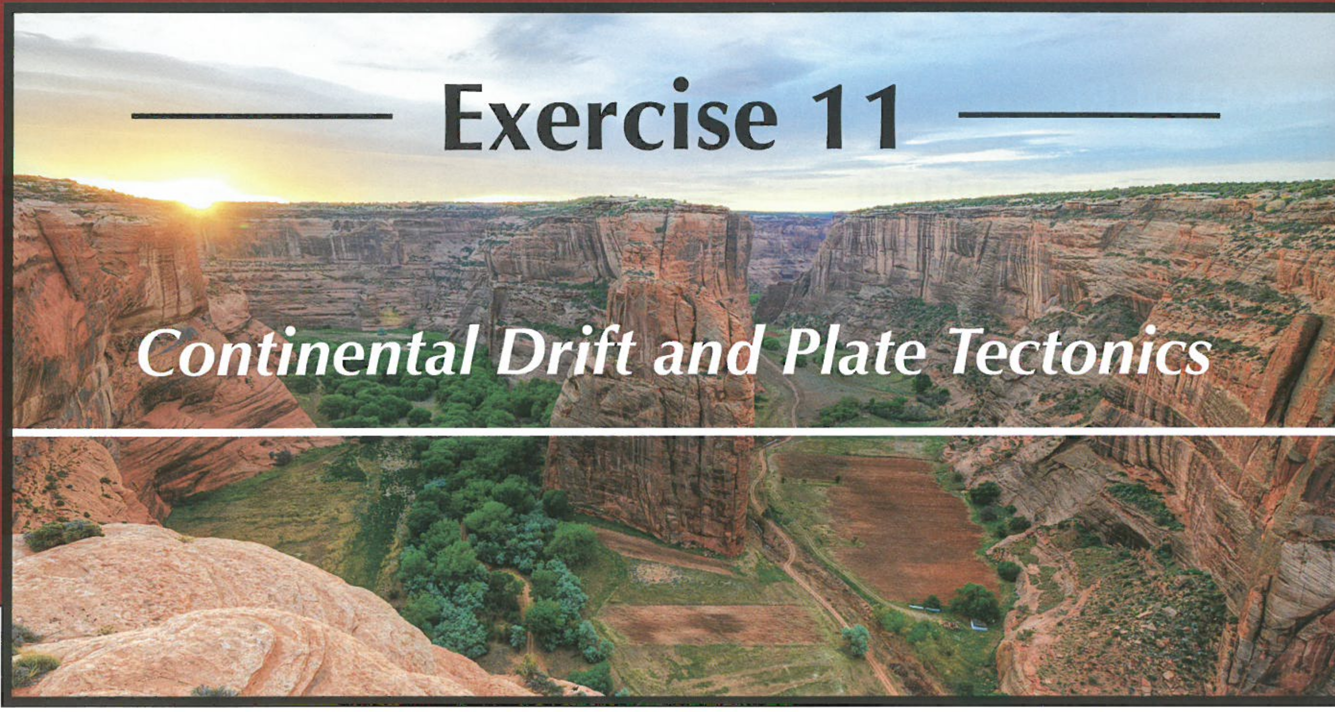


Exercise 11

Continental Drift and Plate Tectonics

LEARNING OBJECTIVES **After completing this exercise you will be able to:**

1. better understand the concept of continental drift as espoused by Alfred Wegener;
2. know how geologists use the distribution of earthquakes to define plate boundaries; and
3. explain how magnetic reversals are used to date seafloor rocks.

The modern theory of plate tectonics was developed from Alfred Wegener's (1912) earlier concept of continental drift. Geologists now explain the mechanism of geologic change in relation to at least 10 major plates making up the Earth's lithosphere. These plates are approximately 100 km thick and move over the Earth's surface at an average velocity of 2 to 4 cm/yr.

Plate interactions are responsible for most of the Earth's major tectonic events and features. Plate margins are classified according to the relative motion of the plate across the margin, such as:

- divergent—plates moving apart;
- convergent—plates moving together; or
- transform faults—horizontal side-by-side movement.

Convergent plate margins are further classified on the basis of the types of crust involved in abutting plate margins, such as:

- continent–continent, where two continental masses collide along opposite sides of plate boundaries;
- continent–ocean, where continental and ocean crusts collide; and
- ocean–ocean, where two slabs of oceanic lithosphere collide.

The combination of plate motion and physiographic character is a reasonable means of analyzing Earth dynamics.

PROCEDURE PART A

Evidence of Continental Drift

Outline maps of South America, Africa, Europe, Greenland, and North America are given in figure 11.1. The stippled area around each of the continents represents the area between the present shoreline and the 500-fathom (900-m) line (continental shelf). The latter is approximately the edge of the granitic continental crustal margin.

A fitting of the continents is best done on a small globe, but various map projections have been used by others. Because of the limitations of representing a curved surface on a plane, most map projections distort either the shape or size of the continents and alter their margins. Because of these difficulties, a modified Mercator projection has been used in the present exercise. This projection minimizes distortion of the coastline to be fitted. Various sections of Central America and Europe have been shifted slightly out of their present-day positions, but these are areas of relatively recent orogenic activity and may have had different positions in the past.

1. Trace the continental outlines following their true margin at the outer edge of the continental shelf from figure 11.1. Adjust their relative positions until the best fit is achieved, not only of continental outlines but also of geologic data, which are summarized on some of the maps.

PROCEDURE PART B

Seafloor Spreading and the Magnetic Timescale

Available evidence suggests that until the Late Paleozoic, the continents of Africa and South America were essentially side-by-side, and that drifting and opening of the Atlantic Ocean began early in the Mesozoic Era. If the continents drifted and the Atlantic Ocean is still enlarging, there must be some evidence on the present ocean floor. Various workers studied the topography, sediments, and igneous rocks of the mid-Atlantic ridge to see if there were clues or evidence to document movement. It soon became apparent that a major linear topographic depression, or rift zone, is superimposed along the crest of the mid-Atlantic ridge along most of its length. Not only was the rift recognized in the Atlantic, but the linear topographic low appears to be part of a major series of rifts and ridges associated with mid-oceanic areas of basaltic volcanic activity and seismic activity. The distribution of this worldwide system is shown in figure 11.2.

The topographic and structural features were documented at about the same time that parallel belts of alternating reversed and normal polarity of the magnetic intensity, or magnetic field strength, were recognized in rocks along the ridge trend. These alternating bands of normal and reversed polarity in the basalts occur symmetrically along the rift zone in the Atlantic Ocean in the fashion illustrated in the generalized diagram in figure 11.3. The location of the segment of the seafloor represented in figure 11.3 corresponds with line A–A′ on figure 11.2. The sequence and ages of polarity reversals for the past 5.5 million years are shown in figure 11.4.

1. Why are the belts of polarity contrast situated symmetrically on either side of the rift zone on the mid-Atlantic ridge?

2. Using figures 11.3 and 11.4, calculate as closely as possible the rate, in centimeters per year, at which seafloor spreading is occurring in the Atlantic Ocean, based upon the paleomagnetic data. Your calculation is the rate at which a single plate is moving.

