THESIS

# SEISMICITY OF LIBYA AND RELATED PROBLEMS

Submitted by

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WE HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER OUR SUPERVISION BY HASSEN A. HASSEN ENTITLED SEISMICITY OF LIBYA AND RELATED PROBLEMS BE ACCEPTED AS FULFILLING IN PART REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE.

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ABSTRACT OF THESIS

SEISMICITY OF LIBYA AND RELATED PROBLEMS

The seismicity of Libya was investigated. Available data of earthquakes, which have occurred in or near Libya during the period 262 A.D. to 1982, have been collected. These data together with geological information are used to investigate the nature of seismic activity and its relationship to the tectonics of the country. Statistical analysis is used to calculate the frequency-magnitude relation for the data in the period from 1963 to 1982. The results indicate that about 140 earthquakes will equal or exceed a Richter magnitude of 5 every 100 years, and one earthquake will equal or exceed a Richter magnitude of 7 every 100 years. The whole country is characterized by low to moderate levels of seismic activity but some segments have experienced large earthquakes in this century and earlier. On the basis of observed and expected seismicity, a four-fold subdivision is suggested defining the activity of the different parts of the country. The highest activity is found to be concentrated in Cyrenaica (northeastern region) and around the Hun graben (northcentral region). The southern part of Libya is considered to be seismically stable. Problems encountered when investigating and predicting future seismicity are discussed. The

principal problem is the absence of seismic monitoring stations in the country.

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# 1. INTRODUCTION

Large numbers of lives are lost and many cities and towns are destroyed by large earthquakes throughout the world almost every year. Such damage results from severe ground shaking, surface rupture and other land-level changes. Secondary effects, such as landsliding, dam failure, etc., are also responsible for much damage.

In order for the seismic hazards to be mitigated and for the earthquake resistant building regulations to be properly applied to different regions, it is necessary to have a seismic zoning map with areas of probable maximum earthquake carefully delineated. Although we cannot, at the present time, accurately predict the time of occurrence of future earthquakes, it is possible to indicate with some degree of accuracy the zones where earthquakes of certain maximum magnitude may occur. Construction of such maps requires certain basic data. However, once constructed, they will guide the engineer in adjusting his earthquake resistant design to the potential seismic danger.

It is necessary to have the fullest possible understanding of the seismicity of the region and of the nature of the ground movements to be expected. In some cases, information can be obtained from the records of seismographs and strong-motion accelerometers, but it is essential that all available historical information concerning earthquake and earthquake damage be compiled, analyzed, and published. In many cases, seismic data alone are insufficient for seismic zoning of a region, e.g., there may have been too few earthquakes during the period of observation. In such cases, one can turn to historical records and tectonics of the region, realizing that seismicity is subject to the tectogenesis of that region (UNESCO Seis. Survey Mission, 1964).

## 1.1 Purpose

Libya is a country without any seismological service or any seismological station, thus all information must be derived from the instrumental data of more distant stations. The closest station is in Athens. Some information also may be obtained from historical records. This investigation was undertaken to better understand the seismic activity and the earthquake potential in this country. Available earthquake data from 262 A.D. to 1982 was collected from different sources including the National Oceanic and Atmospheric Administration and the National Earthquake Information Services of the U.S. Geological Survey. These earthquakes and their parameters are compiled in chronological order in tabular form and plotted on maps, with historical earthquakes plotted separately.

These data are used to investigate the seismic activity and its relationship to the geology and tectonics of the country. The frequency of occurrence of shallow earthquakes is calculated and compared with observed ones. Some engineering aspects relating to seismic hazards are also discussed.

## 1.2 World Seismicity

Each year, nearly one million earthquakes are recorded by sensitive instruments. Of these, just a few major earthquakes account for most of the total energy released, as can be seen from data in Table 1. About 93% of the total energy released is contributed by events of magnitude M ≥ 7. Smaller earthquakes contribute little, despite their higher frequence of occurrence.

Table 1. Mean annual frequency of earthquake occurrence in the world (Kasahara, K., 1981).

| Magnitude M | ≥8 | 7.9-7 | 6.9-6 | 5.9-5 | 4.9-4 | 3.9-3 |
|---|---|---|---|---|---|---|
| Frequency N | 1.0 | 13.0 | 108.0 | 800.0 | 6200.0 | 49000.0 |
| Energy ($10^{23}$ erg) | 13.7 | 12.0 | 1.10 | 0.8 | 0.2 | 0.05 |
| % of total energy released in 1 year | 49.0 | 43.0 | 4.0 | 3.0 | 1.0 | |

Seismic observations have provided us with extensive amounts of information on seismic activity in various regions of the earth during various periods of time. Both earthquake frequency and energy release are well documented. For more information, one should refer to Gutenberg and Richter (1954), Richter (1958) or Lomnitz (1974).

Global tectonics provide an explanation for the worldwide distribution of earthquakes. The Earth's outer shell is regarded as being divided into series of rigid plates that are undergoing slow motion relative to each other (Figure 1). The major active processes of geology such as volcanism and earthquakes are concentrated at or near these plate boundaries. Stresses build up in the vicinity of

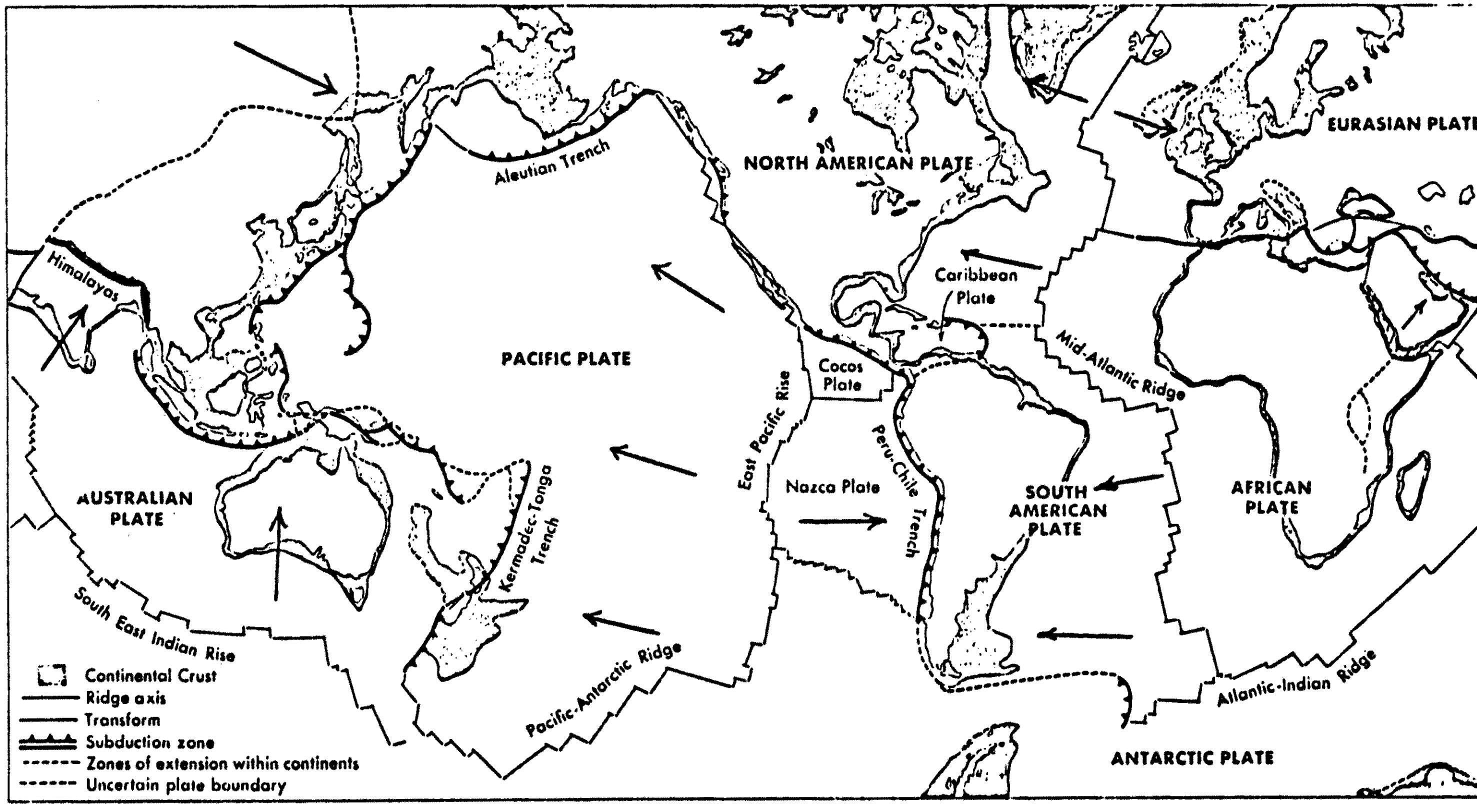



Figure 1. The division of the earth into "plates" (from Turekian, K. K., 1976).

plate boundaries where the plates are opposing each other's motion. When the stresses exceed the lithospheric breaking strength, an earthquake occurs.

An examination of the epicenters of earthquakes (Sykes, et al., 1970) shows that they occur mainly in trenches where, according to plate tectonics, the crust is being subducted under near land masses, along the ridge crests where crust is being formed, and along the portion of the fracture zones that form the offsets between the crests.

At shallow depths, where the edges of two lithospheric plates are pressing against each other, usually there is intense earthquake activity. Many of the world's greatest earthquakes (for example, the Chile earthquake of 1960 and the Alaska earthquake of 1964) and many smaller ones, occur along the shear plane between the subducting oceanic and the continental lithospheres. Deep and intermediate focus earthquakes generally occur along the Benioff zone, a plane that dips toward a continent (Toksoz, 1975). All the deep earthquakes take place in coldest region of the descending slabs (where stresses are highest) of the oceanic type.

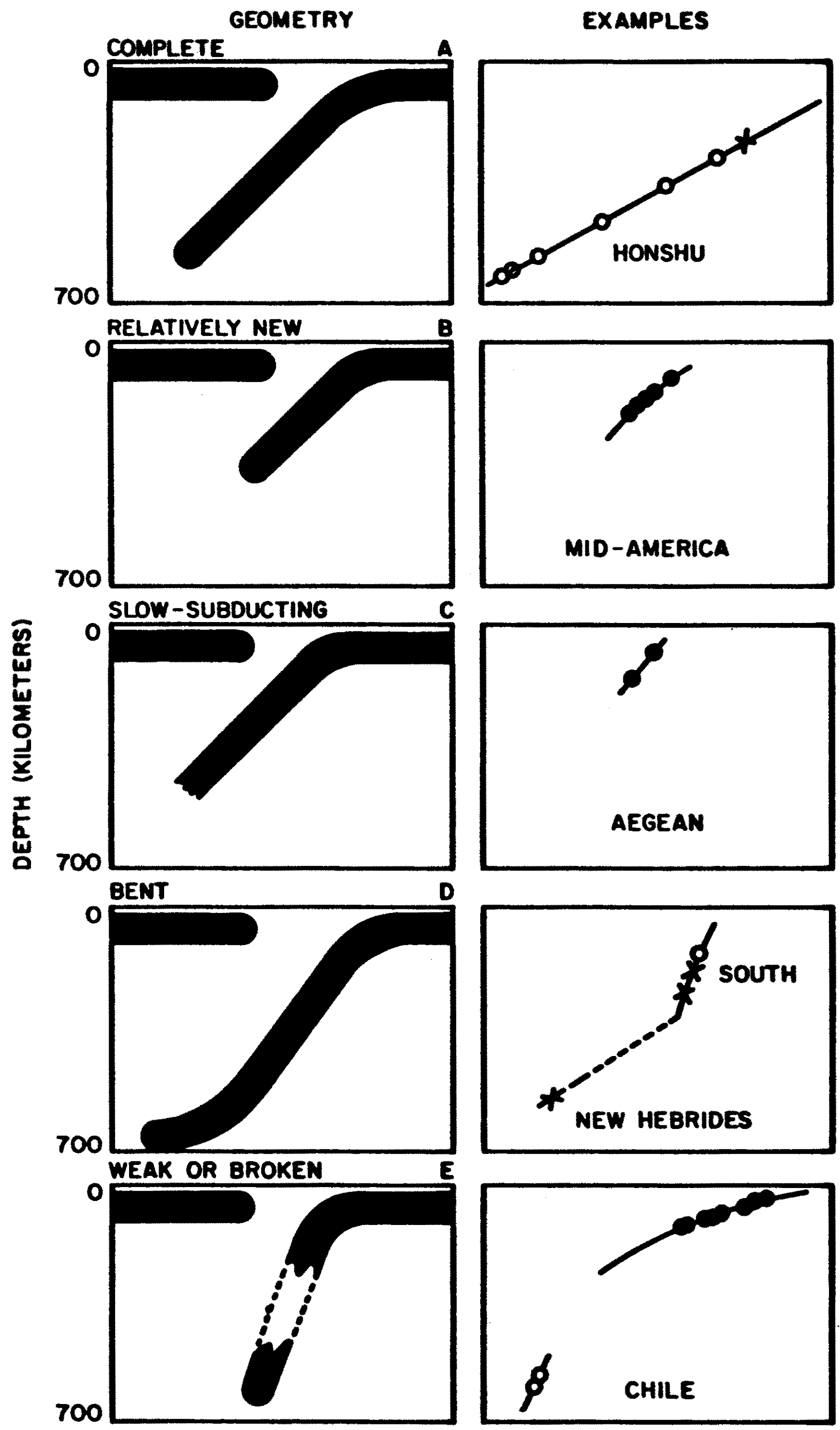
Major subduction zones and some of their characteristics are listed in Table 2. The five principal types of subduction zones (A-B) are shown schematically in the illustration of Figure 2.

The frequency of occurrence varies considerably from region to region and only in a few regions can an average recurrence time be estimated. Countries that have suffered severe earthquake damage include China, Japan, Iran, South and West USSR, Italy, Greece, Turkey, Southern Europe, Spain, Morocco, parts of the United States (California, Missouri), Central America (including Mexico, El Salvador),

Table 2. Major subduction zones (Toksoz, 1975).

| Name | Plates Involved | Type | Length of Zone (kilometers) | Subduction Rate (centimeters) (per year) | Maximum Earthquake Depth (kilometers) | Type of Subducting Lithosphere |
|---|---|---|---|---|---|---|
| Kuriles-Kamchatka-Honshu | Pacific under Eurasian | A | 2,800 | 7.5 | 610 | Oceanic |
| Tonga-Kermadec-New Zealand | Pacific under Indian | A | 3,000 | 8.2 | 660 | Oceanic |
| Middle American | Cocos under North American | B | 1,900 | 9.5 | 270 | Oceanic |
| Mexican | Pacific under North American | B | 2,200 | 6.2 | 300 | Oceanic |
| Aleutians | Pacific under North American | B | 3,800 | 3.5 | 260 | Oceanic |
| Sundra-Java-Sumatra-Burma | Indian under Eurasian | B | 5,700 | 6.7 | 730 | Oceanic |
| South Sandwich | South American Subducts under Scotia | C | 650 | 1.9 | 200 | Oceanic |
| Caribbean | South American under Caribbean | C | 1,350 | 0.5 | 200 | Oceanic |
| Aegean | African under Eurasian | C | 1,550 | 2.7 | 300 | Oceanic |
| Solomon-New Hebrides | Indian under Pacific | D | 2,750 | 8.7 | 640 | Oceanic |
| Izu-Bonin-Marianas | Pacific under Philippine | D | 4,450 | 1.2 | 680 | Oceanic |
| Iran | Arabian under Eurasian | E | 2,250 | 4.7 | 250 | Continental |
| Himalayan | Indian under Eurasian | E | 2,400 | 5.5 | 300 | Continental |
| Ryukyu-Philippines | Philippine under Eurasian | E | 4,750 | 6.7 | 280 | Oceanic |
| Peru-Chile | Nazca under South American | E | 6,700 | 9.3 | 700 | Oceanic |

Figure 2. Five major types of subducting oceanic slabs can be identified. In the examples the solid lines represent the location of all earthquakes projected onto a cross section. The symbols on the lines identify particularly large earthquakes from which the direction of stress was determined. Open circles indicate compression along the length of the slab; filled circles indicate tension along the length of the slab, and crosses show stresses that do not lie in the plane of the cross section. (Adapted from Toksoz, 1975)


GEOMETRY
EXAMPLES
DEPTH (KILOMETERS)
COMPLETE
A
0
700
HONSHU
RELATIVELY NEW
B
0
700
MID-AMERICA
SLOW-SUBDUCTING
C
0
700
AEGEAN
BENT
D
0
700
SOUTH
NEW HEBRIDES
WEAK OR BROKEN
E
0
700
CHILE

South America (particularly Peru and Chile), Alaska and New Zealand.

Communities in many other places also have suffered loss of life and damage through earthquakes. Even the most complete list, however, cannot give complete assurance that a destructive earthquake will not occur in an unexpected locality. "Nevertheless, there is a sufficient knowledge now about the pattern of the global seismicity to allow cautious statements to be made on the likelihood of large earthquakes in a given area" (Wiegel, 1970).

Although earthquakes may occur anywhere, it can be seen from Figure 3 that earthquakes, like volcanoes and high mountain ranges, are not randomly scattered but are for the most part concentrated in narrow belts and the great majority are concentrated in the circum-Pacific belt, where most of the subduction is occurring (Table 2).

As shown in Table 3, this area generates about 80% of shallow shocks (0-30 km deep), 90% of intermediate shocks (30-60 km deep), and nearly all deeper ones. The greatest activity is near Japan, Western Mexico and Philippines. The loop islands bordering the Pacific have a high proportion of great shocks at all focal depths. Considerable activity also occurs along the Mediterranean and trans-Asiatic belt. The old Precambrian Shields of Africa, India, Siberia, Australia, Canada and Brazil are aseismic (with, however, some marginal earthquakes) as is the Antarctic Continent.

The focii of earthquakes located from measurements of seismic waves occur from quite close to surface to down to depths of about 700 km. No deeper earthquakes have been recorded. This is explained by the fact that descending lithosphere heats up below that

Table 3. Numbers and energy of shocks in various regions (Kasahara, K., 1981).

