DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

A TEACHER'S GUIDE

to

QUESTIONS/ANSWERS AND LAB EXERCISES

prepared to accompany the film

"INSIDE HAWAIIAN VOLCANOES"

by

Wendell A. Duffield[1] and Richard S. Fiske[2]

Open-File Report 89-685

[1] U.S. Geological Survey
2255 North Gemini Drive
Flagstaff, AZ 86001

[2] Dept. of Mineral Sciences NHB 119
Smithsonian Institution
Washington, D.C. 20560

1989

FOREWORD

The materials on the following pages were prepared to be used in conjunction with the educational film "INSIDE HAWAIIAN VOLCANOES". This film was coproduced by the U.S. Geological Survey and the Smithsonian Institution and is available in VHS video cassette and 16-mm motion picture formats. Distribution of VHS cassettes is handled by the Smithsonian Institution (see address on title page). Distribution of 16-mm films is handled by the U.S. Geological Survey; enquiries should be directed to the U.S. Geological Survey, Visual Information Services, 790 National Center, Reston, VA, 22092, Telephone: (703) 648-4379.

Q U E S T I O N S

Note: The following questions are only a sampling of what an instructor might propose from the information contained in the film.

(1) What is the name of the rock that Hawaiian volcanoes are made of?

(2) What is the approximate melting temperature of the rock that Hawaiian volcanoes are made of?

(3) What conditions make some eruptions of Hawaiian volcanoes violently explosive, whereas most are quiet and safe to observe at close range?

(4) Approximately how many people have been killed as a result of Hawaiian eruptions in the past 250 years? What kind of eruptions caused these deaths?

(5) One form or shape of Hawaiian rock is called pillow lava. Where and how does this rock originate?

(6) Professor Thomas Jaggar established the Hawaiian Volcano Observatory in 1912. Why did he chose Kilauea Volcano as the observatory location?

(7) What is global plate tectonics?

(8) Describe two types of boundaries between tectonic plates. There is a third type of boundary, not described in the film, where two plates slide laterally past each other. Can you think of an example of this type of boundary in California?

(9) What is the geographic relationship between most active volcanoes and the boundaries of tectonic plates? Do the Hawaiian volcanoes conform to this general relationship? Why or why not?

(10) Why do Hawaiian volcanoes occur in a line, with volcanoes progressively older to the northwest?

(11) If the active volcano Loihi, now 25 miles southwest of Kilauea Volcano and 3,000 feet beneath sea level, has 1 foot of lava added to its summit each year, when will the volcano become an island? Geologists know that the increasing weight of a growing volcano progressively depresses or pushes down the underlying sea floor. How will this process affect the time needed for Loihi to become an island?

(12) Most Hawaiian volcanoes are called shield volcanoes because of their broad, gentle profiles. Why do you suppose this shape is so common for Hawaiian volcanoes, in contrast to shapes of such steep-sided cones as Mount St. Helens and other high volcanic peaks in the Cascade Mountain Range of the Pacific Northwest?

(13) Mauna Loa is about 150 miles wide, is built upon an 18,000-foot-deep sea floor, and rises about 13,600 feet above sea level. Mount Rainier in Washington State is about 15 miles wide, is built upon a continental plateau that is 5,000 feet above sea level, and the summit is about 800 feet higher than that of Mauna Loa. Which is the larger volcano? Assuming that each has the shape of a cone, what is the volume of each?

(14) Hawaiian volcanoes swell or inflate between eruptions. How can the resulting change-in-shape of the ground surface be measured?

(15) What causes a Hawaiian volcano to inflate? Do you think other types of volcanoes, for example steep-sided cone-shaped mountains like Mount St. Helens, inflate between eruptions?

(16) In addition to ground deformation and earthquakes, what other evidence exists that a reservoir of magma is located a mile or two beneath the summit of an active Hawaiian volcano?

(17) Most eruptions of Hawaiian volcanoes begin with lava fountaining that may continue for hours or days and then change to a quiet outflow of lava without fountaining. What do you think causes the fountaining, and why might it stop before the eruption stops?

(18) Most eruptions of a Hawaiian volcano occur in the caldera, a large depression at the summit, or along zones of fracturing or rifting that radiate from the caldera. How does magma get to the site of a rift eruption? What name is given to the solid body that occupies the conduit after it has finished carrying magma to a rift eruption?

(19) Repeated surveys of ground deformation indicate that the coast line along the south side of Kilauea Volcano moves about 6 inches seaward each time magma is intruded (as a dike) into Kilauea's rift zones. If a total of 10 feet of movement accumulated during a 50-year period, how many episodes of magma intrusion occurred? What would the significance be if only 11 rift-zone eruptions occurred during this time? What does this imply about how Kilauea grows? If the coastal part of the south flank continued to move at the rate of 10 feet per 50 years, how much seaward displacement would accumulate in 1,000 years? [Food for thought: Who would own newly created sea-front land formed by ground displacement and/or by lava flows building outward along the coast?].

ANSWERS

NOTE: Most questions have answers that are simple, straightforward, and come directly from information contained in the film. Some, however, can be answered only by drawing on a broader experience; these are aimed to test the imagination and creativity of the student.

(1) Hawaiian volcanoes consist almost entirely of a rock called basalt.

(2) Basalt melts at about 2,100^{o} Fahrenheit.

(3) When water mixes with molten basalt, the result commonly is a series of violent steam-powered explosions.

(4) About 80 people have been killed by violent eruptions of Hawaiian volcanoes. These eruptions were violent steam explosions that were generated when water mixed with magma in the erupting vents.

(5) Pillow lava may form when a lava flow enters the sea, if the mixing of sea water and lava does not result in violent explosions. When a tongue of lava quietly enters the sea, the cooling effect of the water results in the formation of a thin black crust around a still-molten interior that may continue to expand and grow in length, eventually producing a solid body that looks like a pillow.

(6) Professor Thomas Jaggar selected Kilauea Volcano on the island of Hawaii for the observatory, mostly because of the high frequency of eruptions there and because these eruptions generally are safe to observe and study at close range.

(7) Geologists use the phrase, global plate tectonics, to refer to the fact that the crust of the Earth consists of about a dozen huge pieces, or plates, that are in constant motion relative to each other.

(8) At one type of boundary the plates spread apart and at another type they collide. In California, the best known example of a boundary where two plates slide laterally past each other is called the San Andreas Fault.

(9) Most active volcanoes are located along the boundaries between the crustal plates. These are locations where the processes of global plate tectonics favor the formation of magma that can rise to the surface. The Hawaiian volcanoes do not conform to this general situation and instead are near the center of the largest of all of the crustal plates, called the Pacific Plate. The Hawaiian volcanoes receive magma from a "melting spot" or "hot spot" in the mantle, 25 miles and more beneath the ocean floor; the reason for the existence of the "melting spot" is not known.