3. Enter the rate of plate motion determined in question 2 above in the blue box labeled "b." on figure 11.2.

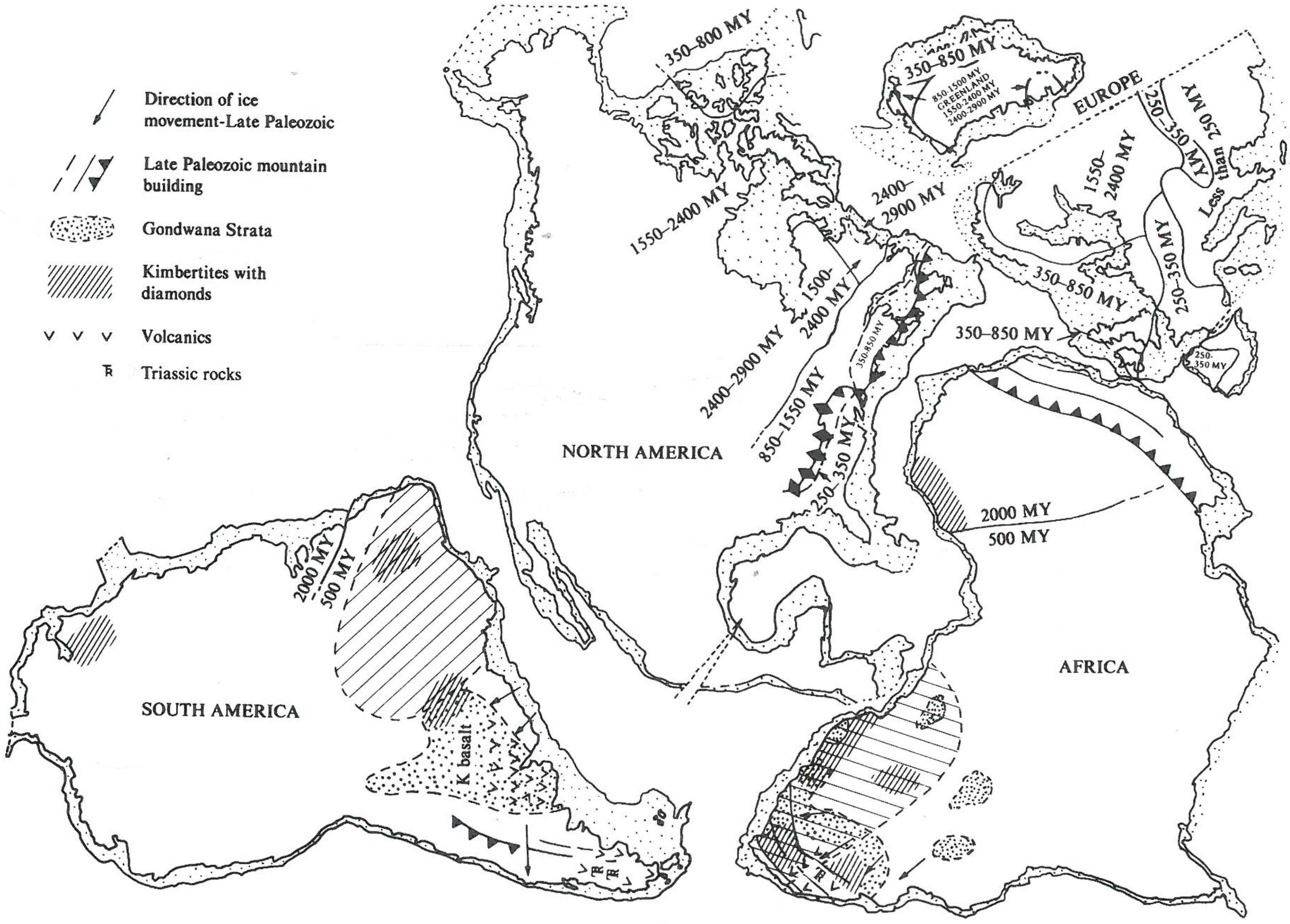


FIGURE 11.1 Maps of outlines of South America, North America, Africa, and Europe showing positions and ages of various major mountain belts. Ruled pattern shows approximate range of Late Pennsylvanian–Early Permian aquatic reptile Mesosaurus in South America and Africa.