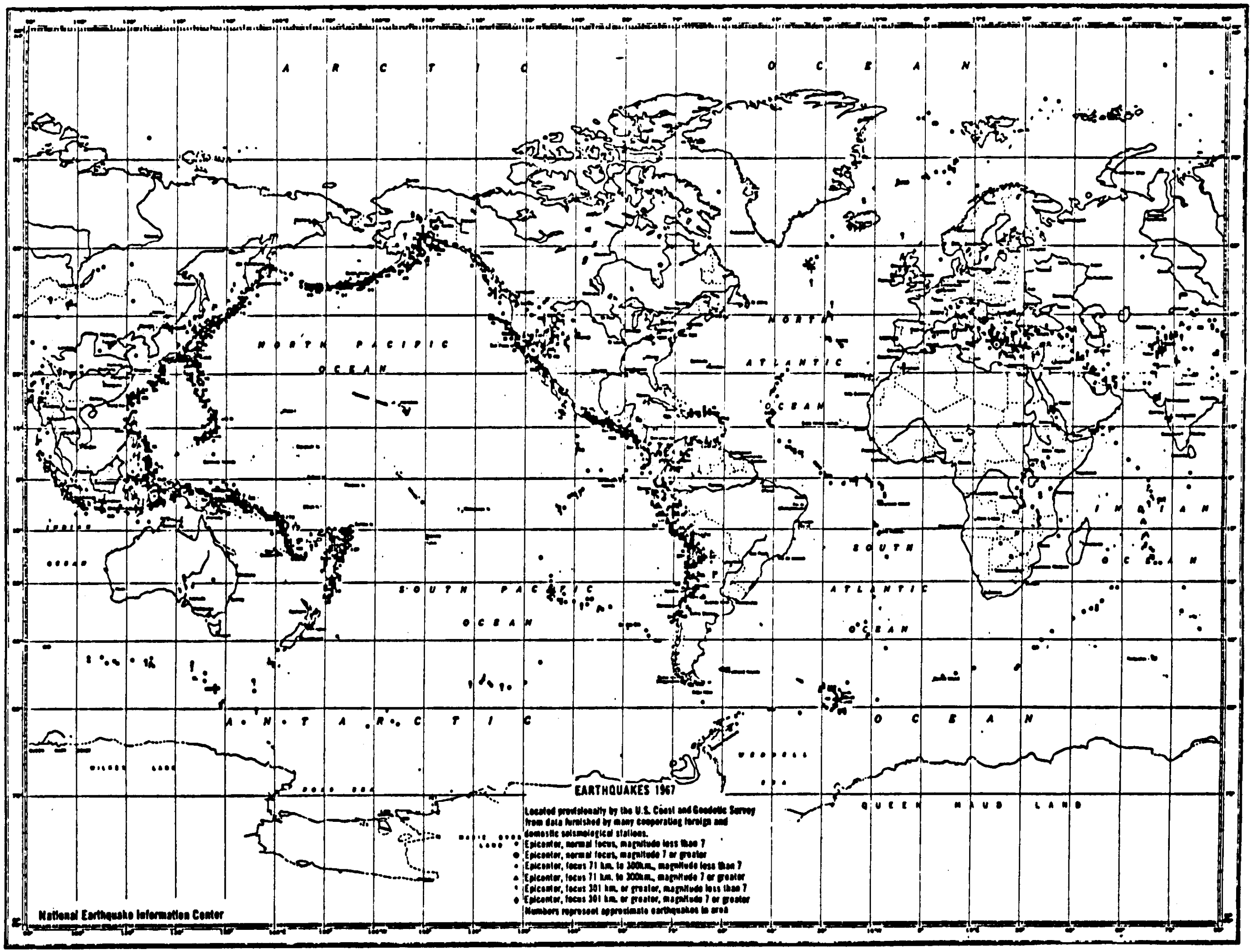
| Region | Total Numbers | | | | Annual Numbers | | | | | Energy in % | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Shallow | | Inter. | Deep | Shallow | | | Inter. | Deep | Shallow | Inter. | Deep |
| | (a) | (b) | (a,b) | (a,b) | (a) | (b) | (c) | (a,b) | (a,b) | | | |
| Circum-Pacific | 74 | 284 | 120 | 31 | 1.75 | 10.14 | 86 | 4.08 | 1.08 | 75.4 | 89 | 100 |
| Mediterranean and trans-Asiatic | 16 | 30 | 12 | 0 | 0.38 | 1.07 | 10 | 0.39 | 0 | 22.9 | 11 | 0 |
| Others | 2 | 20 | 0 | 0 | 0.04 | 0.74 | 12 | 0 | 0 | 1.8 | 0 | 0 |
| Total | 92 | 334 | 132 | 31 | 2.2 | 11.9 | 108 | 4.47 | 1.08 | 100 | 100 | 100 |

(a) - 1904 - 45 for $M \geq 7.8$.

(b) - 1922 - 45 in general, for $7.7 \geq M \geq 7.0$.

(c) - Smaller earthquakes.

Figure 3. Map showing global seismicity for the year 1967 (from Wiegel, R. L., 1970).


ARCTIC OCEAN
NORTH PACIFIC OCEAN
NORTH ATLANTIC OCEAN
SOUTH PACIFIC OCEAN
SOUTH ATLANTIC OCEAN
INDIAN OCEAN
ANTARCTIC OCEAN
QUEEN MAUD LAND
EARTHQUAKES 1967
Located provisionally by the U.S. Coast and Geodetic Survey from data furnished by many cooperating foreign and domestic seismological stations.
Epicenter, normal focus, magnitude less than 7
Epicenter, normal focus, magnitude 7 or greater
Epicenter, focus 71 km. to 300km., magnitude less than 7
Epicenter, focus 71 km. to 300km., magnitude 7 or greater
Epicenter, focus 301 km. or greater, magnitude less than 7
Epicenter, focus 301 km. or greater, magnitude 7 or greater
Numbers represent approximate earthquakes in area
National Earthquake Information Center

depth and no longer behaves as a rigid medium that can have faulting or fracturing, and more, below that depth the stresses are small and they are usually relieved by slow plastic deformation rather than the sudden failure. The statistics of focal depths of earthquakes show that the majority of earthquakes, including those with the greatest energy, appear in the earth's crust, or at a depth of about 60 km or less. They account for over 75% of the average annual seismic energy released by earthquakes.

Deeper earthquakes occur with decreasing frequency down to the 250 km level. Below 250 km down to 700 km the vertical distribution of earthquakes is rather uniform, although in some cases there is a local increase of activity at certain levels (Gutenberg and Richter, 1954). Many subduction zones exhibit a "seismicgap" between 300 and 500 km where no earthquakes occur (Figure 2). It is not known at present whether this is because the slab is broken (Type E) or because stresses are absent at that depth (Toksoz, 1975).

Development in seismometrical techniques has enabled us to study the global distribution in greater details. In oceanic basins which are almost aseismic we are now able to recognize a nearly linear alignment of epicenters running across the middle parts of the oceanic areas (Lomnitz, 1974). In the Atlantic Ocean, for example, a line of epicenters runs through its middle part from north to south turning around the southern tip of Africa to enter the Indian Ocean. Then, it divides into two branches, one reaching the Red Sea, and the other extending eastward to the South Pacific. At a point of the west coast of South America, the South Pacific branch splits again, one branch extending to the Chilean coast, and the other running up to the Gulf of California (Figure 1).

Unlike the major belts previously discussed, these alignments are not the sites of extremely big earthquakes and they present few earthquake hazards, except at their continental intersections, like Iceland, New Zealand, East Africa, Central America and Alaska. Yet, they are of primary importance in the global tectonic system (Bolt, 1970).

As the above description indicates, the study of the global morphology of earthquakes brings to light certain key properties that are important to any attempt to explain earthquake genesis by a general theory. The most important of these points are the following (quoted from Bolt, 1970):

1. Earthquakes are global but their present geographical distribution is structured (Figure 3) with extensive aseismic regions and belts of high seismicity.
2. Earthquakes have a very great range in the amount of energy released.
3. Earthquakes that release relatively moderate-to-large amounts of seismic energy may occur under both continents and oceans. [The cause of most tsunamic (long ocean waves) are the large submarine earthquakes.]
4. Earthquakes sometimes cluster strongly in both space and time (e.g., aftershocks sequence) (Figure 4).
5. Earthquake foci vary in depth from near-surface to depths up to 700 km. The frequency distribution of earthquakes

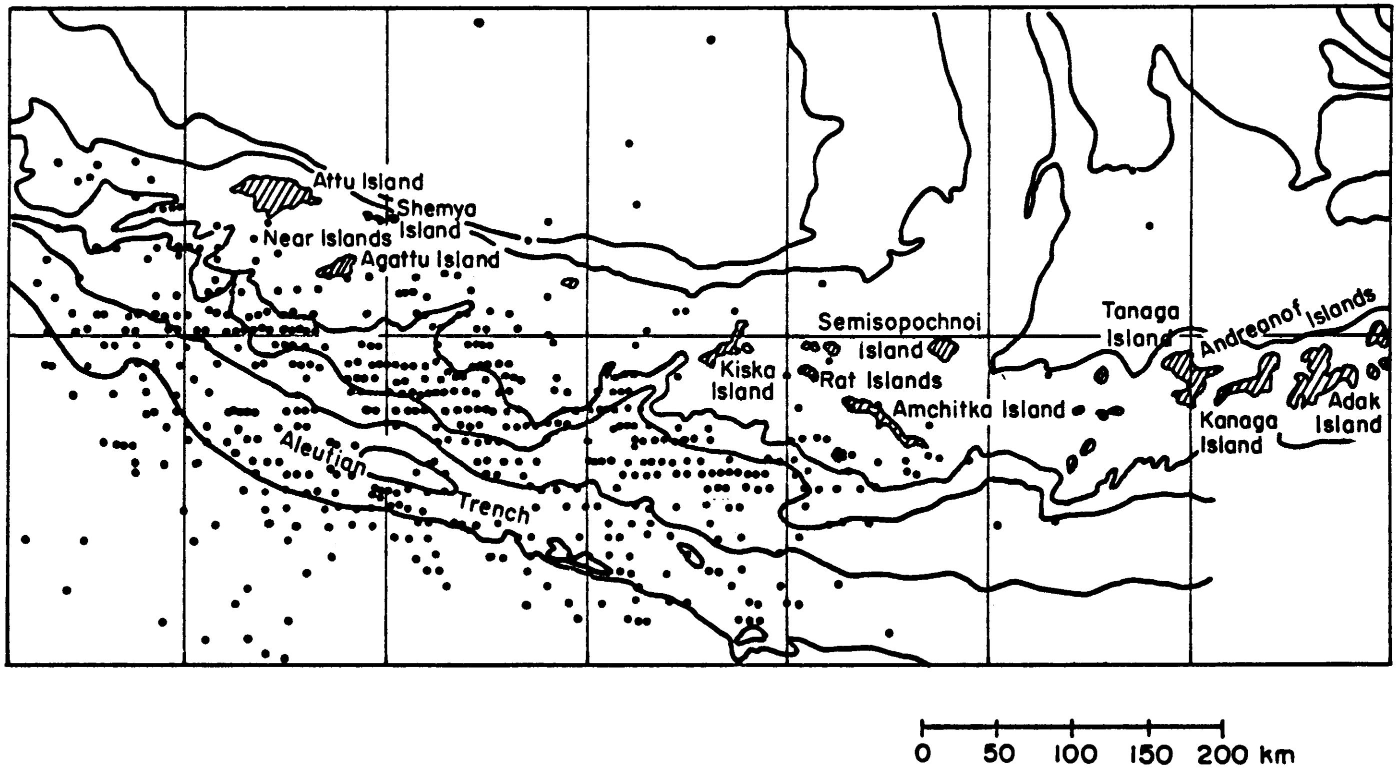



Figure 4. Aftershocks of the earthquake of February 4, 1965, in the Rat Islands of the Aleutians (from Leet, L. D., Judson, S. and Kauffman, M., 1978).

as a function of focal depth is neither uniform with depth nor with geographical region (Figure 3).

It is not possible here to develop each of these points in detail. The main point of the above summary is to emphasize the great range of properties associated with seismicity.

## 1.3 Mediterranean Region

The Mediterranean region forms the limit between the alpine areas and Africa and it extends from the Strait of Gibraltar eastward for a distance of 4,000 km. Italy, Sicily, the Straits of Sicily and Tunisia, which form an almost continuous bridge of land, separate the Mediterranean into western and eastern parts. Gutenberg and Richter (1954), Galanopoulos (1968) and Karnik (1969) have published catalogues containing information on earthquakes with epicenters in the Mediterranean Sea.

The great extent and thickness, and the undisturbed nature of the abyssal deposits suggest that no active plate boundaries cross the western Mediterranean. In the east, however, the sea floor displays an irregular topography, indicating that sedimentation has not kept pace with tectonism (Lort, 1971).

The region is delineated into plates on the basis of seismic activity at their margins (Figure 5). The intervening Aegean, Apulian and Turkish plates are small and rapidly moving, and have intense seismicity at the boundaries. The Aegean arc is underthrusted by the African lithosphere (90 km thick), which moves from the Mediterranean and goes down under the arc at an angle of about 30°C (Papazachos and Comninakis, 1972). Due to the slow rate of

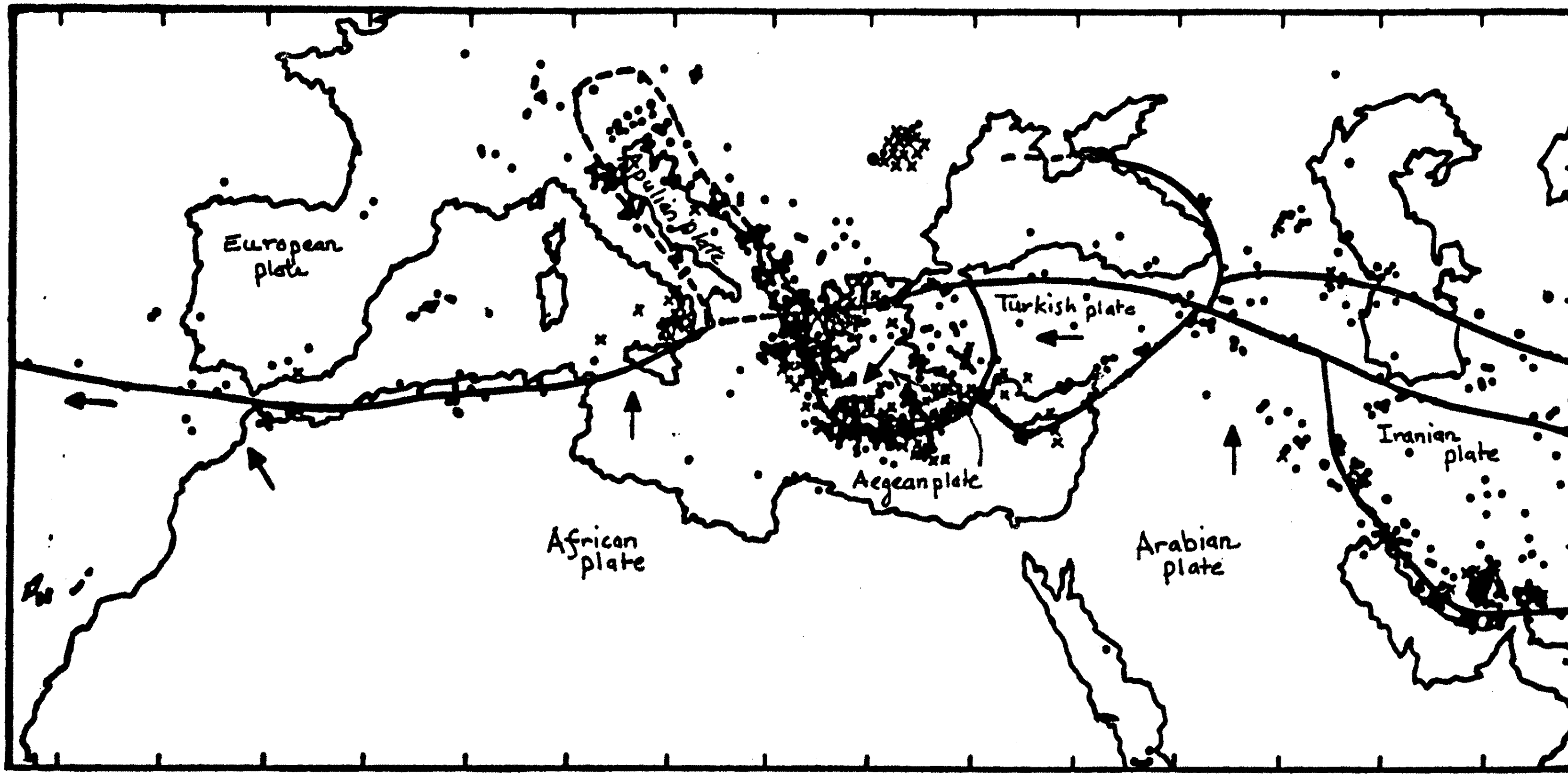



Figure 5. Seismicity of the Mediterranean (after McKenzie, 1970). Blacks dots represent epicenters of earthquakes with foci shallower than 70 km for the period 1962-1967; open triangles repre- foci below 70 km depth since 1925. Active plate boundaries at the present time approximately follow the lines of intense seismic activity. The directions of motion relative to the European plate are shown by arrows.

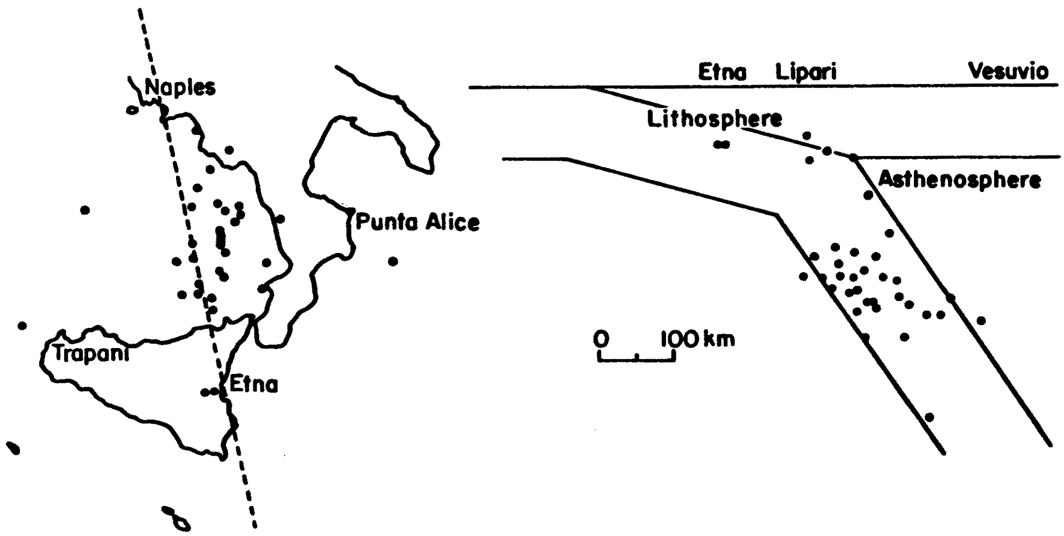
subduction (Table 2 and Figure 2), the subducting slab is well assimilated to the surrounding material before reaching great depths (Toksoz, 1975). All earthquakes are of intermediate depths not exceeding 150 km. Gass and Masson-Smith (1963) considered the positive gravity anomalies observed in Cyprus to be the result of underthrusting. However, they believe that the underthrusting slab is a thin crystalline layer which dips under Cyprus at low angle. It is clear from Figure 5 that in the Western Mediterranean, at the Azores-Gibralter, the intervening plates are absent. The seismicity associated with this line marks the junction between the African and European plates.

Deformation of the Mediterranean region is of interest for the reason that it is an accessible and reasonably well-studied area where the motion between the major plates involved is well known (McKenzie, 1972). Using different analyses of seismicity, different models of the tectonics and deep structures of the Mediterranean were obtained by some researchers; for example, Payo (1972), Caputo, et al. (1970), McKenzie (1972), and Comninakis and Papazochas (1972).

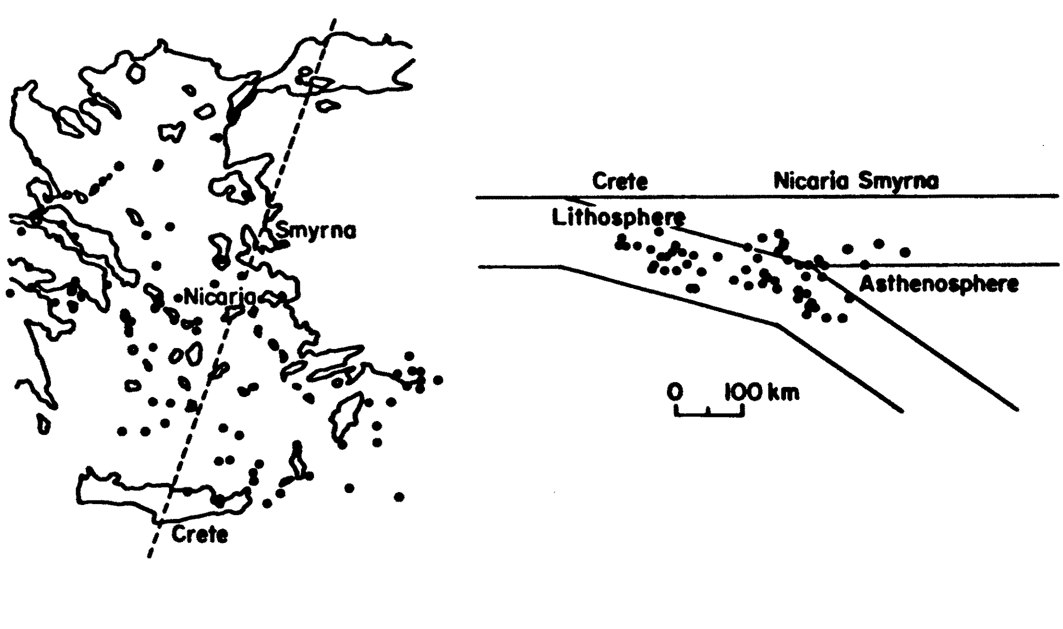
In their model, Caputo, et al. (1970) concluded that the African plate is wedged under the Eurasiatic plate with a slope of approximately 58° in the Lipari region and 35° in the Aegean region (Figure 6). They also considered this model to be able to explain the high seismicity of middle south Italy, the sinking of middle north Italy, and the uplift of south Italy which was confirmed by geological, archaeological and heat flow data. Archaeological data, for example, gave an uplift rate of 0.034 cm/yr.