(10) As the Pacific crustal plate passes over the "melting spot" in the mantle, the motion of the plate is recorded on the surface of the Earth as a chain or line of volcanoes whose magma is fed upwards from the mantle source. The age progression of the volcanoes indicates that the Pacific crustal plate has moved steadily to the northwest relative to the source of magma in the mantle.

(11) At this rate of summit growth Loihi Volcano could become an island in 3,000 years. But because the sea floor is pushed down progressively by the increasing weight of the growing volcano, it will take more than 3,000 years for Loihi to become an island at a summit growth rate of 1 foot per year.

(12) Hawaiian lavas (basalt) flow far more easily (lower viscosity) than the lavas (andesite and dacite) of a volcano like Mount St. Helens; flows of high fluidity tend to spread farther and thinner than the stickier (higher viscosity) Mount St. Helens lavas. In addition, a Hawaiian volcano erupts lava flows at many vent areas on its flanks (rift zones) as well as at the summit, and this wide vent distribution helps to build a similarly wide volcano with a broad gentle profile.

(13) Mauna Loa is much larger than Mount Rainier, because the bottom of Mauna Loa is at the sea floor, 18,000 feet below sea level, whereas the bottom of Mount Rainier is 5,000 feet above sea level, sitting on a platform of older rocks that are not part of the volcano itself. The volume of Mauna Loa (about 35,300 cubic miles) is nearly 340 times greater than that of Mount Rainier (about 105 cubic miles).

(14) Inflation-caused change in shape (ground deformation) of Hawaiian volcanoes can be measured (a) by levelling surveying stations to determine their changes in elevation, (b) by using an electronic-distance-measuring instrument to determine changes in horizontal distance, and (c) by levelling at the corners of a triangle to determine changes in the slope or tilt of the ground surface.

(15) A Hawaiian volcano inflates in response to the addition of magma (that rises from the mantle "melting spot") into a magma reservoir a mile or two beneath the summit of the volcano. Scientists have learned that steep-sided cone-shaped volcanoes also inflate before erupting, although the pattern of ground deformation tends to differ from that of a Hawaiian volcano [this answer is not in the video, but the imaginative student may reason to a correct answer by understanding that the process of magma rising from the mantle into a magma reservoir in the crust on its way toward eruption is broadly the same for both types of volcanoes].

(16) Gases that rise from the ground (at gas vents called fumaroles) on Hawaiian volcanoes also are evidence that a reservoir of magma is beneath the surface. Gases originally dissolved in magma from the mantle "melting spot" start to escape as the upward flow of magma into the crust reduces pressure to a value that is too low to keep the gases dissolved in the molten rock. The escaping gases then flow toward the Earth's surface, where they can be collected at fumaroles.

(17) Lava fountains are driven by the rapid expansion of gases as these gases escape from erupting magma. The gases can escape relatively rapidly and completely at the Earth's surface, because the pressure that otherwise keeps them dissolved in the magma is very low (caused by the weight of the overlying atmosphere) compared with pressure that keeps gases dissolved in magma beneath the Earth's surface (caused by the load of overlying rocks). Before eruption, reservoirs of magma commonly have a gas-enriched upper layer; when this part of the magma has been erupted, the remaining magma may be too gas-poor to drive lava fountains.

(18) Magma gets to the site of an eruption on a rift zone by subsurface flow from the reservoir beneath the summit, through a vertical, blade-shaped conduit or fracture. After eruption stops, magma still in the conduit solidifies to form a body called a dike.

(19) At the rate of 6 inches of seaward movement per intrusion, 20 intrusions occurred during the 50-year period. If only 11 eruptions occurred in the rift zones during this period, 9 of the 20 episodes of magma intrusion must have formed dikes that did not reach the surface. This implies that the volcano grows by magma intrusion without eruption, which moves the sea coast 6 inches seaward with each intrusion, as well as by intrusion with eruption, which moves the sea coast **and** adds a new layer of lava to the surface of the volcano. At a rate of 10 feet per 50 years, the coastal area would move 200 feet seaward in 1,000 years. The ownership of newly created land has been the subject of many law suits in Hawaii.

LAB EXERCISES

EXERCISE ONE

PART ONE

During the 4-month period, October 1971 through January 1972, the summit area of Kilauea Volcano deformed steadily. Figure 1 shows a map of the affected area. Kilauea Caldera and smaller nearby craters are shown with hachured lines. Dots show the locations of surveying stations whose changes in elevation for the 4-month period are indicated in millimeters.

One station, in the northeast part of the area, is assigned zero change. Geologists know that this assignment is reasonable, because experience has shown that this and other stations about the same distance from the center of the deformed area change elevation very little relative to sea level during periods of a few to several months.

Note that the location of maximum change is near the south-central edge of the Kilauea Caldera, the large depression at the summit of the volcano, implying that the magma reservoir, which causes the elevation changes, is not exactly centered beneath the caldera. This situation has prompted some geologists to hypothesize that the magma reservoir enlarges slowly southward with time, and that a new caldera may form in the near geologic future, directly over the location of maximum elevation change shown in Figure 1.

Draw curves of equal elevation change (called contours), with the first curve going through the station of zero change and using a 40 millimeter interval of elevation change between successive contours.

Questions:

(1) Did the volcano inflate or deflate?

(2) The maximum <u>measured</u> change in elevation was 300 mm. What is your estimate of the <u>actual</u> maximum change?

(3) What was the average weekly rate of change in elevation for the location that changed most?

(4) What is the cross-sectional shape of the elevation changes along an east-west line that passes through the point of maximum change?

PART TWO

The horizontal distance between the stations that changed elevations by 140 mm (station A) and by 160 mm (station B, see Figure 1), respectively, increased by about 360 mm during the four-month period. When one attempts to convert this change in horizontal distance to a horizontal movement for each station, one should assume that ground deformation is symmetrical about the location of maximum elevation change.

Questions:

(1) What are the direction and amount of horizontal displacement for stations A and B. Show these as arrows on the map, Figure 1.

(2) Can you think of a way to determine the direction and amount of horizontal movement for the surveying stations without depending on the assumption that ground deformation is symmetrical about the center of maximum uplift? Remember that Kilauea is built on the flank of the much larger volcano, Mauna Loa, and that Mauna Loa did not deform during the period of interest.

