, along with others, is believed necessary to support the unusual animal communities [Corliss et al., 1978], the biological activity in the vent will cease. The total length of this biological cycle appears to be of the order of tens of years. Continued cooling will drop the temperature further below 10°C until only remnants of previous activity are found. The fact that the outer portion of Clambake I (36%) is presently inactive suggests that this vent, as well as others having major dead areas, may already be slowing down.

As cooling of the central intrusion continues, the fissures propagate toward the remaining heated intrusion. Thus there is a hydrothermal age gradient with distance from the heated intrusion. In time, older vents die out, being too far away from the heat source.

As continued rifting occurs, the older crust is pervasively fractured by tensional fissures and faults, while the extensive hydrothermal precipitates in the newer zone rapidly plug up the crust and form a relatively impermeable cap rock. For this reason a new volcanic cycle should erupt in the formerly 'old' terrain, thus ensuring a volcanic periodicity in space and time up and down the strike of the rift valley.

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