Dewey (1969) presented a simple model for orogenic cycles, arguing that since the dimension of the earth's surface is constant,

Figure 6. Subduction of the African plate under the Eurasian plate as suggested by Caputo, et al.




Map of south Italy with number and locations of considered earthquakes. Vertical section is along the dashed line.




Map of Aegean Sea with numbers and locations of considered earthquakes. Vertical section is along the dashed line.

then if the ocean, the Atlantic for example, expands as it is doing at present, the dimension of the Pacific will decrease. Based on this hypothesis, an explanation of the long history of repeated orogenic cycles has been attempted in the manner demonstrated in Figure 7 (Dewey, 1972). According to this idea, he divides the ocean into three types: Pacific, Atlantic and Mediterranean. Both the Atlantic and the Pacific are spreading at the ridges, but the Atlantic is expanding while the Pacific is contracting and the Mediterranean is contracting but not spreading (Figures 7C and F). Figure 7 (Parts A, B and C) shows the spreading-expanding process which generates the Atlantic type in the ocean at the right. Spreading-expanding oceans are then converted into spreading-contracting oceans by the development of marginal oceanic trenches (Part B), and the nonspreading-contracting or the Mediterranean type (Part C). In (D) the ocean at the left has been closed so that the expanding of the Atlantic type at the right has to stop. The eastern Mediterranean provides a clear example of an ocean basin in the final stages of closure by lithosphere loss in the Aegean trench. In (E) the Pacific type at the right and the Atlantic type at the left have started. If the ridge subducts (F), the ocean at the right becomes the Mediterranean type (Dewey, 1969). More details may be obtained from the mentioned references.

Earthquake epicenters in the Mediterranean region are shown in Figure 8. The seismicity of this region is not more than 3 to 4% of the world's total as regards frequency and energy. This means that on the average an earthquake of magnitude of ≥7 occurs once in three years' time, and an earthquake of magnitude ≥6 occurs three to

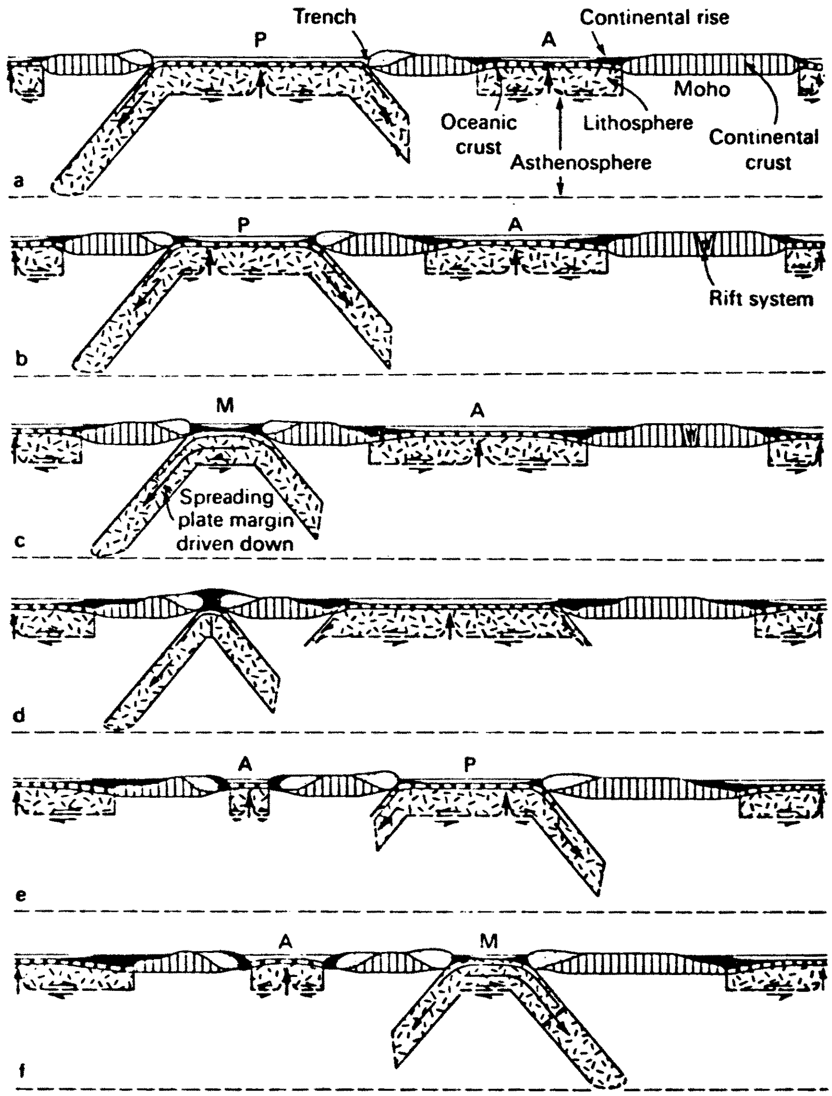



Figure 7. Proposed successive relationship between plates, ocean and continents and orogenic belts suggested by Dewey, J. F., 1969.

four times a year (Ritsema, 1975). Since the Mediterranean is contracting, as mentioned above, it is considered to be active on both north and south sides. The highest activity, however, is occurring in the northern side of the eastern part, where subduction is going on. Seismic events of large magnitudes and great depths have occurred inside the Sicilian-Calabrian seismic arc, and in southern Spain. The famous Lisbon earthquake occurred in 1755. Two more recent earthquakes in 1942 and 1969 were of magnitude 8 or more. Secondary seismic zones occur in the Strait of Sicily and southern Turkey. Coastal shocks in North Africa have been destructive in Tunisia, Libya and Algeria. Occasional damaging earthquakes occurred in the High Atlas of Morocco, the Canary Islands, and Spain (the Azores-Gibralter line), the area that is most active outside the Greece-Italy region (Lomnitz, 1974). The relationships between the pattern of the distribution of the earthquake focii and the geological structure of the Mediterranean have been pointed out by many investigators, as mentioned earlier; it is reviewed by Isacks, et al. (1968).

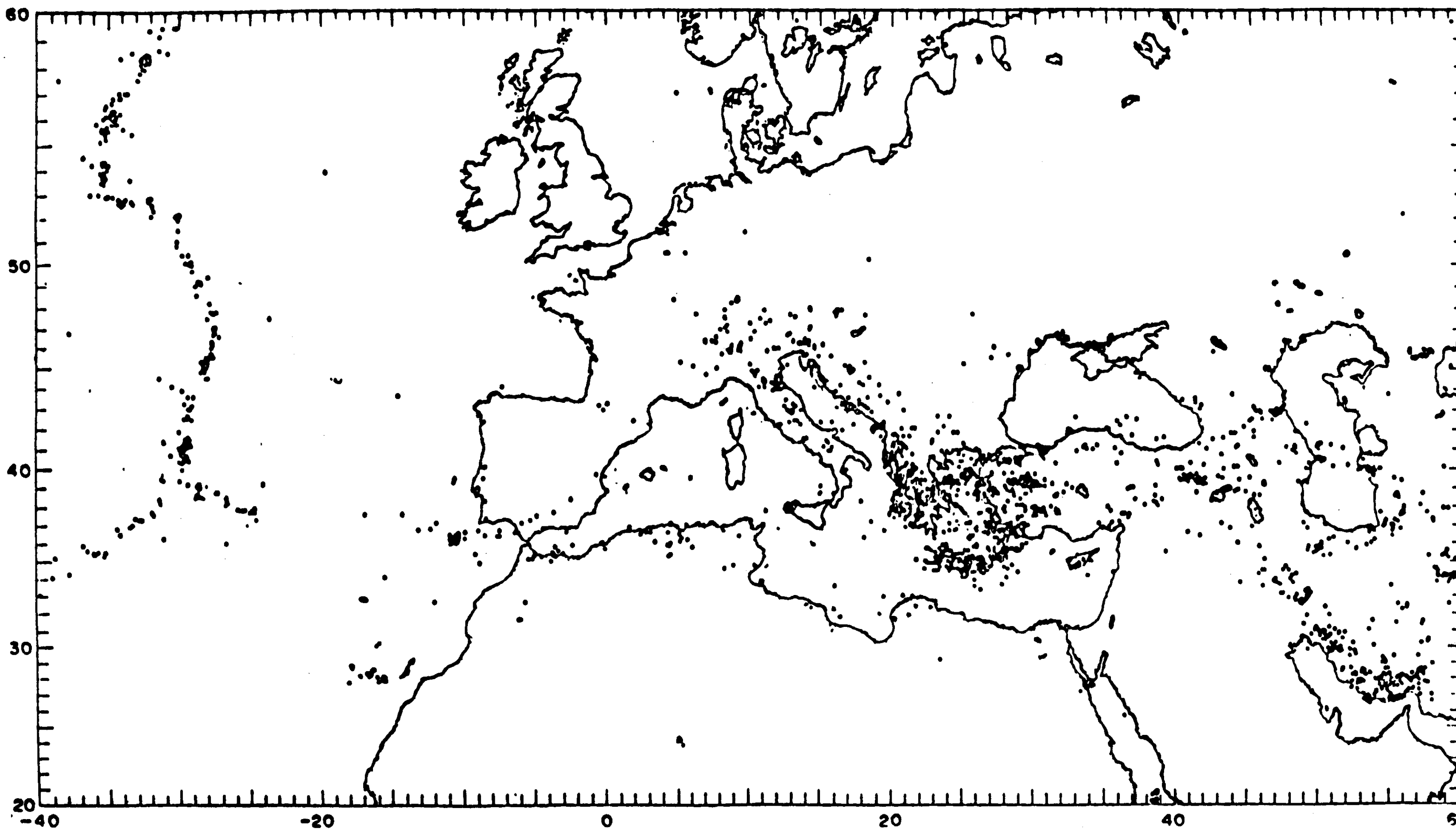



Figure 8. Positions of all epicenters of earthquakes between 40°W and 60°E, 20°N to 60°N located by the U.S. Coast and Geodetic Survey between 1961 January 1, and 1970 July 30 (after McKenzie, 1970).

# 2. SEISMICITY OF LIBYA

## 2.1 Geology and Earthquakes

### 2.1.1 Regional Seismotectonic Setting

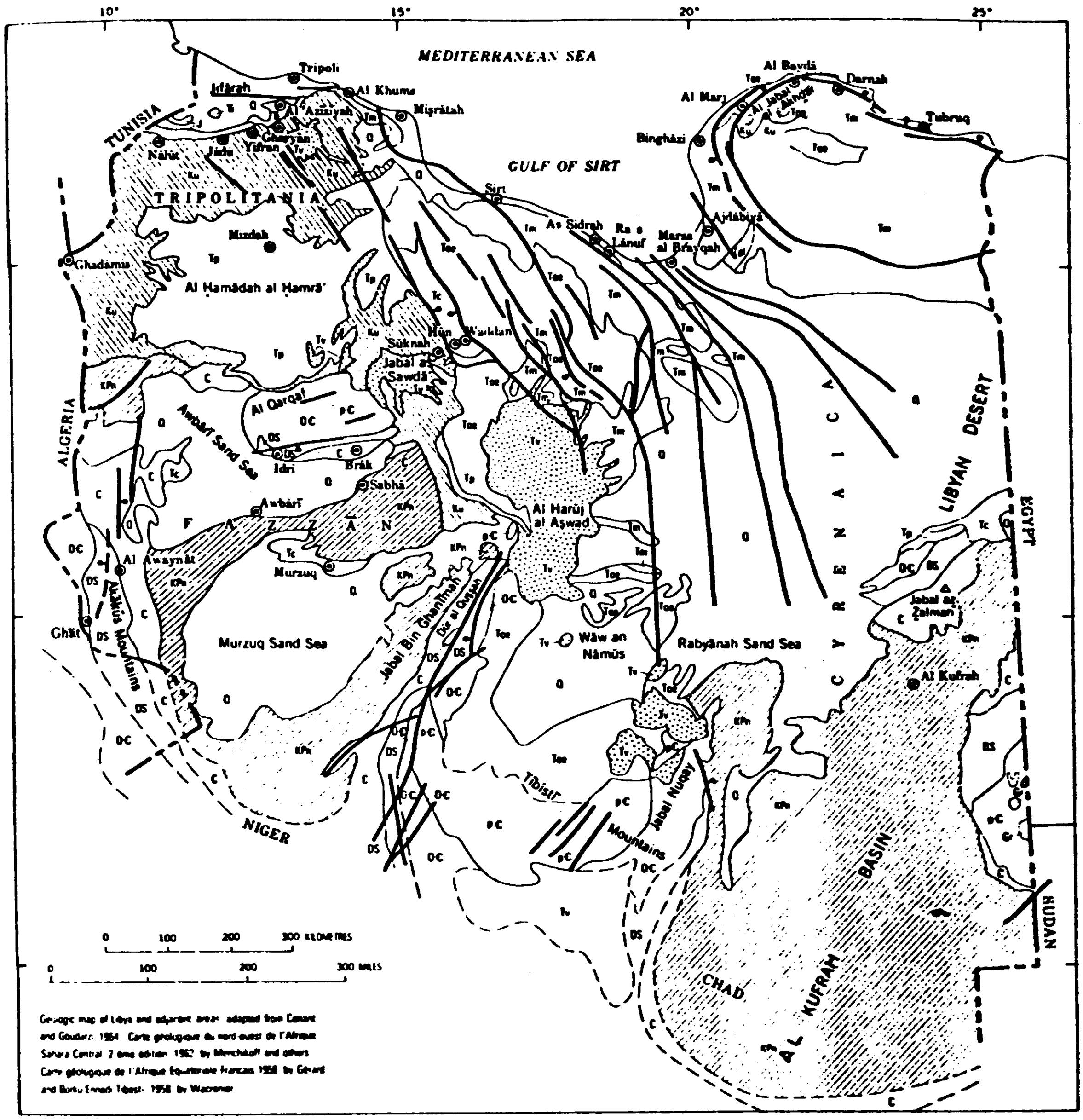
Libya, situated on the Mediterranean foreland of the African Shield, extends over a platform of cratonic basins. The geologic map (Figure 9) shows two sets of faults cutting through the midsection of the country. Near the intersection of these two trends is the largest outpouring of lava in Libya. It is interesting to note that these two fault trends are approximately parallel with the well-known great rift system in the Gulf of Suez and the East African areas. The country's connections with the Mediterranean are clearly defined, the Jeffara-Malta axis prolongs that of the Tibesti-Garian while alpine foldings in Greece affected northern Cyrenaica.

Outside of the Atlas Mountains in Libya and the East African-Red Sea rifts, northern Libya is the most seismically active area of Africa, since the African Shield borders on a tectonically active zone about the middle of the Mediterranean Sea and stresses are expected to build up between the stable shield and the mobile zone to the north. Relief of these stresses is the most probable cause of most of Libyan earthquakes (Campbell, 1968).

### 2.1.2 Elements of Tectonics

Northwestern Libya is marked by a flat coastal plain, the Geffara, that rises gently to the north and ends at the Jabal

Figure 9. Geologic map of Libya (after Conant and Goudarzi, 1967).




## EXPLANATION

| | | |
|---|---|---|
| Q Quaternary | Tv Volcanic rocks, some of Quaternary age | C Carboniferous |
| Tpl Pliocene | Ku Upper Cretaceous | DS Devonian and Silurian |
| Tm Miocene | KPn Nubian Sandstone including Continental Post-Tassilian (Permian to Lower Cretaceous) | OC Ordovician and Cambrian |
| Toe Oligocene and Eocene | | pC Precambrian |
| Tc Continental beds of uncertain age | J Jurassic | Gr Granite |
| Tp Paloeocene | Ŧr Triassic | Fault<br>Dashed where uncertain; bar and bell on downthrown side |

escarpment, a north-facing escarpment several hundred meters high. This escarpment arcs eastward for about 300 km from Nalut to Khoms where the hills come down to the coast. About 35 to 40 km south of the present Tripoli shoreline, north of Azizia, is an east-west faulting (Goudarzi, 1970). According to Burollet (1963) the main structural features of the Jabal area, which was uplifted during Hercynian folding, is the vast anticlinal swelling, the Garian-Yafran arch, that trends to northwest-southeast. The swelling ends near Sirte to the east. This emergence of the land or the Jabal uplift occurred at the end of Cretaceous time and was accompanied by northwest-southeast faulting. Another effect of this movement was the formation of the thin graben faults that also trend northwest and separate the eastern part of the Jabal area from Sirte. During and after Miocene downwarping in the Geffara was accompanied by faulting and folding in the Garian area (Figure 10).

The Hamada area slopes gradually to south from Nalut to Ghadames and rises eastward from Nalut to Garian area. The monotonous Hamada surface of northwestern Libya is interrupted by the vast volcanic mass that rises more than 300 m above surrounding land surfaces (Conant and Goudarzi, 1967). Several northwest-southeast trending fractures and faults occur in the area, but no major fault system is recognized on the surface.