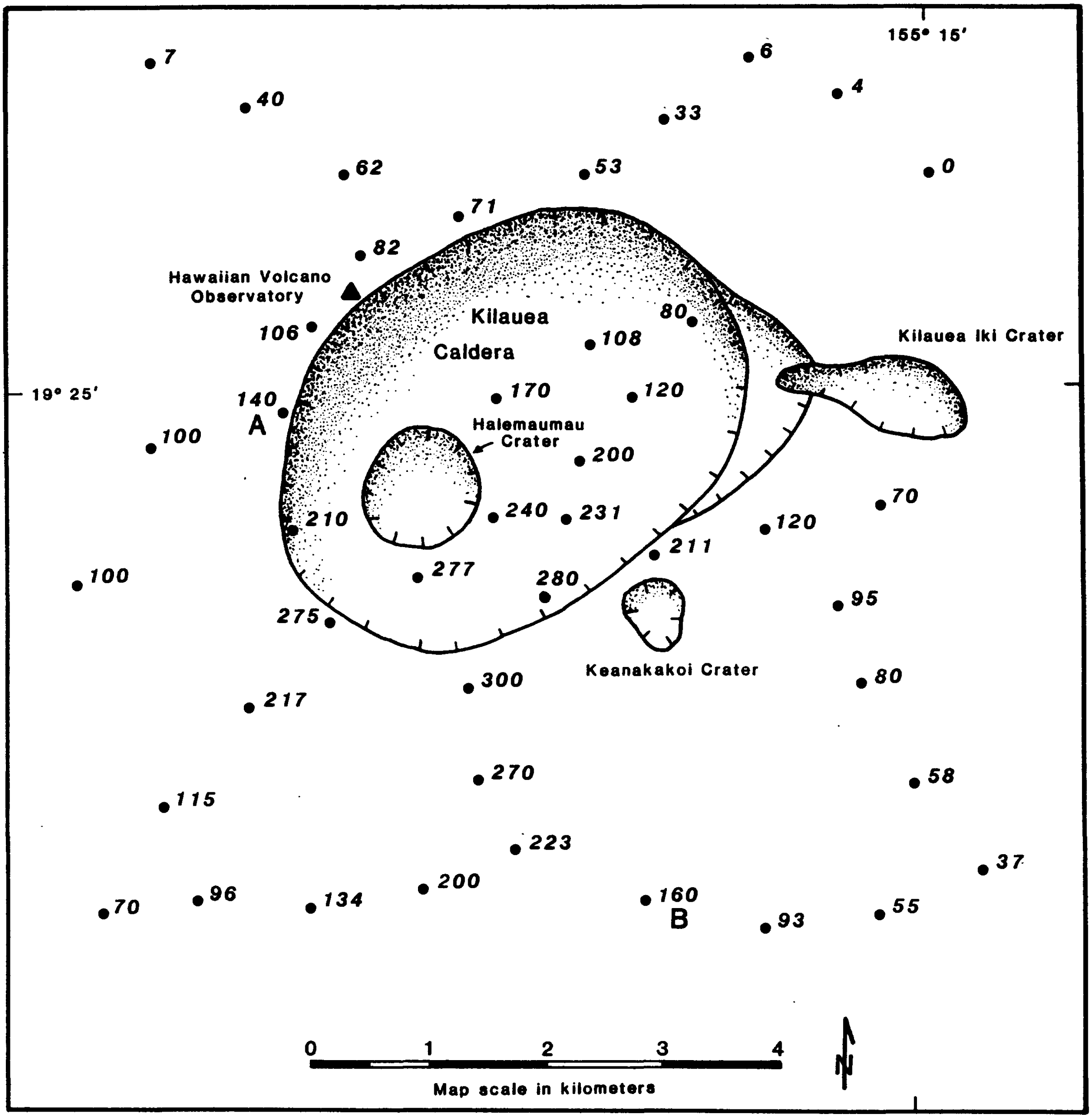

155° 15'
19° 25'
7
40
62
71
82
53
33
6
4
0
Hawaiian Volcano Observatory
106
Kilauea
Caldera
80
108
Kilauea Iki Crater
140
A
100
170
120
Halemaumau Crater
200
210
240
231
211
120
70
100
277
280
95
275
Keanakakoi Crater
300
80
217
270
58
115
223
37
70
96
134
200
160
B
93
55
0
1
2
3
4
Map scale in kilometers
N

Figure 1

EXPLANATION FOR LAB EXERCISES

EXERCISE ONE

PART ONE

Answers:

(1) The volcano inflated. All changes in elevation are positive.

(2) An estimate of maximum uplift in the range of 320 to 330 mm seems reasonable. The student must extrapolate from the maximum measured change, using the general pattern of change as a guide.

(3) 330 mm / 16 weeks = 21 mm / week.

(4) The elevation changes define a dome shape in cross section (see cross-section drawing, Figure 2). The student should be aware (or be made aware) that this shape will appear on a cross-section line of any orientation, so long as the line passes through the point of maximum uplift.

PART TWO

Answers:

(1) Each station moved about 180 mm, directly away from the location of maximum uplift. To arrive at this answer, the student must have contoured the levelling data in such a way that the line connecting stations with uplift of 140 mm (station A) and 160 mm (station B) passes through, or very close to the location of maximum uplift. Even semi-creative contouring of the data should give this result. The student must also note that the two stations are about the same distance from the location of maximum uplift. Then the idea of deformation that is symmetrical about this location should prompt the student to assign equal, or nearly so, displacements that are radial to the center of symmetry for each station.

(2) The main point of this question is to try to get the student to realize that horizontal displacements can be derived without reference to the pattern of vertical displacements. To do so, one needs some survey stations in an area known to be stable. Mauna Loa is often stable relative to Kilauea, and thus is commonly used as a "stationary" reference for deriving horizontal displacements at Kilauea. One might also point out the rapidly developing use of distance measurements made from satellites to survey stations on the ground in order to accurately determine the position (and possible change of position) of these stations.