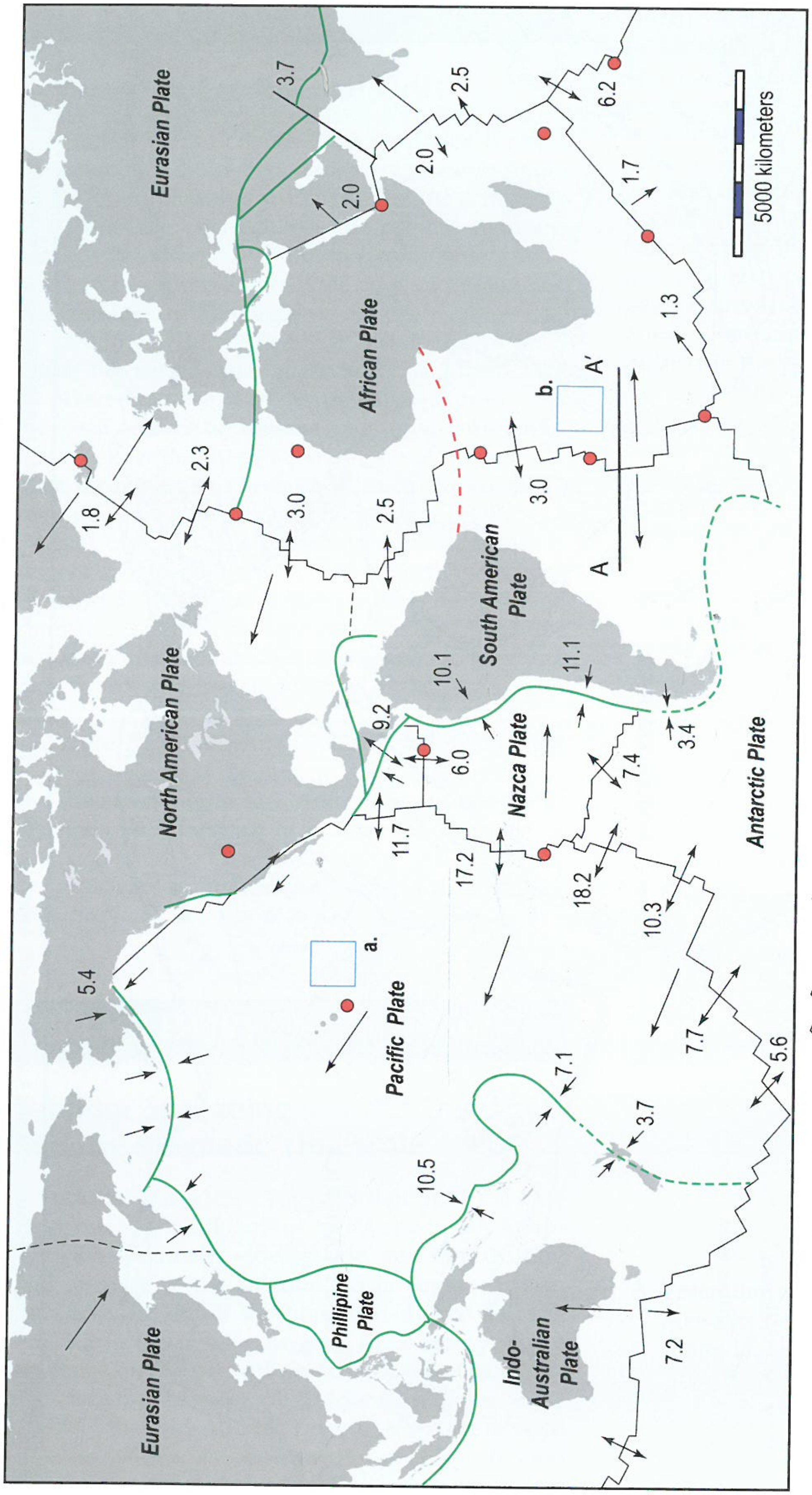


FIGURE 11.2 Map of the world showing the major plates, their boundaries, and direction of motion. Subduction zones are indicated by green lines. Red circles are presently active hot spots. Numbers indicate rate of motion in cm/yr. (Rates after McKenzie and Richter, 1976.)

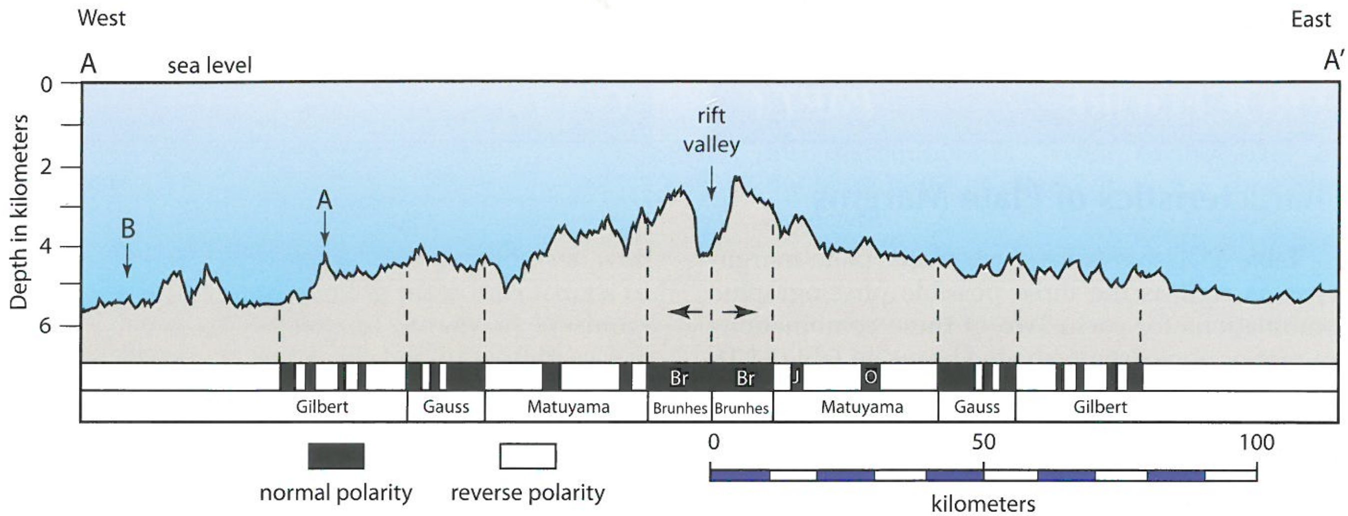


FIGURE 11.3 A schematic cross section of the central part of the mid-Atlantic ridge showing topography and patterns of paleomagnetic data. The dark and light areas correspond to the pattern shown on figure 11.4.

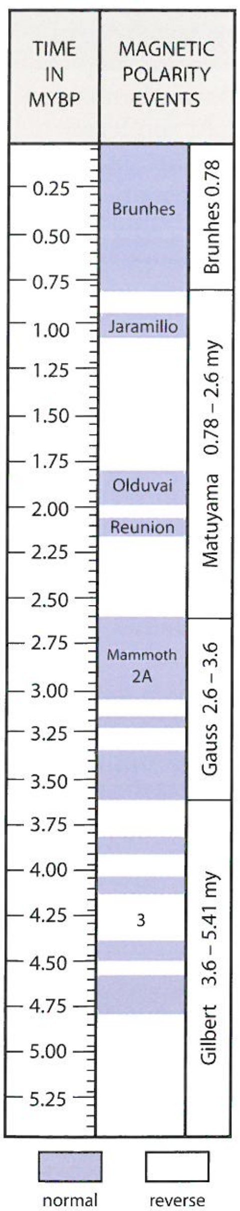


FIGURE 11.4 **Magnetic polarity scale for the last 5.5 million years of Earth history. Purple bands indicate periods of normal polarity. White bands indicate times when magnetic polarity was reversed compared to modern magnetic properties.**

4. Estimate the time necessary for the spread of the South Atlantic Ocean between Africa and South America by dividing the present separation along the trace of the red dashed line on figure 11.2 by the rate of spreading as calculated in question 2.

5. What ages of basalt might be expected at points A and B on figure 11.3, assuming the rate of spreading to have been constant?

PROCEDURE PART C

Characteristics of Plate Margins

Table 11.1 shows the three major plate margin types as well as the three possible physiographic combinations for each. Two of these combinations are rare or nonexistent (shaded boxes on table 11.1). Study figure 11.2 and complete the rest of the table by entering names of modern geographic locations that serve as examples for each of the seven characteristic plate margins.

Plate Margin	Modern Examples by Geographic Name		
	Continent-Continent	Continent-Ocean	Ocean-Ocean
Divergent • Tensional stresses • Crustal lengthening • New ocean crust • Normal faults • Shallow earthquakes • Basaltic volcanism			
Convergent • Compressional stress • Crustal shortening • Ocean crust destroyed • Reverse and thrust faults • Folds • New continental crust • Shallow and deep quakes			
Transform Fault • Shear stress • Shallow quakes • Crust neither created nor destroyed • Strike-slip faults			

TABLE 11.1 Table showing types and characteristics of plate margins.

PROCEDURE PART D

Locating Plate Margins

Seismic or earthquake data provide us with direct information concerning plate interactions or tectonics. The US Geological Survey in Washington, DC maintains and publishes a monthly record of seismic events around the world. These records, distributed to the public by the National Earthquake Information Center, are entitled Preliminary Determination of Epicenters. They include date; time; location of epicenter; depth of focus, or hypocenter; and magnitude of every earthquake of magnitude 3 or greater occurring in the United States and of those greater than magnitude 4 in other places in the world. Further information is included for some earthquakes. Occasional comments include the intensity as measured on the Modified Mercalli earthquake intensity scale. This kind of information is extremely useful for understanding the dynamic nature of our planet. By studying this information, a student can gain firsthand knowledge of the frequency, distribution, and energy of the Earth's seismic activity.