In the southwestern part of the Murzuk Sand Sea, the north-south Acacus Mountain range rises more than 600 m above the valley of Wadi Tenezuft. No direct evidence of faulting has been found, but these sheer cliffs extend far more than 100 km, interrupted only by an offset about 30 km north of Ghat. However, the linearity of the

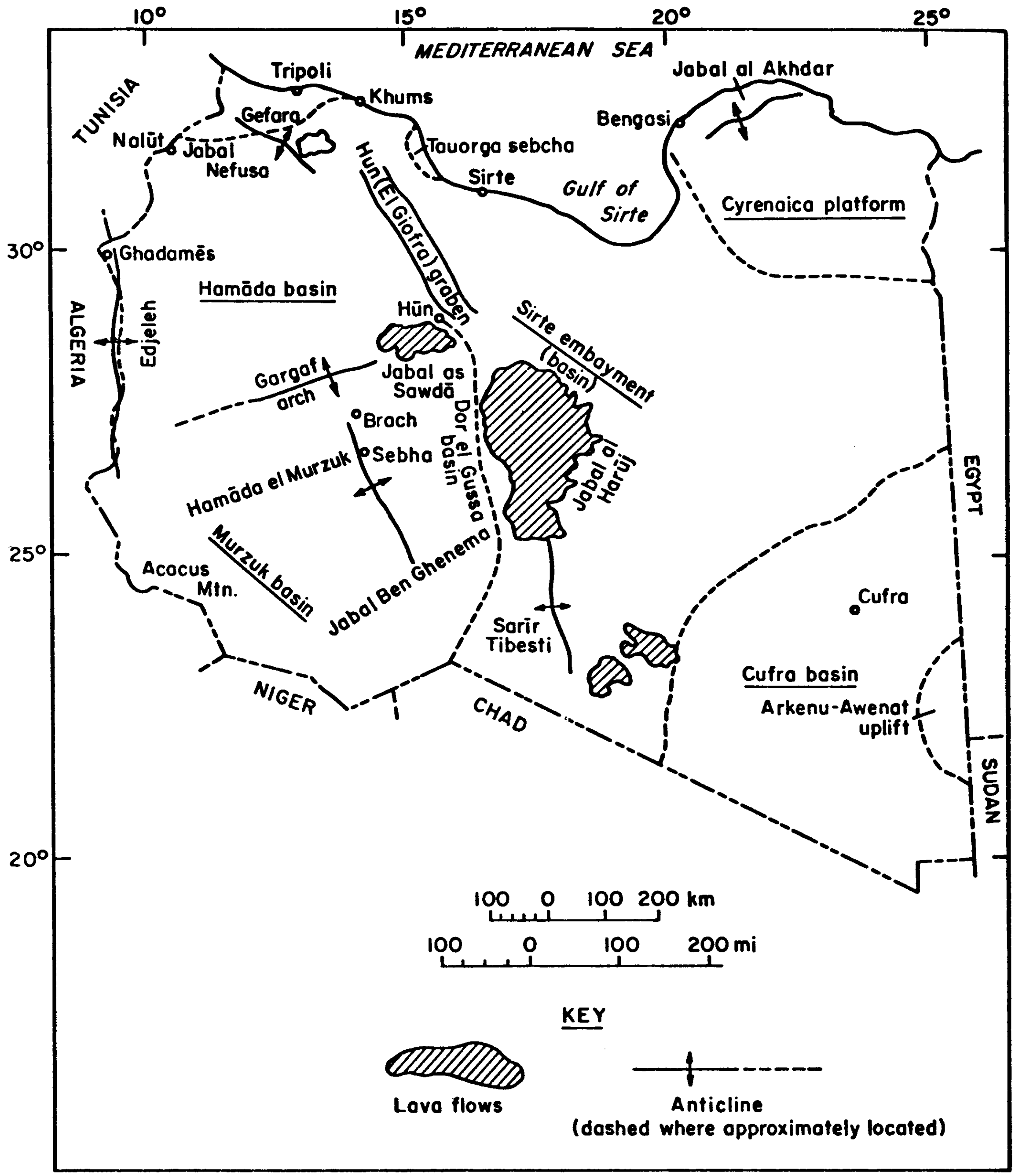



Figure 10. Map showing tectonic framework of Libya (adopted from Goudarzi, 1970).

cliffs is so strikingly suggestive of a fault scarp that many geologists have thought a fault must be present (Goudarzi, 1970). The major structural features of southwestern Libya is the Murzuk-Djado basin, which is delimited on the north by the Gargaf arch, a major east-west structural feature, which is an undulating area of low relief except for the high ranges of Jabal Fezzan that rise more than 300 m above surrounding surfaces. Northeast of Murzuk basin is the Brach-Ben Ghenema uplift, a northwest-trending structural feature that separates the basin from the small Dor el Gaussa basin. The eastern limit is the Ben Ghenėma Jabal, a high, rugged, mountainous massif (Furst and Klitzsch, 1963). Several northeast-trending faults in the same mountainous area extend north from Niger to about the Jabal Al-Harujal-Aswad volcanic flows.

Farther east in south-central Libya are the Jabal Eghei and the Tibesti Mountainous massifs that are in the Northern Chad area and rise to the highest points in the Sahara, about 3,400 m above sea level. These massifs form the western limit of Kufra basin. The Jabal Arknu-Jabal al Awaynat uplift forms the eastern boundary of this basin. The Jabal Arknu uplift probably took place in late or post carboniferous time and may be related to Hercynian orogeny.

In the northeastern part of Libya, in northern Cyrenaica, the high Jabal al-Akhdar plateau is limited on its north and west side by abrupt slopes in the form of successive faultline escarpments and terraces, which were formed by later processes of marine erosion (Conant and Goudarzi, 1967). The Jabal al-Akhdar plateau is a northeast-trending anticline, which plunges sharply to the northeast and gradually to the southwest. An arcuate fault of probable Tertiary age separates the Cyrenaica platform from the generally depressed Sirte embayment of the west and southwest, and from the Mediterranean basin to the north. The structurally elevated area of Cyrenaica platform and the north end of Al-Hamada basin may have been connected by the now tectonically depressed Gulf of Sirte prior to graben faulting in the Sirte basin area (Goudarzi, 1970). The rotation of Africa, which probably began in late Carboniferous time, culminated during the Tertiary Period, at which time Africa was separated from Asia along the Red Sea graben. The Sirte graben probably formed as a result of the Sahara platform moving along the Mediterranean during Late Cretaceous (Klitzsch, 1971).

The Sirte is tectonically a northwest elongated basin in which the major structural features trend northwest. Several northwest trending faults in the basin probably reflect the original basement block faulting and subsequent movement along those faults (Conant and Goudarzi, 1967). In the southern part of the basin the faults trend nearly north. Large scale subsidence and block faulting that began in Late Cretaceous time and continued intermittently into the Miocene, and the Sirte area gradually submerged, probably for the first time since early Palaeozoic time (Colley, 1963).

#### 2.1.3 Data

Libya is not considered to be a highly active seismic region (Gutenberg and Richter, 1954). Magnitudes and other earthquake parameters were given by Gutenberg and Richter (1954), Rothi (1969), and bulletins of the International Seismological Centre and various U.S. governmental agencies, e.g., U.S. Coast and Geodetic Survey, Earthquake Data Reports (EDR), Preliminary Determinations of Epicenters

(PDE). A data file of all the earthquakes reported from the country and its coast by the above mentioned sources has been assembled by the National Geophysical and Solar-Terrestrial Data Center (NGSTD Center) for the period between 1903 to 1981 (NOAA, 1982, Special Order). Historical earthquakes were described by Sieberg (1932), Goodchild (1968) and Campbell (1968). Historic and large earthquakes, which are known to have occurred causing severe to total damage, are listed in Table 4 and plotted on Figure 11.

When investigating seismicity of Libya, one should keep in mind that the country does not have any seismological station at the present time and that, for locations of earthquakes, it depends mainly upon stations in neighboring countries. For this reason, and because of the small number of seismological stations, and the limitations on instrument sensitivity before 1963, we realize that the registered number of earthquakes does not represent the actual total number. This fact was verified in a reconnaissance survey carried out in the Garian area (northwest of Libya) in 1977 (Kebeasy, 1978). A vertical seismograph was operated for only six hours and recorded three moderate earthquakes. These earthquakes were not reported by any other station.

Earthquakes of the data file were grouped according to the occurrence of different magnitudes for three time intervals (Table 5). These intervals represent the stages of improvement and growth of seismological stations in number and quality (Von Hake, 1982). Before establishing the worldwide net of standardized seismographs in 1963 (Appendix D), it was too difficult to judge whether a decrease in the

Table 4. Historic and large earthquakes affecting Libya and Libyan coast, from 262 to 1963 (from Campbell, 1968).

| Date A.D. | | | Time G.M.T. | | | Location | | Magnitude | |
|---|---|---|---|---|---|---|---|---|---|
| Year | m. | d. | h: | m: | s: | Lat°N | Long°E | (Richter) | Remarks |
| 262 | | | | | | Eastern Mediterr. | | Large | Cyrene and other cities destroyed in |
| 365 | 7 | 21 | | | | Eastern Mediterr. | | | 162 A.D. and 365 A.D. (Goodchild, 1968) |
| 704 | | | | | | Fezzan | | Large | Towns & villages in Fezzan destroyed (Sieberg, 1932) |
| 1183 | | | | | | Northern Libya | | Large | Tripoli destroyed, 20,000 killed (Sieberg, 1932) |
| 1803 | | | | | | Tripoli | | Small | |
| 1811 | | | | | | Libyan-Egyptian border | | Large | Temple of Ammon at Siwa damaged (Sieberg, 1932) |
| 1903 | 11 | 22 | | | | Tripoli | | Small | |
| 1914 | | | | | | | | Large | Violent earthquake demolished Gaddahia blockhouse |
| 1918 | 10 | 14 | | | | 33.0 | 22.0 | | Offshore - 10 kms N of Susa |
| 1919 | 8 | 3 | | | | 31.5 | 19.5 | | Offshore - Eastern Gulf of Sirte |
| 1931 | 4 | 24 | | | | 31.1 | 19.9 | | Offshore - Eastern Gulf of Sirte |
| 1935 | 4 | 19 | 15: | 23: | 22 | 31.5 | 15.25 | 7.1 | In area of Hun graben |
| 1935 | 4 | 19 | 20: | 31: | 30 | 31.0 | 15.5 | 6.0 | A total of 8 tremors recorded in this area in the period April 19-29, 1935 (Bellamy, 1947) |
| 1936 | 6 | 13 | 00: | 32: | 39 | 32.7 | 22.5 | 5.3-5.9 | 15 kms W of Derna |
| 1939 | 1 | 23 | 02: | 22: | 46 | 31.5 | 10.0 | 5.3-5.9 | About 25 kms offshore & 70 kms ENE of Al Qaddahia in the Hun graben. A total of 4 tremors reported in this area in the period Jan. 20 to Feb. 2, 1939. |
| 1940 | 1 | 2 | | | | 30.3 | 22.0 | | S. of the Jabal al Akhdar area. |
| 1941 | 3 | 4 | 23: | 45: | 10 | 30.75 | 15.75 | 5.3-5.9 | Hun graben area |
| 1941 | 5 | 3 | | | | 33.3 | 23.5 | | Offshore, 100 kms NE of Derna |
| 1943 | 7 | 16 | | | | 33.0 | 21.5 | | Offshore, about 45 kms WNW of Susa |
| 1948 | 5 | 22 | | | | 33.3 | 23.5 | | Offshore, 100 kms NE of Derna |
| 1957 | 5 | 2 | 02 hrs approx. | | | | | Minor | Felt in Northern Cyrenaica, reported in press (Sunday, Ghibli, May 5, 1957). |
| 1958 | 5 | 17 | 5: | 25: | 33 | 31.8 | 11.3 | | Jabal Nefusa area, E of Nalut |
| 1963 | 2 | 21 | 17: | 14: | 31 | 32.6 | | 5.3 | Barce heavily damaged |

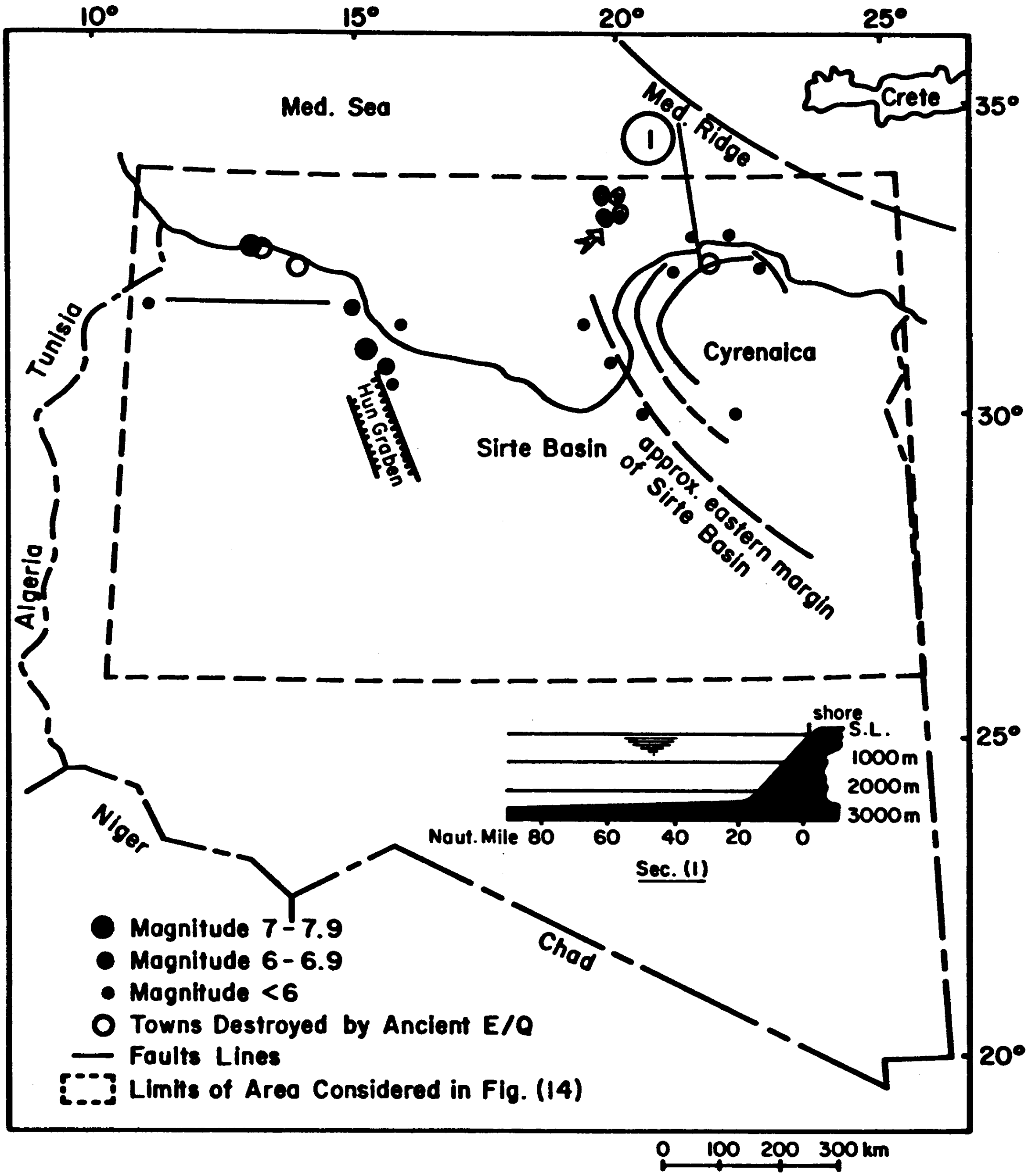



Figure 11. Historic and large earthquakes which are known to have caused severe to total damage in different places in Libya.

reported number of earthquakes is due to decrease in activity or due to the low number and sensitivity of the recording stations.

Table 5. Distribution of earthquakes magnitudes in the interval from 1903 to 1982.

| Observation Period | | Distribution of Earthquake Magnitude | | | | |
|---|---|---|---|---|---|---|
| | | 3→3.9 | 4→4.9 | 5→5.9 | 6→6.9 | ≥7 |
| (Years) | | | | | | |
| 1903-1939 | n | 40 | 40 | 58 | 16 | 11 |
| | t | 0 | 18 | 24 | 8 | 1 |
| 1940-1962 | n | 0 | 29 | 26 | 8 | 1 |
| | t | 0 | 11 | 13 | 5 | 1 |
| 1963-1982 | n | 30 | 235 | 36 | 1 | 0 |
| | t | 11 | 20 | 16 | 1 | 0 |

Note: Magnitudes 3→3.9 were only recorded after the establishment of the W.W.N.S.S. (1963). The increase in the recorded number or larger magnitudes is also remarkable.

n = total number of shocks
t = representative period of observation

Many of the events occurring prior to 1963 had no assigned magnitudes. It is suggested that the locations of all these events be recalculated to reduce the errors resulting from the use of different travel-time tables and different location methods. It will not, however, produce locations that are more accurate than the reported arrival time or the values of travel-time (Jeffery-Bullen Table) that are used as input. Computer programs for relocation of epicenters are described by Bolt (1960) and Engdahl and Gunst (1966).

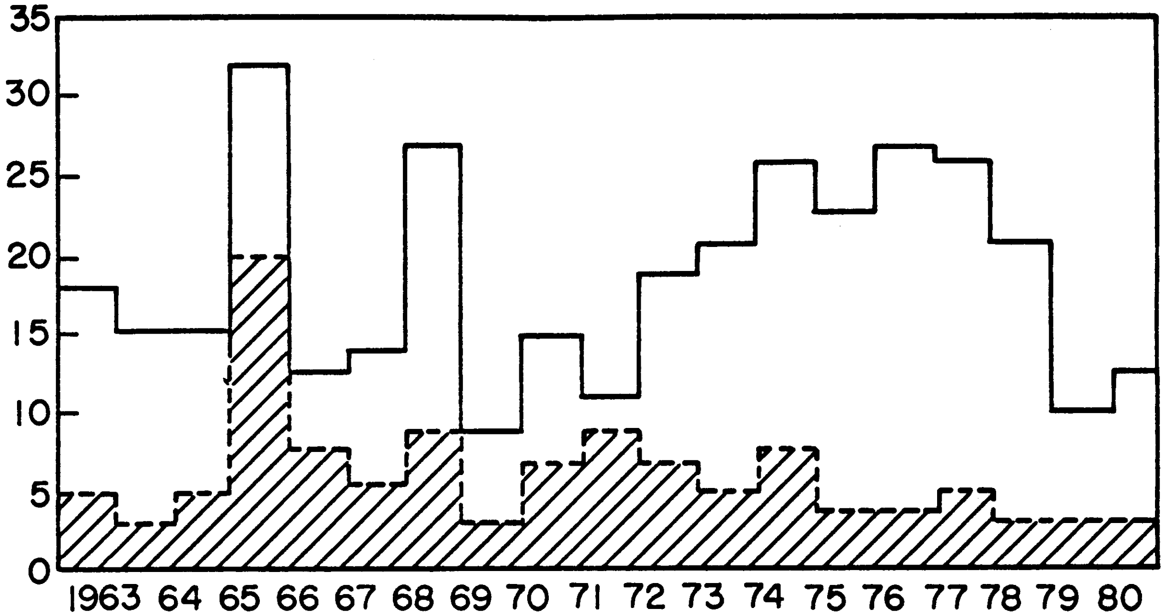



Figure 12. Histogram of the number of earthquakes detected in and around Libya in one-year intervals. Hatched portion represents earthquake magnitude >4.5. Reporting before 1963 was too poor to allow such division.

A breakdown of the activity from 1963 to 1981 in one-year intervals is shown in Figure 12. The total number of events up to 1972 shows an almost constant activity except in 1966 and 1969 periods, where it reached its peak. We notice also that events with magnitudes greater than 4.5 had their highest occurrence during the same periods, before and after that, the occurrence is effectively constant. From 1972 to 1981 the total number shows a clear upward trend indicating an increase in the seismic activity after which it decreased suddenly to the same previous level. This increase in total number could also be partially attributed to the growth of the worldwide standardized seismograph stations network as the number of smaller events (e.g., $M < 4.5$) constitutes the largest percentage.