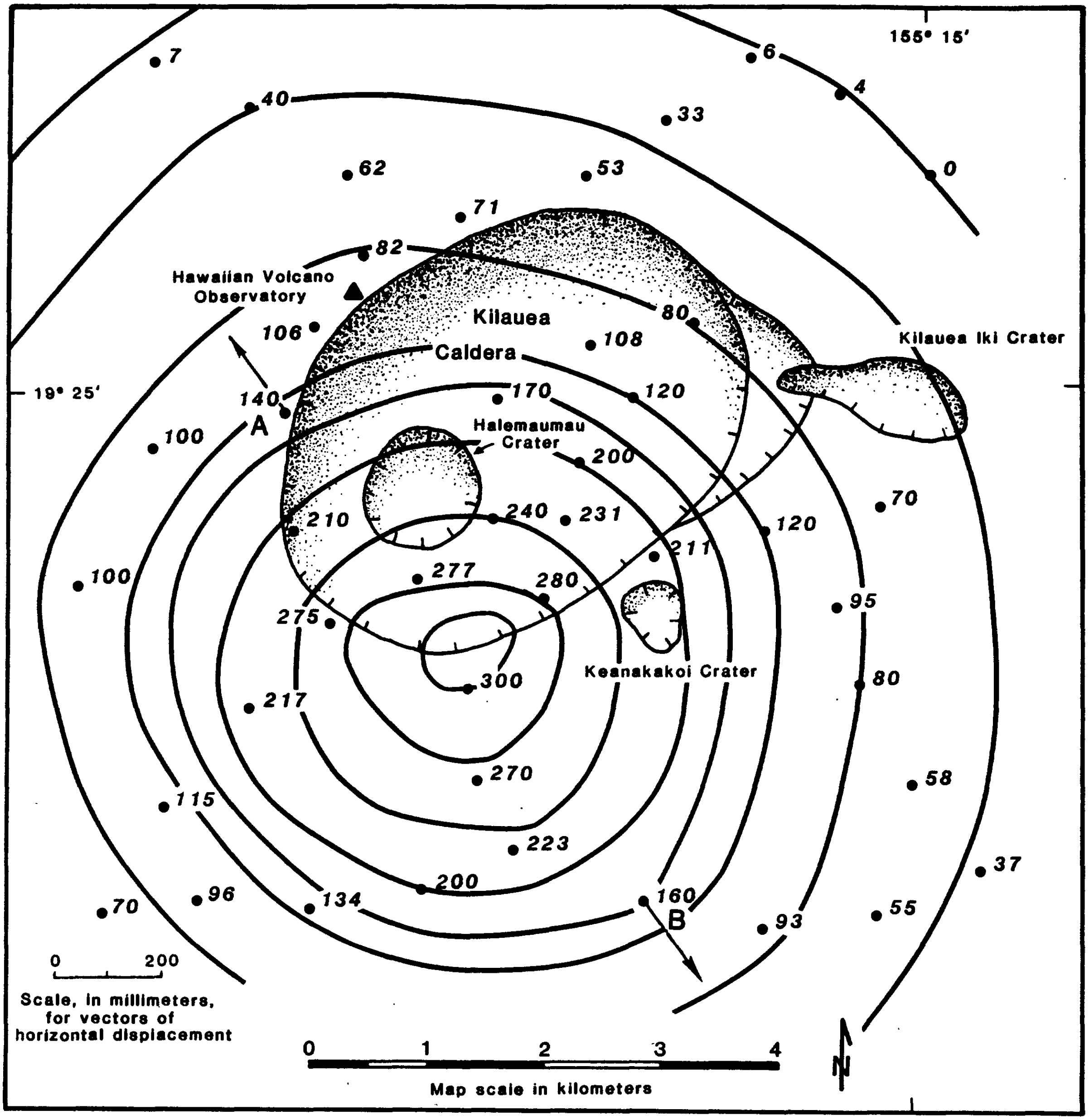


Figure 1 Solutions

9a

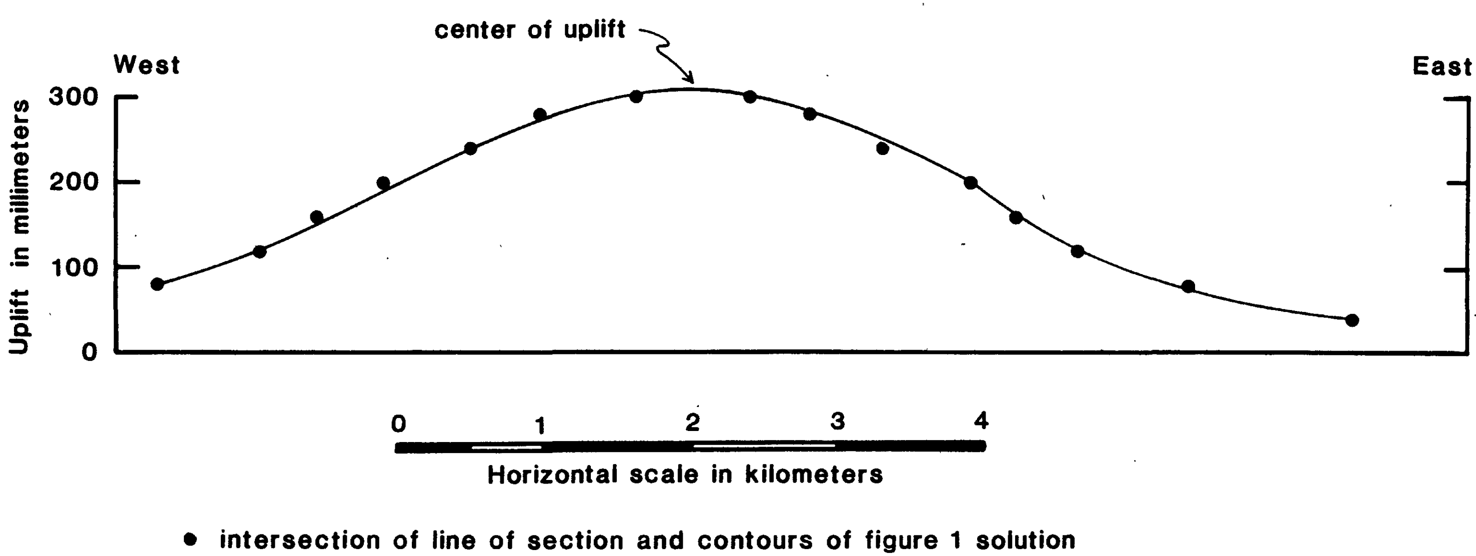

center of uplift
West
East
Uplift in millimeters
300
200
100
0
0
1
2
3
4
Horizontal scale in kilometers
• intersection of line of section and contours of figure 1 solution

Figure 2

L A B   E X E R C I S E S

E X E R C I S E   T W O

PART ONE

Some geologists hypothesize that Kilauea Volcano behaves elastically, somewhat like an inflated balloon, and are thus able to develop mathematical equations to describe the shape of deformation that will result from a change in pressure (similar to a change of air pressure in a balloon) within the magma reservoir beneath the summit area. As a result, the pattern formed by contours of change in elevation measured during levelling surveys may be applied to the equations to calculate the depth of the magma reservoir beneath the ground surface. Figure 3 illustrates mathematical relationships that describe patterns of elevation change for reservoirs of magma at 4 km, 3 km, and 2 km depths for an elastic model.