The epicenters of the selected earthquakes occurring during the month of January 1982 have been plotted on a world map and are illustrated as figure 11.5. In addition, the seismic activity for the week 24–31 December 1981, is presented in table 11.2. Abbreviations used in the headings are: UTC = universal time; GS = geological survey data; MB = magnitude based on "P" seismic waves; and MSZ = magnitude based on vertical surface waves. An asterisk (*) following the time indicates a less reliable solution in the calculation because of incomplete or less reliable data.

1. Using a colored pen or pencil, plot every other epicenter from table 11.2 on figure 11.5. When you are finished, your map will display essentially five weeks of seismic activity. The only information you need to complete this task is the longitude and latitude of the earthquakes.

2. Compare your finished map (figure 11.5) with figure 11.2. Is there a clear correlation between the distribution of recent earthquakes and the boundaries of plates? Is such a correlation expected?

3. The region near the Bonin Islands is a common site for deep earthquakes. Why is this?

4. What is the probable cause of the Kazakh seismic event of 27 December at 03:43 hours? What two things form the basis of your answer?

	Origin Time, UTC			Geographic Coordinates						Magnitudes, GS		
Day, UTC 12/81	Hr.	Min.	Sec.	Lat.		Long.		Region and Comments	Depth	MB	MSZ	No. Sta. Used
24	02	22	07.7	34.017	N	116.767	W	Southern California	20			10
24	04	24	53.6*	14.641	N	119.919	E	Luzon, Philippine Islands	33	4.6		8
24	05	33	21.5	29.956	S	177.701	W	Kermadec Islands	33	6.1	6.8	151
24	09	43	51.5*	30.041	S	177.563	W	Kermadec Islands	33	5.0	5.1	15
24	11	11	17.1*	22.061	S	175.916	W	Tonga Islands Region	63	4.9		14
24	13	02	40.4	29.925	S	177.374	W	Kermadec Islands	33	5.3	5.4	29
24	14	07	39.3*	39.952	N	77.366	E	Southern Sinkiang Prov., China	33	4.9		7
24	14	44	07.4*	14.282	S	74.321	W	Peru	108			8
24	19	44	53.1*	30.228	S	177.378	W	Kermadec Islands	33	4.9		17
24	22	00	51.6*	33.153	N	49.705	E	Western Iran	33	4.6	4.0	28
24	22	36	211.5	30.076	S	177.387	W	Kermadec Islands	36	5.2	5.4	40
25	00	06	09.5*	12.555	N	88.303	W	Off Coast of Central America	33	4.7		26
25	00	28	16.8	4.738	N	118.458	E	Kalimantan	52	5.4	5.2	47
25	04	55	52.7*	17.406	N	61.768	W	Leeward Islands	49	4.2		12
25	06	03	07.9*	77.013	N	6.601	E	Svalbard Region	10	4.4		14
25	08	28	48.0	6.561	N	73.039	W	Northern Colombia	195	4.5		13
25	09	12	06.4	30.313	S	177.489	W	Kermadec Islands	33	5.4	5.4	57
25	10	37	10.7*	30.200	S	177.411	W	Kermadec Islands	33	4.7		12
25	10	48	45.1*	30.324	S	177.301	W	Kermadec Islands	33	5.2		20
25	12	35	49.6*	11.172	N	62.474	W	Windward Islands	102	4.8		55
25	15	27	18.7*	13.613	S	76.425	W	Near Coast of Peru	33			5
25	15	50	33.3*	23.197	N	121.642	E	Taiwan	33	4.5		11
25	17	02	35.5	53.884	N	160.800	E	Near Coast of Kamchatka	33	4.6		19
25	22	26	41.0*	59.871	N	152.716	W	Southern Alaska	113	4.3		14
26	03	42	19.5*	37.952	N	22.702	E	Southern Greece	33	4.0		25
26	10	17	16.6*	2.209	S	139.847	E	Near N. Coast of West Irian	33	4.8	4.5	18
26	11	16	05.8	23.942	S	66.512	W	Jujuy Province, Argentina	207	4.9		49
26	14	29	11.1*	38.950	N	25.310	E	Aegean Sea	10	4.2	3.6	39
26	17	05	32.8	29.812	S	177.854	W	Kermadec Islands	33	6.3	7.1	149
26	17	53	30.6*	29.983	S	177.830	W	Kermadec Islands	33	5.2		17
26	17	53	38.4*	40.213	N	28.778	E	Turkey Felt in the Istanbul area	27	4.3		28
26	19	38	07.7*	9.773	S	119.218	E	Sumba Island Region	100	4.4		10
26	21	50	43.9	7.260	S	129.183	E	Banda Sea	150	5.3		21
26	22	02	18.5*	22.765	S	68.332	W	Northern Chile	119	4.8		11
27	03	43	14.1	49.923	N	78.876	E	Eastern Kazakh SSR	0	6.1	4.3	167
27	06	22	50.3*	30.063	S	177.622	W	Kermadec Islands	33	5.4	4.9	18
27	10	30	44.4	2.160	S	139.825	E	Near N. Coast of West Irian	33	5.6	5.9	60
27	13	25	33.3*	46.331	N	16.832	E	Yugoslavia	10			13
27	16	36	48.3*	5.090	S	139.311	E	West Irian	33	3.7		6
27	17	39	16.7	39.004	N	24.799	E	Aegean Sea Ten houses damaged on Evvoia. Felt strongly in eastern Greece. Also felt in the Izmir, Turkey area	33	5.3	6.5	112
27	20	21	05.9*	7.107	N	73.093	W	Northern Colombia	138	4.6		10
27	20	24	15.5*	34.250	N	117.617	W	Southern California	9			9
27	21	23	13.6	8.278	S	79.875	W	Near Coast of Northern Peru	33	5.2	4.4	41
28	01	53	02.2	6.889	S	130.004	E	Banda Sea	131	4.6		13
28	10	28	15.9*	54.642	N	160.380	W	Alaska Peninsula	33			9
28	12	40	18.4	14.974	S	168.121	E	Vanuatu Islands	33	5.7	5.2	89