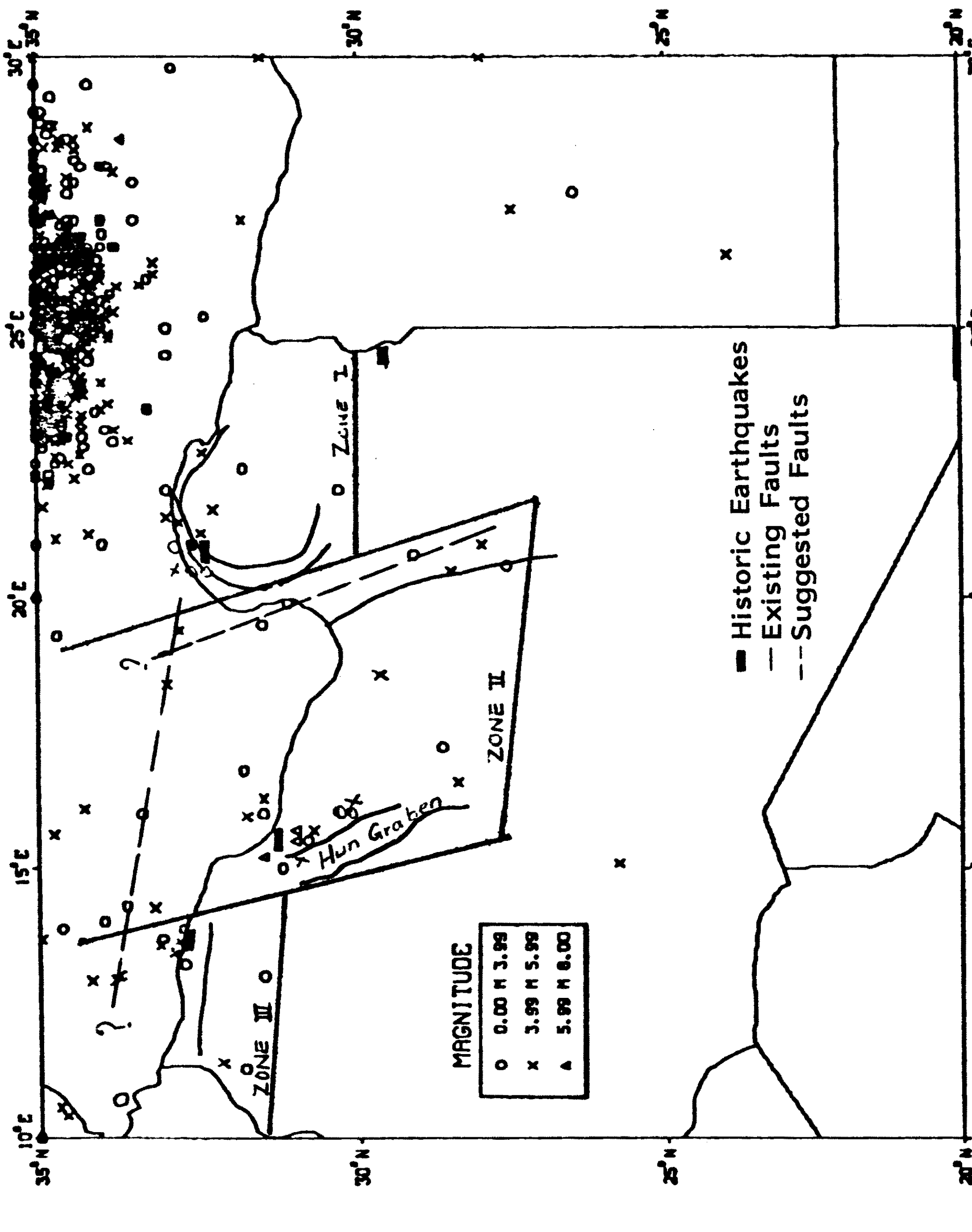
### 2.1.4 Earthquake History and Seismic Activity

The earthquake history of an area is very important in the evaluation of future seismicity because past earthquakes suggest both the location and size of future earthquakes. There are, however, serious limitations in using the historic earthquake record by itself to predict future seismicity (Allen, 1975). Allen (1975) also discusses such limitations and suggests the coordinated use of recent geologic history and earthquake history. The following sections discuss the seismic history of the country. A later section will consider relating this data to young geologic features in Libya.

Libya has a relatively short continuous earthquake record dating back only some 80 years. As shown in Figure 10, the country is on the Mediterranean coast of North Africa and has an area of about 1,600,000 sq km; the country extends about 1,525 km east and west and as much as 1,450 km north and south. Except for the northernmost parts, the country is entirely in the Sahara. Difficulties of travel and survival have long caused the different parts of the country to be separated, and probably many earthquakes have not been included in the record of the country.

Figure 13 shows the epicenters of all the earthquakes known of magnitude 3.5 or greater in the period from 262 A.D. to 1980. The earliest records of earthquakes in Libya are from the Roman period. Devastating shocks occurred in 262 A.D. and 365 A.D. The earthquake of 365 A.D. destroyed most of the temples and public buildings of Cyrene and caused disastrous fires. "Though many efforts were made to rebuild the city, Cyrene never regained its former splendors" (Goodchild, 1963, p. 25). Other Roman cities in Libya were severely

Figure 13. Distribution of epicenters of the earthquakes which have taken place in and around Libya in the period 262 A.D. to 1982. Location of seismic and aseismic zones as suggested by Kebeasy, 1978.



Historic Earthquakes
Existing Faults
Suggested Faults
MAGNITUDE
0.00 M 3.99
3.99 M 5.99
5.99 M 8.00
Zone I
ZONE II
ZONE III
Hun Graben
35°N
30°N
25°N
20°N
10°E
15°E
20°E
25°E
30°E

damaged. A massive seismic sea wave (tsunami) resulted from this earthquake and sea-going vessels were destroyed at Alexandria, Egypt. Sieberg (1932) describes a number of strong earthquakes which affected Libya. In 704 A.D., an earthquake at "Sebcha, near Murzuk" destroyed several towns and willaves in Fezzan. This is the only record of an earthquake which appears to have had its epicenter in southern Libya. In 1183 A.D., an earthquake destroyed Tripoli, killing 20,000 people. This powerful shock was felt throughout Libya and many towns were damaged. Large tremors were felt in Tripoli in 1803 and 1903 A.D.

In 1811 A.D., the ancient temple of Ammon at Siwa in Egypt (just east of the border from Libya) was heavily damaged by an earthquake which was felt in many parts of Egypt and Libya. Since the advent of modern seismographic recording techniques, many earthquakes plus numerous associated aftershocks have been recorded in Libya or just offshore (Table 5). In 1914 the Qaddahia blockhouse was destroyed. In April 1935, seismic stations in many parts of the world recorded a series of earth tremors with epicenters in the vicinity of the Hun graben area about 100 km south of Misurata. The strongest of these had a Richter magnitude of 7.1 and two of the aftershocks had magnitudes of 6.0 and 6.5. These earthquakes are without doubt the largest recorded from Libya in modern times and manifest a release of energy many hundred times greater than the 1963 shock at Barce. In fact, only three earthquakes with magnitudes of 7 or greater have occurred in Africa since 1900 (Gutenberg and Richter, 1954).

No reports of this powerful earthquake can be found in the Libyan publications of the period. The reason for this is that the area was inhabited only by nomadic people and local communications were such that no news of them reached Tripoli. The same area was shaken by two major earthquakes of magnitudes greater than 5 in 1939 and 1941. The 1939 earthquake was followed by four aftershocks.

Barce (Almarj) was heavily damaged by an earthquake of magnitude 5.3 on February 21, 1963, followed by five aftershocks all of magnitudes greater than 4 (Gordon and Engdahl, 1963). The event was not particularly large, and damage may be attributed to shallow focal depth, the presence of alluvium underlying Barce and the extensive use of mud and stone in older structures. More than 300 were killed and more than 10,000 were homeless. On December 19, 1976, Tripoli was shaken by an offshore earthquake with a magnitude of 4.8. This earthquake had its epicenter taken offshore from Tripoli and it was felt with varying degrees of intensity over a wide area. Another earthquake of magnitude 5 occurred in the southwestern part of Egypt. The importance of this earthquake is that it is the first earthquake to be located instrumentally in this area which is considered, as well as the southern part of Libya, to belong to the Sahara stable block of low earthquake potential (Kebeasy, 1979). Space and time distributions (Figures 13 and 14) suggest the division of the country into three major zones as shown in Figure 14.

### 2.1.5 Relationship of Earthquakes to Geology

Any attempt to correlate seismicity with geology in Libya must consider the limitation of the data. Geologic information is limited in that an understanding of the recent history of fault activity is achieved only through detailed investigation of individual faults or fault zones. No fault in Libya has been sufficiently studied to provide the specific information about recent activity needed to be able to predict earthquake occurrence.

The greatest limitation, however, results from the short period of seismic recording since pre-instrumental data does not provide accurate earthquake locations or magnitude determinations. Although a few instrumental studies have been conducted in Libya, Libya does not have a single large motion seismograph station for recording and locating earthquakes. Nearby stations exist in Athens, Rome and Helwan in Egypt. As a result, earthquakes under magnitude of 4 were generally not instrumentally recorded (after 1963, magnitudes as small as 3.5 are recorded). Locations of large earthquakes in Libya can only be located to within ±0.5 degrees in latitude and longitude and ±25 km in depth (Von Hake, 1982).

Since the contact zone between the African and Eurasian plates essentially has an east-west trend (Ritsema, 1975), the distribution of earthquakes in geographical longitude gives a rough insight into the activity of different regions. Papazochos and Comminakeis (1970) utilized the distribution of the foci of earthquakes, and Papazochos and Delebasis (1969) utilized fault solutions of shallow earthquakes to show that the Eurasian lithospheric plate is underthrusted by the African lithospheric plate along the Mediterranean ridge. The seismicity of the ridge is diffused without sharp boundaries and exceeds 100 km in width.

Figure 14 is a histogram showing the number of earthquakes in the period 1903 to 1981 in the region 26° to 34°N longitude, 11° to 25°E latitude. Although actual seismicity increases from west to east, the change from low to high activity is far from gradual (partly

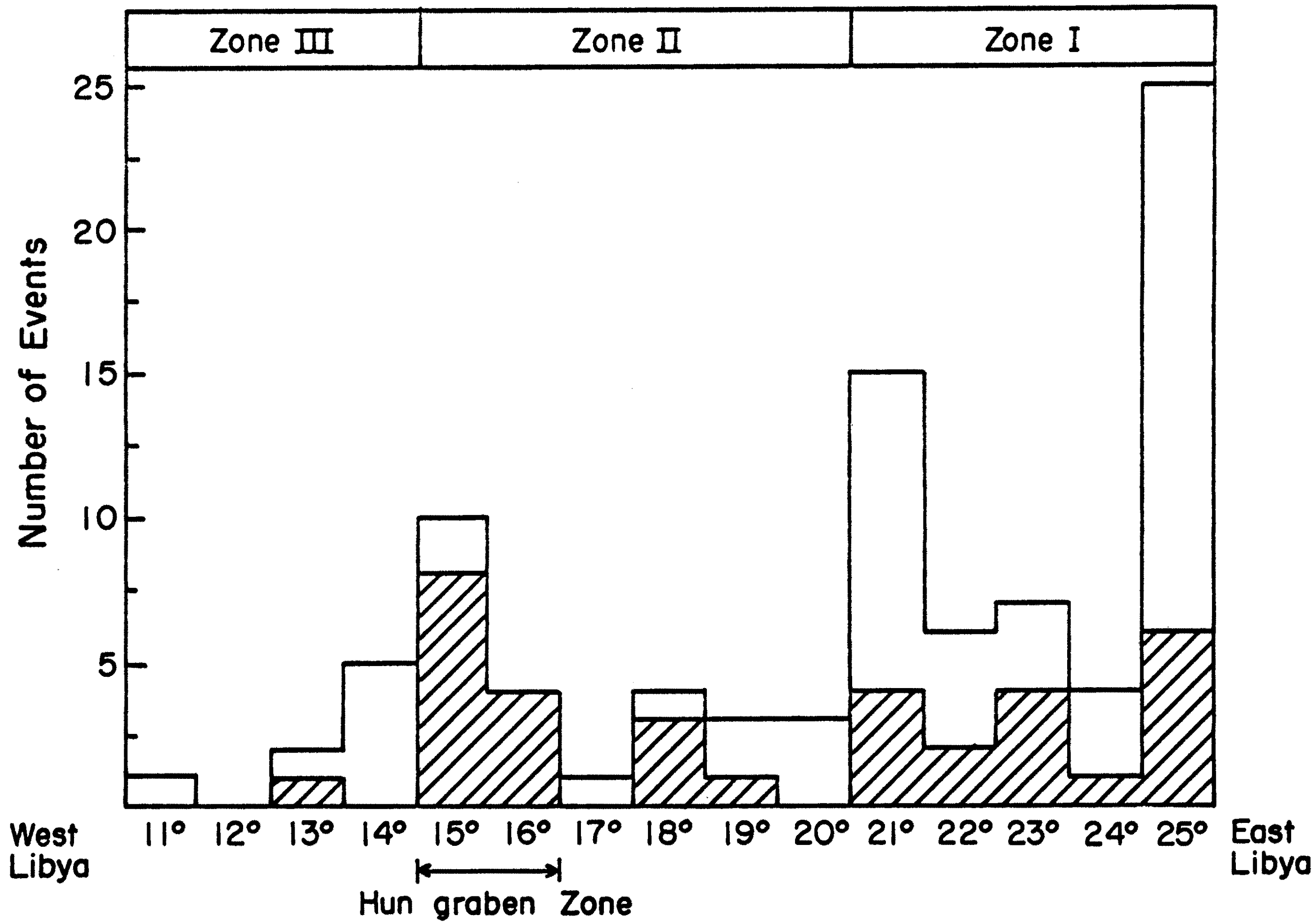



Figure 14. Histogram showing the number of earthquakes in the period from 1903 to May, 1981 in the region 26° to 34°N, along the geographical line from 11° to 25°E located in Figure 11. Total column height represents number of earthquakes of M ≧ 4. The cross hatched portions represent earthquakes of M ≧ 5.

because earthquakes with magnitudes less than 4 were not reported before 1963). The region where seismic activity is maximum is at the west and southwest border of the Mediterranean ridge. Towards the west this activity decreases where at the far west seismicity is not more than 10% of the maximum.

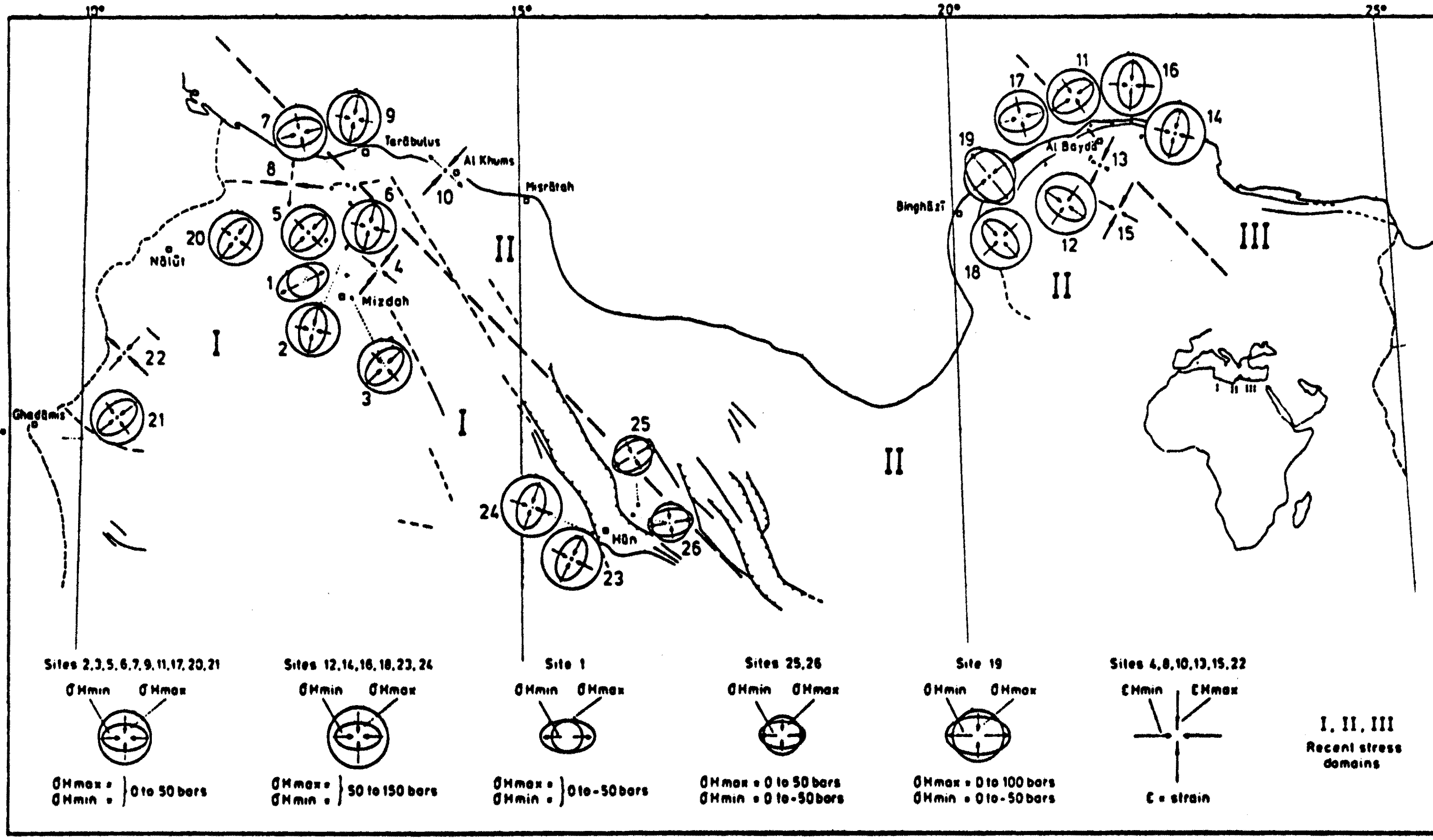
From Figure 14, activity appears to be concentrated in two regions, the first of which is the Hun Graben (Zone II) region between 15° and 17°E where earthquake of magnitudes ≧ 5 represent about 90% of the activity above magnitude 4. The second region is between longitudes 21° and 25°E (Zone I) which has about 70% of the total activity in Libya, but few of the earthquakes exceeded magnitude of 5. After 1963, most of the reported smaller earthquakes occurred in this region. If the smaller earthquakes were recorded before 1963, this zone would have shown higher activity and more homogeneity.

The lowest activity is shown to occur west of the longitude 14°E (Zone III). Number of events is limited and only one of them had a magnitude of 5.2 in the last 80 year period. The major structural feature in this zone is the Al-Aziziah fault which runs E-W from the Tunisian border as far as the Hun graben structure. The occurrence of small to moderate earthquakes, which are characterized by the very shallow depths, to the south of this fault, suggests that this may constitute a seismic plane of which the fault is the surface feature and earthquake foci are distributed along it (Kebeasy, 1979). This zone is the farthest from the Mediterranean ridge where maximum activity is going on. Schafer, et al. (1979) by in situ stress measurements, concluded that Libyan horizontal stresses are trending NE-SW except in this zone where it is NW-SE and these are always compressive and he called them the western stress domain (Figure 15). In a study of the seismicity and earthquake mechanisms of the Mediterranean, Ritsema (1975) suggested that all northwestern African countries except the western part of Morocco are subjected to a recent NW-SE oriented horizontal compressive stresses. "The western Libyan stress domain is, thus, the eastern extension of a large in situ stress regime" (Schafer, 1979).

From Figure 15 we see that the western half of Zone I also has a NW-SE trending compressive stresses. The rest of it has NE-SW trending horizontal compressive stresses. Stresses in this zone are much higher than in Zones II and III as expected, and are considered to be responsible for the increased seismic activity. The epicenter of 1963 Barce earthquake was located near the in situ stress site 18 in Figure 15 which showed the highest absolute compressive stress.

In the Jabal Al-Akhdar, several faults have been mapped cutting Tertiary outcrops and Conant and Gondarzi (1967) show these faults to have had substantial displacements in Tertiary time. These faults are the cause of the earthquakes in this zone. Submarine earthquakes also have occurred a few kilometers off the northern coastline of Zone I. Section (1) in Figure 11 shows an unusually steep submarine profile northwards from the coast (a depth 2,000 m in about 10 kilometers from the coast) and this suggests active subsidence, probably with associated faults downthrown to the north. The steep profile north of Cyrenaica may be an easterly prolongation of the Sicilian escarpment (Campbell, 1968). He indicated that the Sicilian escarpment is associated with a large fault with downthrow to the east. The Mediterranean ridge passes only a 100 km north of Cyrenaica. Tremors

Figure 15. Locations of in situ strain in Libya. Stress ellipses show the orientations and amounts of actual horizontal principal stresses. The circles indicate a state of released strain after overcoring and surround the ellipses if $\sigma Hmax$ and $\sigma Hmin$ are compressive, while they cut through the ellipses if the present horizontal stress is tensile. The broken heavy lines separate recent stress domains of consistent orientation of $\sigma Hmax$ and $\sigma Hmin$. The younger tectonics and the seismological events of Libya seem to be controlled by the actual rock stresses (after Schafer, 1979).