Questions:

(1) Using information from **Exercise One** and recasting it in such a way that data points can be plotted on Figure 3, what is your estimate of the depth to the magma reservoir whose change in pressure was responsible for deformation during the 4-month period? When interpreting your results, remember that the survey station assigned zero change probably rose slightly relative to sea level, and thus would plot somewhat above zero on the Y axis of Figure 3. Also, those stations located very close to the contour of zero change probably rose a bit more than the data of Figure 1 indicate.

(2) Can you think of a way to determine the depth to the magma reservoir, without reference to an elastic model? Remember that, in general, both horizontal and vertical components of change are known, or can be estimated through interpolation for each survey station. When vectors of horizontal and vertical change are added for a station, the resultant vector may point directly away from the source of deformation.

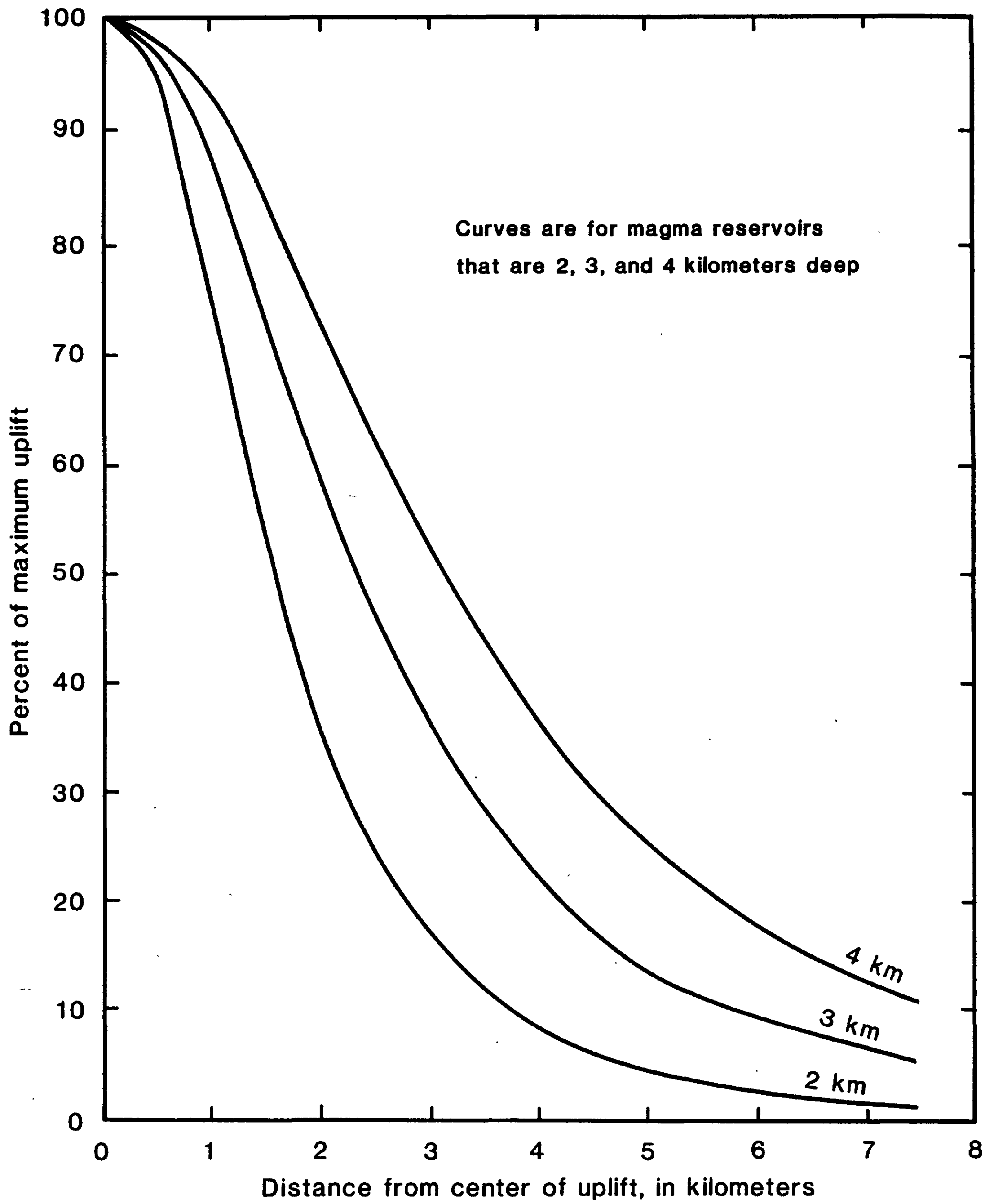

Curves are for magma reservoirs
that are 2, 3, and 4 kilometers deep
Percent of maximum uplift
Distance from center of uplift, in kilometers
100
90
80
70
60
50
40
30
20
10
0
0
1
2
3
4
5
6
7
8
4 km
3 km
2 km

Figure 3

E X P L A N A T I O N   F O R   L A B   E X E R C I S E S

E X E R C I S E   T W O

PART ONE

Answers:

(1) To answer this question, the student probably should be encouraged to create a table with three columns. Column one could be the survey stations of Figure 1 (44 of them), identified by the amount of uplift noted on that figure. Column two could be the ratio of the uplift at a station to the maximum estimated uplift (the answer to question 2, exercise 1, part 1), multiplied by 100 to yield percent of maximum uplift. Then column three would be the distance from a station to the location of maximum uplift, as scaled from the map of Figure 1. The data of columns two and three could then be plotted on Figure 3 for each survey station. Although some variation in results is to be expected in view of the uncertainties associated with defining the actual data points to be plotted, most points should plot between the curves for 4 km and 2 km, and in fact should plot with a suggestion that the 3 km curve offers the best solution.

(2) The idea behind the question is simply to challenge the student to create a graphic method for estimating depth to the magma reservoir, which underlies the center of deformation that is measured at the Earth's surface. The student can reasonably assume that the overall pattern of ground deformation is radially symmetric. Thus, the position of each survey station can be projected laterally to any cross section drawn through the center of uplift and the resultant of adding horizontal and vertical vector displacements at each survey station can then be projected downward. Intersections of these downward-projected lines with a vertical line through the center of uplift may be interpreted as the depth to the magma reservoir, sometimes called the hypocenter of deformation. Figure 4 illustrates the result of applying this procedure for stations A and B of Figure 1.