TABLE 11.2 **Preliminary determination of epicenters.**

	Origin Time, UTC			Geographic Coordinates						Magnitudes, GS		
Day, UTC 12/81	Hr.	Min.	Sec.	Lat.		Long.		Region and Comments	Depth	MB	MSZ	No. Sta. Used
28	13	08	26.2	21.644	N	143.470	E	Mariana Islands Region	33	5.3	5.0	57
28	14	18	15.5*	21.495	N	143.583	E	Mariana Islands Region	33	5.0		30
28	14	38	20.9*	21.893	N	144.109	E	Mariana Islands Region	33	4.5		22
28	14	49	40.6	35.016	N	45.934	E	Iran–Iraq Border Region	33	5.0	4.0	69
28	15	20	11.4*	21.353	N	143.818	E	Mariana Islands Region	33	4.6		13
28	15	40	02.1*	21.642	N	143.718	E	Mariana Islands Region	59	5.1		25
28	16	11	00.4*	14.213	N	92.200	W	Near Coast of Chiapas, Mexico	68	4.7		7
28	16	37	35.8*	21.360	N	143.664	E	Mariana Islands Region	33	4.7		15
28	17	23	52.2	21.511	N	143.789	E	Mariana Islands Region	27	4.9		35
28	17	40	49.8	21.593	N	143.518	E	Mariana Islands Region	33	5.3		36
28	18	10	57.7	13.805	N	95.915	E	Andaman Islands Region	33	5.0	5.1	48
28	18	13	25.5*	21.487	N	143.500	E	Mariana Islands Region	33	5.0		28
28	20	56	01.0*	21.429	N	143.523	E	Mariana Islands Region	33	5.0		29
28	22	01	50.1	63.111	N	150.819	W	Central Alaska	151			13
28	22	45	42.1	37.211	N	114.980	W	Southern Nevada Felt (IV) at Las Vegas Felt in Clark and Lincoln Counties, Nev. Also felt at Toquerville, Utah, and Temple Bar, Arizona.	5			16
28	23	17	50.8*	21.489	N	143.621	E	Mariana Islands Region	33	4.7		11
28	23	35	59.6*	21.645	N	142.958	E	Mariana Islands Region	33	4.7		13
29	02	22	59.7	21.352	N	143.152	E	Mariana Islands Region	33	4.8		26
29	05	07	22.3*	21.337	N	143.680	E	Mariana Islands Region	33	4.6		14
29	06	39	29.8*	21.474	N	143.694	E	Mariana Islands Region	33	4.7		16
29	08	00	44.9	38.796	N	24.720	E	Aegean Sea Felt in the Khalkis–Thessaloniki area	10	4.7	5.3	83
29	09	26	36.0*	21.425	N	143.841	E	Mariana Islands Region	33	4.8		13
29	15	37	03.9*	21.858	N	143.581	E	Mariana Islands Region	33	4.7		12
29	15	38	26.1*	6.066	S	155.274	E	Solomon Islands	150	5.0		12
29	16	11	17.0*	21.459	N	143.643	E	Mariana Islands Region	33	4.6		9
29	16	37	17.9*	19.209	S	68.168	W	Chile–Bolivia Border Region	205	5.0		9
29	19	06	31.3	30.231	S	177.924	W	Kermadec Islands	60	5.5		36
29	22	49	00.4	21.508	N	143.379	E	Mariana Islands Region	33	5.3	4.8	56
29	23	37	53.3*	21.539	N	143.648	E	Mariana Islands Region	33	4.9		9
30	11	26	36.0*	43.756	N	147.678	E	Kuril Islands	33	5.2	4.1	56
30	13	47	27.3	64.589	N	148.080	W	Central Alaska	33	3.9		11
30	14	00	33.8	64.577	N	148.158	W	Central Alaska Felt (V) at Ester and (IV) at Fairbanks	27	4.8		37
30	15	00	53.8*	22.028	N	143.536	E	Volcano Islands Region	79	4.7		13
30	16	46	34.4*	38.812	N	20.803	E	Greece	33	4.4		11
30	17	44	09.6	6.734	N	126.957	E	Mindanao, Philippine Islands	77	5.0		31
30	20	32	36.1*	13.570	N	90.620	W	Near Coast of Guatemala	33	4.5		12
30	21	09	54.0*	4.349	N	126.008	E	Talaud Islands	104	4.7		12
31	05	08	13.5	27.694	N	139.680	E	Bonin Islands Region	494	4.7		38
31	06	54	51.1*	33.935	S	179.331	W	South of Kermadec Islands	33	5.2		28
31	09	20	05.9*	0.796	N	123.883	E	Minahassa Peninsula	294	5.1		20
31	12	15	54.4	61.910	N	151.758	W	Southern Alaska Felt at Wasilla and Houston	128	4.1		14
31	13	48	43.0*	2.150	N	126.451	E	Molucca Passage	125	4.9		14
31	21	38	13.9	21.448	N	143.716	E	Mariana Islands Region	33	5.0		12

TABLE 11.2 Preliminary determination of epicenters.