10°
15°
20°
25°
30°
30°
Tarābulus
Al Khums
Misrātah
Nālūt
Mizdah
Ghadāmis
Hūn
Binghāzī
Al Bayḍā
I
II
III
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
Sites 2,3,5,6,7,9,11,17,20,21
σHmin σHmax
σHmax = } 0 to 50 bars
σHmin =
Sites 12,14,16,18,23,24
σHmin σHmax
σHmax = } 50 to 150 bars
σHmin =
Site 1
σHmin σHmax
σHmax = } 0 to -50 bars
σHmin =
Sites 25,26
σHmin σHmax
σHmax = 0 to 50 bars
σHmin = 0 to -50 bars
Site 19
σHmin σHmax
σHmax = 0 to 100 bars
σHmin = 0 to -50 bars
Sites 4,8,10,13,15,22
εHmin εHmax
ε = strain
I, II, III
Recent stress domains

originating in this ridge may well be felt in Cyrenaica. On the 17th of August, 1981, an earthquake of magnitude 6.5 occurred about 90 km north of Cyrenaica and was felt everywhere in Zone I, but with no major damage. This earthquake's parameters were obtained from GOL[1] and are listed below:

| | G.M.T. | | | | | | |
|---|---|---|---|---|---|---|---|
| Date | hrs | min | sec | Lat | Long | Depth | Mag |
| 8/17/82 | 22 | 22 | 21.3 | 33.73°N | 22.96°E | 10 km | 6.5 |

The Hun graben is a prominent rift valley feature trending N-NW from Hun to Al-Qaddahia. The boundary faults of the graben are marked by escarpments and substantial fault displacement can be mapped at the surface (Campbell, 1968). Since 1935, three earthquakes and associated aftershocks have occurred at the northern end of the graben near Al Qaddahia (Figure 11). The strongest of these had a magnitude of 7.1 Richter and was followed by two powerful aftershocks. The relatively high incidence of earthquakes suggests that structural deformation is still taking place at the northern end of the graben. In Figure 15, Schafer, et al. (1979) showed that this area of Zone II is a transition zone from NE-SW stress domain to NW-SE stress domain and that epicenters are clustered at that area. It is likely that there is a stress concentration along this transition zone that is responsible for

[1]This station is the Bergen Park Station at Golden, Colorado, and is designated GOL by the Worldwide Network of Seismograph Stations (WWNSS).

this high activity and large magnitude. Several earthquakes are known to have occurred in and offshore of Libya at the eastern part of the Sirte Basin, the epicenters of which suggest that the faults marking this margin of the basin (counterparts to the Hun graben at the western) may still be active. Figure 14 shows that some earthquakes occurring in this margin have magnitudes greater than 5. Existing and suggested faults are shown in Figure 13. The recognition of the mentioned active faults at the western and eastern margins of the basin supports the hypothesis that the basin is still undergoing subsidence (Campbell, 1968). Campbell (1968) also noted that the volcanic sea mounts shown on Figure 11 are aligned with eastern margin of the basin and may be interpreted as counterparts to volcanic extrusions such as Jabal al Sawda and al-Haruj at the western margin.

## 2.2 Frequency-Energy Distribution of Earthquakes

After the Alaskan earthquake of March 28, 1964, with its accompanying damage to buildings in the city of Anchorage, an interest in the study of regional seismicity was initiated. Until 1957 the seismicity of the Anchorage area was underestimated (Algermissen, 1966). The damage in 1964, due to this underestimation, was a painful lesson. The seismicity of various regions should be reevaluated from time to time in the light of accumulating data. In particular, the impression has been that the seismicity of Libya is low. A survey of the world-wide data for the period 1961-1967 (Barazangi and Dorman, 1969) showed Libya as a region of almost no seismicity. This sruvey, carried out over a short period of time, gives an impression that has only little relation to reality. A survey extending a longer period is attempted here to arrive at an estimate of the rate of seismic activity in Libya.

In discussing the seismic activity of a region, usually the first topic comes to mind is destructive earthquakes. This in turn consists of two parts: The possibility of a major destructive earthquake occurring in that region and the probability of a major earthquake occurring during an arbitrarily chosen time interval. The first point can easily be settled if, from historical data, it can be definitely shown that at least one major earthquake has occurred in that region. Once the possibility of the occurrences of a major earthquake is established, the estimate of probability of a major earthquake in that region can be concluded from the recurrence frequency of smaller magnitudes during an arbitrary time interval.

One of the basic laws of nature is that events are repetitive and not unique, e.g., similar events will occur under identical conditions.

Accordingly, one can say that if a large earthquake has occurred in a given region, another similar earthquake is very likely to occur even though the time intervals between such events may vary widely.

Historical seismicity records are usually inadequate as mentioned previously. The recurrence interval of large earthquakes in a given region is generally larger than the time period for which a data base is established. Nevertheless, the possibility of major destructive earthquakes in Libya is a high one. The earthquake of 1935 previously mentioned (Zone II, Figure 13) had a magnitude of > 7 and is considered to be one of the few large earthquakes ever recorded in Africa.

No earthquake information is available about this zone before 1900 A.D. mainly due to very low population and limited communication.

In Zone I, the city of Cyrene and nearby towns were destroyed by large earthquakes at least twice during the third and fourth centuries. Since 1900 this zone was hit by many shocks of magnitude > 6. The horizontal stress reversal area where the value of the compressional stress is highest in the country, together with the fact that the Mediterranean ridge is only a hundred kilometers offshore make this zone more active than believed and increase the possibility of large earthquakes. In Zone III, where activity is lowest of all zones, large earthquakes have occurred many times during the period of investigation, the most important of which is the great 1183 shock by which Tripoli was demolished. Due to scarcity of information and descriptions, intensities could not be assigned to these events, but Kebeasy (1978) considers the 1183 shock to have had a magnitude of 8 or greater. The fact that damage was found to occur in an abnormally large area around the epicenter adds to high possibility of a destructive earthquake. This fact is mainly due to small attenuation of earthquake waves in the whole northeastern Africa (Kebeasy, 1971). Lastly, even in the aseismic zone of the southern part of the country, the reported earthquake had caused many towns to be destroyed and it is considered to have had a large magnitude. Because geological conditions have not changed since then, a recurrence of such earthquakes is to be expected. Hence, the possibility of a major, destructive earthquake in or near by Libya has been established.

### 2.2.1 Recurrence-Magnitude Distribution

In seismology, frequency-magnitude relations give the frequency of occurrence of earthquakes of given magnitudes. Such relation also bears the term recurrence relations for the reason that they permit an immediate information on recurrence periods, i.e., average time intervals between earthquakes of given magnitudes. A short discussion is presented here to make a note on the known statistical law regarding earthquakes.

It has been shown empirically (Richter, 1958) that the number N of earthquakes during an arbitrary interval of time in a given seismic region is related to magnitude M by

$$\text{Log } N = A - bM$$

where $A$ = coefficient varies with duration of time of data, geographical region and the choice of $\Delta M$ used to plot the distribution, and

$b$ = slope

Gutenberg and Richter (1954) and numerous subsequent studies showed that the number N(M) of earthquakes with magnitudes greater than or equal to a given value M, obeys a relation of the form

$$\text{Log } N(M) = A - bM \ .$$

This is called the cumulative frequency in which the values of the coefficients a and b to be determined from the data. The values of a and b vary from investigation and usually they are determined by the least squares method. The use of the cumulative plotting and fitting will partly overcome the unwanted effect of empty intervals and large scatter of data. From a set of data for N earthquakes with M magnitude determined for each earthquake, the arbitrary choice of the internals of M is very important (Bath, 1978). Clearly, when N is small we cannot divide M into very small intervals. Tsuboi (1951), for example, considered 1025 earthquakes with magnitudes larger than 3.7 and subdivided them into intervals of $\Delta M = 0.1$. His data showed scatter for magnitudes larger than 7.5. Since earthquakes of such magnitudes are few in number and since the magnitude determinations in that range are subject to error or $\pm$ 0.3 or more, it might be quite meaningless to subdivide data into small intervals of $\Delta M = 0.1$.

The value of a varies with the duration of time of data, geographical location, and choice of $\Delta M$. The value of b, however, is relatively uniform. Considering data gathered worldwide, Gutenberg and Richter (1954) give the following:

| | |
|---|---|
| Shallow shocks | $b = 0.90 \pm 0.02$ |
| Intermediate shocks | $b = 1.2 \pm 0.2$ |
| Deep shocks | $b = 1.2 \pm 0.2$ |

Isacks and Oliver (1964) have tabulated 45 cases of determinations that have been made by various authors of the value of b. All determination gave values of b between 0.45 and 1.4, of the 45 cases, 33 gave values between 0.8 and 1.2.

For a better statistical analysis, using the available data, magnitudes and depths should be recalculated, since values given are determined by different sources using different methods. This has not been done here as the available information is not sufficient to do so. Due to this limitation and the fact that many earthquakes have no assigned magnitude of depth and sometimes the data file has long periods empty of information, the data to be used in the following analysis will use only those of the period from 1962 to 1981 which are obtained from the same source using the same method. A similar recurrence graph drawn for Libyan earthquakes is shown in Figure 16. This analysis was carried out by Kebeasy (1979) who used the same data file, for the period from 1940 to 1981 which has a gap of 7 years with no assigned magnitudes. "The gap in data does affect the values of the recurrence-magnitude distributions, but not the shape of the distribution curve" (Furumoto, 1966). The b value obtained by Kebeasy (1979) is an unusually low value.

For fitting the data to the equation by least squares method, the unit interval of M must be properly chosen. Trial calculations were done with four separate unit intervals of M, $\Delta M=0.1$, $\Delta M=0.2$, $\Delta M=0.3$ and $\Delta M=0.5$ and standard deviations of coefficients and of log N(M)/M were calculated for all four sets. The results are given in Table 6. The results indicate that scatter will be reduced by using unit intervals of $\Delta M=0.1$.

Table 6. Standard deviations of log N(M)/M and coefficient b for various intervals ΔM, using all data.

| ΔM | 0.1 | 0.2 | 0.3 | 0.5 |
|---|---|---|---|---|
| Stand. dev. of Log N(M)/M | 0.158 | 0.165 | 0.17 | 0.251 |
| S and. dev. of b | 0.105 | 0.156 | 0.179 | 0.224 |

The distribution of earthquakes for ΔM=0.1 is given in Figure 17. The results of fitting the distribution to log N(M) = A-bM by least squares method, using all the data available between 1963 and 1982, gave

$$\log N(M) = (6.73 - 1.06\ M) \pm 0.158 \qquad (1)$$

Frequencies of occurrence of earthquakes of different magnitudes for the period from 1963 to 1982 were calculated using equation 1. These frequencies were also extrapolated to a period of 80 years, which covers all the data we have in the data file. A comparison between those frequencies and the actual observed frequency is given in Table 7.

Since the analysis considered only earthquakes occurring during 1963 to 1982 the calculated frequencies are in very good agreement with observed frequencies during the same period. However, when these calculated frequencies were extrapolated to a longer period (80 years) the discrepancy increased largely. This discrepancy can be related to the fact that most of the recorded earthquakes before 1963 had relatively large magnitudes, i.e., greater than or equal to 5.0 and those after 1963 had smaller magnitudes, i.e., smaller than 5.0. This

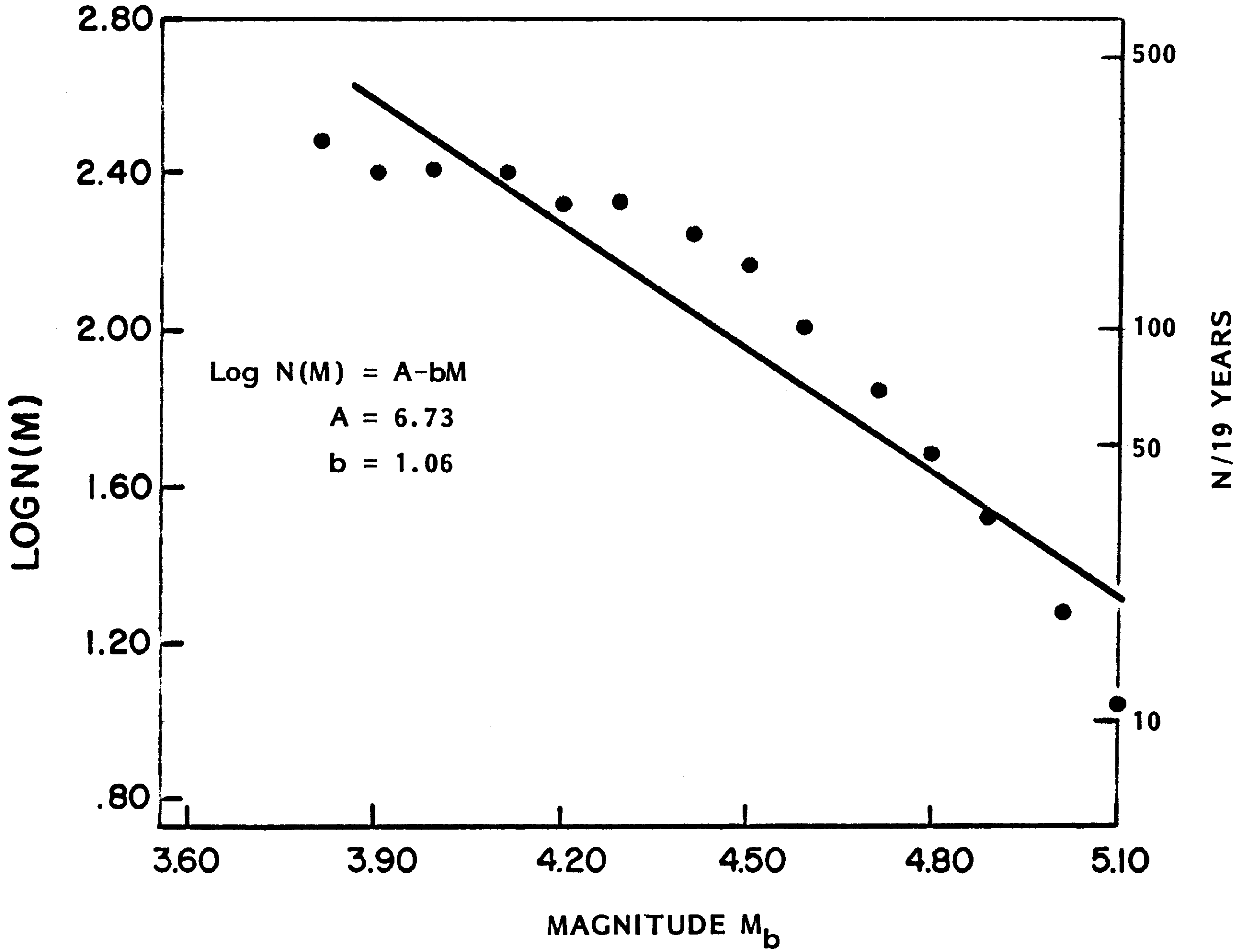
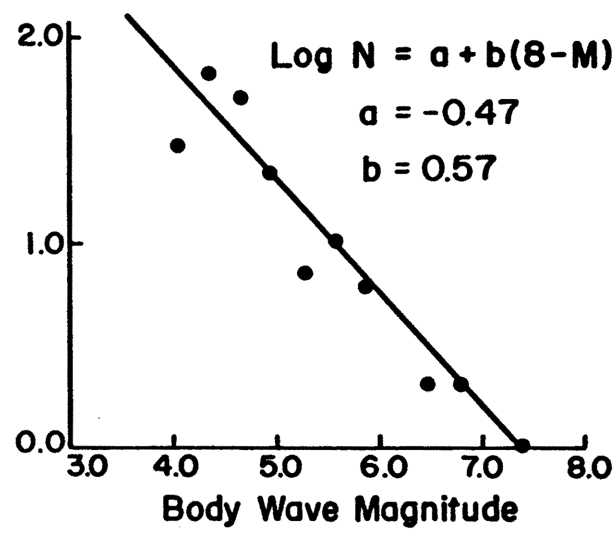



Figure 17. Cumulative frequency vs. body wave magnitude.

Table 7. Calculated and observed frequencies.

| Magnitude | Cal. number in 19 year period | Cal. number in 80 year period | Cal. number per one year | Observed number in 80 year period | Observed number per one year | |
|---|---|---|---|---|---|---|
| | | | | | based on data 1903-1982 | based on data 1963-1982 |
| ≥ 2[1] | 40000 | | 2200 | | | |
| ≥ 3[1] | 3550 | | 185 | | | |
| ≥ 4 | 310 | 1300 | 16.3 | 446 | 5.6 | 14.3 |
| ≥ 5 | 27 | 113 | 1.42 | 135 | 1.72 | 1.52 |
| ≥ 6 | 2.35 | 10 | 0.13 | 22 | 0.3 | 0.1 |
| ≥ 7 | 0.2 | 0.9 | 0.011 | 1 | 0.037 | 0 |

[1]Earthquakes of magnitude less than or equal to 3.0 are not recorded in Libya and so their calculated frequency cannot be compared or checked.




Observed frequency of earthquake occurrences during the past forty years.

| Magnitude | Cal. No. /year | Obs. No. /year |
|---|---|---|
| 2 | 28.00 | 0.00 |
| 3 | 7.50 | 0.17 |
| 4 | 2.00 | 10.10 |
| 5 | 0.52 | 1.00 |
| 6 | 0.14 | 0.17 |
| 7 | 0.04 | 0.025 |

The calculated and observed frequency of earthquakes.

Figure 16. Results obtained by Kebeasy (Kebeasy, 1978).

also shows that linear extrapolation based only on statistics can be totally misleading. It is interesting, however, to note that equation 1, in spite of all the mentioned limitations, successfully predicted the occurrence of earthquakes having magnitudes greater than or equal to 7.0 when extrapolated to 80-year period.

The results of fitting the distribution to log N(M) = A-bM by least squares method using only earthquakes of magnitude greater than or equal to 4.5 gave

$$\text{Log } N(M) = (10.3 - 1.8\ M) \pm 0.0465 \qquad (2)$$

Calculated frequencies obtained using equation 2 showed that this equation excessively underestimates the frequency of occurrence of earthquakes of magnitude greater than or equal to 5.0. While the b value obtained by equation 2 is considered to be too high, the b value obtained by Kebeasy (1978) is using single frequency distribution (Figure 16) is considered to be too small.

The data used in the analysis cover a relatively short period of time. Also, the analysis included all the reported earthquakes, irrespective of the location of epicenters. Therefore, trial analyses were made by grouping earthquakes according to the different seismic zones. The number in such grouping was too small to justify statistical treatment.