EXAMPLE OF TABLE TO BE CREATED BY THE STUDENT FOR USE WITH LAB EXERCISE TWO, PART ONE, QUESTION ONE

Survey Station (Uplift in mm)	Percent of Maximum Uplift	Distance to Center of Uplift in Km
0	0	5.6
4	1	5.6
6	2	5.5
7	2	5.6
33	10	4.7
37	12	4.75
40	13	4.9
53	17	4.1
55	17	4.1
58	18	4.0
62	19	4.1
70	22	3.8
70	22	3.7
71	22	3.7
80	25	3.4
80	25	3.3
82	26	3.45
93	29	3.4
95	30	3.2
96	30	3.2
100	31	3.2
100	31	3.4
106	33	3.1
108	34	2.8
115	36	3.0
120	38	2.7
120	38	2.6
134	42	2.6
140	44	2.6
160	50	2.6
170	53	2.2
200	63	2.1
200	63	1.8
210	66	1.8
211	66	1.75
217	68	2.0
223	70	1.75
231	72	1.4
240	75	1.2
270	84	1.2
275	86	1.2
277	87	0.75
280	88	0.8
300	94	0.3

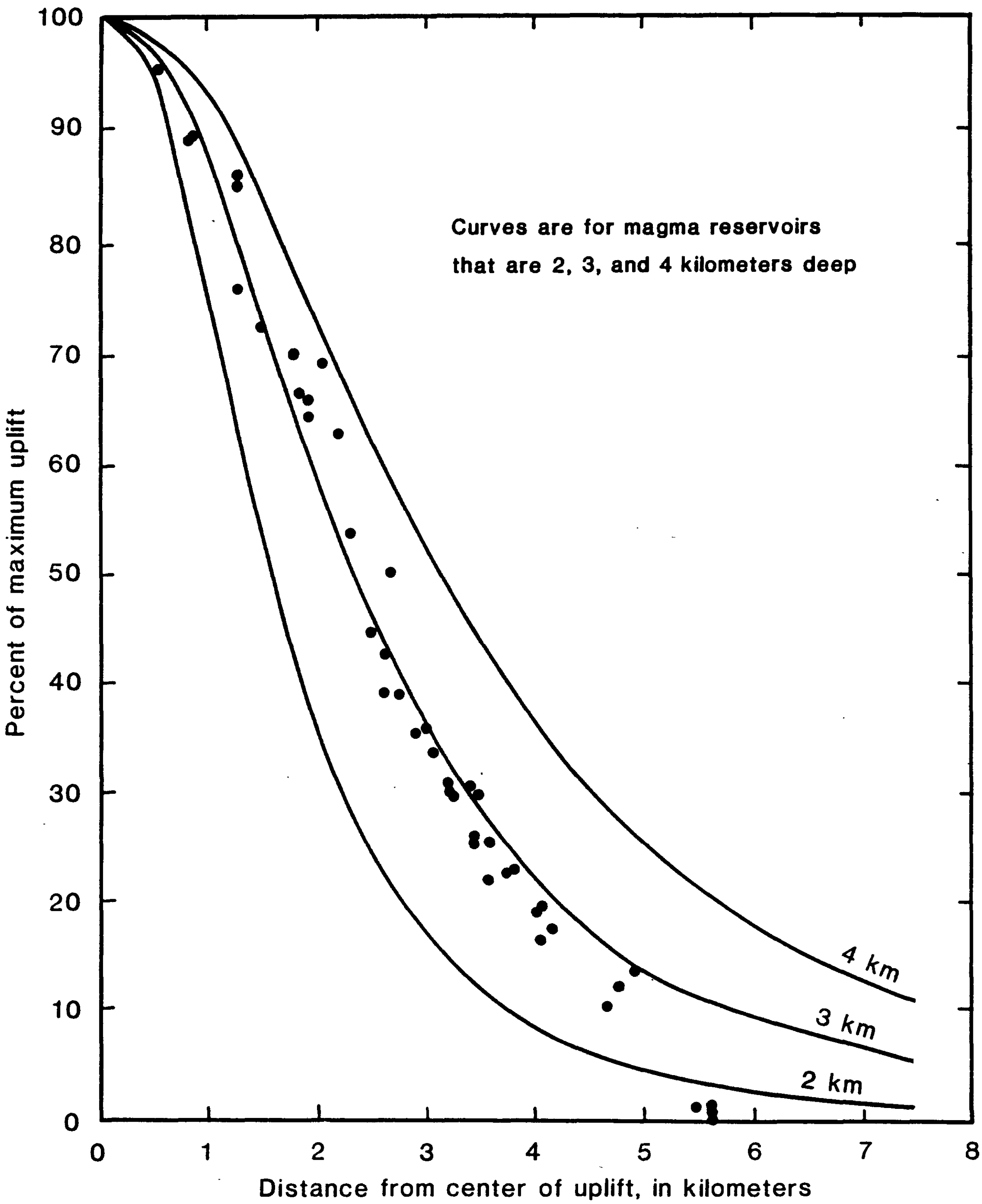
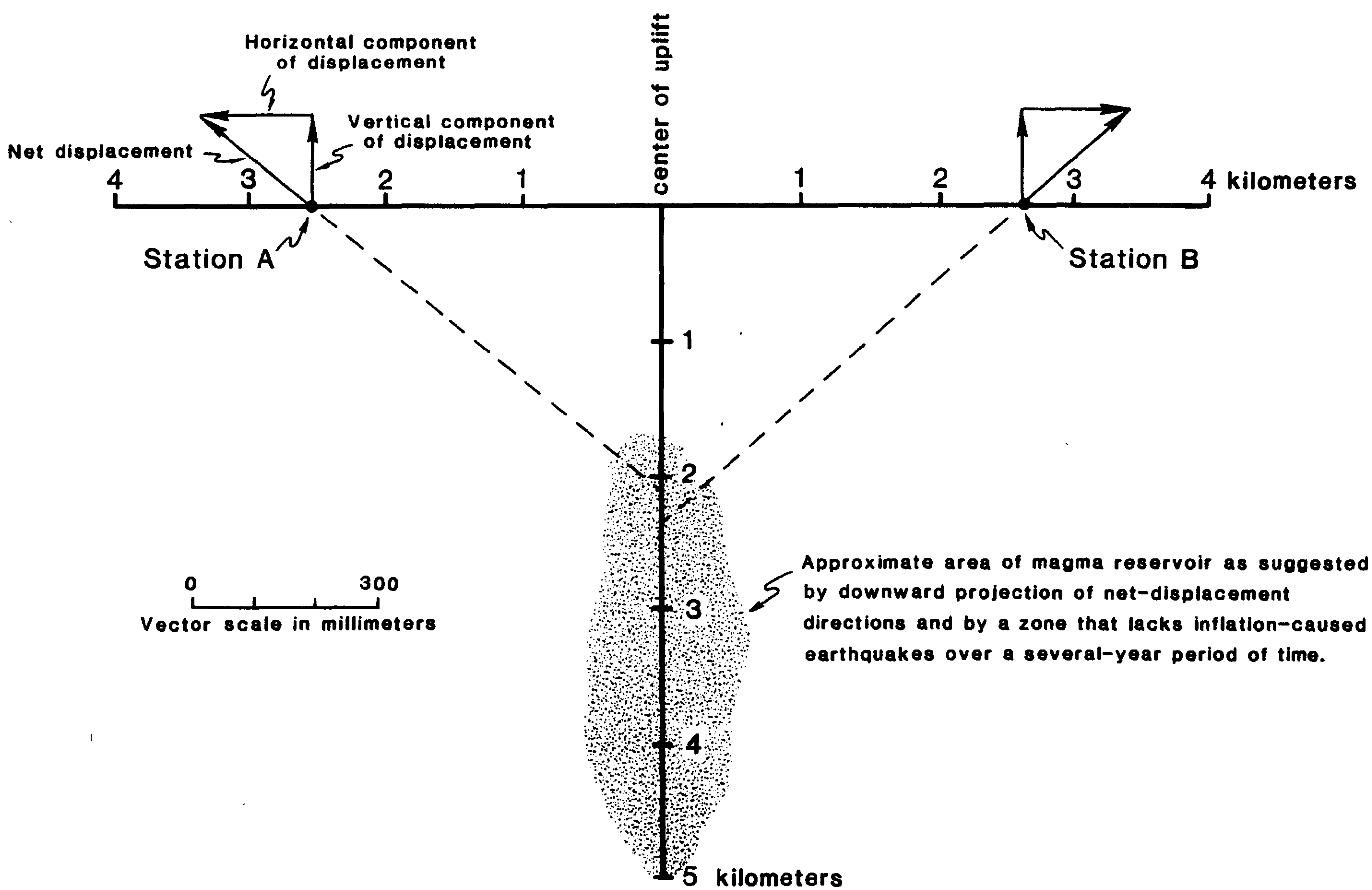