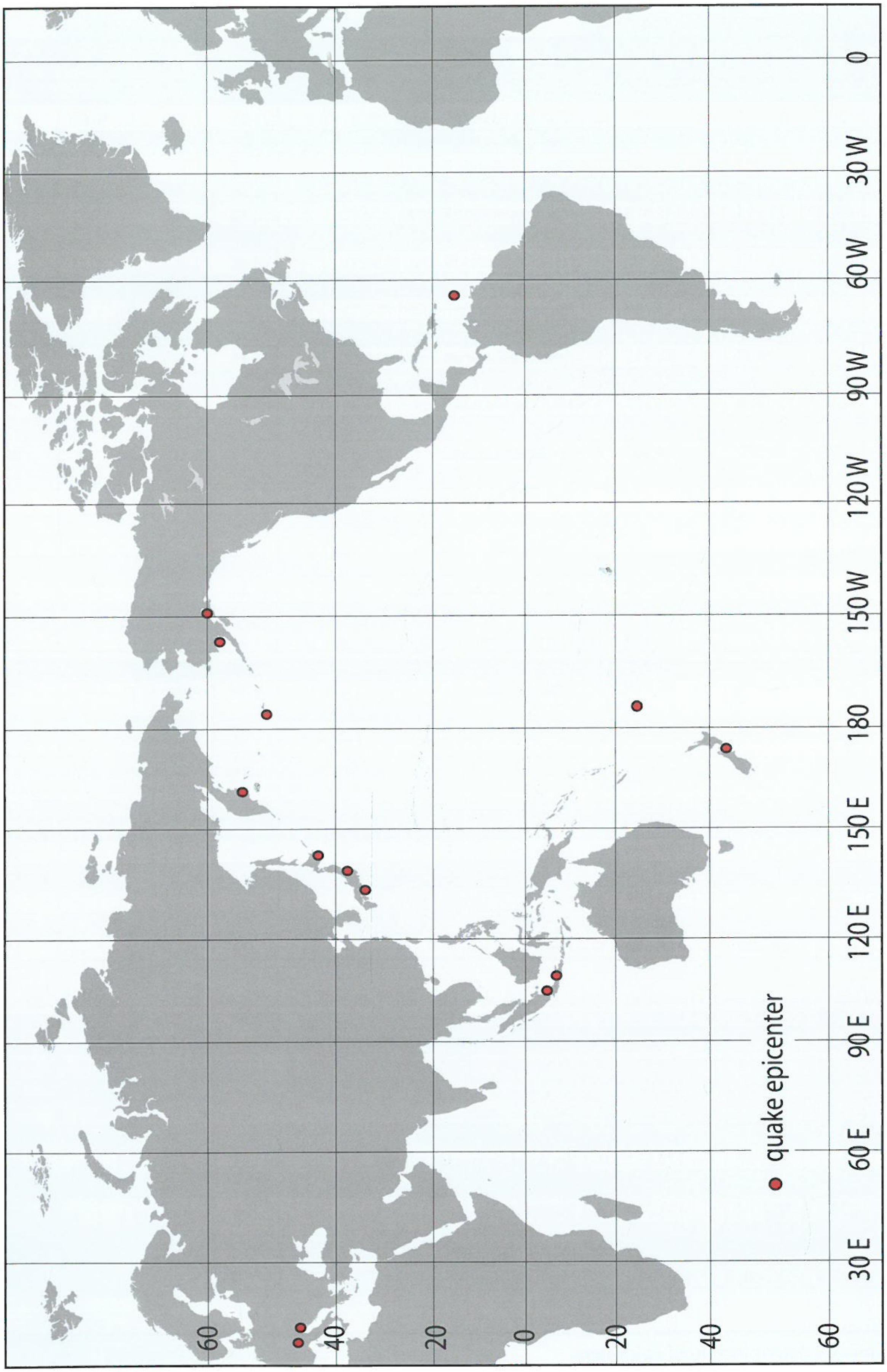


FIGURE 11.5 Map of the world showing the location of epicenters of selected seismic events for the month of January 1982.

PROCEDURE PART E

Hot Spots and Plate Motion

Figure 11.6 is a map of the emergent portion of the Hawaiian Islands chain in the central Pacific Ocean. These islands have a volcanic origin resulting from the outpouring of vast amounts of basaltic lava from a hot spot located southeast of the "Big Island" of Hawaii. The hot spot remains fixed in the mantle while the Pacific plate moves across it in a northwesterly direction. The masses of volcanic rocks that comprise the emergent and submergent portions of the Hawaiian chain are all younger than the seafloor basalts (Pacific plate) onto which they were extruded. The average radiometric ages in millions of years (Ma) of the basalts at eight selected sample stations are shown on figure 11.6.

1. Draw a line from the white dot adjacent to recent basalt flows on the island of Hawaii and the white dot on the north side of Kauai. Using a protractor and the north arrow provided on the map, determine the average direction that the Pacific plate has been moving over the past 5.1 million years.

2. Using figure 11.6, fill in the data pertaining to distance and age differences between the sample station(s) located on each island in table 11.3. Next calculate the rate of plate motion that occurred between the extrusion of lavas at each sample area (right column of table 11.3). Finally, calculate the average rate of plate motion between Hawaii and Kauai (bottom row of table 11.3).

3. Has the rate of plate motion been constant for the past 5.1 million years? What is the range of values of plate motion?

4. Enter the average rate of motion into the blue box labeled "a." on figure 11.2.

STATION	DISTANCE (in km)	DISTANCE (in cm)	AGE DIFFERENCE (in years)	RATE (cm/yr)
Hawaii to SE Maui	125	12,500,000	700,000	17.9
SE Maui to NW Maui				
NW Maui to E Molokai				
E Molokai to W Molokai				
W Molokai to SE Oahu				
SE Oahu to NW Oahu				
NW Oahu to Kauai				
HAWAII TO KAUAI				

TABLE 11.3 Table provided for recording information on the distances of sample localities, ages, and rates of motion of the Hawaiian Islands.

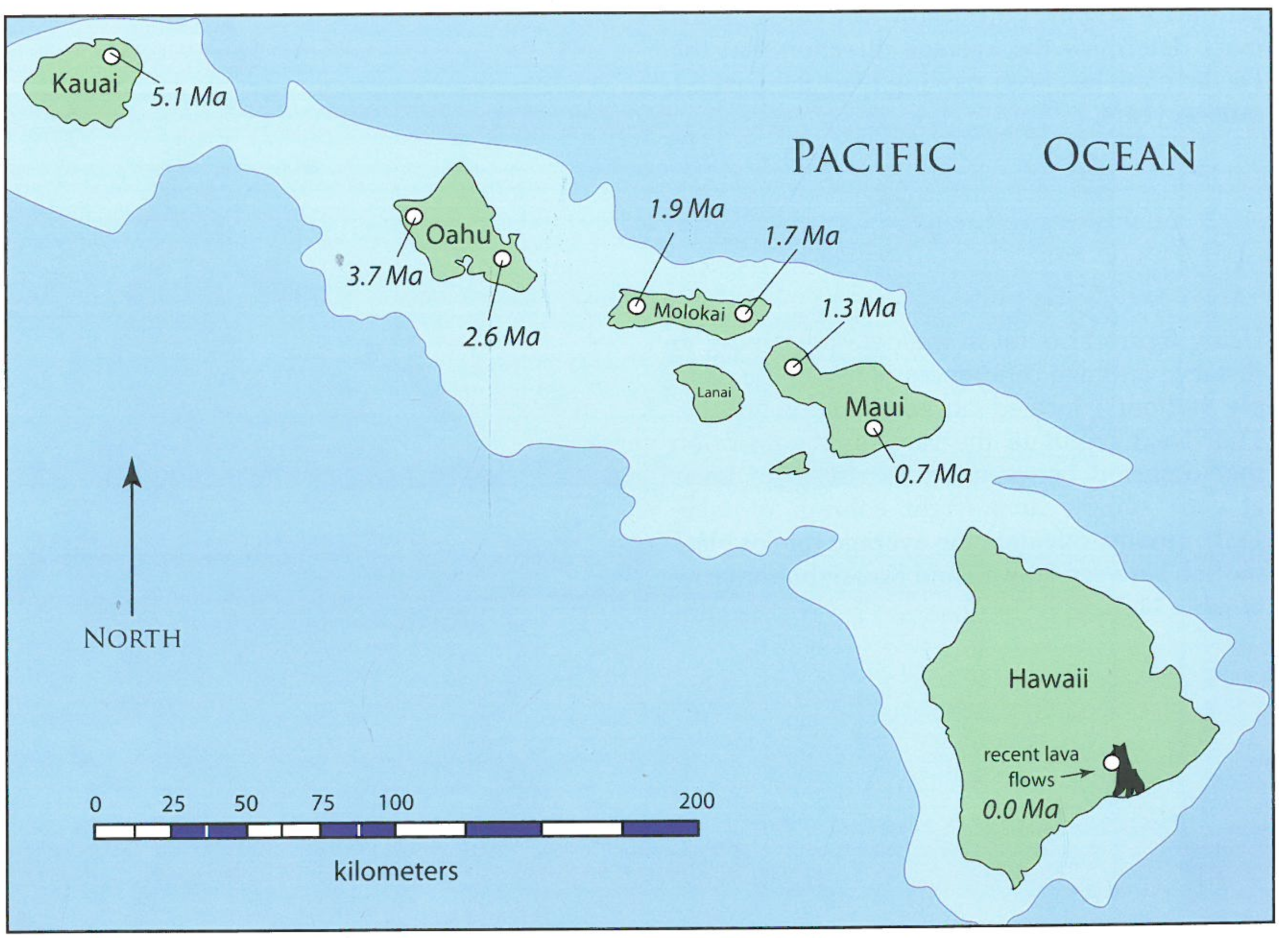


FIGURE 11.6 Map of the Hawaiian Islands with average radiometric dates of basalts comprising each island.