### 2.2.2 Strain Release

Benioff (1951) has shown that elastic strain release is proportional to the square root of J, the seismic wave energy of an earthquake. For plotting strain release, the energy of J in an earthquake is obtained by (Benioff, 1955)

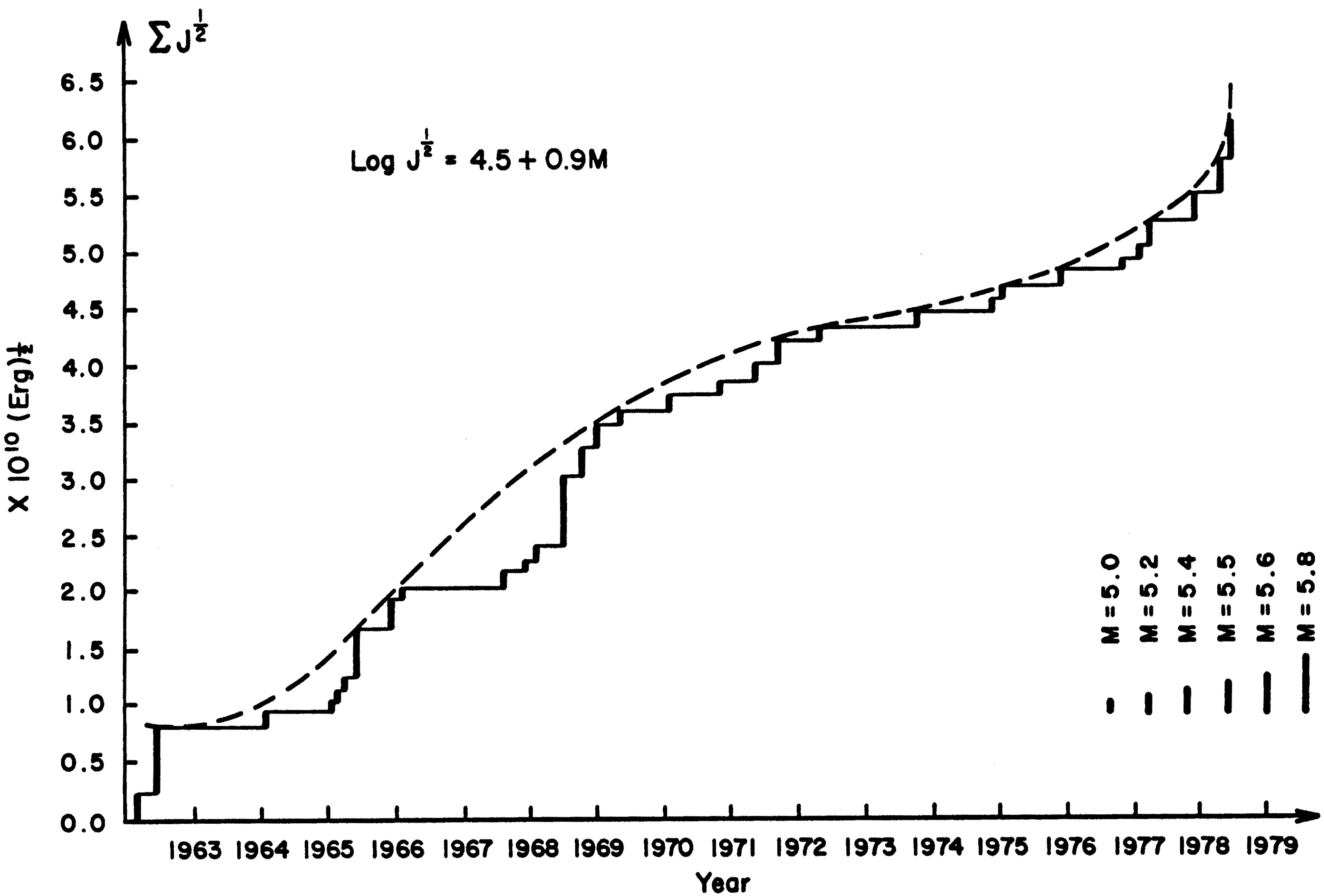
$$\log J = 9 + 1.8M \tag{3}$$

where M is the magnitude of earthquake. Then the cumulative value of $J^{\frac{1}{2}}$ is plotted against time. The magnitude-energy relation is now

$$\log J^{\frac{1}{2}} = 4.5 + 0.9M \; . \tag{4}$$

Figure 18 shows the graph obtained when the cumulative strain release of $J^{\frac{1}{2}}$ is plotted for Libyan earthquakes. For the same reasons mentioned earlier, only the data from 1963 to 1981 were used. The plot is for shallow earthquakes of magnitudes $\geq 5$. When magnitudes $<5$ were used, the shape of the curve remained almost the same. The graph shows intervals of high seismicity and large cumulative strain release separated by intervals of lower seismicity up to 1969. The increasing rate of strain release tapers off in the late 1960's. Activity increases again during 1978. It seems that the period 1969-1975 marked a transition zone between two distinct periods of high seismic activity. Since magnitudes used to plot this curve were only $\geq 5$, the increasing rate of activity indicated by the general shape of the curve is due to actual increase in the activity of the area and not because of the increase in number and sensitivity of the Worldwide Standardized Seismograph Station Network.

Figure 18. Strain release curve.



ΣJ^(1/2)
X 10^10 (Erg)^(1/2)
Log J^(1/2) = 4.5 + 0.9M
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
1963 1964 1965 1966 1967 1968 1969 1970 1971 1972 1973 1974 1975 1976 1977 1978 1979
Year
M = 5.0
M = 5.2
M = 5.4
M = 5.5
M = 5.6
M = 5.8

## 3. SEISMIC HAZARDS AND IMPLICATIONS FOR LAND USE

Several geologic phenomena associated with earthquakes can cause severe damage to man-made structures and may result in loss of human lives.

When a fault moves, the resulting rock rupture may propagate upward and displace the ground surface. Displacement may be in horizontal or vertical directions and may occur rapidly or slowly. Rapid faulting occurs during major earthquakes, but slow movement, called creep may gradually occur over a long period of time and may be associated with microearthquakes. The amount of displacement that may occur during an individual earthquake varies from less than a few centimeters to over several meters. There is a general correlation between fault length and displacement per event. Long faults often have greater displacement and may generate long duration earthquakes. Worldwide, the maximum recorded surface rupture for a single earthquake is 12.8 m of vertical displacement (Bonilla, 1970).

Surface faulting can severely aftect man-made structures by offsetting foundations, roads, utility lines, etc. The simplest way to minimize hazards due to surface faulting is to completely avoid construction on/or across active faults. However, where this is not possible special design may minimize the damage. In Libya, however, the existing data on the location of active faults is too limited to adequately outline all zones where surface faulting may occur.

Detailed, site-specific fault investigations should be a part of design and construction stages for all critical structures such as dams and industrial plants.

Other types of ground failure that commonly occur during earthquakes include landslides, rockfalls, differential settlements due to compaction and liquefaction. Several of these phenomena often occur naturally or by man's activities without any earthquake influence.

From these mentioned phenomena, liquefaction is the least expected to occur in Libya, as the favorable conditions for liquefaction exist in very limited areas. In the city of Benghazi (Zone I), for example, the soil conditions in many places are very susceptible to liquefaction. But, no such occurrence is known to have had happened. However, if this is true, the main reasons would be that it was not reported or that no earthquakes large enough to cause liquefaction have occurred in the area. Again, it should be mentioned that, up to the last few years, Libya existed in a situation such that the occurrence of such phenomena could not be investigated and reported.

Another liquefaction susceptible area occurs to the northwest of the Hun graben at about 50 km from its northern end. It is called Tauorga Secbkha, and again no liquefaction is known to have been reported, probably for the same above mentioned reasons.

Liquefaction is defined as the point when the pore water pressure reaches the confining stress and the shear strength becomes very small (Charlie and Wardwell, 1978). Liquefaction of saturated sands has been reported in many earthquakes; good summary of these cases is given by Seed (1970).

It is recommended that, in areas where water table is high and soil is cohesionless, liquefaction potential be investigated and calculated. Soil type, degree of saturation, initial relative density, initial effective stress, intensity of ground shaking and its duration, initial shear stress, and pore water pressure have shown significant effect on the liquefaction potential of a given site.

Man-made structures are particularly susceptible to earthquakes if the seismic waves have frequencies that coincide with the resonant frequencies of structures. Resonant frequencies typically range from a tenth of a hertz for large structures such as the Empire State Building to 30 hertz or even higher for small structures such as systems of pipes in an industrial plant (Boore, 1977). All buildings as we know are capable of withstanding large vertical forces (at least 1.0 g, or the force exerted on them by the earth gravity) but special precautions must be followed to ensure adequate resistance to large horizontal forces since the largest ground motions are usually in the horizontal direction.

Factors that influence the frequency and the degree of ground shaking include the actual energy released by an earthquake, proximity of the site to the source of energy release and local rock and soil characteristics. Intensity of ground shaking for a particular earthquake is especially dependent on the local rock and soil characteristics. The influence of local soil conditions under strong shaking is shown in Figure 19, which shows that the strong motion is considerably attenuated. This attenuation is due in large measure to the higher damping characteristics of the soft soil under large strain amplitude (Seed, 1969).

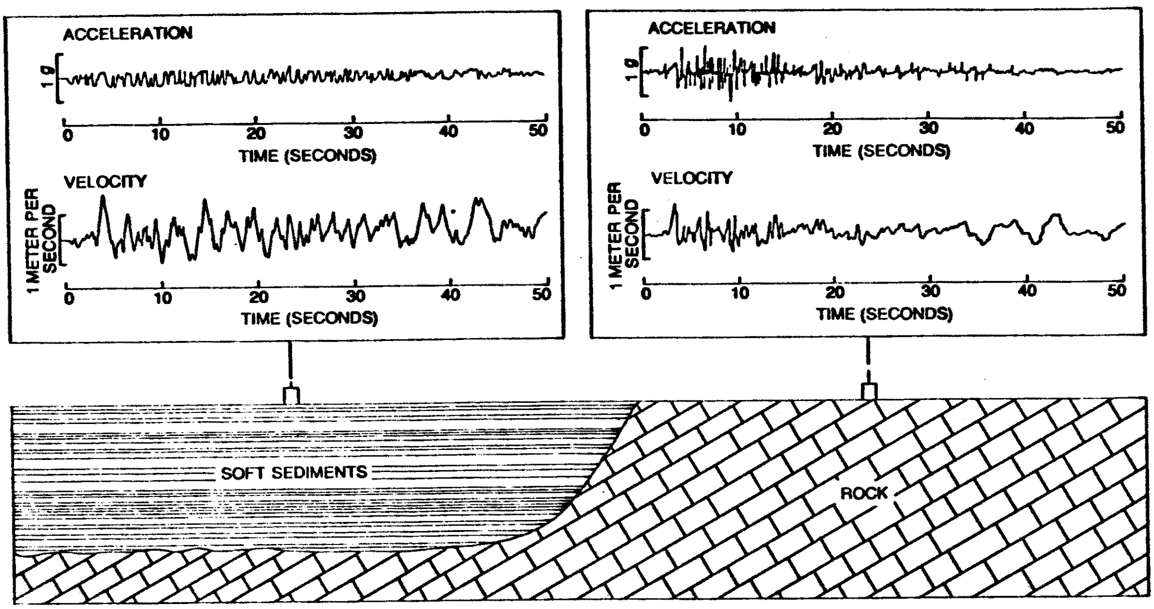



Figure 19. Effects of local site conditions on shaking intensity and frequency of ground motion for sites subjected to <u>strong ground shaking</u>.

When soft soils are subjected to strong shaking from a nearby earthquake, accelerations can actually be attenuated. Above seismograms show that:

soft ground peak acceleration $< 0.5$ g,

and rock peak acceleration $\cong 1.0$ g.

This important effect of local soil conditions on the intensity of shaking fundamental frequency and the resulting building damage was first noted by Wood in his study of the damage caused by the 1906 San Francisco earthquake (Seed and Idriss, 1969). Then, with increased availability of seismograph records and analytical capability, the potential influence of this factors has been more clearly demonstrated in more recent earthquakes.

In the 1957 San Francisco earthquake, recording of ground motions were made at several locations within the city underlain by varying soil conditions. Computations based on these recorded motions show that the maximum base shear for a 10-stories building located at each of these stations would vary by several hundred percent from a low value of about 200 kips for sites underlain by rock to value as high as 900 kips for a site underlain about 300 feet of clay and sand (Seed and Idriss, 1969). Similar examples from recent earthquakes are given by Idriss (1978).

Preliminary studies carried out by Minami and reported by Campbell (1968) indicated that the Barce earthquake of 1963 was no exception and structural damage to low stiff structures was greater where soil depths were relatively low. Damage to other types of structures also seemed to have been related to soil conditions.

In view of the fact that both theory and experience show potentially large significance of these effects, it seems desirable that building codes requirements for lateral force coefficients should reflect the influence of local soil conditions on building response, and that all design engineers should give careful consideration to the effect of local soil conditions on earthquake damage potential for different buildings in different local areas. Until more research and work is done to prepare a local building code for Libya, which will include such effects, it is recommended as a minimum first step, that consideration be given to introduce special requirement for structures exceeding about eight stories in height and underlain by deep soil deposits.

## 4. RECOMMENDATIONS

Strong-motion instruments should be installed in Libya to provide data about the intensity and character of the shocks experienced, and research in the effects of local geology upon the ground movements should be undertaken. It is desirable that earthquakes should be recorded by many stations, both near to and far away from the epicenter. Stations close to epicenters are very important in studying weaker aftershocks and assisting in the determination of the focal depths, while distant stations permit the determination of the epicenters without errors due to local crustal conditions. The recommendations of the UNESCO Seismological Survey Mission to Africa are that the distance between stations of the teleseismic net should be in the order of 1000 km and that for local stations should be not more than 300 to 500 km depending upon local geology and sensitivity of the instruments (UNESCO, 1964).

It is urged by the author that at least one teleseismic station be established in Libya. Detailed site testing and geologic study must be done prior to the establishment of the station. It is also necessary to establish a local network of recording stations throughout the three different zones shown in Figure 13, enabling all earthquakes of magnitude 5 and above to be recorded (such earthquakes are strong enough to cause localized damage). At the same time, the work should be accompanied by geological and geomorphological studies of all major tectonic patterns. A special study should be carried out on the Hun graben area. In addition to this, more detailed studies of local seismicity are needed, to an extent which varies with the seismicity and development in the different zones.

The government of Libya should take steps to ensure that building regulations are adequate to prevent damage caused by earthquake shocks. Seismic coefficients for horizontal accelerations suggested by Mallik (1977) given in Figure 20 are recommended for use in design. Gradually, as new geologic data become available, these values may be changed and the probable seismic danger may be reduced for some parts of the country.

In its report, the UNESCO Seismological Survey Mission to Africa (1964) also suggested that each country has some responsibilities which may, in part, be carried out by the various interested organizations but which should be coordinated by a central agency. These responsibilities, which are also strongly recommended to be undertaken, are quoted below:

1. Collection of all historical data concerning earthquakes in the country, and preparation of a critical catalogue.
2. Organization of a system of reporting the occurrence and intensity of felt earthquakes, and the compilation of lists and isoseismal maps.
3. Collection and custody of the instrumental records of the stations of the network, and the preparation of definitive interpretations.

4. Preparation and publication of standard bulletins containing the information compiled.
5. Determination of epicenters, magnitudes, and other data concerning earthquakes within the territory, and their publication.
6. The calibration and maintenance of the stations of the network.
7. The rapid interchange of data with other countries, and the forwarding of information to the international centers.
8. Participation in specialized warning services (e.g., tsunami, volcanics, storms, etc.).
9. The training of technicians and observers.

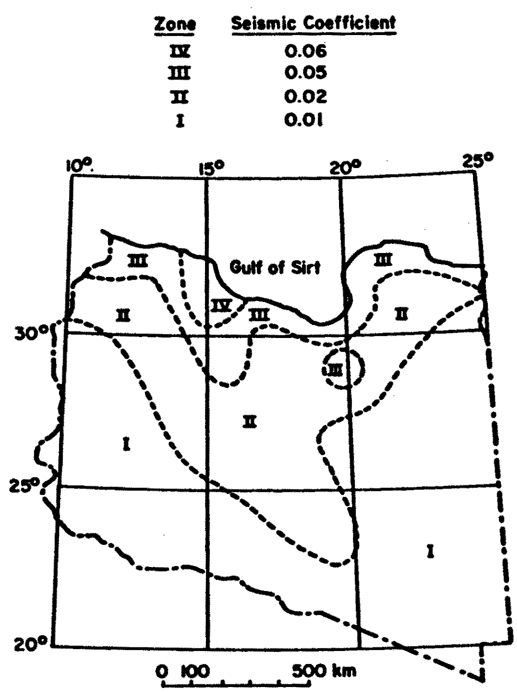



Figure 20. Seismic zones of Libya (from Mallick, 1977).

## 5. SUMMARY AND CONCLUSIONS

Data of earthquakes which have occurred in and around Libya in the period from 262 A.D. to 1982 have been gathered from several sources. These data, together with geophysical and geological information, have been used to investigate the earthquake activities and their relationship to tectonic movements in the country. The whole country is characterized by a low to moderate level of seismic activity, but some segments have experienced large earthquakes in this century and in the past. Based on this investigation, the seismicity of Libya is summarized on the map of Figure 21. On the basis of observed and expected seismicity, a four-fold subdivision was made: (1) areas of low earthquake probability, (2) areas where earthquakes are expected to have a magnitude $<4$, (3) areas where earthquakes are expected to have a magnitude $4 \leq M < 6$, and (4) areas where earthquakes are expected to have a magnitude $\geq 6$.

The seismicity of the country studied can in general be associated with various tectonic features discussed previously. The major patterns, either confirmed or identified in this study, are as follows. The seismic activity in Libya is concentrated in the central Hun graben and Cyrenaica. The locations of epicenters in Cyrenacia (northeastern coast region) match fairly well the interpretation of this region as a zone associated with the collisional boundary between Africa and Eurasia.

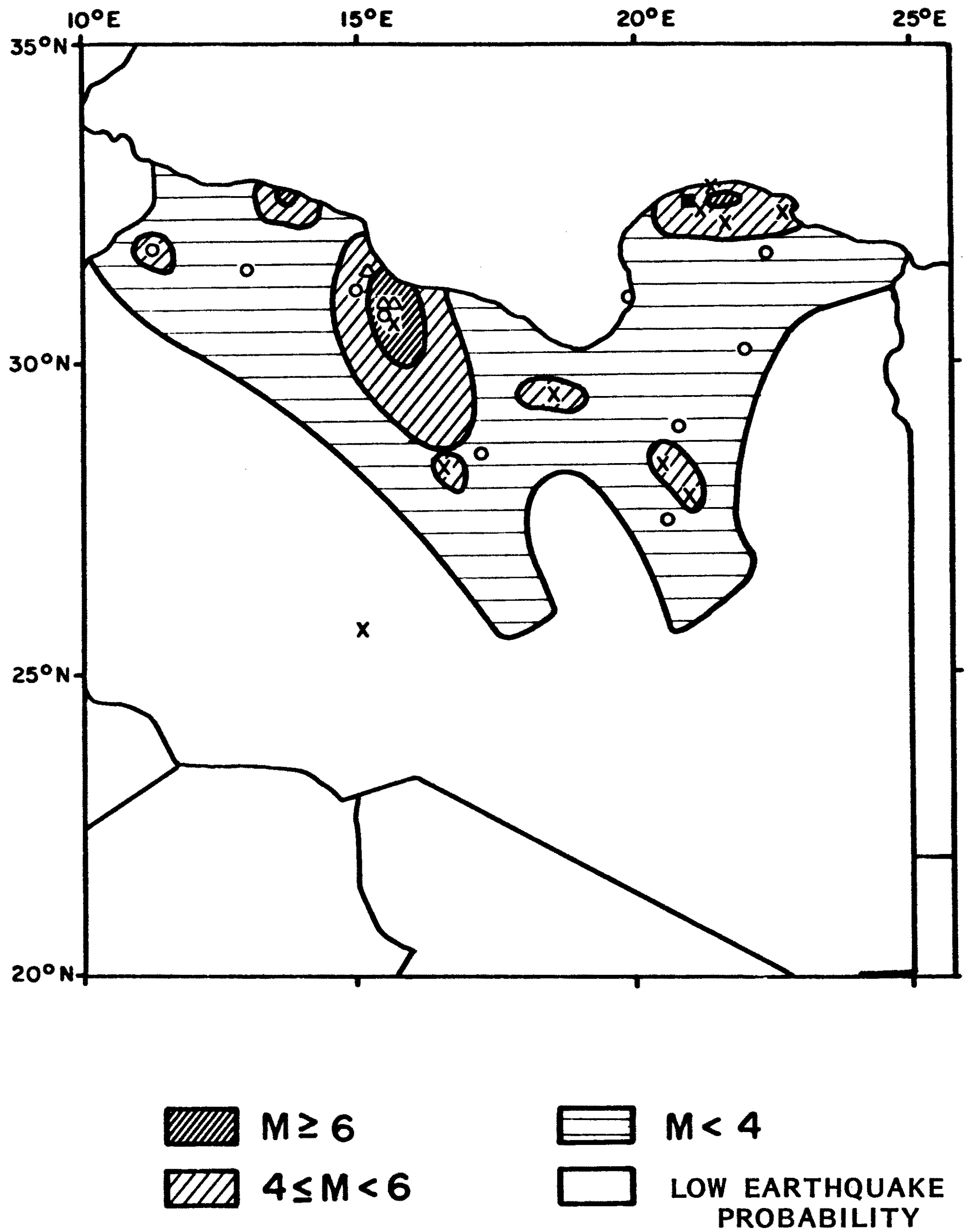



Figure 21. Seismicity of Libya.