Figure 3 Solution

Figure 4 Cross section along a line that passes through Station A , the center of uplift, and Station B of Figure 1. Vectors that represent the net displacements of Stations A and B may be the results of push directly away from an inflating magma reservoir. If so, the intersection of a downward-projected net displacement with a vertical line beneath the center of uplift should mark the location of the magma reservoir. This analysis suggests a reservoir at slightly more than two kilometers depth for the four-month period of study.



11c

L A B   E X E R C I S E S

E X E R C I S E   T H R E E

PART ONE

The Hawaiian Islands are part of a chain of volcanoes that is thousands of miles long. These volcanoes are older to the west and north, up the chain, and are depicted as dots in Figure 5. Geologists hypothesize that the volcanoes grew in succession above a "hot spot" or "melting spot" that remains at a fixed position in the mantle as the overlying Pacific crustal plate moves over this spot. Thus, the volcanoes record the rate and direction of movement of the Pacific crustal plate relative to the "melting spot".

Most of the volcanoes in the southeastern-most part of the chain are islands, whereas most of those up the chain to the northwest are seamounts, sea-floor hills that do not rise above sea level.

The volcanic chain has a sharp bend, or elbow at about its mid-point (Figure 5). The distance from Kilauea Volcano, the presently active part of the chain, to the elbow is roughly 3,500 kilometers, and the age measured on a sample of the volcano at the elbow is about 40 million years. The distance from Kilauea to Kauai (Figure 5) is 725 kilometers, and the age of Kauai is about 4 million years.

Questions:

(1) At what average rate has the Pacific crustal plate moved relative to the "melting spot" mantle source of magma during the past 4 million years?

(2) Using the rate of plate motion determined in question 1, calculate the age of the volcano at the elbow. Does this calculated age differ from that measured directly on a sample of the volcano at the elbow? Why do you think the elbow formed?

(3) On the assumption that the average rate calculated in question 1 continues for another million years and that the Pacific crustal plate continues to move in the same direction, plot on Figure 5 where a hypothetical new volcano will be growing a million years from now.

(4) Why do so few of the volcanoes in the older part of the chain rise above sea level?