PROCEDURE PART F

Plate Tectonics and the Aleutian Trench

Figure 11.7 is a map showing the boundary between the North American and Pacific lithospheric plates. Volcanic activity associated with this margin has produced a 3,000 km-long chain of volcanoes and volcanic islands (island arc) known as the Aleutian Islands. Figure 11.7A shows the location of the volcanic chain between Alaska and Russia. Figure 11.7B shows details of the central portion of the Aleutian chain. The dark line with triangular "teeth" on map B shows the position of the Aleutian Trench, a physiographic feature that marks the line of interaction between the Pacific plate and the North American plate. Red and green dots indicate the epicenters of earthquakes that have been recorded in the area from 1900 until 2010 (Benz et al., 2011). Red dots indicate the locations of shallow-focus earthquakes (those that originate between 0 and 70 km below the surface). Green dots represent the epicenters of earthquakes that originated at depths between 70 and 300 km below the surface (intermediate-depth earthquakes).

1. Plot the point of origination (focus) of each earthquake listed in table 11.4 on figure 11.8. To do this, first determine the position of the epicenter relative to the axis of the Aleutian Trench (red arrow). Positive values indicate quakes occurring in the Pacific plate south of the trench axis. Negative values indicate distance north of the trench axis. Once you have located the epicenter along the surface, use the depth data to locate the focus of the quake. Plot shallow- and intermediate-focus earthquakes using red dots and green dots, respectively.

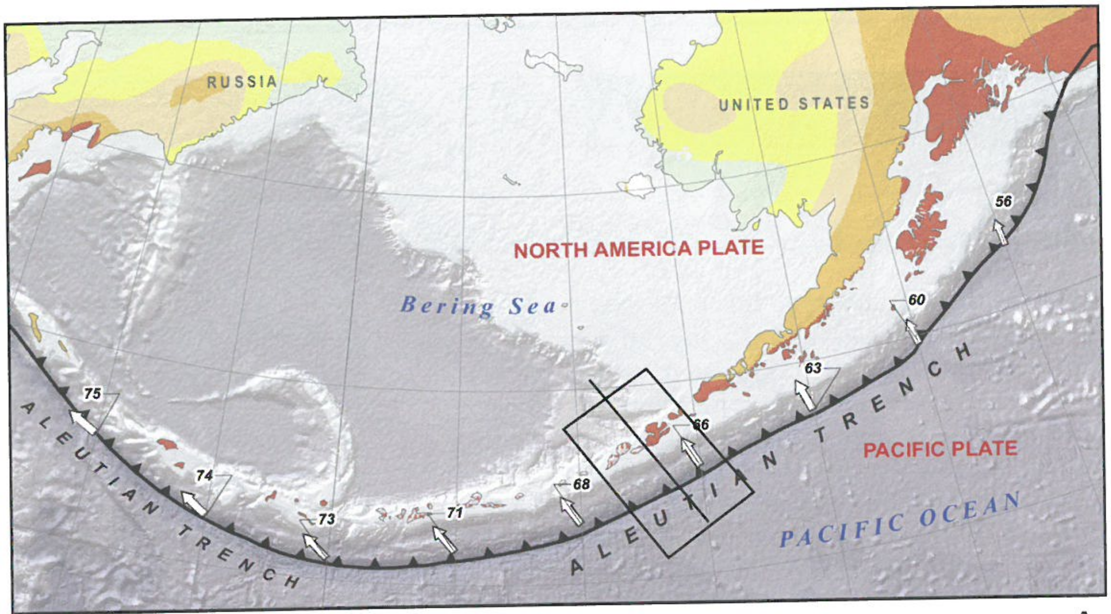
2. What type of plate boundary is represented (convergent, divergent, transform)?

3. What is the range of earthquake depths in the vicinity of the Aleutian Trench?

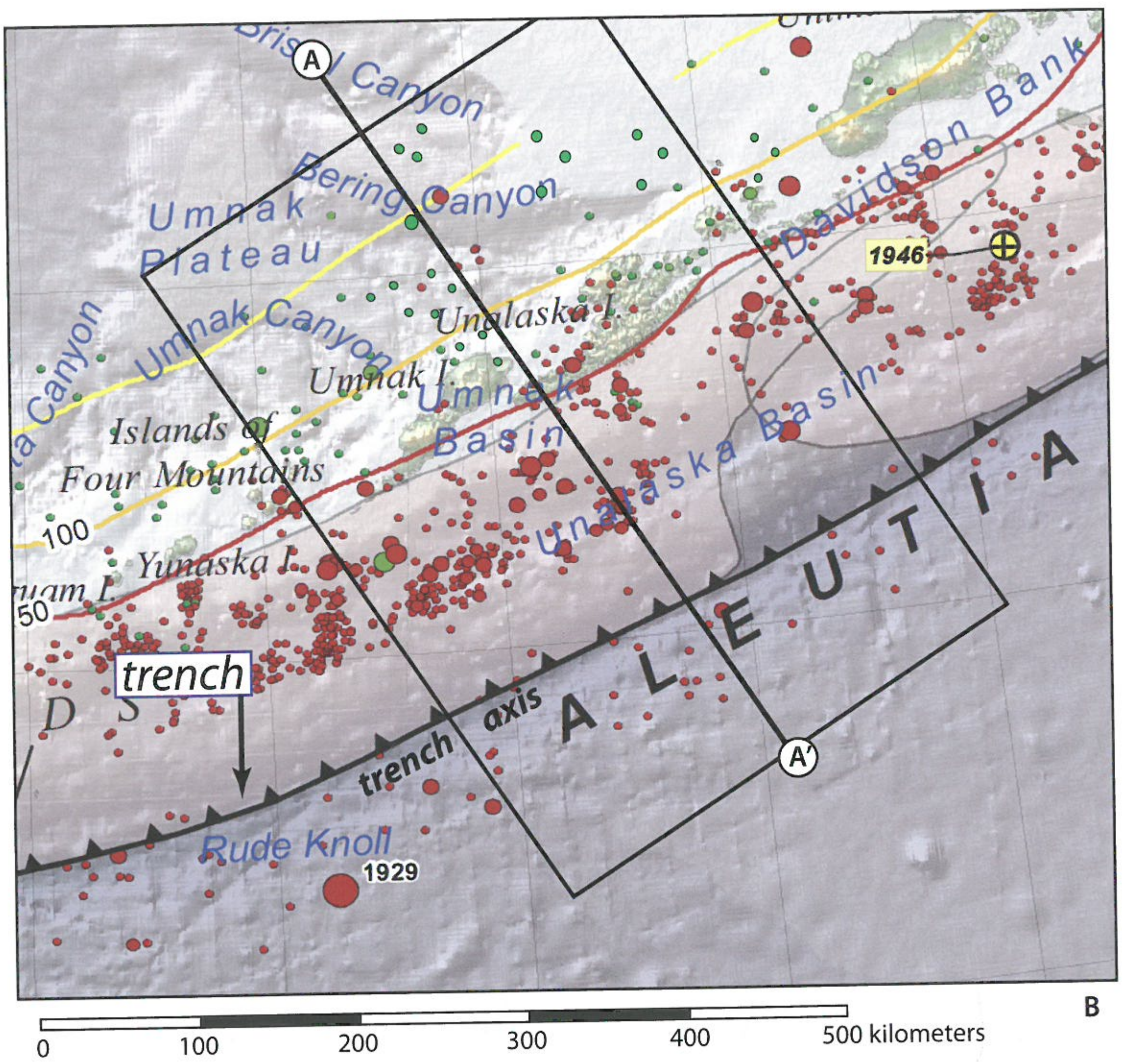
4. Why are earthquakes more numerous north of the trench axis?