The Hun graben is considered to be seismically active along its full length. Some segments, however, have ruptured in large magnitude earthquakes. One segment located at Al-Qaddahia (100 Km. south of Misurata) ruptured during the large 1935 earthquake (M = 7.1).

The northwestern coast of Libya is characterized by a general low level of activity, but was the site of at least one large earthquake. The southern half of the country is considered to be seismically stable but also it was the site of one large earthquake (the large 704 A.D. earthquake which destroyed the whole Fezzan area).

An evaluation of the seismicity of the country was obtained by constructing the magnitude-recurrence curve using the data for the period from 1963 to 1981 (best quality data) and it was found that both observed and calculated frequencies of occurrences of shallow earthquakes were consistent with each other. Unfortunately, the only usable earthquake data for this country are those available from the U.S. National Geophysical and Solar-Terrestrial Data Center (NOAA, 1982), which are limited in number, quality and in the time period covered. It is therefore essential that all epicenters and focal depths be recalculated to be able to carry out a good quality seismostatistical analyses.

For Libya, analyses and mapping based on observed intensities cannot be applied to advantage. The reason is that intensities are not enough representative due to location of parts of the earthquakes zones in the sea or in thinly populated regions. Therefore, it is proposed that all maps and analyses be based on instrumental data, which are free from the mentioned shortcomings.

Damage due to earthquakes is found to cover an abnormally large area around the epicenters, a fact that is attributed mainly to the small attenuation of seismic waves found generally in North Africa, as explained by Kebeasy (1971). Also, the effect of different soil conditions on the type and amount of damage was clearly demonstrated by the Barce earthquake of 1963, which showed that Libya is no exception, e.g., stiff farmhouses were destroyed on places where soil had very low depth, and were slightly cracked where soil deposits had a large depth to the rock surface.

It should be emphasized that the findings presented here are of a preliminary nature. Determination of seismicity is an extremely complex undertaking that must incorporate a thorough knowledge of both historic earthquake and geological evidence of recent fault activity. Available fault information in Libya is very limited, and earthquake history by itself is not adequate for predication purposes. The most significant limitation any seismicity study will face is the absence of seismic monitoring of the country. This problem will continue to hinder any effort to define and predict seismicity until enough number of precisely located seismographs are in full-time operation throughout the country.

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# APPENDICES

# APPENDIX A

## INTENSITY OF EARTHQUAKES

Intensity is measured by means of the degree of damage to the works of man, the amount of disturbance to the surface of the ground and the extent of animal reaction to the shaking.

Mercalli, in 1902, constructed his first scale with 10 grades of intensity, which he later expanded to 12 grades. This form was in turn used as a basis for the modified Mercalli Scale of 1931 (commonly abbreviated M.M.) by H. O. Wood and Frank Neumann (Wood and Neumann, 1931). The M.M. Scale was developed to fit the construction conditions in California.

This way of scaling earthquakes is still important for two reasons. The first is that in widely scattered seismic regions there is no seismograph to measure strong ground motion, and the second is that the long historic records are founded on such descriptions.

One problem is that this method can affect the accuracy of the intensity rating, since at a particular town or place, usually the effect reflecting the greatest intensity is chosen, thus increasing the local rating of the shock. Another difficulty is that landslides are common in many regions, even in the aseismic ones. These landslides can be triggered sometimes by very small shocks. Since the Mercalli Scale gives landslides a rating of intensity (X), it might be quite misleading.

| MODIFIED MERCALLI INTENSITY SCALE | GEOFIAN INTENSITY SCALE (RUSSIA) | JAPANESE INTENSITY SCALE |
|---|---|---|
| I Not felt. Marginal and long-period effects of large earthquakes. | I Oscillations of the ground are detected only with instruments.<br>II In individual cases felt only by sensitive persons at rest. | 0 Not felt by humans, registered only by seismographs.<br>I Slight: felt only feebly by persons at rest or by those who are especially observant of earthquakes. |
| II Felt by persons at rest, on upper floors, or favorably placed. | III Oscillations felt by few persons. | |
| III Felt indoors. Hanging objects swing. Vibration like passing of light trucks. Duration estimated. May not be recognized as an earthquake. | IV Noted by many persons. Windows or doors may rattle. | |
| IV Hanging objects swing. Vibration like passing of heavy trucks. Standing motor cars rock. Windows, dishes, doors rattle. Glasses clink. In upper range of IV wooden walls and frame creak. | | II Weak: felt by most persons; slight shaking of windows and Japanese latticed sliding doors. |
| V Felt outdoors; direction estimated. Sleepers wakened. Liquids disturbed. Doors swing. Shutters, pictures move. Pendulum clocks stop, start, change rate. | V Objects swing, floors squeak, glasses rattle, outer plaster crumbles. | III Moderately strong: buildings shake, windows and doors rattle, hanging objects swing, some pendulum clocks stop; some people run outside. |
| VI Felt by all. Many frightened and run outdoors. Persons walk unsteadily. Windows, dishes, glassware broken. Books off shelves. Pictures off walls. Furniture moved or overturned. Weak plaster and adobe cracked. Small bells ring. | VI Light damage to buildings: thin cracks in plaster, cracks in tile furnaces, etc. | IV Strong: strong shaking of buildings, objects overturn, liquids spill out of vessels. |
| VII Difficult to stand. Noticed by drivers of motor cars. Fall of plaster, loose bricks, tiles, etc. Some cracks in masonry. Waves on ponds; water turbid. Small slides, caving of sand or gravel banks. Large bells ring. Concrete irrigation ditches damaged. | VII Considerable damage to buildings: thin cracks in plaster and falling of individual pieces, thin cracks in walls. | V Very strong: brick and plaster walls crack, stone lanterns, gravestones and similar objects overturn, chimneys and mud-and-plaster warehouses damaged, landslides in steep mountains. |
| VIII Steering of motor cars affected. Damage to masonry; some partial collapse. Twisting, fall of chimneys, monuments, elevated tanks. Frame houses moved if not bolted down. Branches broken. Changes in springs and wells. Cracks in wet ground and on steep slopes. | VIII Damage in buildings: large cracks in walls, falling of cornices or chimneys. | |
| IX General panic. Weak masonry destroyed, good masonry seriously damaged. Frame structures, if not bolted, shifted off foundations. Frames racked. Serious damage to reservoirs. Underground pipes broken. Ground cracked, sand and mud ejected, earthquake fountains, sand craters. | IX Collapse of some buildings; destruction of walls, roofs, floors; landslips. | VI Disastrous: destruction of 1-30 percent of Japanese wooden houses; large landslides, fissures in flat ground and low fields accompanied by mud and waterspouts. |
| X Most masonry and frame structures destroyed with their foundations. Serious damage to embankments. Large landslides. Water thrown on banks of canals, rivers, lakes, etc. Rails bent slightly. | X Collapse of many buildings; fissures in ground about 1 meter wide. | |
| XI Rails bent greatly. Underground pipelines completely out of service. | XI Numerous fissures, large landslides in mountains. | VII Ruinous: destruction of more than 30 percent of the houses; large landslides, fissures, and fault movements. |
| XII Damage nearly total. Large rock masses displaced. Lines of sight and level distorted. Objects thrown into the air. | XII Large scale change in relief. | |

Figure A. Comparison of the modified Mercalli, the Geoffian, and the Japanese intensity scales (after Barosh, 1969 and Krinitsky, and Chang, 1975).

# APPENDIX B

## EARTHQUAKE MAGNITUDE AND ENERGY

If magnitude is to be compared worldwide, it should not depend on, as does intensity, density of population, type of construction, etc. This scale also should be applicable in both inhabited and uninhabited areas.

Richter (1935) defined a local magnitude of earthquakes as the logarithm to base 10 of the maximum seismic wave amplitude (in thousands of millimeters) recorded on a standard seismograph at a distance of 100 kilometers from the earthquake epicenter. This means that every time the magnitude goes up by one unit, the amplitude of the earthquake wave increases 10 times. The type of wave was not specified and later Richter modified his seismograph to account for distances other than 100 kilometers.

It follows from its definition that the magnitude scale has no upper or lower limits, but it is certainly limited on both sides, since it is necessary to have a certain amount of energy released to have an earthquake. This limits the lower end and the upper end is limited by the strength of the rocks of the earth's crust. Generally speaking, shallow earthquakes have to attain a magnitude of 5.5 or more before significant damage occurs near the epicenter. It is common practice now to measure the amplitude of P-wave and largest amplitude of the surface waves that has a period near 20 seconds. These two values given the body wave magnitude ($m_b$) and the surface wave magnitude ($M_s$), neither of which is the original Richter magnitude.

Magnitude is evidently related to that energy which is radiated from the earthquake source. Part of the original potential energy of strain stored in the rock must go into mechanical work, as in raising crustal blocks against gravity or in crushing material in the fault zone and part must be dissipated as heat (Richter, 1958).

The work done in displacing crustal blocks during the California earthquake of 1906 was estimated by Reid to be $1.75 \times 10^{24}$ ergs (Bolt, 1978). Energy released from a number of earthquakes have been estimated from seismographs as it is well established that there is a relatively little material absorption of the seismic wave after leaving the neighborhood of the foci (Richter, 1958). And so, the energy in the moving wave front (which can be estimated from the recorded amplitude and periods) represents most of the energy radiated (Bath, 1955).

"Energy in elastic wave of given period is proportional to the square of the amplitude. If seismograms of different earthquakes at a fixed distance actually differed only in amplitude, the periods would be unchanged and we should have" (Richter, 1958).

$$\log E = c + 2M$$

where E is the energy released

c is a constant

M is the earthquake magnitude

Many equations of the same form were obtained by different researchers. Gutenberg and Richter in 1955 came up with the following equation which is the most used one and works by others give close values, this equation is

$$\log E = 11.4 + 1.5M_s \text{ Ergs.}$$

where $M_s$ is the surface wave magnitude,

and $E$ is the energy released in Ergs

$$1 \text{ erg} = 1 \text{ dyne centimeter} = 7.376 \times 10^{-8} \text{ ft. lbs.}$$

This logarithmic relation indicates that an increase in magnitude of one unit increases the amount of seismic energy E by a factor of about 30.

## APPENDIX C

## EARTHQUAKE $m_b$ vs $M_s$ RELATION

The first earthquake magnitude scale was formulated by Richter for Southern California, where the bodywave magnitudes were determined using the standard Wood-Anderson seismographs. Later, the same scale was extended for distances up to 600 km. However, it was difficult to use this technique for distances larger than 600 km and so, surface wave (of about 20 seconds-period) were used instead. It was noted by Gutenberg and Richter that the difference between $m_b$ (bodywave magnitude) and $M_s$ (surface wave magnitude) is a function of magnitude and they found the following relationship

$$M_s = 1.59\, m_b - 3.97 \qquad (1)$$

This relationship was established for events recorded in California. According to this relation, $m_b = M_s$ at 6.57. For values larger than 6.57, $M_s > m_b$ and for values lower than 6.57, $M_s < m_b$ . A number of relationships between $M_s$ and $m_b$ were found by many other workers.

One of the major factors affecting the variation in $M_s$ and $m_b$ relation has been the different types of instruments used all over the world in their determination. This factor is largely overcome in the CGS (Coast and Geodetic Survey) magnitude determinations after the establishment of the WWSSN.

In view of the variation of the results obtained by different researchers and the difficulty in choosing a standard (Willis, et al., 1974), the 28 shocks in the data file for which both $m_b$ and $M_s$ were available, were used to derive the following relationship.

$$M_s = 2.04\, m_b - 5.31$$

or $$m_b = 2.6 + 0.493\, M_s \qquad (2)$$

Data points of the 28 pairs are plotted in Figure C. These two equations were found to agree at magnitude $m_b = M_s = 5.1$; above this $M_s > m_b$; below it $M_s < m_b$ .

Equation 2 was compared with the equation 1 given by Richter, and it was found that equation 2 would give values always higher than those given by Richter's equation with difference increasing from 0.015 at magnitude of 2 up to 1.5 at magnitude of 7.

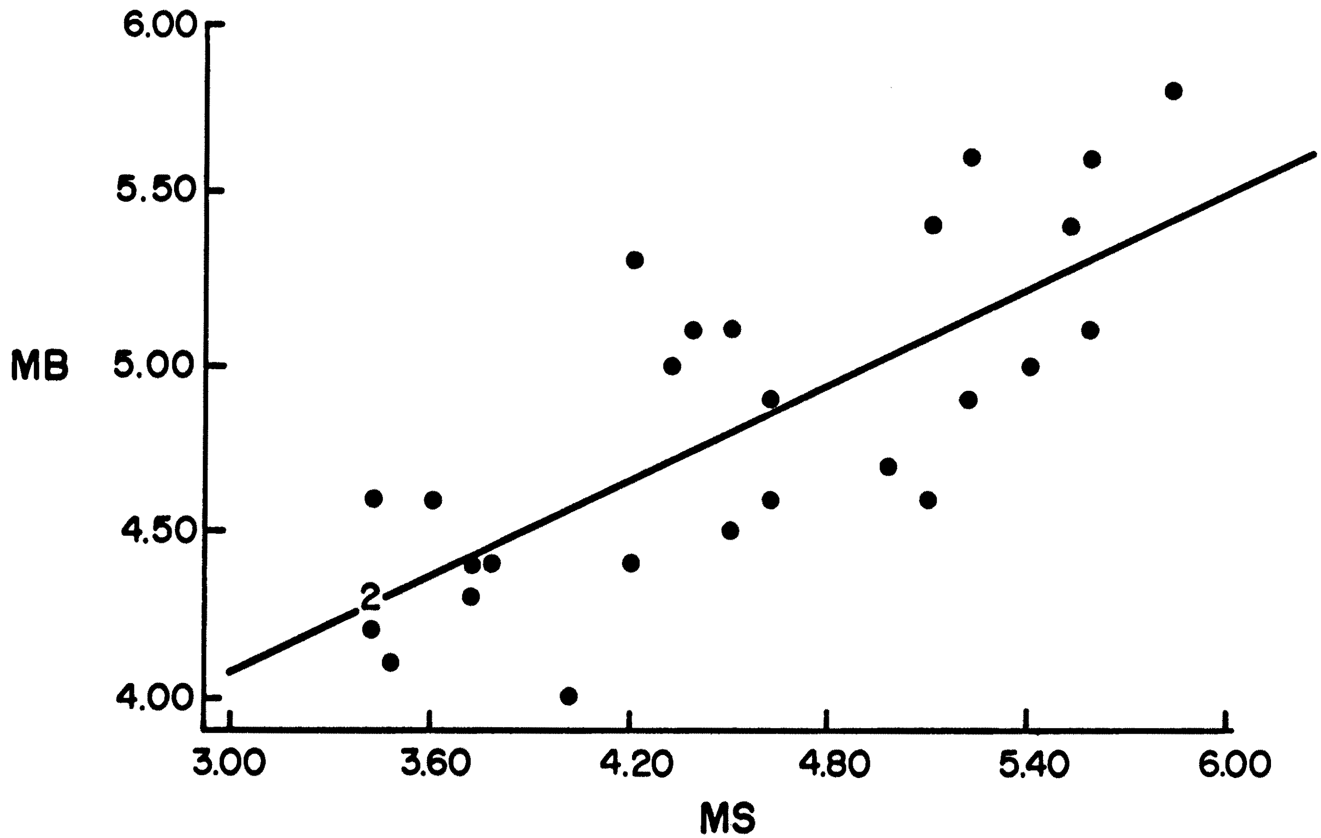


Figure C. Relation between $M_B$ and $M_S$.

## APPENDIX D

## WORLDWIDE STANDARD SEISMOGRAPH NETWORK (WWSSN)

Observational seismology remained backward until the 1900's, when the first reliable seismographs became available. Then, seismographs continued to be developed by different scientists until 1961, when the United States Coast and Geodetic Survey began establishing a worldwide network of seismographic stations (Figure D). Signals from an earthquake or nuclear explosion can be recorded all over the world at 125 stations on instruments of exactly the same characteristics so that accurate comparison of changes of earthquake intensity and magnitudes with distance can be made. A much clearer picture of the worldwide seismicity became available and is getting more definitive as the number of recording stations grows larger and larger. Today, there are over 1,000 operational seismographic stations in the world and earthquakes of magnitude 4.5 or over can be located anywhere on the earth. However, no station is located in Libya.

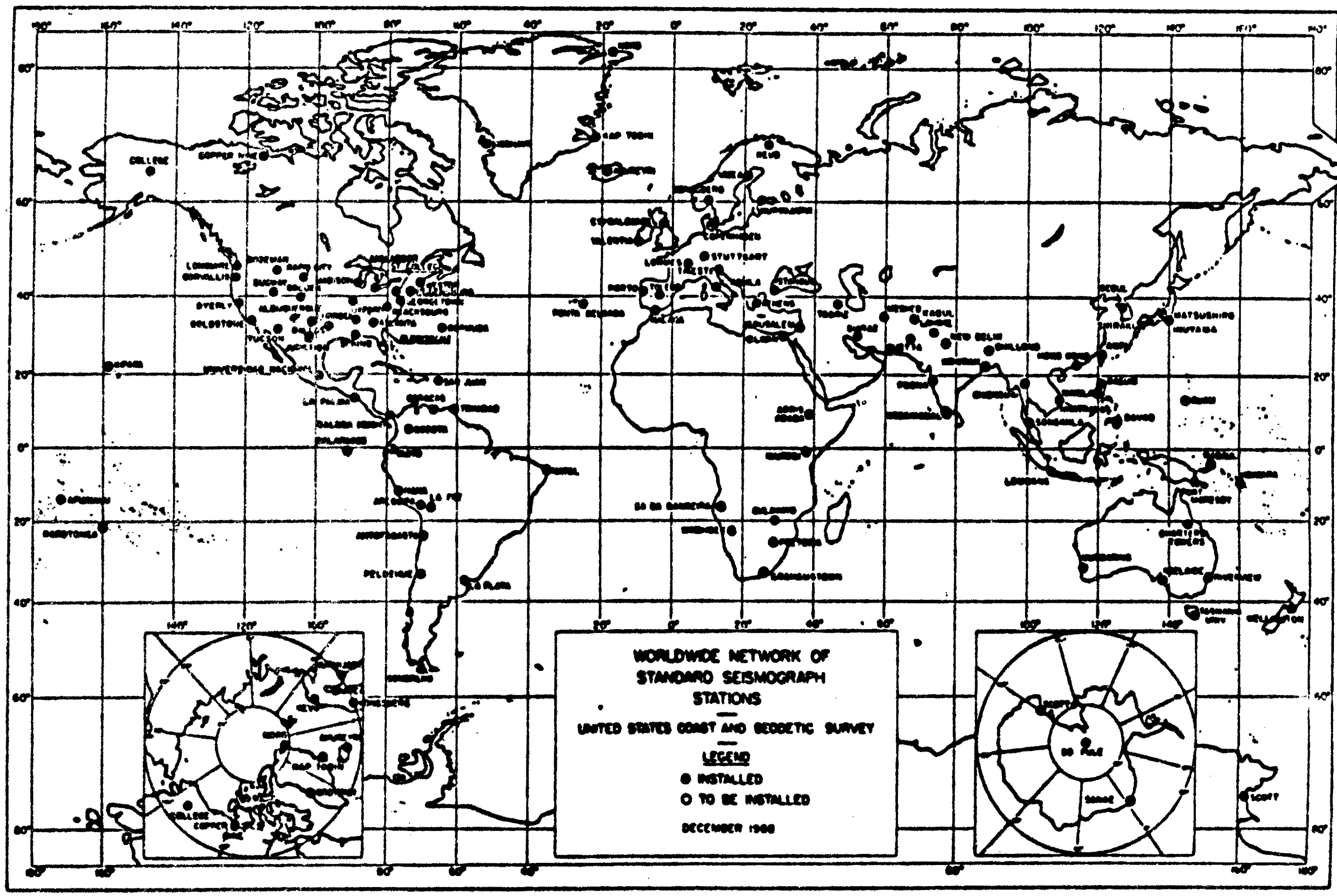


Figure D. Worldwide Standard Seismograph Network (American Geophysical Union, 1968).

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