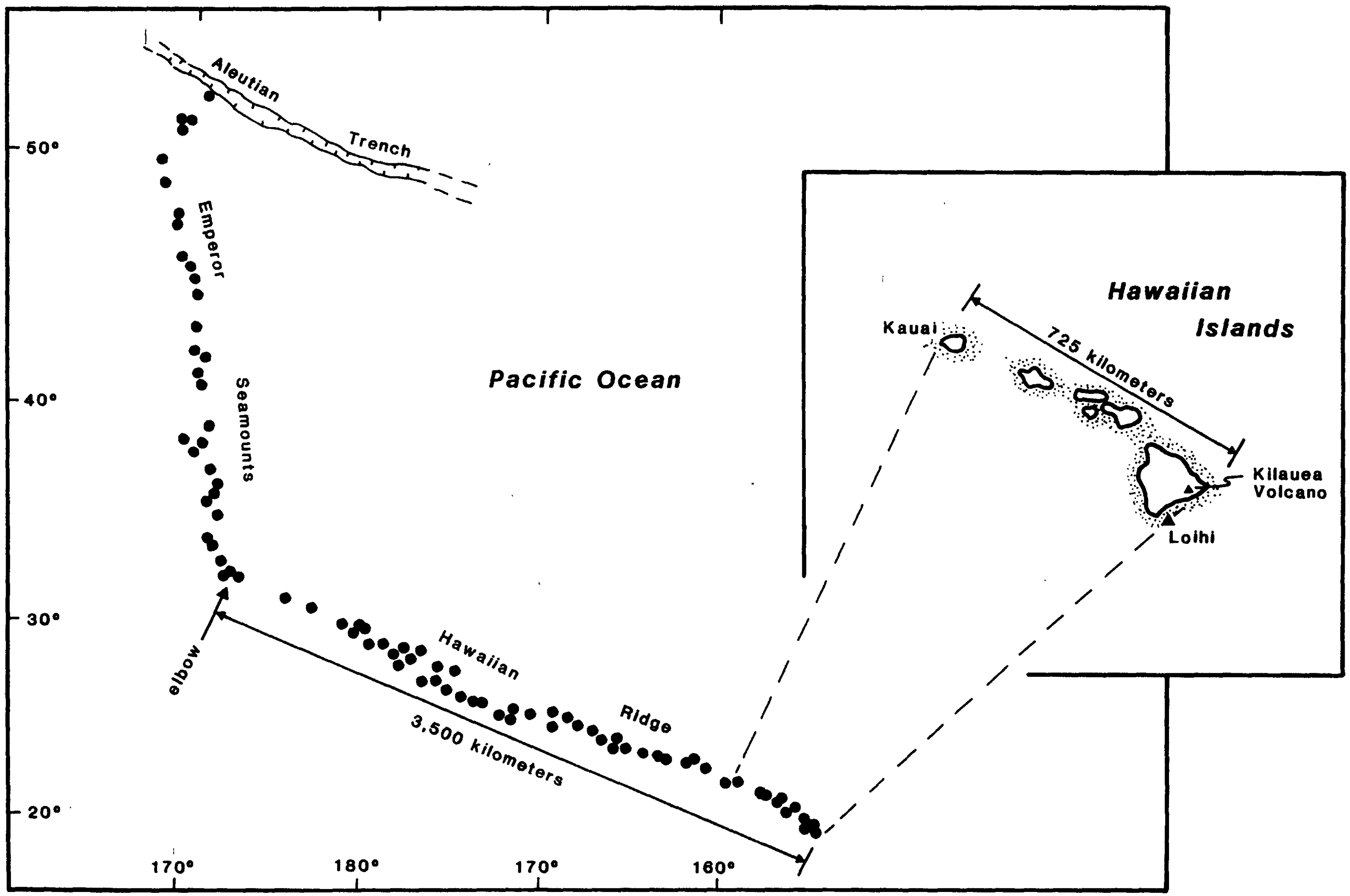

Aleutian
Trench
Emperor
Seamounts
Pacific Ocean
Hawaiian
Ridge
3,500 kilometers
elbow
Hawaiian
Islands
725 kilometers
Kauai
Kilauea
Volcano
Loihi
50°
40°
30°
20°
170°
180°
170°
160°

Figure 5

12a

EXPLANATION FOR LAB EXERCISES

EXERCISE THREE

PART ONE

Answers:

(1) The average rate of motion for the Pacific crustal plate during the past 4 million years is 725 km / 4 million years = 181.25 km / million years.

(2) The calculated age of the elbow at a rate of 181.25 km / million years is [3,500 km] x [1 million years / 181.25 km] = 19.31 million years. This is only about half the age (40 million years) measured directly on a sample of the volcano at the elbow. The rate of motion of the Pacific crustal plate has changed during the past 40 million years; the average rate during the past 4 million years is more than twice the average for the past 40 million years. The elbow formed because there was a change in direction of plate motion. Before the elbow formed, the Pacific crustal plate was moving about north over the mantle "melting spot". Motion after the elbow formed has been about northwest. Thus, island chains of the Hawaiian sort can be used to determine both the rate and direction of plate motion.

(3) The student should draw a line between Kauai and Kilauea and extrapolate, southeastward from Kilauea, 1/4 the distance between Kauai and Kilauea. Solutions will differ somewhat, depending on how the line is draw between the volcanoes.

(4) On the assumption that a roughly constant proportion of growing volcanoes rose above sea level throughout the history of the volcanic chain, most of the older, and thus long extinct volcanoes are now below sea level because there has been plenty of time for erosion to remove their above-sea-level parts.

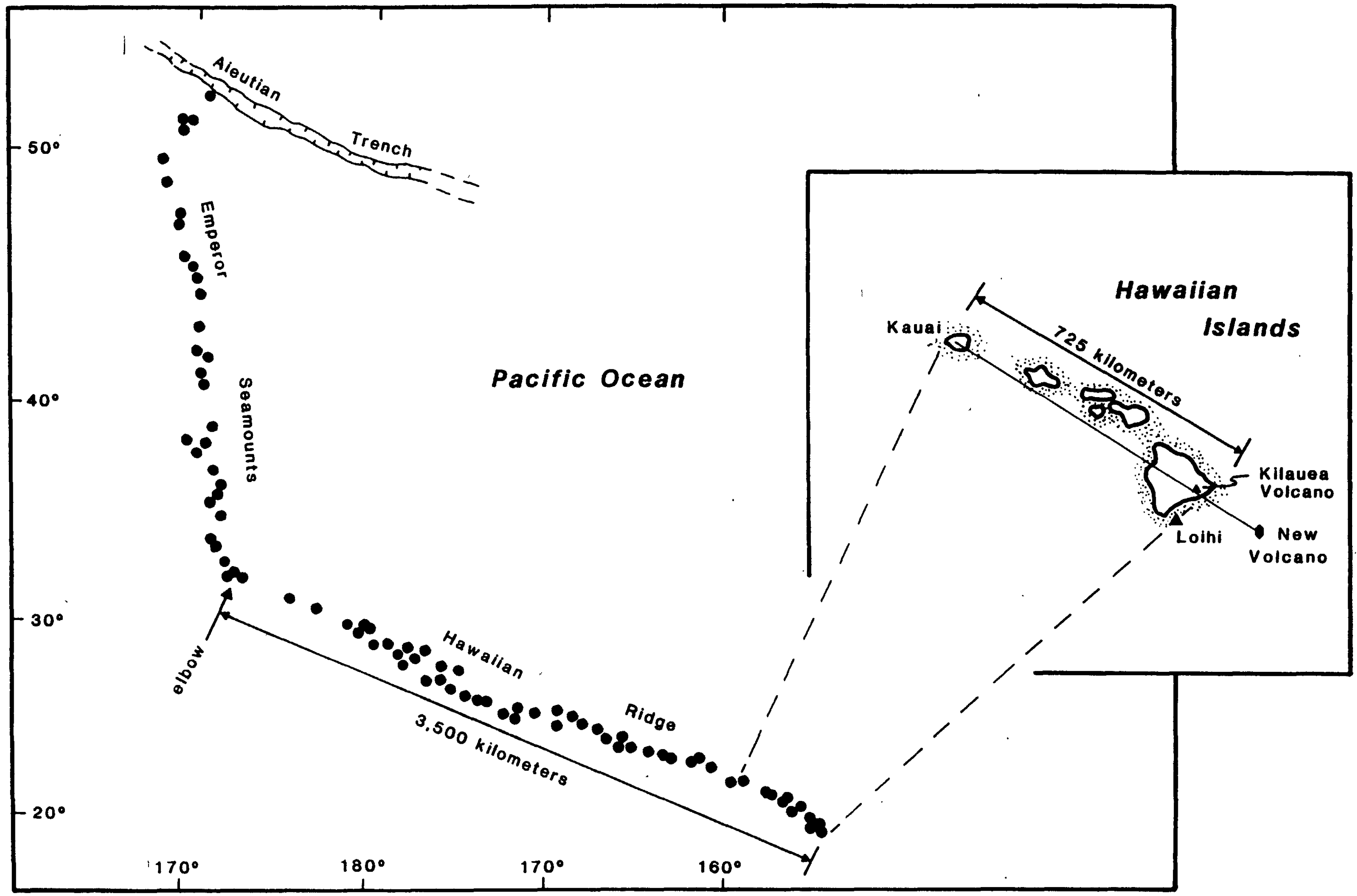


Figure 5 Solution