5. What is the dip of the earthquake zone? Since the horizontal and vertical scales are equal, you can make this determination with a protractor.

6. Label the North American and Pacific plates on the cross section. Draw arrows to illustrate relative motion of the Pacific and North American plates along the zone.



A



B

FIGURE 11.7 Maps of the Aleutian Trench and northern Pacific Ocean basin.

A. Regional map.

B. Detailed tectonic map of the central portion of the Aleutian Trench. The rectangular box bisected by line A–A′ corresponds to the rectangular box in the lower middle portion of the regional map. A–A′ corresponds to the cross section shown in figure 11.8. Scale bar applies to map B.

TABLE 11.4

Distance and depth data for earthquakes occurring in the central Aleutian Islands. The second column indicates the distance of the epicenter from the trench axis along the line A–A′ on figure 11.7. Positive and negative values indicate distances (in km) south and north of the trench axis, respectively. The third column lists the depth of the earthquake (focus) below the surface in kilometers. Greater values indicate greater depths of earthquake originations.

Quake	Distance	Depth	Quake	Distance	Depth
1.	-5	15	18.	+50	15
2.	+60	40	19.	-125	20
3.	-25	10	20.	-125	40
4.	-350	200	21.	-175	40
5.	-300	150	22.	-210	75
6.	-100	25	23.	-250	90
7.	-100	35	24.	-350	220
8.	-50	25	25.	-370	200
9.	+50	50	26.	-175	50
10.	-200	50	27.	-200	70
11.	-150	50	28.	-250	150
12.	-200	90	29.	-275	125
13.	+15	40	30.	-325	150
14.	-240	110	31.	-300	125
15.	-270	150	32.	-150	40
16.	-320	40	33.	-350	175
17.	-325	175	34.	-250	60

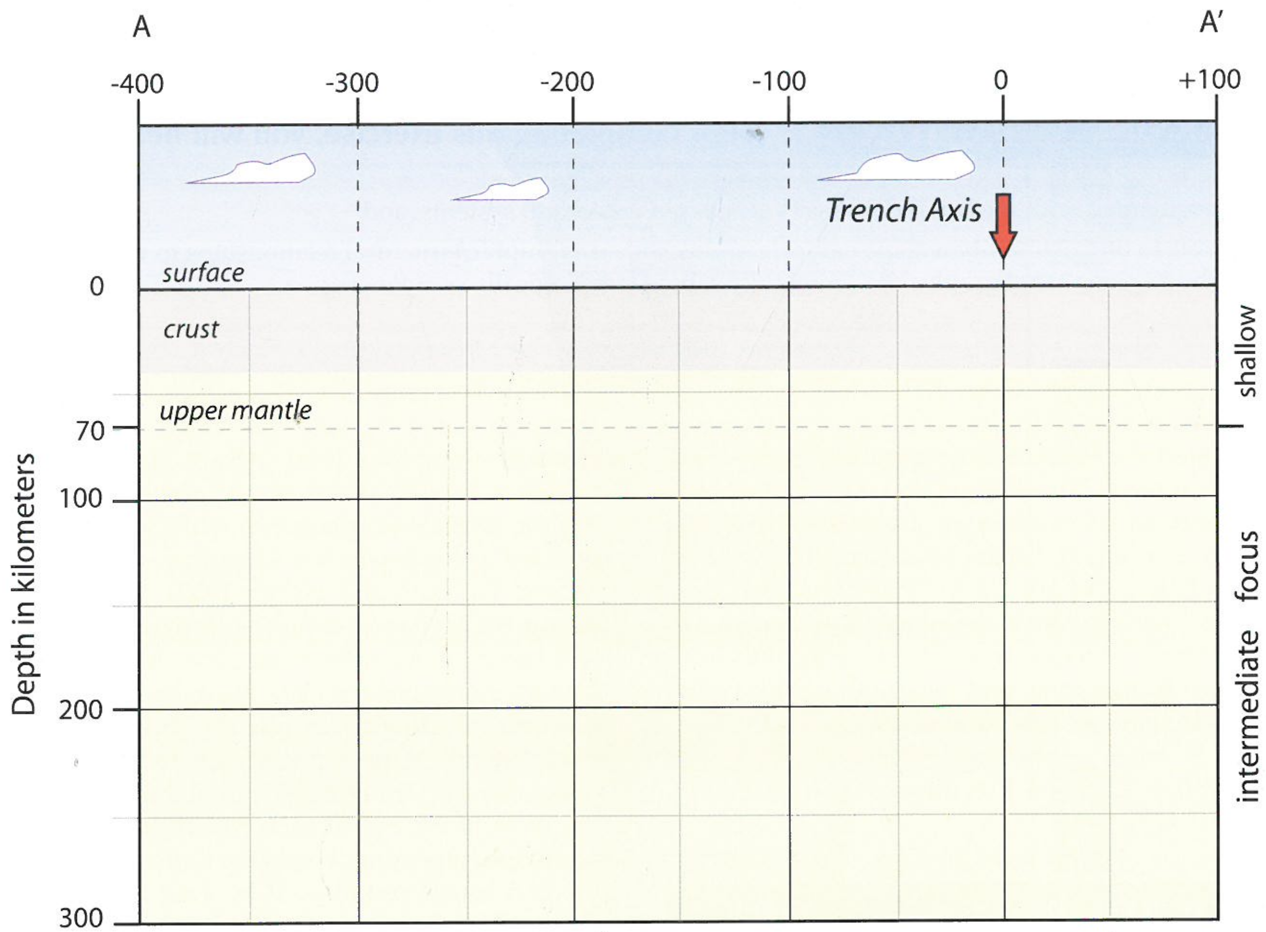


FIGURE 11.8 **Cross section of line A–A′ on figure 11.7B. The horizontal scale is distance from the Aleutian Trench axis measured in kilometers. Vertical and horizontal scale are the same. Depths below the surface are measured in kilometers. Distances seaward of the Aleutian Trench are assigned positive values. Distances northward from the trench axis are assigned negative values. Earthquakes occurring at a depth of 0 to 70 km are called "shallow" quakes; those occurring between 70 and 300 km are considered to be "intermediate-depth" earthquakes.**